

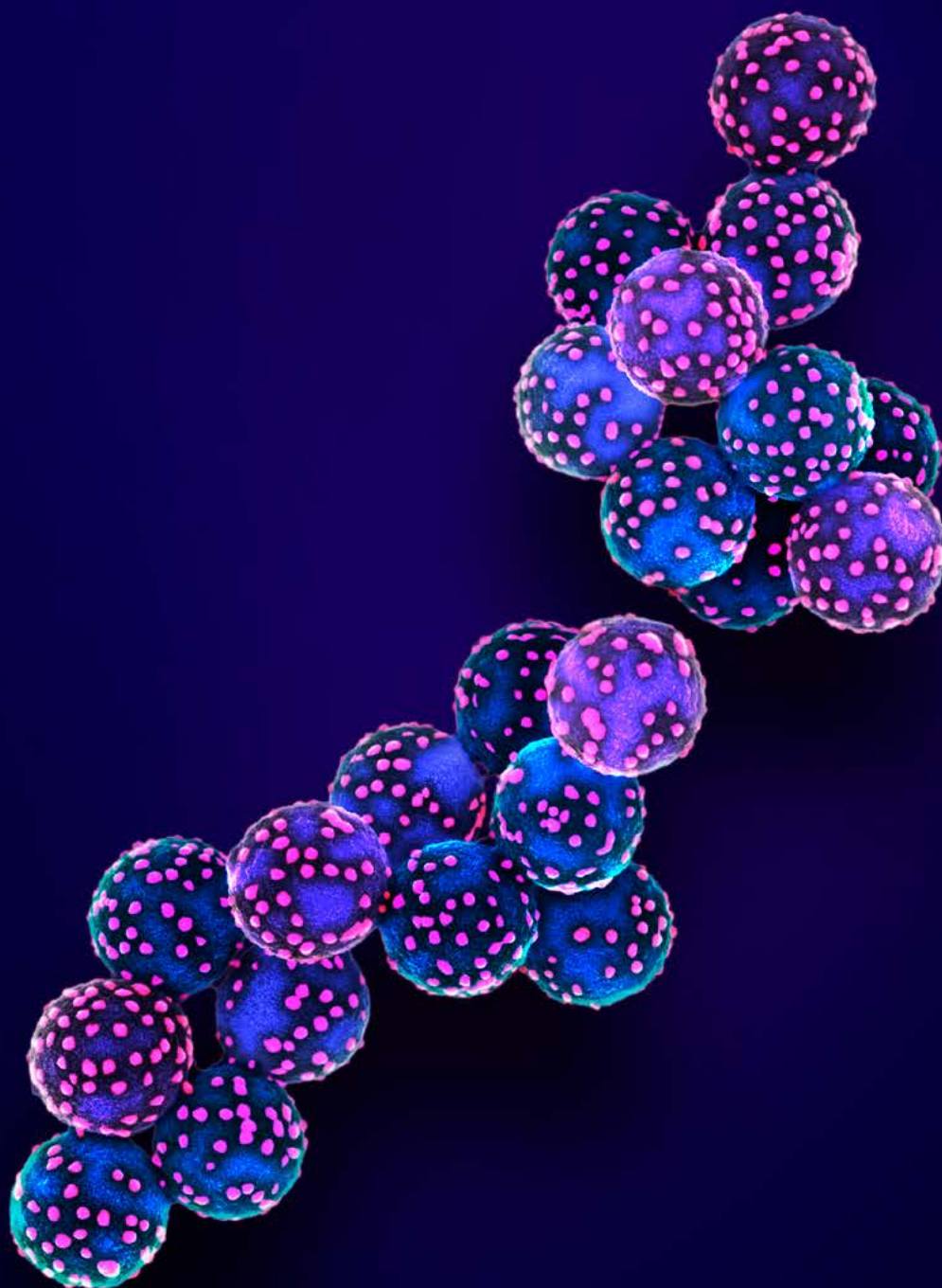


Federal Ministry
of Education
and Research

 THE NEW
HIGH-TECH
STRATEGY
Innovations for Germany

nano.DE-Report 2013

Nanotechnology in Germany today





Federal Ministry
of Education
and Research



nano.DE-Report 2013

Nanotechnology in Germany today

Foreword



Nanotechnology is one of the most important key technologies of our time. It has the potential to help resolve some of the greatest challenges faced by society, such as climate change, energy supply, health and mobility. Over one thousand companies in Germany are now involved in the commercial application of nanotechnology; the sector employs around 70,000 people, and that number continues to rise.

The Federal Government is putting in place a secure, sustainable framework for nanotechnology. Through an extensive programme of support measures and research, we are seeking to avoid successful innovation in this field being put at risk as a result of any unforeseen negative impacts of nanomaterials on man and the environment. For this reason the Federal Ministry of Education and Research (BMBF) has already been funding research into the risks associated with nanomaterials for the past seven years, and the results of this research are now providing us with a detailed picture.

We are committed to providing transparent information on the research into nanotechnology and its applications. Providing a sound and reliable source of data on current research activities, market potential and the social contexts both in Germany and internationally, the nano.DE Report forms an important element in this objective.

In preparing this report relevant players from industry, research and the finance sector were surveyed in order to allow us to derive indicators as to the current economic development of nanotechnology in Germany and to assess Germany's present position in the international environment. The conclusion: Although some Asian states are emerging as rivals in innovation on the international stage, after the USA and Japan Germany continues to be one of the leading locations for nanotechnology. We must continue to build for the future upon the foundations of the excellence of our research institutes and strong industrial commitment.

A handwritten signature in dark ink, reading 'Johanna Wanka' in a cursive script.

Prof. Dr. Johanna Wanka
Federal Minister of Education and Research

Contents

Foreword

Summary	3
1 Introduction	5
1.1 Aims of the nano.DE report	5
1.2 Methodology	5
2 The state of nanotechnology in Germany	9
2.1 Nanotechnology companies	11
2.2 Public sector nanotechnology research institutions	22
2.3 Financial sector and equity capital	29
3 Market and application potential for nanotechnology	33
3.1 Overview of market potential influenced by nanotechnology	33
3.2 Medical technology and pharmaceuticals	37
3.3 Chemicals	44
3.4 Metal and ceramic materials	50
3.5 Electronics	54
3.6 Optics/photonics	60
3.7 Energy	64
3.8 Environmental engineering	68
3.9 Sensor technology and metrology	73
3.10 Automotive sector	77
3.11 Mechanical engineering	81
3.12 Other areas of application	83
4 Socio-economic background	91
4.1 National research funding	91
4.2 Networking and cooperation arrangements	93
4.3 Funding new blood	97
4.4 Safe handling of nanomaterials	99
4.5 Information for the public	104
4.6 International activities	106
List of sources and end notes	113
List of abbreviations	121

Summary

The development of nanotechnology in Germany

The nanotechnology sector in Germany continues to grow. Since 2011 the number of players from business, research and society who are active in nanotechnology has risen from 1,800 to a current figure of some 2,300. This growing commitment to nanotechnology is driven essentially through the continuing funding of research by the Federal Government and the European Commission. Nanotechnology is also playing an increasingly important role in many sectors of the economy where the focus of research and development is on the creation of smaller, faster, more powerful and more intelligent products. Nanotechnology in Germany is broadly established across technological disciplines and application fields. There has been no movement in priorities in this field when compared with the 2011 survey. The majority of institutions remain active in the field of nanomaterials, followed by nanocoatings, nanoanalytics and nanobiotechnology. The areas of application primarily addressed are chemicals and materials, engineering and equipment construction (including metrology), the service sector and health/pharmaceuticals (see Chapter 2).

Employment, turnover and research expenditure in German nanotechnology firms

There are currently around 1,100 companies in Germany involved in nanotechnology in the areas of research and development and in the marketing of commercial products and services. Of these SMEs account for 75%. The rise in the number of companies as against 2011 is due primarily to industry participation in BMBF-funded collaborative projects, although new start-ups and a reorientation of company activities have also played their part. As in previous nano.DE reports, figures for numbers of employees and turnover within the nanotechnology sector in Germany were estimated from data compiled during a survey of participants. From this the number of nanotechnology-related jobs in Germany currently stands at some 70,000, of which around a third are in nanoelectronics, a quarter in nanotools/analytics and around 20% in the chemicals/materials sectors. A good 10% of the jobs are in SMEs who state their business activities are predominantly concerned with nanotechnology. The total turnover of German nanotechnology companies is estimated to be around €15 billion. This shows positive development when compared with the figure of € 13bn derived for

the year 2010. The current economic trend in nanotechnology is also seen as positive by the majority of the companies surveyed, two-thirds of whom expect to grow turnover for 2013 with one-fifth even expecting growth to exceed 10%. As many as 40% of the companies anticipate an increase in nanotechnology jobs and 50% expect increased research investment (see section 2.1).

Publicly funded nanotechnology research

Around 800 research institutions are currently active in the field of nanotechnology, including institutes and professorships in colleges and universities of applied sciences together with establishments within large public sector research bodies such as the Leibnitz Association, the Helmholtz Association, the Max-Planck Society and the Fraunhofer Society. The results from the participant survey show that there have been few structural changes in the nature and direction of nanotechnology research activities over the past two years. Third-party Federal Government funding remains the most important source of financing for nanotechnology research in Germany. This funding stream accounts for over one quarter of the total nanotechnology research budget in 85% of the institutions. These research institutions consider that the results of nanotechnology research will in particular benefit the medicine/pharmaceuticals, electronics and energy sectors over the next five to ten years. The quality and current state of development of nanotechnology research in Germany continues to be very highly rated, only the USA ranking higher. In third place is Japan, followed by (the rest of) Europe and other Asian states, the latter having improved markedly against the 2011 survey. Two-thirds of the surveyed nanotechnology research institutions applied for patents in the period from 2011 to mid-2013. Over the same period eight spin-off companies were established. 20 of the research bodies surveyed intend to found further spin-offs by 2014 (see section 2.2).

Financial sector and equity capital

Around 80 venture capital companies are involved in the nanotechnology sector in Germany. The financial institutions surveyed see chemicals, electronics, medicine/pharmaceuticals, optics, energy and the environment as the sectors most promising for the application of nanotechnology. Considering the barriers to inno-

vation in the commercialisation of nanotechnology products, the lack of a clear regulatory framework and negative reporting by the media on the risks associated with nanotechnology are currently regarded as the most relevant. Ten of the financial institutions surveyed currently have a stake in a total of 22 nanotechnology firms. Of these, five came in during the last two years. These investments are predominantly in German nanotechnology companies and often made in collaboration with one or more public sector co-investors, in particular the KfW (Kreditanstalt für Wiederaufbau, the Reconstruction Loan Corporation) bank and the Hightech-Gründerfonds (high-tech start-up fund – see section 2.3).

Market potential and areas of application

Strong growth in the value of global markets is forecast for many nanotechnology sub-sectors over the coming years. The total market for nanomaterials, nanoparticles, hollow nanostructures, nanofibres, nanocomposites and nanocoatings taken together is predicted to grow to some \$37bn by 2017, with an annual growth rate of 19%. A similarly dynamic growth rate, from \$4.8bn in 2012 to \$11.4bn in 2017, is forecast in the markets for nanotools such as nanomanipulators, near-field optics, nanoimprinting and nanolithography (excl. conventional semi-conductor lithography). Moderate annual growth of 5% is expected in the area of nanoanalytics in the microscopy market, which in 2016 should attain a volume of \$3.4bn. An overview of forecasts for the nanomaterials, nanocoatings, nanoanalytics and nanostructuring market segments can be found in section 3.1 together with the application fields for nanotechnology. Section 3.2 ff. brings together sector-specific nanotechnology applications and developments, examples of R&D projects, and the specific background conditions and challenges for 12 industrial sectors relevant to Germany.

BMBF's nanotechnology research activities

The BMBF provides around € 220m annually in funding for nanotechnology within the framework of collaborative project research (see section 4.1). A summary of the research topics drawn from around 1700 current or recently completed individual projects is set out in tables in the sections covering each field of application in sections 3.2 to 3.12. Supplementary information is provided on European-level research activities under

the 7th RTD Framework Programme, in which Germany is heavily involved (see section 4.6).

Socio-economic background

Socio-economic conditions can have a substantial effect on the success of nanotechnology innovations in the market. Contributions from a number of acknowledged experts in each area present current developments, and individual contributions can be found on the public financing of nanotechnology research in Germany (section 4.1) as well as on nanotechnology networks and collaboration (Leibniz institutes, Fraunhofer Society, the “nano-in-Germany” initiative, and Deutscher Verband Nanotechnologie, see section 4.2). In addition, the activities and successes of the BMBF's program to support young scientists in nanotechnology and materials science are described (in section 4.3). Section 4.4 “Safe use of nanotechnologies” contains contributions on nanomaterial risk research, safe handling of nanomaterials in the workplace, on the regulatory frameworks for the safe use of nanomaterials, and on the detection of nanomaterials in products for regulatory purposes. In section 4.5, “Information for the public” you will find brief descriptions of the “nano-Truck” initiative and the BMBF's Internet-based “DaNa” knowledge platform. With regard to international activities, the European research funding programme, the current state of standardisation efforts at international level and the international activities of the OECD in the field of nanotechnology are all explained in brief contributions in section 4.6.

1 Introduction

As one of the key technologies in the Federal Government's High-Tech Strategy 2020, nanotechnology is of central importance to Germany as a location for technology and science. The promotion of nanotechnology is being driven across different ministries by means of the Nanotechnology Action Plan 2015. This report provides an overview of the current state of nanotechnology in Germany, looking at the development of the industrial and research environment, the market and application potential, support activities and the socio-economic conditions.

New technological solutions are needed to address global challenges such as climate change and the protection of the environment, how to supply a growing world population with energy, food and water, and future-proof concepts in the areas of mobility, security, information and communication. Nanotechnology is one of the key technologies the Federal Government is funding and further developing within the framework of its High-Tech Strategy 2020 as a contribution to solving the urgent problems affecting our future. In many industrial sectors nanotechnology is key to producing innovative and competitive products for the world market. Germany is up against stiff international competition in this respect where, in addition to the USA and Japan, account must be taken of the emerging Asian countries such as China, South Korea or Taiwan.

1.1 Aims of the nano.DE report

With a view to constantly monitoring developments in nanotechnology and Germany's position in the international context, the Federal Ministry of Education and Research has since 2009 attempted to establish the state of play of nanotechnology in Germany over a two-year cycle. The nano.DE report is intended to provide an informational basis for the preparation of a meaningful system of indicators for the economic development of nanotechnology in Germany that can be compared over time. In addition, the report sets out current sector and technology trends along with developments in the markets for different nanotechnology applications. This should improve both the transparency and profile of the nanotechnology sector in Germany and

provide a sound factual basis for both political and business circles. As in the two previous publications in 2009 and 2011, this edition of the nano.DE report also sets out current developments in the socio-economic background to nanotechnology including, for example, public funding of nanotechnology research in Germany and in Europe, the building of networks, the fostering of young scientists, the safe handling of nanomaterials through risk research, risk management and regulation, public information and international coordination and standardisation.

1.2 Methodology

The methodology adopted for the nano.DE report comprises the following elements:

- **Collection of statistical indicators for nanotechnology in Germany through direct survey of players in companies, research institutions and investment bodies. In addition to the questionnaire-based survey, statistical analyses of the competency map database www.nano-map.de were performed in relation to the specific application and technological priorities of the nanotechnology firms and research institutions surveyed.**
- **Research into market evaluations, sector-specific applications and lines of research in nanotechnology through the assessment of relevant studies and databases.**
- **A description of the socio-economic conditions relating to nanotechnology by means of guest articles by acknowledged experts.**

Survey of players to elicit statistical indicators

As an interdisciplinary activity, nanotechnology is not normally treated as an independent topic in relevant research and business databases, meaning it is not possible to derive statistical indicators for nanotechnology from publicly available sources. For this reason, as part of its analysis of the current state of nanotechnology in the country, the BMBF undertook its own survey of players in the various nanotechnology sectors in Germany using discrete questionnaires for each of the three sectors covered: industry, public research and venture capital. As in previous surveys, relevant players were identified from the internet-based "Competency

Map Nanotechnology” (www.nano-map.de) created by the BMBF. It is assumed that the competency map substantially represents the landscape of nanotechnology players in Germany. At the time of the survey in June 2013 the continually updated and extended competency map had 1110 companies, 770 research institutions and 79 financial institutions registered.

To ensure comparability and continuity of the data, the same definition of nanotechnology was used in all the questionnaires:

“Nanotechnology concerns itself with the controlled manufacture, analysis and use of materials and components with functionally relevant structural dimensions between approximately 1 and 100 nanometres in at least one external dimension. As a result of the nano-scale new functionalities and properties emerge that are capable of contributing to the improvement of existing products and applications or to the development of new products and applications.”

This definition, based on the international ISO standards (see section 4.6), focuses on the innovation aspect and technical usefulness of nanotechnologies. At the international level however it has not so far been possible to arrive at a consensus on the definition of nanotechnology. Although internationally agreed ISO definitions exist in some areas, disagreements persist in regard to certain aspects. For example, in a recommendation of the European Commission, nanomaterials are defined solely in terms of the size of the relevant object, regardless of any functionality due to that nanoscale. Additionally, even within a given definition there is often no clear process for a definitive classification and demarcation of nanotechnology (see section 4.4).

For the above reasons, the information requests are subject to a degree of interpretation on the part of the institutions taking part which, depending on the definition used, may or may not class themselves as being involved in nanotechnology. With respect to the institutions listed in the competency map however, we can assume a direct involvement in nanotechnology since the currency and consistency of the entries are periodically reviewed with the institutions.

Survey of nanotechnology companies

For the survey, 1110 questionnaires were sent out to companies that were listed in the nanotechnology competency map at the time of the survey. This included not only companies for which nanotechnology comprised a substantial portion of their business activities but also, in some cases, component and system manufacturers that further process nanotechnology primary or intermediate materials but do not themselves perform any nanotechnology processes. In some cases nanotechnology involvement was limited to research activities performed, for example, within the framework of BMBF funding programmes. Also considered are service companies contracted for research, coating and analytics, risk assessment, sales and marketing and consultancy. Checking into non-returned questionnaires identified 16 companies, until then registered in the competency map, for which no business activities could be traced resulting in these companies being deleted from the database and from Germany’s nanotechnology company population. Non-returned questionnaires were followed up via email and telephone.

A total of 197 companies took part in the survey. The number of responses was thus of a similar scale to that in 2011 (205 responses). Around one-third of responses came from companies that had already participated in the 2011 survey. This represents a response rate of 18% of the total number of nanotechnology companies. 22 companies in the 2013 survey declared that they were inactive in the nanotechnology field as defined for the survey, somewhat more than in the 2011 survey (12 inactive companies). It was believed that one of the reasons for this may have been the discussions on definitions, regulatory restrictions and mandatory labelling requirements for nanomaterials, together with sometimes negative reports in the media on the risks associated with nanomaterials, which could have reduced the willingness of companies to publicly position themselves in the field of nanotechnology. This applies in particular in the chemical industry (see sections 3.3 and 4.4). For all the companies listed in the nanotechnology competency map there exists some link to nanotechnology, at the very least in the context of funded projects. A total of 175 questionnaires were evaluated, the results of the survey being set out in section 2.1.

Survey of nanotechnology research institutions

For the survey of the research sector, questionnaires were sent to 770 research institutions registered with the nanotechnology competency map at the time of the survey. These were research bodies within universities and universities of applied sciences as well as research centres grouped within large-scale public research bodies such as the Leibnitz Association, the Helmholtz Association, the Max-Planck Society and the Fraunhofer Society. The entries in the university sector relate in part to complete institutes but also in some cases to departments or, in individual cases, to research units within the relevant university. In a small number of cases research institutions constituted as an association or foundation are included. It can be assumed that while the data does not fully cover the public-sector research environment in Germany, it does at least give a good reflection of that environment and in particular as regards research institutions participating in publicly-funded nanotechnology projects. 174 questionnaires were returned during the survey, a response rate of approximately 23%. Only one of the institutes responding indicated that they were not actively involved in nanotechnology. 173 questionnaires were thus available for evaluation, the results of which are summarised in section 2.2.

Survey of financial institutions

As was done in the 2011 survey a separate questionnaire was used to bring the financial sector into the scope of the survey, since private equity capital is an important factor in the successful development of new fields of technology. 80 questionnaires were sent out to financial institutions listed in the nanotechnology competency map at the time of the survey.

A total of 19 responses were received. One institution, for which no further business activities could be traced, was deleted from the data set which left a response rate of approximately 24% of the 79 institutions. Two institutions indicated that they were not active in the field of nanotechnology, leaving a total of 17 questionnaires available for evaluation. The response rate is thus significantly lower than in the 2011 survey, at which time 27 questionnaires were available for evaluation. It is surmised that the cause of this reduced level of participation is a consequence of the general reduction in commitment to venture capital funding in

Germany resulting from the financial crisis. In addition, the decision this year on the taxation of free-float dividends arising from smaller shareholdings in domestic joint-stock companies has adversely affected the readiness of venture capital companies to engage in the riskier investments in Germany. In addition, the focus in the finance sector is on application areas and markets (such as healthcare, energy, environment, ICT) while cross-sector technologies are given a lesser profile. The results of the survey are set out in section 2.3.

Overview of market volumes, sector-specific applications and research approaches in nanotechnology

The qualitative and quantitative analysis of market potential and sector-specific applications was based on international market forecasts and sector reports. Unlike in previous nano.DE reports only publications since 2011 were considered. A further source of market forecasts was provided by data from the survey of companies, in which they were asked about the size of the market in 2013 for those nanotechnology applications of interest to them. This yielded in excess of 40 market forecasts, which are summarised in the tables in section 3.1.

The presentation of the research and development priorities in nanotechnology in the individual application fields is based on an analysis of nanotechnology research projects funded by the BMBF. This analysis made use of the Federal Government's PROFI funding database which, amongst other information, contains a brief description of individual funded projects. Only projects either completed after 2011 or which are still in progress were evaluated. The nanotechnology projects identified were assigned to those application areas that were the priority focus of the research activities. In some cases distinct assignment in this way was not however possible. The projects are tabulated against the relevant funding reference. The analysis also drew on further sources, such as the funding activities of other departments and a compilation of the nanotechnology projects funded under the EU's 7th Framework Programme for Research.

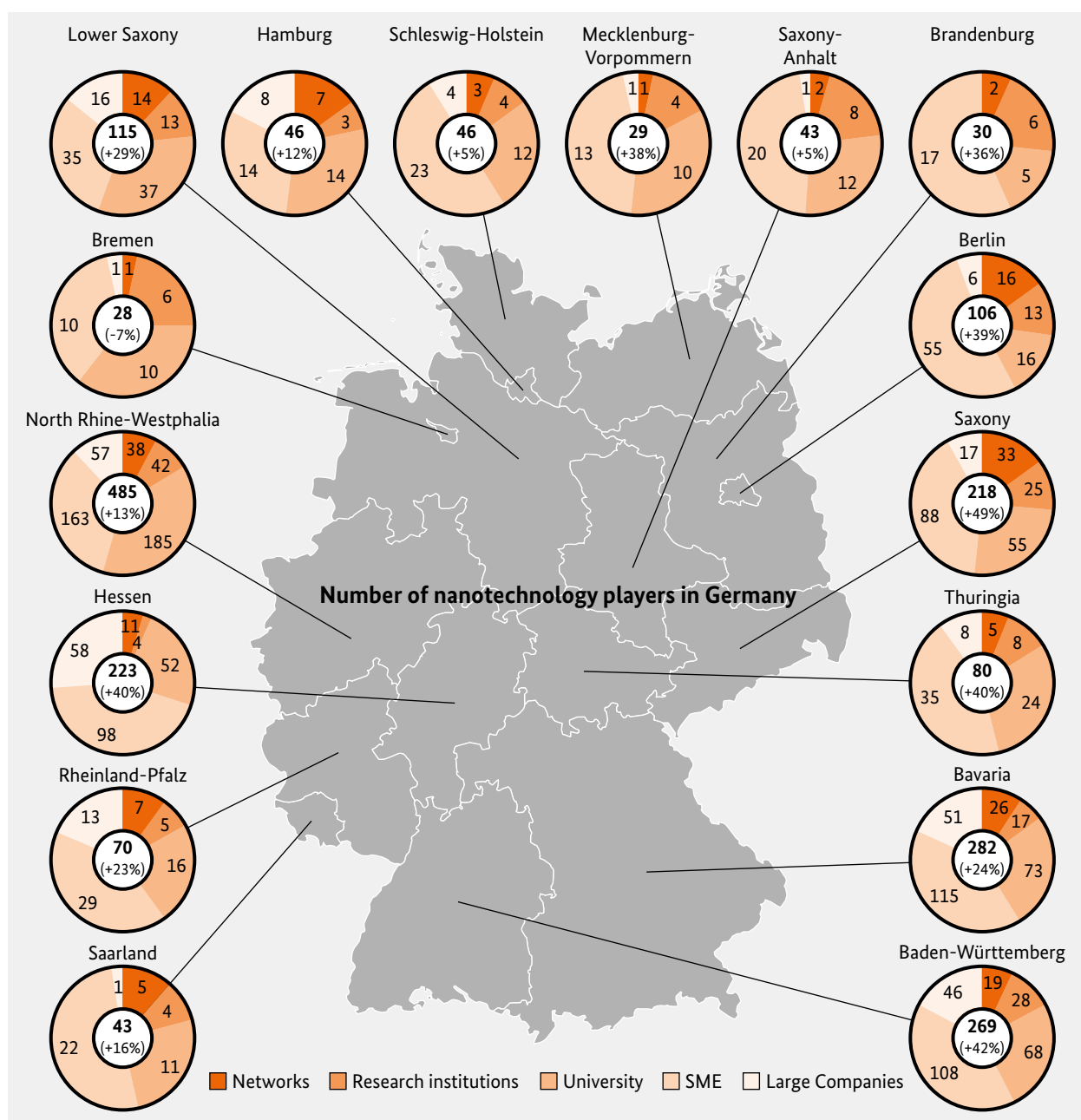
The socio-economic background to nanotechnology

In order to describe the socio-economic background to nanotechnology, both in Germany and internationally, contributions were compiled from acknowledged experts in the relevant subject areas. The topics addressed in this edition of the nano.DE report include an overview of the funding for nanotechnology provided by the Federal Government and the European Commission, support for young scientists provided by the BMBF, the international activities of the OECD and ISO, and an overview of aspects of risk research, health and safety at work and the regulatory regime in the field of nanomaterials.

2 The state of nanotechnology in Germany

Nanotechnology in Germany continues to grow. This is evidenced principally by the number of players from business, research and civil society involved in nanotechnology, which has risen from 1,800 in 2011 to some 2,300 (as at September 2013).

Nanotechnology increasingly impacting many areas of the economy, where the focus of research and product development lies on creating smaller, faster, more powerful and more intelligent solutions.

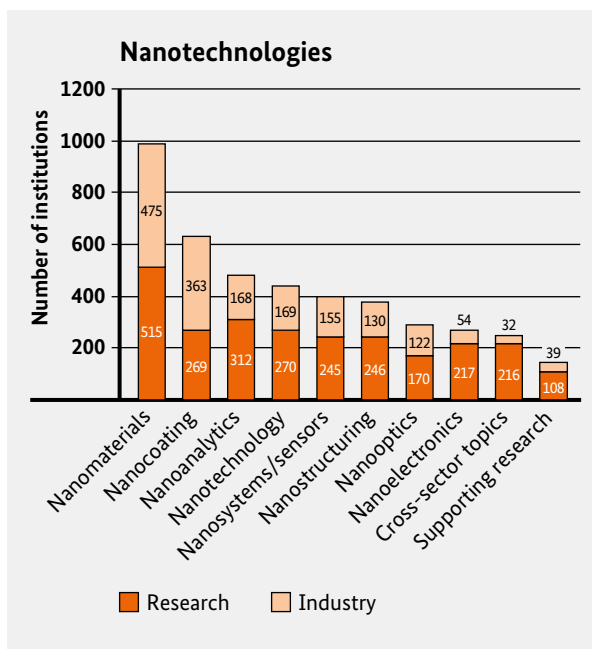


Number and regional distribution of nanotechnology players in research and industry in Germany (Source: www.nano-map.de, as at September 2013). The value in the centre of the diagrams shows the total number of institutions (in brackets is the change compared with the 2011 nano. DE report).

The nanotechnology competency map (www.nano-map.de) provides a comprehensive overview of the player landscape and priority topics for nanotechnology in Germany. Almost 2300 institutions are registered in the competency map, drawn from the categories of networks, research institutes, university research, SMEs, large companies, public authorities, financial institutions, associations/NGOs and media/museums. Half of the institutions registered are companies, with SMEs accounting for 75% of these. Research institutes represent around one third of the players, including 800 university institutions and 160 institutional research bodies. The remaining players are divided between other bodies such as networks, public authorities, associations, financial institutions, NGOs and knowledge transfer organisations (media/museums). Assignment of players to priority areas is based either on self-assessment by the institutions themselves or categorisation by the VDI TZ based on publicly available information.

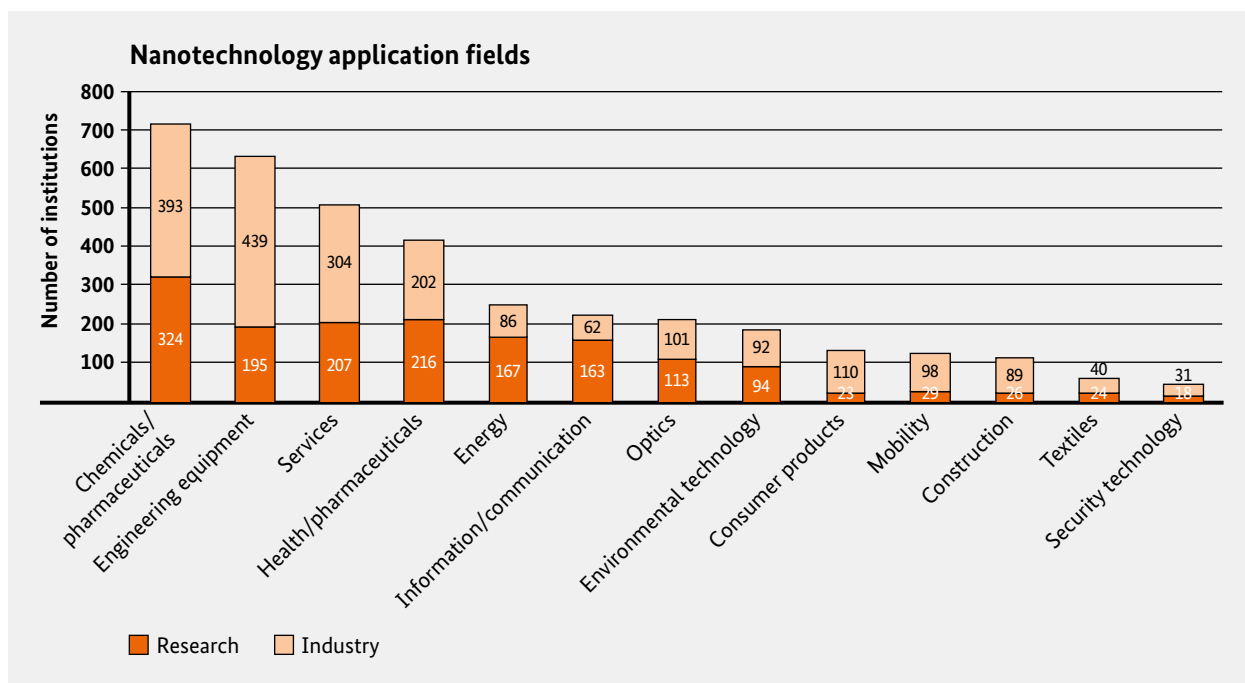
In terms of regional distribution, North Rhine-Westphalia shows the largest number of nanotechnology players, followed by Bavaria, Baden-Württemberg, Hessen and Saxony. Compared to 2011, the number of nanotechnology players recorded has increased in all the federal Länder, with the exception of Bremen. The increase can be explained essentially by the recording of new research institutions and companies participating for the first time in one of the BMBF's or EU's collaborative projects. Further changes result from new start-ups, new areas of activity on the part of companies/research groups, or the termination of business and research activities. Players from Länder that have their own nanotechnology network activities, such as North Rhine-Westphalia, Bavaria, Hessen, Saxony and Baden-Württemberg, are included more fully than Länder without their own nanotechnology networks.

An analysis of the individual sub-areas within nanotechnology shows that all the relevant lines of research in industry and in public research in Germany are addressed. In quantitative terms nanomaterials continue to dominate, followed by nanocoatings, nanoanalytics and nanobiotechnology. These individual sub-areas also involve an above-average proportion of companies.



Assignment to nanotechnology sub-areas of German nanotechnology institutions from the research sectors (networks, research institutes, university research) and industry (SMEs and large companies). (Source: www.nano-map.de, as at September 2013; institutions may be assigned to more than one sub-area).

With respect to nanotechnology application fields in industry and research, no major changes have arisen as against 2011. Chemicals/materials continue to stay ahead of engineering and equipment construction (including metrology), the service sector and health/pharmaceuticals. The largest proportion of companies (439) is to be found in the engineering and equipment construction/metrology sectors.



Assignment to nanotechnology application fields of German nanotechnology institutions from the research sectors (networks, research institutes, university research) and industry (SMEs and large companies). Source: www.nano-map.de as at September 2013. Institutions may be assigned to more than one application field).

2.1 Nanotechnology companies

As of September 2013, 1135 companies involved in nanotechnology research and development or the marketing of commercial products and services were registered on the nanotechnology competency map. This represents an increase on 2011 of 175 companies, and can be attributed primarily to industry participation in the framework of BMBF's collaborative projects funding. In addition some start-ups were recorded within this period, particularly in the fields of nanobiotechnology/metrology but also in simulation/modelling software or the evaluation of risks associated with nanomaterials. Some 20 companies have ceased business activities since 2011 and were deleted from the competency map. Alongside this there have been a number of instances of restructuring, spin-offs, takeovers, or changes in the legal form of companies.

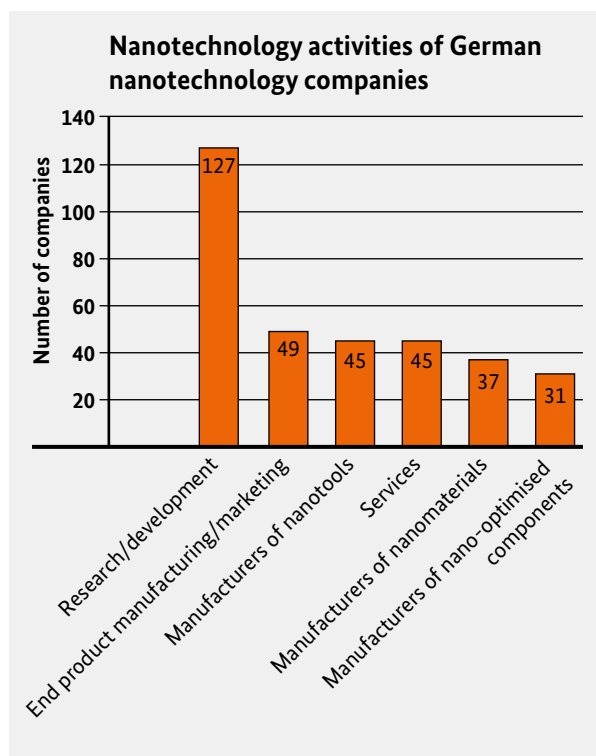
The corporate landscape in nanotechnology in Germany is diverse both in terms of structure and areas of interest and covers every sector of the value chain. It includes nanomaterial producers, manufacturers of de-

vices for creating and analysing nano-scale structures, and companies that employ nanotechnology components to optimise and improve the functioning of intermediate and finished products in various industrial application fields. The services sector also plays an important role supplying nano-specific services at various levels of the value chain including subcontract research and analysis, contracted coating services, consultancy, risk assessment, simulation, marketing etc.

As in previous editions of the nano.DE report, nanotechnology companies in Germany were further classified by means of random sampling of the 175 companies taking part in the survey. Since the makeup of the panel of companies involved in the survey is not stable, but fluctuates relatively widely (some two-thirds of companies responding had not participated in 2011), the first step is to perform a basic classification of the collected nanotechnology companies. By comparing 2013 data with that from 2011 it is possible to draw conclusions as to how well each random sample represents the totality of the companies in Germany.

Type of nanotechnology activity and year established

The participating nanotechnology companies were first classified according to their positioning in the value chain and the year in which the company was founded. Around two-thirds of the companies are involved in research and development in nanotechnology. Manufacturers of nano-optimised end products, service providers and manufacturers of devices for nanostructuring and nanoanalytics each account for around one-quarter of the total. Around 20% of the companies are active in the manufacture of nanomaterials and nano-optimised components. Since the deviations in the composition compared with the 2011 survey are minimal, it can be assumed that the random samples accurately reflect the overall makeup of nanotechnology companies in Germany.

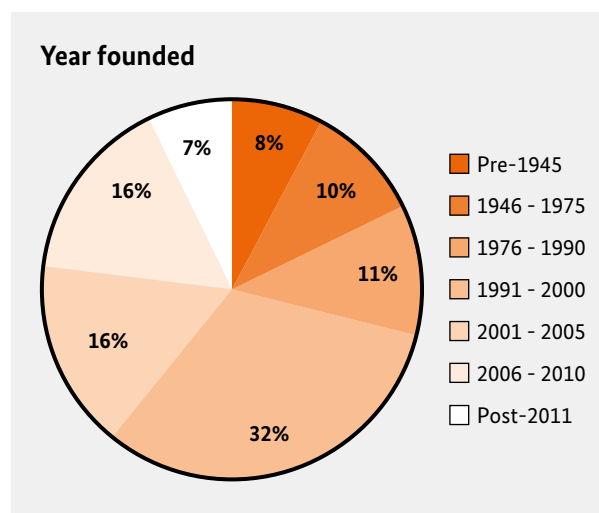


Classification according to their position on the value chain of the nanotechnology activities of German nanotechnology companies (Source: VDI TZ 2013 player survey; n=173, Multiple classification is possible).

A clear majority of the companies (71%) were founded after 1990. A similar picture emerges to that of the 2011 survey; in that survey 69% of the companies were founded after 1990. The number of companies set-up after 2006 is significantly higher (at 23%) compared with the 2011 nano.de report (14%). 12 (7%) of the companies surveyed were founded in the period 2011 to 2013. This underlines the fact that nanotechnology is a young and still developing field of technology in Germany. The companies involved are not all start-ups; some are spin-offs from established companies moving into new areas of business.

Proportion of nanotechnology activities

The companies surveyed vary in the proportion of their business activities accounted for by nanotechnology. For 29% of the companies nanotechnology was part of their core business, accounting for over 60% of their business activities. These are mainly specialised manufacturers of nanomaterials and of equipment for nanostructuring and nanoanalytics, together with component manufacturers in the optics sector (e.g. manufacturers of nanostructured diode lasers) or for the electronics industry (e.g. manufacturers of nanoelectronic components). This value accords closely with that of the 2011 survey. If we extrapolate to the total population of nanotechnology companies, based on the data in the competency map www.nano-map.de,



Year in which nanotechnology companies were founded (Source: VDI TZ 2013 survey of players, n=155).

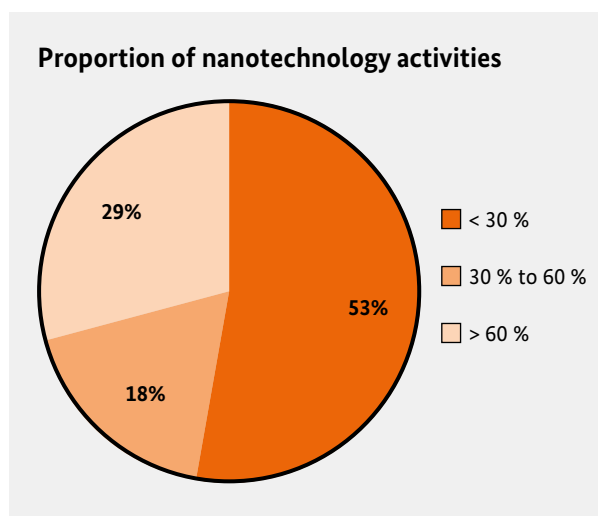
we can assume that around 300 companies in Germany currently have nanotechnology as a predominant part of their business activities. Not all these companies, however, see themselves or present themselves externally as nanotechnology companies. Rather, they are classified in traditional sectors such as semi-conductor manufacturers in the electronics industry.

Nanotechnology is less important for around half the companies, accounting for less than 30% of the company's activities. These are companies involved predominantly in the R&D aspects of nanotechnology or for which nanotechnology accounts for a relatively small proportion of their value-added or business portfolio. The latter applies for example to the large-scale chemical industry. This industry is key to the manufacture of nanomaterials and source materials for nanotechnology, although nanotechnology activities usually account for only a relatively minor part of their overall business.

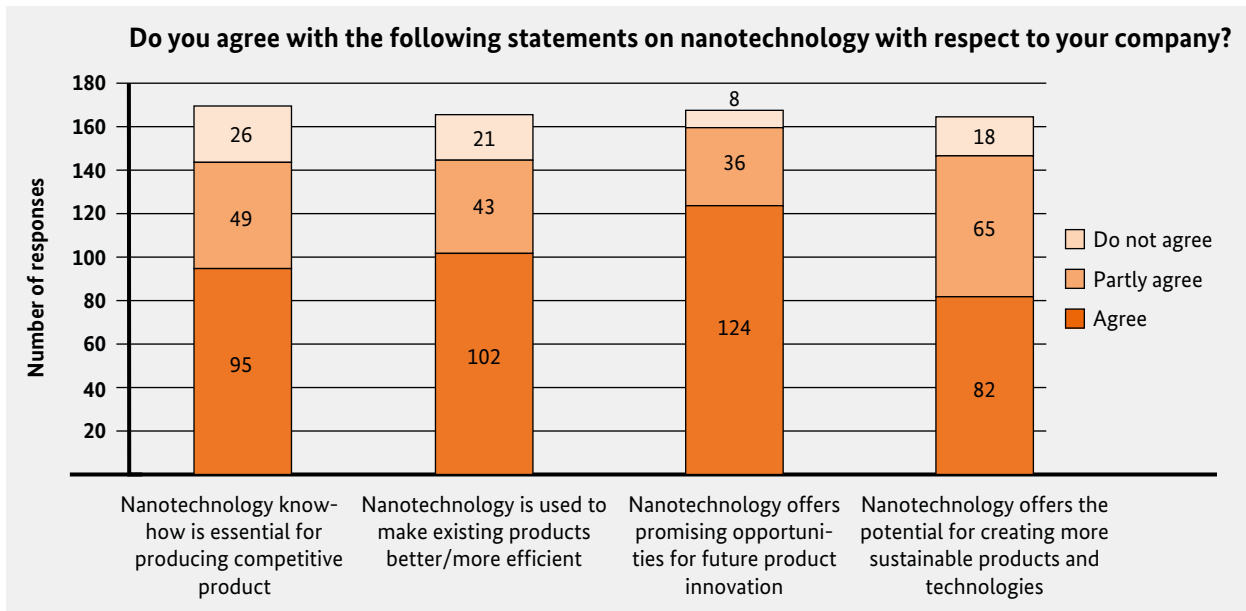
Importance of nanotechnology

In addition to capturing the share of nanotechnology in the business activities of the respondents, the current survey included a question as to the importance of nanotechnology for each company, both in terms of content and technology. Around 75% of the companies are of the opinion that nanotechnology offers prom-

ising opportunities for future product innovation. 5% disagree with this. A clear majority of the companies view nanotechnology know-how as essential to the production of competitive products and use nanotechnology to make existing products better and more efficient. There is also wide agreement with the idea that nanotechnology offers the potential to make products and technologies more sustainable. Only 10% of the companies do not share this opinion.



Nanotechnology as a proportion of overall company activities
(Source: VDI TZ 2013 survey of players, n=172).



Importance of nanotechnology to the companies surveyed (Source: VDI TZ 2013 Survey of players, n=170).

125 of the participating companies were able to cite specific advantages and unique selling points that nanotechnology brought to their own products and processes. In most cases the essential benefit cited of nanotechnology is the improvement of the properties of materials, the achievement of new properties and of better product performance. In many cases, the tuning of particular material properties and the achievement of multi-functional material and product properties is a unique selling point for the use of nanotechnology.

Nanotechnology and Germany's international position

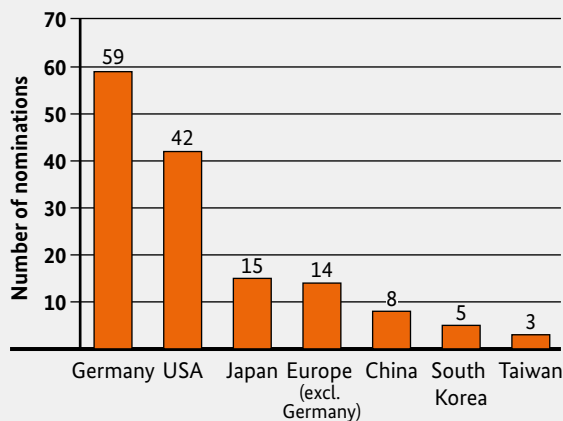
The German nanotechnology companies were asked about their most important nanotechnology products and where they rank in terms of market potential and Germany's position in international competition. The table below reflects the range of responses received. Germany's position is overall seen as positive. It also emerges, however, that in certain markets, such as electronics and, to some extent, pharmaceuticals, Germany is lagging behind its competitors from the USA and Asia. Germany is seen as strong in various areas of metrology and equipment technology (e.g. nanoanalytics equipment, ion beam processing equipment), optics (x-ray optics, diode lasers, OLED) as well as in certain areas of nanomaterials and nanocoatings.

Of the companies questioned, 59 cite Germany as the leading location for the relevant product, with 42 nominating the USA, Japan and the rest of Europe. In a small number of application fields, China, South Korea and Taiwan are also named as the main competitors. Even if the assessment may possibly be subjectively evaluated somewhat too positively, it remains overall possible to conclude a strong position for German nanotechnology companies in the markets considered. It must be borne in mind, however, that the survey represents only part of the total field of nanotechnology.

Assessment of leading countries in individual market segments					
No data		Other country leading	Germany in top 3	Germany leading	
Estimated Market Potential	> € 1bn p.a.	Nanobiotechnology Nanoreformulation of drugs, medical tracer development/ drug delivery Electronics CMOS FinFET Transistors, 22 nm CMOS Technology, 45/40 nm CMOS Technology, 32/28 nm CMOS technology	Nanotools/metrology Hydrogen sensors Nanomaterials/ coatings Anti-reflex coatings for hard surfaces, organic materials for OLEDs, scratch-resistant coatings Electronics/photonics Laser diodes	Nanotools/metrology Pressure sensors	
	€ 50m to 1bn p.a.	Nanotools/metrology Molecular beam epitaxy equipment Nanomaterials/ coatings Ag. Nanowires/conductive surfaces, CNT/electrical conductivity, silica sols, anti-fog coatings Nanobiotechnology nanocarriers as transport modules for targeted delivery of drugs and vaccines, ultra-sensitive protein testing	Nanotools/metrology Scanning probe microscopy, electron beam lithography systems Nanomaterials/ coatings Nanocoatings for dental applications, anti-microbial coatings	Nanotools/metrology Low-temperature/vacuum scanning tunnelling microscopy, IR emitters Nanomaterials/ coatings Antibacterial lacquers, scratch-resistant lacquers Nanobiotechnology Cell isolation/characterisation (Streptamer technology)	
	Up to € 50m p.a.	Nanotools/metrology Dosage analysis for nano-suspensions, beam line end stations, X-ray optics for fluorescence spectrometry Nanomaterials/ coatings Nano-optimised release agents	Nanotools/metrology AFM probes, modelling and evaluation software, particle size analysis in nm range, lab-on-a-chip systems, universal nanomechanical testers Nanomaterials/ coatings Bio-film carrier for biological sewage treatment plants, coatings for medical technology, electroluminescence film, carbon nanohorns	Nanotools/metrology Nanoceramic spray nozzles, Micro-contact printing Nanomaterials/ coatings QD semi-conductors, nanometre multi-layered coatings, dental fillers, nano-additives for UHPC	Nanotools/metrology LEIS analysis devices, x-ray optics for synchrotrons, nano-workbench, TOF-SIMS, x-ray optics for diffractometers, particle size standards Nanomaterials/ coatings Nanoaluminium casting materials, textile coatings, carbon nanomembranes, hard metals with nano-binders, insulating materials, filter materials with nanoadsorbents, magnetic nanoparticles, anti-bacterial nanosilver Nanobiotechnology Retina implants
	No data	Nanomaterials/ coatings Graphene, precious metal nanopowders, nanodiamonds, conductive nano-nonwovens, conductive inks, quantum dots, optical function layer, heat exchanger coating, reflex coatings (UV, VL, IR), decorative coatings, membranes for water treatment, polymer fillers, high-performance concrete, thermal insulation, bitumen additives Nanobiotechnology Highly refractive polymers for ophthalmological implants, intraocular lenses with active agent deposition	Nanotools/metrology Nano-based IR components (emitter and detector) for NDIR gas sensors Nanomaterials/ coatings CNT/carbon paper, CNT, hydrogen storage, chemical and electro-chemical energy storage, nanotechnology-based joining materials for MST manufacture, holographic security labels, encapsulation of ingredients (cosmetics, foodstuffs) Nanobiotechnology Non-viral genetic modification of cells	Nanotools/metrology Microlithography, PVD/PECVD equipment Nanomaterials/ coatings Nanofibres, halloysite nanotubes, non-woven materials for filters, coatings on optical components, architectural colorants, varnishes and lacquers, conductive surfaces/composites Electronics/photonics Functional coatings for photonic/electronic integration on Si base, Si-GaAs substrate	Nanotools/metrology Ion beam processing equipment/precision optics Nanomaterials/ coatings Magnesium fluoride sols, chemical nickel nanocoatings, sealants for galvanised components, tribological surfaces, easy-to-clean properties, façade impregnation, corrosion protection, nano-treated awning fabrics, nanocoated dental implants, PVD coated tools

An overview of examples of important nano-products from German nanotechnology companies with rankings for market potential and Germany's position relative to international competitors (Source: VDI TZ 2013 survey of players, n=148).

Leading countries for nanotechnology applications and products



Assessment of the leading countries for the most important nanotechnology applications and products from the companies surveyed (Source: VDI TZ 2013 survey of players, n=104, multiple voting allowed)

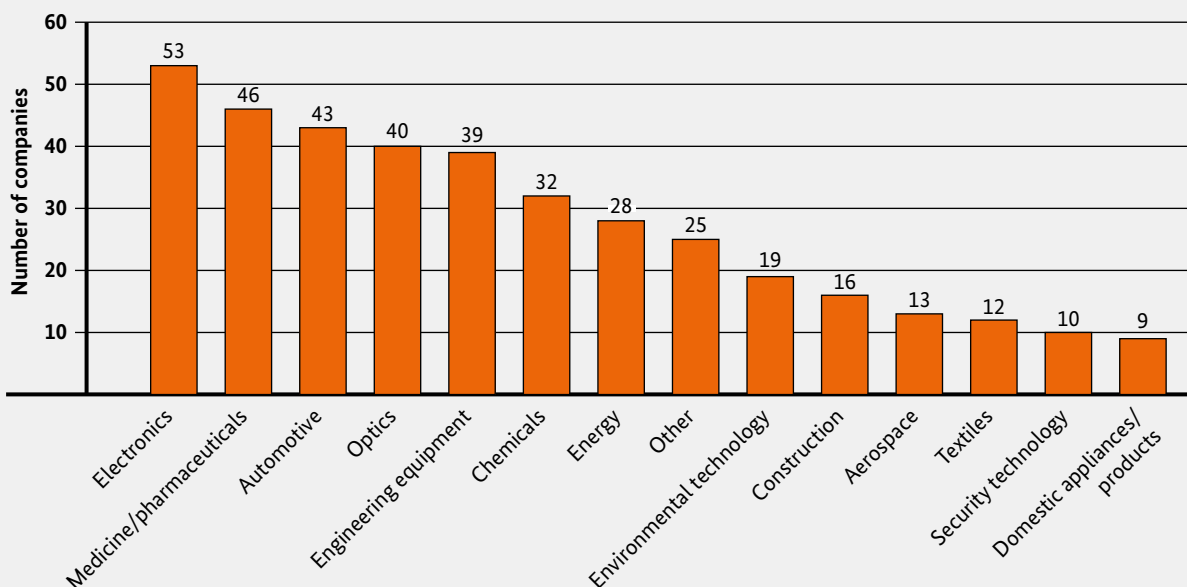
Among the most important areas for the application of nanotechnology products from the participating companies is the electronics sector, followed by medical/pharmaceuticals, automotive, optics and chemicals.

International networking by German nanotechnology companies

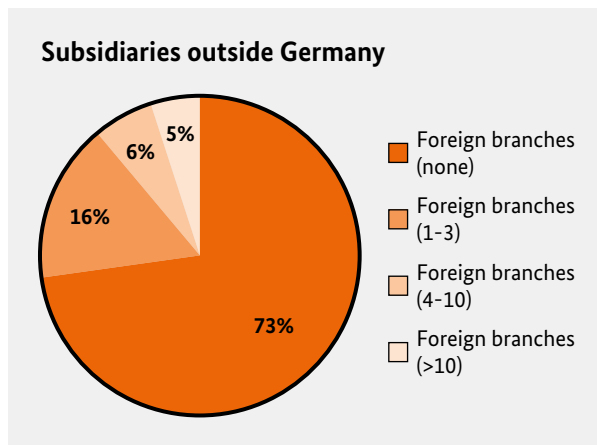
In order to characterise international networking, the participating companies were asked about their head offices, foreign subsidiaries, markets for their products and the importance of cooperation with foreign partners. Almost all participating companies have their head offices in Germany, with just five exceptions (four being in the USA and one in The Netherlands). Around one-quarter of the companies have at least one branch outside of Germany. Five percent are international groups with more than 10 foreign subsidiaries. A clear majority (73%) of German nanotechnology companies manufacture entirely within Germany.

Germany remains the most important market for their products. Compared with the 2011 survey, the proportion of companies producing almost exclusively

Most important areas of application for nanotechnology products

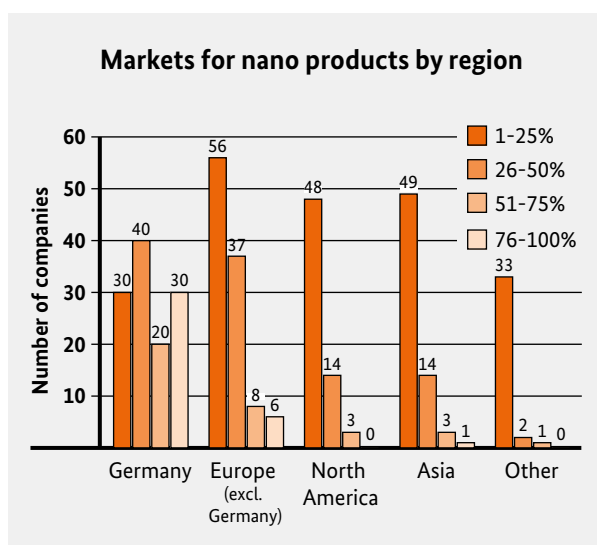


Most important application areas for nanotechnology products produced by the companies surveyed (Source: VDI TZ 2013 survey of players; n=173, a maximum of 3 votes were allowed)



Number of foreign branches of German nanotechnology companies
(Source: VDI TZ 2013 survey of players, n=160)

for the German market has decreased. Regarding foreign markets, Europe remains the most important for German nanotechnology companies. North America and Japan are of roughly equal importance, although these two markets account at most for only one-quarter of total turnover for the majority of companies. The proportion of sales in other markets is very slightly up on the 2011 survey, although only around one-quarter of the companies draw any significant turnover from these markets.



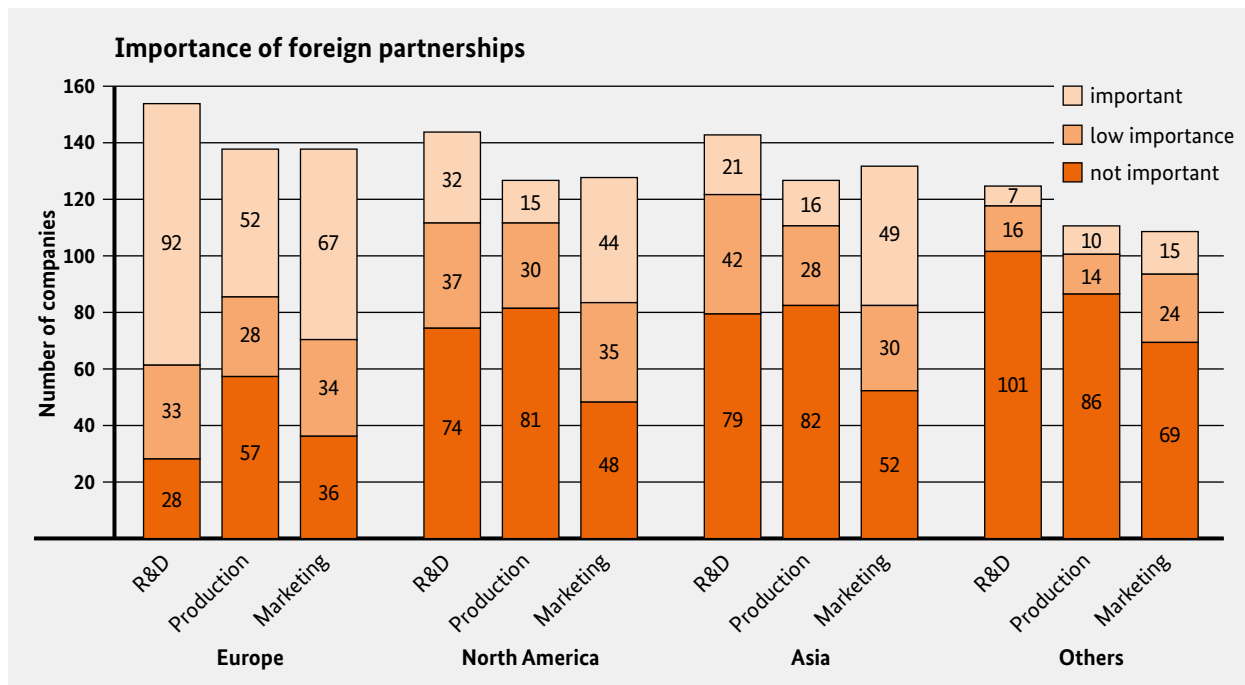
Regional market importance for German nanotechnology companies
(Source: VDI TZ 2013 survey of players, n=120)

A similar picture emerges when we look at the importance of foreign collaboration partners for research and development (R&D), for production and for the marketing of nanotechnology products. Europe is most important, ahead of North America, Asia and “other” regions. Only two thirds of all German nanotechnology companies feel it important to have European R&D partners. In North America, Asia and other regions, sales and marketing partnerships are ranked as most important. North America is more frequently ranked above Asia for R&D partnerships, whereas Asia receives more nominations for the importance of sales and marketing partnerships.

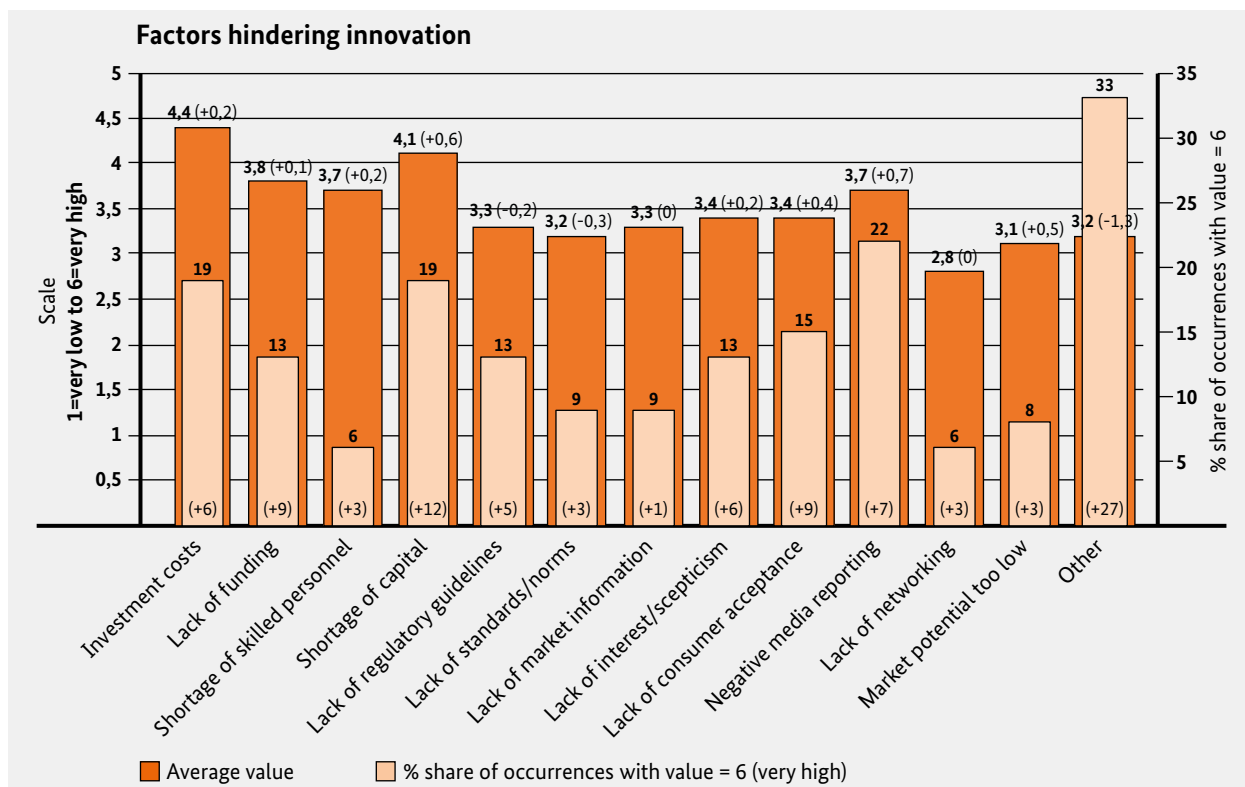
Barriers to innovation

The majority of German nanotechnology companies see no serious barriers to innovation with regard to the commercialisation of nanotechnology products. On a scale of 1 (slight) to 6 (major), values attributed to the factors surveyed fall in the mid-range from 2.8 to 4.4. There are no dramatic movements in the average values when compared with the 2011 survey. The most relevant barriers were again felt to be financial factors such as high investment costs and a shortage of capital and funding support. A shortage of skilled personnel once again scored relatively highly, together with negative reporting by the media on the risks associated with nanotechnology. The latter was rated as a very serious barrier to innovation by almost one-quarter of the companies (up by 7% compared with the 2011 survey). Analysis of the data shows that these ratings do not apply solely to manufacturers of nanomaterials but are spread widely across the various segments and application areas within nanotechnology.

Other barriers to innovation cited by the companies relate primarily to commercial risks, such as uncertainty of obtaining return on their investment within a foreseeable timescale, lack of technological/innovative breakthroughs, and the excessive gap between basic research and commercial application (the “valley of death”). Further barriers cited occasionally were excessive bureaucracy, a general European hostility to technology, and inadequate support for entrepreneurship and start-ups. In the construction sector the slow process for obtaining approval for new materials in accordance with German building regulations was seen as a serious barrier to innovation.



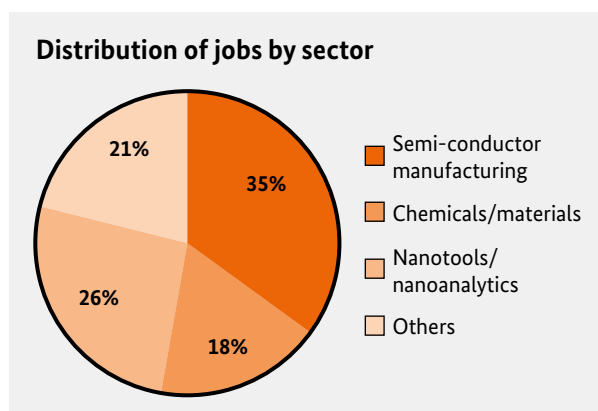
Importance of foreign partnerships for research and development, production, and marketing (Source: VDI TZ 2013 survey of players, n=153).



Assessment of factors hindering the commercialisation of nanotechnology products. Change since the 2011 nano.DE report is given in brackets. (Source: VDI TZ 2013 survey of players, n=173).

Jobs, turnover and research expenditure

As in previous surveys, this one gathered data on nanotechnology-related employment, turnover and research expenditure of participating companies. Data from the companies is based on the companies' own assessment of which business activities could be classed as nanotechnology under the definition utilised. Overall, the 141 responding companies declared around 10,200 employees working in the area of nanotechnology. The composition of the sample becomes clear when broken down by individual fields of technology. Around one-third of the jobs were in nanoelectronics, approximately one-quarter in nanotools/nanoanalytics and around one-fifth in the chemicals/materials sector. 12% of the jobs are in SMEs who identify their business activities as being predominantly concerned with nanotechnology.



Breakdown by sector of nanotechnology-related jobs in the sample (Source: VDI TZ 2013 survey of players, n=141).

In the absence of clear and meaningful criteria for definition, the assignment of jobs to nanotechnology is necessarily somewhat subjective. Assignment is particularly difficult for companies that are only involved with limited areas of nanotechnology. Isolating nanotechnology processes, especially in the case of more complex value chains, isn't really possible and often not sensible from a commercial point of view. This applies in particular to large-scale industry where nanotechnology cannot be clearly assigned to individual organisational structures. Allocation is possible, for example, in semi-conductor manufacturing or the production of

nanotechnology equipment (such as lithography devices) as the divisions involved can normally be assigned in their entirety to nanotechnology. Additionally SMEs who consider themselves nanotechnology companies also normally class all their business activities as nanotechnology. In the latter case all employees of the company are included, while for other companies only those scientists and technicians working directly on nanotechnology developments and projects are included. Assignment is problematic in the chemical industry, since nanomaterials are defined at EU level for regulatory purposes independently from any functional nano-property, with the result that the definition can also include conventional chemical products. This renders demarcation more difficult while at the same time reducing the readiness of businesses to define themselves as nanotechnology companies for fear of possible regulatory restrictions.

Despite the problems of assignment described above and the lack of objectivity, the results of the survey can be used to assess the importance of nanotechnology to the economy, if only as order of magnitude. To obtain an estimate of the total number of jobs in nanotechnology in Germany, linear extrapolation was performed from the sample to the total number of companies recorded in the nanotechnology competency map at the time of the survey. This is based on the simplifying assumption that the sample is representative of the overall number of nanotechnology companies in Germany. The data basis comprises the 1094 companies recorded in the competency map www.nano-map.de at the time of the survey. As around 11% of the companies surveyed in the sample declared that they were not working in the nanotechnology sector, the overall number of companies in Germany is corrected by that percentage to give 975 companies to be used in the extrapolation. Linear extrapolation from the 141 companies responding to the survey to the total of 975 companies produces a figure of approximately 70,000 jobs in nanotechnology in Germany. The estimate fits well with the previous series of surveys. This is primarily due to the ongoing participation of a number of large-scale companies that account for over 50% of the sample in terms of number of employees. The large-scale companies in question are involved in semi-conductor production or optics/metrology (lithography and nanoanalytics equipment, and precision

optics). In this respect, the chemical industry is a special case (see the BASF contribution in sidebar).

It is plausible to assume that the companies participating in the survey are balanced by companies that did not participate but which we can assume, on the basis of their size and fields of operation, are engaged in similar activities. It can therefore be assumed that the figure of 70,000 obtained from the survey arrived at reflects, at least as an order of magnitude, the economic importance of nanotechnology in Germany. For credibility it is worth adding that the cluster of electronics companies in Dresden alone accounts for 51,000 employees^[2], a large proportion of which are involved in nanotechnology. Nanotechnology is one of the important core competences in the chemical industry in Germany, which has around 43,000 employees engaged purely in research^[3]. Nanotechnology issues are also of considerable importance in the photonics/optics sector, which currently employs 134,000 people in Germany (see section 3.6). In addition there are some 300 SMEs involved exclusively in nanotechnology which, in accordance with extrapolation from the sample, must employ around 8,000 people in Germany. The estimate is however not suitable for deriving economic trends as too much uncertainty surrounds the process for extrapolating from the sample, the definition of nanotechnology, and the ability to classify individual business activities as nanotechnology.

Guest contribution: Nanotechnology from the chemical industry perspective – The objective is products, not technologies

Professor Dr. Martin Strohrmann, Senior Vice President, Material Physics & Analytics, BASF SE

What contribution does nanotechnology make to employment in Germany? This is once again a fundamental question in this, the third edition of the nano.DE report. And, once again, the most important “nano players” are asked how many staff they employ in the field of nanotechnology and, yet again, this includes BASF. At least one thing has changed this time, however: For the first time, BASF will not be returning any figures for employment in this field because nanotechnology is a true cross-sector technology and, as such, we use it in the most diverse areas in order to drive sustainable solutions. Nanotechnology enables us to develop materials and systems with, for example, special surface properties, mechanical strength, optical properties or an insulating effect. To give one example, nano-porous insulating materials allow us to achieve significantly more efficient building insulation than traditional insulating materials permit. In this way, nanotechnology is making an important and indispensable contribution to sustainability. However: nanotechnology, as a means of creating specific structures at the nano-scale, is just one of a variety of technologies alongside other tools such as process technology, computer-aided modelling and “traditional” chemical synthesis. We do not see the number of employees working in this area as of major importance. We concentrate on developing products with certain specific properties and use the technology that in each case allows us to achieve this objective, because what counts for our customers are the properties of a product. They don’t care whether a product was developed and manufactured with the help of nanotechnology or not. An exception here is customers in sectors who fear consumers will reject the product as a result of the discussions of possible risks, or who are subject to regulatory requirements. At the root of this are the definitions applied for regulatory purposes. These differ fundamentally from the “general understanding” of nanotechnology, as defined by the ISO and which forms the basis for this nano.DE report. For example according to the ISO, nanostructured materi-

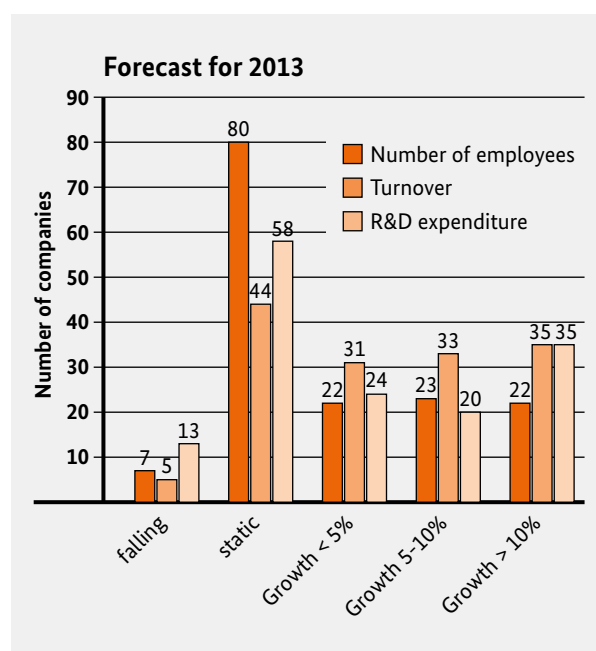
als and nanoobjects count as nanomaterials. However, the definition of nanomaterials used by the EU for regulatory purposes refers only to the proportion of nanoobjects in a particular material. As a company, we have to concern ourselves with the EU regulatory definition in order to understand the requirements of our customers and to meet our legal obligations. This is a difference between nanotechnology and most other technologies.

A further difference, arising from our own responsibility, is the special research into the safety of nanomaterials. Over the past eight years, we at BASF have developed a high level of expertise and reputation. We have to date undertaken more than 150 studies into safety and participated with various partners in 27 national and international projects. These include BMBF-funded projects such as NanoCare and NanoGEM. The central result from NanoGEM is that it is the properties of a substance that essentially determine how a nanoparticle behaves in the body, rather than its size. This opinion has now come to be shared by several renowned scientists such as Donaldson and Poland,^[4] who have squashed the myth of a nano-specific toxicity in a joint publication. It appears that the boundaries between nano and non-nano are slowly disappearing, even in toxicology.

It is no longer possible to imagine our laboratories without nanotechnology. It is a powerful driver for innovation in the development of sustainable solutions, which we need if we are to meet the major challenges of our times. We are nowhere near being able to see its full potential yet. How we achieve the ambitious aims we have set for ourselves, such as the transition of Germany to a sustainable economy – whether with or without nanotechnology – will not matter in the final analysis, but one thing I am sure of is that we will not get there without nanotechnology.

111 of the companies surveyed have provided information on turnover from nanotechnology for the year 2012. From this information we arrive at a figure of approximately € 1.7bn. Through linear extrapolation to the overall number of active nanotechnology companies in Germany (975 as of June 2013, corrected for inactive companies as described above), the total turnover of German nanotechnology companies can be estimated at around € 15bn. Comparing this with the 2010 estimate of € 13bn, we can deduce positive development. However, the same caveats relating to the accuracy of these estimates that applied to the number of jobs also apply here.

The companies were asked about their total company expenditure on research, and the expenditure that can be allocated to nanotechnology. On the basis of responses from 111 companies, the total investment in nanotechnology research in 2012 can be put at € 42m. This value is significantly down on the 2011 survey, which is explained primarily by the effect of the absence of data from large-scale companies in the present survey. If we extrapolate using the procedure described above, the total investment by companies in



Forecast for business development for 2013 as of July 2013
(Source: VDI TZ player survey; n=154)

nanotechnology research in Germany would amount to somewhere in the region of € 370m. In view of the fact that large-scale companies were under-represented in the sample as regards data on research expenditure, this estimate is probably on the low side.

The companies were asked about business trends in the current financial year 2013. The estimates as of June/July 2013 provide a reliable data basis with respect to the trend in business activities of the various companies and, taken overall, offer a healthy outlook for the economic development of the nanotechnology sector as a whole. We can therefore at this time look forward to a positive economic trend in nanotechnology in Germany. Two-thirds of the companies are expecting to grow turnover, with one-fifth even expecting growth of over 10%. The estimates are somewhat more moderate when looking at employee numbers and research investment. Nevertheless, in 2013 40% of the companies expect an increase in nanotechnology jobs and 50% expect a rise in research investment. Fewer than 5% of the companies predict a fall in turnover and employment. Around 8% are expecting a drop in nanotechnology research investment.

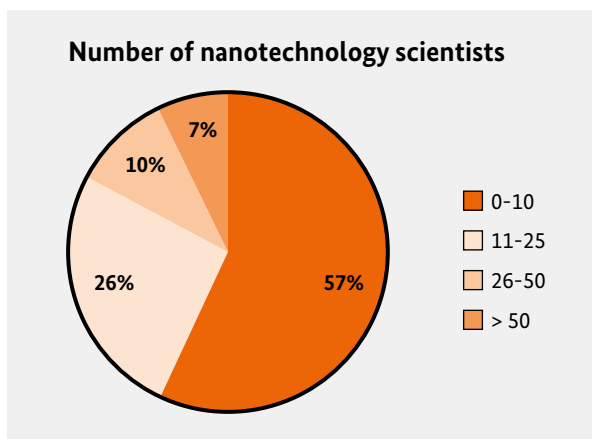
2.2 Public sector nanotechnology research institutions

As part of the survey of players carried out by the VDI TZ, public research institutions were addressed with a separate questionnaire. The following data is based on a sample of 174 research institutions. This corresponds to a participation rate of 23% of the nanotechnology research institutions recorded in the nanotechnology competency map (see section 1.2). To ensure comparability, the same questionnaire was used as in the 2011 survey. Since around 60% of the responding research institutions were participating in the survey for the first time, comparison with the 2011 results allow conclusions to be drawn not just as regards changes in commitment to nanotechnology but also as regards how well the samples depict the nanotechnology research landscape in Germany as a whole.

Classification of German nanotechnology research institutions

The nanotechnology research institutions were first analysed with respect to the number of scientists and the proportion of nanotechnology activities in the total activities. The responses from the research institutions related partly to the whole institution and partly to individual departments, university professorships and research units.

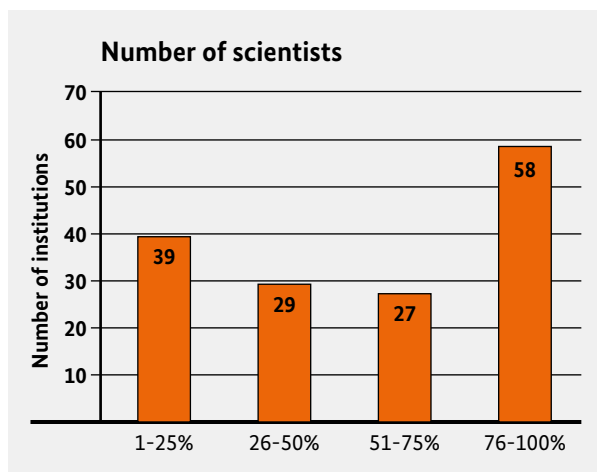
For the majority of the institutions questioned, the size of the research teams is limited to between 1 and 10 scientists. In 7% of the institutions more than 50 researchers are involved in nanotechnology, while the largest research team is a university nanotechnology network spread across several institutes and comprising 350 scientists.



Number of scientists in the participating public-sector nanotechnology research institutions (Source: VDI TZ 2013 survey of players, n=153).

A good one-third of the institutions are specialised nanotechnology research centres in which scientists make up over 75% of the total employed. 49 institutions are devoted entirely to nanotechnology. The majority of the centres are engaged in other research fields in addition to nanotechnology.

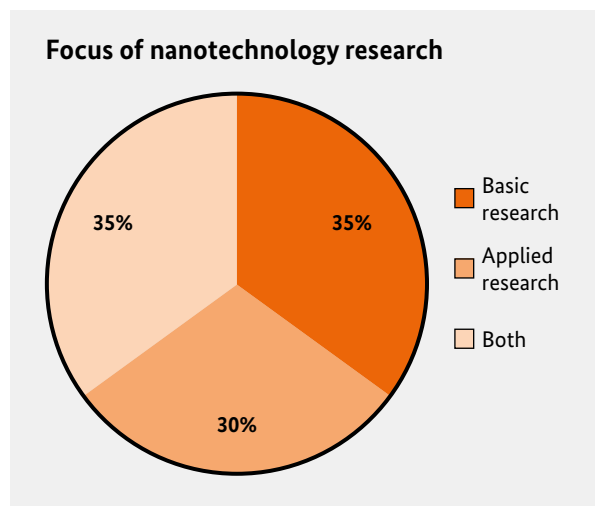
58% of the research institutions have already been engaged in the nanotechnology field for over 10 years. 14% have either only extended their range of activities



Number of scientists involved with nanotechnology, compared with the total number of scientists in the participating research institutions (Source: VDI TZ 2013 survey of players, n=153)

to nanotechnology within the last five years, or are newly founded.

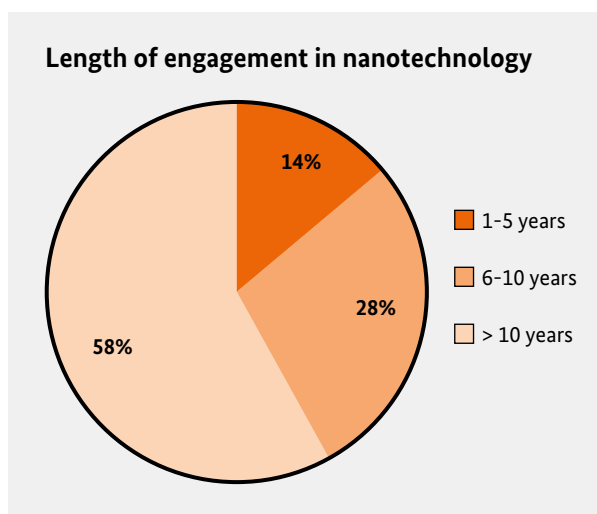
As in the 2011 survey, organisation of the nanotechnology research landscape in Germany presents a very balanced picture with respect to basic and applied research. Around one-third of the bodies are devoted exclusively to basic research, one-third to applied research and a further third engage in both aspects.



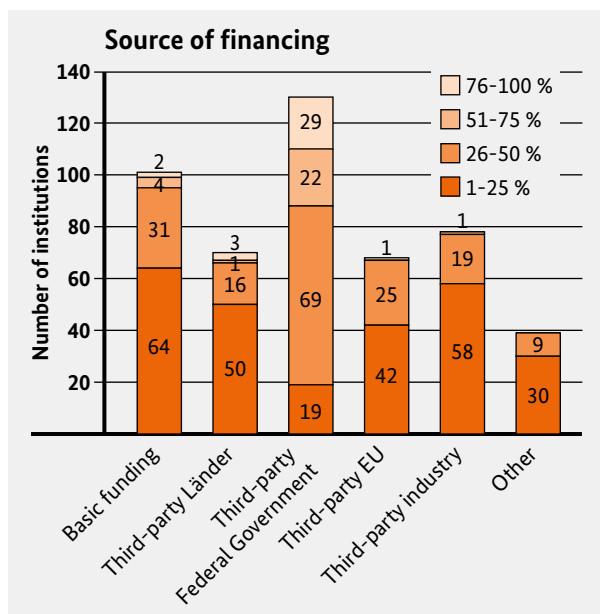
Focus of nanotechnology research (Source: VDI TZ 2013 survey of players, n=167).

Financing of research activity

Looking at the financing of nanotechnology in Germany, we again see similar results to the 2011 sample. Third party funding continues to constitute the most important source of funding. The Federal Government is the largest provider of funding, followed by third-party funding from industry, from the Länder and the European Commission. Basic financing accounts for less than 50% in almost all institutions. Other sources of financing play only a minor role.



Length of research institutions' engagement in nanotechnology (Source: VDI TZ 2013 survey of players, n=155).

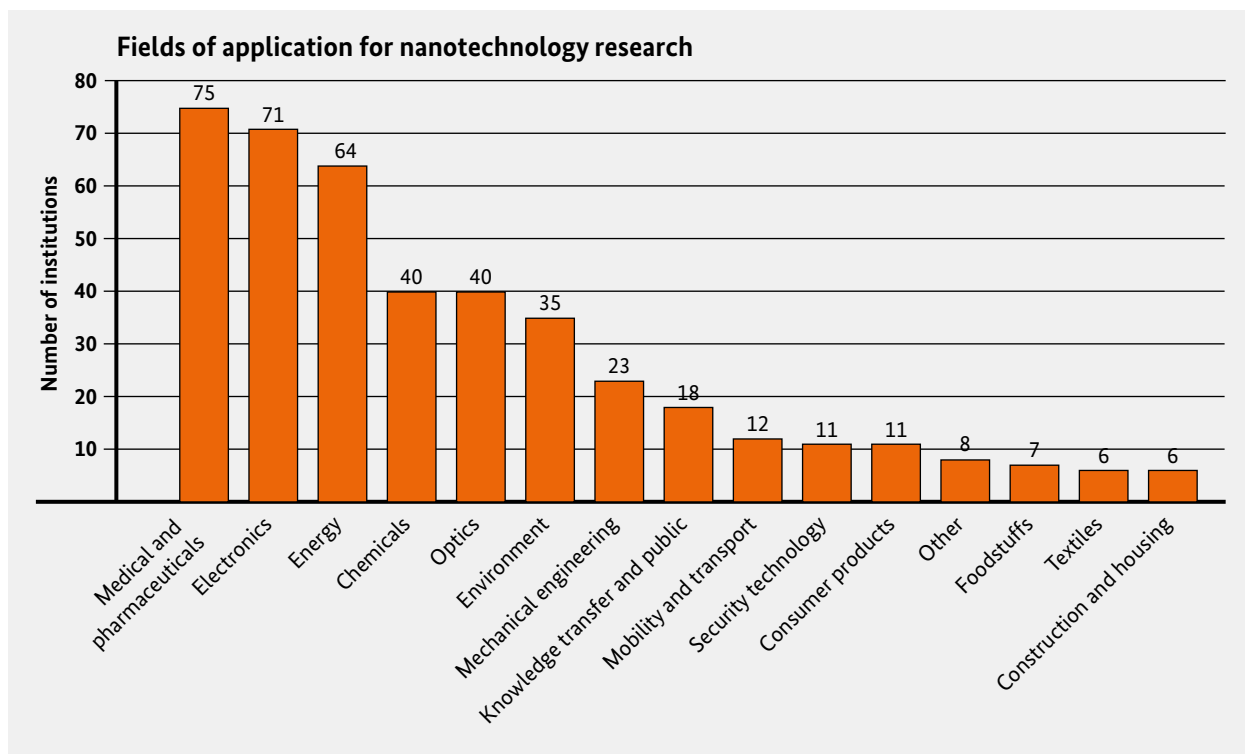


Financing of nanotechnology research (Source: VDI TZ 2013 survey of players, n=153).

Research topics and application focus

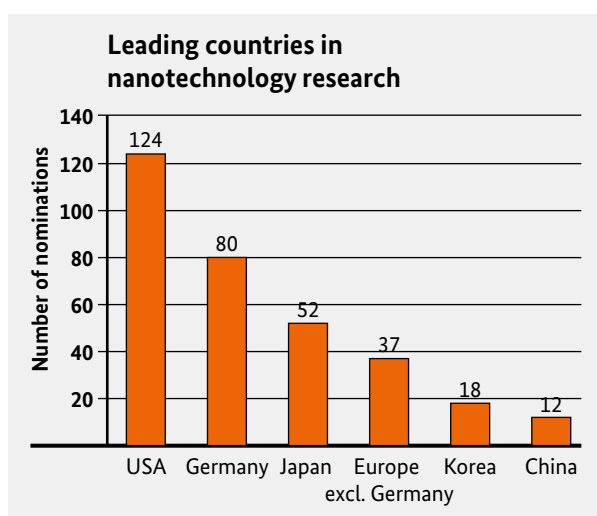
The research institutes surveyed estimate that the results of nanotechnology research will benefit the medical/pharmaceuticals, electronics and energy sectors in particular over the next five to ten years. The estimate is in line with the results of the 2011 survey, with the exception that medicine/pharmaceuticals have displaced electronics as the most important field of application and now hold a slight lead. The next fields of application in importance are chemicals, optics and environment. Overall a broad spectrum of applications is being addressed, reflecting the cross-sector nature of nanotechnology.

As in previous surveys, the research bodies were asked which of their areas of research they think are the most relevant in terms of market and product potential over the next five to ten years. They were also asked for the fields of application together with the leading countries in each area of research. In the responses, the USA was mentioned most frequently (124



Fields of application that will benefit most significantly from nanotechnology research in the next five to ten years (Source: VDI TZ 2013 survey of players, n=159, up to three votes per institution).

nominations) as the leader in those areas of research cited as having the most promising market and product potential. 80 of the institutions counted Germany as one of the leading countries in the various research fields, ahead of Japan (52 nominations), Europe excluding Germany (37), Korea (18) and China (12).

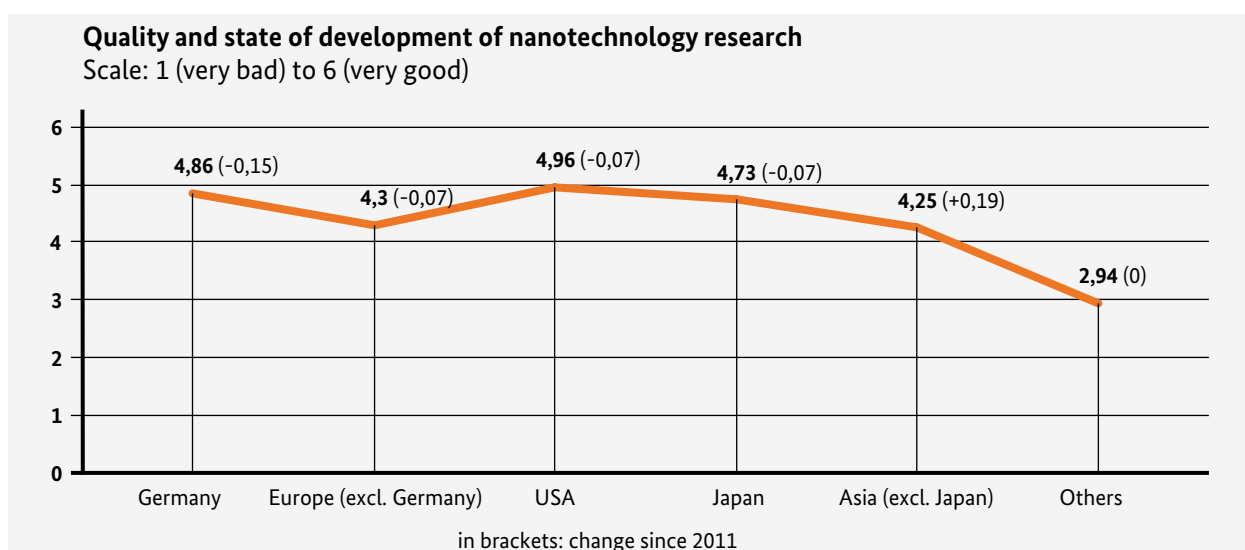


Leading countries in areas of nanotechnology research having promising market and product potential over the next five to ten years. The data is based on assessments by the nanotechnology research bodies surveyed (Source: VDI TZ 2013 survey of players, n=151, multiple votes permitted).

As expected, topics addressed by the participating research institutions cover a broad spectrum. Germany is ranked among the leading countries in many of the research areas. Only in the field of electronics do we see the countries of Asia and the USA with a clear lead. However, there are also electronic areas in which Germany is seen as having significant capability such as spintronics, printable electronics or graphene research.

Germany as a research location in international comparison

In assessments returned by the research bodies, the quality and current state of development in their own areas of research in Germany are highly rated. Only the USA is ranked higher. Japan is placed third on the rating scale, followed by other European states and other countries of Asia. The gaps between Germany, the USA and Japan are judged to be relatively small, amounting on average to 0.2 points on the scale used. The biggest change compared with the 2011 survey is in the clear improvement in the assessment of the Asiatic states (excl. Japan), which are now almost on a par with the countries of Europe (excl. Germany).



Assessment of the quality and state of development of their own nanotechnology research areas in different regions. The chart shows the average values of the assessments across all fields of technology (Source: VDI TZ 2013 survey of players, n=149).

Application area	Germany named among the leading countries	Germany not named among the leading countries
Health	Plasmonic nanosensors (D, USA), non-invasive magnetotaxis (D), bio-nano interaction/risk research (USA, D), molecular imaging (D), drug delivery, nano-encapsulation (USA, JP, D), Biosilica/Biominalisation (D), magnetic nanoparticles for diagnostics/therapy/biotechnics (USA, D, F), drug delivery (USA, D)	Bio-compatible materials for prosthesis/implants (USA), nanoparticles for pulmonary pharmaceuticals (USA), spin hybrids (Magnetohybrids) for therapy/diagnostics (USA), cell replacement therapy for neuro-degenerative disorders (USA, SE), colloidal vaccine carriers (USA), bone augmentation materials for regenerative medicine (n/a), wound dressings (n/a)
Electronics	Graphene (KR, USA, UK, CN, D), Spintronics (USA, JP, KR, D), printable electronics (USA, EU, D)	Polymer electronics (Asia, USA), atomic layer deposition for electronics (FI), non-volatile memory (JP), magnetic memory (JP), nanomagnetism (JP, USA), inspection semiconductor technology (USA), nanoparticles for printable electronics (USA), 2-D materials for electronics (USA, CN), quantum information processing/Qubits (JP, USA, EU), ferroelectrics (USA, KR, JP)
Optics	Green photonics for computer interconnections (D), gallium nitride/silicon photonics for lighting (D), 3-D laser nanolithography (D), nano-optics for lithography (D, NL), light emitters for lighting, displays, communication (D, JP, KR)	Quantum communication for cryptography (EU, CH, F), silicon photonics (JP), GaN-based laser on Si for optical data transfer (JP), meta-materials (USA), plasmonics for sensing and energy, OLED for lighting (KR)
Chemicals	Filler effects in rubbers for tyres (D, FR, USA), nano-granular metal for sensors (D), continuous nanoparticle synthesis (D, NL), hyperbranched polymers as “Quat primer” for surface coating (JP, USA, D), corrosion protection (EU, D)	SPS sinter technology (JP), ODS steel for fuel cells (JP, USA), microwave synthesis/nanoparticles (USA), magnetic catalysts and reagents (USA), nano-reinforced fibre composites for aircraft (USA), nanoporous adsorbents (USA), Metallic oxide nanoparticles (USA), dispersion coatings as abrasion protection in shaping tools (n/a), tribological control of friction and abrasion (n/a), bonding with reactive nanofoils (n/a)
Energy/environment	Thermoelectrics (D, JP, USA), removal of contaminants in groundwater and aquifers (D, USA, CZ), nano-optimised solar cells (D, USA), catalysts for fuel cells (D, JO, USA)	Electromobility (Asia), organic solar cells (KR), magnetocalorics for cooling (CN), electrolytes and electrodes for lithium batteries (CN, JP, KR), organic batteries (JP), nano-scale non-woven materials for filters (JP), photocatalytic removal of pollutants (JP), thermoelectric generators (USA)
Metrology	Nanoparticle detection for process control (USA, D), nano-granular magnetic sensors (USA, D), desorption of surface adsorbents for mass spectrometry/proteomics (USA, D)	Gas sensorics (CN, KR), integration of nanostructures (CNT), quantum dots for sensor applications (EU, JP), scanning probe metrology (USA), magnetic thin films, biosensorics (USA, JP), optochemical nanosensors (n/a)
Other	Self-cleaning surfaces for textiles (D, CH), nano/micro mirror arrays for construction/energy/security (D)	Low emissivity glazing for construction (JP, USA, EU), functionalisation of leather matrix (n/a), nanofunctionalisation of leather surfaces (n/a)

Areas of nanotechnology research with promising market and product potential over the next 5 to 10 years, classified by area of application. The leading countries in each case are shown in the brackets. The data is based on assessments by the nanotechnology research bodies surveyed (Source: VDI TZ 2013 survey of players, n=151).

The assessment for other regions has dropped significantly and is only estimated as being “average”.

The breakdown of assessments into individual fields of technology shows that the quality and state of development in Germany in each area are mainly rated as good to very good (5 and 6). There is only one below-average mark (3) relating to nanotechnology in the foodstuffs field. In certain sub-areas the assessments of Germany's position is variable. For example; research into organic electronics and polymer electronics in Ger-

many is rated between above average (4) and very good (6). The quality and state of development of research in nanotoxicology and risk research looking at the effects of nanomaterials on man and the environment are rated as good in Germany.

Location conditions and success factors

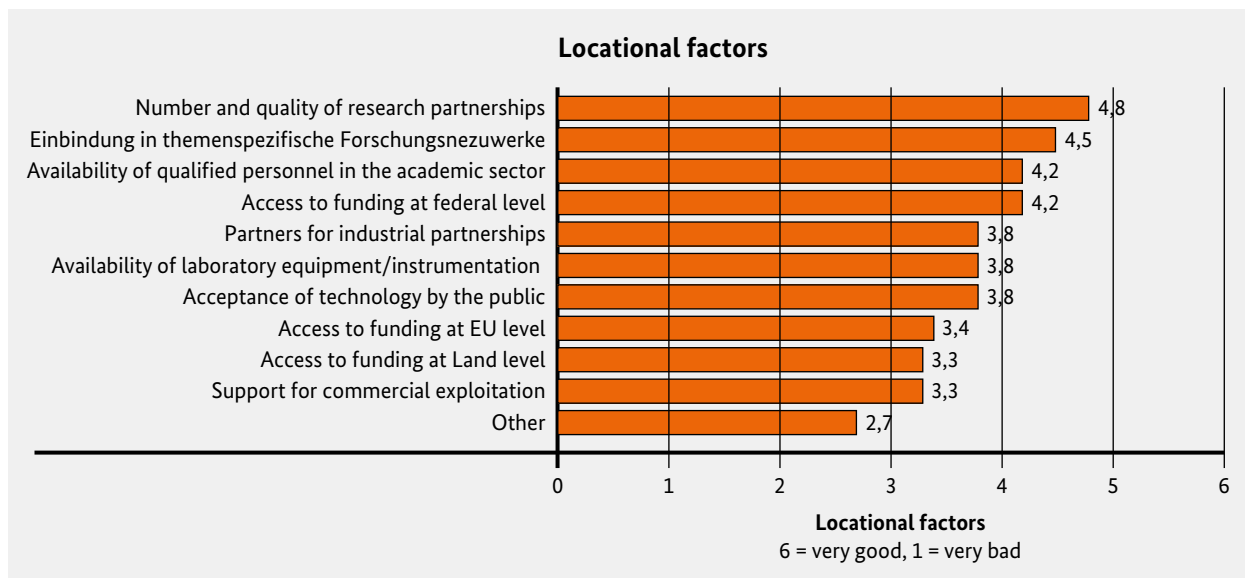
Conditions in Germany as a location for undertaking nanotechnology research activities were assessed by the research institutions as above average to good.

Quality and state of development in respondents' own fields of nanotechnology research in Germany from 1 (very bad) to 6 (very good)		
Score 6	Score 5	Score 3-4
<ul style="list-style-type: none"> • Nano-optics • Nanostructured materials for thermoelectronics • Nanocrystals as non-traditional light sources • Nanomaterials • Non-invasive magnetotaxis • Polymer electronics (PV, OLED, sensors) • Microreactors • Nanomagnetism • Nanophotonics • Medicine/health • Electrochemistry • Semi-conductor quantum dots 	<ul style="list-style-type: none"> • Organic electronics • Nanocoatings and processes • Functional thin films for sensors • Photonics, THz • Controlled release systems • Nanoapplications for textiles • Molecular functionalisation of semiconductor surfaces • Bio-nanointeractions/health, nanotoxicology, environmental risk assessment • Nanobiotechnology, nanobiophotonics • Nanoindentation • Electrocatalysts • Porous materials • Photocatalysis on nanomaterials • Nanomaterials for optical electronics/spintronics • Thermoelectronics • Chemical nanotechnology, synthesis of nanomaterials, functional nanocomposites • Nanostructured semiconductors • Solid state quantum information • Groundwater/aquifer purification 	<ul style="list-style-type: none"> • Food nanotechnology • Surface functionalisation and nanostructuring • Organic electronics • Nanoelectronic materials • DLNA nanocarriers • Atomic layer deposition • Nanowires • Nanocrystalline materials

Assessment of the quality and state of development in respondents' own fields of nanotechnology research in Germany on a scale from 1 (very bad) to 6 (very good). (Source: VDI TZ 2013 survey of players, n=51).

The most positive aspects were seen as the number and quality of research partnerships, inclusion in topic-specific networks, the availability of qualified personnel in the academic sphere and access to funding at federal level. Support for commercial exploitation of products and access to financing at Länder and EU level are down at the lower end of the evaluation scale. Technical acceptance by the population was ranked somewhere in the middle of the scale. This assessment matches the 2011 survey to a great extent, allowing us to assume that the samples are representative of the nanotechnology scene as a whole and that there have been no changes in the location conditions in the last two years.

Looking at the factors for successful expansion of nanotechnology activities in Germany, public funding for research is well out in front, followed by strengthened research partnerships with companies. The biggest shift in the assessment compared with 2011 relates to the scientific training of young academics, which only 23% of the institutions regard as important by compared with 57% in 2011. On the other hand, clear regulatory guidelines are increasingly nominated as an important factor for success. 13% now consider this relevant compared to 5% in 2011. A coordinated marketing campaign for Germany as location, and public/private partnership models, were mentioned by a only few institutions as relevant to success.



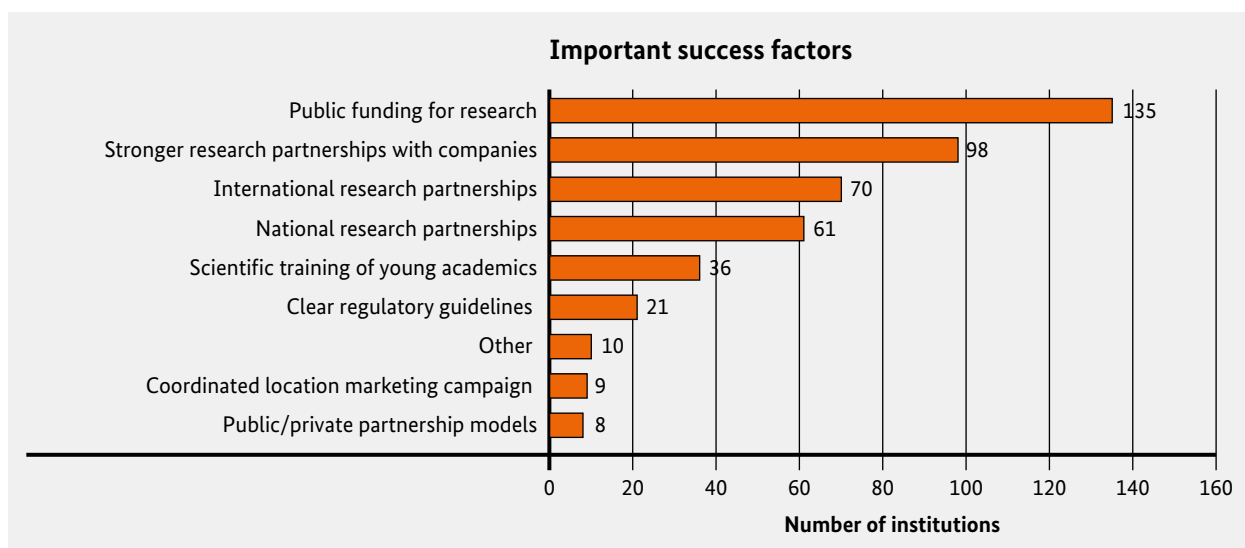
Assessment of locational conditions affecting performance of nanotechnology research activities (Source: VDI TZ 2013 survey of players, n=153).

Commercial exploitation of research results

With respect to the economic exploitation of the results of nanotechnology research, the questionnaire asked about patent applications and the founding of spin-offs.

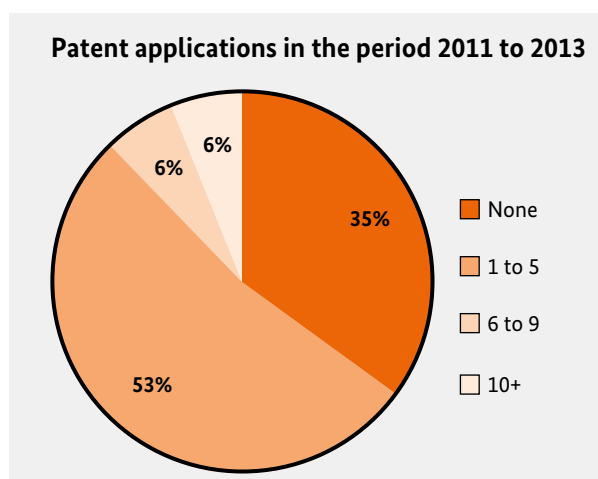
Patent applications

Patent application activity by German nanotechnology research bodies in the period 2011 to mid-2013 was almost unchanged when compared with the period 2009 - 2011. Around one-third of the bodies filed no patent applications while a good half filed between 1



Success factors for the expansion of nanotechnology in Germany (Source: VDI TZ 2013 survey of players, n=157, up to three votes allowed per institution).

and 5 applications. 6% of the institutions were very active, filing 6 to 10 patent applications during the period covered by the survey.



Patent applications filed in the period 2011 to mid-2013 by the research bodies surveyed (Source: VDI TZ 2013 survey of players, n=153).

Founding of spin-offs

The founding of spin-offs is an important indicator of success in the commercial exploitation of the results of research. The research bodies reported the founding of a total of eight spin-offs in the period from 2011 to June 2013. Approximately 20 of the research bodies surveyed plan to found further spin-offs by 2014.

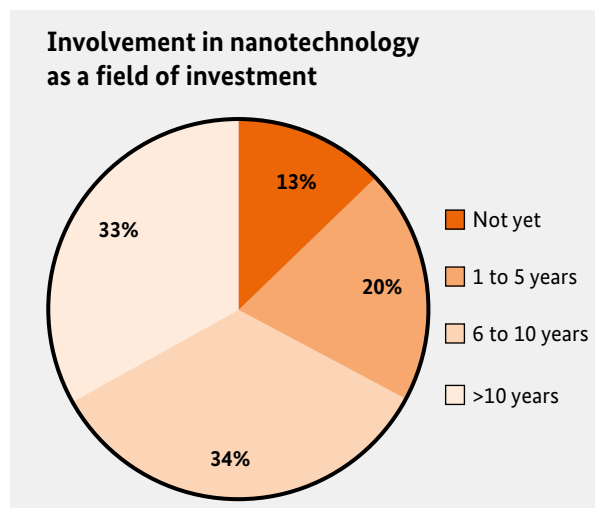
2.3 Financial sector and equity capital

As in the 2011 nano.DE report, venture capital companies involved in the field of nanotechnology were again surveyed. Particularly in high-technology fields such as nanotechnology, risk capital plays an especially important role in bringing new technologies commercial success. Only a small number of venture capital providers in Germany specialise in the field of nanotechnology. One exception is Nanostart AG, which for some years has been successfully involved in the venture capital market both nationally and internationally with a special focus on investment in nanotechnology. According to the data in the nanotechnology com-

petency map, there are currently 79 venture capital companies engaged in the field of nanotechnology. The following data is based on the 17 financial institutions that returned a questionnaire during the survey of players. In view of the small sample size (see section 1.2) the results are more qualitative in nature and cannot be considered as representative. The participating companies comprised 14 venture capital companies and three other private equity companies such as small and medium-sized private equity companies.

Duration of engagement in nanotechnology

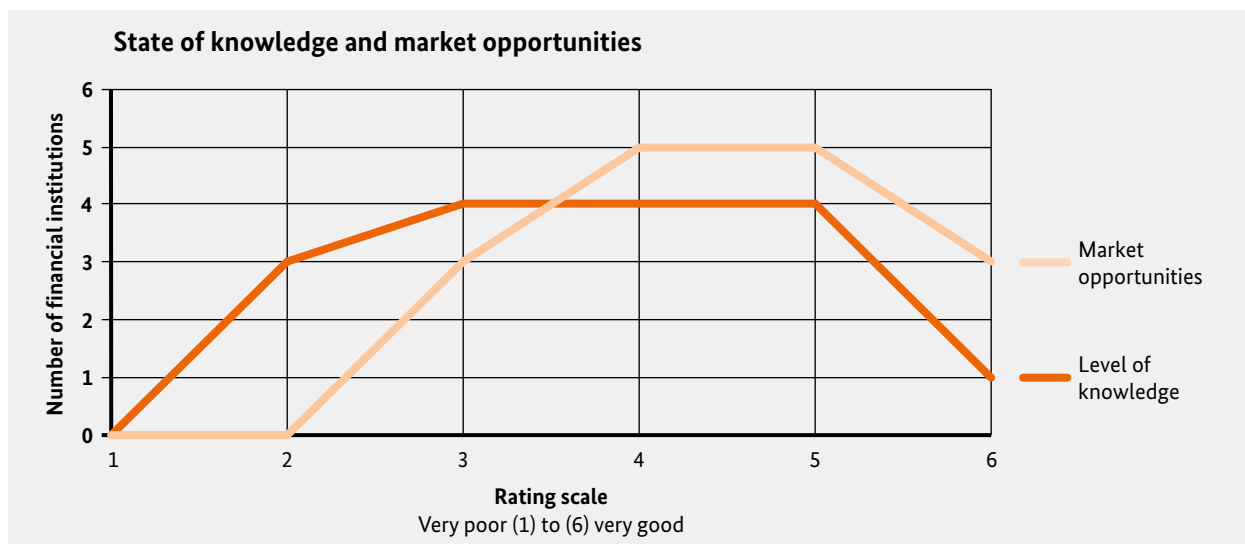
Of the private equity companies that responded, only two have not invested in nanotechnology while one-third have been involved for over six years and another third involved for more than 10 years. Five of the financial institutions plan to increase their involvement in nanotechnology over coming years.



Length of time the participating financial institutions have been investing in nanotechnology ((Source: VDI TZ 2013 survey of players, n=17).

Level of knowledge and assessment of market opportunities

As was the case in the 2011 nano.DE report, it is clear that the level of knowledge about nanotechnology within the venture capital sector is felt to be relatively heterogenic. On a scale from 1 (very poor) to 6 (very good), the 16 institutions that responded put their own



Assessment by the participating financial institutions of their own knowledge of nanotechnology and market opportunities for nanotechnology (Source: VDI TZ 2013 survey of players, n=16).

level of knowledge of nanotechnology at an average of 3.8, although all values from 1 to 6 occurred in the responses. Market opportunities were estimated at 4.5 on the same scale. Overall, the assessments of market opportunities in 2013 were therefore somewhat more positive than in the 2011 survey (average 4.0).

The financial institutions were also asked for an assessment of market opportunities for various areas of nanotechnology application up to 2020. Ranking of these application areas is largely unchanged from that in 2011. The most promising areas are considered to be chemicals, electronics, medicine/pharmaceuticals,



Assessment of market opportunities for nanotechnology in various areas of application up to 2020 (Source: VDI TZ 2013 survey of players, n=16).

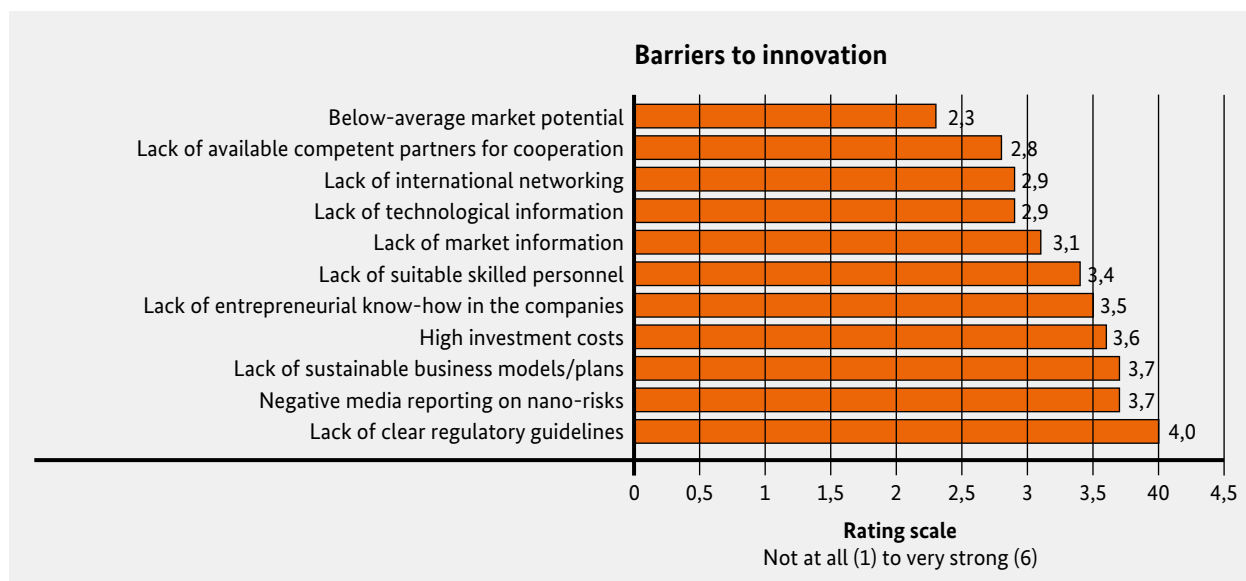
optics, energy and environment. The least promising market opportunities are felt to be in foodstuffs, mobility and transport, and mechanical engineering.

Barriers to innovation and nanotechnology investments

In the assessment of barriers to innovation relating to the commercialisation of nanotechnology, there was some movement in the rankings of individual factors as against 2011. The lack of clear regulatory guidelines and the negative reporting in the media of the risks associated with nanotechnology have moved to pole position. It can thus be seen that investors place rather greater weight on these factors than do the nanotechnology companies themselves (see section 2.1). Overall however the evaluation falls only slightly above the average at 4.0 and 3.7 on a scale of one to six. Against this, more significant economic factors such as a lack of sustainable business models and business plans, high investment costs, and a lack of entrepreneurial skills within the companies are judged as being of above-average importance as barriers to innovation.

Ten of the financial institutions surveyed currently have holdings in a total of 22 nanotechnology companies, five of which were added in 2011. The vast majority of these holdings are in German nanotech-

nology companies. Two of the equity capital companies restrict their investments to North America. One provider of venture capital is active in North America and Asia as well as Germany. The level of investment varies considerably, ranging from less than € 100,000 to over € 5m. Total investment by the participating venture capital firms in nanotechnology companies amounted to around € 23m in 2012. With respect to investment phases, instances of early phase, growth phase and late phase investment were all present. The majority of holdings were in the form of direct investments. In some instances both fund-related and silent holdings were mentioned. Six financial institutions have cooperated with one or more public-sector co-investors. In five of these cases the partner involved is the KfW (Kreditanstalt für Wiederaufbau, the Reconstruction Loan Corporation) bank, and in three the Hightech-Gründerfonds (high-tech start-up fund).



Assessment of factors inhibiting the conversion of the results of nanotechnology research into commercial products (Source: VDI TZ 2013 survey of players, n= 16).

3 Market and application potential for nanotechnology

As a key cross-sector technology, nanotechnology is a fundamental driver for innovation in German industry. Developments in nanotechnology comprise two strands: first is the further development and refining of established processes such as lithography and coating processes, and second are new directions for technologies such as organic electronics, nano-structured carbon materials or controllable nanotransporters for medical drugs. Recognising how nanotechnology cuts across sectors, its market potential can only be sensibly determined by studying defined application areas and technologies. Previous editions of the nano. DE report presented the market and application potential of nanotechnology in the various sectors in great detail. The current edition presents an update based on market forecasts, developments in the various sectors, research activities, and the background and challenges against which nanotechnology operates.

3.1 Overview of market potential influenced by nanotechnology

In the table below you will see a summary of market forecasts for sub-sectors and areas of application that are relevant to nanotechnology. Differentiating this report from earlier editions, this one only contains figures published since 2011. In addition this report contains market forecasts from companies who as part of the player survey quantified the global value of markets influenced by the nanotechnology fields in which they are active. The table distinguishes between the categories of nanotechnology products (i.e. specifically produced technical nanomaterials as well as equipment for the manufacturing and analysis of nanostructures and nanoobjects) and nano-optimised products. The latter category relates to markets that are targeted, at least partially, by products to which nanotechnology has made a substantial contribution.

Market segment	World market value (for the year specified)		CAGR	Source
Nanomaterials				
Total market for nanomaterials (nanoparticles, hollow nanostructures, nanofibres, nanocomposites and nanocoatings)	\$15.9bn (2012)	\$37.3bn (2017)	19 %	BCC 2012 ^[5]
Carbon nanotubes	\$239m (2012)	\$527m (2016)	22 %	BCC 2012 ^[6]
MWCNT	\$219m (2012)	\$292m (2016)	9 %	
Few Wall CNT	\$1.8m (2012)	\$120m (2016)	131 %	
SWCNT	\$1.2m (2011)	\$115m (2016)	149 %	E.ca 2012 ^[7]
Carbon nanohorns	€0.1m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Polymer nanocomposites	\$920m (2011)	\$2.4bn (2016)	20 %	BCC 2012 ^[9]
Nano-scale ceramic powders (USA market)	\$612m (2011)	\$1.2bn (2016)	16 %	BCC 2011 ^[10]
Magnesium oxide nanopowder	\$18.3m (2011)	\$31.2m (2018)	9 %	TMR 2012 ^[11]
Colloidal silicic acid	250m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Aerogels	\$174m (2012)	\$1.4bn (2017)	52 %	MaM 2012 ^[12]
Nanofibres (Aluminium oxide, polymers, carbon, cellulose)	\$352m (2011)	\$852m (2017)	16 %	FM 2011 ^[13]
Metallic nanoparticles, nanoinks, nanoadhesives	n/a	\$2bn (2017)	n/a	E.ca 2012 ^[14]
Nano-silver for anti-microbial applications	€50m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Quantum dots	n/a	\$7.5bn (2022)	55 %	E.ca 2012 ^[15]
Nanofillers for circuit boards	€5m (2013)	n/a	n/a	VDI TZ 2013 ^[8]

Market segment	World market value (for the year specified)		CAGR	Source
Electro-active polymers	\$2.2bn (2011)	\$3.4bn (2017)	8 %	E.ca 2012 ^[16]
Conductive polymers	\$1.8bn (2011)	n/a	n/a	
Magnetic nanomaterials (nanocrystalline weak magnetic cores, magnetic liquids, catalysts and environmental purification)	\$97m (2012)	\$209m (2017)	17 %	BCC 2013 ^[17]
Nanocoatings				
Thin-film materials	\$9.3bn (2011)	\$14.9bn (2016)	10 %	BCC 2012 ^[18]
Physical processes: Evaporation, sputtering, ion-deposition	\$4.2bn (2011)	\$7.5bn (2016)	12 %	
Chemical processes (gas-phase/liquid-phase deposition, plating)	\$5.1bn (2011)	\$7.4bn (2016)	8 %	
High-performance ceramic coatings (North America)	\$1.4bn (2011)	\$2bn (2016)	7 %	BCC 2012 ^[19]
Thermal spraying	\$935.2m (2011)	\$1.3bn (2016)	8 %	
PVD	\$208.4m (2011)	\$294.6m (2016)	7 %	
Total market for nanocoatings	\$1.6bn (2011)	\$7.8bn (2017)	27 %	FM 2011 ^[20]
Anti-fog coatings	€300m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Anti-microbial coatings	€100m (2013)	n/a	n/a	
Scratch-resistant coatings	€2bn (2013)	n/a	n/a	
Anti-reflex coatings	€1.3bn (2013)	n/a	n/a	
Energy-efficient films for heating and energy technologies	€100m (2013)	n/a	n/a	
Scratch-resistant lacquers	€500m (2013)	n/a	n/a	
Anti-bacterial lacquers	€200m (2013)	n/a	n/a	
Nanoscale multi-films for x-ray lenses	€20m (2013)	n/a	n/a	
Nanoanalytics				
Total microscopy market (optical, TEM, SEM)	\$2.7bn (2011)	\$3.4bn (2016)	5 %	BCC 2011 ^[21]
Microscopy accessories (illumination, cameras, manipulators)	\$488m (2011)	\$632m (2016)	5 %	
Electron microscopy	€400m (2013)	n/a	n/a	
Photoelectron microscopy	€80m (2013)	n/a	n/a	
Low-temperature scanning tunnelling microscope	€60m (2013)	n/a	n/a	
AFM devices	€100m (2013)	n/a	n/a	
Probes	€15-20m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Evaluation software	€2m (2013)	n/a	n/a	
Calibration standards	€10m (2013)	n/a	n/a	
TOF-SIMS analysis equipment	€25m (2013)	n/a	n/a	
LEIS analysis equipment	€2m (2013)	n/a	n/a	
Particle size analysis in nm range	€35m (2013)	n/a	n/a	
Nanomechanical test instruments (nanoindentation)	€25-30m (2013)	n/a	n/a	
Nanostructuring				
Total nanotools market (incl. nanomanipulators, near-field optics, nanolithography, nanoimprint, etc.)	\$4.8bn (2012)	\$11.4bn (2017)	19 %	BCC 2012 ^[5]
PVD deposition equipment	\$7.1bn (2011)	\$10.4bn (2016)	8 %	BCC 2012 ^[22]
Electron beam lithography systems	€120m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Molecular beam deposition equipment	€300m (2013)	n/a	n/a	

Examples of market forecasts for nanotechnology products in the fields of nanomaterials, nanocoatings, nanoanalytics and nanostructuring.

Market segment	World market value (for the year specified)		CAGR	Source
Health				
Nanomedicine	\$43.2bn (2011)	\$96.9.2bn (2016)	14 %	BCC 2012 ^[23]
Applications for cardiovascular disease	\$4bn (2011)	\$8.6bn (2016)	17 %	
Nanomedical anti-cancer products	\$5.5bn (2011)	\$12.7bn (2016)	18 %	
Applications for disorders of the central nervous system	\$14bn (2011)	\$29.5bn (2016)	30 %	
Anti-inflammatory applications	\$7.3bn (2011)	\$14.8bn (2016)	15 %	
Anti-infection applications	\$3.9bn (2011)	\$14.8bn (2016)	10 %	
Bio-chips (DNA analysis, protein analysis, drug research, etc.)	3,9 Mrd.\$ (2011)	\$9.6bn (2016)	20 %	BCC 2011 ^[24]
Nanoparticle applications for biotechnology, drug delivery, drug development and formulation	\$21.6bn (2012)	\$53.5bn (2017)	20 %	BCC 2012 ^[25]
Nanotransporters for drug active ingredients	€250m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
DNA transfer using magnetic nanoparticles	\$50m (2013)	n/a	n/a	
Cell isolation and marking by means of functionalised nanoparticles	\$70m (2013)	n/a	n/a	
Immuno-PCR for ultrasensitive protein detection	\$400m (2013)	n/a	n/a	
Nanocomposites for dental fillers (Germany)	\$50m (2013)	n/a	n/a	
Retina implants	€2m (2013)	n/a	n/a	
Electronics				
Consumer electronics, software, ICT (value of German market)	Approx. €151bn (2011)	Approx. €153bn (2013)	1-2 %	BITKOM 2013 ^[1]
Total semi-conductors market (global)	Approx. \$ 290bn (2013)	\$ 366bn (2017)	5 %	ZVEI 2013 ^[26]
22 nm CMOS technology	Approx. € 100bn (2013)	n/a	n/a	VDI TZ 2013 ^[8]
32/28 nm CMOS technology	Approx. € 100bn (2013)	n/a	n/a	
45/40 nm CMOS technology	Approx. € 100bn (2013)	n/a	n/a	
Compound semi-conductors - electronics	\$ 27bn (2012)	\$ 47.4bn (2017)	12 %	E.ca 2012 ^[27]
NAND Flash memory	n/a	\$ 31.1bn (2014)	n/a	TechNavio 2011 ^[28]
Flexible electronics via roll-to-roll production process	\$ 10.8bn (2012)	\$ 22.7bn (2017)	16 %	BCC 2013 ^[29]
Printed electronics	\$ 4bn (2013)	\$15bn (2018)	30 %	BCC 2013 ^[30]
Transparent conductive coatings for touch displays	\$ 956m (2012)	\$ 4.8bn (2019)	26 %	E.ca 2013 ^[31]
Conductive inks	\$ 2.9bn (2012)	\$ 3.4bn (2018)	3 %	IDTE 2012 ^[32]
Nanosilver for conductive coatings/inks	€ 100m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Optics				
Global photonics market	Approx. € 350bn (2011)	Approx. € 615bn (2020)	6,5 %	SPECTARIS, VDMA, ZVEI, BMBF 2013 ^[33]
Domestic photonics production (Germany)	Approx. € 27bn (2011) Approx. € 28bn (2012)	Approx. € 44bn (2020)	5,6 %	
Nanophotonic components (nano-LEDs, OLEDs, holographic data storage, amplifiers, switches, photonic crystals, plasmonics, etc.)	\$ 2.5bn (2011)	\$ 10.9bn (2016)	35 %	BCC 2012 ^[34]
Nanophotonic light-emitting diodes	\$ 2.4bn (2011)	\$ 9.9bn (2016)	33 %	
Near-field optics	\$ 53m (2011)	\$ 59m (2016)	2 %	

Market segment	World market value (for the year specified)		CAGR	Source
OLED materials (emitters and injection, transport and blocking films)	\$ 1.7m (2012)	\$ 1.1bn (2019)	152 %	NanoMarkets 2012 ^[35]
Organic materials for OLEDs	€ 1bn (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Laser diodes	€ 1bn (2013)	n/a	n/a	
Saturable absorbers for ultra-short pulse lasers	€ 5m (2013)	n/a	n/a	
X-ray optics for diffractometers	€ 25m (2013)	n/a	n/a	
X-ray optics for synchrotrons	€ 10m (2013)	n/a	n/a	
X-ray optics for fluorescence spectroscopy	€ 10m (2013)	n/a	n/a	
Energy and environmental technology				
Nanotechnology in the energy sector (excl. enzyme catalysts)	\$ 2.5bn (2012)	\$ 5.8bn (2017)	18 %	BCC 2013 ^[36]
Nanomaterials for energy technologies (catalysts, fuel additives, thermal insulation, Li-ion batteries, hydrogen storage, supercapacitors, fuel cells, thermoelectrics, photovoltaics, wind energy)	\$ 203.7m (2010)	\$ 2.3bn (2017)	41 %	Future Markets 2011 ^[37]
Nanooptimised photovoltaics (Use of nanomaterials such as fullerenes, CNTs, metallic oxides, quantum dots in thin-film solar cells such as dye or polymer solar cells, and CIGS and cadmium telluride solar cells)	\$ 68m (2011)	\$ 820m (2015)	86 %	Future Markets 2011 ^[38]
Materials for protection against electrostatic discharge in photovoltaics (incl. carbon nanomaterials, conductive polymers, etc.)	\$ 1.4bn (2012)	\$ 3.4bn (2019)	13 %	NanoMarkets 2012 ^[39]
Solid-state thin-film batteries	\$ 65.9m (2012)	\$ 5.95bn (2017)	146 %	WGR 2012 ^[40]
Nanooptimised lithium-ion battery systems	\$ 63m (2010)	\$ 575m (2017)	37 %	FM 2011 ^[41]
Superconductivity applications (magnets, electrical engineering)	\$ 1.8bn (2012)	\$ 3.3bn (2017)	13 %	BCC 2012 ^[42]
Superconductivity in electrical engineering (transformers, generators, motors, current limiters, cables)	\$ 26.9m (2012)	\$ 920.1m (2017)	103 %	
Membrane filtration (nano and micro-filtration, reverse osmosis)	n/a	\$ 16bn (2017)	n/a	GIA 2011 ^[43]
Biofilm-carriers for biological sewage treatment plants	€ 10m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Filter materials with nanostructured adsorbents	€ 50m (2013)	n/a	n/a	
Packaging				
RFID	\$ 1.1bn (2011)	\$ 4bn (2016)	29 %	C&M Research 2012 ^[44]
Construction				
Nanocoatings for applications in construction (incl. self-cleaning, anti-soiling protection, UV protection)	\$ 130m (2011)	\$ 400m (2015)	32 %	Future Markets 2011 ^[45]
Switchable glazing	\$1.6bn (2011)	\$ 4.2bn (2016)	22 %	BCC 2012 ^[46]
Nano-SiO ₂ as a cement additive for ultra-high performance concrete	€ 5m (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Automotive				
Nanocoatings for automotive applications (incl. self-cleaning, anti-soiling, anti-bacterial, flame, corrosion and abrasion protection)	\$ 125m (2011)	\$ 310m (2015)	25 %	Future Markets 2011 ^[47]
Vehicle emissions catalytic converters	\$ 6bn (2013)	n/a	n/a	VDI TZ 2013 ^[8]
Glazing for the automotive sector	€ 500m (2013)	n/a	n/a	
Sensor technology				
Nanomaterial-based magnetic sensors (GMR, biosensors and bioassays)	\$ 53m (2012)	\$ 108m (2017)	15 %	BCC 2013 ^[48]

Examples of forecasts for markets addressed by nanooptimised products.

3.2 Medical technology and pharmaceuticals

Sector development

The medical technology sector, with some 1160 companies in Germany, is showing a positive economic trend. In 2012 turnover was up by 4.2% to € 22.3bn while in the same period employment in the sector rose by 2.6% to 94,500. This positive development can be traced back to a strong growth in turnover from business outside Germany (up 6.7% to € 15.1bn giving an export ratio of 68%).^[49] The pharmaceutical industry comprises around 900 companies with some 105,000 employees. The current economic trend can be described as moderately positive. Compared to 2011, there was a slight rise in turnover in 2012 to around € 27bn, with exports on the other hand down by 1.4%.^[50] Both medical technology and the pharmaceutical industry are among the most research-intensive sectors in Germany, each having an R&D ratio of around 9%.

Nanotechnology products are already of considerable economic importance in the medical industry.^{[51], [52]} World-wide turnover in this class of products was estimated by market research company BCC to be worth around \$ 43bn in 2011 and is set to more than double by 2016 (see section 3.1). Pharmaceutical applications already established for some time include processes to improve the absorption and bioavailability of active agents by means of, for example, encapsulation with liposomes and polymers, enlarging of the surface area of the active agent by means of milling and emulsification or by chemical attachment of polyethylene glycol to protein active agents (PEGylation). Commercial products in the field of medical technology are to be found predominantly in in-vitro and in-vivo diagnostics, bone replacement materials or nanocoated devices and medical equipment. The number of nanomedical products on the world market has been put at over 100, of which about one-third are in the pharmaceutical area. To this must be added some 150 products currently undergoing clinical trials.^[53] The trend here is clearly upwards, driven by intensive funding of research at national, European and international level that is addressing health as a priority area for research. Also not to be ignored is the potential of nanotechnological processes and analysis techniques in biomedical basic research from which important insights into the causes and mechanisms of disorders are emerging that have

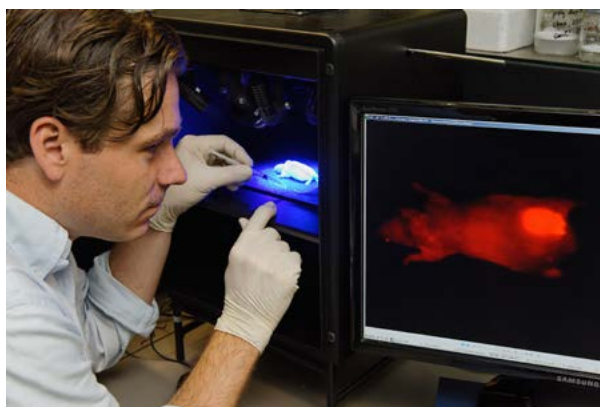
the potential to make a significant contribution in the future to the development of novel diagnostic and therapeutic processes.

BMBF research activities

Innovative nanotechnological developments in the pharmaceutical and medical technology fields are supported by the BMBF through numerous funding measures in materials and health research. One promising field is the use of nanoscale, functionalisable transporters to carry the active agents more efficiently across biological barriers to the target location. Carrier systems in development are based for example on lipids, macromolecules, biopolymers or hydrogels, into which can often be integrated additional functionalisation such as the ability to trigger drug release (e.g. by pH level or magnetic fields) or targeted enrichment at the required location through, for example, specific antibodies. This allows the addressing of a large number of pathologies (tumours, inflammatory and skin disorders, Alzheimer's, etc.), delivery routes (skin, gut, bloodstream), and target organs (brain, skin, gastrointestinal tract, other organs). Nanoparticles are also being developed as efficient containers for delivering DNA into cells (transfection) for gene therapy.

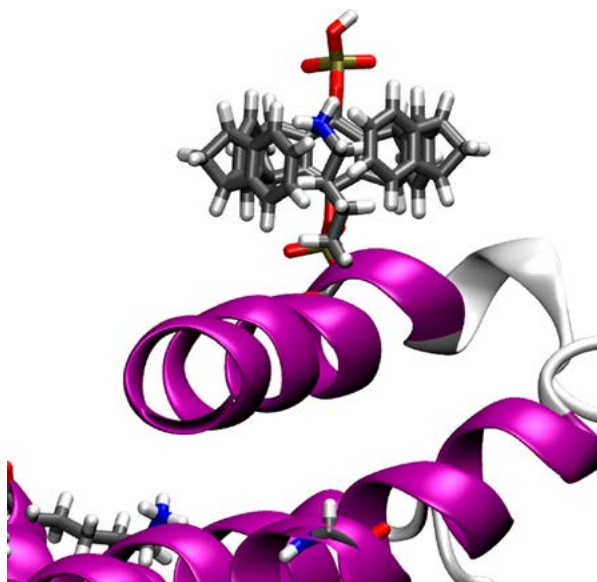
In diagnostics the focus is on optimising in-vitro procedures such as microfluidic lab-on-a-chip sensors, marker-free detection processes (such as via nanowires) or using nanoparticles to improve processes such as in, for example, DNA analysis or cell separation and diagnostics. In-vivo diagnostics benefits from novel nanoparticle-based probes for molecular imaging that can also be combined with therapeutic drugs as a theranostic agent.

A further field of research is looking into biocompatible, implantable sensors for uses such as early diagnosis of thromboses in artificial heart valves or as glucose sensors for diabetics. Improvements in wound healing and hygiene are related to developments such as anti-bacterial coatings on medical equipment and or wound dressings, or self-adhesive sutures that use the "gecko effect".

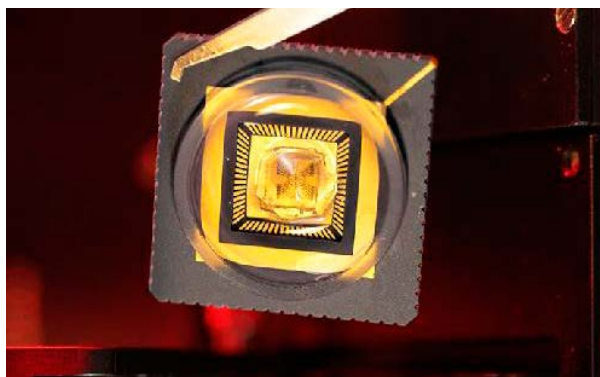


Use of nanomaterials for molecular imaging in cancer diagnosis and therapy (Source: RWTH Aachen, Photo: Peter Winandy).

The application area of body tissue replacement and implants benefits greatly from nano-functionalised surfaces to improve biocompatibility and cell growth together with the option of integrating controlled-release drugs.



Using so-called “molecular tweezers”, certain molecule groups such as amino acids can be gripped and so the functioning of peptides and proteins influenced. This opens up potential applications in the treatment of diseases such as Alzheimer’s or cancer (Source: Max Planck Institute for Coal Research, Mülheim/Ruhr)



Electronic components made of graphene are being researched to achieve improved contact between nerve cells and electronics for use in neural implants (Source: Jülich Research Centre).

In the field of basic bio-medical research the focus is currently on the use and improvement of nanoanalytical processes such as near-field, atomic force and fluorescence microscopy to throw light on life processes such as protein folding and dynamics in living cells together with nanotechnological procedures such as the manipulation of cells and biomolecules.

Public funding for research is increasingly focusing on questions relating to toxicological side-effects of nanomedical processes. For example, one BMBF collaborative project is investigating and evaluating the effects on health of innovative, nanoscale MRT contrast agents.

While the transfer into medical practice of knowledge gained from the BMBF’s applied nanomedical research is generally prolonged and tortuous, passing through several stages in the licensing process by the relevant licensing authorities, there have already been many successful examples of transfers to the commercial world. Examples include the nanoparticle-mediated hyperthermia cancer therapy (see the 2011 nano.DE report) and the use of magnetic nanoparticles in cell separation and therapy (see the box below).

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
In-vitro diagnostics	Nanopore analytics for “marker-free” detection of individual molecules	13N10969-70
	Enhanced immunoassay using dye-embedded nanocontainers for point-of-care applications	0315844A-B
	Nanowire transistors as marker-free immune sensors for fully electronic analysis of DNA hybridisation and antigen-antibody bonds	17042X11
	Microfluidic lab-on-a-chip sensor based on plastic film structuring to detect glycated haemoglobin	16SV5424
	Ultra-fast PCR by means of local heat production for fractionation of DNS using laser-heated nanoparticles	0316032
	Diagnostics, cell separation and cytometry by means of magnetic particles and MT sensors	16SV5396-403, 13N12013-20, 16SV3739-43
In-vivo diagnostics/theranostics	Nanoparticle probes (fluorescent marker, QDs, PET tracer) for molecular imaging and, combined with active agents, for treatment of tumours, myocarditis, etc.	17PNT031, 13N11094, 13N10354-60, 13N10280-8, 01DG12045
	Sensory films on artificial heart valves for the early diagnosis of thromboses	01DQ12042
	Diagnostic implants based on nanofunctionalised sensors and membranes for remote monitoring of patients with cardiac and renal insufficiencies	16SV5459-65
	Subcutaneously implantable glucose sensors based on organic electronics	13N10790 -3
Nanoscaled active substances and formulations	Use of nanobodies (antibody fragments) in the treatment of strokes	01EW1208-9
	Nanogel-based RNA vaccine for prevention of hepatitis C	13N11738-9
	Nanoformulations for extending stomach retention time of active agents and controlled release of the active agent	13N11368-70
	GMP-compliant process for accelerated development of liposome formulations for clinical use	13N11280-1
	Novel injection system for painless ballistic injection of vaccines in powder form with nanoparticle formulation materials	13N11315-9
Organ replacement and implants	Development of nanostructured bioactive/biomimetic blood vessel prosthesis for treatment of vascular disease	0316023
	Nanostructured coated titanium surface for biocompatible implants	01DJ12064
	Nanofibres for implant materials for regeneration of bone and cartilage	01DN12043
	Implantable nanomaterials (polysiloxane structures, peptide matrices) with neuronal-regeneration-promoting properties for applications in neuroprosthetics	16SV5367, 13N11036-7
	Nanostructured implant materials with optional release of active agent for use in synthetic intraocular lenses, coronary stents, etc.	13N10944-6, 13N11219-21
	Biocompatible, thermosensitive hydrogels as a vitreous substitute	13N10324-6
	Aural tissue regeneration by means of nanostructured cellulose scaffolds as cell carriers	13N11075-6
	Nanocomposite material from stem cells for corneal implants	13N11121
	Nanostructured cochlear electrodes for prevention of cell accretion	13EZ1001A-C
Dialysis technology	New membranes and functional disposable systems for the adsorption and separation of uremic toxins in dialysis (renal replacement therapy)	13N11416-8
	Novel, highly-selective dialysis membranes for removal of pro-inflammatory substances	13N11796-99
Wound healing	Multi-functional hollow fibre membranes (such as nutrient supply, pH regulation, etc.) as a dressing for accelerated healing of wounds	13N11575-6
	Polymer fibres with nanofibres for self-adhesive sutures	01EZ1105A-C
Dental technology	Dental implants with a nanostructured, hydrophilic, anti-microbial surface for improved growth into the bone	13N11140-2

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Drug transport	Functionalised nanocapsules, nanoparticles, nanoemulsions (lipids, macromolecules, biopolymers, hydrogels) as carrier systems for transporting drugs across biological barriers. Areas of application: <ul style="list-style-type: none"> • Deeper layers of skin (treatment of skin cancer and acne) • Blood-brain barrier (Alzheimer's) • Intestinal tissue • Urogenital tract • Tumour cells • Oral administration 	01DK12018, 13N11801-4, 13N11339-41, 13N11454-8 01DQ12031, 01DN12072 01EW1009-10 13N11845-6 13N11304-9, 13N11032 01DN12009 13N11385-90
	Multifunctional scaffold substances made from natural polymers (e.g. sodium alginate) and nanoscale, bioactive glass particles for combined drug delivery and bone regeneration	01DN12095
	Multifunctional nanocapsules with a magnetically activated, heat-sensitive shell for combined diagnosis and treatment of malignant diseases	13N11275-6
Transfection/gene therapy	Nanooptimised transfection technology in-vitro and in-vivo (incl. use of magnetic nanoparticles, synthetic peptides)	0315728
	Magnetic nanoparticles combined with viral vectors for gene therapy in neurodegenerative disorders	01DN12044
	Biocompatible nanotransporter for in-vivo transfer of siRNA	13N11533-36
Medical hygiene	Hygienically effective nanocoatings on complex medicinal products	13N11353-8
Biomedical basic research	Study of protein interactions in living cells, characterisation of protein folding reactions and protein dynamics	0315649, 03IS2211A-I, 0315513A-E
	Marker-free presentation of chromosomes by means of multimodal, site-dependent spectroscopy and using near-field microscopy	17036A10-B10
	Study and influencing of cell surface interactions (adhesion, proliferation, differentiation) by means of nanostructured surfaces with gradually adjustable or thermosensitive properties	01DR12063, 13N11974-80
	Synthesis of radioactively marked medicinal and diagnostic products for molecular imaging	13N11260-1, 13N10270-2
	Selective imaging fluorescence microscopy with fluorescing proteins and organic dyes with an optical resolution of less than 100nm	13N11018-21
	New solid-state and fibre laser systems as light sources for STED microscopy	13N11173
	GSDIM far-field nanoscopy for life sciences	13N11066-9
Nanotoxicology	Interactions of (fluorescence) magnetic nanoparticles with cells	0315773A_H
	Evaluation of the effects of innovative, nanoscale MRT contrast agents on health	03X0100A-E, 03X0104A-E

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

An example of successful transfer of research results into practice: Nanotechnology for cell separation and therapy

Dr. Ralph Schaloske, Miltenyi Biotec GmbH

Magnetic cell separation

Superparamagnetic nanoparticles are key tools for cell separation in biomedical and clinical research. The range of possible clinical applications is constantly being extended, particularly in the fields of personalised immunotherapy and regenerative medicine. Nanoparticles – bound to cell-type-specific antibodies – permit the magnetic enrichment of almost any cell type.

The transplantation of stem cells obtained from the bone marrow, umbilical cord or circulating blood of donors using such nanoparticles is an established method so far been used to treat over 25,000 leukaemia patients. The success of the treatment and the extent of side-effects is critically dependent however on the composition, and hence quality, of the cell transplant. The quality of transplantation can be continuously improved by the development of new nanoparticle-based reagents. Their clinical suitability is for example being investigated in a BMBF-funded study intended to show whether, following a heart attack, a transplant of adult stem cells from the body of the patient is able to improve the patient's capacity and quality of life. This example clearly demonstrates how BMBF funding can support the move of biotechnological research into regenerative medicine, so making nanotechnology of commercial value.

The medical technology needed for cell therapy is also being constantly refined and adapted to the growing demands of clinical research and routine. A recently developed instrument for automated clinical cell separation opens the way for numerous new applications of nanoparticles in clinical research: Every step, from sample preparation via cell separation and the cultivation of the isolated cells, through to formulation of the finished cell product, is performed automatically in a closed system under GMP-compliant conditions.



Automated system for the specific enrichment or removal of certain cells from the blood or bone marrow for clinical research purposes. This system is especially suited for applications in personalised immunotherapy and regenerative medicine (Source: Miltenyi Biotec GmbH).

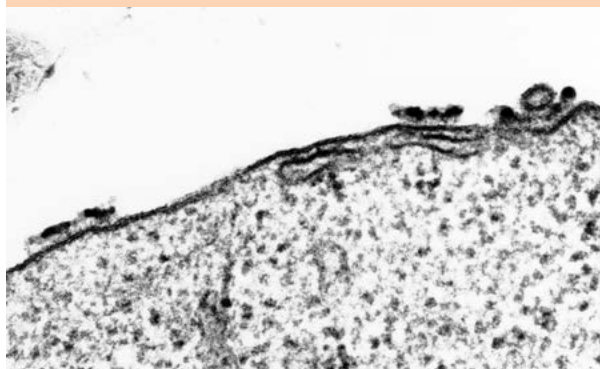
Imaging processes

Superparamagnetic nanoparticles are used for example in imaging procedures in pre-clinical studies of cell transplantation in neurodegenerative disorders. The particles are implanted, for example, into isolated precursor cells that will form nerve cells. The cells marked in this way are then injected into an animal model. The movement and localisation of the cells in the living organism can be tracked using MRT allowing conclusions to be drawn on the interaction between the transplanted cells and the organism.

Semiconductor-based cell sorting

The latest development in cell isolation is a device with core technology based on a silicon wafer valve which enables fluorescence-marked cells to be sepa-

rated from a stream of cells. The valve is controlled via an impulse triggered by the fluorescence signal of the target cells. Valve opening times must be in the μ s range to enable sorting of around 100m cells per hour. Unlike traditional cell analysis in flow procedures, this technique avoids exposing the cells to high pressure, with a positive effect on the viability and functionality of the cells.



The paramagnetic nanoparticles on the cell surface measure approximately 50nm (Source: Prof. Groscurth, Zürich).

Other activities and sample applications

Nanotechnology research now encompasses almost every area of medical application. Nanomedicine is also a focal element within the 7th Research Framework Programme. Some 100 nanomedicine projects have been funded in the period 2007 to 2013, including some large collaborative projects funded to the tune of over € 10m addressing the following topics:

- **Highly specific and sensitive test systems for early detection of cancer:**
Research into rapid test platforms using the photoluminescent, plasmonic, magnetic and non-linear optical properties of nanomaterials for the early detection of cancer (Project runs until 2014. Further information is at www.namdiatream.eu).
- **Nanooptimised diagnosis and treatment of pancreatic cancer:**
Research into nanoparticles for diagnostic purposes using MRT/PET as well as therapy using transporter capsules for non-classical anti-tumour drugs (e.g. si-RNA) (Project runs until 2015. Further information at

<http://fp7-saveme.com>).

- **Improved procedures for DNA sequencing and analysis:**
Development of fast cost-effective procedures for DNA/RNA analysis with the aid of new approaches to single molecule analysis using nanopores and nanotubes (Project runs until 2013. Further information at www.cng.fr/READNA).
- **Ultrasound-activated drug delivery systems:**
Research into drug-loaded nanocarriers in which drug release can be precisely triggered by ultrasound when in the diseased tissue (Project runs until 2012. Further information at www.sonodrugs.eu).
- **Diagnosis and treatment of Alzheimer's disease:**
The aim is to develop nanoparticle systems capable of crossing the blood-brain barrier that contain additional compounds able to recognise and remove the harmful protein deposits (Project runs until 2013. Further information at www.nadproject.eu).
- **Biophotonic diagnostics:**
New light sources should expand the possibilities for biophotonic screening and imaging for medical diagnosis from the subcellular to the organ level. The main area of application for this is seen as ophthalmology and cancer check-ups (Project runs until 2016. Further information at <http://www.famos-fp7.eu>).

Background conditions and challenges

The healthcare system in Germany is facing major challenges as a result of various social developments. These include the demographic trend towards an ageing society linked with a sharp increase in age-related illnesses, on top of which is the growing need for individual and personalised medical diagnosis and treatment processes. The economic environment in the pharmaceutical sector is also challenging. By 2015, patent protection will expire for drugs having an annual turnover of \$ 130bn.^[54] The development of new drugs entails enormous costs and serious business risks. For these reasons the use of nanoscaled carrier systems to improve the efficiency of known drugs seems promising from a business perspective as well. Extending the range of medical indications for which existing nanomedical developments are indicated also offers potential, as shown by hyperthermia cancer therapy^[55] or the nanoparticle-based drug Abraxane.^[56]

Nanomedicine offers potential solutions to a large number of healthcare problems. However, as the range of nanotechnology-based procedures in medicine expands, the spotlight is coming to bear on questions of safety, regulation and standardisation. One problem arises out of the fact that developments in nanotechnology often blur the boundaries of classical regulatory fields such as pharmaceuticals, medical technology or food additives/cosmetics (the so-called nutraceuticals/cosmeceuticals). This is for example the case with implants functionalised with drugs. For such combined products the regulations to be applied must be defined even more precisely. In addition, questions of safety and possible side-effects of nanomedical applications require more research before patients can benefit from such products and methods.

Guest contribution: Nanomedicine from the viewpoint of the Bundesverband der Pharmazeutischen Industrie [Federal Association of the Pharmaceuticals Industry]

Dr. Pablo Serrano, Federal Association of the Pharmaceuticals Industry

Definition

The term nanomedicine defies any clear definition. Discussion often centres around the size limit of 100nm in the ISO definition of nanoobjects. Studies show that it is impossible to draw a sharp boundary for size-dependent material properties in biology and medicine. A good example of this is liposomes. These are membrane-forming molecules from the chemical class of lipids that enclose a medically relevant active agent and are capable of transporting it through the body to its target location. Studies with liposomes 150 to 200nm in size have shown that these are retained in the bloodstream longer than are smaller versions (<70nm).

Areas of application

The application areas for nanoparticles in medicine are many and diverse. A detailed breakdown is provided in a recently published meta-study of nanomedicine^[57]. The authors identified amongst others over 300 applications (already on the market or undergoing trials)

and divided these between therapeutic applications and medical technology applications.

Two-thirds of the therapeutic applications are in the field of cancer, followed by the use of nanotechnology in the fight against infectious diseases. The remainder were spread evenly across hepatitis, anaesthetics, cardio-vascular complaints, inflammatory and immune disorders and chronic degenerative diseases together with disruptions to glandular functions. The use of nanotechnology in medical technology ranges from in-vivo tests via in-vivo imaging processes, in-vivo coatings, nano-bio-separation, bone and tooth replacement, cancer treatment using the heating of nanoparticles, surgical equipment and targeted drug transport and carrier systems together with tissue engineering.

The therapeutically relevant products employed in this field of medicine can be readily divided into so-called “hard” and “soft” nanoparticles. “Hard” particles mostly comprise iron oxide, gold, silver or ceramics. Newer particles, about to enter clinical trials, are composed of carbon or hafnium oxide.

Liposomes, micellae, emulsions and dendrimers, together with other polymers and protein nanostructures are classed as so-called “soft” medical nanomaterials.

Importance of the market

The USA currently holds the largest number of patents in the field of nanotechnology. This can be traced back primarily to the early commercialisation by US companies of some nanoproducts. Europe is the second-largest market for nanotechnologies with medical applications, with France, Germany and Great Britain functioning as European centres for their development and marketing. As part of the EU's Nanomed 2020 project in which around 200 players from universities, research institutes, clinics and public-sector health bodies, SMEs and small and large organisations representing the various sectors participated, recommendations were made as to how Europe could be developed into a centre for nanomedical research, development and implementation.^[58]

Outlook

Nanomedicine already offers a host of possibilities and tools that can be used to improve and expand medical patient care. Much of this is still in its infancy and it is clear we will have to look carefully at the distinctive characteristics of nanostructures when considering their use in the fight against disease. Amongst other things, residence time or concentration in the body, metabolic transformation, long-term effects and other ways in which the function of the organism could be affected must be studied in the greatest detail and continuously documented – as for that matter is done for “conventional” drugs and medical products. Nonetheless, nano-medicinal products already on the market have demonstrated that their use brings enrichment of healthcare.

3.3 Chemicals

Sector development

Following the effects of the rebound after the global economic crisis in 2009, growth in the chemical industry has weakened in the intervening period. In 2012, turnover in Germany's third largest industrial sector amounted to € 186bn. Although turnover was stagnant in the first six months of 2013, the VCI is forecasting a growth in turnover of 1.5% for the whole year resulting primarily from exports. 430,000 people are currently employed in the chemical industry in Germany.^{[59][60]} Expenditure on research by the chemical-pharmaceuticals industry has continued to grow over the past years, amounting to around € 9bn in 2012 according to VCI figures.^[61]

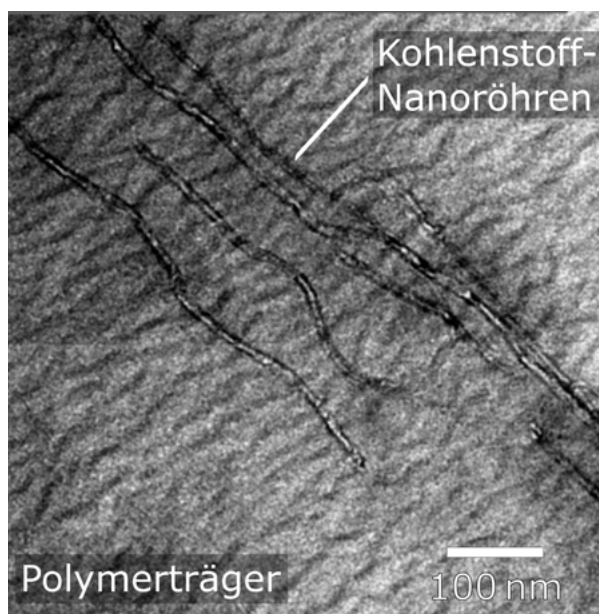
Nanotechnology plays an important economic role in the chemical industry in the production and processing of nanomaterials. The total global market for nanomaterials, comprising the nanoparticles, hollow nanostructures, nanofibres, nanocomposites and nanocoatings segments, is estimated by the American market research company BCC at \$ 15.9bn for 2012. The market is forecast to grow to \$ 37.3bn by 2017 at an annual growth rate of 19%.^[62] The strongest-growing segments of the overall nanomaterials market include carbon nanomaterials, quantum dots, nanofoams and polymer composites. Clear demarcation of nanoma-

terials within the chemical products classification is not possible due to the difficulties surrounding the definition and its analytical verification (see section 4.4). According to a definition proposed by the European Commission, the term nanomaterials covers all materials where more than 50% of the total elements in the material is made up of so-called nanoobjects.^[159] This definition could also catch conventional products such as inorganic pigments in which the nano-scale character is not the result of deliberate functional improvement but is due to the particle size distribution in materials in powder form. The present report by contrast targets developments in which nanostructuring is deliberately aimed at improving functionality of the material.

BMBF research activities

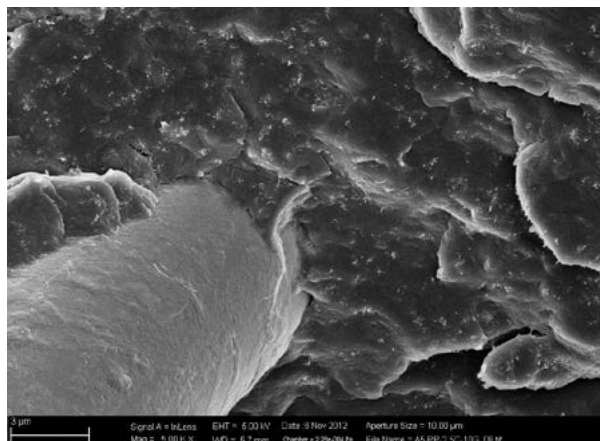
One focus of BMBF funding activities for nanotechnology developments within the chemical industry is on functional coatings and surface functionalisation through the use of nanoparticles and nanocoating technologies. This application field in particular demonstrates the functional flexibility of nanotechnology, since a very wide spectrum of properties can be achieved depending on the nanoparticle, coating process or substrates employed. In the current funding activities this applies principally to anti-microbial and biocidal properties (e.g. through use of silver, titanium dioxide or stannous oxide nanoparticles), mechanical properties (scratch and abrasion resistance), chemical properties (dirt repellent, adhesive, separation of materials) or electrical properties (electrical conductivity of plastics created by nanocarbon additives). Deliberate optimisation of the coating substrate and coating process is normally required for each specific application area.

Two further priority areas are the development of polymer nanocomposites and materials research in the field of organic electronics. As a result of extensive support measures, considerable progress has already been made in the integration of nanostructured carbon materials such as carbon nanotubes and graphene to optimise the properties of polymer composites.



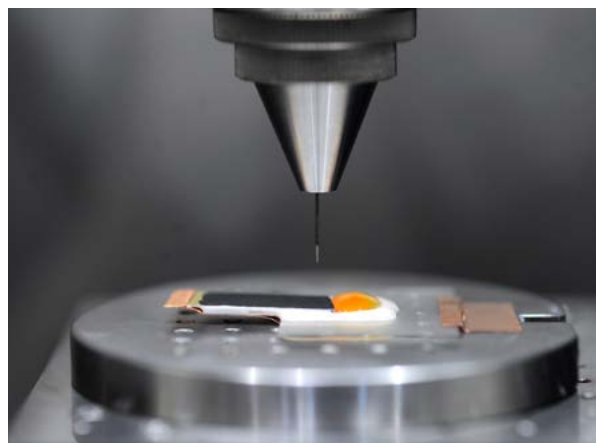
TEM image of aligned carbon nanotubes in a polymer matrix. (Source: Jena University, photo: AG Jandt).

Nanotechnology research is also delivering the bases for innovative precursor compounds that can be used to deposit organic and inorganic films at lower process temperatures. More complex problems are also being addressed within the BMBF funding framework, such as multifunctional films with surface properties that



Electron microscope image of a polypropylene (PP)/carbon nanotube (CNT)/Glass fibre (GF) composite. The composite combines the CNTs' electrical conductivity with the glass fibres' good mechanical properties. (Source: Fraunhofer Institute for Chemical Technology).

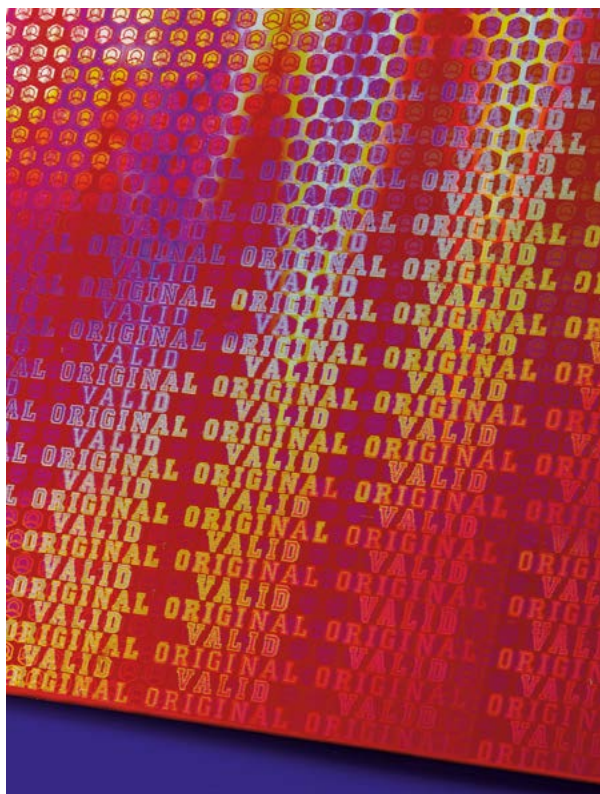
can be gradually adjusted, switchable functions, sensors/actuators integrated into materials, or self-healing properties.



The Max Planck Institute for Iron Research is undertaking studies into self-healing, corrosion-resistant films based on electrically conductive polymer nanocapsules. The effectiveness of the corrosion-resistant films can be precisely investigated using a Kelvin probe. (Source: Max-Planck Institute for Iron Research Photo Christian Niehlinger).

Nanotechnology innovations are also being promoted to optimise traditional chemical products such as films, membranes, catalysts, lacquers, pigments and lubricants. In addition, nanotechnology is extending the possibilities for the use of regenerative raw materials and energy carriers through chemical conversion and bioprocess technology via nanostructured catalysts, material separation processes or substrates.

A very important BMBF funding area is research into the potential effects on health and the environment of the use of synthetic nanomaterials. Within the framework of BMBF funding, research has since 2006 been underway into the exposure of man and the environment to nanomaterials along with the toxicological and eco-toxicological effects, which has yielded reliable, quality-assured and practical processes for assessing possible risks (see section 4.4). In this way the research has made important contributions towards the safe and responsible handling of synthetic nanomaterials.



Nanostructured painted surface for copyright protection (Photo: Fraunhofer IFAM).

In Germany in addition to the BMBF other Federal Government departments with responsibility for the environment, health and safety at work and consumer protection, together with their subordinate federal authorities, are contributing significantly towards research into nanorisks. In the period 2007 to 2011 more than 80 individual projects researching the risk aspects of nanomaterials were undertaken.^[65]

Other activities and sample applications

European research funding is providing important stimuli for nanomaterials research in Germany. Over the period 2007 to 2013, around 80 projects having direct application in the chemical industry were initiated under the 7th Research Framework Programme. A broad spectrum of topics relating to classical applications of nanotechnology, such as surface functionalisation or catalysts, are being addressed in this way alongside newer lines of research such as self-organisation and multifunctional hybrid materials as well as multi-disciplinary topics such as multi-scale modelling of nanomaterials. One priority area is the development of organic materials for electronics and photonics for which the ONE-P collaborative project alone provided € 18m.^[63] Questions relating to the safety of nanomaterials and their effects on man and the environment are also the subject of more intensive research using European funding. Funding in excess of € 100m, spread across 34 projects, is being provided in FP7 for research into the risks posed by nanomaterials.^[64]

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Films, membranes	Nanofluidic aluminium oxide membrane for the separation of fatty acids from aqueous media	13N11391-2
Functional coatings and surface functionalisation	Nanofilms with anti-microbial effect (Ag, TiO ₂) on surfaces using gas-phase processes for textiles and medical technology	03WKBR7A-G, 13N11353, 03X0095A-C
	Coatings to avoid biological adhesion on a ZnO nanostructure base	03X0096A-B
	Metal-polymer nanocomposites films using atmospheric-pressure plasma jet sources for dirt-repellent and electromagnetic applications	03X0119A-B
	Surface functionalisation of bio-plastics by the use of inorganic nanoparticles for improved UV protection, weather resistance, gas tightness, scratch resistance or dirt repellence	03X2517A-E
	Nanoparticle resin coatings to improve the mechanical properties of paper	01DJ12044
	Transparent and electrically conductive films with single-walled CNT hybrids, CNTs for intelligent, two-dimensional temperature monitoring of electronic components in explosion-protected equipment	03X0202A-H, 03X0116A-B
	Multi-functional, gradually adjustable surface properties by means of nanoscale hybrid polymer films	03X0099A-D
	Coatings with switchable adhesive properties based on functionalised polymers and nanoparticles	03X2515A-C
	Deposition of functional metal oxide films from dissolved organometallic source material at low process temperatures for organic solar cells	13N11777
	Nanofilms as highly efficient separation media in chromatographic separation of materials	13N11030-1
	Development of soluble polysilanes as the primary material for creation of semiconducting silicon thin films	13N11345-7
Catalysts	Nitrogen-doped carbon nanotubes for chlorine-alkali electrolysis	03X0207A-D
	Use of CNTs as catalyst and catalyst carrier	03X0204A-D
	Photocatalytic layers for the treatment of waste water from pulp production	17N0310
	Resource-efficient selective oxidation of alkanes using crystalline borophosphate	033R028A-E
	Multifunctional metal polymers as efficient catalysts in continuous reaction processes	13N11313
	Nanostructured metal nitride electrodes for the (photo)electrocatalytic production of hydrogen	03SF0353A-E
Lacquers, pigments	CNT-modified lacquers for improved discharge behaviour in aviation, wind power and electrical technology	03X0203A-E
	Nanoparticle-based lacquer systems with innovative properties (active corrosion protection, detectability of material damage, self-healing of mechanical defects or scratch-resistance)	03X0074A-D
	Electrically conductive, nanoparticle-based printing inks for large-scale printing processes	13N10653-5
	Environmentally friendly sol-gel lacquers for corrosion protection	03X0073A-B
Use of alternative raw material sources for chemical base materials and energy storage	Solar-thermochemical production of chemical products from HO ₂ and CO ₂ using nanoporous and nanoparticulate metal composites	01RC1103A-C
	Photocatalytic CO ₂ reduction with dye-sensitised semiconductors for methanol recovery	13N11791-4
	Hydrogen production by the photocatalytic splitting of water	03IS2071A-G
Bioprocess technology	Coated nano/microporous enzyme carriers for large-scale industrial processes	0316063A-E
	Magnetic particle technology for enzyme immobilisation for industrial biocatalysis	0315815

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Polymer composites, macro-molecules	Electrically and thermally conductive plastics based on CNTs, expanded graphite, graphene or graphenoid layers	03X0206A-G, 01DG12046,
	Elastomer composites based on graphene, e.g. for car tyres	03X0111A-D, 03X0110A-B, 03X0108A-C
	Development of sensory and adaptive systems based on elastomers with magnetic nanoparticles	16SV3763
	Flexible electrodes for miniaturised dielectric elastomer actuators based on conductive nanoparticles	16SV5370
	Polymer-encapsulated magnetic nanoparticles for applications in the life sciences	17PNT025
	Hydrophilic, gas-permeable SiO ₂ /polyacrylate nanocomposites for bio-compatible contact lenses	13N10756-7
	Lithium-gel polymer electrolytes for Li-ion batteries based on newly synthesised homo and block copolymers	03SF0390
	New materials for OLEDs from solution	13N10614-22
	Morphology and electronic structure of organic/organic and organic/metal oxide hybrid systems	13N10721-5
Lubricants	Plastic bearings with functionalised CNTs for optimised lubricant interaction	03X0205A-E
	Tribological innovation using graphenes: Approach to extreme friction reduction for microsystems technology	03X0107A-D
	Self-conditioning plastic surfaces for water lubrication	13N10645-7
Research into risks associated with nanomaterials • Effects on man	Safety, health and quality aspects of the handling of CNTs and screening procedures to investigate any possible carcinogenic potential	03X0043A-D, 03X0109A-B
	Prediction of the toxicological effect on humans of synthetic carbon black nanoparticles	03X0093A-E
	Resonance sensors for weighing nanoparticles for measurement of the exposure of individuals to nanoparticles	03X0098A-B
	Nanosilver particles – mechanisms of action and investigation of their possible interactions with tissues, cells and molecules	03X0103A-E
	Nanostructured materials – health, exposure and material properties	03X0105A-O
• Effect on the environment	Mobility of synthetic nanoparticles in water-saturated and variably water-saturated sub-soils	03X0077A-C
	Nanoparticle lifecycle studies based on ^[45 Ti] TiO ₂ and ^[105 Ag] Ag ⁰	03X0078A-C
	Assessment of the environmental hazards from silver nanomaterials – from chemical particles to the technical product	03X0091A-H
	Material properties, release and behaviour in the environment of CNT materials	03X0114A-E

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

An example of European funding initiatives: ERA-NET SIINN – Research funding and networking in the safety of nanotechnology

Dr. Rainer Hagenbeck, Project Management Jülich

ERA-NETs (ERA = European Research Area) are projects financed by the EU Commission for networking national research programmes and activities. The European ERA-NET SIINN project on nanosafety got underway in August 2011. SIINN stands for “Safe Implementation of Innovative Nanoscience and Nanotechnology“. ERA-NET SIINN concerns itself with the safety of, and any risks associated with, the use of artificially manufactured nanomaterials. In the SIINN project 20 European organisations have come together under the leadership of the Federal Ministry of Education and Research (BMBF). The Jülich (PtJ) research centre has been commissioned to manage the project. The main objective of this project is the preparation and implementation of common transnational initiatives for financing research into the risks posed by nanomaterials.

ERA-NET SIINN supplements national and European funding measures for research into the safety aspects of, and any possible risks associated with, industrially manufactured nanomaterials and the nanotechnology and nanoproducts based on these materials. SIINN enables German companies, possibly in conjunction with German research centres, to cooperate within the framework of internationally agreed funding measures with academic and industrial partners in participating countries and regions in the rest of Europe in R&D projects that can only be successfully implemented through international collaboration.

The first transnational projects were launched in June 2013; some examples of the results of those projects are set out below.

nanoIndEx (Assessment of Individual Exposure to manufactured nanomaterials by means of personal monitors and samplers)

This project is designed to investigate the accuracy, comparability and practicality of personal monitors that have only recently become available. These are devices that capture data on the concentration levels

of airborne, synthetic nanoparticles around the nose and mouth areas in relevant workplaces. Research partners from Germany, France, Switzerland and Great Britain are participating in this project. The project coordinator is the Institut für Energie- und Umwelttechnik e. V. (Institute for Energy and Environmental Technology) in Duisburg.

NanOxiMet (Assessment of the use of particle reactivity metrics as an indicator for pathogenic properties and predictor of potential toxicological hazard)

The objective of this project is contributing towards simplification of the predictability of pathogenic properties in synthetically manufactured nanoparticles. The grouping of different types of nanoparticles is envisaged for this. This grouping should be based on in-depth investigations of the physical properties of selected nanoparticles and their toxic effects on human cells. The study will concentrate on those metrics that, according to our current state of knowledge, are most suitable for predicting the toxic properties of nanoparticles – size and structure of the nanoparticle surface and the potential to form oxidants. Partners from Germany and France are participating in this project. The coordinator is again the Institut für Energie- und Umwelttechnik e. V. (Institute for Energy and Environmental technology) in Duisburg.

Nanoheter (Fate of engineered nanoparticles in the water column under natural conditions. Role of the heteroaggregation with naturally occurring suspended matter)

This project is concerned with the persistence of synthetic nanoparticles in surface waters such as rivers. In this context, the project will study the role of aggregation mechanisms with naturally occurring mineral and organic suspended matter.

ERA-NET SIINN is being funded by the 7th European Research Framework Programme (Grant Agreement No. 265799). More information can be found on the Internet at www.siinn.eu.

Background conditions and challenges

The situation regarding the deployment of nanotechnology in the chemical industry continues to be marked by political and social debate on possible risks to health and the environment together with the question of regulation of the industrial application of nanomaterials. In its examination of the existing legal framework, the EU Commission drew the conclusion that the existing rules for chemicals can also be applied to nanomaterials and that any dangers should be dealt with on a case-by-case and application-specific basis. The methods in use thus far for the evaluation of risks should be applicable, even if they have to be specifically adapted in places.^[66] Adaptations have already been made in individual areas of the regulations, such as the labelling requirements for cosmetics, foodstuffs and biocides. Controversial discussions are ongoing at the political level and in expert circles regarding further adaptations to, for example, chemicals legislation or the introduction of mandatory product registration for nanomaterials (see section 4.4). Lack of certainty as to further regulatory restrictions and possible additional costs relating to the declaration and registration of nanomaterials can act as barriers to innovation when bringing nanomaterials to the market. This is especially the case for SMEs. The increased highlighting of risks in the media and growing awareness of risks on the part of the public, possibly as a consequence, has also led to some companies in the chemical industry being reluctant to position themselves within the context of nanotechnology. Further development will depend heavily on the results of research into nanorisks. One conclusion that can be drawn from the research over the past few years is that nanomaterials cannot be classified across the board as more dangerous than more coarsely structured materials. Instead the evaluation depends on the particular material and area of application (see section 4.4).

In addition to the risk aspects, technical and economic questions continue to pose fundamental challenges to the commercialisation of nanomaterials. Due to problems relating to the production of nanomaterials on an industrial scale, their further processing and integration into existing value chains, together with the frequent cost disadvantages when compared to existing solutions, we are as yet nowhere near full exploitation of nanotechnology's potential in the chemical industry.

3.4 Metal and ceramic materials

Sector development

The economic trend in the metals and ceramics sector is currently slightly downward. In the metal production and processing sector, turnover was down by 7% in 2012 at € 109bn while employment remained largely stable at 254,000 employees.^[67] The negative trend has been felt in particular by the steel industry which currently employs 88,000 employees and has a turnover of € 46bn (2012) in Germany, to a fall of around 7% compared with 2011.^[68] A slight downward trend can also be observed in the non-ferrous metals sector which employs some 109,000 people and turned over € 50bn in 2012, a slight decline that can be traced back primarily to weaker demand from southern Europe.^[69] There was a positive movement in the ceramics industry in Germany, which employed approximately 33,000 people in 2011 and posted a slight rise in annual turnover at € 5.4bn. The technical ceramics sector, which is the most immediately relevant for developments in nanotechnology, accounts for slightly less than 10% of the overall economic output of the ceramics sector with some 3,000 employees and annual turnover of € 530m.^[70]

In the ceramics sector the economically-relevant nanotechnology developments are in the field of high-performance coatings and nanoscale ceramic powders. The market for high-performance coatings in North America is estimated at \$ 1.4bn with an annual growth rate of 7% forecast from now until 2016.^[71] For nanoscale ceramic powders, turnover in North America is set to grow by 16% per year to reach \$ 1.2bn in 2016.^[72]

Turnover from metallic nanoparticles for conductive inks, adhesives, anti-bacterial additives etc. is forecast to reach \$ 2bn by 2017.^[73]

BMBF research activities

Only occasional projects within the BMBF's nanotechnology research activities related directly to the metals and ceramics sector. Research activities concern themselves for example with the use of CNTs to improve the mechanical properties of ceramic composites and aluminium materials. Further development objectives are serial production techniques for the manufacture

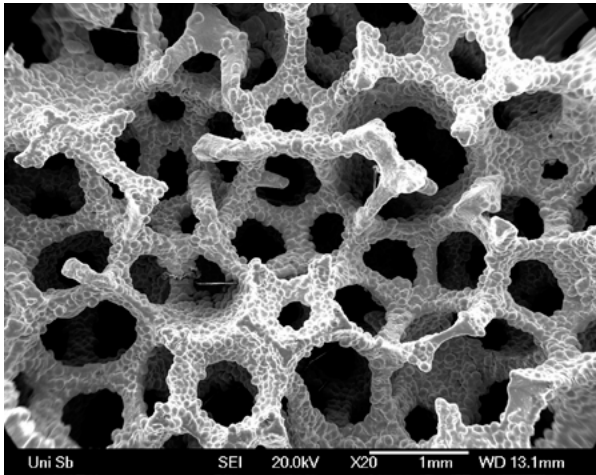
of abrasion-resistant nanocomposite cutting ceramics using plasma- and field-activated sintering techniques, and the replacement of lead in piezo-ceramic materials. In the field of metal forming, surface layers incorporating nanoparticles have been developed to improve the abrasion-resistance of forming tools. Coating systems using metal oxide nanoparticles are being researched to protect steel sheets from high-temperature corrosion during open-die forging. A further application area is in medical technology where nanocoatings are used to improve the bio-compatibility of titanium implants.

Other activities and sample applications

The use of nanocrystalline nickel coatings to improve the mechanical properties of aluminium metal foams is being researched at Saarbrücken University. From this research are emerging potential new applications for which conventional aluminium foams have until now been too weak and unstable. A materials researcher at Saarbrücken was awarded the Deutscher Studienpreis 2013 for development of the coating process, for which a patent has subsequently been applied.^[74]

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Ceramic materials	CNT-reinforced ceramic composite material by the formation of an atomically-bound CNT network within the ceramic matrix	03X0084A-C
	Mass production of faceted ceramic nanocomposite cutting ceramics inserts using FAST/SPS (Field Assisted Sintering Technology/Spark Plasma Sintering)	01QE1122A-B
	Structural properties of lead-free piezo-ceramic materials in multi-layer systems for actuators and heat-sensitive resistances	17PNT014
Metallic materials	Increasing the abrasion-resistance of forging dies for hot forging by means of nano-particle-reinforced surface layers	03X0118A-H
	Improvement of energy efficiency in aluminium casting by means of nanostructured oxides and additives	01LY1108A-F
	Use of nanoscale coating systems to reduce high-temperature corrosion when reheating the billet in hammer forging	03X0088A-C
	High-performance materials on aluminium base by means of combination of CNTs in the light metal matrix	03X0057A-H
	Biomedical properties of nanostructured and coated titanium	01DJ12064

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.



Electron microscope image of an aluminium foam coated with nanocrystalline nickel. In addition to improving mechanical properties, such as load-bearing capacity and energy absorbance, nanocrystalline coatings also improve surface properties such as the corrosion stability and high-temperature resistance of metal foams. (Image: Saarland University, Chair of engineering mechanics).

An example of basic research: Nanoanalytics for the investigation of corrosion processes

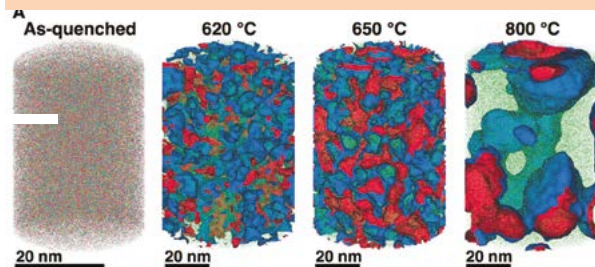
Frank Uwe Renner, Jazmin Duarte, Julia Klemm, Max-Planck-Institut für Eisenforschung GmbH (Institute for Iron Research), Düsseldorf

Corrosion (known colloquially as rust) and the associated erosion of materials are a serious problem of modern times. Use of a wide range of metal alloys and steels forms the basis for innumerable applications in everyday life in areas such as infrastructure, mobility and energy.

To date, nanoanalytical investigations aimed at understanding corrosion at the atomic level and hence finding ways to limit this, or even make use of it, have so far been scarce. Linking the microstructure with how the material behaves in use would not just help in the battle against corrosion but also suggest ways to manufacture new materials using innovative process technologies.

Frank Renner and his research team at the Max-Planck-Institut für Eisenforschung have now for the first time succeeded in detail in linking the micro-

structure with the corrosion behaviour of the metallic glass Fe₅₀Cr₁₅Mo₁₄C₁₅B₆ in its amorphous, partially and fully nanocrystalline form.^[75] While the composition of the material is similar to that of a stainless steel, metallic glass is an alloy that at the atomic level displays an amorphous (unordered) structure rather than a crystalline (ordered) one. This unordered arrangement of the atoms, unusual for a metal, results in unique properties such as a high degree of hardness or excellent resistance to corrosion.



Microstructure analysis of the metallic glass Fe₅₀Cr₁₅Mo₁₄C₁₅B₆ using atomic probe tomography illustrating the dependence of the nanostructure on temperature. Through manipulation of the temperature the metallic glass becomes at first partially crystalline, then fully crystalline at 800 °C, visible in the image of large surface area ordered structures contrasting with the finely mixed result in the amorphous state (left). Green: Iron, Blue: Chrome, Red: Molybdenum (Source: Max-Planck-Institut für Eisenforschung).

Examination of the microstructure using modern atomic probe tomography shows variations in the distribution of the elements during crystallisation of the material. Electrochemical investigations show that this uneven distribution has a strong effect on corrosion. The amorphous and partially crystalline material resists corrosion better than the fully nanocrystalline form. Using a flow cell with a constant electrolyte flow (scanning flow cell) coupled with mass spectrometry allows the dissolution of the various elements of the material to be analysed in real time. The analysis shows that a connection exists between the distribution of the chromium and the resistance to corrosion. When the chromium is enriched on the surface in the amorphous material, the resistance to corrosion is better than the nanocrystalline material in which molybdenum phases, which are susceptible to corrosion, are present along with the chromium phases.

The newly acquired knowledge was used directly by the research team to develop a new material possessing electro-chemically produced porous structures that are suitable for use as membranes for filters or as a support material for catalysts.

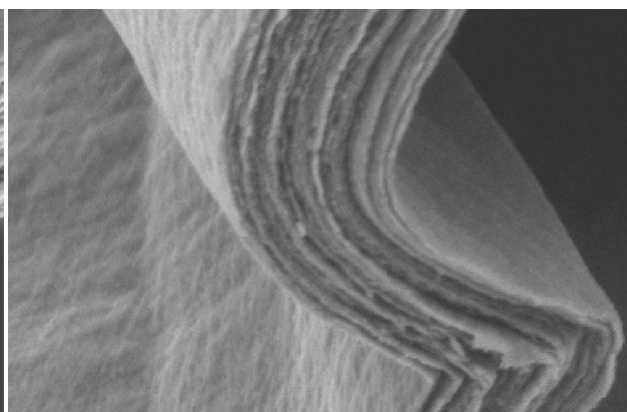
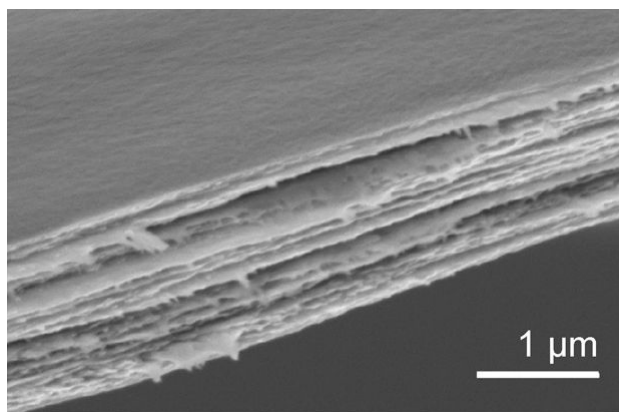
In the ceramics field, a planned hierarchical arrangement of nanostructures offers the potential to create novel (and for ceramics, unusual) material properties such as high resistance to breakage and mechanical flexibility. By imitating these properties, which are known to occur in bioceramics such as mother-of-pearl or bones, it is possible to create hierarchically structured composite materials using nanotechnological processes. As part of a DFG project researchers from Stuttgart University, the Max Planck Institute for Intelligent Systems and the Max Planck Institute for Solid State Research succeeded in producing a multi-layered ceramic paper from electrically conductive nanofibres of vanadium pentoxide. The special structure and ordering of the nanofibres, in a matrix with embedded water, makes the material highly elastic while at the same time being very tough and electrically conductive. Potential applications include electrodes in batteries, flat and flexible gas sensors, or actuators in artificial muscles.

Research performed under the EU's research funding programme is looking at the development of CNTs for very strong electrically conductive composite

materials that may, for example, be of interest in aerospace applications in aircraft structures. CNT composite materials for repairing aircraft structures were researched as part of an EU project funded to the tune of over € 2m. The material is intended to simplify the repair process for aluminium structures and improve damage and fatigue tolerance while at the same time enabling damage to be quickly detected, without expensive investigation, through changes in conductivity of the material.^[76]

Background conditions and challenges

The major drivers for nanotechnology developments in metal and ceramic materials emanate from the areas of resource and energy efficiency. Nanooptimised materials broaden the range of possible applications in lightweight construction, in corrosion and abrasion protection, or in the substitution of scarce or toxic raw materials. Responding to this, research efforts increasingly focus on multi-functional materials with integrated sensor, actuating and self-healing properties. Similarly to the chemical industry, a major challenge in the metals and ceramics sector is the safe management of nanoparticulate materials, which may for instance be processed in the form of dry powder or mixed with liquids. The aspects of health and safety and environmental protection in particular need to be kept in mind here. Further work is also needed on the cost-effectiveness of the manufacturing process for ceramic and metal nanocomposites, and the suitability of that process for mass production.



Folding ceramic paper: The stacked layers of the composite material, composed of vanadium pentoxide and water, can be seen in these scanning electron micrographs. The material is so elastic and tough that it can be folded (Source: Advanced Materials/ Stuttgart University).

3.5 Electronics

Sector development

The world market for semi-conductors managed as early as 2010 to recover the ground lost in the crash of 2008/2009, and was worth some \$ 290bn in 2012. The market is expected to grow by 5% per annum, reaching \$ 366bn by 2017. Japan continues to hold the world's largest production capacity with a 20% share of the world's wafer production. Germany's share of this market amounts to 2.7%. The strongest growth in any segment is in semi-conductors for communications technologies, while traditional computing makes up a declining share of the market. In Germany the strongest growth is in semi-conductors for the automotive sector.

Due to strong overall growth of the market in Asia, Europe's share of the world market came to just 11.4% in 2012 compared to 12.5% in the previous year. Germany's share fell from 4.8% to 4.3%.^[77] In absolute terms, the German market for electronics and ICT maintained its moderate annual growth rate of 1 - 2%, amounting to € 151bn in 2012. This is expected to attain a good € 153bn in 2013. The majority comes from telecommunications, software and IT services, while electronics in the form of IT hardware and consumer electronics contribute a good € 33bn.^[78] The industrial association BITKOM expects the sector for the first time to be employing over 900,000 people in 2013, corresponding to growth of 12,000 employees compared to the previous year. The market for printable electronics and related production processes in the field of roll-to-roll technology will also grow strongly, being expected to more than double from its current level of barely \$ 11bn to over \$ 22bn by 2017.^[79]

In electronics the miniaturisation of structures and the associated increase in integration density continues unabated. Basic components such as transistors have long achieved the nanoscale, with current processors displaying a structure size of 35nm and sometimes even 22nm. Further extensive R&D effort worldwide aims to develop new electronics concepts that go beyond silicon-based CMOS technologies. These new approaches are based on a variety of nanomaterials and structures such as quantum dots, nanowires, nanotubes or graphene.

Nanotechnology is not however limited to improving integrated circuits, but is also opening up possibilities in other application areas of electronics. In data storage, novel nanoscale non-volatile storage structures are being developed as alternatives to RAM, flash and hard-disk memory. In display technology new possibilities are emerging for the production of more transparent, higher performance, and flexible – so foldable – displays. This appears economically attractive as the global market for touchscreens is forecast to grow from barely \$ 1bn currently to almost \$ 5bn in 2019.^[80] The BMBF is supporting numerous nanotechnology-related activities of this kind through its research projects.

BMBF research activities

R&D activities related to the development and production of semiconductor circuits and chips are focused very strongly on the CMOS-compatible manufacture of structures in the 30nm range. Here fundamental objectives are the robustness, and particularly energy-efficiency, of the nanoelectronic structures and material systems together with manufacturing technologies. The intention is to increase integration density even further with yet smaller structures of 20nm or less. Nanolithographic processes based on projection optics for far-UV light are being developed for this purpose. The decisive element here is the further development of EUV lithography based on light wavelengths of less than 20nm. However, light in this shortwave region is difficult both to generate and to manage.

Increased storage density also plays a central role in data storage. Research here is looking at bit-structures of quantum dots based on compound semiconductors.

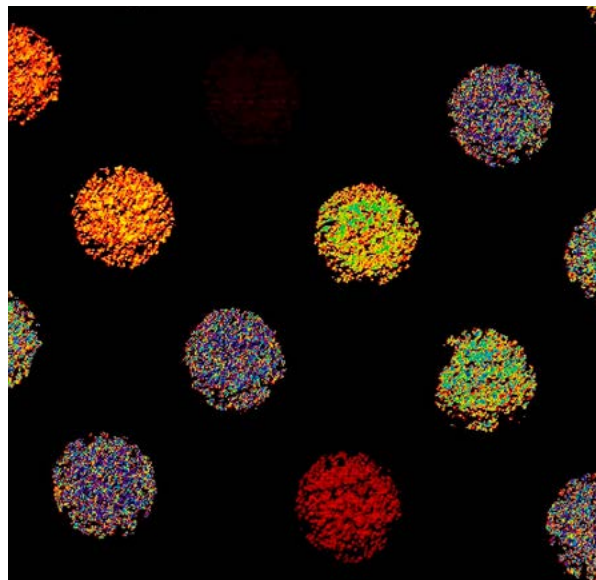
The use of nanoeffects and nanostructures are also being addressed through nanosystem integration in which micro and nano-scale electromechanical systems (MEMS/NEMS), embedded sensors and nano-structured interfaces are being developed for future electronics. Innovations in nanoelectronics should also in particular expand mobile communication systems for applications in man-technology interaction in support of older people, a business area perceived to have great economic potential in view of the aging populations in industrialised countries.



EUV illumination system (Source: Carl Zeiss SMT GmbH).

New nanoscale material systems for applications in electronics are being investigated in many places and should optimise microelectronic contacting and packaging technologies, make new insulation technologies possible or improve the efficiency of high-performance electronic components. In addition to compound semiconductors and super-conductive materials, a further priority is nanoscale carbon such as CNTs or graphene. These are being researched for nanoelectronics applications but also with a view to new, highly efficient electron sources or high-resolution electrode grids for use in medical diagnostics and other areas. Nanocarbon is also seen as a promising material for transparent, conductive films of the type increasingly used for touchscreen displays. CNT structures could in particular replace indium tin oxide (ITO) which is extensively used in this field but relies on the scarce raw material indium.

Numerous BMBF-funded research activities are concerned with the development of material systems and structures for organic electronics. One of a number of activities at the centre of attention is printing technologies for the manufacture of circuits and storage elements. Methods for nanostructuring and the use of nanoscale materials are often essential for the precise functioning of electronic components.



Integration of carbon nanotubes (CNTs) in copper-damascene interconnects: Conductive Probe Atomic Force Microscopy image of CNT-filled vertical interconnect accesses (VIA) after chemical-mechanical polishing – different colours carry different currents in the single CNT (Source: H. Fiedler in cooperation with M. Toader/Prof. M. Hietschold, Physics Institute, TU Chemnitz).



Transparent and conductive PolyTC® film in a machine from PolyIC (Source: PolyIC GmbH & Co. KG).

From where we stand today, any prospect for the application of future quantum information technology seems a very long way off. Nonetheless, the BMBF is supporting a range of technological developments in this area. Nanoscale components also play an important role in the field of quantum communications. Various R&D projects are based on nanoscale surface

structures, semiconductor quantum dots or integrated nano-electromechanical systems for storing quantum bits as the smallest unit of information. Further lines of research are looking at the representation and processing of such quantum bits based on stored ions or ultra-precisely positioned colour centres in diamond.

Other activities and sample applications

Nanoelectronic aspects are in the meantime being addressed across the entire breadth of the electronics field as microelectronics increasingly transfigures into nanoelectronics. Numerous developments in more than 70 larger projects have also been, and continue to be, funded under the 7th Framework Programme for Research (FP7), the largest of these being financed to the tune of over € 10m. Priority areas in R&D activities are:

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Chip and semiconductor design and manufacture	Research towards a future CMOS technology for the manufacture of ICs with 32/28nm structures	01M3089A-B, 01M3089E-F
	Design of highly efficient high-frequency circuits in 28nm CMOS technology	13N11484-86
	Energy-efficient nanosystem integration and development of production technologies for the creation of nanoscale reactive material systems (RMS) as a reactive functional film	13N11231-34
	Design for 3-dimensional, compact and energy-efficient nanoelectronic systems	01M3090A-F
	Design of robust nanoelectronic systems	01M3087A-F
	Simulation of new semiconductor structures in nanotechnology and micro systems technology	03MS613A-G
	Development of innovative nanoelectronic components and systems for human-technology interaction on mobile platforms	16SV5607, 16SV4056-63
	Modelling of Schottky barrier-based multi-gate field-emission transistors with a structure size less than 30nm.	1779X09
Data memory	Development of highly functional memory based on self-organised quantum dots made from GaSb, InAs and GaP compound semiconductors	16V0196
Electrodes and field-emitters	Development of integrated high-definition nanomodified multi-electrode grid based on nanoporous iridium oxide and a CNT “nanograss”	16SV5322K, 16SV5323
	Development of CNT and graphene systems for highly efficient field emitters	03X0201A-C
Insulation technologies	Optimisation of special insulation material for electronic sub-assemblies with nanoscale filled coating materials and hardening via microwave technology	03X0106A-F
Bonding and connection technologies	Development and application of nanocoated Cu and Ni wires for microelectronic connection technology	03X0117A-F
	Development of novel Josephson contacts based on superconductor-insulator-superconductor-contacts with variable quantum mechanical transmissivity	01DK12026
Power electronics	Power converter in GaN technology for capturing unused energy potential	16N10906-13
Lithography	Nanolithography – development of EUV projection optics for 14nm and 22nm structures	13N12256-60, 13N10567-72, 13N11303, 13N11314
New electronic materials and structures	Research into new materials (Graphene, topological insulators, Ti superconductor nanostructures) and their applications in nanoelectronics	01DJ12029
	Nanosystems integration; development of nanoscale material systems, NEMS/MEMS system integration, material-integrated sensors and nanostructured interfaces for use of nanoeffects in future electronics	03IS2011A-I, 03FO3292

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Organic and printable electronics	Printed organic circuits and memory, development of process techniques and manufacture of functional precision films of electronic functional materials using nanostructuring methods	13N10204-14, 13N11384, 13N12083-91, 13N10296-98, 13N12126-28, 13N11901-04
	Electrically conductive nanoparticle-based printing inks for large-scale printing processes	13N10653-55
	Morphology control for efficient and stable components in organic electronics	13N11701-06
Quantum communications	Development of integrated systems of superconductive quantum bits and nanomechanical resonators	01DK12019
	Research into topological quantum computing on nanoscale surface structures	01BM0900
	Development of new methods of quantum information processing based on quantum-mechanical interactions of stored ions in highly excited (Rydberg) states	01BQ1101, 01BQ1102
	Research into a quantum communications network based on semiconductor quantum dots	01BQ1103
	Use of nanoscale structures – such as semiconductor quantum dots – for the development of quantum information components	01BQ1030-42, 01BQ1000-14, 01BQ1110, 01BQ1107, 01BQ1108
	Development of a nano-electromechanical sensor for integration into a quantum interferometer or a synthetic atom (superconducting flux quantum bit)	01DJ12013
	Positioning of colour centres in diamond with nanometre precision for use as components for a scalable quantum processor	01BQ1104, 01BQ1105
Transparent conductive films	Development of conductive, transparent and flexible CNT composite materials	03X0200A-B
	Characterisation of defects introduced into ZnO bulk material and ZnO nanostructures for the optimisation of transparency and conductivity	01DG12036, 01DG12037
	Transparent and electrically conductive films with single-walled CNT hybrids	03X0202A-H

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

- **The further development of CMOS technology down to even smaller structure sizes of 22nm and below together with further increase in integration density.**^[81]
- **The development of new electronic concepts under the heading of “beyond CMOS”. In this context the following approaches in particular are being researched:**
 - **Nanocarbon-based concepts** for micro-components or nano-components such as field-effect transistors, condensers, circuit connections, etc., in which the electronic properties of carbon nanotubes and graphene are pivotal.^[82]
 - **Quantum information concepts.** Work is underway into nanomaterials-based possibilities for the manufacture and manipulation of quantum bit structures.^[83]
 - **Spintronic concepts** that, instead of electrical charge, use the angular momentum of defined molecular, atomic or electronic structures for processing information.^[84]
 - **The optimisation and further development of organic and printable electronics, the emphasis being on commercial-scale manufacture and the implementation of large surface area integrated circuits.**^[85]

Background conditions and challenges

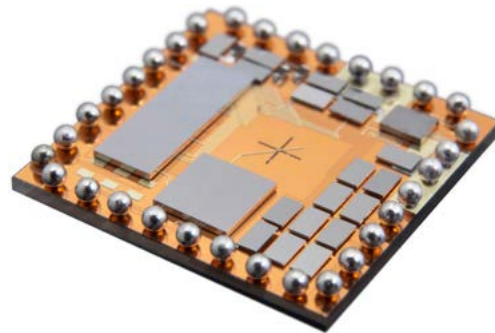
Political administrative conditions affect nanotechnology developments in the electronics field through, for example, the Restriction on Hazardous Substances in Electrical and Electronic Equipment (RoHS) directive. Thus, a decision was taken in the European Parliament during renegotiation of the RoHS directive in 2010 to extend the list of banned substances to include carbon nanotubes and nano-silver. This was not however included in the new version of the RoHS directive of 8th June 2011.^[86] On the other hand, the directive also provides incentives for nanotechnology developments to establish alternatives to banned substances such as lead-containing solder pastes or halogen-containing flame retardants. In the field of information technology centre-stage is taken by data protection aspects and “informational self-determination”. Here the fear exists that, with the rapid pace of digitalisation, the state will in future be less able to protect individual personal rights.

According to sector associations both the ICT and electronics sectors are affected by a shortage of skilled personnel that will become even more serious in the future. The current demand for 43,000 specialist IT professionals thus threatens to become a barrier to growth.

Guest contribution: Nanoelectronics and smart systems – an opportunity for Europe

Prof. Dr. Hubert Lakner, Joachim Pelka, Fraunhofer Group for Microelectronics

Across the world a transition is underway to the so-called „knowledge-based economy“. This form of society is characterised by the production and use of research-intensive key technologies and above all by an increasing need for electronics. As a consequence, “micro- or nano-electronics” and the closely associated “microsystems technology” have become dominant technologies without which (almost) nothing happens in the economy or in society.



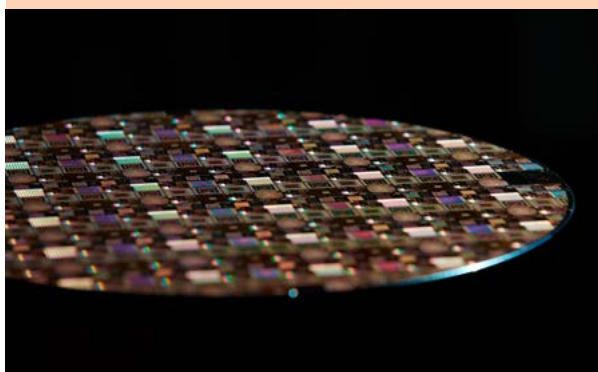
Heterointegration of different nanoelectronic components and sensors to create smart systems: Wafer-level system-in-package (SiP) for near-field determination of object positions (Photo: Fraunhofer IZM)

»Smart systems« is the heading which today characterises the ubiquitous electronics that long ago permeated all areas of society. Classical ICT technology for digital signal processing is enhanced by sensors and actuators, by high-frequency and high-performance electronics. With wafer-level integration, electronic and microsystems technology components merge into complete and high-grade miniaturised systems, the “smart systems”.

We now find these “smart systems” in all areas of daily life. They have become not just an accompaniment to our lives but are increasingly developing into an important tool with which major social challenges can be countered. They help to save energy and other

resources, to guide goods and traffic flows; they simplify daily life and support the sick and the aged, as well as making the environment safer. Regardless of the application, they comprise highly complex nanoelectronics, sensors and actuators, energy supplies, communications interfaces and software.

Now that the digital IC industry has largely migrated to Asia, Europe's strength lies in the mastery of this complex systems technology and in the development of complete system solutions. In order to be able to retain control over this systems know-how, it is necessary to be able to access not just More-Moore technologies but also More-than-Moore technologies.



Silicon connection technology (thickness 100µm) with Cu-filled Through-Silicon-Vias (TSV) and integrated passive components as the basis for a 3D System-in-Package (Source: Fraunhofer IZM-ASSID).

More-Moore describes the scaling in traditional digital IC technology while More-than-Moore describes the functional diversification and integration of non-digital components. Where we have previously been content to propagate the separation of these two technology paths, this must now be recognised as outmoded since advanced “smart systems” have long presented a combination of miniaturisation and functionality.

A basis for sustainable economic success in both wider Europe and in Germany therefore demands a broad technology base, secure in the long term, which must include an advanced nanoelectronic sector. Long-term development in the high-technology sector

cannot therefore be neglected in favour of short-term, demand-driven direction in terms of application. Realistically such development can only be sustained at European level and through direct collaboration between the large European “research and technology organisations” (RTOs) and the European semiconductor industry.

On the back of average annual growth of 5% since 2000, the European electronics industry, notwithstanding the tendency towards relocation, directly employs 200,000 people and indirectly provides the basis for a further 1m jobs, and also needs more qualified people. At least 10% of GDP depends on electronic products and services. This economic importance has been clearly recognised by the vice-president of the European Commission, Neelie Kroes: “I want to double our chip production to around 20% of global output. I want Europe to produce more chips in Europe than the United States produces domestically”

A European nanoelectronics strategy should thus be based upon three key pillars:

- **More and better coordinated investment in R&D** – maximising the effect of this through increased cross-border cooperation with investment split between the EU states (70%) and the EU (30%).
- **Expansion of Europe's three world-class electronics clusters:** Dresden (DE), Eindhoven (NL)/Leuven (BE) and Grenoble (FR).
- **Focus on cheaper** (450nm SI wafers), **faster** (“More Moore”) and **more intelligent** (“More than Moore”) chips.

Alongside this, acceptance and tolerance by society is a fundamental condition if technical visions are to be developed into corresponding market success. Change will become “business as usual” meaning that technical developments must be focused on people. To achieve this, alongside technical developments, technical training is also needed together with more intensive provision of public information, since we now live in an environment in which: Microelectronics isn't everything – but without microelectronics there would be (almost) nothing.

3.6 Optics/photronics

Sector development

Photonics offers vast potential for meeting our future challenges. Optical technologies are on the rise in sectors such as ICT, and increasingly so in modern manufacturing techniques as well as energy production, energy storage and energy efficiency. Also of growing importance are healthcare, environmental protection and safety. Photonics is of great importance in a wide range of application areas, throughout many parts of the value chain. Experts calculate that as a result of the leveraging effect of this key technology, between 20% and 30% of the European economy and some 10% of all jobs in Europe are dependent on the photonics sector.^[87]

The German photonics industry accounts for some 8% of the global photonics market and around 40% of the European market. With over 10% of global market share the core areas of production technology, image processing and metrology, optical components and systems, together with medical technology and life sciences, lie well above this average.^[88] The sector was also able to make successful economic progress over the past two years. Domestic production in 2012 rose to just short of € 28bn,^[89] representing an annual growth rate of some 8% when compared with the € 16.3bn achieved in 2005. Experts expect a further rise in production, to around € 44bn by 2020, corresponding to a slight slowdown in annual growth of 5.6%.

The export ratio of production output, 66% in 2012, further indicates the photonics sector to be a heavily export-oriented part of the economy. Taking into account the supplier side as well, the sector employed 134,000 people in 2011 corresponding to a rise of 30,000 jobs as against 2005, a figure set to rise to around 165,000 by 2020.^[90]

Innovations in nanotechnology find wide application in the photonics and optics sector, with nanoscale structures such as quantum dots, optical coatings, plasmonic surface structures etc. playing a critical role in numerous applications. Despite this, it is often difficult to determine the share of nanotechnology in photonic or optical products. According to a study by the market research company BCC, global turnover for

nanophotonic products such as nano-based light-emitting diodes, organic light-emitting diodes, holographic memory, optical circuit components, photonic crystals or plasmonic components was \$ 2.5bn in 2011 and is expected to rise to just under \$ 11bn by 2016. This equates to an expected annual increase of over 30%. The major market share (97%) is accounted for by nanophotonic light-emitting diodes.^[91] These rates of growth, which are significantly above the rate for the sector as a whole, can be seen as an indicator of the continually growing importance of nanotechnology within optical technologies.



Silicon nanocrystals enable the production of silicon-based light-emitting diodes: By changing the size of the silicon nanocrystals, the colour of the light emitted can be varied. (Source: F. Maier-Flaig, KIT/LTI).

BMBF research activities

Research activities in the lighting sector are focussed on the development of organic light-emitting diodes (OLED). OLED research is looking at new material systems, optics, and structures, along with manufacturing processes suitable for mass-production in printing technologies and roll-to-roll production. The manufacture of functional films at nanometre scale, together with nanoscale structuring, are decisive in the performance of the components, something equally applicable to semiconductor-based inorganic light-emitting diodes (LEDs). These are also being optimised with respect to their composition and manufacture for lighting applications. In addition, efficient LEDs emitting light in the UV range are being developed which

contribute to the optimisation of production processes in organic electronics.

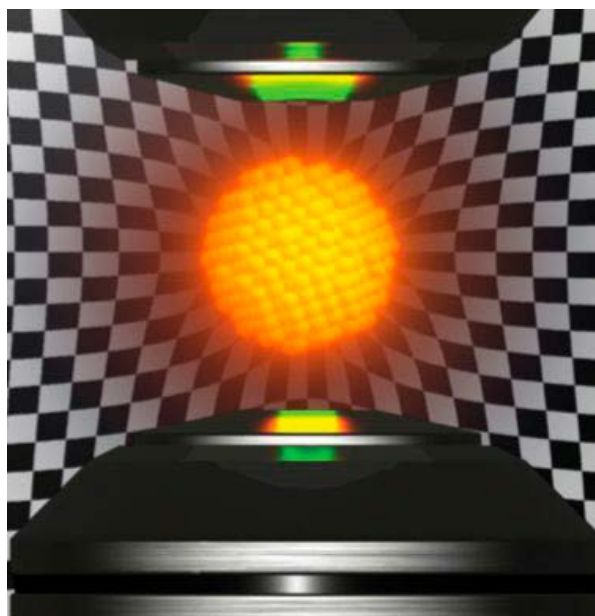


OLED pendant lights for general lighting applications (Source: Novaled AG).

The focus of development in the opto-electronics sector is on components for optical data communications and telecommunications. The R&D focus in this sector is on beam guidance and beam preparation via fibres, freeform optics, tuneable optical filters, beam deflectors and wave guides, together with light production and modulation from electronic signals by means of, for example, optimised surface emitters (VCSELs) and the integration of photonic components in silicon structures. Within this context research is underway into nanoscale crystal, composite and film systems. In the field of lasers, in addition to VCSELs narrow-band laser diodes are being developed for spectroscopy while fibre-linked diode lasers are being developed for industry. Research is also underway into novel photonic materials such as meta-material optics for the THz range, plasmonic structures, photonic nanomaterials for lithography, optoceramics, nanostructured diamond and carbon optics, and the development of graphene layers as transparent conductive coatings. In optical analysis priority is being given to the measurement of optical surfaces and the quality control of semiconductor structures.



Within the BMBF-funded “nanett” nanosystems integration skills network, sensitive optical sensors are being developed able to show the mechanical forces acting on materials. The illustration shows a test specimen that has been coated with minute, i.e. nano-metre-sized, semiconductor particles. When the tiny semiconductor particles are excited with UV light, they begin to fluoresce. The colour of the light emitted depends on the size of the particle. If a mechanical stress is operating on the material at multiple positions, this fluorescence stops. (Source: Fraunhofer ENAS, Photo Hr. Thieme).



Impression of the photothermal microscopy of gold nanoparticles. Photothermal microscopy makes it possible to visualise gold particles below the limit of optical resolution. The nanoparticles are slightly heated by means of a laser, and using a second laser the interactions that occur with the surrounding material can be detected. Potential application areas are emerging ranging from optical data processing through to tumour therapy (Source: Leipzig University, Illustration: Markus Selmke).

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
General lighting and new light sources for various applications	Research and further development of OLED applications (materials, optics and external structures) and OLED material systems and production technologies suitable for mass production for general and vehicle lighting and also using nanostructures and nanoscale material systems.	13N10526-36, 13N10610-12, 13N10740-44, 13N11235-37
	Research and characterisation of new material systems for solution-based organic light-emitting diodes	13N10614-22, 13N11452
	Development of printable organic light-emitting diodes (OLEDs) based on functional films with thicknesses of less than 100nm for lighting and PV applications	13N10758-62, 13N12279-81, 13N12309
	Roll-to-roll production of highly efficient organic components, in particular organic light-emitting diodes and solar cells, on flexible substrates using methods such as nanostructuring and nanocoating	13N11053-63
	Development of efficient, cost-effective InGaN LEDs on silicon substrates for general lighting using nanoscale structures and structuring processes together with the development of automated process chains for their manufacture	13N10251-55, 13N10555-56, 13N10558-59, 02PK2188-91
	Development of scalable high-performance UV LEDs for the production and sealing of organic and printed electronics with protective lacquers	03WKBT01A-D, 03WKB-T02A-D, 03WKBT04A-D
	The realisation of highly efficient UV LEDs in the wavelength range 300nm to 350nm and UV photodetectors with micro and nanocoating processes together with the development of material systems and process analytics for these	03WKBT05A-B, 03WKB-T06A-B, 03WKBT08A-C
Lasers	Development of laser-coupled, high brilliance diode lasers through to the achievement of industry standard by means of nanostructuring, optimisation of quantum well structures and other methods	03IPT613A-D
	Development of narrowband emitting laser diodes at 435.9nm for spectroscopic applications	03WKBT03A-C
Novel photonic materials	Development of photonic nanomaterials and nanostructures for optical applications	03IS2101A-F
	Development of photonic nanomaterials for lithography	03IS2101B, 03IS2101E
	Development of optoceramic materials and components from nanoscale powders for use in optosensory and light technology applications	13N10802-05
	Novel electronically and optically tuneable meta-material optics for THz technology	13N11905
	Application of nanostructuring to the manufacture of plasmonic structures	01DQ12034
	Designing complex micro and nanostructured photonic components based on diamond and carbon optics together with the development of manufacturing technologies	03Z1HN31, 03Z1HN32
	Development of electrically conductive graphenoid layers with a large surface area as flexible, optically transparent coating materials	03X0108A-C
Opto-electronics, silicon photonics, photonic components	Monolithically integratable, silicon-based photonic components for data communications and telecommunications	01BL080, 01BL1009, 01BL1010
	Organic-inorganic nanocomposite and multi-layer systems for advanced applications in optoelectronics	01DK12024
	Development and manufacture of GaN crystals as energy-efficient materials for the telecommunications sector using nanostructuring and nanoanalytics	01BM1200-05
	Development of nanostructured surfaces for controllable optical components and microsystems (tuneable filters, variable imaging elements, beam deflectors, etc.) with new functionality	16SV5372-77

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
	Further development of long-wavelength surface emitters (VCSELs) with optimised optical performance, novel wavelengths, and reduced costs using nanocoating processes	16N10447, 16N10448
	Development of rare-earth-doped fibres for high-performance applications	01DQ12066
	Study of opto-electronic properties of ZnS nanostructures	01DO12033
	Development of ultra-high precision silicon optics and optical components on processable silicon films with structure sizes and roughness in the nanoscale range	03WKP11A-D
	Development of precision freeform optics made from glass and novel materials with film thickness around 100nm for optoelectronic applications or to increase beam quality in VCSEL high-performance lasers	13N10823-28, 13N10837-42, 13N10849-52, 17098A10-C10
Optical coatings	Colour-neutral reflection-reduction techniques with organic nanostructures	13N12155-60
	Research into novel nanocomposite materials for contact lenses and nanotechnological material design for improvement of compatibility and comfort levels	13N10756, 13N10757
	Production of low-loss, highly refractive oxide films for precision optics	13N12124, 13N12125
Optical analysis and sensors	Terahertz laser spectroscopy of semiconductor nanostructures	01DJ12001
	Metal-organic chemical vapour deposition and characterisation of InGaN films for quantitative analysis	03WKBT06C
	Development of multiscale measuring technologies for optical free forms and detection of nanostructures, defects and roughness on optical surfaces with varying geometries	13N10853-59, 13N11120

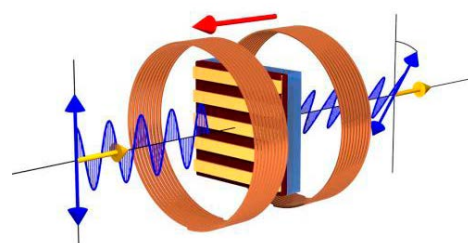
Summary of research topics in the BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the award number.

Other activities and sample applications

Photonics is a growth market and extensive research is being carried out worldwide. At European level numerous research projects in optics/photonics are being funded, with the largest receiving from € 3m to over € 10m. These are addressing:

- portable, low-cost lasers based on quantum dots,^[92]
- tuneable micro-lens systems based on natural processes,^[93]
- nanostructured semiconductors for lighting,^[94]
- mass production processes for light-emitting components,^[95]
- the development of meta-materials with optical applications,^[96]
- the development of non-diffraction-limited optical processes for data storage,^[97]
- the development of new optoelectronic components for telecommunications.^[98]

Further research activities at national and European level include novel photonic materials, plasmonic structures and quantum-optical systems for quantum information processing.



Researchers at Stuttgart University have developed a novel gold nanostructure that allows the plane of polarisation of light to be rotated (the Faraday effect). The image shows the architecture and geometry of the thin-film Faraday rotators. The magnetic field coil is arranged around the sample. The red arrow represents the magnetic field. The gold nanowires can be seen (in yellow) along with the magnetic-optical thin-film layer (in red). The electromagnetic light wave is shown in blue. (Source: Stuttgart University).

Background conditions and challenges

The German photonics sector is well-placed in respect of international competition, due in no small part to many years of ongoing innovative effort. At an average of 9%, the sector's R&D ratio is maintaining its high level. A few particular risks can be perceived within administrative regulations under European environmental legislation. For example, the "Restriction on Hazardous Substances in Electrical and Electronic Equipment" (RoHS) directive bans the use of substances such as lead and cadmium. This also impacts optical glass, which may contain these heavy metals for particular functional properties. The European REACH chemicals directive further requires companies to collect and pass on extensive information on the substances contained within products, putting an administrative burden on the photonics sector that is believed to be very high.^[99]

3.7 Energy

Sector development

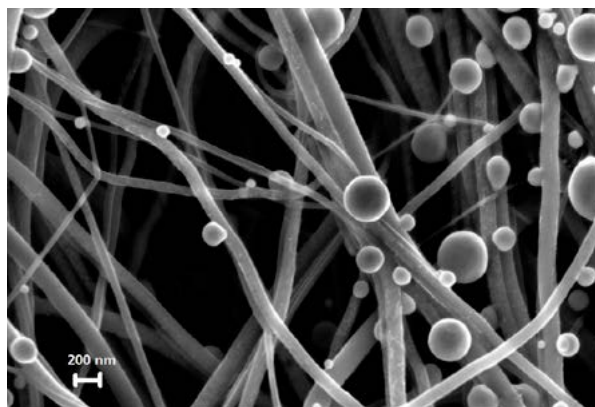
The energy sector in Germany is marked by the "Energiewende", the transition to green energy, which calls for an increase in the energy obtained from renewable sources. Thus, as early as 2012, 11.6% of the primary energy consumption of 3790 TWh in Germany was able to be met from renewable energy sources.^[100] The share of renewable energy in gross electricity production rose to 23% in 2012 (up from 17% in 2010 and 20% in 2011) to reach 135bn kilowatt hours. This continued the steady upward trend since the start of the century and was in line with the Federal Government's energy policy which foresees a share of 35% by 2020 and even 50% by 2030. The majority of energy generated from renewable sources is funded under the Renewable Energy Sources Act (Erneuerbare Energien Gesetz: EEG). Payments under the EEG will rise in 2013, probably to € 19bn (2011: approximately € 17bn; 2012: approx. € 18bn).^[101] The number of people employed in the renewable energy sector in Germany rose by 135% between 2004 and 2012 to some 378,000. There was however a slight fall between 2011 and 2012 of some 3500 in the number of persons employed, which can be attributed to the crisis in the solar industry at that time. The number of employees in that industry fell by 20% as against the previous year, while it rose by 17% in wind energy and remained somewhat stagnant in other sectors such as

bio-mass, geothermal energy, hydroelectric, research and administration.^[102]

Nanotechnological innovations can be found in almost every area of the energy sector and contribute to increased energy efficiency as well as to improvements in energy conversion, storage and transmission. Nanotechnology acts as a key cross-sector technology, offering many opportunities for optimisation that can help renewable energy make the breakthrough. In the energy sector nanotechnologies are primarily relevant in the areas of solar cells, electro-chemical energy storage, fuel cells, thermoelectrics and energy-efficient materials.

BMBF research activities

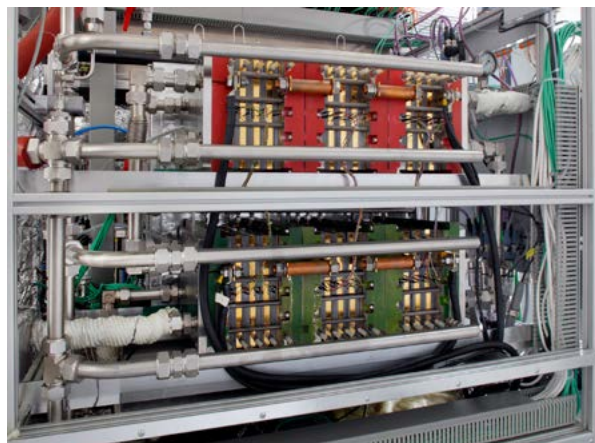
Electro-chemical energy storage devices are an important funding priority for the BMBF. Particular attention is being paid to lithium-ion batteries and their optimisation by means of nanoscale materials such as graphene or novel composites for electrodes and other cell components.



Tin-carbon nanofibres from the KoLiWiIn project. In this BMBF-funded project new concepts for materials and technologies from the project partners were evaluated at the Fraunhofer ISC for their application in lithium-ion batteries. (Source: Hanne Andersen, Fraunhofer ISC).

Higher energy densities should be achieved by means of so-called "high voltage systems" with cell voltages of up to 5 volts. A further focal point is operational safety, for which safe electrolyte and membrane systems in particular are decisive factors. Further

promising electro-chemical concepts are also being investigated that go beyond conventional Li-ion systems. Alkali-sulphur batteries, and lithium-sulphur systems in particular promise a significant increase in storage capacities. Even higher energy densities are promised by lithium-air cells in which the cathodes are replaced by air and the oxygen required for the reaction is drawn from the ambient air. High power densities, such as are needed while an electric vehicle is accelerating, can however only be achieved using supercapacitors. The BMBF is funding the optimisation of these based on approaches such as nanoparticles or graphene and nanostructured system components.



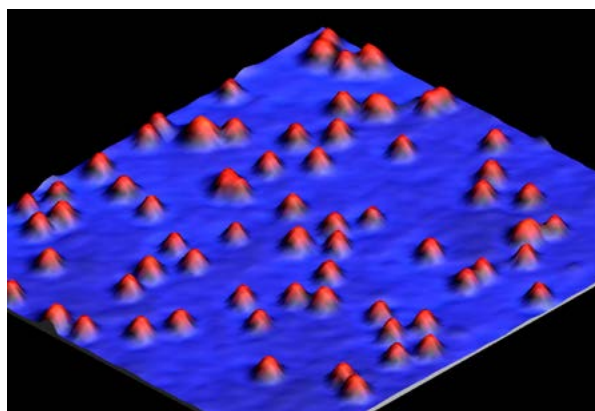
A stack of high-temperature polymer electrolyte fuel cells (Source: Jülich Research Centre).



Coating of the electrodes in lithium-sulphur batteries in the roll-to-roll process. (Source: Jürgen Jeibmann/Fraunhofer IWS).

Nanostructured, and particularly graphene and CNT-based, materials also play a central role in BMBF activities funding fuel cell technology, in which the electricity is produced directly from the energy contained in gases such as hydrogen and methane.

The reverse process – the production of hydrogen from temporary surpluses in renewable electricity – goes under the name of “power-to-gas” and is seen as a promising way of storing energy. In this context the BMBF is supporting the development of efficient electrolyzers capable of flexible operation. In addition, the production of hydrogen by the light-induced splitting of water on nanostructured surfaces with a photocatalytic effect is also being investigated. Nanoporous metal-carbon-materials are being investigated for hydrogen storage. In energy transmission, the manufacturing of optimised high-temperature superconductors is being addressed.



An atomic force microscopy image of nanoscale copper particles that were generated in an ion source, selected by size for use as a particle beam and subsequently deposited on glass. The particular optical properties of the nanoparticles influence the photocatalytic splitting of the water. (Source: Rostock University).

In photovoltaics research a key priority is improvement in the effectiveness of solar cells. Particularly the subject of research is the further development of both CIGS and silicon-based thin-film solar cells. A key role in this research is played by novel concepts for highly efficient absorber materials based on nanoscale structures. Further activities are the investigation of organic solar cells along with organic-inorganic hybrid systems based on nanostructures and nanoparticles. Nanos-

tructures are also key elements for thermoelectrics where the focus is on the extraction of electricity from waste heat from industrial plants and especially from the exhaust gas systems of motor vehicles. The BMBF is funding the development of innovative, efficient material systems for use in the high-temperature range as well as the development of printable thermoelectric generators based on hybrid systems from polymers and inorganic nanoparticles.

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Batteries, supercapacitors, fuel cells	Material concepts for alkali-sulphur batteries	03X4618A, 03X4618B
	Use of graphenes in lithium-ion batteries and fuel cells	03X0112A—D
	Development of a lithium-sulphur battery for electric mobility based on nanostructured silicon anodes	03X4627A-C
	Metal-air batteries: Development of (nano)structured or nanoporous electrodes in particular for lithium-air batteries with optimised performance	03X4620A, 03X4620B
	Development of efficient air or oxygen electrodes for lithium-air batteries as future high energy storage systems	03X4624A-E
	Development of rechargeable lithium-air cells with glass-based solid-state electrolytes and protected anodes for future applications in electric vehicles	03X4623A-E
	Development of new electrodes and electrolytes for high-energy lithium-ion batteries and development of new types of lithium batteries (in particular li/air and li/sulphur)	03X4612M, 03X4612O, 03EK3005, 03SF0390
	Development of safe electrolyte systems for lithium/ion/polymer batteries with optimised long-term stability based on new molecular structures	03X4607C
	Development of a new generation of lithium-ion batteries based on a novel type of nanoscale composite materials	03X4613A-F, 03SF0344A-B, 03SF0343A-H, 16V0213
	Study and optimisation of new nanoscale electrode materials for (lithium-ion) batteries	03SF0397, 13N11930, 03EK3008, 03EK3004, 13N11930
	Development of novel electrical energy storage systems (double layer capacitors) based on three-dimensional nanostructuring	03EK3013
	New super capacitors based on ferro-electrical nanoparticles for energy storage	03FO3262
	Development of innovative electro-chemical super-capacitors including via the use of graphenes as a novel electrode material	03EK3010D
	Optimised manufacture of PEM fuel cells by injection moulding using CNT-polymer composite materials	03X0048A-F
	Study of defect-creating mechanisms in the synthesis of nanostructures in electrodes and electrolytes of solid oxide fuel cells	01DK12017
Electrolysis	Development of new membrane-electrode units for alkaline PEM electrolysis for flexible hydrogen production from renewable energies with frequent variations in load	03EK3012A-B
Space heating	Development of highly-resistant, nanostructured ceramic coatings for operation at high temperatures and for optimising the efficiency of the burner in oil-fired heating systems	03X0089A-C

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
High-temperature super-conductivity	Development of optimised high-temperature super-conductor based on improved chemical deposition procedure for the production of nanoscale film systems	03X0090A, 03X0090C
Solar cells	IR-optical nanostructures for photovoltaics for improving the effectiveness of solar cells	03SF0401A-D
	Nanoscale III-V-/silicon heterostructures for highly efficient solar cells	03SF0404A-E
	New absorbent materials from abundantly available raw materials for thin-film solar cells using nanoparticles	03SF0402A-E
	Development of thin-film solar cells with new highly absorbent compound semi-conductors using, for example, nanostructuring	03SF0358A-F
	Development of new organic solar cells using fullerenes as electron acceptors	01LY0820B
	Development and characterisation of silicon-based, nanostructured thin-film materials for high-efficiency solar cells	03SF0352A-G
	Development of nanoparticle thin-film solar cells	03SF0363A-F
	Development of printable thin-film photovoltaics based on organic-inorganic (CIGS) hybrid systems using nanostructures and nanoparticles	13N10745-9
	Expanding the „Kompetenzzentrums Dünnschicht und Nanotechnologie für Photovoltaik“ Berlin (Competence centre for thin-film and nanotechnology for photovoltaics)	03IS2151A-G
	Manufacturing, (nano)structuring and characterisation of thin CIS and CIGS films together with optimised concepts and beam shaping for a customised photovoltaic	13N11783-90
Thermoelectronics	Industrialisation concept and novel materials for thermoelectric generators capable of operating at high temperatures for using heat from the exhaust gases emitted by motor vehicles	03X3551A-E
	High-temperature generators for using the heat in exhaust gases in motor vehicles and industrial combustion plants	03X3548A-H
	Innovative materials and generators for thermoelectric heat recovery from the exhaust gas system in motor vehicles	03X3555A-G
	Development of efficient thermoelectric thin-film components on a silicon and germanium base by means of nanostructuring	03X3541A-F
	Development of printable organic thermoelectric generators based, for example, on hybrid materials made from organic polymers and inorganic nanoparticles	13N12026
	Development of nanostructured, oxodic thermoelectric materials	01DQ12068
	Development of highly efficient, high-temperature thermo-generators for use in motor vehicles based, for example, on oxodic nanoparticles	03X3547B
	Development of highly effective thermoelectric semiconductor with low-concentration additives based on self-organising nanostructures in complex chalcogenides	03X3540A-D
Hydrogen production and storage	Development of light, static and mobile high-capacity hydrogen tanks having high levels of operational safety, energy-efficiency and storage capacity based on novel, nanoporous metal-carbon composites	01DJ12071
	Nanostructures for light-induced hydrogen production from the photocatalytic splitting of water	03IS2071A-G, 03SF0353A-E
	Development of large surface area, three-dimensional nanostructuring techniques for producing high-performance nanocomponents for tandem solar fuel cells, super-capacitors, optical sensors and organic non-volatile memory	03Z1MN11

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

Other activities and sample applications

Energy research is now being pursued very actively worldwide. It affects all forms of energy extraction, storage and transmission. Nanotechnological innovations are contributing to this in many ways. In Europe one priority in nanotechnology activities is renewable energy sources and energy extraction from renewable raw materials. Over 60 larger energy research projects within the European Research Framework Programme are in some way related to nanotechnology, with some of these being funded by the European Commission to the tune of over € 5m. They are predominantly addressing topics in the field of photovoltaics and are looking at increasing efficiency by means of concentrators^[103] along with the development and mass production of thin-film solar cells based both on silicon^{[104][105]} and on compound semiconductors (CIGS).^{[106][107]} The NANOHEX project on the other hand is developing novel, energy-efficient heat exchangers based on nanofluidic coolants.^[108]

The SUPRA-BIO project, which is receiving the largest funding at over € 12m, is looking at the sustainable production of fuels, materials and chemical substances from bio-mass.^[109] In addition to genetic approaches one focal point of the project is on the development of nanocatalytic processes.

Further activities are addressing improvements in thermoelectrics, CO₂ deposition and replacement of critical raw materials such as rare earths for permanent magnets by nanomaterials, together with a plethora of energy storage and conversion processes. To the latter category we can also allocate the development of materials, architectures and manufacturing processes for certain super-conductors. For example, the EU's EU-ROTAPES project is producing superconductive tapes with lengths up to several hundred metres to be used in energy-efficient power electronics and high-performance magnets.^[110]

Background conditions

How the market for solar cells and electrochemical storage in particular will develop in the near future will depend very much on the political and legislative conditions. An improvement in batteries as regards their range, speed of recharging, lifespan, safety, cost reductions and reliability is essential for increasing

customer acceptance and achieving the objectives of the National Development Plan for Electric Mobility that is aimed at having one million electric vehicles on the market in Germany by 2020. In parallel with this, static battery chargers are becoming ever more important to even out the fluctuating feed of electricity into the network from renewable sources. Since 2013, the Federal Government has been providing investment aid as a way of promoting the spreading of decentralised battery systems as a supplement to domestic PV devices. Systems of this type are being increasingly offered commercially. Market expectations are high. Thus, the global market for solar power storage is forecast to grow between 2012 and 2017 from \$ 200m to \$ 19bn.^[111] In addition, the Renewable Energy Act (Erneuerbare Energien Gesetz: EEG), which regulates the preferential terms for renewably generated electricity fed into the grid, will remain decisive for photovoltaics.

3.8 Environmental engineering

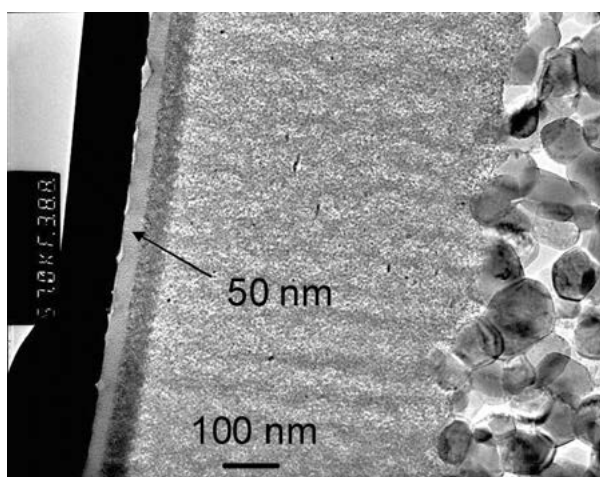
Sector development

Environmental technology is a relatively heterogeneous branch of the economy with its main areas of application being in climate protection, air quality control, water pollution control, waste control and noise reduction. According to figures from the Federal Statistical Office (Statistisches Bundesamt), 216,000 people are employed in nearly 9,000 companies providing goods, construction and services for environmental protection, with a total turnover of € 61bn (as of 2010).^[112] The export ratio is around 40%. Around two-thirds of the turnover was generated in climate protection which also includes photovoltaics as the largest sub-sector. The photovoltaics sector in Germany, which employs some 110,000 people, is currently undergoing a structural change as a result of the sharp drop in prices for solar modules due to competition from Asia (see section 3.7).^[113]

In environmental protection, nanotechnology has a special economic relevance in the areas of treatment and remediation technology, environmental sensors and resource-efficiency. It is estimated that the world market for nanotechnology applications in environmental engineering will be worth \$ 21.8bn in 2014.^[114]

Within this, the important markets for the application of nano-optimised products are membrane filtration and environmental catalysis. The total market for membrane filtration is forecast to grow to \$ 16bn in 2017^[115] with the total market for environmental catalysis forecast to reach \$ 14.6bn in 2015.^[116] In addition to this, a large part of the world market for nanocoatings, which is forecast to be worth \$ 7.6bn in 2017,^[117] is for environmental applications such as self-cleaning surfaces, photocatalysis, and wear and corrosion protection.

nology is another important area of research. Environmental sensors, used for example to detect pesticides or gaseous pollutants, benefit from nano-optimised sensors with greater selectivity and greater sensitivity when detecting pollutants. Current research topics concern the replacement of scarce raw materials and aspects of recycling such as the use of recycled raw materials (see boxes on the BMBF's MatRessource support measure). Part of the NanoNature support measure studied lifecycle aspects of the use of nanomaterials along with any possible eco-toxicological effects.



Ceramic nanofiltration membranes (on the left of the electron microscope image) are used as an effective method for treating waste water and separating products without harming the environment (Source: Fraunhofer IKTS).

BMBF research activities

Protection of the environment and resources is one of the central fields for social action in the Federal Government's high-tech strategy. Within the BMBF's nanotechnology research programme, the area of environmental engineering is being addressed in a variety of ways. One development target is the improvement of resource-efficiency in products and processes. Improved dirt-repellent and biofilm reducing coatings can save on environmentally harmful cleaning materials and energy. Nanostructured catalysts are being developed for resource-saving production processes in the chemical industry but also for an efficient conversion of harmful substances in environmental catalysis. Keeping the air and water clean by means of nano-optimised separation of substances and membrane tech-

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Improvement of resource efficiency of products and processes through surface functionalisation and catalysis	Nanolacquers for dirt repellent films with improved cleanability	03X0115A-B
	Biocide-free, biofilm-reducing facade systems	1793X09
	Hard materials and abrasion-resistant films for longer lifespan based on novel and recycled nanomaterials	03X3573A-C
	Nanocomposites for lightweight construction by means of tandem catalysis, compartmentalised multi-centre catalysts and nanostamping techniques	03X3565A-D
Environmental catalysis/pollutant conversion	Development of resource-efficient catalytic converters for motor vehicles with a significantly reduced precious metal and rare earth content	03X3563A-C
	Development of nanoscale SCR catalysts for combined NO _x and soot particle reduction in diesel engines	03X0079A-D
	Iron-based nanoparticles and nanocomposite structures to remove pollutants from groundwater and waste water	03X0097A-H, 03X0082A-G, 03X0085A-E
	Nanomodified diamond electrodes for process-integrated disinfection for use in various areas	03X0087A-H
	New photocatalytically active compound materials to eliminate pharmaceutical residues	03X0094A-I
	Novel filters for simultaneous separation of particulate and gaseous components of air by coating glass-fibre fabrics with photoactive nanomaterials	03X0065A-D
	Microbial synthesis and recycling of hybrid palladium-nanocatalysts and their use in treatment of persistent environmental pollutants	03X3571A-E
Protection of the environment and biosphere	Biosensor platform based on monoclonal antibodies for species identification for applications such as policing catch quotas in fisheries	01DG12055
Pollutant recognition/environmental sensors	Fast optical tests for pesticides based on nanoporous membranes in microfluidic chips	16SV5595-600
	Nanotechnological receptor films on field effect transistor gas sensors for improved trace gas detection	16SV5477
	Selective measurement of trace gases using nanoporous sensors	13N11138-9
	Nano balance detectors for personal measurement of nanoparticle exposure	03X0098A-B
	Study of microbially catalysed material flows in the Baltic ecosystem using NanoSIMS technology	03F0626A
Separation/membrane technology	Biofilm and chlorine-resistant reverse osmosis membranes based on nanoparticle-functionalised polymer coatings	01DH12008
	Nanoporous ceramic membranes for sustainable reductions in water and solvent use through closed-loop systems	03X0080A-L
	Nanoparticle-stabilised polymer filter membranes for ultra-filtration with optimised property profile for technical applications	17N1610
	Nanoscale composite microscreen in combination with UV LED decontamination for treatment of water and waste water	03X0083A-F
	Composite membranes for organophilic nanofiltration for energy-efficient separation of substances	01RC1001A-D
Recycling/use of recycled raw materials	Nanoscale silica slurry – development of technologies for use in mineral building materials with the aim of improving the material properties	03X0081A-J
Replacing scarce raw materials	Nanoscale rare-earth-free magnets and magnetic composites	03X3582A-D
	Substitution of tungsten in abrasion protection films	03X3584A-H

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Analysis of the lifecycle of nanomaterials and their potential for harming the environment	Material properties, release and behaviour of CNT materials in the environment	03X0114A-E
	Assessment of environmental harm by silver nanomaterials	03X0091A-M
	Research into the mobility of synthetic nanoparticles in the ground and in groundwater	03X0077A-C
	Nanoparticle lifecycle studies based on $^{45}\text{TlTiO}_2$ and $^{105}\text{Ag}^0$	03X0078A-C

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.



Nanomembranes are used for treating water in an opencast mine. The treatment plant can clean a large proportion of the waste water from the mine, rendering the process of extracting the ore more environmentally friendly. A pilot plant for the new treatment technology is installed at a copper mine in Chile (Source: Siemens).

Example of a BMBF support measure: MatRessource

Dr. K. Otten, Project Management Jülich

The world's population is growing, demand for energy and materials is rising, but the availability of raw materials is finite – reasons to manage the resources we do have with better foresight. Using available resources efficiently is not just driven by sustainability, but for reasons of cost and competitiveness is also a task for the future – and one the Federal Government has set itself. Do more with less: this is the rule of thumb supporting the path forward into resource-efficient, environmentally-friendly industry and society. Against this backdrop the BMBF has since 2012 been funding selected research topics in the “MatRessource”

measure – “Materials for a resource-efficient industry and society”, with selected research topics aimed at improving resource utilisation through new materials. More than 130 companies and over 80 research centres have for 3 years been collaborating in 34 funded projects to develop new materials able to significantly improve resource efficiency. The total BMBF funding of around € 50m is being supplemented with some € 30m from industry. In all these collaborative projects the improvement in resource efficiency through material innovations should contribute to permanently reducing dependency on imported raw materials, improve international competitiveness through reducing energy and material costs, and ease pressures on the environment. Five of the MatRessource projects show clear links to nanotechnology, and these are outlined below.

multiKAT – The multiKat project is aimed at developing resource-efficient polyethylene materials. Key components are novel highly active multi-centred catalyst systems and new technologies for the process-integrated creation of fully recyclable and tightly bound nanoscale, ultra-high molecular weight polyethylene that is not currently technically available either as nanofillers or as nanofibres. The new polyethylene materials should increase the corrosion resistance and reduce the weight of, for example, containers for biofuels, liquid gases and chemicals.

NanoPOP – In the NanoPOP project concepts are tested for sustainable recycling and an economically competitive alternative for reclaiming precious metals from metal-bearing solid waste and waste water. In a

nano-biotechnological process, heavy-metal tolerant bacteria are used as “recyclable” producers. In this process microbial growth, metal reduction and nanoparticle creation happen concurrently. The precious metal nanoparticles produced by the bacteria should be used to remove long-lived pollutants and pathogenic microorganisms.

nanoRec – This project’s objective is the reduction of specific demands for strategic metals such as tungsten and cobalt and the efficient use of recoverable nanoscale materials. The work is aimed at improving abrasion resistance of components reinforced with hard metals and sprayed coatings. Instead of using known hard metals and similar abrasion-resistant films, the hard particles used in the project are not monocrystals but comprise instead polycrystals of nanoscale crystallites sintered together.

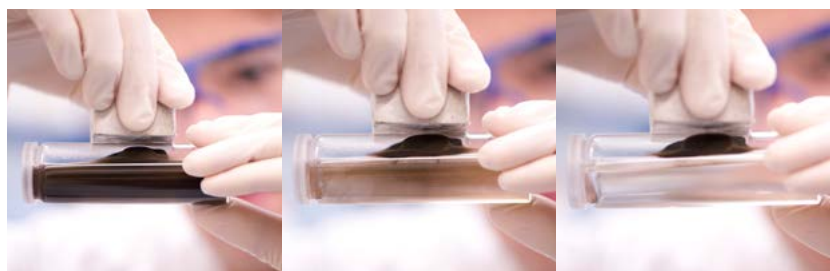
NanoEmission – The NanoEmission project studies the behaviour and precipitation of nanoparticles in thermal waste treatment for selected nanoparticle-containing products in wide commercial use. The project follows the complete journey from residue, via incineration, filtering of flue gases, and release into the environment through to the toxicological evaluation of the effect on humans and the environment.

KomMa – The KomMa project is looking at novel material concepts for magnetic materials for use in electrical generators (e.g. for wind farms) and electrical motors with the objective of reducing the need for rare earths in these permanent magnets. The approach is based on the development of new magnetically-hard materials based on hard ferrites and transition metals. In this magnetically-hard material systems are to be combined with weakly magnetic material systems in the nanometre range, in line with the concept of exchange interaction, in such a way that the rare earths component can be eliminated or at least reduced.

More information on the MatResource funding measure and on all funded projects can be found on the Internet at www.matresource.de.

Other activities and sample applications

Environmental technology is an important area of application within the European research funding programme. Around 30 nanotechnology projects, with funding to the tune of more than € 80m over the period 2007 - 2013 and forming part of measures aimed at environmental and NMP topics, are looking at environmental technology applications. One focus in this research is on nanotechnological developments for water treatment, such as nanofunctionalised ceramic and polymer membranes protected from bio-fouling and pore obstruction, for the treatment of drinking and process water together with the desalination of seawater. One example is the “Lblbrane” project, which has received some € 4m worth of grants and uses the layer-by-layer absorption technique to develop durable and regenerable polyelectrolyte membranes offering high separation performance.^[118] The German contribution to the project comes from the Berlin-based company Surflay Nanotec which brings know-how from the company’s patented Layer-by-Layer technology.



Magnetic separation of superparamagnetic nanocomposite particles for the recovery of pollutants and recyclables from waste water (Source: K. Dobberke for Fraunhofer ISC).

Background conditions and challenges

The growing demand for resource-saving and environmentally-friendly technologies is a strong driver for nanotechnological developments. A large part of research funding by public bodies at national and European level addresses environmental applications or the raising of energy and resource efficiency in other areas, such as in information and communications technology or mobility. Safe handling and the avoidance of potential negative environmental impacts are

central challenges in the use of nanomaterials. Important contributions in this respect are being made by environment-related risk research and by international activities aimed at standardising measurement techniques for the assessment of environmental risks (See section 4.6).

3.9 Sensor technology and metrology

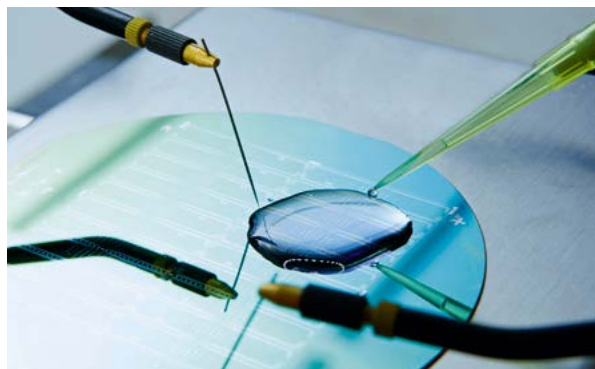
Sector development

The sensor technology and metrology sector in Germany continues to grow. Turnover and employment were both up slightly in 2012 as against the previous year, rising to € 35bn and 250,000 employees respectively. In total, between 2,000 and 2,500 companies are active in the field of sensor technology and metrology. The export ratio is around 35-40%. The outlook for further development is seen as positive.^[119]

Nanotechnology developments are a strong innovation driver in sensor technology. Nanotechnological processes are being increasingly employed in the global growth market for micro-electromechanical systems (MEMS) with this market set to grow by 15% to reach \$ 6.5bn by 2016. Nanocoatings and aspects of nano/micro integration are playing a part in this growth. Excluding the MEMS sector, the market for nanostructured sensors in applications such as chemical, biological or thermal sensors is forecast by BCC to grow to \$ 38m by 2016.^[120] The world market for nanomagnetic materials in sensor technology in, for example, magnetoresistive sensors and bioassays is forecast to grow from \$ 53m in 2012 at an annual growth rate of 15%, to reach \$ 108m in 2017.^[121]

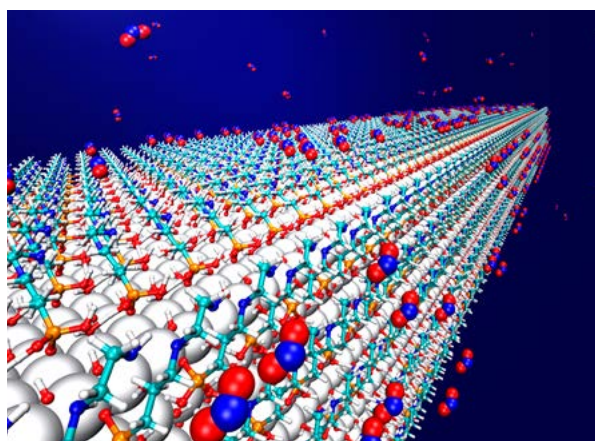
BMBF research activities

Metrology and sensor technology is addressed extensively in the BMBF's nanotechnology research programme. An important part in this is played by the use of nanoanalytical procedures for the fundamental study of nanoscale structures and processes. A whole range of spectroscopic and microscopic procedures are deployed using various types of beam (synchrotron, ion, electron, x-ray, terahertz, nuclear magnetic resonance, fluorescence, etc.) and various sources (e.g. FEL and storage rings). A further priority is nanosensors for rapid testing procedures in bio-medical diagnostics and



Production of a nanosensor with CNT sensor elements: A voltage is applied at the needle-shaped electrodes which guides the nanotubes out of the solution to electrodes on the silicon wafer (Source: Max-Planck-Institut für Festkörperforschung (Max-Planck Institute for Solid State Research), Photo: Axel Griesch).

analytics. Some examples of applications are nanowires for marker-free analyses, nanoparticles as diagnostic markers or printable sensors based on organic electronics. Chemical analysis and gas sensors benefit from nanostructures such as nanoparticles, nanowires and nanopores for the highly sensitive and selective detection of low molecular weight compounds.



Schematic representation of a tin oxide nanowire that has been functionalised with a monolayer of sensory molecules. The system acts as a highly selective and highly sensitive gas sensor for noxious NO₂ gas (represented by the 3-atom, red-blue molecule). The resistance of the functionalised nanowire increases in the presence of even small concentrations of NO₂ in the ppb range (by 2100% at 400 ppb) while other gases produce either no, or a very small, signal (Source: Fraunhofer IWM).

Magnetic sensors based on magnetoresistance effects (GMR, TMR) are used in applications in electronics and automation engineering. Industrial process and quality control, through optical and AFM procedures, for example, continue to be an important application area for nanosensors. Developments aimed at cost-effective sensor elements are centred on sensors produced using printing technology based on CNTs, metallic nanoparticles and electroactive polymers.

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Nanoanalytics in basic research	Study of the growth and structure of nanomaterials using synchrotron radiation	05K10 -KTB, -KT2, -VH3, -KE2, -HRB, -PM1, -VH4, -GU4, -EBA, -WEC
	Study of technologically important nanostructured materials by means of high-resolution ion-beam analysis	01DK12039
	Development of AFM systems and conductive AFM tips for electronic measurement	01QE1005, 1759X09
	Development of NMR relaxometry and diffusometry for characterisation of molecule dynamics in bio-compatible polymer beads	01DN12087
	Developing the bases for GSDIM wide-field nanoscopy	13N11066-69
	Basics and procedure for the illustration of function and structure in nanoscopy for bio-sciences and health	13N11401-404
	Coherent short-pulse x-ray source for application experiments in nanotechnology	01DR12011
	Capillary-aided optical nanodetection for colloid and boundary layer research	01DR12011
	Study of fluidic particle transport at boundary layers by means of actuator-controlled microhairs with switchable nanostructuring	16SV5339-341
	Development of high-speed AFM modules for detection of dynamic processes on sample surfaces	13N12162-64
	Terahertz laser spectroscopy of semiconductor nanostructures	01DJ12001
Bio-medical analysis and diagnostics	Research into new nanomedical diagnostic tracers using bio-technological procedures	13N10264-69
	Research into novel glucose sensors based on organic electronics	13N10790-93
	Nanobio-sensors for rapid identification of fish species for sustainable fisheries and maintenance of catch quotas – The Future Ocean	01DG12055
	High-resolution fluorescence microscopy of malarial parasites with a resolution of around 20nm	01DG12058
	Development of nanostructured ZnO bio-sensors for detection of very low concentration of analytes in bio-medical applications	01DN12092
	Nanowire-based parallel bio-analysis	16SV5386-387
	Nanowire transistors as marker-free, fully electronic immunosensors	17042X11
	Mikrocartridge-integriertes schnelles, hochsensitives, markierungsfreies DNA-Detek-tionsverfahren auf Basis von Mikro- und Nanopartikeln	16SV5427
Chemical analysis	Miniaturised raman spectroscopy based on enzymatically generated silver nanoparticles as a SERS substrate for detection of low-molecular substances	03IPT513A-D
	Integration of nanowire heterostructures with optical microsystems for innovative chemical sensors.	16SV5383K-385

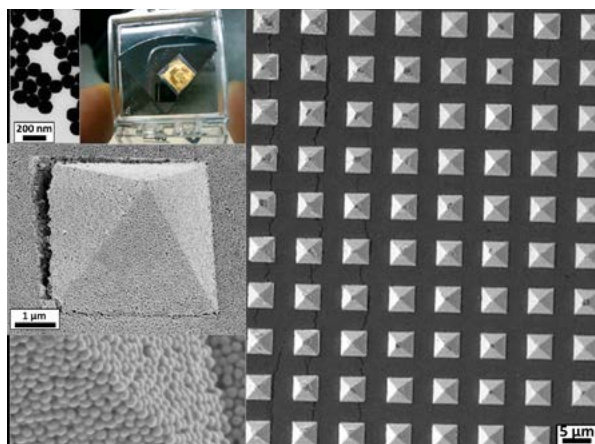
Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Gas sensors	Low-energy film sensors for sensing gases	03WKP15A-C
	Nanotechnological receptor films for improved detection of trace gas	16SV5379-82, 16SV5378K, 16SV5477
	Nanosensor system for intelligent gas sensing	16SV5591-593
	Selective measurement of trace gases using nanoporous sensors	13N11138, 13N11139
	3-dimensional micro-nano integration for gas flow sensing	16SV5476
	Optical nanotechnology-based gas sensing; research into novel nanoplasmonic hydrogen sensor elements	13N12201, 13N12202
	Development of a catalytic gas sensor with minimal energy consumption and high resistance to catalytic poisoning based on chemically highly-effective nanoparticles	16SV5324
	Development of microtechnical dew point sensors with nanostructured condensation nuclei for rapid determination of minimal moisture content in gases	16SV5345K-354
Pressure sensors/weighting technology	Development of sensory and adaptive systems based on elastomers with magnetic nanoparticles	16SV3757-64
	Novel sensors by means of nanoparticle-based function and bonding films on ultra-thin ceramic DMS carriers	13N10919-22
Magnetic sensors	Materials and manufacturing technologies for production of microstructured magnetic components and systems, and microsensor components	16SV3849-52
	Innovative TMR sensor elements in monolithic connection with ICs	16SV5757
	Integration of ultra-thin magnetic field sensors in intelligent automation components	16SV3732-36, 16SV4069
	Development of a flexible, scalable GMR absolute encoder system	16SV3720-22
Temperature sensors	Nanocomposite films for intelligent, 2-dimensional temperature monitoring of electronic components in explosion-protected devices	03X0116A-B
	High resolution infra-red low-temperature thermometry based on III/V semi-conductor sensors	13N10880-82
Position-sensitive sensors	Electromechanical sensors with one-dimensional nanoobjects for multi-axial sensing of positions and angles	16SV5475
Process analytics/process control/function monitoring/quality control	Novel high-resolution metrology using high-performance photomasks for energy-efficient nanoelectrics	13N11495-500
	Construction of systems with nanomodified surfaces for automotive and industrial sensors	16SV5328K, 16SV5469, 16SV5329-34
	Development of a scanning probe microscopy analysis module for characterising organic field-effect transistors in printed integrated circuits	1759X09
	Procedures for the detection and tracking of fractures for the characterisation of multi and nanoscale-dominated damage mechanisms	13N11926-28
	Development of nanotechnology-based microsystems for process-integrated monitoring of flow processes	16SV5339K-341
	Optical in-situ process sensors for high-productivity manufacturing of multi-film optical systems	13N11004-5
	Multi-scale metrology platform for quality assurance of optical free-forms	13N10853-59, 13N11120
Printable sensors	Printed nanomaterials (CNTs, metal nanoparticles) for microsensing and actuating	16SV5325-327, 16SV5388-393, 16SV5342-344

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

Other activities and sample applications

Sensor technology and metrology counts as one of the most important fields of application within nanotechnology research in the FP7. In the period 2007 - 2013, over 60 projects have been financed to the tune of around € 200m. These have also included larger projects that received more than € 5m for research into the following R&D topics:

- **High-precision sensors for measuring frequency superimpositions (interferometer)** with high resolution and scanning speed for process-integrated quality control and defect detection in large-surface area film substrates such as solar cells. (Project runs until 2015, more information at <http://nanomend.eu>)
- **Laser absorption spectroscopy for detection of pollutants:** Development of quantum cascade lasers with tuneable frequencies in the mid-infrared range for the selective detection of trace gases by means of laser-absorption spectroscopy. (Project runs until 2016, more information at www.mirifisens-project.eu)
- **Nanoparticle measurement devices for occupational health and safety:** Objective is to develop new concepts and processes for measurement of an individual's exposure to airborne nanoparticles in the workplace (Project runs until 2013, more information at www.nano-device.eu)
- **Nanosensor systems for ambient intelligence:** The objective of the project is to develop reliable nanosensor systems for the intelligent discovery of ambient parameters. The project addresses the bio-chips, active implants, infra-red imaging, ultra-sound probes, and intelligent gas sensing fields of application (Project runs until 2013, more information at www.e-brains.org)
- **Improved procedures for DNA sequencing and analysis:** Development of fast cost-effective procedures for DNA/RNA analysis with the aid of new approaches to single molecule analysis using nanopores and nanotubes (Project runs until 2013. Further information at www.cng.fr/READNA).



Using pyramids of gold particles, trace gases can be detected with great sensitivity by means of surface-enhanced raman scattering (SERS). Right: Scanning electron microscope image of the gold nanopyramids. Above left: Individual gold particles in a TEM image; next right: Photograph of a portable SERS sensor consisting of a square centimetre surface on which the coated gold nanopyramids are arranged. Left centre: Scanning electron microscope image of a pyramid; Left bottom: Close-up image of the spherical nanoparticles on one side of the pyramid (Source: Bayreuth University, Images: Dr. N. Pazos Pérez).

Guest contribution: Innovation potential for sensors and metrology by means of nanotechnology

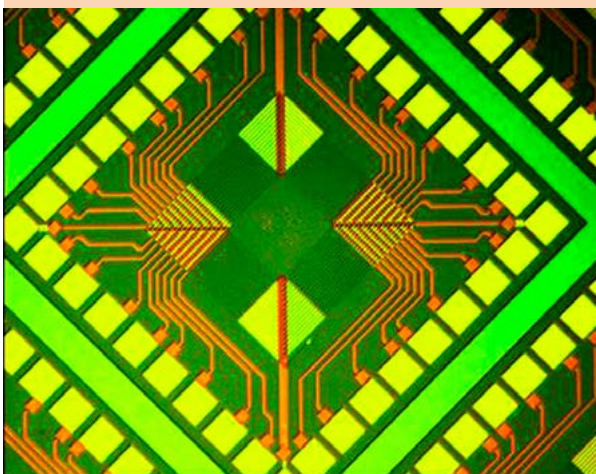
Prof. Dr. Andreas Schütze (Saarland University),
Chairman of German Council of Science and Humanities, AMA Fachverband für Sensorik (Association for Sensors and Measurement)

Sensor technology and metrology are two of the key technologies that facilitate technological progress and provide support for solutions to the social challenges of our times. Nanotechnologies improve the functionality of sensors and in so doing, expand the spectrum of measurable sizes.

In terms of the number of items, the most important fields of application currently are the automotive and consumer goods industries. Every smartphone is equipped with several sensors; it knows where it is via a position sensor, provides bearings via an electronic compass, operates the microphone through an acoustic sensor, the camera through an optical sensor, and so on. As cross-sector technologies, sensors and metrology enable ever more new applications while

nanotechnologies reinforce the potential for innovation.

Some real-life examples: Nanotechnological coatings, for example in flow rate sensors, improve resistance to abrasion and dirt, nanoscale films in the assembly and packaging technologies enable jointing processes even at lower temperatures. Novel strain gauge strips for force and pressure sensors with nanostructured functional films promise higher levels of sensitivity as well as greater adaptability to use in different applications by means of an adjustable temperature coefficient. GMR/TMR effects enable highly sensitive and extremely small magnetic field sensors for data storage and open up new applications in such areas as angular and displacement measurement. For optical sensing, nanotechnology creates new anti-reflex coatings and functional dye films. In medical applications, nanocoatings serve to improve the bio-compatibility and long-term stability of implanted sensors. In chemical sensors, nanowires and nanoparticles enable the controlled preparation of sensor films with extremely active surfaces while in bio-sensing they enable the labelling of bio-molecules, so improving for example DNA diagnostics. Research is currently underway into potential uses of carbon nanotubes and graphene films as sensitive layers for force sensors or for (bio)chemical sensors. These few examples show



In modern multibit sensors, nanostructured magnetic tracks are used to simultaneously store the rotation information in the form of domain walls and to read it by using the giant magnetoresistance (GMR) effect (Source: Sensitec GmbH).

clearly the enormous potential for innovation that the various nanotechnologies are opening up for sensor technology and metrology.

Background conditions and challenges

Turnover in the German sensor technology sector has doubled over the past decade, and this despite a sharp decline due to the world-wide economic crisis. More dynamic growth is also expected for the future. The term “smart systems”, referring essentially to the use of miniaturised, integrated and networked sensor technology components, has by now come to impact almost every area of application in the economy (smart home, smart textiles, smart grid, smart city, etc.) and almost every sector, such as automotive, security, production, energy or medical technology. Further integration development at the nano and micro level of sensor and actuator components presents enormous market potential but at the same time brings social challenges in terms of safety, data protection and informal self-determination. Norms and standards are also playing a growing role, for example in the establishment of reference procedures for nanoanalytics (see section 4.6).

3.10 Automotive sector

Sector development

The German automotive industry achieved a total turnover of € 357bn in 2012, a slight increase of 1.6% on the previous year. Domestic turnover was € 128bn while that in the rest of the world was considerably higher at € 229bn. Over the year the industry as a whole employed on average 742,000 people in 2012, 3.1% more than in 2011. Expenditure on research and development was up 2.1% against the previous year, reaching € 16.1bn and corresponding to an R&D ratio of 4.5%.

German manufacturers produced more than 13.6m passenger cars in 2012 compared to just under 13m in 2011, with 5.4m vehicles being produced in Germany while 8.2m were produced abroad. Domestic production fell 3.7% while production abroad rose by 11.5% compared with 2011. 77% of the vehicles produced

in Germany went for export, corresponding to 4.1m passenger cars. The main customers were EU states although demand from these countries was significantly down. The figures were up in Asia and America.^[122]

Numerous innovations in the automotive sector can be traced back to developments in nanotechnology. In this context should be mentioned nano-impregnated upholstery, along with display technologies and interior multi-media systems or LED and OLED-based lighting systems. Vehicle paints have been made more scratch-resistant through admixture of nano-scale quartz crystals. Further developments anticipate self-healing paints based on nanoscale material components that are able to close-up small scratches themselves. Nanostructured, dirt-repellent coatings on mirrors or novel films that reduce heat entering the vehicle through the windows, together with coatings that protect against fire, corrosion and abrasion, are also in development. Nanocoatings for applications in the automotive sector achieved a global turnover of \$ 125m in 2011, and this market is forecast to more than double to reach \$ 310m by 2015.^[123]



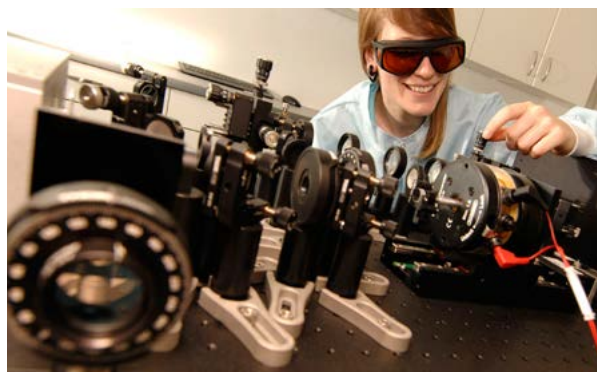
Scientists at Jülich are using a specially developed equipment to study the mechanisms of tyre adhesion on asphalt surfaces. It could be demonstrated that at low speeds, the actual contact area is the decisive factor. At a microscopic level, the friction level of the rubber is determined by a sort of lubricating film comprising rubbed-off material and liquid residues. These findings yield starting points for the further optimisation of the rubber mixture used in tyres. (Source: Jülich Research Centre).

Further applications exist in the automotive sector for e.g. nanofillers. Around 30% of the rubber mixture in tyres currently comprises materials such as silica and carbon black, which contribute to optimised adhesion, abrasion and fuel consumption properties.

BMBF research activities

Through its project funding the BMBF supports numerous nano-inspired developments that benefit the automotive sector. The majority of these innovations were however originally assigned to other branches of technology, upstream of the automotive industry. Application areas central to the automotive industry however are emissions control, in which the catalytic effect of nanoscale particles is the subject of intensive research, and friction reduction to reduce fuel consumption in the engine and power train. In this area, novel wear-resistant material systems are being developed for components within the engine.

For bodywork new corrosion-protection systems and weather-resistant, nanotextured UV protective coatings are in development. In the area of automotive electronics the focus is on developing high-performance electronic systems for electric mobility, an area in which nanoelectronic components are becoming increasingly important. Another topic being widely



Nanomaterials form the basis for the development of thermoelectric generators capable of operating in high-temperature environments to make use of the heat in vehicle exhaust systems. Stress and deformation due to temperature can result in material failures in the module. Using a laser-based optical measuring system allows the smallest surface deformation to be detected. (Source: Rhein-Waal University of Applied Sciences, Photo: Michael Bergmann).

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Emissions control	Development of nanoscale SCR catalysts for combined NO _x and soot particle reduction in diesel engines	03X0079A-D
	Development of resource-efficient catalytic converters for motor vehicles with significantly reduced precious metal and rare earth metal content	03X3563A-C
Automotive electronics	Nanoelectronics for intelligent and reliable power trains for electric vehicles based on new electric motors, novel high-performance electronics and novel manufacturing technologies	13N11476-83
	Development of innovative nanoelectronics-based system components for energy-efficient electric vehicles (e3CAR applications)	13N10393-98
Bodywork	Development of novel corrosion protection systems for high-strength, hot-formed steels	03X3560A-D
	Manufacture of large-area, transparent, weather-resistant coatings with integrated UV protection by means of nanotexturing	13N10520-24
Thermoelectronics	Industrialisation concept and novel materials for thermoelectric generators capable of operating at high temperatures for using heat from the exhaust gases emitted by motor vehicles	03X3551A-E
Wear-resistant materials for engine manufacture	Nanoferro coatings for cylinder linings in high-performance engines	03X3536A-E
	Development of novel nanocrystalline aluminium material for highly-stressed cylinder head screws and screw joints in the crankshaft bearing	03X0101

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

researched is energy recovery from the heat in the exhaust system, for which thermoelectric generators able to operate in a high-temperature environment are being developed based on novel materials systems.

Guest contribution: Nanotechnology in motor vehicles

Stefan Wöhr, Verband der Automobilindustrie (Association of the Automotive Industry) e. V. (VDA), Berlin

The German car industry has its acknowledged high level of innovation to thank for its world-leading position. Materials are the driving force behind innovative industrial product developments, shaping the automotive industry's technological performance and boosting the companies' competitiveness.

Nanomaterials now find application in many areas of our lives. From the point of view of automotive companies, the properties of nanoparticles are there

to be used in the manufacture of parts and vehicles, to optimise technologies, and facilitate day-to-day activities. At the forefront are product differentiation in international competition and customer benefits in terms of safety, environment and comfort.

Nanotechnologies have been firmly established in the automotive industry for many years. One of the first applications was scratch-resistant paint; using nanoparticles locked into the paint allows scratch resistance to be improved by a factor of three, while also giving a more brilliant shine even after many years of use.

Vehicle safety is of great value and can be significantly increased through the use of nanotechnology. Dimmable mirrors that avoid the driver being dazzled, non-reflective instruments and heat insulating glass are examples of the use of nanotechnology. A further application is the so-called "anti-fogging coatings" on the windows, in which the use of nanotechnology allows the windows to remain largely free of conden-

sation. Yet another area in which nanomaterials are employed is at the interface between vehicle and road, where nanoparticles help the tyres to grip better on different road surfaces and adapt more effectively to road conditions – a fundamental gain in safety.

We can envision nanotechnology helping the car of the future to respond more intelligently to environmental factors and driver behaviour. Windows and mirrors will adapt to external light conditions and numerous sensors will proactively monitor the driving conditions as the weather changes or danger of a collision arises.

Equally in the area of the powertrain, nanotechnologies offer considerable optimisation potential to further reduce fuel consumption and emissions. Since component wear affects the vehicle's functional properties, such as working life, consumption, emissions and noise, nanotribology is opening-up new potentials. By means of optimal nanotechnological treatment of material surfaces resistance to wear can be enhanced; so, for example, the life of cylinder linings can be extended by coating them with nanoparticles.

The deployment of new technologies may also entail possible risks. These need to be explored and resolved during basic research if the project is to move from the design stage to a solid concept. Partnerships with research centres all over the world are of the greatest importance in this regard. The risks that today are under discussion relating to free nanoparticles will not affect car users since nanoparticles in the motor vehicle are normally firmly embedded in matrices. Even as a result of abrasion no nanoparticles will be released. During production, workers in the automotive industry are protected by health and safety regulations.

The use of nanotechnologies strengthens and promotes the profitability and competitiveness of the automobile industry in Germany. Politicians and business circles are called upon, together with the automotive industry, to help nanotechnologies make the breakthrough.

Other activities and sample applications

Europe is one of the world leaders in innovation in the automotive sector and is home to numerous renowned manufacturers and suppliers. The EU for its part supports the automotive sector through extensive funding of innovation. The automotive sector also benefits from nanotechnology developments that are really geared more to other sectors. However, there are a number of large nano-oriented projects funded under the EU's 7th Framework Programme for Research that are of interest in the context of motor vehicles. The following in particular are being developed in projects funded by the EU:

- **Self-healing paints and coatings based on nanostructures,**^[124]
- **Embedded, non-volatile on-chip data storage systems,**^[125]
- **Intelligent and energy self-sufficient, variable-colour, flexible thin-films to regulate the light and heat entering the car together with large-area manufacturing processes,**^[126]
- **Exhaust gas catalysts based on transition metal nanoparticles,**^[127]
- **New micro and nanocrystalline metal-ceramic materials for components in the exhaust, power transmission and braking systems subject to high thermal and mechanical stress levels,**^[128]
- **Novel on-chip energy supply for motor vehicle electronics,**^[129]

Further activities address topics including bio-mass based composite materials (bio-polymers, nanocellulose, etc.) with nanofillers,^[130] the development of friction-optimised internal engine surfaces^[131] and low rolling-resistance tyres.^[132]

Background conditions and challenges

The automotive sector is currently characterized by discussion on climate and energy. Political administrative requirements, primarily from the European Union but also emanating from the Federal Government, have considerable bearing on the development directions adopted by the automotive industry.

CO₂ emissions by a vehicle play a central role in achieving climate protection goals. Meeting the relevant European regulations presents a particular

challenge to German manufacturers with their strong market position in mid-range and executive vehicles. Concerns exist in the sector with respect to European competitors that focus primarily on smaller vehicles.

The Federal Government's goal of having a million electric vehicles on the roads by 2020 is also seen as ambitious. Faced with these targets, a lot of innovation effort is going into the development of electric mobility. Work is underway on purely electrically-driven vehicles, and also into fuel cells and hybrid systems.

3.11 Mechanical engineering

Sector development

Mechanical and plant engineering are traditionally seen as one of the pillars of the German economy. While the sector was seriously affected by the 2008/2009 financial crisis, it has recovered well in the intervening period. Strength in export markets in particular and a base of largely small and medium-sized firms contributed to what is, by international standards, Germany's good economic position in the current European economic and currency crisis.

Worldwide turnover in the sector rose in 2012 by some 10% against the previous year to a record level of € 2,250bn. The German mechanical engineering sector accounted for a good 11% of this at € 250bn. This puts Germany in fourth place in the sector behind China, the USA and Japan on a turnover basis.^[133] Exports rose by 5% to slightly over € 150bn. Employment figures rose by 30,000 in 2012 to 978,000.^[134]

In mechanical engineering, nanotechnology makes an appreciable contribution to improved products and processes. The focus in this context is on mechanical properties. Hence the targeted use of nanostructuring and nanoscale coating of surfaces by carbon, hard metal or ceramic materials significantly reduces friction and wear on moving and load-bearing components. The same is true of protection from corrosion and soiling, with the result being a longer life and reduced energy consumption. Other aspects addressed by innovative use of nanotechnology are lightweight construction through the use of stable composite materials, the incorporation of nanoscale security labels to

protect against counterfeiting and product piracy and the development of precise actuators for mechatronic components.

BMBF research activities

Reduction of friction and protection against wear are also the focus of a series of R&D projects funded by the BMBF. These projects have developed material systems

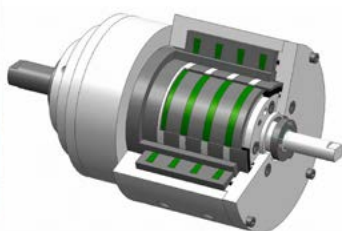


Turbine blade processing by nanoscale carbide milling tools with extremely long service life (Source: Fraunhofer Institute for Ceramic Technologies and Systems).

for surfaces that are under heavy mechanical loading. They contribute to the optimisation of various applications such as tool surfaces, seals, pumps, bearings, turbines, forming dies, nozzles, etc.

An essential role is also played by the development of processes and production techniques for nanostructuring, nanocoating and functionalisation of surfaces and materials. Specific topics addressed include thermal spraying, plasma technical processes, nanoimprinting technologies and the manufacture of nanotube-modified technical textiles.

Ultra-precise actuators are playing an ever more important role in microsystems technology and in numerous mechanical processes. Within this context the BMBF is funding the development of new, efficient actuators, particularly piezo- and membrane-based.



A magnetorheological liquid solidifies in the magnetic field into a rigid state. Novel coupling systems are being developed on this basis for propulsion and braking technologies. Force is transmitted via the flexible activation of a magnetic field. (Source: Ostwestfalen-Lippe University of Applied Sciences).

Magnetic liquids, which change their flow and viscosity properties under the effect of magnetic fields, are also being considered as actuator components. Their potential for application, particularly in mechanical power trains and braking technologies, is also being researched.

Other activities and sample applications

Mechanical and plant engineering represents a highly innovative sector with a very practical attitude. Innovations from the fields of materials, chemicals, sensors or production are frequently implemented and applied. This is also where most innovation funding has gone, to the benefit of the mechanical engineering sector. At international level however it is frequently difficult to originally classify R&D activities to mechanical engineering. For example, at EU level there is no nano-related funding under this heading. There are however

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Drive and braking technology	Innovative shaft sealing applications with new magnetic liquids	03X0092A-B
	High load brakes with a long service life based on magnetorheological liquids	1713X09
Actuators	New energy-efficient actuators based on the piezo-electric effect	01QE1136B
	Virtual membrane actuators on nanostructures in micro-pumps	16SV5368
Nanobased processes in surface structuring and production technology	Intelligent production systems for nanostructured coatings by means of thermal spraying	02PJ1220-21
	Nanostamping technologies for production of structures with high aspect ratios (ratio of height to width) for microsystems technology	03FPF00041
	Efficient production of ultra-precise, innovatively structured functional surfaces by means of adaptive plasma technology	13N12147-51
	Researching and implementing an "energy filter for ion-implantation equipment"	17N0411
	Development of carbon nanotube (CNT) modified single fibres for use in textiles for paper manufacture and other applications	03X0061A-D
Tribology and protection against wear	Nanodynamic, tribological pairings on plasma-structured surfaces and their manufacture	02PO2480-85
	Development of nanoceramic spray nozzles for abrasive, high-pressure conditions	01DJ12049A-B
	Demonstration of the use of diamond-like films, structured during manufacture, for sealing, pumping and bearing technology	01RI0906A-E
	Novel nanodispersion Ni films for tool surfaces optimised for wear and abrasion	03X0120A
	Application of highly-ionised plasma for deposition of damage-tolerant, nanolaminar thin-film systems for protection of forming dies against wear	03X0122A-B
	Surface coatings for turbine and pump equipment subject to friction	RUS10B53

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

a number of EU projects that deal with nano-inspired friction and surface aspects or joining technology.

Accordingly, within the framework of the STEEL-PROST project which is receiving almost € 2m in funding, new solutions are being developed for achieving heat and fire-resistant surfaces in light steel structures.^[135]

Welding the most important technology for joining metals is being addressed by the “MINTWELD”^[136] project which is receiving funding to a value of € 3.5m. The project is developing new, more refined welding techniques to avoid microscopic weak spots in the area of the weld.

Reduction of friction is the objective in various projects in which, for example, novel liquid lubricants are being developed based on nanoscale additives^[137] and the mechanisms of the friction or interaction between the surface and the lubricant are being studied.^[138]

Metrology for nanoscale production processes is being funded with € 3.2m in the “AIM4NP” project. The objective is to determine processes for measuring key parameters such as topography, morphology, roughness, hardness and adhesion of surfaces in the production environment and during the production process.^[139]

Background conditions and challenges

In the mechanical and plant engineering sector a stable political and regulatory situation is important. The sector is largely made up of small and medium sized enterprises; these are indeed often family firms. Representatives of the sector stress the importance of reliable taxation policies in this context and point to the negative effects of property taxes on the ability of companies to invest.

In addition the mechanical and plant engineering sector is being heavily influenced by the transition to green energy. The profitability of conventional power stations and the future interaction between fossil and renewable energies is currently creating an uncertain outlook for the future, which could influence decisions about investment in building power stations. A growing problem, in particular for the small and medium-sized

companies outside the metropolitan areas, is the shortage of qualified personnel. The sector is trying to counter the very high dropout rate for students – a particular problem in engineering studies – through information and support programmes and collaboration with the universities.^[140]

An increasingly relevant topic in the sector is that of protecting know-how on processes, products, customers and markets. Billions are being lost in this way through theft of this knowledge. Companies are taking the matter very seriously, but are predominantly each adopting their own approach to the problem. Most companies are unaware of any norms or standards to help them protect their know-how. More expedient would be uniform, sector-wide measures to determine the need for protection and convert this into corresponding measures.^[141] Nanotechnology offers a host of technological approaches to establish effective security features for product protection.^[142]

3.12 Other areas of application

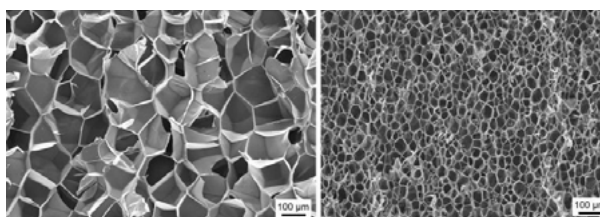
Construction

Economic development in the construction sector in Germany has changed little compared with the previous year. Construction recorded turnover of some € 93bn in 2012; a slight increase is forecast for 2013. The number of employees in construction will average 745,000 for 2013 which is roughly the same as the previous year.^[143]

Developments of particular economic relevance to the construction sector are nanocoatings for applications in self-cleaning, protection from dirt, anti-fouling and scratch and UV protection, for which the global market is forecast to reach € 400m by 2015.^[144] Similar growth is also forecast for the market in nanoporous foams for sound and heat insulation in buildings. The global market for aerogels is expected to rise from \$ 175m in 2012 to \$ 1.4bn in 2017.^[12]



Nanotechnology-based films as solar protection on glazing in buildings. The approximately 60µm thick, transparent solar protection films comprise 200 nanoscale films of acrylic and polyester overlaid on each other. The structure of the films means a large proportion of the heat and UV radiation in sunlight is filtered out while visible light is largely unaffected (Source: 3M).



The heat insulation properties of polystyrol foams can be improved by the use of graphenes. Left: Polystyrol foam with a conventional talc filling, and, right, with the graphene additive. The giant carbon molecules reduce the size of the cells in the foam considerably, but account for just 1% of the weight of the polystyrol foam. (Source: Department of Polymer Engineering, Bayreuth University).

Examples of BMBF funding: Nanotechnology in the construction sector

Dr. Ralf Fellenberg, VDI Technologiezentrum GmbH

Increasing urbanisation against a background of essential resource and energy efficiency requires us to target our research toward those new materials and technologies important for future construction and living and all the associated infrastructure. In this context it is a matter of urgency for us to develop new materials, to more efficiently arrange and service residential and office buildings along with the traffic and other infrastructure required. The range of topics for these future markets extends from construction planning, building

engineering, via decentralised energy supplies and intelligent energy use through to traffic infrastructure.

By using innovative developments in nanotechnology, these multidisciplinary technologies can be used across the whole construction sector. To this end the BMBF has implemented the “Nanotechnologie im Bauwesen – NanoTecture” (Nanotechnology in the construction sector – NanoTecture) funding programme with the objective of developing new or significantly improved building materials, products and processes by the application of nanotechnologies. The priority topics for the research relate to the following fields:

- **Increasing the durability of building elements (e.g. facades, windows, doors, roofs)**
- **Reducing the energy requirements through nanotechnological effects**
- **Improving the climate, comfort and security of the interior space**
- **Improving the energy efficiency and longevity of cement-bound materials**
- **Improving the durability of road surfaces**

In the period 2008 – 2013, 12 collaborative projects involving 56 partners were funded by the BMBF to the tune of around € 16m.

As an example, a project on the nanoscale activation of granulated slag and Portland cement using an innovative milling process was successfully completed.



A manufactured bridge component at Fa. Runkel (Source: Zoz GmbH).

The resulting high-performance or ultra-high-performance concrete with improved properties was used following the project as a demonstrator for an element for a bridge to be built on a pedestrian and cycle trail.



A manufactured bridge component at Fa. Runkel (Source: Remmers Baustofftechnik GmbH).

Another equally successful project was the HeliClean project. This involved the development of nanotechnologically-functionalised building materials for solar catalytic air purification and surface cleaning. Through the catalytic disintegration of airborne pollutants by means of nanotechnologically-functionalised building material surfaces, sunlight could be used in such a way that a self-cleaning effect was achieved and the build-up of bio-films and the associated bio-corrosion of the material was prevented. Following completion of the project, an additional field trial was launched in collaboration with the Bundesanstalt für Straßenwesen (BASt). The trial centred on a coating for a sound barrier alongside the A1 at Osnabrück that was intended to reduce NO_x .

It could be further shown that it is possible to design a multi-functional carriageway of nano-optimised, ultra-high-performance concrete that demonstrates clear advantages. This highly-sustainable, low-noise, resource-saving, durable concrete carriageway made from ultra-high-performance concrete (UHPC) was able to reduce the lifecycle costs for construction,



A UHPC fine screed, optimised with nanoparticles with an imprinted, noise-reducing texture for the top layer of a concrete carriageway (Source: Kassel University).

maintenance and use by 55%. At the same time a noise reduction of -6 decibels was achieved, which is more effective than a 4m high sound barrier.

Application area	Nanotechnology R&D activities	Examples of BMBF projects (award number)
Construction		
Self-cleaning surfaces	Nanotechnologically-functionalised building materials for cleaning air and surfaces by solar catalysis (degradation of air pollutants and biofilms by doped titanium dioxide and zinc oxide nanoparticles)	03X0069A-H
	Biocide-free biofilm-reducing façade systems using IR-active paints, titanium dioxide or silicon dioxide coatings on ceramic surfaces and PCM additives in coatings of fibre-reinforced façade elements	1793X09
	Titanium dioxide-modified fine concrete recipes for degrading pollutants and self-cleaning textile-reinforced concrete	13N10735-9
Nanooptimised polycarbonate building materials	Thin-layer systems with nanoscale vertical layer structure for glass-like scratch protection with good adhesion and good UV protection in polycarbonate panels	13N10520-4
Monitoring of the condition of building materials/structures	Reactive marker system for testing the quality of deep water repellent treatment of nanoporous cement-bonded materials	13N10648-52
Nanooptimised concrete and binders	Nanoscale binder matrices using suspension concrete technology to reduce cement clinker content and save energy and CO ₂	13N10365-8
	Futur-Zement – nanoscale activation of granulated slag and Portland cement by means of an innovative grinding process to produce high-performance and ultra-high-performance concrete with improved properties	03X0068A-C
	Multifunctional roads made of nanooptimised ultra-high-performance concrete	13N10492-500
Thermal insulation	Development of insulation system components and surfaces based on nanoscale high-performance IR opacifiers to reduce the transfer of heat radiation in insulation systems, together with that of pigments with nanoscale coatings for low-emission paints	03X0071A-D
Textile technology		
Surface functionalisation of yarns and textiles	Permanent antimicrobial layers on yarns and textile surfaces	03WKBR7A-G
	Functionalisation and structuring of a textile surface with nanoparticles for targeted repulsion of dry dirt and improvement of cleaning properties	17PNT029
	Functionalisation of technical textiles with water-based nanoscale coating sols	03X0121A-F
Textile membranes and textile filters	Novel breathable membranes based on elastomers and sustainable biomaterials such as cellulose and lignin	01QE1010
	Nanostructured textile fibre systems as high-performance reactive gas and liquid filters	03X0126A-D
Textile-integrated electronics	Corrosion-resistant textile-based solar cells	16SV4042-5
	Technology platform for textile-based organic light sources and addressable light-emitting textiles	16SV4038-41

Summary of research topics in BMBF-financed nanotechnology-related collaborative projects (ending post-2011) broken down by application area. Further information can be found in the Federal Government's funding catalogue (<http://foerderportal.bund.de/foekat>) which can be accessed by entering the project award number.

Textile technology

The textile industry in Germany comprises around 1200 companies represented by the Gesamtverband der deutschen Textil- und Modeindustrie e. V. (Confederation of the German Textile and Fashion Industry). Its economic development has remained largely unchanged in the last few years. In 2012, the industry employed around 120,000 people and posted a turn-

over of 28 billion euros. The German textile industry leads the field in Europe and has a research share of approx. 2.5%.

Guest contribution: Nanotechnology applications in textile technology

J. Beringer, T. Hammer, Hohenstein Institut für Textilinnovation GmbH; V. v. Arnim, Institut für Textil- und Verfahrenstechnik der Deutschen Institute für Textil- und Faserforschung Denkendorf; K. Jansen, Forschungskuratorium Textil

The last two years have seen a certain degree of consolidation in the application of nanomaterials in textiles. Only those products demonstrating evident and sufficiently long-term nanoeffect, and that make economic sense, have made it as far as market. The fields of application for nanotechnology today encompass high-quality functionalised clothing textiles as well as technical textiles.

The main applications for clothing textiles are dirt-repellent clothing (such as ties and outer clothing) based on nanotechnology coatings/impregnating agents, as well as hygienic antibacterial properties based on incorporated nano-silver particles (such as for socks, sports underwear, household textiles etc.).

In the highly innovative technical textiles sector nanotechnology offers the option of multifunctional treatment of textile fibres, for example in medical engineering through the controlled dispensing of medicinal active ingredients, or wound dressings with antibacterial properties based on silver nanocoatings, or in environmental engineering through highly efficient filter media for environmental pollutants. Tent and marquee fabrics with a superhydrophobic nanostructured surface modification are currently another field of application.

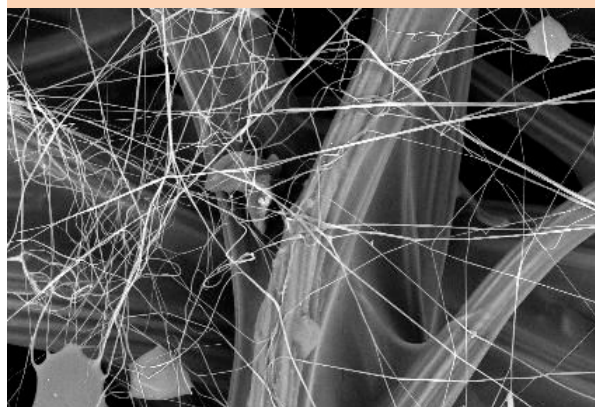
Current research work is looking at applications including nanoscale fillers which can be used to produce textile fibres with specific functions, such as electrically conductive and antistatic textile fibres through the incorporation of nanocarbon modifications, or the screening of electromagnetic radiation (IR-/micro-/radiowaves) through transparent conductive layers (based for example on ITO nanoparticles).



Superhydrophobic nanostructured textile. (Source: Hohenstein Institut)

Examples from the BMBF NanoTextil funding measure

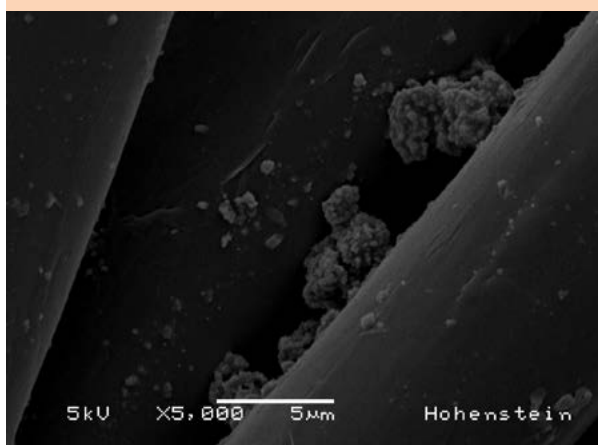
The BMBF's "Nanotextile – Nanotechnologies for textile applications" funding measure took fibre-based materials as its research focus, developing amongst other things nanostructured emulsion filters for more efficient diesel engines and wastewater treatment plants. Washproof, ecologically harmless flame-retardant systems for textiles were tested on a sol-gel basis. New processes for manufacturing ultrafine fibres have been developed for more efficient air filters. Extended service life for fabrics subject to high abrasion loads has been achieved using nanoparticle coating systems.



PAN nanofibres on a cellulose mat as a filter medium (Source: ITV Denkendorf)

Examples from the BMBF's NanoNature funding measure

One of the focuses of the “NanoNature: Nanotechnologies for environmental protection – the impact of synthetic nanomaterials on the environment” funding measure was research into the potential impact of synthetic nanomaterials on the environment. The project funded in this programme “CAUTION – assessment of the hazards to the environment posed by silver nanomaterials: from chemical particle through to industrial product” looked at aspects such as the behaviour, persistence and effect of silver nanoparticles resulting from the abrasion and washing of textiles in the environment. The project involved a large consortium drawn from universities, research institutions and industry representatives who worked along the entire textile chain with the aim of providing clear recommendations on the developments of textiles containing nanosilver. This should on the one hand mean the products fulfil the desired purpose and on the other rule out, with a high degree of safety, any adverse effect on microorganisms and their downstream food webs in the environment.

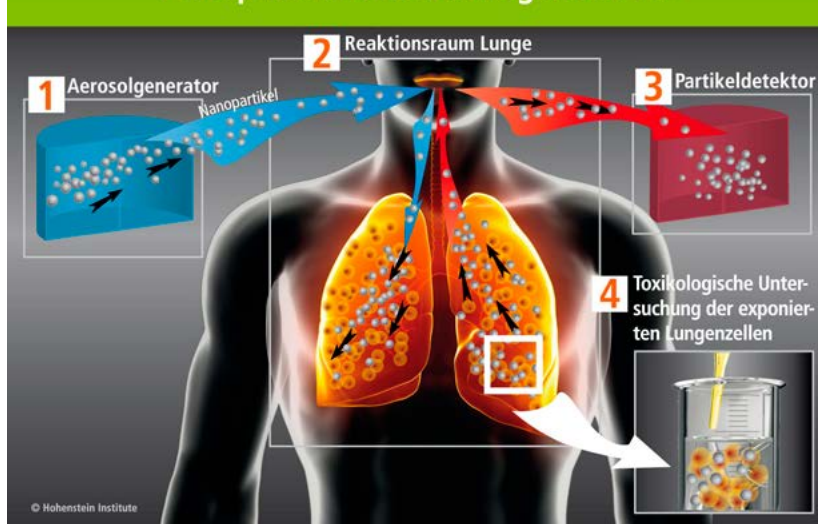


Nanosilver agglomerates on textile fibres. (Source: Hohenstein Institut)

Further funding measures

The “TechnoTox” research project, sponsored by the Ministry for Finance and Economic Affairs of Baden-Württemberg at the initiative of the Allianz Faserbasierte Werkstoffe e. V. (Alliance of Fibre-Based

Prinzip des Technotox Lungenmodells



Lung model in the Technotox research project (Source: Hohenstein Institut)

Materials), examined the safety of textile nanoproducts using data on the behaviour, persistence and biological impact of nanofunctionalised fibre-based materials in relation to environmental conditions, and undertook an example risk assessment. The most up-to-date investigation methods for human and ecotoxicology were used, including a specially developed lung model to simulate exposure via respiratory air. As they were unable to find any evidence in the samples examined to support any elevated risk to man or the environment, the researchers advised all-clear.

Background conditions and challenges

Nanotechnology also offers options for the textile industry to move into new growth markets with high-quality innovative product solutions, particularly in technical textiles, and so provide impetus for innovation in other industries such as automotive and aerospace construction and medical, environmental and structural engineering. Challenges lie more than ever in the safe handling of nanomaterials. Accompanying research into human and ecotoxicological safety aspects are needed in all new developments and research projects involving nanotextiles with regard to acceptance by society, and so form an ongoing component of sustainable development by research

institutes and manufacturers. The potential effects on man and the environment of nano-silver materials as an antibacterial active ingredient in the textile sector have been investigated in depth in recent years as part of the above-mentioned research projects.

An ongoing challenge lies in the further establishment of positive nanoquality labels which enable the measurement against objective test criteria of the functionality and durability of nanotechnological developments such as dirt-repellent properties. The “Nanotechnology” Hohenstein Quality Label and the Denkendorf Test Label for self-cleaning textiles are examples that have already been implemented. An application for standardisation is also currently being made for ISO standardisation via the DIN to develop a test concept for textiles using nanocomposite equipment.

Further examples of BMBF funding measures: “Nano-Textil – Nanotechnologies for textile applications” and “NanoMat-Textil – Technical textiles for innovative applications and products”

Dr. Andrea Geschewski, Project Management Jülich

Technical textiles today account for the largest share in textile production in Germany, and this market is growing! Germany occupies a leading position in Europe in the technical textiles market segment, and this should be reinforced and broadened by the development of new or significantly improved technical textiles. Key technologies including nanotechnology can be successfully employed here, and nanotechnology – as a key and cross-sector technology – thus opens up attractive market potential for German textile companies whose market success depends greatly on the innovative strength of their products. To promote this, in 2007 the BMBF initiated the funding measure “Nanotextil – Nanotechnologies for textile applications”.

Within the funding measure were promoted industrial collaborative projects leading to the development of new or significantly improved textiles and processes, while at the same time ensuring safer handling of nanotechnology. At the forefront were the fields of medical engineering, automotive, textile architecture,

construction, health, hygiene and functional clothing, as well as environmental and safety technologies. The funding measure sponsored a total of 12 collaborative projects totalling some 13 million euros. The projects involved 67 partners, of which 27 were large enterprises, 18 were SMEs and 22 were research institutes, pursuing new avenues to utilise nanotechnologies in textile applications.

In 2012, the “NanoTextil” funding measure was enhanced by the “NanoMatTextil” funding measure as part of the Federal Government’s High-Tech Strategy, with the aim of developing new fibre materials, textile equipment and surface functionalisation and textile structures. This commitment is driven by the high economic potential of the newly-developed solutions. 58 proposals were submitted for the funding measure, of which 15 were selected and invited to submit an application. Of these, eight collaborative projects were initiated in 2013. All the other projects are to be approved in 2014.

One of the approved collaborative projects is titled “Development of nanoadditive polyamide-nonwoven combinations to increase life and improve energy efficiency in the example of abrasion-resistant press felts – HighReF”. The aim of the collaboration project is to develop nanomodified plastic fibres for the production of press felts, for use in paper machines, having improved abrasion resistance and reduced energy consumption in the end product. This involves developing new nano composite materials which can be used as a starting material in fibre production. A demonstrator must provide evidence that suitable nonwovens can be

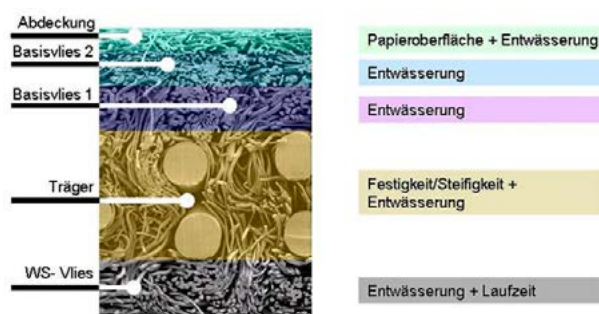


Figure: Basic structure of a press felt (Source: Heimbach GmbH & Co. KG).

produced as press felts from the fibres. German press felts, for the pressing element in paper machines, are of great importance on the world market. The continuous ongoing development of these materials and the improvement of product performance are the key to retaining and growing this market position. The new materials to be developed will increase the product life of textile coverings in the paper machines, and will in addition reduce energy consumption. The project results are generally transferrable to other nonwovens, so high leverage can be expected for the German textile industry.

4 Socio-economic background

The market success of nanotechnology innovations depends to a large extent on the socio-economic framework conditions at both national and international level. Key factors in this are public research funding in Germany and in Europe, networking and cooperation arrangements, funding of young scientists, safe handling of nanomaterials by risk research, risk management and regulation, information and communication with the public, and international coordination and standardisation. The following sections look at current developments in these areas using contributions from well-known experts in the respective fields.

4.1 National research funding

Public research funding for nanotechnology in Germany
Dr. Gerd Bachmann, VDI Technologiezentrum GmbH

Funding activities in the Federal Government

In 2006 the Federal Government initiated the High-Tech Strategy to provide support in finding solutions to global challenges, but also – amongst other reasons – because Germany, as an export-oriented country having few natural resources of its own, depends for its industrial competitiveness upon future global markets. The aim of this High-Tech Strategy is to coordinate R&D policy and innovations in socially important areas such as medicine, climate, energy, environment, mobility and communications. Nanotechnology is becoming increasingly important in the high-tech sector, and in order to better utilise the existing potential for Germany and gear value chains towards innovation, as from 2006 the work of eight federal ministries has also been focussed and driven forward on the basis of the “Nano-Initiative – Action Plan 2010”. Led by the Federal Ministry of Research and Technology (BMBF), implementation of the action plan involves the Federal Ministries of Labour and Social Affairs (BMAS), Food, Agriculture and Consumer Protection (BMELV), Health (BMG), the Environment, Nature Conservation and Nuclear Safety (BMU), Transport, Building and Urban Development (BMVBS), Defence (BMVg) and Economics and Technol-

ogy (BMW). The action plan brings together in a joint approach a range of activities covering SME funding, new leading innovations, risk research and comprehensive dialogue with the public on the opportunities and impact of nanotechnology.

As a result of the further coordinated activity of its Interministerial Steering Group, which continues the excellent and responsible collaboration of the various players drawn from research, training, economic affairs, politics and society, at the beginning of 2011 the Federal Government presented its “Action Plan Nanotechnology 2015” in order to ensure through a common platform the opportunities for nanotechnology through safe, sustainable and successful use. In this the commercial exploitation, responsible handling of materials and technology, improvement of the framework conditions and public discussion are the primary factors addressed. The associated funding activities are undertaken autonomously by the individual work units within the ministries. The Interministerial Steering Group provides a forum for regular exchange of information on these activities and the discussion of jointly achievable strategies and the current state of the regulatory agenda. The results of the nano risk research provides a basis for supporting the policy of establishing regulatory frameworks appropriate to the ensuring of the safe and responsible handling of nanomaterials, but that do not unnecessarily restrict innovation and the industry’s international competitiveness. In addition to the Interministerial Steering Group, a group of Länder has nominated nanotechnology as an additional network for discussion and exchange of information. This brings together research sponsors from the Länder who share information on their activities with the Federal Government and each other, and also sound out what potential may exist for collaborative progress, for example through presence at international trade fairs, future coordination of funding measures, or for joint Federal-Länder funding strategies.

BMBF funding activities

The BMBF has been funding nanotechnology research and development for over 20 years. Although when funding first started the projects were still very ba-

sis, as funding strengthened they were able to become increasingly relevant to real applications. Networking of industry – primarily SMEs – with science was started with the collaborative projects in order to more swiftly transfer the results of R&D into applications. Nanorisk research has been heavily funded from as far back as 2006. Research facilities, higher education establishments and industry joined forces on an interdisciplinary basis to research the impact of synthetic nanomaterials on man and the environment. The priorities of the projects include extensive investigation of the effect of synthetic nanomaterials on man and the environment and research into the responsible use of nanotechnology. After 2006, innovation alliances – with representatives from the scientific, economic and political fields – were set-up as a new funding instrument to consider areas with global market perspectives and decide which, through a strategically-applied long-term perspective, should achieve significant economic leverage. Innovation alliances such as these relating to nanotechnology were initiated for organic light-emitting diodes (OLED), organic photovoltaics (OPV), carbon nanotubes (inno.CNT), lithium-ion batteries (LiB2015), and molecular imaging (MoBi-Tech). BMBF funding was also extended to leading-edge and excellence clusters, some of which look at questions of nanotechnology.

In addition to research funding, supporting measures appropriate to the topic are also important for a successful innovation policy. These measures were introduced when work on the topic first began back in the early 90s, in the form of technology scouting, innovation and technical analyses and innovation-accompanying measures. They include funding activities such as nanoTruck, the production of brochures and information portals in a generally understandable form, and dialog with citizens and interested parties. Cross-sector activities aimed at targeted support for SMEs (SME-Innovative Nanotechnology, formerly NanoChance) and at funding for young scientists (NanoMatFutur, formerly NanoFutur) have also been put in place. Various accompanying measures address safety questions regarding nanomaterials and technical information, so that citizens can use nanoTruck or the DaNa website (www.nanoparticle.info) to learn about the opportunities and risks of nanotechnology. This internet portal also provides the layman with readi-

ly-understood information, and an opportunity for exchange with scientists. Another aspect of the supporting measures is the work of the Nationale Kontaktstelle Nanotechnologie (NKS) (National Contact Point, NCP) which is commissioned by the BMBF to advise German applicants on EU tenders.

BMBF research funding in 2011 accounted for around 222 million euros of project funding including innovation-supporting measures. A total of 26 BMBF advisers across all departments were involved in funding of some 1700 individual projects. 43% of the funding went to industry and 57% to public research institutions. The New Materials and Nanotechnology sector accounted for the largest share of this funding, at almost 40%. The BMBF employed some 18 million euros of this funding in 2011 on around 170 projects in preventive and supporting research through NanoCare, NanoNature and accompanying innovation measures.

Overall presentation of the German funding investment in nanotechnology

In addition to BMBF funding already discussed of almost 222 million euros in 2011, in the same year the other federal ministries involved in the Interministerial Steering Group released around 45 million euros for nanotechnology R&D.

That means that in 2011 the federal ministries in total expended something over 266 million euros in support of nano projects. This included around 26 million euros on preventive and risk research together with accompanying measures, equating to almost 10% of the total federal ministry funding.

Funding in million euros	2009	2010	2011
Total federal ministries	247,6	252,8	266,3
BMBF	212	215,5	221,6
Other federal ministries	35,6	37,3	44,7
Länder	59,1	67,1	79,9
Institutional funding	178,4	250,2	279,3
Other (VW Foundation)	5	5	5
Whole of Germany	490,1	575,1	630,5

Development of public funds for nanotechnology in Germany in the period 2009 to 2011 (Source: VDI TZ).^[160]

The overall presentation of nanotechnology funding in Germany also includes the activities of the Länder. Taken together, the Länder spent around 80 million euros in 2011 on Land-based funding activities for nanotechnology. The Federal Government and the Länder were also jointly responsible for supporting R&D institutions through institutional funding, the German Research Foundation (GRF) being the largest funding organisation in the field of nanotechnology. The Helmholtz and Leibniz research associations along with the Fraunhofer and Max Planck Society are also financed by institutional funding. In 2011, approximately 279 million euros were spent on institutional funding for nanobased activities, and the Volkswagen Foundation should also be mentioned as a relevant representative of the nationwide foundations with a contribution of 5 million euros.

In all, public funding of nanotechnology in Germany in 2011 totalled around 630 million euros. It can be assumed that contributions for nanotechnology funding development in 2012 und 2013 will continue at the same level.

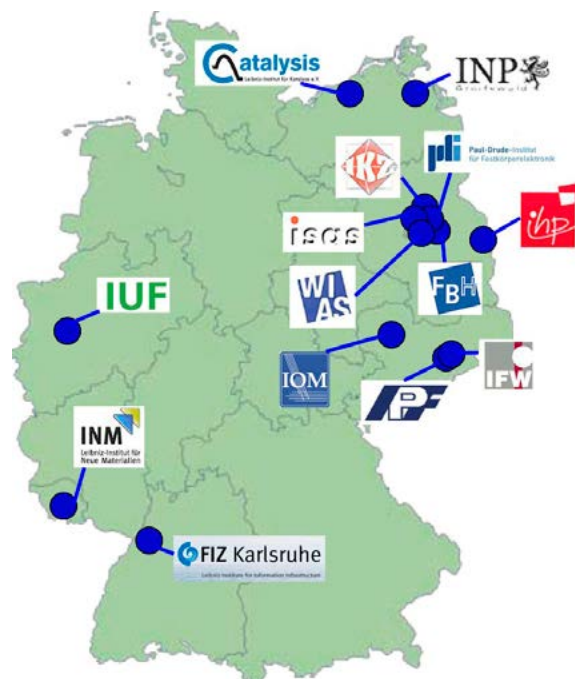
4.2 Networking and cooperation arrangements



Leibniz Nano Network – a network of Leibniz institutes with activities in nanotechnology

Dr. Mario Quilitz, INM Saarbrücken,
Coordinator of the Leibniz Nano Network

Many of the institutes at the 86 institutions of the Leibniz Association are working on research topics in the field of nanotechnology. This has led to the founding of a Leibniz Nano Network with the aim of consolidating the know-how and activities related to this in the Leibniz Association. The Network's Coordination Office is based at the INM – the Leibniz Institute for New Materials at Saarbrücken. The spokesperson for the Network, currently active at 15 institutes, is Prof. Dr. Eduard Arzt, with coordination being the responsibility of Dr. Mario Quilitz.



Partner institutes in the Leibniz Nano Network (Source: INM)

The topics studied at the partner institutes are already very diverse: surfaces with special functional properties, for example, make possible switchable adhesion or special catalytic effects. New solutions for example in printed electronics, in chemical or magnetic sensors or in semi-conductor modules with special electronic properties are being developed in the fields of nanoelectronics, nanosensors and nanooptics, another important field being the examination of analytical methods and their performance for investigations in the nanometer range. Other notable priorities are ultimately nanomedicine, nanobiology and nanosafety.



Production of nanoscale layers at pilot scale (Source: INM, Uwe Bellhäuser, photography)

A central aim of the Leibniz Nano Network is to raise the profile of the activities and players in nanotechnology within the Leibniz Association, but even more important is the fact that the Network is also becoming the central contact point for all “nano” topics in the Association for partners and interested parties outside the Leibniz Association.

Another important goal is the gathering of information on the competences assembled in the network, the setting up of a “competence matrix” and its sharing with interested parties. This also includes putting in touch potential project partners within and external to the association.

Last but not least, the Network can initiate or organise joint activities, examples being workshops, seminars, joint trade fair attendance, and exhibitions.

The common interest in questions of nanosafety led to the founding in 2013 of a Nanosafety research collaboration which brought together six institutes. They are attempting to answer questions such as: How safe are nanomaterials in contact with human cells, tissue and organs? How – should the situation arise – are the particles absorbed into cells? Are the cells damaged or do they die? What lessons can be learned for safe handling of nanomaterials?

Fraunhofer Nanotechnology Alliance



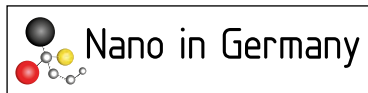
Prof. Dr. Günter Tovar, Fraunhofer IGB
Spokesman for the Fraunhofer Nanotechnology Alliance

The Fraunhofer Nanotechnology Alliance (Fraunhofer NANOTECH) is run jointly as a cooperation platform of 20 Fraunhofer institutes with different competences. Fraunhofer is the largest organisation for application-oriented research in Europe, with our research fields focussed on the needs of man: health, safety, communications, mobility, energy and environment.

Fraunhofer NANOTECH covers the whole of the supply chain from application-oriented research through to industrial implementation, and develops for example multifunctional layers for optical applications, automotive construction and the electrical equipment industry. Metal and oxidic nanoparticles, carbon nanotubes and nanocomposites are used in actuators, structural materials and biomedical applications. The competences of the alliance are shown in the following chart.

Fraunhofer institutes that are part of the Fraunhofer Nanotechnology Alliance and their fields of activity	Nanomaterials/nanochemistry	Nanoparticles/nanofluids	Thin films/interfaces	Nanooptics/nanoelectronics	Nanobiotechnology	Cross-sector topics		
						Modelling/simulation	Analysis, tools, safety	Production technologies, technology transfer, advice
Fraunhofer Institute for Electronic Nanosystems (ENAS), Chemnitz								
Fraunhofer Institute for Industrial Engineering (IAO), Stuttgart								
Fraunhofer Institute for Applied Polymer Research (IAP), Golm								
Fraunhofer Institute for Chemical Technology (ICT), Pfaffzettel								
Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM), Bremen								
Fraunhofer Institute for Factory Operation and Automation (IFF), Magdeburg								
Fraunhofer Institute for Interfacial and Biotechnology (IGB), Stuttgart								
Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Erlangen								
Fraunhofer Institute for Ceramic Technologies and Systems (IKTS), Dresden								
Fraunhofer Institute for Laser Technology (ILT), Aachen								
Fraunhofer Institute for Production Technology and Automation (IPA), Stuttgart								
Fraunhofer Institute for Silicate Research (ISC), Würzburg								
Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg								
Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe								
Fraunhofer Institute for Toxicology and Experimental Medicine (ITEM), Hannover								
Fraunhofer Institute for Process Technology and Packaging (IVV), Freising								
Fraunhofer Institute for Mechanics of Materials (IWM), Halle/Freiburg								
Fraunhofer Institute for Material and Beam Technology (IWS), Dresden								
Fraunhofer Institute for Non-Destructive Testing (IZFP), Saarbrücken/Dresden								
Fraunhofer Institute for Structural Durability and System Reliability (LBF), Darmstadt								

Fraunhofer NANOTECH is an active participant in dialog processes on nanotechnology (nanodialog), organises visits to trade fairs by the Alliance, works on recommendations for treatment in handling nanomaterials, organises industry workshops on current issues in nanotechnology and actively participates in funding for young scientists. Further information on the Fraunhofer Nanotechnology Alliance can be found at www.nano.fraunhofer.de.



“Nano in Germany” initiative

Prof. Dr. Andreas Leson, Fraunhofer IWS, Dresden, spokesperson for the “Nano in Germany” initiative

The notable feature of nanotechnology is that a number of conventional disciplines such as physics, chemistry and biology as well as the engineering sciences are involved. This high degree of interdisciplinary coordination makes nanotechnology exciting because new developments arise at the interfaces and also because it requires a particularly intensive collaboration and cooperation between all the players in the value chain to purposefully seek out and market new innovations.

It is not least for this reason that the competence centres were set up and funded in the initial phase of nanotechnology, dealing with the targeted reinforcement of interdisciplinary cooperation and networking and which for the most part remain active today. In addition, a number of other initiatives have been set up at both regional and national level to take these goals into account.

The “Nano in Germany” initiative was set up in 2012 with the aim of bringing together these various activities under one umbrella at national level. Its aim is to offer the players in Germany a common voice and a neutral and objective platform through which a higher profile, at both national and international level, can be achieved by working together. The initiative is also about seeking out and processing relevant and reliable information and thus providing support for members. Greater acceptance of nanotechnology in the public awareness is also achieved.

Founder members of the initiative include Beiersdorf GmbH and RunKom, the Fraunhofer Nanotechnology Alliance and the IVAM Microtechnology Network, the Association of German Engineers with its Nanotechnology section and the VDI Technologiezentrum GmbH and the German Nanotechnology Association. The initiative is based at the Association of German Engineers and to date has signed-up more than 100 members from industry, research and science.

Particular attention is focussed on the development and implementation of joint marketing activities such as the “World of Nano” at the Hanover trade fair, and strategy development for technology challenges in the next ten years.



German Association of Nanotechnology

Dr. Ralph Nonninger, President of the DVNano

The prospects for Germany lie in the ecological conversion of the industrial society, something driven to a significant degree by nanotechnologies. Outstanding research, efficient technology transfer, far-sighted economic and education policy and entrepreneurship in the high technology fields safeguard today's workplaces and create the workplaces of the future.

These beliefs led in 2011 to the founding in Saarbrücken of the German Association of Nanotechnology (DV Nano), the professional association for those working in nanotechnologies or who are engaged in their funding. At the same time, the association is open in particular to small and medium-sized companies.

The aim of DV Nano is to promote nanoknowledge and technologies wherever they can offer solutions to challenges for society both now and in the future. The Association covers research and application fields in subjects such as environmental engineering and energy, medical engineering and pharmaceuticals, mobility, information and communications.

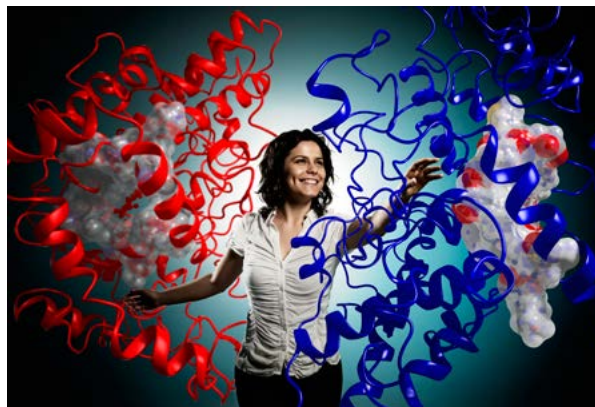
Environmental and consumer protection enjoy the highest priority and are therefore firmly established in the Association's articles. The association signposts responsible handling of high technology, promotes the contribution of nanotechnologies for a post-nuclear and post-fossil energy supply, and communicates nanotechnology solutions for clean drinking water or breakthroughs in combatting disease.

The Association brings together the competences of its members in questions surrounding the nanotechnologies, and formulates and represents its positions on these. Because it is independent of political and economic interests, the DV Nano can serve as a contact point for all the society interest groups. It is an arbiter on information and advice for politicians at Land and government level, for decision-makers at higher education establishments and in enterprises, and is also a portal for the public, journalists and non-governmental organisations.

Advising, communicating, networking – the Association's core activities

The DV Nano is the competent contact for all relevant bodies in ministries and authorities for drafting directives and decisions such as in dialogue with authorities or in technical dialogue regarding nanotechnologies in the NanoCommission. The Association communicates the opportunities, potential, and actual merits of nanoapplications and takes part in the discussion of potential risks and new ethical questions arising.

The Association links its members together to give them the opportunity to find technology or research partners or have a say through their personal commitment in the future of nanotechnologies. With its bodies – the “Deutscher Nanotag” general meeting, the Management Board and the extended Management Board – as well as its study groups and regional registries, the German Association of Nanotechnology has the structures to represent nanotechnology in Germany. For more information on the Association visit www.dv-nano.de



The German Association of Nanotechnology: For those who shape the future. (Source: Uwe Bellhäuser/DV Nano)

4.3 Funding new blood

NanoMatFutur: Funding for young scientists in nanotechnology and material sciences

Dr. Marc Awenius, VDI Technologiezentrum GmbH,
Dr. Hans-Jörg Clar, Project Management Jülich

The innovative work of highly-qualified and creative scientists makes an important contribution to the success of an enterprise, ensuring its success and providing the opportunity for countries with few raw materials, such as Germany, to be able to compete globally. This applies especially to the cross-sector technologies nanotechnology and material sciences which, because of their wide application and their leverage effect for new fields of technology, are important in several key sectors such as the chemical and automotive industries. However, demographic change and increasing global competition for the best minds are making it difficult to attract highly-qualified scientists and present an increasingly serious risk for science and industry in Germany. The funding of outstanding young scientists is therefore vitally important for safeguarding and expanding a knowledge-based society and thus a key priority in the Federal Government's High-Tech Strategy.

Funding measure

Since 2002, the focus of the BMBF's funding has been to attract the best young scientists. The 2011 excellence measure “NanoMatFutur” published in 2011 broadened the scope of the “NanoFutur” funding measure, previously restricted to nanotechnology (see nanoDE-Report

2011), to include the important field of material research. In three rounds of competition, the BMBF each year sponsors up to seven young scientists and enables them to build an independent young research group. Funding for these young research groups covers four years, but can be extended to up to six years depending on a successful interim evaluation of the project.

The measure focusses on funding outstanding young scientists with new interdisciplinary approaches to research in nano or material technologies. In addition to basic aspects, projects receiving funding must also demonstrate a clearly recognisable relationship to industrial implementation in the energy, environment/climate, mobility, health or information/communications technology sectors. In the sense of excellence funding, “NanoMatFutur” offers young scientists the best possible starting conditions, creates new incentives for those willing to return from abroad and ensures that creative minds will stay in Germany in the long term.

Interim situation

As a result of the first two rounds of competition, of 66 applicants a total of 14 junior scientists were recommended for funding. The BMBF is making available a total of 22 million euros for the setting-up of their own working group at a German university or research institution. A third round of competition has been running since October 2013. Up-to-date information on the funding measure can be found on its website at www.nanomatfutur.de or on the BMBF's homepage at www.bmbf.de.



NanoFutur: A success story using the example of Prof. Dr. Stefan Kaskel

Brief profile

Born: 1969 in Bonn

Area of expertise: Inorganic chemistry

Position: Professor, Chair of Inorganic Chemistry I at the TU Dresden (2004); Head of the Chemical Surfaces and Reaction Technology Department, Fraunhofer Institute for Material and Beam Technology (IWS), Dresden

Support provided: NanoFutur 2004–2008

Subject: Nanocomposites and hybrid materials

Internet link: <http://www.chm.tu-dresden.de/ac1/bmbf/index.shtml>

Interview

Professor Kaskel, what scientific questions are you currently working on?

Prof. Kaskel: The focus of my work at present is in the area of nanoporous materials. I am particularly interested in how pore sizes can be specifically set in different chemical material systems so that the materials take on new functionalities. At the centre of this is the uptake of gases or even the uptake of liquids, pollutants, enzymes, as well as the immobilisation of enzymes and material separation. On the basis of this, porous materials can even be used in battery systems such as the lithium sulphur battery.

What is it about nanotechnology that fascinates you?

Prof. Kaskel: In general I am fascinated by materials whose properties are defined by their huge surfaces. We have been able to produce materials that have specific surface areas of over 5000 m²/g. Interface-dominated materials such as this occupy a key position in

different technological concepts such as catalysis, battery technologies, adsorption and storage processes.

Could you please describe your professional situation prior to becoming involved in the BMBF's NanoFutur funding measure. Where do you stand today?

Prof. Kaskel: At the time, I was a group leader at the Max Planck Institute for Coal Research and had already built up a small team there. The working conditions were excellent, but from this career situation I was only able to drive forward a limited number of subjects in relevant research work. Today I am heading both the Institute for Inorganic Chemistry at the TU Dresden and the Department of Chemical Surface and Reaction Technology at the Fraunhofer Institute. The combination of basic research that can be conducted in a university environment and the integration of the materials we have developed in applications at the Fraunhofer Institute for Material and Beam Technology means that today I can focus on a number of different areas. Curiosity and creativity are the precondition for being able to progress top scientific publications. And the Fraunhofer Institute also makes it possible the scaling-up of new materials and their integration into systems by scalable production techniques.

What in your view have been the main success factors for your career?

Prof. Kaskel: The position as group leader at the Max Planck Institute for Coal Research at Mülheim an der Ruhr was an ideal springboard for beginning a career in science. The Institute's tradition of converting patents into commercially successful applications was a defining factor. The mentoring I received from Ferdi Schüth was also revolutionary for me, and the BMBF's NanoFutur funding measure enabled me to develop a completely independent research profile which was very attractive to innovative higher education institutions. The transfer of the project to Dresden then laid the foundation for a successful career there.

What advice can you give to junior scientists starting out in the field of nanotechnology?

Prof. Kaskel: Young scientists should have the courage to tackle really new subjects arising from the dissertation sphere and, if possible, also from that of post-doctorate work.

4.4 Safe handling of nanomaterials

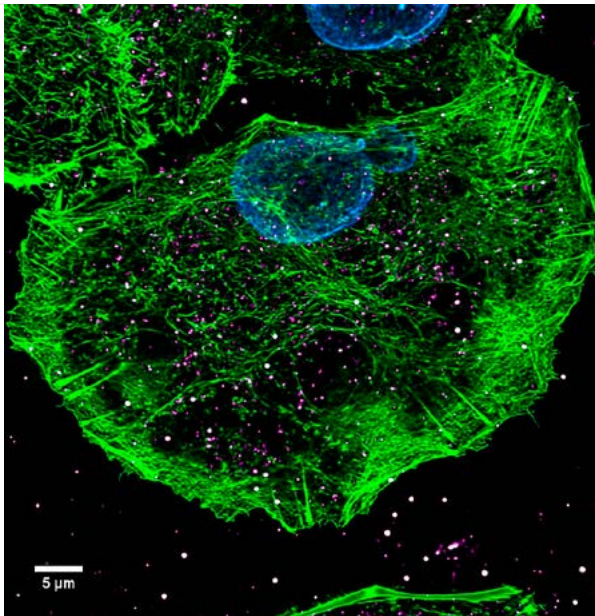
Research into risks associated with nanomaterials

Prof. Dr. Harald F. Krug, Empa, Switzerland

Ten years ago, the first report in the German language was produced looking at nanotechnology and with it the opportunities and risks of this new technology.^[145] Just one year later, the contribution made by the Royal Society in London covering the discussions arising around the globe appeared as highly critical comments on the problems of the safety of man and the environment resulting from synthetic nanomaterials.^[146] There is now a nanotechnology action plan in virtually all the industrialised countries, mostly in the form of national research programmes, addressing questions on the potentially adverse consequences of nanomaterials. Germany leads the way in this, because with the funding of the first major projects in 2006 safeguards were put in place at an early stage for coordinated risk research on nanomaterials. The "NanoCare" project has become a beacon in matters of quality and significance.^[147]

Following the international discussion which also resulted in the EU's framework programmes, there have been further initiatives in Germany as part of the WING programme and the High-Tech Strategy. The most important of these is the new version of a funding programme for research into the uses and potential risks of any exposure of man and the environment to nanomaterials. In both the "NanoCare" and "NanoNature" programme modules, 20 projects with a total of around 36 million euros have now been funded since 2009. An important aspect in this is that academic research institutions are working with partners in industry to also be able to work in detail on marketable products or their starting materials. Four of these projects have in the meantime been concluded, and several more are in the final phase of evaluation. Even before all the projects have been completed, the BMBF has already started the second round of tendering for funding; new projects are already starting.

Results published to date have reached a reassuring conclusion: that nanomaterials are not toxic simply because they are so small. There is therefore no general correlation between particle size (or small size) and their biological action. A number of studies – not just



Uptake of nanoparticles in cell structures: (Source: INM)

those funded by the BMBF – have come to similar conclusions. There are clear indications that any uptake of very small particles via the lungs can lead to problems even if this is probably only the case with higher levels of exposure. The project groups have therefore largely come to the conclusion that workplace monitoring is recommended and also that the particle size should be recorded in the process. The question of whether and to what extent a limit for nanomaterials should be set irrespective of the previous dust thresholds still requires further clarification. The low toxicity which has so far been determined for the materials, however, would suggest that the current limits are adequate. Certainly there are nanomaterials with cause for greater reservations, particularly if they are materials that demonstrably contain toxic substances (such as quantum dots of cadmium selenide) or have a particular geometry that can trigger a mechanical or physical action (for example carbon nanotubes in their highly agglomerated and rigid form).

The results of the projects together with processed data from international literature have been made available to the public in a project also sponsored by the BMBF. This information can be found at www.nanoparticle.info and experts can also be contacted

directly. This is a good source of reference for anyone wishing to obtain objective and authentic information on nanomaterials.

The risk research on nanomaterials has borne valuable fruit in the past 10 - 15 years. Working with nanotechnology is as a result becoming safer, an estimate of potential hazards is now possible and the published data gives no cause for great concern regarding the use of nanomaterials. It is nevertheless important that now and in the near future newly-developed materials are investigated with the same care in order to safely manage their industrial production and use by the consumer. Safety research parallel with technology is always necessary; this is the only way to sustainable development of new technologies for the benefit of all concerned.

Safe handling of nanomaterials in the workplace

Dr. Rolf Packroff, Federal Institute for Occupational Safety and Health (BAuA)

From the beginning, nanotechnology has been linked with the concern that because of their extremely small size, synthetically manufactured nanoparticles are distributed in the organism after take-up and can lead to as yet unknown health risks. In addition to this, it was feared that fibrous nanomaterials can constitute a cancer risk comparable to asbestos. These risk assumptions were the starting point for a number of for the most part publicly funded research projects which have tackled the issue of the safety of nanomaterials. They have made it possible to provide recommendations on occupational safety in activities involving innovative materials at an early development stage in which potential dangerous properties are not sufficiently well known. The Federal Institute for Occupational Safety and Health (BAuA) jointly with the Association of the Chemical Industry therefore published a guidance note for the safe handling of nanomaterials in the workplace back in 2007.

In the meantime, the results of a large number of completed projects on safety research give a detailed picture of potential risk aspects of nanomaterials. The findings from toxicological investigations in fact show no new risks, but do support and improve on the scientific hypotheses on the harmful effects of inhaled

particles. In the meantime, they are enabling groups to be assembled that are also helpful in assessing hazards in the workplace.

At an appropriate dose inhaled synthetically manufactured nanoparticles can, in the same way as other unintentionally-generated or naturally-occurring nano- and microparticles, such as from diesel engine emissions and welding fumes, lead to inflammation reactions in the lungs and to respiratory diseases. A key factor in the expression of these effects is a low solubility, or insolubility, of the particles in the lung fluid, something also termed “biopersistence”. Further to a proposal by the Senate Commission of the German Research Foundation (GRF) for testing harmful substances (“MAK Commission”), the Committee on Hazardous Substances is currently preparing for a clear reduction in the occupational exposure limit for granular biopersistent particles (“GBP”) which places the dust, formerly classified as inert and so non-reactive dust for occupational safety purposes, on a level with harmful hazardous substances. According to the current state of knowledge, differences exist in the potency of nano- and micro-scale particles, but are not serious.

In the case of carbon nanotubes, research into the case of rigid, so stiff, fibres does confirm original fears. The harmful effects of low-flexibility fibrous particles were particularly apparent if their form is similar to that of asbestos. For these it does appear that strict occupational safety measures are needed to protect the health of people working with such materials in research, development, production or recycling.

The third group relevant from an occupational safety perspective are those materials that – perhaps in combination with the particulate effects – have a specific “chemical” toxicity. This may result for example from the release of heavy metal ions from absorbed particles, which can trigger toxic effects in the body similarly to the chemical absorbed in its directly dissolved form. Catalytic effects or chemical-functional groups on particle surfaces can however also be linked to specific effects, and for these nanomaterials a case-by-case assessment of the risks for man and the environment is essential.

In May 2013 the Hazardous Substances Committee published Announcement BekGS 527 “Manufactured Nanomaterials” which supports the current findings from safety research. On the basis of the Hazardous Substances Ordinance, this contains recommendations for ascertaining information and assessing hazards for activities with nanomaterials. It is aimed in particular at research institutions and start-up enterprises faced with the question of how they can protect health while working on material innovations. An important key to this are low-emission nanomaterials which exhibit dusting behaviours favourable to health. Many commercial nanomaterials in fact release relatively small amounts of respirable particles in dustiness tests, but with carbon nanotubes there is a wide range. Low-dust design, in the sense of “safety-by-design”, represents a challenge here for a sustainable nanotechnology that must also always bear in mind the health of employees.



BAuA testing facility for ascertaining the dusting behaviour of nanomaterials (shaker process) (Image: BAuA/Fox).

Regulatory framework conditions for the safe handling of nanomaterials

Dr. Hans-Jürgen Klockner, German Chemical Industry Association

At this time in the EU decisive directions are being set out in the legal framework conditions for nanotechnology. This is also about striking an appropriate balance between the precautionary principle and the encouragement of innovation.

EU definition of nanomaterial broadly interpreted

In its recommendation of October 2011, the EU Commission has followed the requirements of the European Parliament, many EU member states and the scientific advisory bodies: it has presented a broadly interpreted definition of the term nanomaterial for precautionary reasons, applicable in the various legislative areas. According to this, a “nanomaterial” is a natural or manufactured material or one occurring in processes, which contains particles in the unbound state as an aggregate or as an agglomerate, and in which at least 50% of the particles in the number size distribution have one or more external dimension in the range of 1 to 100 nanometers. In addition, fullerenes, graphene flakes and single-wall carbon nanotubes with one or more external dimensions of less than 1 nanometer are to be considered nanomaterials. This very broadly interpreted definition also embraces many finely-divided powders and dispersions from industrial production and natural mineral provenance, pigments and fillers, which have in fact in some cases been used for centuries. The Commission therefore stresses that the exclusively size-based definition does not mean that products defined as nanomaterials possess hazardous properties per se.

Legal obligations result only when the definition – if necessary in a modified form – is included into laws and regulations, something not the case with the new Biocide Regulation. Older nanomaterial definitions established by the EU Parliament are to be found in the European Cosmetics Regulation and the EU Food Information Regulation. Currently under review is the adaptation of these older definitions to the new EU definition recommendation. The definition is not yet legally binding for REACH, but according to EU Commission statements it is

“relevant”. A measuring method to establish whether a substance is a nanomaterial is still to be developed and declared binding.

Laws to protect man and the environment

In October 2012, the EU Commission published its second review of the legislation for nanomaterials. The report was supplemented by an accompanying document with information on nanomaterials on the market, their uses and their safety.

The EU Commission stresses that various scientific studies had shown that from a safety point of view nanomaterials should be dealt with as “normal” chemicals. Potential risks are linked with certain nanomaterials and specific types of use, so, as with other chemicals, a risk assessment may be indicated on a case-by-case basis. The risk assessment methods currently available can be used. The Commission considers the greatest challenge to be the completeness of information on any hazards arising from nanomaterials and the development of methods for measuring and assessing exposure.

The reaction to the conclusions and planned actions of the EU Commission varies. Some EU member states along with environmental and consumer associations have criticised a lack of direction in the precautionary principle. Industry considers the EU Commission’s approach to be appropriate and in line with the results of the safety research and the considerations of the OECD.

The EU Commission regards the EU’s chemical regulation REACH as the core regulation for the safe manufacture and use of nanomaterials because REACH also provides material data for sectoral and media regulations. Clarification and more precise definitions are required for nanomaterials in the appendices of the REACH regulation, although not in the core text of the regulation. The EU Commission therefore sees no need to change registration dates and quantity thresholds, or for a separate substance identity for nanomaterials. In the first half of 2014, the EU Commission aims to present a proposal for the nanospecific adaptation of the REACH appendices, and has to this end initiated a stakeholder consultation in which authorities from the member states, including the competent German Federal authorities together with environmental or-

ganisations and industrial associations, have included their proposals.

In Germany, the Committee on Hazardous Substances, based at the Federal Ministry of Labour, adopted the announcement “Manufactured Nanomaterials” in May 2013 which serves to protect employees when working with manufactured nanomaterials.

Product register and consumer information

Many EU member states along with consumer and environmental organisations are calling for greater transparency on the use of nanomaterials in products handled by consumers and with free access to the environment so that the authorities and consumers can be kept informed.

The EU Commission will first of all set up a web platform on “NanoProducts” which will contain advice on all the information sources available, including national and industry-based registers. It has also commissioned a study to ascertain the means best suited to further-improved transparency. This study will look at nanomaterials that do not currently fall within the scope of valid provisions for reporting, registering or authorising products. At the beginning of 2015, the Commission will decide whether it will put forward a legislative proposal for further transparency obligations.

Proposals for setting up a Europe-wide nanoproduct register have been drawn up by several authorities in the member states, among them the German Federal Environment Agency. Some member states, such as France, Belgium and Denmark, are also looking at using tailor-made national registers which will in some cases involve substantial restrictions on the EU Commission’s recommendation on the definition of nanomaterials so that the registers are manageable and there are no duplications of notification requirements.

For products with applications in close proximity to the body, consumer organisations are providing directions for the use of nanomaterials on the packaging. This is now a legal requirement in the cosmetics sector and in future will also apply to biocides and food.

Industry supports the plans by the EU Commission for improved market transparency. It is asking to use the existing substance-based and sectoral databases for the planned European internet platform on the use of nanomaterials, but industry is against a general sector-overarching nanoproduct register. Labelling should, from the point of view of the chemical industry, by and large remain limited to products containing ingredients with hazardous properties.

Detecting nanomaterials in products for regulatory requirements

Dr. Hermann Stamm, European Commission, JRC Ispra

An increasing number of products containing nanomaterials (NM) are appearing on the market, and against the background of the unclear effects of NM on health and the environment several institutions and organisations, such as the European Parliament, some EU member states and various non-governmental and consumer organisations, have called for consumers to be better informed on the use of NM in products and for the provision of greater transparency on tracking them on the market. This can in principle be achieved by labelling products containing NM or by creating product registers. Pushing through the legal provisions needed for this, as with those already existing or planned for food, cosmetics and biocides, however requires analytical measuring processes to enable NM to be detected in the affected products.

Definition of nanomaterials

The special regulation and specific mention of NM in legislation requires a definition of the term “nanomaterial”. In October 2011, the European Commission issued a recommendation for a general definition of NM allowing existing definitions, for example in the regulation for cosmetics and for food, to be standardised and harmonised. A clear and enforceable definition is also needed to classify the ingredients used in products accordingly and to check whether finished products have been labelled in accordance with the legal requirements. This requires analytical methods that permit determination of the properties ascribed by the definition to an NM, and on the basis of measured values then allow such classification as an NM to be made. In addition to this, validated analytical methods are needed for checks enabling NM to be detected in

a complex matrix such as those typically present for example in cosmetics or food.

Methods and strategies

There are currently three different classes of analytical methods for detecting NM in products. These are based on imaging processes, light scattering and separation processes.

- Imaging processes such as scanning and transmission electron microscopy are two of the most reliable methods for characterising NM. They are extremely accurate, particularly in the case of metal nanoparticles, and can also be used for mixtures of NM of different sizes. These measuring methods are sophisticated and expensive and require careful selection of samples and costly sample preparation.
- There are several methods based on light scattering, for example dynamic light scattering (DLS), multi-angle light scattering (MALS) and particle tracking analysis (PTA). These are quite simple, rapid and relatively good value, but only give good results for nanoparticles with a homogeneous size. DLS- and MALS-based methods give misleading results in terms of size distribution for mixtures with a different particle size.
- Centrifugation methods (centrifugal particle sedimentation, analytical ultracentrifugation) along with field flow fractionation are predominantly used as separation methods for NM. Compared with methods based on light scattering, they are distinguished by the fact that mixtures of different particle sizes can be analysed more accurately. This is the case particularly for the promising method of field flow fractionation in which particles up to a lower limit of 1 nm can be separated and the various particle size fractions separated off for further investigations.

A number of newer methods are currently being developed, for example mass spectroscopy and pore-based particle counting methods. The methods used for NM must be validated in order to guarantee monitoring of the legislative measures and ensure that uniform results are achieved in state control laboratories in the EU member states. To this end, the JRC has begun a first collaborative trial to detect silver nanoparticles in aqueous dispersion in which a number of laboratories from the EU and Japan are participating.

Need for research

The current need for research involves upgrading present methods or combining them so that the advantages and disadvantages of the individual methods can be balanced out. This is important in order to overcome the specific problems of detecting NM in a complex matrix and involves for example improving the limits of detection regarding size and concentration, detecting nanoparticles in a matrix with a nanoscale structure, ruling out analytical artefacts, separating mixtures of NM of various chemical composition and determining the properties of the NM in the specific matrix. Reliable validation and standardisation of the methods is also needed, and this requires the availability of suitable reference materials in order to restrict the scope of the methods.

4.5 Information for the public

Focus on the Federal Ministry of Education and Research's "nanoTruck – Meeting Place Nanoworlds" initiative

Christine Beringer, Flad & Flad Communication GmbH

In order to secure Germany's position as the leader in basic research on nanotechnology and consistently expand the development of internationally marketable products, the cooperation between science and practice must be more closely dovetailed and above all the education of qualified skilled workers promoted. At the same time, interest in and engagement with nanotechnology through proactive information must be strengthened and the effects of this field of technology on man and the environment discussed transparently with the public.

The nationwide information initiative on nanotechnology by the Federal Ministry of Education and Research (BMBF) "nanoTruck – Meeting Point Nanoworlds" plays an important role here, providing comprehensive information that is as extensive as it is generally understandable on the status quo of nanotechnology research and practice, together with a number of interesting supporting events. This is geared to interested consumers as well as to school pupils, students, teaching staff, and small and medium-sized enterprises interested in the research and use of nanotechnology.

In the nanoTruck, large display boards and interactive exhibit positions guide visitors through the various issues in nanotechnology research and application. Fascinating product innovations, revolutionary processes and new therapies play an important role here, just as much as do the presentation of projects and initiatives in the accompanying risk research. But it isn't just topic immersion and interactive exhibits in the nanoTruck that offer useful information on "the tiny that could be enormous". A whole range of tried and tested experiments and hands-on displays help to better understand the opportunities and potential risks of nanotechnology. In special student workshops, for example, young people can use a mobile scanning electron microscope to investigate for themselves the nanostructures of materials and substances they have brought with them or play about in so-called "idea workshops" on their own nanoinnovation.



The nanoTruck visiting the Hanover Fair 2013 (Source: Flad & Flad)

Figures, data, facts

The BMBF's nanoTruck visits some 100 locations right across Germany on around 220 working days a year. More than 110,000 visitors step aboard the double-decker exhibition vehicle at schools and universities and in town and civic centres, as part of science and technology days or vocational information and trade fairs. Information on nanotechnology, tips on education and study opportunities, dates, the latest news

and much more can be found on the project website at www.nanoTruck.de and the nanoTruck Facebook page at www.facebook.com/nanoTruck.

DaNa – the knowledge platform on nanomaterials – scientifically sound and easy to understand

Dr. Christoph Steinbach, Dechema e. V.

German researchers have in recent years build up an excellent skills base in the field of nanotechnology and synthetic nanomaterials. This technology has in many places already made its way into practical implementation and in some cases even applications. Nanoparticles are now playing a role not only as catalysts in process engineering, but have also become part of our everyday life. We can find them in care products, medicines and food, and also encounter them in textiles and in interior and exterior paints, as well as PET bottles and many other items in everyday use. As a result, debate on the potential risks of nanomaterials in the media and consumer associations has steadily increased in the last few years. However, a number of players are having difficulties correctly evaluating the properties of nanomaterials, and above all their safety aspects. Consumers in particular are often confused by the lack of clear information in the media, and are unsure of who or what they should believe.

This is why the BMBF has since 2009 been funding the DaNa Project, which on its website provides national and international research results from the fields of synthetic nanomaterials, and findings on toxicology and risks, in an easily-understood way.

The internet platform www.nanoparticle.info gives the public the opportunity to find sound and unbiased information on synthetic nanomaterials and their effects on man and the environment. The evaluation of current research results for the DaNa knowledge base is then made on the basis of careful scientific procedures using their own publicly-accessible criteria catalogue. This ensures that all the studies evaluated are of good quality, including with regard to realistic exposure conditions and quantities and adequate analysis of the materials examined.

The DaNa knowledge base, available in both German and English, currently provides information on

25 materials found in the most common consumer applications. Summaries and in-depth articles provide information not only on the properties of the coarse-grained and nanoscale materials, but also on whether and how nanomaterials can be released and what the impact of this may be for man and the environment.

A key feature of the DaNa knowledge base is the so-called “slot machine” which uses a three-column arrangement to link potential nanomaterials with current applications and more extensive information. An application is first of all selected and the nanomaterials used for this are highlighted in the next step. When a nanomaterial is then selected, a further column lists potential more extensive information. The special feature of this is that this information relates directly to the selected material application combination. In addition to this special differentiation by application, the “slot machine” offers further benefits for the visitor, who is able to “play” with the applications and materials here and ascertain wherever “nano” is contained. In addition, the internet platform gives an overview and information on the individual projects funded by the Federal Ministry of Education and Research on nano risk research and their results.

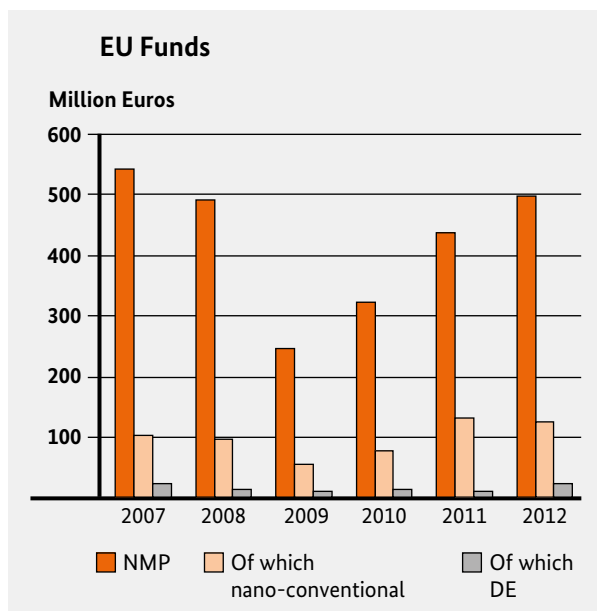
4.6 International activities

European funding in the nanotechnology field – from the 7th to the 8th Framework Programme

Dr. Christian Busch, National Contact Point Nanotechnology, VDI Technologiezentrum GmbH

In addition to the German funding measures, European research funding is providing a second important pillar in R&D funding for German applicants in the 7th Research Framework Programme (FP7, 2007-2013) which is now coming to an end. By the end of the framework programme, of all participating sectors of the Commission 3.5 billion euros are expected to have been invested in nanotechnology research, just under 1.8 billion euros of which is in industrial technologies. In this field in particular, throughout the framework programme a high participation level of 18% and a good success rate of German applicants has been recorded. 22% of the funds, based on the total funding, has gone to Germany. German applicants are therefore also the leaders in the competition for European funding. The setting up of the three Public Private Partnerships (PPP) Factories of the Future (FoF), Energy-efficient Buildings (EeB) and European Green Cars (GC) from the 5th round of tendering, however, has led, particularly in the field of nanotechnologies, to a clear turning point in the level and allocation of funds. Whilst the budget for nanotechnology, new materials and production technologies (NMP), some of which however have been added on to the new PPPs in which nano aspects were below average, has on the whole significantly risen, there has clearly been less left over for the “conventional tenders” in the field of nanotechnologies. This applied more to the LARGE (large/major collaborative projects) and SME (tailored to SMEs) funding instruments relevant to the applications and short to medium-term implementation.

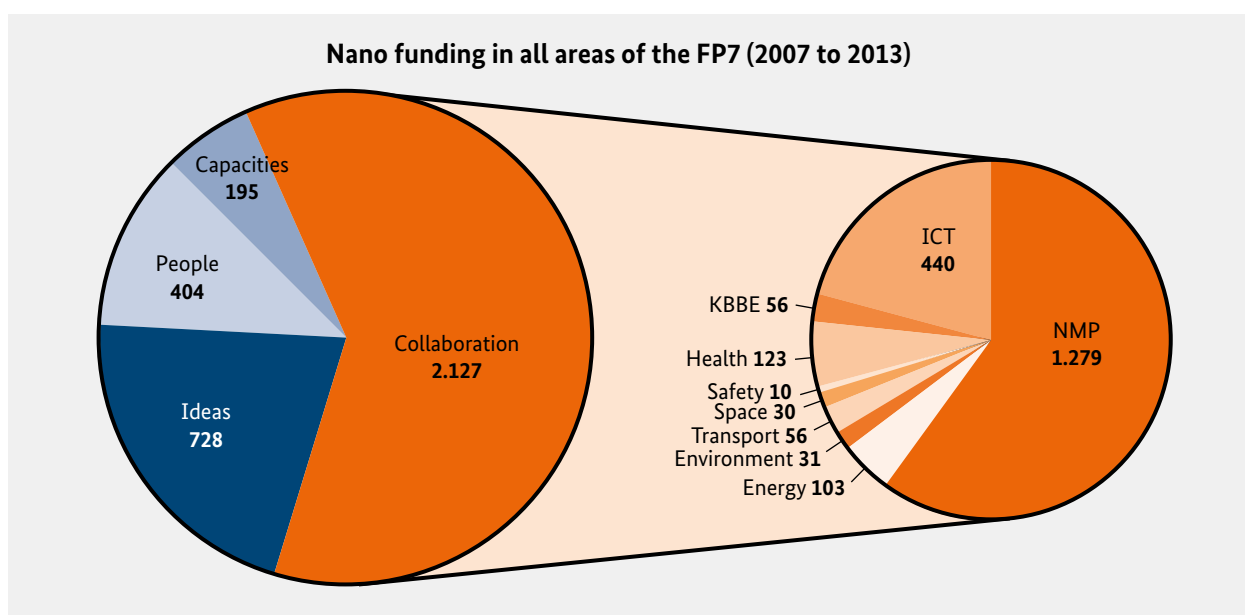
In addition, previous tenders have been shaped by the recommendations of the second implementation report on the European NanoAction Plan^[148] to remove hurdles to the market. Thus in the selection of projects credible presentation of the project’s effects on the economy and society (referred to as impact) has in the meantime come to take on almost as much significance as the scientific and technical content. Most particularly in questions of safety, toxicology and the devel-



Development of the budget for NMP and nanotechnologies. With the introduction of the PPPs from 2010, the conventional topics have not benefited to the same extent from the overall increase (Source: NKS Nanotechnology).

opment of standardisation (EHS: environment, health, safety), holistic approaches to research are increasingly in demand. All funded EHS projects have to be linked to the EU Nanosafety Cluster and closely reconciled with the relevant points in ISO/CEN; for example in the NanoReg project which, with a pragmatic and realistic risk assessment system for synthetic nanoparticles, should facilitate future coordination between legislative bodies, industry and science. Another project in the latest round of tendering will look at the development of a holistic approach to support the Commission in implementing the recommended definition of nanomaterials, but in other topics too, funded FP7 projects have also experienced considerable interchange in order to ensure as broad and smooth a transferability of results as possible.

In the coming “Horizon 2020” EU Framework Programme for Research and Innovation, the concept of innovation plays a central role and is built on three pillars: 1) scientific excellence, 2) industrial leadership and 3) societal challenges. Nanotechnology will essentially come under the second, the focus being on a leading role in basic and industrial technologies in which, together with nano- and microelectronics, advanced



Distribution of EU nanotechnology funds (figures in mill. euros). Most nano funds have gone into collaborative projects (“Collaboration”). NMP and ICT projects are the leaders in this group (Source: NKS Nanotechnology).

materials, biotechnology and production technologies, it will form the “key-enabling technologies” (KETs). Work programmes spanning several years are now feasible with multi-KET tendering.

In this context, the “Nanofutures” technology platform in 2012 presented a comprehensive roadmap for European nanotechnology for 2013 - 2025^[149] subsequently opening up public consultation through as many stakeholders as possible. This could also provide contributions for future work programmes.

Status of the international standardisation of nanotechnology

Prof. Dr. Georg Reinert, Federal Institute for Materials Research and Testing, Berlin

Background

At the end of 2005/beginning of 2006, the ISO/TC 229^[150], IEC/TC 113^[151] and CEN/TC 352^[152] committees were set up at international level to address nanotechnology topics. The German mirror committees needed for collaboration, DIN NA 062-08-17 (mirroring ISO/TC 229 and CEN/TC 352) and DKE K 141 (mirroring IEC/TC 113) were created shortly after.

Current status of international standards

The figure shows the structure and interlinking of the most important international standards organisations in the field of nanotechnology. Between the IEC and ISO there are two Joint Working Groups, which enables direct cooperation in the drafting of standards. The ISO, IEC and CEN have organised exchange of their information through liaisons. ISO/TC 229 additionally has a liaison with the OECD, the internationally acknowledged organisation for the drafting of directives and regulations in the important areas of occupational safety, environmental protection, health, toxicological effects of chemicals, etc.

ISO/TC 229 still possesses great political significance, reflected in the high number of participants (typically 150 experts), 34 voting nations and the political and financial support of the meetings in the various countries involved. ISO/TC 229 has 30 internal ISO and 9 external liaisons with other TCs or organisations for the exchange of information and harmonisation of topics. IEC/TC 113 handles standardisation topics pre-

dominantly relevant to electrical equipment and electronics. CEN/TC 352 possesses high importance for the European Union as in 2010 this committee was granted a mandate (M/461) by the European Commission to develop European standards in nanotechnology. This remit is financially supported in individual projects by the Commission.

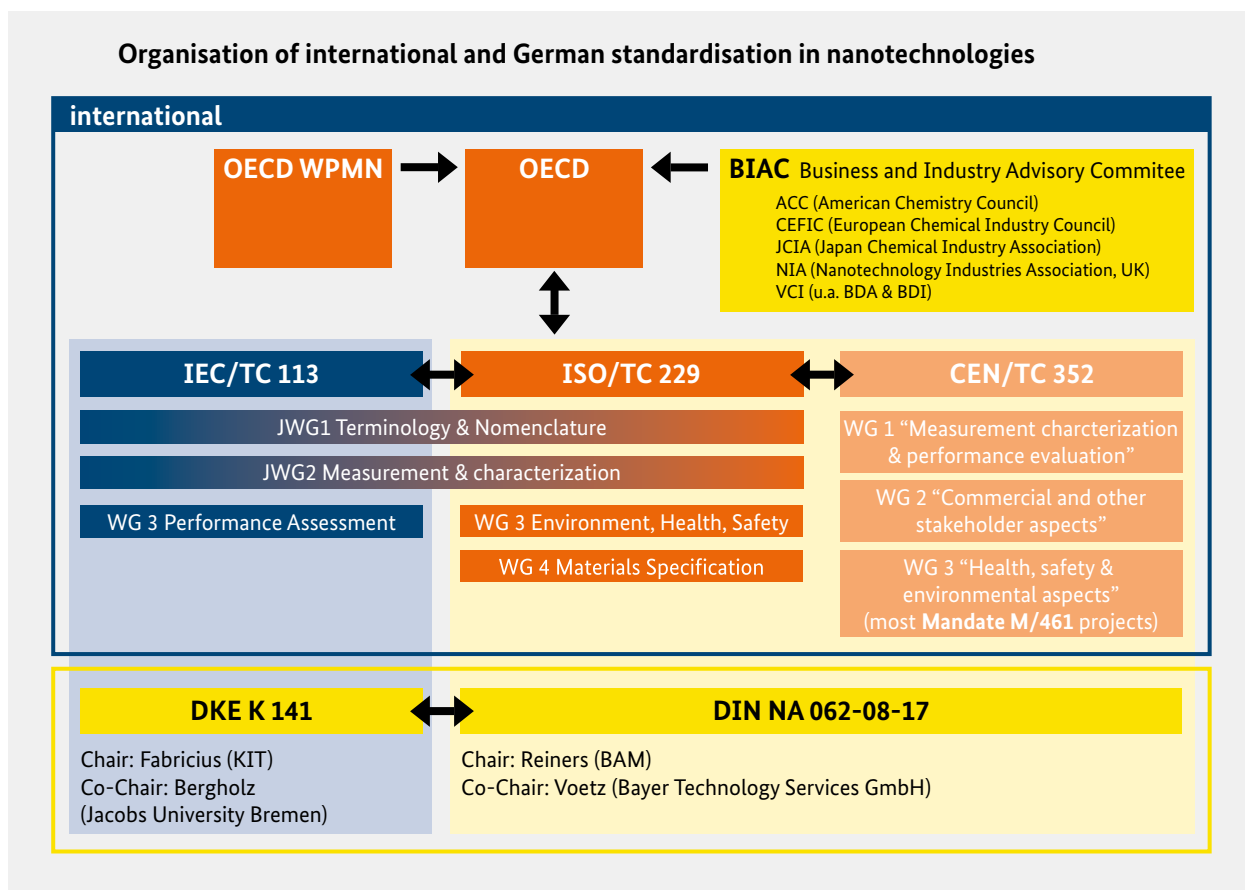
Document ISO/TC 229

As of August 2013, 35 documents have been published. With respect to terminology, the “ISO/IEC 80004 Nanotechnologies—Vocabulary Series” was issued jointly with the IEC and currently comprises 12 parts of which six are already published and the others are at different stages of preparation.

An important outcome of the work of the ISO/TC 229 is the establishment of the “nanoscale” range in the range of 1 nm to 100 nm, the definition of the term nanomaterial and the development of the generic term “nanoobject” for the nanoparticles, nanofibres and nanoplatelets groups.

In the area of measurement methods, 12 documents – describing primarily the characterisation of nanoparticles and carbon nanotubes – have already been published.

WG3 develops documents for the environment, health and safety sectors, whilst WG4 focusses on documents describing the composition, properties and characteristics of specifically produced nanomaterials.



Organisation of international and German standardisation in nanotechnologies (Source: BAM)

IEC documents

As of August 2013, six documents of its own in addition to those mentioned above have been published jointly with the ISO published documents.

CEN documents

As of August 2013, five documents have been published. These are documents taken from the work of the ISO/TC 229 and published as CEN-ISO documents. At present, four topics from the mandate issued by the European Commission have been initiated, with other topics at the tendering stage.

Safety of nanomaterials – international activities by the OECD

Dr. Klaus Günter Steinhäuser, Federal Environment Agency, Dessau-Roßlau

For seven years, the OECD Working Party on Manufactured Nanomaterials (WPMN) has been working on international benchmarks for the safety of nanomaterials.^[153] The group's remit includes gathering and developing appropriate methods, science-based and suitable for international regulatory approaches, for the hazard, exposure and risk evaluation of nanomaterials.

Interim assessment

A core activity of recent years has been the testing of 13 significant and globally-distributed nanomaterials, with various delegations taking on the responsibility for testing. Meanwhile files on a number of nanoma-

terials are to be published. The aim of this so-called sponsorship programme is to obtain an impression of the harmful properties of the materials investigated and to examine the suitability of the OECD test process for the testing of nanomaterials.

In an interim assessment the Working Party reached the conclusion that existing approaches for the testing and assessment of chemicals are also suitable for nanomaterials but – particularly with regard to sample preparation and dosimetry – require in some cases specific adaptations and extensions. The development of entirely new test and assessment approaches will not be necessary.

Expert workshops

The adaptation of existing and – where specifically required – additional test methods is therefore a core task of the Working Party. In order to bring together the new scientific findings with the experience from the sponsorship programme, the OECD has organised so-called “Horizontal Workshops” which concentrate on core topics in the experimental testing of nanomaterials (see table). The results of the workshop on inhalation toxicity have already been published^[154]; the reports on the meetings of experts on ecotoxicology and environmental behaviour and on physical-chemical properties will follow shortly. At previous events, it was possible to identify a very real development need for the test guidelines which is now being tackled in line with the rules of the respective OECD programme.

Nanosafety worldwide

The knowledge gathered in the OECD is an important input to the UN’s SAICM (Strategic Approach to an International Chemicals Management). The International Conference on Chemicals Management ICCM 3 in Nairobi in 2012 adopted a resolution to include nanotechnology and nanomaterials as an “emerging issue” in the Global Plan of Action (GPA).^[155] Among other things, the OECD together with UNITAR is supporting a number of regional SAICM workshops introducing developing and newly industrialised countries to the subject. The resolution furthermore calls for the competent bodies to review the international GHS system for classifying and labelling chemicals in terms of whether adaptations and extensions are needed with

respect to nanomaterials. The questions around nanotechnology will be further dealt with, including with regard to the standardisation of technical directives and procedures, in four action areas as part of the GPA.

Nanomaterials and REACH

The OECD’s activities, however, not only form an essential platform for global consultations on the safety of nanotechnologies, but are also the basis for legislation activities in the EU. Special provisions on nanomaterials are already contained in some special legal norms such as the Cosmetics Regulation or Biocide Regulation, but are not however in the core chemical regulation REACH which the EU used in 2006 to reformulate its chemicals management and which has not to date specifically addressed nanomaterials. Nanomaterials are in fact substances like other chemicals and therefore in principle covered by REACH, but REACH does not yet cater for the special features that the OECD noted in regard to the testing and assessment of nanomaterials. According to this, many nanomaterials differ from coarser material not only in their technical characteristics but also with respect to their toxicological and ecotoxicological hazard profile. There remain differences of opinion on whether nanomaterials should be regarded as separate substances. The lack of clarity of the REACH requirements – and hence also the need to adapt REACH 0 is also demonstrated by the fact that in the second registration period, according to an ECHA notification of 3 June 2013, the registration dossier stated that only 4 of 2923 substances were identified as nanomaterials. Many registrants were apparently unaware of how they should handle the ECHA’s recommendations.

The German Higher Federal Authorities BAuA, Federal Environment Agency (UBA) and Federal Institute for Risk Assessment (BfR) have therefore drafted a proposal as to how nanomaterials could be implemented in REACH.^[156] In this, they have decided to view the particular properties of nanomaterials not as features describing the identity of a substance (identifier) but as characteristics of a chemical substance (characterizer), to be listed within a registration dossier and to be the subject of separate risk assessment. The problem is however that the macroscale material can not only differ significantly from the nanoscale material, but also

from different nanomaterials having the same chemical composition. This also includes variations due to surface modification which can lead to very different property profiles. This complexity cannot be dealt with by an approach that views each nanoform as a separate substance, yet it is essential to characterise each nanoform within a registration file and to then show what similarities exist between the different variants that justify where (particular) investigations into the harmful properties, and thus separate risk examinations, may be waived.

In its Second Regulatory Review on Nanomaterials in October 2012, the EU Commission announced that adaptation of the REACH annexes regarding nanomaterials is indicated from their point of view.^[157] It states its intention to make changes solely in the annexes and not in the article section of the regulation. Many member states have subscribed to this because the cost of consultation on a change in the article section of REACH would be very high. Many sensible amendments cannot however be made in this way – for example, the much-debated lowering of the tonnage limits for nanomaterials can only be achieved through changing the regulation itself. Nonetheless, much can be achieved by adaptation of the annexes using the OECD's technical results and a lot of uncertainty amongst the manufacturers, importers and users eliminated. This would also result in improved safety in the handling of synthetic nanomaterials.

Current status and results of the OECD Working Party on Nanotechnology (WPN)

Dr. Gerd Bachmann, VDI Technologiezentrum GmbH

The OECD brings together 34 member countries around the world supporting democracy and market economy. It employs comprehensive data and information drawn from a variety of topics and sectors to help governments in the promotion of prosperity and combatting poverty through economic growth and financial stability. The impact of economic and social development on the environment is also discussed. A realistic balancing of opportunities and risks is needed in order to shape sustainable and healthy future development. This is the background against which the Working Party on Manufactured Nanomaterials was created in 2006 to address safety concerns in the man-

ufacture and use of nanomaterials within a framework of international cooperation (see above).

Another working party, the Working Party on Nanotechnology (WPN), was set up by the OECD in 2007 under the umbrella of the Committee for Scientific and Technological Policy (CSTP).^[158] It operates as a policy consultation body on issues of responsible global nanotechnology development. The WPN discusses the topics of scientific and economic indicators, analysis of national policies, identification of barriers to innovation and the challenges in implementing results, the contribution of nanotechnology to overcoming global problems, international collaboration, education, public dialogue and policy forums on political issues of international significance. Current members of the WPN represent 26 nations as well as the European Commission, the International Organization for Standardization (ISO) and the Business and Industry Advisory Committee (BIAC) of the OECD.

Over the last 6 years, the WPN has published a number of reports covering subjects. These include; An Inventory of National Science, Technology and Innovation Policies for Nanotechnology (2008), Nanotechnology: An Overview Based on Indicators and Statistics (2009), The Impacts of Nanotechnology on Companies: Policy Insights from Case Studies (2010), Fostering Nanotechnology to Address Global Challenges: Water (2011), Public Engagement and Outreach in Nanotechnology (2012) and Regulatory Frameworks for Nanotechnology in Foods and Medical Products (2013). In addition to these, symposiums, workshops and round-table discussions have been held on "Nanotechnology and Access to Clean Water", "Risk Governance", "Nanotechnology for Sustainable Energy Options", "Challenges in the Innovation Environment of Nanomedicine", "Public Engagement" and "Assessing the Economic Impact of Nanotechnology". The reports and contents/outcomes of the events can be found on the WPN website.

The Working Party is currently looking at possibilities for analysing the economic impact of R&D in the nano sector, examining questions of marketing through policy support, case studies on the environment of Green Growth and on the significance of science and technology policy on the basis of responsible

development and training and education in an increasingly multidiscipline environment. Greater attention will in future also be given to the topics of “Economic Growth” together with “Nanotechnology Foresight”.

List of sources and end notes

- 1 BITCOM 2013: „Deutscher ITK-Markt wächst um 1,4 Prozent“; BITKOM press release, 4. 3. 2013
- 2 Wirtschaftsförderung Sachsen GmbH 2012: „Mikroelektronik/ IKT in Sachsen“ (http://www.invest-in-saxony.net/set/157/mikro_dt_WEB.pdf)
- 3 VCI 2013: „VCI fordert mehr Tempo in der Forschungspolitik, Forschungsetat der Chemieindustrie steigt auf Rekordniveau“, VCI press release, 14.08.2013
- 4 Donaldson, K. and Poland, C. A.: „Nanotoxicity: challenging the myth of nano-specific toxicity“, *Curr Opin Biotechnol* 2013, 24(4):724-34
- 5 BCC 2012: „Nanotechnology: A Realistic Market Assessment“, Markt report abstract (<http://www.bccresearch.com/report/NAN031E>)
- 6 BCC 2012: „Global Markets and Technologies for Carbon Nanotubes“, Markt report abstract (<http://www.bccresearch.com/report/NAN024E.html>)
- 7 Electronics.ca Research Network 2012: „Global Revenues from Carbon Nanotube Production to reach \$527 Million in 2016“, press release, 23. Juli 2012 (<http://www.electronics.ca/presscenter/articles/1860/1/Global-Revenues-From-Carbon-Nanotube-Production-to-Reach-527-Million-in-2016/Page1.html>)
- 8 VDI TZ 2013: Unternehmensbefragung nano. DE-Report 2013, June 2013
- 9 BCC 2012: „Global Markets for Nanocomposites, Nanoparticles, Nanoclays, and Nanotubes“ Markt report abstract (<http://www.bccresearch.com/market-research/nanotechnology/nanocomposites-global-markets-nan021e.html>)
- 10 BCC 2011: „Advanced Ceramics and Nanoceramic Powders“, Markt report abstract (<http://www.bccresearch.com/market-research/nanotechnology/advanced-ceramics-nanoceramic-powders-nan015f.html>)
- 11 Transparency Market Research 2012: „Global Magnesium Oxide Nanopowder Market is Expected to Reach USD 31.2 Million in 2018“, press release, 17.12.2012 (<http://www.prnewswire.com/news-releases/global-magnesium-oxide-nanopowder-market-is-expected-to-reach-usd-312-million-in-2018-transparency-market-research-183747771.html>)
- 12 MarketsandMarkets 2012: „Global Aerogel Market worth \$1,379.6 Million by 2017“, press release, 2.7.2012 (<http://www.ad-hoc-news.de/marketsandmarkets-global-aerogel-market-worth-1-379-6-de/News/23755599>)
- 13 Future Markets 2011: „The global market for nanofibers (Alumina, Polymer, Carbon and Cellulose) to 2017“, Marktreport abstract (http://www.researchandmarkets.com/reports/2303361/global_market_for_nanofibers_alumina_polymer)
- 14 Electronics.ca 2012: „NanoMarkets Report Projects Rapid Growth in Metallic Nanomaterials Over the Next Eight Years“, press release, 19.1.2012
- 15 Electronics.ca 2012: „Global Quantum Dots (QD) Market worth of \$7480.25 Million by 2022“, press release, 21.5.2012 (<http://www.electronics.ca/presscenter/articles/1807/1/Global-Quantum-Dots-QD-Market-worth-of-748025-Million-by-2022/Page1.html>)
- 16 Electronics.ca 2012: „Global Electroactive Polymers Market Trends, Applications and Forecasts“, Marktreport abstract (<http://www.electronics.ca/presscenter/articles/1811/1/Global-Electro-Active-Polymers-Product-Market-is-Expected-to-be-Worth-34-billion-by-2017/Page1.html>)

- 17 BCC 2013: „BCC Research Projects the Global Nanomagnetic Materials and Devices Market to Reach \$9 Billion by 2017“, press release, 21.5.2013 (<http://www.prweb.com/releases/2013/5/prweb10757241.htm>)
- 18 BCC 2012: „Global Markets, Technologies and Materials for Thin and Ultrathin Films“, Marktreport abstract (<http://www.bccresearch.com/report/ultrathin-films-markets-technologies-smc057b.html>)
- 19 BCC 2012: „High-Performance Ceramic Coatings: Markets and Technologies“, Marktreport abstract (<http://www.bccresearch.com/report/AVM015F.html>)
- 20 Future Markets 2011: „World market for Nanocoatings to grow by 2017“, press release European Coatings, 30.12.2011 (<http://www.european-coatings.com/Markets-companies/Coatings-market/World-market-for-Nanocoatings-to-grow-by-2017>)
- 21 BCC 2011: „Microscopy: The Global Market“ Marktreport abstract (<http://www.bccresearch.com/market-research/instrumentation-and-sensors/microscopes-global-market-ias017d.html>) (<http://www.giiresearch.com/report/bc208746-microscopy-global-market.html>)
- 22 BCC 2012: „Physical Vapor Deposition (PVD): Global Markets“, Marktreport abstract (<http://www.bccresearch.com/market-research/manufacturing/physical-vapor-deposition-pvd-global-markets-mfg015e.html>)
- 23 BCC 2012: „Nanotechnology in Medical Applications: The Global Market“, Marktreport abstract (<http://www.bccresearch.com/report/HLC069B>)
- 24 BCC 2011: „Global Biochip Markets: Microarrays and Lab-on-a-Chip“, Marktreport abstract (<http://www.bccresearch.com/market-research/biotechnology/biochip-markets-microarrays-bio049e.html>)
- 25 BCC 2012: „Nanoparticles in Biotechnology, Drug Development and Drug Delivery“, Marktreport abstract (<http://www.bccresearch.com/market-research/biotechnology/nanoparticles-biotechnology-drug-development-delivery-bio113a.html>)
- 26 ZVEI-Fachverband „Electronic Components and Systems; Mikroelektronik-Trendanalyse bis 2017“, April 2013
- 27 Electronics.ca 2012: „Global Compound Semiconductor Component Sales To Reach \$47.4 Billion In 2017“, press release, 12.9.2012 (<http://www.electronics.ca/presscenter/articles/1924/1/Global-Compound-Semiconductor-Component-Sales-To-Reach-474-Billion-In-2017-/Page1.html>)
- 28 TechNavio 2011: „Global NAND Flash Device Market 2010-2014“, Marktreport abstract (<http://www.reportlinker.com/p0490623-summary/Global-NAND-Flash-Device-Market.html>)
- 29 BCC 2013: „BCC Research Projects the Flexible Devices Manufactured by Roll-to-Roll Technologies to Reach Nearly \$22.7 Billion by 2017“, Marktreport abstract (<http://bccresearch.wordpress.com/2013/05/23/roll-to-roll-technologies>)
- 30 BCC 2013: „Global Markets for Roll to Roll Technologies for Flexible Devices“, Marktreport abstract (<http://www.electronics.ca/store/global-markets-for-roll-to-roll-technologies-for-flexible-devices-gb-smc082a.html>)
- 31 Electronics.ca 2013: „Touch Panel Transparent Conductive Film Market Shares, Strategy, and Forecasts, Worldwide, Nanotechnology, 2013 to 2019“, Marktreport abstract (<http://www.electronics.ca/store/touch-panel-transparent-conductive-film-market.html>)
- 32 IDTechEx 2012: „Conductive Ink Markets 2012-2018: Forecasts, Technologies, Players“, Marktreport abstract (<http://www.giiresearch.com/report/ix235628-conductive-inks-markets-2012-2018.html>)

- 33 SPECTARIS, VDMA, ZVEI, Bundesministerium für Bildung und Forschung (BMBF); Photonik Branchenreport 2013; Mai 2013
- 34 BCC 2012: „Nanotechnology for Photonics: Global Markets“, Marktreport abstract (<http://www.bccresearch.com/market-research/photonics/photonics-nanotechnology-markets-pho003a.html>)
- 35 NanoMarkets 2012: „NanoMarkets New Report on OLED Lighting Materials Market, Sees \$1.3 billion (USD) Markets by 2018“, press release, 15.10.2012 (http://nanomarkets.net/news/article/nanomarkets_issues_new_report_on_oled_lighting_materials_market_sees_1.3_bi)
- 36 BCC 2013: „Nanotechnology in Energy Applications“, Marktreport abstract (<http://www.giiresearch.com/report/bc51640-nanotech.html>)
- 37 Future Markets 2011: „Nanotechnology and Nanomaterials for the World Energy Market-Applications, Products, End User Markets, Companies and Revenues“, Marktreport abstract (www.futuremarketsinc.com/index.php?option=com_content&view=article&id=43:the-world-market-for-nanoenergy&catid=1&Itemid=49)
- 38 Future Markets 2011: „Nanotechnology and Photovoltaics: Market, Companies and Products“, Marktreport abstract (http://www.futuremarketsinc.com/index.php?option=com_content&view=article&id=46:the-world-market-for-corroion&catid=1&Itemid=53)
- 39 NanoMarkets 2012: „NanoMarkets Issues New Report on ESD and Antistatic Materials and Products in the Electronics Sector“, Marktreport abstract (http://nanomarkets.net/news/article/nanomarkets_issues_new_report_on_esd_and_antistatic_materials_and_products)
- 40 Winter Green Research 2012: „Solid State Thin Film Battery: Market Shares, Strategies, and Forecasts, Worldwide, Nanotechnology, 2013 to 2019“, Marktreport abstract (http://wintergreenresearch.com/reports/thin_film_battery.html)
- 41 Future Markets 2011: „Nanomaterials and the World Lithium Ion Battery Market: Applications, Products, End User Markets, Companies and Revenues“, Marktreport abstract (http://www.futuremarketsinc.com/index.php?option=com_content&view=article&id=45:the-world-market-for-corroion&catid=1&Itemid=52)
- 42 BCC 2012: „Superconductors: Technologies and Global Markets“, Marktreport abstract (<http://www.bccresearch.com/market-research/advanced-materials/superconductors-technologies-applications-markets-avm066c.html>)
- 43 Global Industry Analysts 2011: „Global Membrane Separation Technologies Market to Reach US\$16 Billion by 2017, According to a New Report by Global Industry Analysts, Inc.“, press release, 14.11.2011 (http://www.prweb.com/releases/membrane_separation/technologies/prweb8953901.htm)
- 44 C&M Research 2012: „Chipless RFID market to grow at a CAGR of 29.3%“, press release, 30.7.2012 (<http://www.companiesandmarkets.com/News/Information-Technology/Chipless-RFID-market-to-grow-at-a-CAGR-of-29-3/NI4732>)
- 45 Future Markets 2011: „Nanocoatings for the Construction and Exterior Protection Industry“, Marktreport abstract (http://www.researchandmarkets.com/reports/1199857/nanocoatings_for_the_construction_and_exterior)
- 46 BCC 2012: „Global Markets and Technologies for Smart Glass“, Marktreport abstract (<http://www.bccresearch.com/market-research/advanced-materials/smart-glass-technology-global-markets-avm065b.html>)
- 47 Future Markets 2011: „Nanocoatings for the Automotive Industry“, Marktreport abstract (http://www.futuremarketsinc.com/index.php?option=com_content&view=article&id=14:nano-coatings-for-the-automotive-industry&catid=1&Itemid=16)

- 48 BCC 2013: „BCC Research Projects the Global Nanomagnetic Materials and Devices Market to Reach \$9 Billion by 2017“, press release, 21.5.2013 (<http://www.prweb.com/releases/2013/5/prweb10757241.htm>)
- 49 SPECTARIS, Fachverband Medizintechnik: Zahlen und Fakten (<http://www.spectaris.de/medizintechnik/zahlen-fakten.html>)
- 50 Bundesverband der Pharmazeutischen Industrie (Federal Association of the Pharmaceuticals Industry) e. V. (BPI): „Pharma-Daten 2012“, 42. revised edition, December 2012
- 51 Eckensberger, D.: „Kleine Partikel – große Hoffnung“, Nachrichten aus der Chemie| 60 | July/August 2012
- 52 Duncan, R., Gaspar, R.: „Nanomedicine(s) under the Microscope“, Mol. Pharmaceutics, 2011, 8 (6), 2101–2141
- 53 Etheridge, M. L., Campbell, S.A., Haynes, C.L., Wolf, S.M., McCullough, J.: „The big picture on nanomedicine: the state of investigational and approved nanomedicine products“, Nanomedicine: Nanotechnology, Biology and Medicine, Volume 9, Issue 1, 1–14, January 2013
- 54 Accenture GmbH 2010: „Überalternde Sortimente setzen Pharma-Unternehmen unter Druck“, press release, August 3, 2010 (<http://www.accenture.com/de-de/company/newsroom-germany/Pages/pharma-unternehmen-medikamente-patenschutz.aspx>)
- 55 Thomsen Reuters: „MagForce vereinbart präklinische Forschungskooperation zur Untersuchung der NanoTherm® Therapie bei Magen- und Darmkrebskrankungen in den USA“, press release, 22.6.2012 (<http://hugin.info/143761/R/1621461/518165.pdf>)
- 56 Deutsches Ärzteblatt: „Nano-Medikament verlängert Leben bei Pankreaskarzinom“, Press release, 23.1.2013 (www.aerzteblatt.de)
- 57 Michael L. Etheridge et al., „The big picture on nanomedicine: the state of investigational and approved nanomedicines products“, Nanomedicine 9 (2013) 1–14
- 58 White Paper to the Horizon 2020 Framework Programme for Research and Innovation – Recommendations from the Nanomedicine Community, May 2013
- 59 Chemiewirtschaft in Zahlen, Verband der chemischen Industrie, Stand Juli 2012 (www.vci.de)
- 60 „Die Zukunft gewinnen mit einer starken Chemie“, VCI press release, 11.7.2013 (www.vci.de)
- 61 „Forschung trotz der Krise: Branche gibt 6,5 Prozent mehr aus“, VCI Press release, 11.9.2012 (www.vci.de)
- 62 BCC 2012: „Nanotechnology: A Realistic Market Assessment“, Marktreport BCC, September 2012 (<http://www.bccresearch.com/market-research/nanotechnology/nanotechnology-market-applications-products-nan031e.html>)
- 63 Further details at www.one-p.eu
- 64 Further details at www.nanosafetycluster.eu
- 65 BMU 2012: „1. Bilanz zur gemeinsamen Forschungsstrategie der Ressortforschungseinrichtungen des Bundes „Nanotechnologie – Gesundheits- und Umweltrisiken von Nanomaterialien“ (2007 – 2011) (http://www.nano.bam.de/de/nano_medien/ntfo_stra.pdf)
- 66 European Commission: „Second Regulatory Review on Nanomaterials“ COM(2012) 572 final, 3.10.2012
- 67 Source: Statistisches Bundesamt 2012
- 68 Wirtschaftsvereinigung Stahl: Stahl in Zahlen (www.stahl-online.de)
- 69 Wirtschaftsvereinigung Metalle Quartalsbericht, Ausgabe 11, May 2013 (www.wvmetalle.de)

- 70 IG Bergbau, Chemie, Energie: „Innovationsprozesse in der keramischen Industrie – Möglichkeiten und Grenzen der Mitarbeiterbeteiligung“, December 2012
- 71 BCC 2011: „High-Performance Ceramic Coatings: Markets and Technologies“ Marktreport Juni 2011 (www.bccresearch.com/report/AVM015F.html)
- 72 BCC 2011: „Advanced Ceramics and Nanoceramic Powders“, Marktreport Juni 2011 (<http://www.bccresearch.com/market-research/nanotechnology/advanced-ceramics-nanoceramic-powders-nan015f.html>)
- 73 Electronics.ca 2012: „NanoMarkets Report Projects Rapid Growth in Metallic Nanomaterials Over the Next Eight Years“, Press release, 19.1.2012 (www.electronics.ca)
- 74 „„Deutscher Studienpreis für Materialforscherin: Metallschaum für Leichtbau und Aufprallschutz“, Saarland University, press release (<https://idw-online.de/de/news545979>)
- 75 M. J. Duarte, J. Klemm, S. Klemm, S. Borodin, K. Mayrhofer, M. Stratmann, A. Romero, M. Madinehei, D. Crespo, J. Serrano, S. Gerstl, P. Choi, D. Raabe und F. U. Renner: „Element-Resolved Corrosion Analysis of Stainless-Type Glass-Forming Steels“, Science, 26. July 2013; doi: 10.1126/science.1230081
- 76 <http://www.iapetus.eu>
- 77 ZZVEI-Fachverband Electronic Components and Systems; Mikroelektronik-Trendanalyse bis 2017; April 2013
- 78 BITKOM, EITO; ITK-Marktzahlen; March 2013
- 79 BCC 2013: „Global Markets for Roll-to-Roll Technologies for Flexible Devices“, Marktstudie abstract, BCC Research, April 2013
- 80 Wintergreen 2013: „Touch Panel Transparent Conductive Film Market Shares, Strategy, and Forecasts Worldwide, Nanotechnology, 2013 to 2019“, Markt report abstract (<http://www.electronics.ca/store/touch-panel-transparent-conductive-film-market.html>)
- 81 Cf. EU FP7 projects „MAGIC“ or „SNM“
- 82 Cf. EU FP7 projects „TECHNOTUBE“, „CONCEPT GRAPHENE“ or „GRAND“ (www.grand-project.eu)
- 83 Cf. EU FP7 projects „SIQS“, or „AQUTE“
- 84 Further details at www.ifox-project.eu
- 85 Further details at www.one-p.eu oder www.smartronics.eu
- 86 DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast)
- 87 Photonics 21; The Leverage Effect of Photonics Technologies: The European Perspective; Final Report March 2011
- 88 Optech Consulting; Photonik 2013; Study, 2013
- 89 SPECTARIS 2013: „Daten und Fakten zur deutschen Industrie für optische, medizinische und mechatronische Technologien“, May 2013 (www.spectaris.de)
- 90 SPECTARIS, VDMA, ZVEI, Bundesministerium für Bildung und Forschung (BMBF): „Photonik Branchenreport 2013“, May 2013
- 91 BCC 2012: „Nanotechnology for Photonics: Global Markets; Marktstudie abstract, BCC Research, Feb. 2012
- 92 Further details at www.fast-dot.eu
- 93 Further details at www.parylens.eu

- 94 Cf. EU FP7 project „SMASH“ or EU FP7 project „NWS4LIGHT“
- 95 Further details at www.light-rolls.eu
- 96 Further details at www.magnonics.org; EU-FP7-Projekt „NIM_NIL“
- 97 Cf. EU FP7 project „SURPASS“
- 98 Information for example at www.fp7-firefly.eu; www.delightproject.eu; EU FP7 project “ULTRA-MAGNETRON”
- 99 SPECTARIS-Spotlight; Die deutsche Photonik-Industrie 2012 (www.spectaris.de)
- 100 Weltenergierat Deutschland e. V.: „Energie für Deutschland 2013 – Fakten, Perspektiven und Positionen im globalen Kontext“; May 2013
- 101 BDEW Bundesverband der Energie- und Wasserwirtschaft e. V.: „Erneuerbare Energien und das EEG: Zahlen, Fakten, Grafiken (2013)“; January 2013
- 102 Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: „Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2012“; February 2013
- 103 Further details at www.ngcpv.org
- 104 Further details at www.fast-track.eu
- 105 Further details at www.silicon-light.eu
- 106 Further details at www.scalenano.eu
- 107 Further details at www.r2r-cigs.com
- 108 Further details at www.nanoheX.org
- 109 Further information for example www.suprabio.eu
- 110 Further information for example www.eurotapes.eu
- 111 S. Wilkinson: „PV Storage Market Set to Explode to \$19 Billion in 2017; Germany leads Again“; IMR-Research, press release, 25. 04. 2013
- 112 Statistisches Bundesamt 2012: „Umwelt – Umsatz mit Waren, Bau und Dienstleistungen für den Umweltschutz“, Fachserie 19 Reihe 3.3, July 2012
- 113 „BMU: Bruttobeschäftigung durch erneuerbare Energien in Deutschland im Jahr 2011 – eine erste Abschätzung“, Stand 14. März 2012
- 114 BCC 2009: „Nanotechnology in Environmental Applications: The Global Market“; Marktreport abstract, BCC Research Inc. (www.bccresearch.com)
- 115 PRWEB, press release, 14.11.2011: „Global Membrane Separation Technologies Market to Reach US\$16 Billion by 2017, According to a New Report by Global Industry Analysts, Inc.“ (http://www.prweb.com/releases/membrane_separation/technologies/prweb8953901.htm)
- 116 BCC 2010: „Catalysts for Environmental and Energy Applications“, Marktreport abstract, BCC Research Inc. (www.bccresearch.com)
- 117 European Coatings, press release, 30.12.2011 „World market for Nanocoatings to grow by 2017“ (<http://www.european-coatings.com/Markets-companies/Coatings-market/World-market-for-Nanocoatings-to-grow-by-2017>)
- 118 <http://www.lblbrane.eu/>
- 119 AMA Fachverband für Sensorik und Messtechnik: „Branche bleibt stabil und optimistisch“, press release (www.ama-sensorik.de)
- 120 BCC 2012: „MEMS Biosensors and Nanosensors“, Marktreport abstract (www.reportlinker.com/p0461665/MEMS-Biosensors-and-Nanosensors.html)

- 121 PRWEB 2013: „BCC Research Projects the Global Nanomagnetic Materials and Devices Market to Reach \$9 Billion by 2017“, press release, 21. May 2013 (www.prweb.com/releases/2013/5/prweb10757241.htm)
- 122 VDA-Verband der Automobilindustrie; Jahreszahlen; 11.04.2013 (<http://www.vda.de/de/zahlen/jahreszahlen/allgemeines/index.html>)
- 123 FutureMarkets 2011: „Nanocoatings for the Automotive Industry“; FutureMarkets; Marktstudie abstract 2011
- 124 Cf. EU FP7 project „MUST“
- 125 Cf. EU FP7 project „ATHENIS“ (www.athenis-fp7.eu)
- 126 Cf. EU FP7 project „SMART-EC“ (www.smart-ec.eu)
- 127 Cf. EU FP7 project „NEXT-GEN-CAT“
- 128 Cf. EU FP7 project „MATRANS“
- 129 Cf. EU FP7 project „POWERSWIPE“ (www.powerswipe.eu)
- 130 Cf. EU FP7 project „ECOPLAST“ (www.ecoplastproject.com)
- 131 Cf. EU FP7 project „2020INTERFACE“ (www.2020interface.eu)
- 132 Cf. EU FP7 project „LORRY“ (www.lorryproject.eu)
- 133 VDMA 2013: „Weltmaschinenumsatz 2012 erreicht neues Rekordniveau“; VDMA-Meldung, 03.04.2013 (<http://www.vdma.org/article/-/articleview/1334599>)
- 134 M. Schäfer; VDMA: „Neue Technologien und Innovationen führen zu weiterem Wachstum im deutschen Maschinenbau“; VDMA press release, 08.04.2013
- 135 www.steelconstruct.com/old/steelprost/project.html
- 136 Further details at www2.le.ac.uk/projects/mint-weld
- 137 Cf. EU FP7 project „ADDNANO“
- 138 Cf. EU FP7 projects „MINILUBES“ and „MICROPADS“
- 139 Further details at www.aim4np.eu
- 140 Maschinenhaus-Campus für Ingenieure; VDMA-Initiative für Studienerfolg
- 141 VDMA 2013: „Status Quo des Know-how-Schutzes“; VDMA-Studie 2013
- 142 Völcker, T.: „Nanotechnologie im Einsatz für Echtheitsprüfung und Fälschungsschutz von Produkt und Verpackung“, Präsentation auf dem BMBF Branchendialog „Nanopackaging – Nanotechnologie und Neue Materialien für die Verpackungsindustrie“ am 16. Mai 2011 in Düsseldorf
- 143 Zentralverband Deutsches Baugewerbe 2013: „Analyse und Prognose 2013“ Bauwirtschaftlicher Bericht 2012/2013, January 2013
- 144 Future Markets 2011: „Nanocoatings for the Construction and Exterior Protection Industry“ Marktreport abstract (www.futuremarketsinc.com)
- 145 Paschen H, Coenen C, Fleischer T, Grünwald R, Oertel D, Revermann C (2003) „Nanotechnologie“, TAB-Bericht Nr. 92, Büro für Technikfolgenabschätzung beim Deutschen Bundestag, Berlin
- 146 Royal Society (2004) „Nanoscience and nanotechnologies: opportunities and uncertainties“. Royal Academy of Engineering, London
- 147 Kuhlbusch TA, Krug HF, Nau K (2009) „NanoCare: health related aspects of nanomaterials“. Final Scientific Report, Kuhlbusch TA, Krug HF, Nau K, (eds.), DECHEMA e. V., Frankfurt, Karlsruhe, St. Gallen

- 148 Communication from the Commission to the Council, the European Parliament and the European Economic and Social Committee – Nanosciences and Nanotechnologies: an Action Plan for Europe 2005-2009. Second Implementation Report 2007-2009 COM/2009/0607 final
- 149 Integrated Research and Industrial Roadmap for European Nanotechnology, (version July 2012). NANO futures Platform (www.nanofutures.eu)
- 150 http://www.iso.org/iso/iso_technical_committee?commid=381983
- 151 http://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1315,25
- 152 <http://www.cen.eu/cen/Sectors/Sectors/Nanotechnologies/Pages/default.aspx>
- 153 <http://www.oecd.org/science/nanosafety>
- 154 [http://www.oecd.org/officialdocuments/displaydocument/?cote=env/jm/mono\(2012\)14&doclanguage=en](http://www.oecd.org/officialdocuments/displaydocument/?cote=env/jm/mono(2012)14&doclanguage=en)
- 155 http://www.saicm.org/index.php?option=com_content&view=article&id=235:addition-of-new-activities-to-the-global-plan-of-action-on-nanotechnologies-and-manufactured-nanomaterials&catid=215:comments-received&Itemid=473
- 156 <http://www.umweltbundesamt.de/publikationen/nanomaterialien-reach>
- 157 [http://ec.europa.eu/nanotechnology/pdf/second_regulatory_review_on_nanomaterials_-_com\(2012\)_572.pdf](http://ec.europa.eu/nanotechnology/pdf/second_regulatory_review_on_nanomaterials_-_com(2012)_572.pdf)
- 158 www.oecd.org/sti/nano
- 159 European Commission 2011: „Commission Recommendation of 18 October 2011 on the definition of nanomaterial“, 2011/696/EU
- 160 The funding figures were compiled by VDI TZ based on direct survey by funding and research institutions in the period up to and including 2013.

List of abbreviations

AFM	Atomic force microscopy	IC	Integrated circuit
BMBF	Federal Ministry of Education and Research	IEC	International Electrotechnical Commission
CAGR	Compound annual growth rate	ICT	Information and communications technology
CEN	European Committee for Standardisation	InAs	Indium arsenide
CIGS	Copper indium gallium diselenide	InGaN	Indium gallium nitride
CIS	Copper indium diselenide	IR	Infrared
CMOS	Complementary metal oxide semiconductor	ISO	International Standardisation Organisation
CNT	Carbon nanotubes	IT	Information technology
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)	ITO	Indium tin oxide
DIN	Deutsches Institut für Normung (German Institute for Standardisation)	JRC	Joint Research Centre
DLNA	Double ligand nanoparticle matrix	KBBE	Knowledge-based bio-economy
DLS	Dynamische Lichtstreuung	KET	Key-enabling technologies
DMS	Strain gauge	KfW	Kreditanstalt für Wiederaufbau (Reconstruction Loan Corporation)
DNA	Deoxyribonucleic acid	LEIS	Low-energy ion scattering
EEG	Renewable Energy Sources Act	MAK	Maximum workplace concentration
EMV	Electromagnetic compatibility	MALS	Multi-angle light scattering
EU	European Union	MEMS/NEMS	Micro-/nanoelectromechanical system
EUV	Extreme ultraviolet	MRT	Magnetic resonance tomography
FEL	Free electron laser	MST	Microsystems technology
FP7	7 th European Research Framework Programme	MWCNT	Multi-walled carbon nanotube
GaN	Gallium nitride	NDIR	Nondispersive infrared sensor
GaP	Gallium phosphide	NGO	Non-governmental organisation
GaSb	Gallium antimonide	NCP	National Contact Point
GDP	Gross domestic product	NM	Nanomaterial
GHS	Globally Harmonised System for the Classification of Hazardous Chemicals	NMR	Nuclear magnetic resonance
GMP	Good Manufacturing Practice	NMP	Nanotechnology, new materials and production technologies
GMR	Giant magnetoresistance effect	ODS	Oxide dispersion-strengthened
GSDIM	Ground state depletion imaging microscopy	OECD	Organisation for Economic Cooperation and Development
		OLED	Organic light-emitting diode

OPV	Organic photovoltaics	VIS	Visible light
PCR	Polymerase chain reaction	WG	Working party
PCM	Phase change material	WING	Werkstoffinnovation für Industrie und Gesellschaft (Materials Innovations for Industry and Society)
PECVD	Plasma-enhanced chemical vapour deposition		
PEG	Polyethylene glycol	ZnO	Zinc oxide
PEM	Polymer electrolyte membrane	ZnS	Zinc sulfide
PET	Positron emission tomography		
ppb	parts per billion		
PPP	Public Private Partnerships		
PTA	Particle analyse		
PV	Photovoltaics		
PVD	Physical vapour deposition		
QD	Quantum dot		
R&D	Research & Development		
RAM	Random access memory		
RFID	Radiofrequency identification		
RNA	Ribonucleic acid		
SEM	Scanning electron microscopy		
SERS	Surface-enhanced Raman scattering		
Si-GaAs	Silicon gallium arsenide		
siRNA	Small interfering ribonucleic acid		
SME	Small and medium-sized enterprise		
STED	Stimulated emission depletion		
SWCNT	Single-walled carbon nanotube		
TEM	Transmission electron microscopy		
THz	Terahertz		
TMR	Tunnel magnetoresistance		
TOF-SIMS	Time-of-flight secondary ion mass spectroscopy		
TWh	Terawatt-hour		
UHPC	Ultra-high performance concrete		
UV	Ultraviolet		
VC	Venture capital		
VCI	German Chemical Industry Association		
VCSEL	Vertical cavity surface-emitting laser		

Imprint

Publisher

Federal Ministry of Education and Research (BMBF)
Department New Materials, Nanotechnology, KIT
53175 Bonn

Orders

In writing to
Publikationsversand der Bundesregierung
P.O. Box 48 10 09
18132 Rostock
E-mail: publikationen@bundesregierung.de
Internet: <http://www.bmbf.de>
or by
Phone: 030 18 272 272 1
Fax: 030 18 10 272 272 1

October 2014

Printed by

Bonifatius GmbH, Paderborn

Layout

ecosense – media & communication, Cologne

Photo credits

Titelbild: © Alessandro Cumbo, Artwork: Martin Oeggerli/
www.micronaut.ch

Edited by

VDI Technologiezentrum GmbH,
Dr. Wolfgang Luther, Dr. Leif Brand

This publication is distributed free-of-charge as part of the public relations work of the Federal Ministry of Education and Research. The publication is not intended for commercial distribution. It may not be used by political parties, or by campaigners or electoral assistants during any election for the purpose of campaigning. This applies to federal, state and local elections as well as elections to the European Parliament. Misuse constitutes, in particular, distribution at election rallies and information stands of political parties, as well as inserting, imprinting or affixing of party-political information or advertising. Transmission to third parties for the purposes of campaigning is also prohibited. Regardless of when, by which means, and in which quantity this publication reaches the recipient, it must not be used - even without reference to an upcoming election - in a way which could be construed as favouring of individual political groups by the Federal Government.



Federal Ministry
of Education
and Research