



Europäische Akademie

zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen
Bad Neuenahr-Ahrweiler GmbH

Direktor:
Professor Dr. Carl Friedrich Gethmann

Small Dimensions and Material Properties

A Definition of Nanotechnology

by

**G. Schmid, M. Decker, H. Ernst, H. Fuchs,
W. Grünwald, A. Grunwald, H. Hofmann,
M. Mayor, W. Rathgeber, U. Simon, D. Wyrwa**

November 2003



Europäische Akademie

zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen
Bad Neuenahr-Ahrweiler GmbH

Direktor:
Professor Dr. Carl Friedrich Gethmann

Small Dimensions and Material Properties

A Definition of Nanotechnology

by

**G. Schmid, M. Decker, H. Ernst, H. Fuchs,
W. Grünwald, A. Grunwald, H. Hofmann,
M. Mayor, W. Rathgeber, U. Simon, D. Wyrwa**

November 2003

This booklet is the final report of the Europäische Akademie's study group "Miniaturization and Material Properties".

Publisher:



Europäische Akademie

zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen
Bad Neuenahr-Ahrweiler GmbH

Wilhelmstraße 56, D-53474 Bad Neuenahr-Ahrweiler

Telefon: ++49 - (0)2641 - 973 - 300, Telefax - 320

e-mail: europaeische.akademie@dlr.de

Director:

Professor Dr. Carl Friedrich Gethmann (V.i.S.d.P.)

ISSN 1435-487 X

Editing:

Dipl.-Päd. Sevim Kiliç

Dipl.-Ing. Wolfgang Rathgeber

Print:

Warlich Druck Ahrweiler GmbH, Bad Neuenahr-Ahrweiler

Foreword

Technology Assessment (TA) is usually mentioned as problem oriented research which aims at contributing to the solution of a political, social, ecological problem. Since in most cases the development of such solutions needs input from different scientific disciplines, TA becomes to be an interdisciplinary endeavor in which the same social, political, ecological problem is tackled from different scientific perspectives. The main tasks for TA are then identifying the different relevant scientific disciplines, combining their perspectives to a comprehensive interdisciplinary whole and developing concrete recommendations on how to act from this basis. Usually such interdisciplinary projects start with an introductory phase in which the central notions of the TA-project have to be defined in order to ensure that the different scientific disciplines use these core-notions in the same sense.

In the case of a TA of Nanotechnology, this procedure starts even one step earlier. On the one hand side, Nanotechnology is mentioned as key technology of the next century with revolutionary impact on our daily life. On the other hand, there is no common understanding not to mention a general definition of what Nanotechnology is about. Looking at the different research activities and technology developments labeled as to be Nanotechnology, one might remain with the impression that the length scale “nanometer” is the only common feature.

It is the aim of this volume to propose a definition of Nanotechnology which can be used as a starting point for TA. With the help of this definition it should be possible to decide in concrete cases if a research activity or a certain technique is to be allocated to Nanotechnology or not. Or to put it in the context of TA: It should be possible to decide if a certain technique has to be taken into account in a TA-project of Nanotechnology or not.

We reached this aim by scrutinizing existing definitions of Nanotechnology and by transforming the comparatively diffuse aspects mentioned there into three concrete criteria on which the distinction “Is it Nanotechnology or not” can be based. In order to demonstrate the feasibility of our definition, scientific effects usually pulled together under the heading “Nanotechnology” have been compiled and categorized according to the definition.

We would like to thank the director of the Europäische Akademie GmbH, Professor Dr. Carl Friedrich Gethmann, for initiating and supporting this endeavor. Moreover we would like to thank Wolfgang Rathgeber and Sevim Kiliç, who assisted with and finally took over the editing of this volume.

For the study group

Dr. Michael Decker
(coordinator)

Professor Dr. Günter Schmid
(Chair)

TABLE OF CONTENTS

Foreword	3
1 Introduction – Miniaturization and Nanotechnology	8
2 Reflection on Existing Definitions of Nanotechnology	13
3 Reflection: Which Purposes Should Definitions Serve?	19
3.1 The Relevance of Definitions	19
3.2 The Pragmatic Character of Definitions	20
3.3 Which Purposes Should a Nanotechnology Definition Serve?	21
4 An Operationalizable Definition of Nanotechnology	24
4.1 The Definition	24
4.2 Clarifying Examples	27
4.2.1 Nano-effects Dominated by a Quantum Mechanical Behavior	27
4.2.2 Nano-effects Dominated by Particular Interface Effects. .	27
4.2.3 Nano-effects Resulting from a Limited Number of Constituents	28
5 Operationalization of the Definition	29
5.1 The Tables	29
5.2 The Brief Descriptions of the Effects in Table 1	35
5.2.1 Hard Magnets, Ferrofluids and Superparamagnetism (A1/2)	35
5.2.2 High Strengths Materials (B1/2/3)	38
5.2.3 Materials with Switchable Fermi-levels (C1)	41
5.2.4 Thermoelectric Materials (C1/2/3)	42
5.2.5 Quantum Size Effects (QSE) (C1/2/3) Formation of Discrete Energy Levels (D1/3) Photoluminescence (D3) . .	43
5.2.6 Plasmonics (D1) Photonic Surface Plasmons (D5)	45
5.2.7 Surface Plasmon Resonance (D1/6)	46
5.2.8 Size as Additional Variable in Thermodynamics (E1/2/3) .	48

5.2.9	Magnetic Dipole-Dipole Interaction (G1)	50
5.2.10	Ferroelectrics and Superparaelectrics (C2)	52
5.2.11	Transparent Ceramics (D2)	53
5.2.12	Phonon Engineering (F2/3)	54
5.2.13	Quantum Antidots (A3)	56
5.2.14	Molecular Magnetism (A4)	57
5.2.15	Molecular Motors (Machines) (B4)	59
5.2.16	Molecular Switches (C4)	61
5.2.17	Field Emission (Nanotubes) and Field-Emission Display (FED) (C4)	64
5.2.18	Brownian Ratchet (E4)	65
5.2.19	Nanoarchitectures (Nanostructures) (G4)	68
5.2.20	Shape Complementarity (H4)	70
5.2.21	Giant Magneto Resistance (GMR) (A5)	71
5.2.22	High Strengths Composites (B5)	74
5.2.23	Lowered Percolation Threshold (C5)	75
5.2.24	Photochromism (PhChr) (D5)	76
5.2.25	Systems with Diffusion Limited Electrode Reactions (D5)	77
5.2.26	Self Assembly of Metal Nanoparticles (G5)	80
5.2.27	Coordination Polymers (G5)	82
5.2.28	Biosensors (H5)	83
5.2.29	Proximity Effect (A6)	84
5.2.30	Self Cleaning of Surfaces (Lotus Effect) (B6)	86
5.2.31	Gas Sensors and Catalysts (C6)	87
5.2.32	Low-Loss Dielectrics (C6)	90
5.2.33	Antireflection (Moth Eye Effect) (D6)	91
5.2.34	Clean Surfaces, Photo-Catalysis (D6)	92
5.2.35	Defusion Systems (E6)	94

5.2.36 Self-Organized Complex Patterns; Phase Separated Block Copolymers (G6)	95
6 Miniaturization, New Materials and Nanotechnology – Challenges for Technology Assessment	98
6.1 Overview	98
6.2 Technology Assessment as Research for Giving Advice	98
6.3 Technology Assessment and Materials Research	105
6.4 Nanotechnology Assessment	109
7 Commercial Potential of Nanotechnology – A First Look	114
References	121
List of Authors	125

1 Introduction – Miniaturization and Nanotechnology

Miniaturization is a general aim of technology development and is taking place in nearly all areas of technology. It is first of all due to practical reasons that – as soon as the functioning of a new technology has been demonstrated – the miniaturization of this technology starts in order to reach an easier to handle, less heavy tool. Moreover, one needs less material which reduces the production costs and in general smaller devices also need less energy. Therefore miniaturization of technology contributes significantly to a sustainable usage of raw materials and energy. Due to these reasons, miniaturization of technology became one of the most important “side aims” of technology development.

Electronics can be taken as a paradigm for the ongoing miniaturization process of a technology. The technical development of cellular phones as well as of video cameras can be taken as “every day use”-examples. In the market place of the latter, miniaturization is even mentioned as one of the driving forces¹. Basically this “success story of micro electronics”² can be described referring to Moore’s law. Moore observed an exponential growth in the number of transistors per integrated circuit and predicted this trend would continue (Moore 1965)³. Nowadays, the following formulations can be found referring to Moore’s law: “that roughly every two years the overall number of transistors, which can be fitted in a commercial integrated connection, is doubled”⁴, “roughly every 18 month the capacity of microchips doubles”⁵ or also “every 18 month the relevant structure sizes are divided in half”⁶.

This dynamic technical development has been realized over the last decades and is thoroughly accompanied by the above sketched economical

¹ see <http://www.schnittpunkt.de/Systemhaus/Fachartikel/NLE/teil4/resuemee.htm>

² “schneller, kleiner, funktionsreicher“ Forum Forschung 2002/2003 Forschungsmagazin der Gerhard-Mercator-Universität Duisburg S.123-127

³ In this original paper Moore predicts the continuation of the growth until 1975.

⁴ see <http://www.elektroniknet.de/topics/bauelemente/fachthemen/2002/02028/> (translation MD)

⁵ Dr. Rolf Froböse “Miniaturisierung treibt Maskenhersteller in die Innovationsoffensive” in “aboutIT” (<http://www.aboutit.de/02/04/06.html>) (translation MD)

⁶ “schneller, kleiner, funktionsreicher“ Forum Forschung 2002/2003 Forschungsmagazin der Gerhard-Mercator-Universität Duisburg S.123-127 (translation MD)

and ecological improvements. Heinrich Rohrer⁷ writes in the *Neue Zürcher Zeitung* (translation Michael Decker [MD]):

“...The watch word of the information technology industry is “smaller, faster, cheaper”. In each of the last five decades the computers became ten to hundred times more powerful for the same amount of money.

Smallness allows for more distribution. Electronics became to be the “control hinge” of the main technological developments: From the cardiac pacemaker and the hearing aid to the laptop, from the “innocent” washing machine to the “guilty” intercontinental missile equipped with nuclear warheads. Smaller means also more sustainable in usage of materials, investments and energy consumption. Nowadays one calculation step needs around trillion times less energy compared to fifty years ago; nevertheless the overall annual sum for electricity used in information technologies is around one trillion Swiss francs.”

However, the development describable through Moore’s law seems to reach a limit. Froböse identifies this limit referring to the technical possibilities of the light-optical lithography which “limits the miniaturization of microelectronics in no time according to both economy and technology”⁸. Monticelli argues in a similar way and refers to the “International Roadmap for Semiconductors“ (ITRS⁹) in which the development of semiconductors is described according to so called “Technology Nodes” which reproduce the respective structure sizes. The milestone for the year 2003 is 90 nm, in the year 2006 structure sizes of 65 nm should be reached¹⁰.

⁷ Nobel prize laureatus Heinrich Rohrer (1986 together with Gerd Binning). The article has been published on 22.8.2001 and is available online (<http://www.nzz.ch/2001/08/22/ft/page-article7L0MR.html>):

“...Die Lösung der Datenverarbeitungsindustrie heisst «kleiner, schneller, billiger». In jeder der letzten fünf Dekaden wurden Computer zehn- bis hundertmal leistungsstärker fürs gleiche Geld. Kleiner erlaubt verteilter. Elektronik wurde zum Kontrollscharnier des meisten technischen Geschehens: vom Herzschrittmacher und Hörgerät zum Laptop, von der «unschuldigen» Waschmaschine bis hin zur schuldbeladenen interkontinentalen Rakete mit nuklearen Sprengköpfen. Kleiner heißt auch nachhaltiger in Materialaufwand, Investition und Energieverbrauch. So kann heute eine Rechenoperation mit etwa einer Billion Mal weniger Energie ausgeführt werden als vor 50 Jahren; trotzdem beläuft sich die jährliche Elektrizitätsrechnung der Datenverarbeitung auf etwa eine Billion Franken.“

⁸ Dr. Rolf Froböse “Miniaturisierung treibt Maskenhersteller in die Innovationsoffensive” in “aboutIT” (<http://www.aboutit.de/02/04/06.html>) (translation MD)

⁹ <http://public.itrs.net/>

¹⁰ The physical gate length of the individual transistor is considerably smaller, namely around 50nm resp. 30 nm.

However, Monticelli identifies considerable difficulties already for reaching these milestones (translation MD):¹¹

These extremely small structures of connections are much more than only astonishing achievements of lithography technique. They are rather something like engineers art on an atomic level. The current thickness of the gate-oxide-layer of around 2 nm corresponds with no more than eight atoms of silicon. Less is hardly possible but the gate-oxide is still a good insulator. The reaching of the 90 nm node corresponds with a gate-oxide-layer which is only half of the current thickness. Here, quantum mechanical effects (like tunneling) will lead to leak currents, which causes serious problems. In connection with the 65 nm node the gate-oxide layer requires a new material with a high dielectricity which has to be adapted to the conditions of the wafer production. This is by all means a mayor step of development because the outstanding electrical, mechanical, and thermic properties of silicodioxid are hardly to be reached.

Here, it becomes obvious that within the area of electronics (and in other areas of application as well) the miniaturization has already reached the size of manometers but as the size decreases, the difficulties increase even more. In a similar way the transition into the “Nano world” is described as “much more then just an ongoing miniaturization”, because “the empire of the dwarfs has its own rules” within which “quantum effects become relevant”, “which have no analogies in the macro world”¹².

All these citations refer more or less explicitly to the fact that the usual continuous miniaturization processes reaches a limit. The transition to Nanotechnology can therefore be described as “step crossing this limit“, entering an area, in which “new rules“, “quantum size rules“, etc. are or become valid. Due to the fact that most of these effects become relevant in the

¹¹ Diese äußerst kleinen Schaltungsstrukturen sind allerdings weit mehr als nur erstaunliche Errungenschaften der Lithographietechnik. Sie stellen eher so etwas wie Ingenieurkunst auf atomarer Ebene dar. Die gegenwärtige Dicke der Gate-Oxid-Schicht entspricht mit etwa 2 nm gerade einmal acht Siliziumatomen. Weniger ist kaum möglich, aber dennoch stellt das Gate-Oxid einen guten Isolator dar. Wenn beim Erreichen des 90-nm-Node die Gate-Oxid-Schicht nur noch halb so dick ist, werden quantenmechanische Effekte (Tunnelung) zu Leckströmen führen, die ein ernstes Problem darstellen. Bei 65 nm wird für das Gate-Oxid ein neues Material mit hohem Dielektrizitätswert erforderlich sein, das an die Bedingungen der Waferfertigung angepasst werden muss. Dabei handelt es sich durchaus um einen bedeutenden Entwicklungsschritt, denn die herausragenden elektrischen, mechanischen und thermischen Eigenschaften von Siliziumdioxid werden nur schwer zu erreichen sein.

¹² dpa as found at http://www.tachauch.de/background/natur/technik/0301_nano.html

length scale of nanometers, Nanotechnology can be described as a research area in which this limit is reached or strategies are developed to overcome it.

Not surprisingly the description of this “crossing the border” aspect has been used the other way to define what Nanotechnology is. In the following paragraph different definitions of Nanotechnology are mentioned in order to demonstrate that. However, it becomes obvious very soon that these definitions remain to be rather fuzzy, if one tries to “use” them. For example, this might be necessary in order to decide, if a certain technology should be mentioned under the headline “Nanotechnology” or not.

In the last couple of years, there has been a boom of the term “Nanotechnology”. The high expectations concerning future applications and the – up to now – good acceptance in the public led to an inflated use. Sometimes it seems that “Nanotechnology” has become a synonym for all things which are innovative and highly-promising. This boom, however, shows some risks. First of all, the inflated use of the term might contribute to hide the most interesting ongoing scientific activities in this field among a lot of others (in chemistry, biology, engineering or micro systems technology, for example) which have their own potential but are not as “revolutionary” as it would be suggested by denoting them as Nanotechnology. It becomes unclear what Nanotechnology stands for. Second, there is the risk of “free-loaders” in the area of research funding. The increased budgets for Nanotechnology research might invite others to use the term “Nanotechnology” to get funding for their ongoing research in other areas. And without an operationalizable definition, funding agencies have no chance to distinguish.

While the definition of the term “Nanotechnology” is not that decisive for researchers within the field of Nanotechnology, it becomes relevant if one wants to start a reflection on the research process as it will be done in Technology Assessment. One has to define the object to reflect on. The public discussion about the chances and risks of Nanotechnology has been taken up by the mass media as well. It has been asked if Nanotechnology is the next “candidate“ after nuclear power and gene technology (NZZ No. 164, 18.07.2003, 13). The spectrum reaches from taking a favorable view on the

topic (e.g. bdw 10/2002, 80–98) to asking for a moratorium (etc group 2002¹³). However, up to now the public discussion is neither refusing nor enthusiastic but realistic. But this could change fast if headlines like “The Fantasy-Utopia-Fear-Complex (FAZ No. 166, 21.07.2003, 40) became the majority. The open question concerning the toxicological impact of nanoparticles and nanotubes is in the focus of the reporting. It is mostly combined with the enormous potential impact on future markets and the impressive research funding worldwide, lead by the US government (NZZ see above, Financial Times Germany 04.08.2003, 25). Concerning the potential applications the medical sector and computer technology are preferred issues. Non Governmental Organizations like Greenpeace (Arnall 2003) and etc-group (etc-group 2003) have taken up the topic. Moreover, several Technology Assessment endeavors have been started on Nanotechnology in general as well as on different subtopics like economic aspects and health care.¹⁴

It is the purpose of this volume to develop an operationalizable definition of Nanotechnology as an initializing point for a rational Technology Assessment and thereby for these “reflecting” endeavors. According to this definition it should be possible to categorize the different research activities summarized within Nanotechnology at present. This endeavor starts with a brief reflection on existing definitions of Nanotechnology and on definitions in general, in which the aspect is underlined that definitions are made “to do” something. After that, a concrete definition is mentioned and recommended to be used if one has to decide if a concrete technology should be summarized under the notion Nanotechnology or not. The capability of this definition to be the basis for decisions like that will be demonstrated on the most popular research topics. At the end of this volume, a potential research program for a following Technology Assessment is presented with an extra focus on commercial aspects of Nanotechnology.

¹³ available on http://www.etcgroup.org/documents/Comm_NanoMat_July02.pdf

¹⁴ For example the German Federal Ministry of Education and Research (BMBF 2002) funds three studies on the economic meaning of Nanotechnology, Nanotechnology and sustainable development, and Nanotechnology in the health care sector. The Office of Technology Assessment at the German Parliament (TAB) is doing a project on Nanotechnology (<http://www.tab.fzk.de/en/projekt/skizze/nano.htm>). The TA-Swiss is organising a project on Nanotechnology in Medicine (http://www.ta-swiss.ch/www-remain/projects_archive/life_sciences/nano_e.htm).

2 Reflection on Existing Definitions of Nanotechnology

Analyzing what kind of endeavors are summarized under the topic “Nanotechnology” leads e.g. to the well known distinction between so-called “top down”- and “bottom up”-approaches. The top-down-approach approximates to the above mentioned border by perpetuating the miniaturization aspect by continuing size reduction of the so-called Microsystems Technology. The bottom-up-approach aims at direct manipulation of atoms or molecules in order to build new devices. This can be described as an approximation from below the border. Nanotechnology therefore can be identified as an area which investigates the border from two perspectives and searches for possibilities to overcome it.

In the following, different definitions of Nanotechnology will be mentioned. Most of them refer to a kind of border in the sense mentioned above.¹⁵

Definition 1

Nanotechnology is made up of “areas of technology where dimensions and tolerances in the range of 0.1 nm to 100 nm play a critical role.”
(Glossary of the Nanoforum¹⁶)

Obviously the borderline is drawn referring to a concrete order of magnitude in length scale which can be taken as “name-giving“ for Nanotechnology¹⁷. However, in this definition it is the “critical role” which needs further explanation. But it is remarkable that the range starts from 0.1 nm and ends at 100 nm. For some reasons the usual nanometer-interval of the SI-System has been shifted by one decimal power.

In most cases the concrete specification of size is complemented with additional descriptions. The Brockhaus-encyclopaedia¹⁸, for example, only refers to the bottom-up approach within Nanotechnology by mentioning

¹⁵ The following discussion expands Fleischer (2002) and confirms the critical assessment there.

¹⁶ <http://www.nanoforum.org/>

¹⁷ One could also take the view that Nanotechnology derives directly from nanos (greek for “dwarf“). However, the explicit reference of most definitions to the order of magnitude give evidence for the indirect “name-giving“.

¹⁸ <http://www.brockhaus.de> “Brockhaus in einem Band“, 07.05.2003

next to the 1–999 nm interval the ability to manipulate matter on the atomic or molecular level (translation MD):

Definition 2¹⁹

Nanotechnology, production and processing of structures and particles in the nanometer area. Nanotechnology allows for manipulation of matter on the atomic measure. The purpose is the precise structurization for the production of extremely small devices or structures with prescribed properties.

Other definitions combine the bottom-up and the top-down approach with the lateral scale:

Definition 3²⁰

Nanotechnology describes the creation and utilization of functional materials, devices and systems with novel functions and properties that are based either on geometrical size or on material-specific peculiarities of nanostructures. Purely geometrically the prefix “Nano“ (Greek: dwarf) describes a scale 1000 times smaller than that of present elements of the micrometer-sphere (1 nm corresponds to the millionth part of a mm). This scale has become accessible both by application of new physical instruments and procedures and by further diminution of present microsystems. Also structures of animated and non-animated nature were used as models for self-organizing matter.

Moreover this definition tries to reach a kind of completeness in describing Nanotechnology. It takes into account functional materials, devices and systems and refers explicitly to *novel functions and properties*. It also mentions self-organization and animated structures. These novel functions and/or properties can be found in many definitions:

Definition 4²¹

Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1–100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have

¹⁹ Nanotechnologie, die Herstellung und Verarbeitung von Strukturen und Teilchen (»Nanostrukturen, -teilchen«) im Nanometerbereich (Nano...). Die N. erlaubt die Manipulation von Materie im atomaren Maßstab. Ziel sind präzise Strukturierungen zur Herstellung extrem kleiner Bauelemente oder Strukturen nach vorgegebenen Eigenschaften.

²⁰ <http://www.nanoforum.org> “What is nano?”

²¹ National Nanotechnology Initiative (http://www.nano.gov/omb_nifty50.htm)

novel properties and functions because of their small and/or intermediate size. The novel and differentiating properties and functions are developed at a critical length scale of matter typically under 100 nm. Nanotechnology research and development includes manipulation under control of the nanoscale structures and their integration into larger material components, systems and architectures. Within these larger scale assemblies, the control and construction of their structures and components remains at the nanometer scale. In some particular cases, the critical length scale for novel properties and phenomena may be under 1 nm (e.g. manipulation of atoms at ~ 0.1 nm) or be larger than 100 nm (e.g. nanoparticles reinforced polymers have the unique feature at ~ 200 - 300 nm as a function of the local bridges or bonds between the nanoparticles and the polymer).

Also here, one strives for a kind of completeness by mentioning the atomic, molecular and macromolecular level and the creation and use of structures, devices and systems. The relevant length scale is described in detail. Additionally this definition underlines that the novel properties and functions are reached *because of the small and/or intermediate size*. This is taken up by the following definition as well (Bachmann 1998; translation MD):

Definition 5²²

Object of Nanotechnology is the production and application of structures, molecular materials, internal and external surfaces in critical dimensions or production tolerances of some 10 nm to atomic scales. [...] Aim is the preparation of material dependent properties of solids and their dimensions and new functionalities based on new physical-chemical-biological impact principles, caused by the submicroscopic respectively the atomic or molecular area. [...] Nanotechnology is dealing with systems with new functions and properties which depend solely on nanoscale effects of their components.

This definition adds two new things to our discussion. Firstly, the physical-chemical-biological impact principles are mentioned and secondly, the

²² Gegenstand der Nanotechnologie ist die Herstellung und Anwendung von Strukturen, molekularen Materialien, inneren Grenzflächen und Oberflächen mit Kritischen Dimensionen oder Fertigungstoleranzen von einigen 10 nm bis zu atomaren Abmessungen. [...] Ziel ist die Präparation materialabhängiger Festkörpereigenschaften, -dimensionen und neuen Funktionen basierend auf neuen physikalisch-chemisch-biologischen Wirkprinzipien, deren Ursache im submikroskopischen bzw. im atomaren und molekularen Bereich begründet sind. [...] Nanotechnologie beschäftigt sich mit Systemen, deren neue Funktionen und Eigenschaften nur allein von den nanoskaligen Effekten ihrer Komponenten abhängig sind.

nanoscale *effects* which cause the new functions and properties. Moreover the material optimization is explicitly mentioned here.

Definition 6 (BMBF2002)²³

Object of Nanotechnology is the production, analysis and application of functional structures whose scales are in the area of below 100 nm. [...] An atom or a molecule does not show the physical properties we are “used to” like electrical conductivity, magnetism, color, mechanical rigidity or a certain melting point. [...] Nanotechnology is taking place in the intermediate area between individual atoms or molecules and larger ensembles of atoms and molecules. In this area new phenomena appear which cannot be detected on macroscopic objects.

This definition (translated by MD) mentions physical properties well known from macroscopic devices, which change at the nanometer level. Moreover, *new phenomena* are mentioned which cannot be detected in the macroscopic area.

Reading these definitions²⁴, one gets a good impression what Nanotechnology is about. All definitions refer explicitly to the length scale. This is done in a general way like in Definition 2 (in the area of nanometer), by mentioning a concrete limit (below 100 nm, Definition 6) or by describing it in detail (Definition 4). The description of the relevant order of magnitude is maybe the most pragmatic way to define Nanotechnology. The described new effects and phenomena or new functions take place around and within this order of magnitude. However, it remains arbitrary, *because there is no direct causality from size to these effects or functions*. That is why most definitions complement the specification of the order of magnitude with the reference to these effects/phenomena (Definition 5 and 6) or the new functions (Definitions 3 and 4). It seems that in both cases nearly the same is

²³ Gegenstand der Nanotechnologie ist die Herstellung, Untersuchung und Anwendung von funktionalen Strukturen, deren Abmessung in dem Bereich unter hundert Nanometer liegen. [...] Einem Atom oder einem Molekül kommen jedoch uns vertraute physikalische Eigenschaften wie elektrische Leitfähigkeit, Magnetismus, Farbe, mechanische Härte oder ein bestimmter Schmelzpunkt noch nicht zu. [...] Nanotechnologie spielt sich also in einem Übergangsbereich zwischen individuellen Atomen oder Molekülen und größeren Ensembles von Atomen oder Molekülen ab. In diesem Bereich treten Phänomene auf, die man an makroskopischen Gegenständen nicht beobachtet.

²⁴ The selection of definitions is not claimed to be complete. However, the main aspects of the distinguishing arguments are represented.

meant. On the one hand side, one focuses on the function of a nanosystem and refers by that to the technology context and the future use of the nanodevice. This becomes a component of the macroscopic device or can be used as a device itself. On the other hand, effects or phenomena refer to a fundamental science context. One can identify concrete physical-chemical-biological effects/phenomena which can be allocated to Nanotechnology. Due to the fact that the new functions of nanodevices are usually based on these physical-chemical-biological effects or phenomena, this can be taken as two sides of the same coin.

Concerning the tasks, Nanotechnology deals with the production, analysis, investigation, and application of nanoscale structures, devices and systems (Definitions 4, 5, 6). Therefore it covers both the development of the individual structures or devices and the development of the strategies to combine them to larger modules or systems.

However, the impression what Nanotechnology is about remains fuzzy, because it is never explained in detail what the conditions for these new functionalities are. Here, it is not helpful to know that the new functionalities are caused by the nanoscale size of the device (Definition 4 and 5). Only Definition 6 refers to a concrete hint how a definition of Nanotechnology can be operationalized, namely in relation to physical properties. However, even using Definition 6 one would get a problem when the decision whether a concrete phenomenon should be labeled as Nanotechnology or not is at stake. This is because one would have to demonstrate that a physical property “we are used to from macro-scale devices”, is not detectable or, the other way round, that a new phenomenon appears which is not known from macro-size objects.

The reflection on existing definitions should be rounded off with the following definition on *mesoscopic* devices. It focuses on electronic properties of materials with respect to miniaturization (Datta 1995):

Definition 7

“Small conductors whose dimensions are intermediate between the microscopic and the macroscopic are called mesoscopic. They are much larger than microscopic objects like atoms, but not large enough to be ‘ohmic’. A conductor usually shows ohmic behavior if its dimensions are much larger than

each of three characteristic lengths scales: (1) the de Broglie wavelength, which is related to the kinetic energy of the electrons, (2) the mean free path, which is the distance that an electron travels before its initial momentum is destroyed and (3) the phase relaxation length, which is the distance that an electron travels before its initial phase is destroyed. The length scales vary widely from one material to another and are also strongly affected by temperature, magnetic field etc. For this reason, mesoscopic transport phenomena have to be observed in conductors having a wide range of dimensions from a few nanometers to hundreds of microns“.

The mesoscopic area obviously has some overlap with the Nanotechnology area. Its devices are “much larger than atoms” but not macroscopic. The strength of this definition is that it refers to physical characteristics which can be used as concrete criteria in order to decide if an individual conductor should be categorized as mesoscopic or not. Even this definition has some fuzzy aspects like the “much larger” than the characteristic length scales. However, it is an operationalizable definition which takes into account the dependence of external conditions like temperature, magnet fields, etc. as well. The reference to size therefore becomes only a description following the use of these defining criteria.

The lessons learned from the six definitions of Nanotechnology and the complementing one on mesoscopic systems are that the existing definitions of Nanotechnology sketch a fuzzy picture of what Nanotechnology is about. One reaches a “feeling” about the topic, at least after taking all definitions into account simultaneously and thinking about a kind of intersection or set union. However, these definitions are hardly usable in concrete decision situations. If somebody wants to decide if an individual research proposal or a concrete technological application should be taken into account under the heading “Nanotechnology” or not, she or he does not want to go through 6 different definitions. Especially so, if some of these definitions reach a length of more than 10 lines, due to the fact that describing parts are necessary in order to make the distinguishing parts of the definition understandable. Therefore in the following chapters of this volume an operationalizable definition of Nanotechnology should be developed and applied to a structured sample of research activities presently allocated to Nanotechnology. We start this endeavor with a reflection on purposes of definitions in general.

3 Reflection: Which Purposes Should Definitions Serve?

3.1 The Relevance of Definitions

There is generally a very high relevance of definitions, especially of the definitions of very basic terms. It is obvious that defining key notions like “risk”, “sustainable development” or “precautionary principle” will have considerable impact on the way and the means by which these could be made operable. Definitions are not only concerning the wording in discussing scientific or societal problems but also influence the ways in which these problems are dealt with. Definitions and classifications also influence the way in which research is organized and institutionalized – and the possibility to relate specific research programs or measures of research promotion and funding. Furthermore, they are the point of departure for structuring university faculties and research institutes.

Take, for example, the history of material sciences. The basic definitions and distinctions have been made in the 19th century. The separation into research on metals, semiconductors and isolators is valid as established classification in the field of materials research still today (Harig/Langenhach 1999). However, this classification itself is not the expression of a natural law though it is related to natural properties of materials derived from physics. There might have been other distinctions which, for some reasons, did not succeed in a similar way in structuring the materials sciences.

Definitions and subsequent classifications are structuring a subject area in a certain way which is regularly not the only one. Accordingly, definitions and classifications are not purely *describing* something but by applying a specific structure to a subject area they are also *shaping* that area. They are not only descriptive but also *constructive*. This aspect illustrates that defining something is not a value-neutral endeavor. The respective definition includes the expectation that the definition in the way chosen should be “better” in some sense than possible alternatives. The underlying criteria of what is being understood as “better” relates the definition to the level of values. A “rational” definition, therefore, cannot claim to be value-neutral –

this is impossible – but should uncover the underlying normativity in a transparent way and should explicitly reflect on the purposes aimed at.

3.2 The Pragmatic Character of Definitions

Defining something is, in pragmatic terms, a specific type of *action*. Something is defined by subsuming it under a concrete notion in order to meet a certain objective. Definitions shall serve purposes. Their performance is measured by analyzing if they are really purposive in the intended sense. Definitions shall constitute (and regulate) the use of a new term or notion (“constituting definition” [“festsetzende Definition”], Enzyklopädie 1997, 439: “constituting definitions are different from statements therefore they cannot be true or false” (“Festsetzende Definitionen sind keine Aussagen und können daher auch nicht wahr oder falsch sein”)[translations MD]). By definitions knowledge and skills may be structured and ordered but no additional knowledge will be created (Enzyklopädie 1997, 441).

Therefore, Constituting definitions are means to specific ends. They are not either true or false. In contrary, definitions are more or less purposive. It does not make any sense to argue in favor of or against specific proposals for definitions without raising the questions for the respective purposes.

Definitions are conventions. There are no straightforward and forcing logical arguments why a specific definition has to be made in a particular way and not in an alternative one. There are always alternative possibilities for definitions – nevertheless, definitions are not arbitrary. Though there is no *logical* reason for choosing a definition in a specific way, *pragmatic* reasons concerning the adequateness of a proposed definition to serve certain purposes help selecting a specific definition among alternatives. Controversies about definitions are related to the question which purposes shall be fulfilled by the respective definition and which possible definition would serve the respective purpose best.

Defining something is an operation relating specific notions to other notions. It happens within language. A definition consists of relating a term to be defined (*definiendum*) to a subject area by describing the specific properties of elements from the subject area which are essential for subsuming them under the *definiendum*. This relation is called the *definiens*.

The definition shall allow a replacement of the new term by terms already known without loss or gain of information. If needed, the definiens shall be eliminable by inserting the defining relation (Enzyklopädie 1997, 441).

For example: the term “Nanotechnology” shall be defined (Nanotechnology then is the definiendum). The subject area is, as point of departure, the complete set of known processes, technologies, research activities in physics, chemistry, biology, and engineering. The definition shall identify a (small) subset within this large subject area which then shall be denoted as Nanotechnology. Which part this shall be has to be clarified by formulating a *definiens*: by giving the properties the elements of the larger subject area shall fulfill in order to be classified as Nanotechnology.

Definitions, as it can be seen from this example, allow drawing distinctions. The definiens consists in the description of a border which separates the elements belonging to the subset called “Nanotechnology” and those which are outside of “Nanotechnology”. The ideal situation is that the definition allows for each element of the subject area a clear classification whether it belongs to the specific subset due to the definition or not – showing the validity of the “tertium non datur“. Each element of the subject area should be either Nanotechnology or not Nanotechnology; there should be nothing in between. In reality, however, there are frequently “grey zones” which often give raise to an improvement of the definition by making it more precise.

3.3 Which Purposes Should a Nanotechnology Definition Serve?

What we have seen is that the respective purposes of definitions are essential in debating about their appropriateness and adequateness. There is a general level of purposes which shall be met by every definition, and there are specific purposes in the concrete case of Nanotechnology.

Generally, definitions shall serve the following purposes:

Creation of order: Drawing distinctions creates order. Defining something by distinguishing something from something else is the basic mode of mind and, simultaneously, its necessary precondition (Spencer Brown 1979).

Generation of knowledge: Our knowledge is organized in systems and hierarchies of distinctions, reaching from basic distinctions to highly differentiated and specialized ones, depending on definitions. The world can be seen as the sum of all distinctions which have been made so far (Mittelstraß 1974).

Enabling inter-subjective understanding and cooperative action: To work with common notions based on agreed definitions is a necessary pre-condition of inter-subjective understanding and of cooperative action. This applies at different social levels, reaching from micro-groups like families to large social communities.

Basis of scientific disciplines: Scientific disciplines are based on a common understanding of basic notions according to agreed definitions (Janich 1997).

Why do we need a definition of Nanotechnology and which specific purposes shall it serve? The need for a definition seems to be obvious because of the general purposes mentioned above. Especially for the purpose of inter-subjective understanding it should become clear what is to be subsumed under “Nanotechnology” facing the situation that recent developments in several disciplines and sub-disciplines meet each other and create new interfaces between different scientific disciplines and approaches which, obviously, should get a clearly defined name.

The following more specific purposes shall be fulfilled by a Nanotechnology definition:

Cognitive purposes: The definition should allow separating Nanotechnology from established fields of technology (like micro systems technology, for example, or like technical chemistry). The character of Nanotechnology as a “newly” emerging field of technology should become visible. This means the availability of new technological capabilities, knowledge and skills.

Interfaces to the established disciplines: The definition should be usable to characterize and describe the interfaces to established scientific and technological disciplines, especially to describe the use of scientific input from physics, chemistry, biology and engineering.

Contribution to the identity of the actors involved: The definition should contribute to the constitution and the identity of the new Nanotechnology research community (new scientific journals, new chairs and institutes).

Political purposes: The definition should allow establishing relations to funding programs in ministerial departments, funding agencies and authorities.

Public relations: Furthermore, it should be taken into account that “Nanotechnology” has become a well-known term with highly positive connotation. A definition should take this fact into account and should prevent an inflationary use of it.

Communicative purposes: In order to use the notion in public and political communication the definition should be clear and as short as possible.

This list of purposes shows that the definition of Nanotechnology is relevant for mostly social and political reasons. Scientific advance does not need a clear definition of Nanotechnology. It does not matter whether certain activities at the nanoscale are being classified as Nanotechnology, chemistry or mesoscale physics. However, there is an extra-scientific need for a clear definition in order to structure the communication with the outside world of science – and to establish such a definition in accordance with scientific advance and the specific purposes in this field is also a challenge for the scientists working in this field. History shows that such deep-going definitions mostly have been controversial: “... at least the framing definitions which determine the ongoing development of science were highly controversial due to science-political interests and its consequences“ (“... dass zumindest die Rahmendefinitionen, die das Vorgehen in den Wissenschaften bestimmen, wegen der wissenschaftspolitischen Interessen und deren Konsequenzen häufig umstritten waren“ [translation MD]) (Enzyklopädie 1997, 440).

4 An Operationalizable Definition of Nanotechnology

Now, the lessons learned from the previous chapters will be used for developing a definition of Nanotechnology. It takes into account the fuzzy picture sketched by the definitions mentioned in chapter 2 and it tries to transcribe the general remarks on definitions made in chapter 3.

4.1 The Definition

The purpose of the following definition is to justify answers to the question: Is a concrete technology to be allocated to Nanotechnology or not? Therefore, the main criterion to evaluate the definition is: Is it possible with this definition to divide the world of technology into Nanotechnology and non Nanotechnology? Moreover, we tried to keep the definition terse. Therefore it is combined with a description of the defining key words.

Definition:

Nanotechnology is dealing with functional systems based on the use of sub-units with specific size-dependent properties of the individual sub-units or of a system of those.

Functional system and subunits:

The term “system” is used to separate a specific part of a larger subject area (in nature, society, technology or in the life-world) being under special consideration. The constitution of the system boundaries in a concrete case is guided pragmatically by scientific or technological objectives and purposes. Functional systems are systems where the (technological or natural) functionality to be considered provides the criteria for defining system boundaries.

A functional system may be described as a collection of a certain number of interacting subunits forming a new entity with system specific properties. The subunits are ideally combined in a directed manner and are hierarchically organized on different levels of complexity leading to new qualities of the functional system which can not be achieved by uncontrolled combination of the subunits.

An example of a functional system for information storage could be a DNA molecule consisting of individual base pairs as subunits or even a decorated copper surface with individual carbon monoxide molecules as subunits. Another example of a functional system would be a single electron transistor consisting of nanoparticles attached to electrodes both acting as subunits. In contrast silica particles in Ketchup improving the rheological behavior are not combined in a directed manner while the same silica particles forming a super-lattice in a photonic crystal fulfill these criteria.

Specific size-dependent properties:

Material properties cover magnetic, mechanic, electronic, optical, thermodynamic and thermal features as well as the abilities for self assembly and recognition.

The specific-size dependence of these properties becomes evident when they

- no longer follow classical physical laws but rather are described by quantum mechanical ones;
- are dominated by particular interface effects;
- exhibit properties due to a limited number of constituents, since the usual term “material” refers to an almost infinite number of constituents (e.g. atoms, molecules) displaying an averaged statistical behavior.

These properties have no equivalent in the macroscopic world.

For example, the nature of electronic properties roots in quantized features based on the wave character of the electrons that becomes solely relevant in typical length scales. Such length scales are the De Broglie wavelength, the mean free path, and the phase relaxation length of an electron. Here we refer to Definition 7 (Datta 1995).

In contrast to that, scaling laws which hold for macroscopic objects and also keep their validity in the nanometer range continuously do not imply new size specific properties. The examples of the following chapter should clarify this distinction.

If we compare our definition with the definitions discussed in chapter 2, it becomes evident that the “specific size dependent properties” explained in detail above, cover what most probably has been meant by the “novel properties and phenomena” (Definition 4) or by “new physical-chemical-biological impact principles” (Definition 5). The functional system in our definition corresponds to the functional “structure” mentioned in Definition 6. It is also in Definition 6 where the definition itself is supplemented by the description that the new phenomena cannot be detected on macroscopic devices. We took that over in our description above. At the end we followed the idea behind the definition on mesoscopic devices in which concrete criteria are mentioned to differentiate between mesoscopic and not mesoscopic, i.e. macroscopic devices. Therefore the specific size dependent properties became the central part of our definition.

Finally, we would like to discuss the “nanometer regime”. All definitions in chapter 2 refer to a concrete metrological length scale in which Nanotechnology “has its home”. “Below 100 nm” (Definition 6) or “around 10 nm” (Definition 5) are mentioned there. More flexible, Definition 1 states the interval 0.1 nm–100 nm and in Definition 4 it is discussed that it can be below 1 nm and above 100 nm. We agree with the authors of these definitions that the area 0.1 nm to 100 nm can be used as a good approximation for deciding if a certain technology represents Nanotechnology or not. However, a lateral scale in one or more dimensions is not a physically plausible measure to define Nanotechnology because we can find both effects which are within the interval between 0.1 nm and 100 nm and are not Nanotechnology according to the definition mentioned above and effects which occur above 100 nm (or even 1000 nm) but show these “specific size dependent properties”. Therefore we propose that the name-giving size of Nanotechnology should not be mentioned in the definition, because this would imply exclusion criteria independent from a scientific evaluation of the fundamental working principle of a functional system.

4.2 Clarifying Examples

4.2.1 *Nano-effects Dominated by a Quantum Mechanical Behavior*

For electronic and optical properties, the well known “*quantum confinement effect*” apparent in Quantum dots, Quantum wires and Quantum wells is the most important effect. The quantum confinement effect can be observed when the diameter of the particle is of the same order of magnitude as the wavelength of the wave function of electrons. In this case, the energy spectrum changes from continuous to discrete. Most simply an electron in a nanoparticles can be imagined as an “electron in a box” where energy levels are considered as the solutions of the Schrödinger equation for the box of a given size and geometry. The critical length is reached if the size of the crystal is smaller than the exciton’s Bohr radius (i.e. radius of lowest energy Bohr orbital). For Si this is reached at 4.9 nm, for CdSe at 6.1 nm. For metals, this value is even smaller. Consequently, this example fulfills the definition as a quantum size effect (see 4.1).

Ferromagnetism is believed to be caused by magnetic fields generated by the electrons’ spins in combination with a mechanism known as exchange coupling, which aligns all the spins in each magnetic domain. This coupling is quantum mechanical in nature and not purely due to the magnetic forces acting between neighboring atoms. The energy related to this exchange energy can be expressed as $C \cdot V$, where C is a constant including all energy related to this interaction and V is the volume of the magnetic material or structure. In the case of $C \cdot V < \text{thermal energy}$, a randomizing of the ordered magnetic moments will occur and the ferromagnetic material will show a paramagnetic behavior. From the above relation, a critical size can be determined. Similar to this effect, known as the ferro-paramagnetic transformation, a ferroelectric-paraelectric transformation is possible. Consequently, this example fulfills the definition as a quantum size effect (see 4.1).

4.2.2 *Nano-effects Dominated by Particular Interface Effects*

In bulk semiconductors an increase of the energy levels near the surface can be observed. The reason for this phenomenon is a surface charge (effected by defects, adsorbed molecules, etc.) which generates a space charge region

in the bulk near the surface (in the thermal equilibrium the Fermi level of the bulk must be the Fermi level of the surface). This surface depletion layer can be expressed by the Debye length, which is a material constant and depends on the carrier concentration, in the material. Under standard conditions, the Debye length in silicon is 41.5 nm. For a particle or structure smaller than the Debye length an increase of the band gap can be observed, because of the overlap of the space charges. Consequently, this example fulfills the definition as a particular interface effect (see 4.1).

An illustrative counter-example not fulfilling our definition is the influence of the grain size on the strength of ceramics. Because no dislocations are active, a deformation occurs mainly via grain boundary sliding. Decreasing grain sizes will increase the amount of grain boundary areas and phases just to the extreme case of an amorphous material and will therefore change the strengths of the ceramics in a monotonous way. This reflects a continuous change of physical properties passing from the macroscopic world down to the atomic level. Similar conclusions are valid for nanocomposites.

4.2.3 Nano-effects Resulting from a Limited Number of Constituents

As an example the design of a supramolecular system consisting of a well defined number of constituents may include a pigment molecule to quench an excited state of a subunit in close vicinity. Therefore, an ideal spatial arrangement between the pigment molecule and the excited subunit is required. The function of the pigment molecule is to quench the excited state and to radiate light of a particular color. This event is the last step of a series of events in the supramolecular assembly. Such a complex architecture of several subunits represents Nanotechnology as defined above, since its function results from the spatial order of a limited number of constituents.

In contrast to that, an arbitrary collection of the same pigment molecules in a bucket serving as color paint is obviously not considered to belong to Nanotechnology, as the color of the wall results from their averaged statistical behavior.

5 Operationalization of the Definition

5.1 The Tables

The ability to operationalize this definition shall be demonstrated as follows. We sampled effects/phenomena which are usually mentioned as being Nanotechnology. In order to structure this sampling process we developed the following table 1. In the next step we apply the definition to the items in the table. After a brief description of the item it is decided if the effect is Nanotechnology or not using the definition (section 5.2). This leads first of all to table 1a in which only items are mentioned which are found to be allocated to Nanotechnology. Therefore table 1a allows for immediate decisions: If the effect an individual technical application is based on is mentioned in table 1a, it is categorized as being Nanotechnology according to our definition. Moreover, it leads to table 1b in which for the sake of completeness the remaining effects which represent “continuous changes” are mentioned. Technical applications based on these effects are, according to our definition, not Nanotechnology. In the following the structure of the tables will be described.

The columns include relevant materials relating to Nanoscience and Nanotechnology. Columns 1–3 contain metals, insulators and semiconductors which, in combination with the hybrids and composites of column 5, cover all known solid state systems. In addition, column 4 contains molecules being nanosized from “nature”. The tables are completed by column 6 where boundary surfaces are considered, thus regarding all imaginable relevant systems except the solid state systems.

In combination with the magnetic, mechanic, electric/electronic, optical, thermodynamic, and thermal properties as well as ability for self-assembly and recognition ability primary nanotechnologically relevant combinations are considered.

The classification of the lines, following the physical properties of the materials, is useful since the listed effects become obvious with the change of the physical properties when the nanoscale is achieved. In some cases

columns are combined. This results from the physical relationship of metals, semiconductors and insulators, differing only by their band widths.

In the following, the capability of our definition to distinguish between nanotechnological and not nanotechnological effects will be demonstrated. Table 1 contains effects resulting from the combination of properties and materials. Afterwards all effects in table 1 are described and categorized according to our definition. This leads to table 1a which contains nanotechnological effects. As an example the transition from ferromagnetism to superparamagnetism of metals shall be mentioned. It becomes obvious at a specific size of the corresponding materials for being a quantum size effect (field A1/A2).

In contrast, table 1b comprises those effects which also appear in the nanometer range but do not fulfill our definition. An example is the self-cleaning surface effect (Lotus effect, A6). This phenomenon already becomes obvious in the microregime and is continued down to the nanoscale changing only the extent of self-cleaning, not the effect as such. So, tables 1a and 1b complete each other to give table 1.

There may be some nano-relevant building blocks that are not listed in table 1. The reason will be that we are not aware of the resulting effects or that they still are so unimportant or so unpredictable that a discussion within the framework of this study seems not appropriate. Doped fullerenes may be mentioned as such an example. They are of some academic interest, however, it can not be foreseen if and when they might become relevant at all.

Table 1a and 1b can be used to decide if a technological idea or development is to be considered as a nanotechnological phenomenon in the sense of our definition or not. As an example, there might be the idea to develop a novel biosensor. Biosensors can be found in table 1a, which means that they are to be categorized as Nanotechnology according to our definition (H6). On the other hand, the tables can be used to find nanotechnologically relevant effects, for instance when looking for new products.

These tables are not claimed to be complete. However, they allow for analogical conclusions along the descriptions presented in section 5.2.

Remark on Nanobiotechnology:

The size of biological functional systems is typically in the nanometer regime. Due to their organized molecular nature, they should be considered in the context of this work. For instance, a cell is a hierarchically organized complex biological system performing a huge variety of different functions and actions at the same time. Often the cell itself is a building block for an even larger, hierarchically organized system, like e.g. a plant or a human being. The extension of cells is between micrometers and several hundreds of micrometers. The emerging ability of Nanotechnology to structure, address, transport, manipulate, etc. very small objects leads to a new level of investigation and interaction with biological systems. Endeavors to stimulate and communicate via nanotechnological fabricated electrodes with nerve cells (Fromherz 2002) or to integrate biological transport systems in nanotechnological fabricated substrates (Hess and Vogel 2001, Hess et al. 2002) are only first examples of this young emerging field. The scientifically very rich and challenging interface between biology and Nanotechnology, often referred to as NANOBIO, is not cited on the table in particular, because its novelty and complexity do not allow a comprehensive categorization in this preliminary study. However, the authors are aware of the potential of the new field and actions to expand the focus of the study in that directions are planned.

Table 1

Table 1 Properties	Size Dependent Properties			Engineered Functions		
	Metals (1)	Insulators (2)	Semiconductors (3)	Molecules (4)	Hybrids/Compos. (5)	Boundary Surf. (6)
magnetic (A)	Hard Magnets; Ferrofluids and Superparamagnetism	High Strength Materials	Quantum Antidots	Molecular Magnetism	Giant Magneto Resistance (GMR)	Proximity Effect
mechanic (B)						
electronic/ electronic (C)	Materials with Switchable Fermi Levels; QSE; Thermoelectric Materials	Ferro- and Super paraelectrics; QSE; Thermoelectric Materials	QSE; Thermoelectric Materials	Molecular Switches; Field Emission (Nanotubes); Field-Emission Display (FED)	Lowered Percolation Threshold	Low-loss DK; Gas Sensors; (Catalysis)
optical (D)	Formation of Discrete Energy Levels; Plasmonics; Surface Plasmon Resonance	Transparent Ceramics	Formation of Discrete Energy Levels; Photoluminescence (QD/QSE)			Antireflection; Surface Plasmon Resonance; Self-Cleaning Surfaces (TiO ₂)
thermodyn. (E)		Size as Additional Variable in Thermodynamics				
thermal (F)		Phonon Engineering		Brownian Ratchets		Diffusion Systems
Ability for self assembly (G)	Magnetic Dipole-Dipole Interaction			Nanoarchitectures (Nanostructures)	Self Assembly of Metal Nanoparticles; Coordination Polymers	Self-organized Complex Patterns; Phase Separated Block Copolymers
Recognition Ability (H)				Shape Complementarity	Biosensors	

Table 1a

Table 1a Properties	Size Dependent Properties			Engineered Functions			Boundary Surf. (6) Proximity Effect
	Metals (1)	Insulators (2)	Semiconductors (3)	Molecules (4)	Hybrids/Compos. (5)	Boundary Surf. (6)	
magnetic (A)	Ferrofluids and Superparamagnetism		Quantum Antidots	Molecular Magnetism	Giant Magneto Resistance (GMR)		
mechanic (B)	High Strength Materials			Molecular Motors			
electric/ electronic (C)	Materials with Switchable Fermi Levels; QSE; Thermoelectric Materials	Ferro- and Superparaelectrics; QSE; Thermoelectric Materials	QSE; Thermoelectric Materials	Molecular Switches Field Emission (Nanotubes) Field-Emission Display (FED)		Gas Sensors; (Catalysis)	
optical (D)	Formation of Discrete Energy Levels; Plasmonics; Surface Plasmon Resonance	Transparent Ceramics	Formation of Discrete Energy Levels; Photoluminescence (QD/QSE)		Photochromism; Photonic Surface Plasmon	Surface Plasmon Resonance; Self-Cleaning Surfaces (TiO ₂)	
thermodyn. (E)	Size as Additional Variable in Thermodynamics			Brownian Ratchets			
thermal (F)		Phonon Engineering					
Ability for self assembly (G)	Magnetic Dipole-Dipole Interaction			Nanoarchitectures (Nanostructures)	Self Assembly of Metal Nanoparticles; Coordination Polymers	Self-organized Complex Patterns; Phase Separated Block Copolymers	
Recognition Ability (H)				Shape Complementarity	Biosensors		

Table 1b

Table 1b	Size Dependent Properties			Engineered Functions		
	Metals (1)	Insulators (2)	Semiconductors (3)	Molecules (4)	Hybrids/Compos. (5)	Boundary Surf. (6)
magnetic (A)	Hard Magnets					
mechanic (B)		High Strength Materials	High Strength Materials		High Strength Composites	self cleaning surfaces (Lotus effect)
electric/ electronic (C)				Field Emission (Nanotubes) Field-Emission Display (FED)	Lowered Percolation Threshold	Low-loss DK
optical (D)					Diffusion Limited Electrode Reactions	Antireflection
thermodyn. (E)						Defusion Systems
thermal (F)						
Ability for self assembly (G)						
Recognition Ability (H)						

5.2 The Brief Descriptions of the Effects in Table 1

In the following the entries of the table are briefly described column by column. In some cases it was sensible to combine effects of different table cells in order to avoid double explaining. Here, all table cells are mentioned behind the headline. For the convenience of the reader the references to these effects are mentioned at the end of each description and not at the end of this volume.

5.2.1 *Hard Magnets, Ferrofluids and Superparamagnetism (A1/2)*

Cell of the table: Magnetic properties of metals and insulators

Explanation:

Magnetism of nanostructures has been investigated intensively since the early beginning of Nanotechnology. The first results have been published by Herzer and Warlimont (1992). They found that coercivity H_c increases with decreasing grain size D down to values of about 40 nm independently of the kind of material. The increase of H_c is proportional to $1/D$. The reason for this is that in small particles the formation of a closed magnetic flux becomes energetically less favorable so that the magnetic domain size with a uniform magnetization becomes more and more identically with the grain size. This grain size can be defined as a first critical size where the multidomain materials change to a monodomain material. This leads to a strong increase of the coercivity (or high remanence) because a change of magnetization in this case can not happen only by shifting the domain walls (“Bloch walls”) which normally requires only a relatively weak magnetic field. A change of magnetization can only be achieved by rotation of the magnetization of a single particle as a whole which requires strong magnetic fields depending on the shape and anisotropy of the particles.

As the size of magnetic elements scales below 20 nm, a transformation from ferromagnetic to superparamagnetic behavior occurs (Herzer and Warlimont 1992). In the superparamagnetic state of the material, the room temperature thermal energy (kT) overcomes the magnetostatic energy well of the domain or particle, resulting in zero hysteresis (Cornell and Schwertmann 1996). In other words, although the particle itself is a single-domain

ferromagnet, the ability of an individual magnetic “dot” to store magnetization orientation information is lost when its dimension is below a threshold. Consequently, the magnetic moments within a particle rotate rapidly in unison, exhibiting the superparamagnetic relaxation phenomenon. This phenomenon can be described by the relaxation time which depends exponentially on the volume of the particle. Typically particle sizes for the ferro- to superparamagnetic phase transformation are between 10 and 20 nm for oxides and 1-3 nm for metals. The phenomenon can also be described by a blocking temperature T_B . At temperatures lower than the blocking temperature or at measuring times smaller than the relaxation time the material still shows ferromagnetic behavior. However, at $T > T_B$, because relaxation time is longer than the measuring time, the time averaged value of the ferromagnetic characteristics (e.g. magnetization and coercivity) vanish within the measuring time. Then the system is in an apparent paramagnetic or superparamagnetic state even though within each particle the magnetic moments remain ferromagnetically aligned. Because of the superparamagnetic relaxation, the value of remanent magnetization (M_R) and coercivity (H_c) decrease with increasing temperature and vanish at the blocking temperature (T_B). On the other hand, the saturation magnetization is nearly unchanged. Especially this unique combination of high magnetization and paramagnetic behavior opens to this material a very large field of application, especially for medical biotechnology.

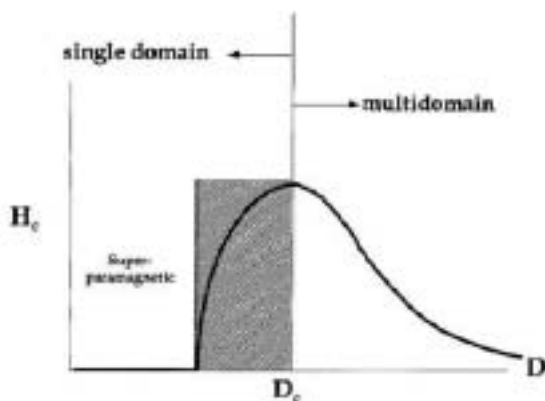


Figure 1: Qualitative illustration of the behavior of the coercivity in ultrafine particle systems as the particle size changes. (Leslie-Pelecky and Riecke 1996)

Superparamagnetic particles can be dispersed in a liquid, e.g. oil, without any agglomeration. By applying an external magnetic field the superparamagnetic particles are arranged in chains of particles along the magnetic field and thus the viscosity of the fluid is increased considerably within milliseconds. When the magnetic field is switched off the originally maintained viscosity is reproduced. Magnetorheological fluids can be used in gaskets of bushings. Another important application of this effect could be in suspension control systems of automotive vehicles. Figure 2 displays the change of the damping force, when a relatively low magnetic field is applied (Cornell and Schwertmann 1996).

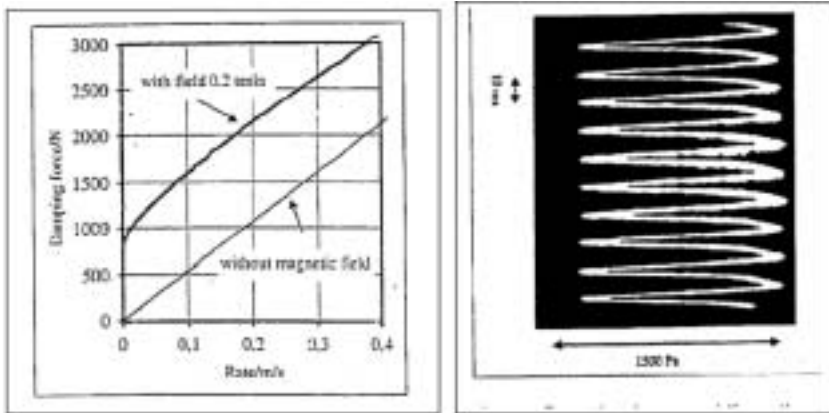


Figure 2: Damping properties of magneto-rheological fluids (BASF 1997)

Evaluation referring to our definition of Nanotechnology:

Magnetic materials show a variety of behaviors with decreasing grain or domain size:

1. The increase of coercivity or the remanence of single domain hard magnets is no nanoeffect, the single domain can appear in the micrometer range.
2. The transition from ferro- to superparamagnetic behavior is a nanoeffect and is clearly shown by the drastic change of the collective behavior of the magnetic dipoles. Based on quantum mechanic rules, each sub-unit is changing the dipole direction independently of the neighboring grain or particles, which will lead macroscopically to paramagnetic behavior of

the material. For oxides used in ferrofluids for example, the critical length is in the area of 15 to 20 nm, for metals very often below 2 nm.

Application:

Iron or iron alloy particles with high remanence (diameter < 3 nm) are used for data storage devices (the effect is important here as a lower limit for the miniaturization because the particles still have to show ferromagnetic behavior [hard magnets]), ferrofluids, medical biotechnology (Cell-, DNA, and Protein separation or tracking Drug delivery, hyperthermia, MRI, molecular imaging) or loud speaker.

References:

BASF-Flyer 1997

Cornell R.M., Schwertmann U., VCH Verlagsgesellschaft GmbH, Weinheim, 1996

Herzer Chr., Warlimont H., *Nanostructured Materials*, 1992, 1, 292

Leslie-Pelecky D.L., Riecke R.D., *Chem. Mater.*, 1996, 8, 1770

5.2.2 *High Strength Materials (B1/2/3)*

Cell of the table: Mechanical properties of metals, insulators and semiconductors

Explanation:

In the field of mechanical properties of nanostructured metals the inverse Hall-Petch relationship is of interest. The classical effect of grain size on yield stress can be explained by a model invoking a pile-up of dislocations against grain boundaries which results in dependence of the hardening increment on the square root of the grain size D . This is the classical Hall-Petch effect.

Whereas many metallic materials obey such a relationship over several orders of magnitude in grain size, it is observed that the reasoning behind the Hall-Petch relationship breaks down for very small grains. Decreasing the size to lower than a critical limit which is given by the minimum radius

of a dislocation loop, the normal mechanism of plastic deformation is blocked. A clear limit for the occurrence of dislocation plasticity in a polycrystal is given by the condition that at least one dislocation loop must fit into average grain. The plastic behavior of nanocrystalline materials with grain sizes below the critical value is not fully clear. Some authors also report an “inverse” Hall-Petch effect; others find insensitivity to grain size. The decrease in hardness of nanostructured materials with $d < d_{\text{crit}}$ can be explained with a simple model of a mixture of hard, crystalline grains showing no plastic deformation embedded in a soft amorphous phase (grain boundary). Because the grain boundary thickness is constant, the amount of the amorphous phase increases with decreasing crystal size.

The unsolved problem still is the fabrication of such materials. Typical methods are crystallization of amorphous metals, severe plastic deformation, powder technology and, more severe, the stability of the nanostructures at higher temperature or under stress. Therefore, simulation and modeling of the plastic deformation behavior of nanostructured materials is a strongly increasing research field today.

Nanostructured ceramics with grain sizes < 100 nm for structural application are not yet developed. The use of nanosized powders for the production of ceramics has been well known and used on an industrial scale for years. The advantage of lower sintering temperature (higher reactivity of the powder) is overcompensated by the difficulties of processing fine powders as well as of the unsolved grain growth problem. Only sophisticated powder processing or expensive consolidation methods like hot pressing or plasma sintering can overcome these problems. These are the reasons why most of the nanostructured ceramics are nanocomposites where a second phase is well distributed in the matrix. The strength increase observed in nanocomposites can be explained by a decrease in critical flaw size. It can be shown that not only the size of processing flaws decreased, but that also their morphology changes completely. In the case of a ceramic/ceramic composite (example: Alumina with nanosized silicon carbide), the matrix grain size is reduced with a narrow size distribution due to the grain boundary pinning by inert SiC particles. Dislocation networks only play a minor role.

In pure ceramics, deformation occurs mainly via grain boundary sliding. Decreasing grain sizes will increase the amount of grain boundary area and phases (these phases less than a few nanometers in thickness behave as amorphous) just to the extreme case of an amorphous material and will therefore change the strengths of the ceramic in an monotone way. At higher temperatures, this effect is enhanced. Low amount of an amorphous grain boundary phases can significantly increase the ability of plastic deformation of nanostructured ceramics.

Evaluation referring to our definition of Nanotechnology:

In the field of mechanical behavior of materials, we can distinguish very clearly between the behavior of metals and that of rigid materials like ceramics or semiconductors:

In *metals*, where the dislocation mechanism is the dominant deformation mechanism, we can define the nanoeffect as a mechanical confinement effect: if the grain size is smaller than the radius of the dislocation loop which corresponds to the theoretical strengths of the material, the deformation mechanism is changing. Consequently, this example fulfills our definition of Nanotechnology due to a limited number of constituents (atoms).

In rigid materials, like *ceramics*, a clear identification of the toughening or strengthening mechanism remains difficult. All known possible mechanisms also seem to be active at larger volume. Consequently, this example does not fulfill our definition of Nanotechnology.

Application:

Because elastic properties of metals are not influenced by the size of the crystal, beside a small influence of the increasing amorphous phase for very small grains, unique property combinations of strength, hardness and elastic modulus are possible if the materials reach the critical grain size. Applications are not known at the moment.

From nano-grained ceramics an increased superplastic deformation will be possible. This will allow near net shape fabrication processes of ceramics parts. Better wear resistance will be another positive effect of nanosized

ceramics in bulk as well as in layers. Applications in structural ceramics are still limited to ceramic nanocomposites.

References:

Arzt E., *Acta mater.*, 1998, 46, 5611

Sternitzke M., *Journal of the European Ceramic Society*, 1997, 17, 1061

Van Swygenhoven H., Spaczer M., Caro A., *Acta mater.*, 1999, 47, 3117

5.2.3 *Materials with Switchable Fermi-levels (C1)*

Cell of the table: Electric/electronic properties of metals

Explanation:

Some nanoporous metals show a charge-induced reversible strain. The dimension changes by approximately 0.1 % or even more in response to an applied electric field, as they are known for many other materials, like ceramics, polymers or carbon nanotubes, have most recently been discovered for metals with high specific surface areas. The strain amplitudes are comparable to those of commercial piezo ceramics and can be induced in an electrochemical set-up by switching the Fermi-levels of the metal and, by this, controlling the surface electronic charge density through an applied potential relative to an electrolyte impregnating the pores of the metal.

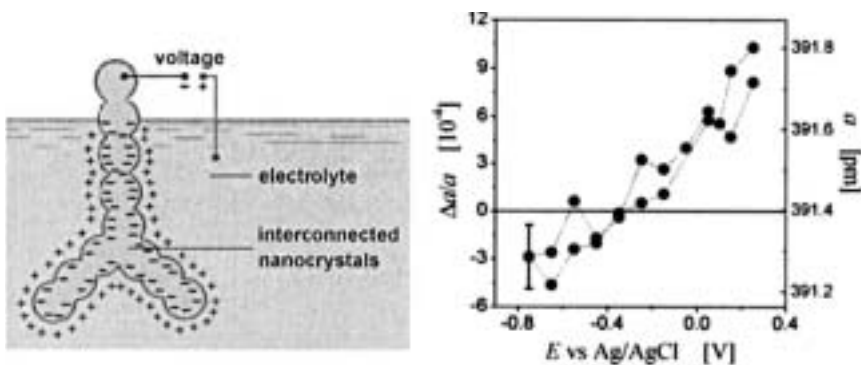


Figure: Left side: Schematic representation of an interconnected array of charged nanoparticles immersed in an electrolyte.

Right side: Lattice parameter a (right ordinate) and lattice strain $\Delta a/a_0$ (left ordinate) as a function of the applied potential.

Evaluation referring to our definition of Nanotechnology:

This effect turns out to be a nanoeffect, following a non-continuous trend with the particle size. Consequently, this example fulfills the definition as a particular interface effect (see 4.1).

Application:

Substitution of piezo ceramic components. Besides the control over strain, this effect may lead to applications for materials with tunable electrical conductivity, optical absorption, and magnetic interactions.

Reference:

Weissmüller J., et al., *Science*, 2003, 300, 312

5.2.4 Thermoelectric Materials (C1/2/3)

Cells of the table: Electric/electronic properties of metals, insulators and semiconductors

Explanation:

One-dimensional nanowires, two-dimensional superlattices as well as zero-dimensional quantum-dots in segmented nanowires can exhibit substantially higher efficiencies in the thermoelectric power compared to the three dimensional bulk materials. This is due to an enhanced density of states (DOS) at the energy band edges cause by quantum confinement effects, since the thermoelectric power factor increases with DOS. Together with the increased phonon scattering from the surfaces in low-dimensional systems, this will lead to a reduction in the lattice thermal conductivity and hence to an increase in ZT , which depends on the Seebeck-Coefficient, the specific electrical conductivity, the thermal conductivity and the temperature, being the dimensionless figure of merit of a thermoelectric solid.

The most important thermoelectric materials are Bi metal as well as Bi-Te, Bi-Sb and Pd-Te intermetallic compounds. So far, the best bulk material is $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$.

With nanowires of these materials, an enhancement of the thermoelectric performance could be achieved.

Evaluation referring to our definition of Nanotechnology:

This example fulfills the definition as a quantum size effect (see 4.1).

Application:

Important for the development in solid state refrigerators as well as of cooling elements on integrated microelectronic chips.

References:

Dresselhaus M.S., et al., *Microscale Thermophysical Engineering*, 1999, 2, 89

Ryan M.A., Fleurial J.-P., *Interface*, The Electrochemical Society, 2002

5.2.5 Quantum Size Effects (QSE) (C1/2/3)

Formation of Discrete Energy Levels (D1/3)

Photoluminescence (D3)

Cells of the table: Electric/electronic properties of metals, insulators and semiconductors; Optical properties of metals and semiconductors

Explanation:

If nanoparticles are much smaller than the characteristic length scales characterized by the De Broglie wave length, the mean free path and the phase relaxation length, so called size quantization effects or quantum size effects (QSE) dominate the physical properties. Therefore these particles are described as ‘‘quantum dots’’. The band gap increases and the energy spectrum of these particles tend from a continuous density of states (DOS) into discrete energy levels (i.e. quantization of the energy states) as in an artificial atom. The energy of electronic excitations (i.e. the levels spacing) is a material specific property and scales with the particle size following roughly a $1/r^3$ scaling law.

Accordingly, a decrease in particle size shifts the optical absorption of semiconductor nanoparticles from the infrared to the visible range of the electromagnetic spectrum. According to a chemically based notation, the highest occupied energy state and the lowest unoccupied state may be described as a HOMO and a LUMO, respectively.

Optical absorption spectroscopy is typically used to study the quantum-size effects in semiconductor nanoparticles, particularly the enlargement of the energy gap and the enhancement of the excitation energy. Due to broadening effects in absorption spectroscopy, resulting from particle size distribution, the resolution of the discrete states by quantum confinement is extremely difficult. Utilizing photoluminescence excitation and analysis of a narrow spectral line of the full luminescence appears to be of great advantage. In nanoparticles, the emission characteristics can chemically be tuned by surface modification. In technologically relevant semiconductors, like Silicon or Germanium, which do not show luminescence in the macroscopic state, size dependent emission occurs.

In metal nanoparticles the discreteness of the electronic states effects the self capacitance of the particles as well as the electrical transport properties (tunneling rate and time), since the electron distribution is no longer a pure Fermi one. The self capacitance determines the charging energy of the particles, which represents the change in the potential energy of the particle when an extra charge is added. The charging energy scales in a classical description with $1/r$.

Evaluation referring to our definition of Nanotechnology:

Although scaling laws can be determined, this effect represents a quantum effect, which can only be achieved in the nanometer range. The particles may be regarded as systems consisting of atoms, ions and additional stabilizing molecules as sub-units or as sub-units, being building blocks for single electron tunneling or quantum-optical devices. Consequently, this example fulfills the definition as a quantum size effect (see 4.1).

Applications:

Nanoelectronics, quantum optics, data communication, solar energy conversion, catalysis (due to the high surface to volume ratio), diagnostics (optical labels), therapy (hyperthermia).

References:

Simon U., Schön G., *Handbook of Nanotechnology and Nanostructured Materials*, Academic Press, 2000

5.2.6 Plasmonics (D1)

Photonic Surface Plasmons (D5)

Cells of the table: Optical properties of metals and hybrids/composites

Explanation:

Plasmons are collective electron oscillations which can be excited by external electromagnetic radiation such as light or by the impact of electron on conductive systems (c.f. D1). Surface electrons as a subset of plasmons are bound to the surface or interfacial region of a metallic object and thus can be used for probing the vicinity of interfaces and surfaces due to the presence of evanescent electromagnetic fields close to these interfaces.

In two-dimensional metallic layers, these plasmons are representing guided non radiative electromagnetic waves. Since the dispersion relation of surface plasmons is different from freely propagating electromagnetic waves such as light, special setups need to be used to satisfy energy and momentum conservation. This can be done for example by using the so-called Kretschmann setup, consisting of a transparent (glass) prism and a thin metallic coating (thickness typically 50 nm) allowing to excite surface plasmons by means of total reflection of the incoming light at the basis of the optically transparent prism.

The field enhancement normal to the surface on small metal particles together with the high sensitivity of the surface plasmon to the index of refraction of the surrounding medium can be used to probe changes in the chemical or dielectric environment of the particle.

Field localization effects can be used by means of arranging plasmon resonators to guide surface plasmon polaritons (plasmonics). In this way, nanoscopic devices can be made which allow us to generate optical waveguide structures exhibiting spatial dimensions far below the wavelength of light.

Evaluation referring to our definition of Nanotechnology:

This effect fulfills our definition of Nanotechnology due to the requirement of thin conducting layers consisting of a limited number of constituents.

Applications:

The application of surface plasmon ranges from the generation of interference lithography patterns by using resonant surface plasmons to the set-up of optical guides in nanooptical devices as well as to sensor devices based on the interaction of molecular systems at the plasmon guiding metal surface or a nanoparticles. The latter effect can be used, for example, for the generation of highly sensitive and specific biosensors (c.f. H5) by modifying the metal surface with biologically active molecules. Another application is in the field of nearfield optical applications as well as the generation of novel nearfield optical probes making use of surface plasmons at glass/metal interfaces (tetrahedral tip). These systems can then be used to generate novel nearfield optical probes with high transmission factors.

References:

Maas H.-J., Heibel J., Fuchs H., Fischer U.C., Weeber J.C., Dereux A., *J. Micr.*, 2003, 209, 241

Okamoto T., Yamaguchi I., Kobayashi T., *Optics Lett.*, 2000, 25, 372

5.2.7 Surface Plasmon Resonance (D1/6)

Cell of the table: Optical properties of metals and boundary surfaces

Explanation:

The surface plasmon resonance of metal nanoparticles is based in the confined electron gas of the particles: the surface electrons are oscillating with respect to the positive metal core. Due to the excitation of plasmon resonances in the electron gas by visible light, nanoparticles of numerous transition metals show intensive absorption maxima in the UV-visible spectra. For instance, gold, silver, and copper nanoparticles of ca. 20 nm exhibit plasmon resonances at ca. 520nm, 385 nm, and 560 nm, respectively. These absorption phenomena are quantitatively described by the Mie theory (Mie

1908; Kreibig and Vollmer 1995), in which the theoretical absorption spectrum of dilute spherical particles is related to their size and relative dielectric properties compared to the surrounding medium. The wavelength of the absorption maximum is also dependent on the size and shape of the particles and on their proximity to each other. It has been shown that the absorption spectrum for gold nanoparticles in water changes characteristically with changes in the aspect ratio of the particles. For instance, if the ratio of the major to the minor axes changes from 1 to 4, the absorption maximum splits into two peaks, one corresponding to the transverse resonance and a second corresponding to the longitudinal resonance which shifts from 520 nm to 770 nm.

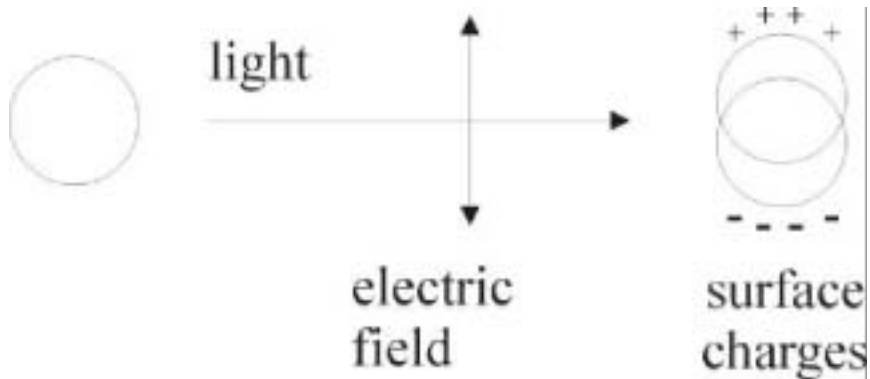


Figure: Excitation of a dipolar surface plasmon polariton by the electric field of an incident light.

The surface plasmon band is also sensitive to changes in the surface composition of the particles and to the presence of adsorbates. Deposition of a second metal at the surface also has a marked effect on the spectra. The amplifying effect of two combined appropriate metals constitutes new knowledge.

Evaluation referring to our definition of Nanotechnology:

The plasmon resonance of distinct metals is appearing spontaneously when the particles' size reaches an extension where electron confinement has developed to an extent to interact with visible light. Therefore, this phe-

nomenon follows the conditions of the definition, since the relevant particles exhibit their properties due to a limited number of constituents (atoms).

Application:

Coloring of glasses, ceramics, etc. Tuning of the color by the kind of metal, shape and size of the nanoparticles and of the surrounding medium.

References:

Kreibig U., Vollmer M. (eds.), *Optical Properties of Metal Clusters*, Springer Series in Materials Science 25, Springer, 1995

Mie G., *Annal. Phys.*, 1908, 5, 377

5.2.8 *Size as Additional Variable in Thermodynamics (E1/2/3)*

Cell of the table: Thermodynamic properties of metals, insulators and semiconductors

Explanation:

The very often simplified definition of thermodynamic functions must be modified to take into account the large contribution of the interface and surface energy which in the nano-regime is comparable to that of the nanoparticles volume energy. The characteristic thermodynamic size associated with the qualitative modification of thermodynamic parameters in nanoparticles depends strongly on the relation between volume and surface energy. Typical values for this characteristic length are ~ 10 nm. Phase diagrams with one of the constituent phases being a nanophase are quite new. Simplest estimates of phase equilibrium may be obtained by taking into account the contribution of surface energy to the free energy. Melting temperature, temperatures of polymorphous transformations and other characteristics of phase diagrams depend on the nanophase size. Thus, the phase diagram of binary nanophase materials become three-dimensional, the third coordinate being the size.

The relative difference of phase transition temperature between nanoparticles and massive bodies may be derived from the Clausius-Clapeyron relationship. One particular phenomenon of interest is the size-dependent melt-

ing point depression in nanomaterials – small particles have a lower melting point than the bulk. The first tries for a theoretical understanding of the melting of small particles were made within a macroscopic framework, using thermodynamic concepts such as surface energy. These analytical models predict a progressive depression of the melting point with decreasing particle size. While this approach is found for mesoscopic particles with thousands of atoms, its applicability to much smaller clusters (where most if not all atoms are on the surface) is obviously tenuous. The melting point depression is a direct consequence of the increase in the number of surface atoms with decreasing size. These atoms are more loosely bound than in the bulk that facilitates the melting of the nanostructure. These changes in the melting temperature with decreasing size can roughly be described by thermodynamic models.

In the solid state, with decreasing nanoparticles size the phase with lower surface energy (packed more tightly) becomes energetically favored. For example, in the case of the common body-centered cubic (BCC) and face-centered cubic (FCC) crystal lattice, the latter may become energetically more favorable, since its specific volume and surface energies are less than those of the bcc lattice.

It is interesting to note that 1963 Hill has developed a thermodynamic model of small systems which goes much further than only to stay in the macroscopic approach and to add a surface term. The work was not developed any further by him, but since 1994, after re-publication of earlier books, thermodynamics play an ever growing role in understanding mesoscopic phenomena (Hill 1994; 2001a; 2001b).

Evaluation referring to our definition of Nanotechnology:

Thermodynamic properties are changing in a monotonous way with decreasing sub-unit size. This can be easily seen with the decreasing melting temperature with decreasing particle size. Also the phase change (at a given temperature) is the result of a continuous process, because it is the free energy of the systems which is changing in a continuous way with decreasing domain or particle size. On the other hand, we know that we need a significant extension of classical thermodynamics to describe

nanoscale phenomena. Consequently, this example fulfills the definition as an effect due to the limited number of constituents; moreover particular interface effects might be relevant (see 4.1).

Application:

An application of this “nanoeffect” is the low temperature sintering. Nanometer-sized CeO₂ can be sintered at low temperatures to dense ceramics with nanometer-scaled grain size by the additions of transition metal oxides. The rapid densification may be attributed to size-dependent melting of the dopant in the neck region of the particle contacts.

References:

Hill T.L., *Nanoletters a*, 2001, 1, 111

Hill T.L., *Nanoletters b*, 2001, 1, 273

Hill T.L., *Thermodynamics of Small Systems*, Dover, New York, 1994

5.2.9 *Magnetic Dipole-Dipole Interaction (G1)*

Cell of the table: Ability for self-assembly of metals

Explanation:

Colloidal forces or capillary forces which are generated during drying processes are very often responsible for the ordered array of particles. Therefore, it must be distinguished between such common effects and intrinsic forces leading to an ordered arrangement of particles. Ferromagnetic particles or superparamagnetic particles in a magnetic field interact via magnetic forces rather than via capillary forces. If the particle height is much smaller than the interparticle distance, they may be approximated by short magnetic dipoles with the pair-interaction energy W which depends directly from the magnetic moment m of the particles and of the inverse of the distance between the particles r .

$$W_{ij} = \frac{\mu_0 m_i m_j}{4\pi r_{ij}^3}$$

For identically oriented particles, the interaction is repulsive; therefore, a confinement like a topological or chemical structured surface is required to

hold particles together. When few hundreds of particles are confined within the walls of a trough the particles in the center exhibit an ordering with a hexagonal symmetry. Formation of crystalline like structures with the preference of hexagonal over square ordering in large 2D arrays of interacting particles is quite a general phenomenon and has been theoretically demonstrated for several isotropic long-range and short-range interaction potentials. Experiments on colloidal particles with electric dipole interactions, and magnetic holes in ferrofluids also demonstrate hexagonal ordering (Golosovsky et al. 1999).

Cobalt nanodiscs are ferromagnetic and can spontaneously self-assemble into long ribbons from stacked nanodiscs lying perpendicular to the substrate. Note, that a side view of the nanodiscs in transmission electron microscopy (TEM) images (Figure) strongly resembles nanorods and TEM tilting experiments are necessary to verify the disc shape (Puntes et al. 2002). As-prepared FePt nanoparticles exhibit the chemically disordered fcc structure with relatively poor magnetic properties. Thus, fcc FePt nanoparticles are superparamagnetic at room temperature and can be handled in form of colloidal solution for casting films, making self-assembled arrays, etc.

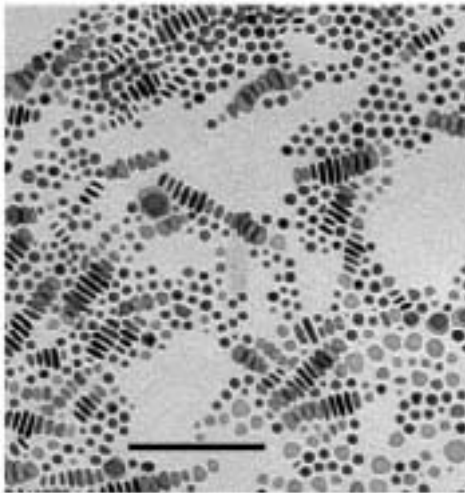


Figure: TEM partially self-assembled Co nanodiscs. Bar is 100 nm (Puntes et al 2002).

Evaluation referring to our definition of Nanotechnology:

The ability for self-assembly or self-organization is a “nanoeffect” if others than colloidal forces are used. Due to the fact that the particles have to be smaller than the distance between the particles and the forces used are only active in a short range, only nanosized particles can show this effect. Consequently, this example fulfills the definition as a particular interface effect (see 4.1).

Application:

The self-assembly is a very important process for the realization of nanostructures in 1 and 2 as well as in 3 dimensions. Such structures will be used in electronic devices, sensors and in biomedical applications like tissue bioengineering or in the synthesis of biomimetic structures.

References:

Golosovsky M., Saado Y., Davidov D., *Appl. Phys. Lett.*, 1999, 75, 4168

Puntes V.F., Zanchet D., Erdonmez C.K., Alivisatos A.P., *J. Am. Chem. Soc.*, 2002, 124, 12874

5.2.10 Ferroelectrics and Superparaelectrics (C2)

Cell of the table: Electric/electronic properties of insulators

Explanation:

Ferroelectrics are dielectric materials (e.g. Perovskites) which show a spontaneous polarization and in which the direction of the polarization can be reoriented between crystallographically defined states by an external electric field. The polarization appears in a uniform direction and extends over domains. The domains are separated by domain walls, which have a typical size of 1-10 lattice parameters. The domain size itself depends on the material and can be as small as 20 nm, whereas the orientation of neighboring domains is anti-parallel. Below this size a transition from the ferroelectric phase to the superparaelectric phase appears, which has no spontaneous polarization, whereas epitaxial thin film piezoelectric activity was observed down to 4 nm.

Evaluation referring to our definition of Nanotechnology:

This transition reflects a collective phenomenon and represents a nanoeffect, due to the limited number of constituents.

Application:

Ferroelectrics are very promising materials for logic devices, i.e. ferroelectric field effect transistors as well as in ferroelectric random access memories.

Reference:

Richter D., Trolrier-McKinstry S., in: *Nanoelectronics and Information Technology*, Waser R. (ed.), Wiley-VCH, Weinheim, 2003

5.2.11 Transparent Ceramics (D2)

Cell of the table: Optical properties of insulators

Explanation:

Conventional “transparent“ alumina ceramics exhibit poor mechanical properties and a low in-line transmission of unscattered light (< 15 %) because of coarse micro-structures (grain size > 20 μm); in fact, they are optically not clear and rather translucent than transparent. The new nano-sized $\alpha\text{-Al}_2\text{O}_3$ ceramics avoid these shortcomings and can be manufactured with very complex shapes. Such materials show in-line transmission (wave length = 640 nm) > 70 % at thickness 0.8 mm, the same high infrared transmission as sapphire in the 3–5 μm range and an extremely high strength (600–850 MPa) because the defect size is also in the nm range. The hardness, scratch and wear resistance are also very high.

Many different reasons for scattering events in an alumina ceramics exist: rough surfaces, pores, inclusions and grain boundaries. Of these mentioned reasons, only scattering at the grain boundary and pores is of interest in the framework of this project. The other scattering effects can be eliminated by optimized processing or the use of very high purity powder. At grain boundaries, the scattering has two reasons: reflection and refraction. The reflection at grain boundaries of alumina is caused of its hexagonal crystal

structure, alumina is birefringent. The Raleigh-Gans-Debye Theory shows that at grain sizes smaller than 1mm, the scattering of light caused by refraction is negligible. The scattering at pores shows a maximum in the region of the wavelength of the light (Mie theory); nearly no scattering can be observed at pore sizes smaller than 10 nm. Between these extreme values, significant scattering of light occurs because the refractive index of pores (air) and the ceramics bulk material is too different.

Evaluation referring to our definition of Nanotechnology:

Transparent ceramics is an example which shows that the observed “macroscopic” properties can change in a continuous manner, but the mechanisms behind the observation are changing strongly. At a given grain size, they change relatively fast. The type of scattering is changing for materials with nanosized pores. Consequently, this example fulfills the definition as a particular interface effect (see 4.1).

Application:

The importance is relatively low, only some niche markets exist (lamps, watches).

References:

Krell A., Blank P., Ma H.W., Hutzler T., van Bruggen M.P.B., Apetz R.,
Journal of the American Ceramic Society, 2003, 86, 12

Krell A., Ma H.W., *CFI-Ceram Forum Int.*, 2003, 80, 41

5.2.12 Phonon Engineering (F2/3)

Cell of the table: Thermal properties of insulators and semiconductors

Explanation:

Phonon heat transfer at the nanoscale differs from that at the macroscale due to several fundamental reasons. In bulk materials, internal scattering dominates the heat transfer processes. As the size shrinks, the frequency of the phonon–boundary collision increases. The interface scattering of phonons and the associated thermal boundary resistance can dominate heat

conduction in nanostructures. The size effects, however, are not limited to the thermal processes inside nanostructures. In the vicinity of small devices, phonons become rarefied when their mean-free-path is comparable or larger than the device size, which effectively increases the thermal resistance for removing heat from the devices. In addition, the phonon spectra can also be altered in small structures. Understanding these physical processes is important not only for the prediction of the microelectronic device temperature rise and reliability, but can also enable new technology development such as low dimensional thermoelectrics .

Beside the thermal conductivity, the influence of the nano-regime on the specific heat is of interest. As mentioned above, the phonons are scattered at the boundary of the nanocrystals. This scattering generates new phonon frequencies in a nanocrystal which contributes to the specific heat. The well known Debye law for the specific heat at low temperature will be suppressed by this kind of boundary scattering if there are a large number of small particles. In ferromagnetic materials scattered spinwaves contribute also to the specific heat. Compared to bulk material, the specific heat of nanocrystalline material is enhanced by 10 to 20 % for temperature $<$ the Debye temperature. For temperature $>$ the Debye temperature, no influence of the size of the crystals is reported.

Evaluation referring to the above mentioned definition of Nanotechnologie:

The “nanoeffect” is a mixture of quantum effects and surface or interface effects and therefore fulfills our definition.

Application:

Assisted by recent advances in materials processing and techniques for phonon generation and control, phonon engineering can significantly enhance the performance of nanostructure solid-state devices. The interest is to identify, develop, and implement device configurations in which phonons and the coupling of phonons to electrons and holes leads to enhanced device performance. Unlike bulk materials, the phonon properties of these low-dimensional systems and, in particular, the phonon fre-

quency, group-velocity, spectral density, as well as the strength of the interaction with carriers can be widely modified.

Another interesting field of application is the use of nanostructured layers for improved thermal barriers. Calculations as well as experimental investigations have shown that the thermal conductivity of insulators can be decreased by a factor of 10 (Braginsky et al. 2002).

References:

Braginsky L., Lukzen N., Shklover V., Hofmann H., *Phys. Rev. B*, 2002, 66, 134203

Chen G., Zeng T., Borca-Tasciuc T., Song D., *Mat.Sci.Eng. A*, 2000, 292, 155

Klemens P.G., Gell M., *Mat Sci. Eng. A*, 1998, 245, 143

5.2.13 *Quantum Antidots (A3)*

Cell of the table: Magnetic properties of semiconductors

Explanation:

A quantum antidot (*qad*) is formed when a potential barrier is introduced into a two dimensional electron system subjected to an external magnetic field. *Qads* can be produced by lithography or by self organization processes resulting in arrangements of electronically and optically inactive or hole structures (nano-rings), which localize electronic states. This is complementary to conventional quantum dot structures which confine an electronic system to the size of extension of dot (c.f. D 1-3). Thus, *Qads* represent regions of electronic exclusion rather than confinement as in the case of quantum dots.

The structures can be used for inducing resonant tunneling and also many fundamental body quantum mechanical effects.

Evaluation referring to our definition of Nanotechnology:

The effect occurs only when the Debye length of the electronic system under consideration is comparable to or larger than the spatial extension of

the antidot structure. Consequently, this example fulfills the definition as a quantum size effect (see 4.1).

Application:

Qad structures can be used in electronic and optical devices such as for building a novel highly sensitive electrometer device for the observation of fractionally quantized electrical charges (quantum Hall regime). Due to many body interactions around *qad*, magnetic effects such as Kondo behavior may be induced.

References:

Karakurt I., Goldman V.J., Liu J., Zaslavsky A., *Phys. Rev. Lett.*, 2001, 87, 146801

Kataoka M., et al., *Phys. Rev. Lett.*, 2002, 89, 226803

5.2.14 *Molecular Magnetism (A4)*

Cell in the table: Magnetic properties of molecules

Explanation:

Particular molecular subunits provide small magnetic moments due to the spin of unpaired electrons. Organic stable radicals or open spin metal complexes are typical members of such subunits. Modern chemistry enables one to combine several of such subunits to larger molecular architectures as nano-objects. Current endeavors are focused on the control of the interactions of the individual magnetic moments of the subunits in such a nano-object. Of particular interest is the combination of subunits in a way that adds up the small magnetic moments of each subunit to a larger over-all moment of the nano-object, entitled “single molecule magnet” (SMM) (Barbara and Gunther 1999; Sangregorio et al. 1997). Considerable progress has been made by combining several open spin metal complexes to so-called spin clusters. A typical example of a spin cluster that combines 12 open spin manganese atoms is shown in the figure bellow (Sessoli et al. 1993; Gatteschi et al. 1994).

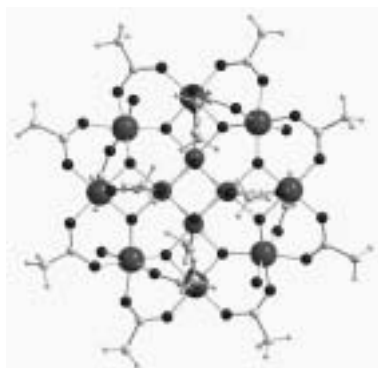


Figure: Model of the “Mn12” spin cluster $Mn_{12}O_{12}(CH_3CO_2)_{16}(H_2O)$. Mn: red, O: blue, C: grey.

Such single molecule magnets are magnetic particles well defined in size and shape which display a slowly relaxing magnetic moment.

Evaluation referring to our definition of Nanotechnology:

Molecular Magnets are based on the tailored coupling of molecular subunits. Due to the nm scale-length of the building blocks, the interaction between subunits and the magnetic behavior of the resulting “Molecular Magnet” can only be described with quantum mechanical rules instead of classical physical laws. Hence “Molecular Magnets” fulfill the requirements of the definition for Nanotechnology as a quantum size effect and due to the limited number of constituents (see 4.1).

Application:

Molecular magnets are of particular interest as nanoscale objects which may serve as very small memory units in the future. Applications are low cost short time memory devices like phone cards.

References:

Barbara B., Gunther L., *Physics World*, 1999, 35

Gatteschi D., Caneschi A., Pardi L., Sessoli R., *Science*, 1994, 265, 1054

Sangregorio C., Ohm T., Paulsen C., Sessoli R., Gatteschi D., *Phys. Rev. Lett.*, 1997, 78, 4645

Sessoli R., Gatteschi D., Caneschi A., Novak M.A., *Nature*, 1993, 365, 141

5.2.15 Molecular Motors (Machines) (B4)

Cell of the table: Mechanic properties of molecules

Explanation:

A *Molecular Motor* is an object consisting of at least two parts which can be moved relatively to each other. These parts are either molecular subunits that are linked by a covalent bond which is at the same time the rotation axis of the motor, or the parts of the molecular motor are supramolecular subunits (individual molecules) assembled by supramolecular interactions. A beautiful example of a rotating supramolecular system has been found in the biological system F_1 -ATPase (Noji et al. 1997; Elston et al. 1998). Its rotation axis is a rod like molecular structure surrounded by a molecular substructure of the second subunit as bearing. There have been attempts to realize molecular motors that rotate due to the thermal motion in only one direction with a design concept comparable to a Brownian ratchet (Kelly et al. 1997). However, this concept has not been realized yet (Davis 1998). A few examples of molecular motors with rotations based on sequences of chemical reactions are reported (Kelly et al. 1999; Koumura et al. 1999; Balzani et al. 2000). These motions are not fast enough or useful for any technical application, they rather allow to investigate fundamental basics on molecular motors in details.

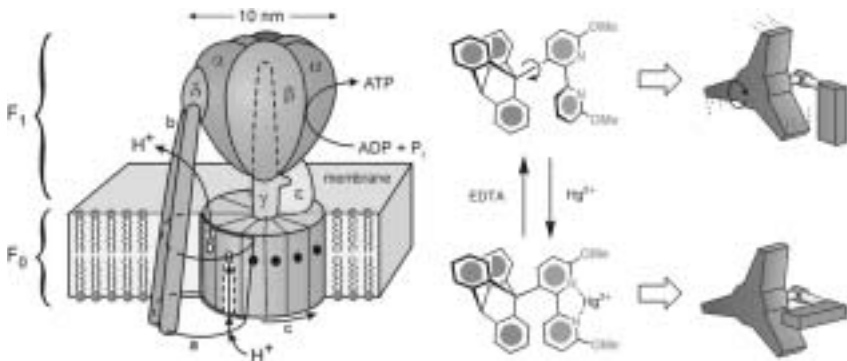


Figure: Left side: The structure of F_0F_1 ATP synthase embedded in a lipid bilayer membrane (Noji et al. 1997; Elston et al. 1998; picture from Balzani et al. 2000) Right side: A molecular brake is engaged upon complexation of mercury ions in a molecular motor with a carbon-carbon single bond as rotation axis (Kelly et al. 1994; picture from Balzani et al. 2000).

The mechanical motion is not limited to rotations. There are molecular systems known where two subunits approach and separate from each other or where molecular subunits move on molecular rods or on particular surfaces. These objects are rather called molecular machines (Balzani et al. 2000). An example is a supramolecular system consisting of two identically interlocked objects, namely a ring connected to a rod-like structure. The rod like structure of one unit is in the ring of the other unit and by electrochemical manipulation, the relative position of the rings on the rod can be adjusted. Thereby the supramolecular system behaves like an electrochemically triggered muscle (Jiménez et al. 2000).

Evaluation referring to our definition of Nanotechnology:

Molecular Motors and *Machines* display motions of (supra)molecular subunits relative to each other that are inspired by the engines of the macroscopic world. These motions are properties that evolve from a limited number of constituents and hence, these systems fulfill the definition for Nanotechnology.

Application:

The natural system F_1 -ATPase is controlling two different potentials across a membrane which are coupled to each other by the F_1 -ATPase as a system resulting in a mechanical motion. However, particular reasons to couple this control to a mechanical molecular motion have not been found by the authors. Currently, there are no commercial applications of this emerging scientific field realized, but it provides a promising potential for the future.

References:

- Balzani V., Credi A., Raymo F.M., Stoddart J.F., *Angew. Chem. Int. Ed.*, 2000, 39, 3349
- Davis A.P., *Angew. Chem.*, 1998, 110, 953
- Elston T., Wang H., Oster G., *Nature*, 1998, 391, 510
- Jiménez M.C., Dietrich-Buchecker C., Sauvage J.-P., *Angew. Chem. Int. Ed.*, 2000, 39, 3284

Kelly T.R., Bowyer M.C., Bhaskar K.V., Bebbington D., Garcia A., Lang F., Kim M.H., Jette M.P., *J. Am. Chem. Soc.*, 1994, 116, 3657

Kelly T.R., Tellitu I., Sestelo J.P., *Angew. Chem. Int. Ed.*, 1997, 36, 1866

Kelly T.R., Da Silva H., Silva R.A., *Nature*, 1999, 401, 150

Koumura N., Zijlstra R.W.J., van Delden R.A., Harada N., Feringa B., *Nature*, 1999, 401, 152

Noji H., Yasuda R., Yoshida M., Kinoshita K., *Nature*, 1997, 386, 299

5.2.16 *Molecular Switches (C4)*

Cell of the table: Electric/electronic properties of molecules

Explanation:

Molecules and supramolecular systems that can be switched between two different states (metastable) by external stimuli may be referred to as *Molecular Switches*. Of particular interest are systems that provide rather large differences in the physical property of interest (like absorption, emission, conductance, etc.). In addition, if this difference in the physical property is sufficiently high, these molecules may be used as molecular storage elements if good control of the addressing, switching and reading of the actual state of the molecules is realized. Some possibilities of such bistable molecular switches are (Mayor et al. 2003).

- a) A reduction-oxidation (redox) process may change between neutral and ionized acceptor/donor groups of a given molecule.
- b) A configuration change may take place through a reversible re-arrangement reaction.
- c) A conformation change may be controlled in a manner that both conformations are sufficiently stable at the operation temperature of the designated storage element.
- d) Electronically excited states may be used as one state, if the lifetime of excited state R^* is sufficiently high.
- e) Spin magnetic moments may also be used as states for memory devices.

In all cases, bistable switches are characterized by double well potentials concerning their energy and exhibit a hysteresis when driven between the two states. Often only the combination of more than one of the above described effects results in the desired hysteretic properties.

An example of a supramolecular system as a molecular hysteretic switch is the catenane synthesized by Asakawa et al. (1998). It consists of two interlocked rings (definition of a catenane) that are decorated with electrochemically active subunits. Temporary charging of particular subunits by an applied electric potential results in a controlled motion of one ring relative to the other to another stable configuration due to Coulomb interactions. It is noteworthy that the system can hence be considered as *Molecular Machine* (see above, B4) as well. Both configurations are stable at zero volt. However, immobilized between two electrodes as monomolecular layers (Collier et al. 2000), they differ considerably in the observed tunnel currents, an effect that allows to observe the actual state of the switch.

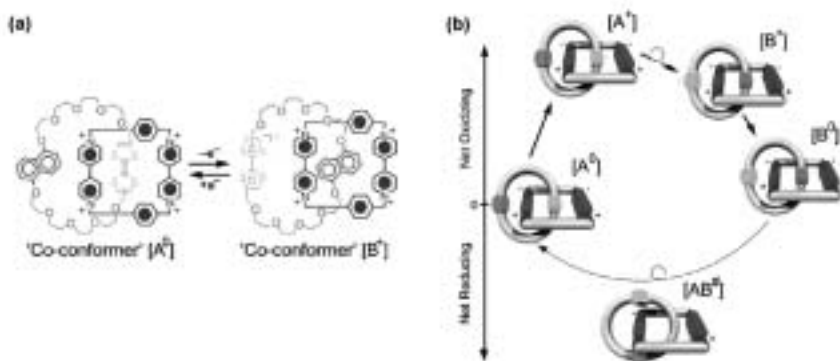


Figure 1: (a) Schematic representation of both stable configurations of the supramolecular catenane switch. (b) Switching by temporary charging of particular electrochemical active subunits on the rings.

An example of a molecular system as switch is the light driven system first described by Irie (1993). The switch is based on the fact, that the forward and back reaction of an intramolecular ring-closure can both be triggered by light of different wave-lengths. As both states display pronounced differences in their electron transport abilities, the system as switchable molecular subunit has already been integrated in numerous experiments.

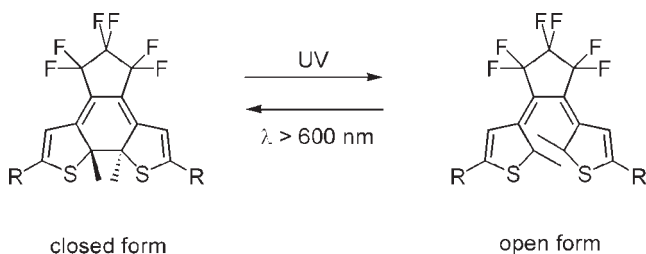


Figure 2: The “Irie”-switch based on two light induced ring-closure and ring-open reactions. Charge can be moved much easier between the thiophene units in the closed conjugated state on the left side.

An overview of molecular switches is given in the recent book “molecular switches” by Ben Feringa (2001).

Evaluation referring our definition of Nanotechnology:

Molecular Switches based on the relative mechanical rearrangement of molecular subunits (like e.g. the catenane described above) can be considered as *Molecular Machines* and hence obey the definition for Nanotechnology (see above B4). Other molecular switching behavior like e.g. a chemical rearrangement reaction can only be described by quantum chemical laws. Therefore, such systems also fulfill the definition of Nanotechnology.

Application:

The most promising application of molecular switches is their use as memory cells in the future. Companies like Hewlett Packard, Infineon, etc. have already signaled their considerable interest in such systems by increasing their research activities and cooperation related to the field.

References:

- Asakawa M., Ashton P.R., Balzani V., Credi A., Hamers C., Mattersteig G., Montalti M., Shipway A.N., Spencer N., Stoddart J.F., Tolley M.S., Venturi M., White A.J.P., Williams D.J., *Angew. Chem. Int. Ed.*, 1998, 37, 333
- Collier C.P., Mattersteig G., Wong E.W., Luo Y., Beverly K., Sampaio J., Raymo F.M., Stoddart J.F., Heath J.R., *Science*, 2000, 289, 1172

Feringa B.L. (ed.), *Molecular Switches*, Wiley-VCH, Weinheim, 2001

Irie M., *Mol. Cryst. Liq. Cryst.*, 1993, 227, 263

Mayor M., Weber H.B., Waser R. in: *Nanoelectronics and Information Technology*, Waser R. (ed.), Wiley-VCH, Weinheim, 2003

5.2.17 Field Emission (Nanotubes) and Field-Emission Display (FED) (C4)

Cell of the table: Electric/electronic properties of molecules

Explanation:

Carbon nanotubes and other inorganic nanorods have excellent materials properties which make them have attractive field emission characteristics. These properties are:

- a) Large aspect ratio > 1000
- b) Atomically sharp tips
- c) High chemical stability
- d) High temperature stability
- e) High electrical and thermal conductivity

They are hence capable of producing very high current densities at low operating voltages. Most of the studies on field emission from carbon nanotubes have focused on two terminal devices, which have limited potential for electronic device application.

Evaluation referring to our definition of Nanotechnology:

Since field enhancement at a conducting tip becomes continuously larger with decreasing tip diameter, extremely good emission properties may be expected from nanoscale objects, like nanotubes. At the same time, the reason for the high thermal and electrical conductivity as well as for the high temperature and chemical stability is not yet really understood and it remains unclear whether the individual nature of the carbon nanotubes

additionally effects the emission. Therefore, a final categorization turns out to be inappropriate at the moment (appears in table 1a and 1b).

Application:

The most developed idea of a CNT-device is a new kind of flat-screen display called the “field-emission display“, or FED. Conventional liquid crystal displays are certainly flat, but have a number of drawbacks like low image quality, a very restricted field of view, and high cost. FED technology addresses all these problems.

References:

Frankfurter Allgemeine Zeitung, *Bildschirm aus Nanoröhren*, Natur und Wissenschaft, 21. April 1999

Hoffschulz H., *Physikalische Blätter*, 2000, 26, 53

VDI-Nachrichten, *Nanotechnik kommt immer größer raus*, 22. September 2000, 38

5.2.18 Brownian Ratchet (E4)

Cell of the table: Thermodynamic properties of molecules

Explanation:

A *Brownian Ratchet*, currently under controversial discussion, is a device that converts random *Brownian* motion into an unidirectional momentum. A typical example is shown in figure 1 below. The *Pawl machine* consists of two parts, an asymmetric cogwheel with a pressed on mechanical lever that allows for rotation in only one direction and a vane which is randomly bombarded by small objects. As the device allows for only one sense of rotation it becomes selective concerning the bombardment events and hence should lead to a unidirectional rotation.



Figure 1: The Pawl machine is consisting of a vane and a wheel that can only turn in one sense of rotation. The vane is in a thermal bath of gas molecules at equilibrium. The whole device is considered to be reduced to microscopic size so gas molecules can randomly bombard the vane to produce motion.

However, this spontaneous motion is violating the second law of thermodynamics (at equilibrium the effect of thermal noise is symmetric, even in an anisotropic medium) and thus is very unlikely to happen, as was cited already 1914 by M. Smoluchowski: “No automatic, permanently effective perpetual motion machine can violate the second law by taking advantage of statistical fluctuations.” However, he added the surmise: “Such device might perhaps function if appropriately operated by intelligent beings.” (Smoluchowski 1914) That statement was countered in 1989 by W. H. Zurek: “The second law is safe from intelligent beings as long as their abilities to process information are subject to the same laws as these of universal Turing machines”. Models for brownian ratchets are objects of current research. The unidirectional rotation of a *Molecular Machine* based on the principle of a *Pawl* machine has been published (figure 2) (Kelly et al. 1997), but these objects were not able to overcome the second law of thermodynamics (Davis 1998).

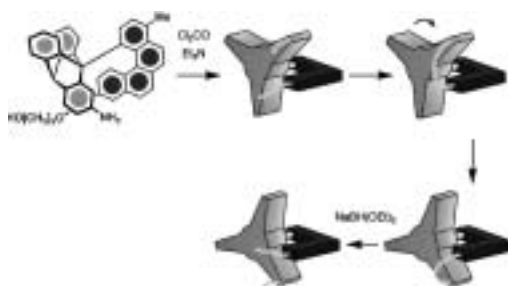


Figure 2: Compound 1 as molecular model of a Pawl machine allowing for unidirectional rotation (Kelly et al. 1999). The rotation is assisted by the formation of a covalent chemical bond that occurs only in one direction.

Another approach to *Brownian Ratchets* is focused on lateral random motion exposed to a saw tooth profile. As schematically shown in figure 3, the setup is designed to result in a directional movement of the particles.

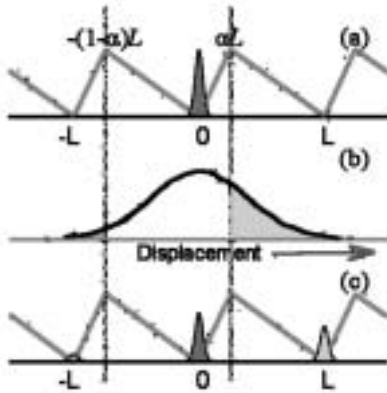


Figure 3:
The mechanism of the ratchet potential:
The Gaussian distributions of the particles' energy should result in a directional movement to the right side.

Currently there are several approaches to investigate biomolecules in combination with nano- and micro- patterned arrays (Bader et al. 1999; Oude-naarden and Boxer 1999). For example the transport of DNA molecules on a micromachined *Brownian Ratchet* silicon-chip device has been reported recently (Bader et al. 1999).

Evaluation referring to our definition of Nanotechnology:

The devices are designed to profit from the *Brownian* motion of particles. For example, to have a directional selectivity in a rotation device, the numbers of events acting on the device during an action step must be reduced enormously (ideally to one). On the other hand, the few numbers of events must provide enough energy to perform the action step. Hence, such concepts may work either theoretically or in reality at most for very small devices. Depending on the required size of a successful system, *Brownian Ratchets* may fulfill the definition of Nanotechnology (interactions of a limited number of constituents). However, whether this will be the case is still a subject of speculation.

Application:

Controlled directional motion of molecules on surfaces may be useful for future analysis devices.

References:

- Bader J.S., Hammond R.W., Henck S.A., Deem M.W., McDermott G.A., Bustillo J.M., Simpson J.W., Mulhern G.T., Rothberg J.M., *PNAS*, 1999, 96, 13165
- Davis A.P., *Angew. Chem.*, 1998, 110, 953
- Kelly T.R., Tellitu I., Sestelo J.P., *Angew. Chem. Int. Ed.*, 1997, 36, 1866
- Kelly T.R., Da Silva H., Silva R.A., *Nature*, 1999, 401, 150
- van Oudenaarden A., Boxer S.G., *Science*, 1999, 285, 1046
- von Smoluchowski M. in: *Vorträge über die Kinetische Theorie der Materie und der Elektrizität*, Teubner, Leipzig, 1914
- Zurek W.H., *Nature*, 1989, 341, 119

5.2.19 Nanoarchitectures (Nanostructures) (G4)

Cell of the table: Ability for self assembly of molecules

Explanation:

Molecules possess the ability to assemble themselves to highly ordered and perfectly defined nano-scale objects, which consist of several – in some cases even similar – molecules (Lehn 1995; Vögtle 1992; Beer et al. 1999). These objects, entitled *nanoarchitectures* or *nanostructures*, are held together by supramolecular interactions between the individual molecules, and sometimes coordinative interactions with particular ions are involved. The construction plan of a particular nanoarchitecture is an intrinsic property of its building blocks as it is stored in the structural features of the involved molecules and ions. As a consequence, these nanoarchitectures are designed by the chemical synthesis of their molecular building blocks. As physical properties (optic, magnetic, electronic, etc.) of a nanoarchitecture evolve from the interaction of the properties of the individual building blocks, they can be tailored to some extent by chemical synthetic means as well (Lehn 1995; Vögtle 1992; Beer et al. 1999). In addition, such nanoarchitectures may provide very promising self healing features as the perfectly designed molecule results in the most stable nanoarchitecture; an altered

molecular building block would be replaced by a perfect one resulting in the most stable architecture anew.

Numerous nanoarchitectures have already been synthesized and investigated in detail. As only one example, a supramolecular nanoarchitecture consisting of two flat ligands as bottom and top and three ligands as pillars held together by six copper(I) ions is shown below (Baxter 1993).

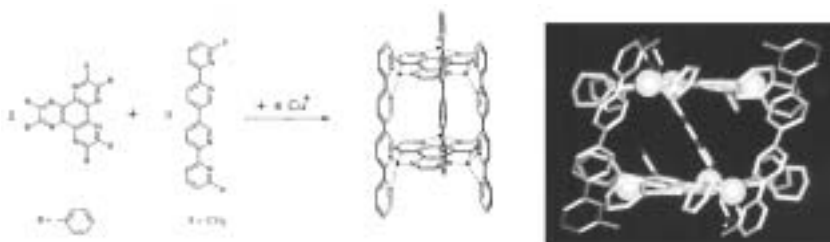


Figure: Left side: Synthesis of a supramolecular box, consisting of a top- and bottom-plate, three pillars and six copper(I) ions that hold everything together by coordinative bonds. Right side: solid state structure of the supramolecular box.

It is noteworthy that some of the objects described in the table elements *Molecular Magnetism*, *Molecular Motors* and *Molecular Switches* are nanoarchitectures as well.

Evaluation referring to our definition of Nanotechnology:

Physical properties of nanoarchitectures evolve from the interaction of molecular building blocks which consist of a limited number of constituents and are subject to quantum mechanical rules. Hence, these objects fulfill the conditions given in our definition of Nanotechnology.

Application:

Nanoarchitectures have already found numerous applications like sensors in environmental analysis and life science, signal amplifiers and transducer for optical signals, drug delivery systems and many others more. However, their application potential is much larger and many new applications are still to come.

References:

- Baxter P.N.W., Lehn J.-M., De Cian A., Fischer J., *Angew. Chem. Int. Ed. Engl.*, 1993, 32, 69
- Beer P.D., Gale P.A., Smit D.K., *Supramolecular Chemistry*, Oxford Chemistry Primers, 74, 1999
- Lehn J.-M., *Supramolecular Chemistry, Concepts and Perspectives*, VCH, Weinheim, 1995
- Vögtle F., *Supramolekulare Chemie*, Teubner Studienbücher, Stuttgart, 1992

5.2.20 Shape Complementarity (H4)

Cell of the table: Recognition ability of molecules

Explanation:

Closely related to the above discussed self-assemble features is the ability of molecular structures to recognize shapes and chemical properties of other molecules or surfaces. The most prominent example to illustrate this amazing properties are the base pairs of the DNA double helix, which encode our genome by shape complementarity of the arrangement of hydrogen bond donors and acceptors (see Figure below) (Watson and Crick 1953).

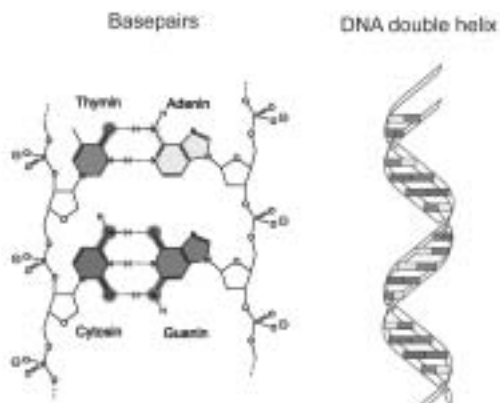


Figure: Left side: The two base pairs encoding the whole genome in a DNA double helix. Right side: schematic representation of a DNA double helix.

Numerous supramolecular recognition processes are known to be size selective. A typical example is the complexation of ions in crown ethers and cryptands, both molecular structures with cavities for ions (Lehn 1995). The stability of the formed molecule- ion-complexes is drastically increased when the size of the cavity is adjusted to the size of the particular ion. These selective complexation properties are known to be crucial in natural systems. For example the information exchange in nerve cells is based on ion gradients which are built up by selective complexation and the resulting transport events through the membrane of the nerve cell.

Evaluation referring to our definition of Nanotechnology:

The selective recognition of shape, size and function is based on interactions of a limited number of constituents on the molecular level which can only be described by quantum mechanical laws. According to our definition, these systems belong to Nanotechnology.

Application:

The main field of application of these recognition events is in life-science. Already the first known antibiotics for example were based on an increased ion transport through the bacteria's membrane. DNA binding is predetermined for life science and numerous applications are known today.

References:

Lehn J.-M., *Supramolecular Chemistry, Concepts and Perspectives*, VCH, Weinheim, 1995

Watson J., Crick F., *Nature*, 1953, 171, 737

5.2.21 Giant Magneto Resistance (GMR) (A5)

Cell of the table: Magnetic properties of hybrids/composites

Explanation:

The GMR-effect has been independently discovered in 1988 by Grünberg in Jülich and by Fert in Paris. They investigated 2-dimensional (2D) multilayers with an alternating series of ferromagnetic and non ferromagnetic

layers where the thickness of the layers is only a few atoms. The effect is based on an antiferromagnetic coupling of the magnetic layers via the non ferromagnetic layers. This leads to a decrease of the electrical resistance of the layer system when an external magnetic field is applied and all spins of the conducting electrons become oriented parallelly.

Meanwhile, the magneto resistive (MR) effect has also been found in nano wires (1D) and nano-granular systems (0D).

2D Magnetoresistive Systems (MR-Systems)

MR layers, e.g. Ag/NiFe, can be produced by Molecular Beam Epitaxy (MBE) or, much cheaper, simply by sputtering. The optimum layer thickness is in the range between 1 and 1,5 nm. During an optimization process by annealing between 200 and 300°C, an Ag-Ni-Fe-alloy is formed at the layer interfaces. These systems display a good antiferromagnetic coupling at moderate magnetic saturation fields of in the range of up to 1 Tesla combined with a reasonably detectable MR-effect of up to 20 % in dependence of the magnetic and the non magnetic layer thickness.

A comprehensive overview on magnetoelectronics in layered structures has recently been presented by Bürgler and Grünberg (2003).

1D Magnetoresistive Systems

1D MR-wires can be easily produced by intermitting galvanic deposition of ferromagnetic and non ferromagnetic layers consisting of a few atoms in nanoporous templates (Piroux et al. 1994; Ansermet 2003). The electrical resistance of a single nano wire is in the range of some 10 Ohms. This value is much higher than that in 2D-systems, which facilitates the evaluation of the effect. However, contacting discrete nano wires is much more difficult than it is in two-dimensional systems.

0D Magnetoresistive Systems

Granular systems with a mixture of powders of non magnetic and ferromagnetic materials can easily be produced e.g. by thick film technology (TFT) or by sputtering. Layers with granular powders display a large MR-effect up to 60%. But the required magnetic fluxes are at least one order of magnitude higher than in 2D-systems. This fact prevents an application of these systems up to now.

Colossal Magneto Resistance (CMR)

Some Perovskites like Lanthanum Strontium Manganese Oxide display a resistance change of up to 600 % at low temperatures at about 100 to 200 K when high external magnetic fields are applied. The limitations to high magnetic fields and to low temperatures prevent the application of the effect in an industrial environment up to now.

Spin Valve systems

IBM has developed a special GMR-structure called “spin valve” which is commonly used in magnetic read elements. In this structure, one magnetic film is pinned by adding a strong antiferromagnet as a fourth layer. The second magnetic film has a free variable magnetic orientation. When a weak magnetic field, such as that from a bit on a hard disk, passes beneath such a structure, the magnetic orientation of the unpinned magnetic layer rotates relative to that of the pinned layer, generating a significant change in electrical resistance due to the GMR effect. This structure was named the spin valve.

Evaluation referring to our definition of Nanotechnology:

The spin coupling effect is extremely sensitive to the geometrical dimensions in the nanometer regime. Thus, this example fulfills the definition as a quantum size effect (see 4.1).

Applications:

The 2-dimensional GMR is being used extensively in magnetic recording heads. Other applications under investigation are contactless working position sensors, e.g. for automotive steering wheel position or in anti lock systems (ABS).

References:

Ansermet J.-P., EPFL, ETH Lausanne, private communication

Bürgler D.E., Grünberg P.A. in: *Nanoelectronics and Information Technology*, Wiley-VCH, Weinheim, 2003

Piroux L., et al., *Appl. Phys. Lett.*, 1994, 65

5.2.22 High Strength Composites (B5)

Cell of the table: Mechanic properties of hybrids/composites

Explanation:

If the mechanical properties of nanotubes can effectively be incorporated into a polymer matrix, composites with very high strength can be achieved. Because of the large interphase surface present in nanocomposite materials, there is also the potential for enhanced dissipation of impact energy in these systems by crack deflection or crack branching. In the case of a high interface strength, the strength of a composite material is linked to the strength of the fibers embedded in the matrix. As both carbon and BN nanotubes have also an exceptionally high elastic modulus, using them as reinforcement fibers is a possible way to obtain ultra resistant materials. For its good chemical inertness, especially to oxygen, BN is the best candidate. The typical problem encountered practically is the adherence at contact surface between tubes and matrix material.

Polymeric nanocomposites (PNCs) (or polymer nanostructured materials) represent an interesting alternative to conventional-filled polymers or polymer blends. Uniform dispersion of nanosized filler particles produces ultra-large interfacial area per volume between the nanoparticles or nanofiber and host polymer. Literature provides many examples of PNCs, demonstrating substantial improvements in mechanical properties. Development of multicomponent materials, whether microscale or nanoscale, must simultaneously balance four interdependent areas: constituent-selection, fabrication, processing, and performance. Two main PNC fabrication methodologies exist: in-situ routes and exfoliation. Currently, exfoliation of layered silicates, carbon nanofibers/nanotube-polymer nanocomposites, and high-performance resin PNC's are of high interest. The objective of the exfoliation method of PNC fabrication is to uniformly disperse and distribute the inorganic mostly layered compound within the polymer.

Evaluation referring to our definition of Nanotechnology:

The increased toughness of the composite is mainly based on the increased strengths of the reinforcement nanosized material and the largely increased

interface area. Consequently, this example does not fulfill our definition of Nanotechnology.

Application:

Several potential applications have been identified in automobile (gasoline tanks, bumpers, interior and exterior panels, silica in tires etc.), constructive (shaped extrusions, panels), electronics and electrical sectors (printed circuits, electric components) and in food packaging (containers, films). Polymer based nanocomposites are the economically most important application of nanostructured materials today.

References:

Hamed G.R., *Rubber Chem Technol*, 2000, 73, 524

Thostenson E.T., Ren Z.F., Chou T.W., *Compos Sci Technol*, 2001, 61, 1899

Zilg C., Mulhaupt R., Finter J., *Macromol Chem Physic*, 1999, 200, 661

5.2.23 *Lowered Percolation Threshold (C5)*

Cell of the table: Electric/electronic properties of hybrids/composites

Explanation:

By using electrically conducting nanoparticles as fillers in polymer composites the percolation threshold can be considerably reduced down to the range of contents between 5 and 10 Vol%. From the agglomerated nanostructured powder different sieve fractions have been investigated. This property is not yet completely understood in theory.

Evaluation referring to our definition of Nanotechnology:

With decreasing grain size, a higher filling volume with decreasing overall density of the filling material can be achieved. This is already evident in macroscopic systems.

On account of the higher filling volume, many small particles are brought together so close that the electrons as charge carriers can tunnel from one grain to the other. Although the tunneling process which dominates the

electrical conductivity is a quantum mechanical effect, the change in the system properties follows a continuous trend and therefore does not fulfill the criteria of our definition.

Applications:

The effect can be advantageously applied in conductive adhesives which can be used for the mounting of Silicon chips on a substrate.

Reference:

Fa. Panacol, Fa. Bosch, Fraunhofer Institut FhG-IFAM Bremen, BMBF-Projekt 1996

5.2.24 Photochromism (PhChr) (D5)

Cell of the table: Optical properties of hybrids/composites

Explanation:

PhChr has been defined (Crano 1993) as a reversible change in the color, or darkening, of a material caused by absorption of ultraviolet (UV) or visible light. The reversion of the system to its original state can be driven either by thermal or photochemical energy (“photobleaching”), or both.

PhChr systems are naturally separated into two principal categories: inorganic and organic. There are several types of organic photochromic systems (Bouas-Laurent and Dürr 2001) involving a multitude of mechanisms. The photochromic reactions can be uni- or bimolecular.

Within the inorganic category, the mostly studied and commercially utilized systems are those containing silver halide nanocrystallites dispersed throughout a glass matrix. The mechanism of the silver halide PhChr is the reversible formation of the silver metal atoms with subsequent formation of silver clusters on the halide crystallite surface. Both the photochemical formation of the metal and the reformation of silver halide are catalyzed by copper ions.

Evaluation referring to our definition of Nanotechnology:

As already mentioned, the organic systems above are rather molecularly based, while the effect in inorganic photochromic systems is combined

with the nanoparticles and thus a real nanoeffect. Larger particles would display almost no visible change in transparency and color. Consequently, this example fulfills the definition for the limited number of constituents (see 4.1).

Applications:

Silver halide glass systems have been used in photochromic eyewear. Other possible application in the future could be smart windows, displays and memories (Fujishima 2002).

References:

Bouas-Laurent H., Dürr H., IUPAC Technical Report, *Pure Appl. Chem.*, 2001, 73, 639

Crano J.C. in: *Kirk-Othmer Encyclopedia of Chemical Technology*, Wiley-VCH, Weinheim, 1993

Fujishima A., *Nature Materials AOP Published Online*, 2002, |doi:10.1038/nmat796

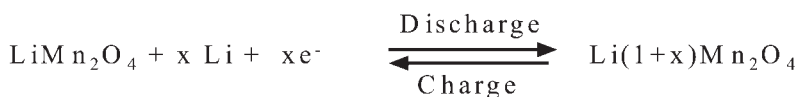
5.2.25 *Systems with Diffusion Limited Electrode Reactions (D5)*

Cell of the table: Optical properties of hybrids/composites

Explanation:

Lithium-Ion-Batteries with nanostructured electrodes

Batteries with Lithium Anodes have the highest electrical storage capacity with respect to weight and the highest standard potential²⁵ which makes them interesting for application in batteries. The cathode in these batteries is made of Lithium-Manganate. During the charging and discharging process, lithium-ions are moving between the electrodes due to the following reaction:



²⁵ www.powerstream.com/battery FAQ.html

The Lithium-ions are intercalated in the Carbon anode and embedded in the Lithium-Manganate cathode by a diffusion process. As figure 1 below on the left side displays, the diffusion path in nanostructured electrodes is much shorter than in bulky electrodes. This means that charging and discharging processes are facilitated (figure 2) and that the capability of loading the battery is considerably increased.

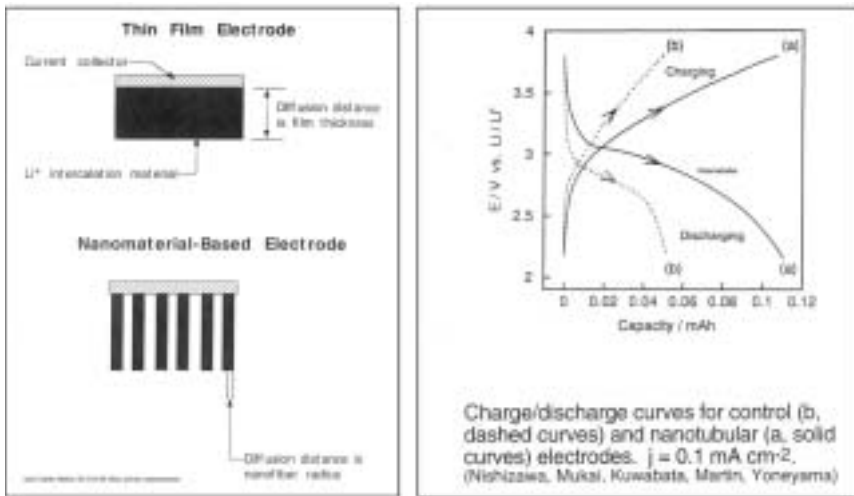


Figure 1 (C. Martin)

Figure 2

The nanostructured electrodes can be produced e.g. by using nanoporous templates made by anodic oxidation of Aluminum. Also, Carbon nanotubes seem to be promising as Anode material.

Electrochromic systems with nanoporous electrodes

In electrochromic systems, the chemical reaction of an electrolyte cell of alkaline ions e.g. Lithium with Tungstentrioxide (WO_3) is used to switch the optical transparency of the cathode layer.

The reaction in the cathode can be described by



This reaction reversibly switches the color of the cathode from transparent to dark blue.

Normally, the cathode layer is a compact polycrystalline layer leading to rather long diffusion paths for the Lithium-ions for this reaction, which means that the switching times can be in the range of minutes.

By using nanoporous electrodes, the diffusion paths can be decreased by orders of magnitude as it is shown schematically in the figure 1 below.

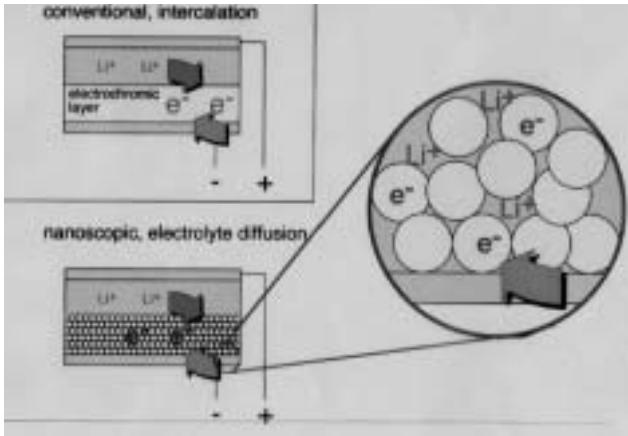


Figure 3 (H.Weller)

Evaluation referring to our definition of Nanotechnology:

Both effects are based on diffusion controlled electrode reactions with the diffusion path length as limiting quantity. The diffusion path length is continuously reduced with increasing porosity. Consequently, the effects in the Lithium battery as well as in the electrochromic systems do not fulfill our definition of Nanotechnology.

Applications:

Alkaline batteries can be used for electrical energy storage with very high storage capacities and storage densities for mobile and stationary applications.

As for electrochromic systems, switching times can be reduced to the range of some ten milliseconds. So, many applications of this effect are imaginable, e.g. to switch the transparency of windows in a house or in a car.

Other possible applications could be flat displays even for TV which can store the information after switching off the external applied voltage.

References:

Martin C., Colorado State University Fort Collins CO, private communication

Weller H., University of Hamburg, private communication

5.2.26 Self Assembly of Metal Nanoparticles (G5)

Cell of the table: Ability for self assembly of hybrids/composites

Explanation:

The organization of metal and semiconductor nanoparticles is of decisive relevance. The final goal in generating and investigating those particles is their use in nanoelectronics, optoelectronics, and storage systems etc., based on the size-quantized properties. To use specific properties of the nanoparticles, the organization in three (3D), two (2D) or even in one (1D) dimension is indispensable. It is especially the 2D organization that currently attracts most interest. Self assembly of the nanoparticles is one of the most relevant procedures to yield 2D arrangements of nanoparticles. The ability for self-organization requires specific properties of the building blocks. Most important is a dispersity that should be as close as possible to real monodispersity, although deviations of up to 10 % are tolerated. Interaction between the nanoparticles and/or the substrate is another condition to give ordered 2 D structures. These interactions should be of limited strength, since otherwise rearrangements during the organization process are excluded. Too weak interactions, however, prevent well organized structures due to high mobility. Appropriate chemical modification of the nanoparticles' surface, the substrate's surface or of both has turned out to give the best results. Figure 1 shows a transmission electron microscopy (TEM) image of 1.4 nm ligand stabilized gold nanoparticles on an appropriately modified surface.

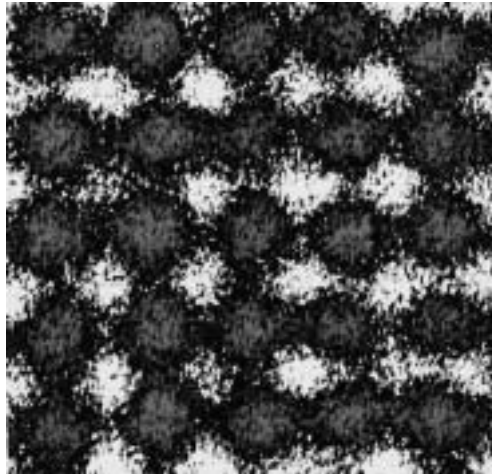


Figure: TEM image of square packed ligand protected 1.4 nm Au particles.

One-dimensionally organized structures of metal or semiconductor nanoparticles are still very rare. They require appropriate templates to arrange the particles in one dimension. First approaches look promising; however, 1D organization is much more difficult compared to formation of 2D arrangements.

Evaluation referring to our definition of Nanotechnology:

The ability for self-organization is a nanoeffect following the definition's conditions. The weak interactions of the nanoparticles among themselves and between them and a substrate via protecting ligand molecules happens on a specific molecular level, based on a limited number of constituents.

Applications:

2D, but also 1D and 3D organized metal and semiconductor nanoparticles are the basic systems to use in nano- and optoelectronics, storage systems and many other future applications.

Reference:

Schmid G. (ed.) in: *Nanoparticles – From Theory to Applications*, Wiley-VCH, Weinheim, 2003

5.2.27 Coordination Polymers (G5)

Cell of the table: Ability for self assembly of hybrids/composites

Explanation:

Coordination polymers are metal-ligand compounds of one- (1D), two- (2D) or three-dimensional (3D) structures, as can be seen from Figure 1.

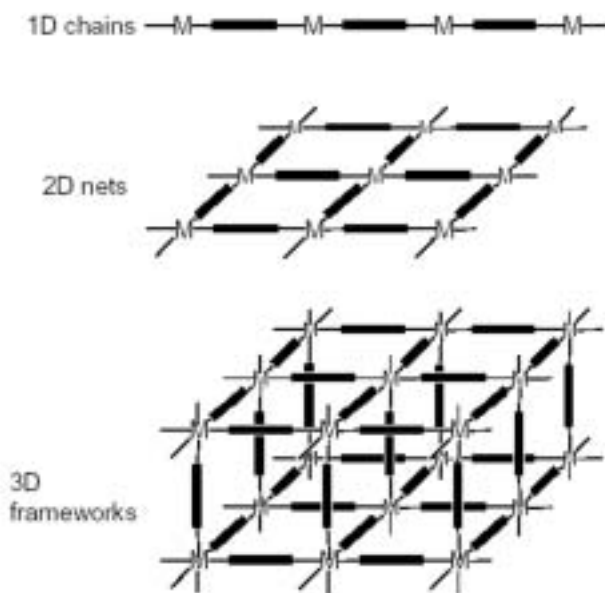


Figure 1: Principles of 1D, 2D and 3D coordination polymers.

The bonds between metal and ligand usually are but don't have to be of covalent character. A discrete example for 1D is shown in Figure 2.

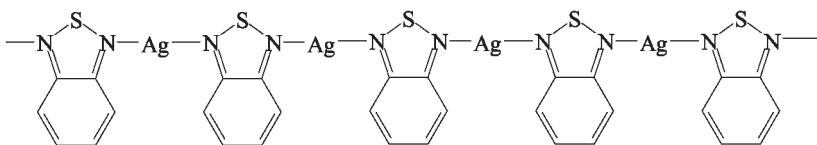


Figure 2: Sketch of a 1D coordination polymer consisting of 2,1,3-benzothiadiazole molecule linked by silver ions.

Coordination polymers have gained an enormous interest during the last decade. The formation of coordination polymers follows self-assembly processes ending up in novel systems with highly interesting properties.

Evaluation referring to our definition of Nanotechnology:

Coordination polymers exhibit properties that depend strongly on the nature of the building blocks, the dimensionality and the dimension of the resulting architecture and thus follow quantum mechanical rules instead of classical physical laws valid for a “material”. Herewith, they fulfill the conditions given in the definition for Nanotechnology.

Applications:

Applications of coordination polymers can be expected on the fields of non-linear optics (NLO), molecular magnets, catalysis, spin-crossover, sensors, zealot analogs and many more.

References:

Janice C., *J. Chem. Soc. Dalton Trans*, 2000, 3885 and references therein

Mankato M., Kuroda-Sowa T., Macaw M., Nakamura M., Akiyama S., Kitagawat S., *Inorg. Chem.*, 1994, 33, 1284

5.2.28 *Biosensors (H5)*

Cell of the table: Recognition ability of hybrids/composites

Explanation:

Semiconductor and metal nanoparticles with their unique and size dependent properties (c.f. C1-3, D1,3,5) are useful labels for biomolecular detection. In conjunction with biomolecules with their highly specific recognition abilities (oligonucleotides, proteins, anti-bodies, enzymes; c.f. H4), they represent functional hybrid systems, whereas bimolecular reactions and binding events can be detected by means of electrical, optical or magnetic measurements. This covers the fields of simple detection, sensing, imaging, diagnostics and therapy. Thus, the hybrid systems can be applied *in vivo* or, at least, can be immobilized on solid supports, applicable for

high throughput experimentation as well as for chip technologies. In this sense, miniaturization down to the nanometer scale will be one of the great challenges within the next years and will contribute essentially to the field of home-care diagnostics. Furthermore, these systems can be relevant in the self organized assembly of electrical circuits (c.f. G4).

Evaluation referring to our definition of Nanotechnology:

The sub-units which are relevant for biosensing devices are de facto building blocks with unique, size-specific properties on the atomic or molecular length scale. Consequently, this example fulfills our definition, as the sensing action results from the interaction of a limited number of constituents (see 4.1).

Application:

Biomedical applications, micro- and nanoelectronics (chemical information technology).

Reference:

Katz E., Shipway A.N., Willner I. in: *Nanoparticles: From Theory to Applications*, Schmid G. (ed.), WILEY-VCH, Weinheim, in press

5.2.29 *Proximity Effect (A6)*

Cell of the table: Magnetic properties of boundary surfaces

Explanation:

The proximity effect is a nearfield effect that generally occurs when a current carrying system is brought in close vicinity of another sample. These currents can be macroscopic external currents induced by an external source or also be based on the electronic system of two bodies interacting via fluctuating electromagnetic fields giving rise to van der Waals and dispersion forces. In nanocrystalline systems consisting of small non-magnetic particles embedded in a magnetic matrix or in a non-magnetic interacting system exhibiting strongly differing Fermi levels, magnetism can be induced in otherwise diamagnetic system by shifting the Fermi level of a non-magnetic component. Thus, under these conditions magnetic proper-

ties of diamagnetic systems such as copper can be induced. This requires a precise control of the particle sizes and distribution of nanoparticles in an appropriate inducing matrix. The local electric fields may then be much higher than the corresponding dielectric breakthrough fields. The effect occurs when the electronic screening length becomes smaller than the range of the inducing local fields and coherence lengths involved. This can be adjusted by choosing particles in the nanometer size.

A similar effect can be induced in the area of superconductivity, where the investigation of small particles between nanoelectrodes and electronic influence of the superconducting electrons on normal conducting systems is to be expected. Using small particles in the close vicinity of superconducting materials may thus induce superconductivity in the nearfield regime of the inducing elements.

Evaluation referring to our definition of Nanotechnology:

This effect occurs only below a certain particle size and can not be induced in macroscopic samples. Consequently, this example fulfills the definition as a quantum size effect (see 4.1).

Application:

Applications of the proximity effect are in the field of inducing magnetism in diamagnetic metals and also in shifting electronic states of magnetic particles so that they become non-magnetic. In addition, the effect can be used to induce superconductivity on small particles or thin layers in otherwise non superconducting materials such as gold. Applications include switchable magnetic materials and sensor devices based on superconductivity.

References:

Handel P.H., *Physica Status Solidi B*, 1996,194, 393

Morpurgo A.F., Conk J., Marcus C.M., Dai H., *Science*, 1999, 286, 263

Scheer E., Belzig W., Naveh Y., Devoret M.H., Esteve D., Urbina C., *Phys. Rev. Letters*, 2001, 86, 284

5.2.30 Self Cleaning of Surfaces (Lotus Effect) (B6)

Cell of the table: Mechanic properties of boundary surfaces

Explanation:

Wetting of surfaces by water in air as a surrounding medium depends on the ratio of the interfacial tension between water/air, solid/water, and solid/air. The ratio of the tensions determines the contact angle of a water droplet on a surface. A contact angle of 0° means complete wetting, i.e. a water droplet deliquesces to a monomolecular film, whereas a contact angle of 180° corresponds with a total non wettability: the droplet contacts the surface only punctually. Surfaces with a high interfacial tension are easier to be wetted than those with a low interfacial tension. Two properties determine a surface's properties: the chemical composition and the roughness. A hydrophobic nature of a surface, for instance consisting of waxes (Lotus leaves) or polymers (Teflon) can be improved by an additional micro- and nanostructure, called superhydrophobizing. If a hydrophilic surface is additionally micro- and nanostructured, the opposite is the case: the surface becomes superhydrophilic.

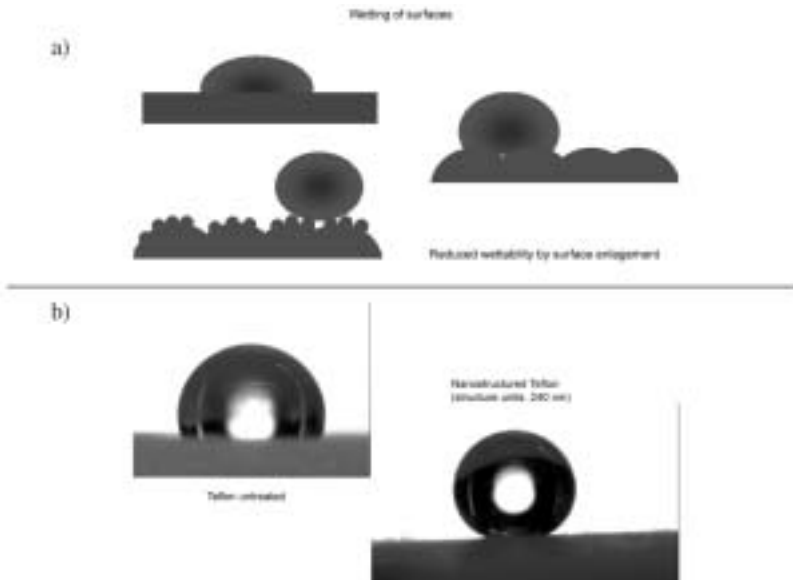


Figure: a) Illustration of the Lotus Effect using micro- and nanostructures on chemically optimized surfaces. b) Water droplets on untreated and nanostructured Teflon.

Evaluation referring to our definition of Nanotechnology:

The Lotus effect develops continuously from micro- to nano sized units and so does not fulfill our definition of Nanotechnology.

Application:

Self cleaning of many surfaces used in everyday life, such as glass, facades, clothes, roofs.

References:

Barthlott W., Neinhuis C. in: *Bionik. Ökologische Technik nach dem Vorbild der Natur?*, Gleich A. v. (ed.), 2. Edition, B. G. Teubner, Stuttgart, 2001

Barthlott W., Cerman Z., Neinhuis C. in: *Faszination Lebenswissenschaften*, Beck E. (ed.), Wiley-VCH, Weinheim, 2002

Levering M., Thesis, University of Essen, 2003

5.2.31 Gas Sensors and Catalysts (C6)

Cell of the table: Electric/electronic properties of boundary surfaces

Explanation:

Semiconductor nanoparticles as well as nanoporous solids are increasingly used for the fabrication of highly selective sensors. The nanoparticles reduce the grain size of the gas sensitive material to the relevant size of approximately the Debye-length, corresponding to the length of the space-charge or depletion zone. At the same time, they provide an increased surface area, making the materials more accessible towards the applied gases. This will allow further miniaturization and integration of single sensor elements and sensor arrays, e.g. for the set-up of an electrical nose for various applications. Essential for this design routes will be the development of new material compositions on the nanometer scale, i.e., semiconductor nanoparticles with variable compositions and huge variety in volume and surface doping.

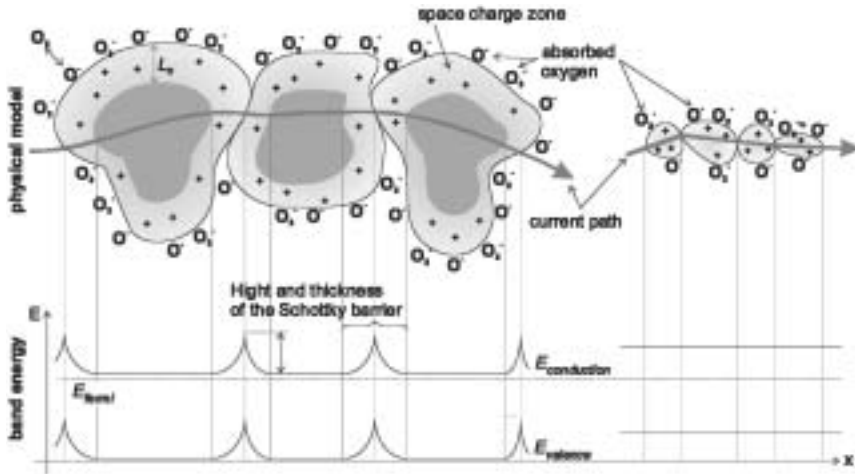


Figure 1: Physical model and band structure of a gas sensor material, illustrating the meaning of the Debye-lengths for the sensitivity. In nanoparticles the Debye-length extends over the entire volume of the particles.

Surface doping provides the opportunity of utilizing size effects of the respective catalytically active material when it is applied as nanoparticles with a narrow size distribution. With this method, the sensitivity of a sensor can be tuned via the particle size.

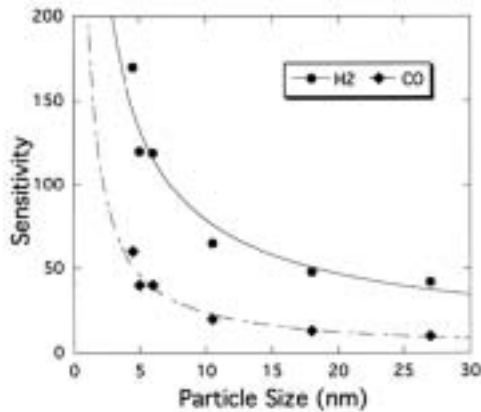


Figure 2: Sensitivity of a nanoparticles doped SnO_2 sensor expressing the increasing sensitivity with decreasing particle size.

Nanoporous sensor materials, like zeolites, have a great potential in terms of selectivity. Comparable to the shape selectivity of heterogeneous catalysts one might expect new materials with high selectivity. This can be utilized in applying the material as the gas sensing materials as well as filters in combination with conventional sensor materials.

In heterogeneous catalysis most effects are related to the microstructure of the catalyst as well as on the topology and topography of the catalytically active sites on the nanometer length scale. The technical relevance of nanomaterials in catalysis cannot be underestimated. But it will be an impossible task to foresee those fields of technical application, which will profit from a rational design of nanomaterials, since the complex interplay of the multiple reaction parameters in catalysis as well as in sensor development need at least an empirical or semi-empirical strategy for system optimization. A powerful method in this field will be high-throughput experimentation and combinatorial chemistry.

Evaluation referring to our definition of Nanotechnology:

Volume as well as surface doping effects are not finally understood. They result from superimposed phenomena, such as quantum size effects as well as catalytic effects and hence may be considered to fulfill our definition.

Application:

Sensor technology is one of the most important mass-markets of the future with a constantly increasing number and variety of applications in both the industrial and domestic sectors. Ever more sensors and sensor arrays are being used in the control of technical processes, within environmental protection, applications in health care, for use in automobiles and aircraft and the control of (chemical) production processes.

Reference:

Göpel W., *Sensors*, WILEY-VCH, Weinheim, 1998

5.2.32 Low-Loss Dielectrics (C6)

Cell of the table: Electric/electronic properties of boundary surfaces

Explanation:

The further miniaturization of electrical circuits requires new materials with extraordinary low dielectric loss and high breakdown voltages to allow an effective electrical insulation of neighboring and crossing leads on a chip. The materials must suppress the leakage currents and unwanted cross-talk in electrical circuits. Therefore, semiconductor industry is forced to look for alternatives to SiO₂, i.e. for materials, which have a lower dielectric constant. Promising materials are fluorinated SiO₂ and polymers, such as PTFE. To further decrease the dielectric constant, nanoporous materials, either silica-based (e.g. so-called *Nanoglas*®) or polymer-based (e.g. so-called *Nanofoam*®) are currently studied. To increase the porosity, molecularly linked silica-oligomers (silsequioxanes) forming a network with nanometer sized pores and channels may be very promising for this application.

Evaluation referring to our definition of Nanotechnology:

The decrease of the dielectric loss with decreasing material density is not restricted to the nanometer range and so does not fulfill our definition.

Application:

Dielectrics for electrical circuitry on integrated chips are essential for further miniaturization.

References:

Lercher J., TU-München, private communication

Loboda M.J., Singh R., Ang A.S., Rathor H.S., *The low and high Dielectric Constant Materials*, Electrochemical Society, New York, 2000

5.2.33 Antireflection (Moth Eye Effect) (D6)

Cell of the table: Optical properties of boundary surfaces

Explanation:

The so-called moth eye effect is observed in nature on the lenses of some night-active insects. The effect is based on micro- and nanostructures with a periodicity of 250 nm and a depth of more than 200 nm. This structure reduces or even prevents light reflection from the eyes surface. The effect is physically explained by a continuous transition of the refraction index from air to a surface. Propagating light is reflected to a large extent when it enters another medium with a discontinuity of the refractive index at the interface (e. g. from air with $n = 1$ to glass with $n = 1.5$). To avoid this unwanted effect, surfaces can be micro- and nanostructured. In order to elucidate the effect, the figure below shows the situation between air and glass (a) and of a system with a *quasi* continuous transition (b) by using micro- and nano-structured surfaces as indicated by (c).

Air: Refract. index ca. 1



Material: Refract. index ca. 1.5

a

b

c

Figure: Illustration of the moth eye effect by micro-/nanostructured surfaces. a represents a combination of two media with differing refractive indices, resulting in a high reflectivity. A micro/nano structure as indicated in c leads to a continuous transition from the one to the other medium resulting in a non-reflecting system indicated in b.

Antireflection character of structures can be generated lithographically, via sol-gel or by Laser and holographic techniques. Another approach is a nanoimprinting process using nanoporous alumina membranes as stamps.

Usually, structure units in the micrometer regime are used but structures down to less than 300 nm are generated.

Evaluation referring to our definition of Nanotechnology:

The antireflection is not appearing at a distinct size of the surface's structure units, but develops continuously from the micro to the nano size regime and so does not fulfill our definition.

Application:

Very important for antireflection behavior of any kind of glasses, lenses, displays, photovoltaic cells etc.

References:

Aydin C., Zaslavsky A., Sonek G.J., Goldstein J., *Appl. Phys. Lett.*, 2002, 80, 2242

Macleod B., Sonek G., *Thin Films-Moth Eye Surfaces Reflect Little Light*, Laser Focus World, 1999, 8

5.2.34 *Clean Surfaces, Photo-Catalysis (D6)*

Cell of the table: Optical properties of boundary surfaces

Explanation:

Semiconductor photo-catalysis has proven to be a promising technology for use in the clean-up of water contaminated with hazardous industrial by-products. Particular semiconductors have shown to be light harvesting materials and mediators in the photochemical degradation of environmental contaminants. When the size of a semiconductor crystalline particle is less than the De Broglie wavelength physical confinement of electrons and holes in the wells defined by the crystallite boundaries occurs. As a consequence, only those orbitals that fulfill the condition to have a node at the crystalline boundary become allowed, and therefore the levels available for the electrons and holes in the conduction and valence band become discrete. Additionally, when a semiconductor is brought in contact with an electrolyte, the migration of charge carriers occurs until the Fermi level of

the semiconductor is equilibrated with the chemical potential of the electrolyte. These result in the formation of a space charge layer in the surface region of the semiconductor and a Helmholtz double layer in the electrolyte adjusted to the semiconductor surface. The space charge region in a semiconductor is relatively large, extending up to 100nm. When the size of the semiconductor particle is smaller than the space charge region, the particle is too small to develop a space charge layer and as a consequence, the position of the band edges of semiconductor nanoparticles will shift and the band gap will increase. Absorption of light of energy larger than the bandgap generates conduction band electrons and valence band holes. In large single crystal semiconductors, it is the electric field in the depletion layer that separates the charges and decreases the probability of charge pair recombination. In colloidal particles smaller than the space charge layer thickness, such a depletion layer does not exist and there is no electric field to separate the charges. Semiconductor nanoparticles offer interesting advantages in the heterogeneous photocatalysis process: high absorption cross section of the incident photons, fast carrier diffusion and suitable redox levels of the valence and conducting band edges that can yield high efficiencies in converting light energy to interesting and useful redox reaction. For example, if the reduction of a particular species in the solution is of interest, the conduction band of the semiconductor must be more negative than the relevant redox level, while the oxidation of the particular species by valence band holes must be more positive than the relevant redox potential. All redox couples having a standard redox potential more positive than that of the conduction band and more negative than that of the valence holes can, in principle, be reduced and oxidized respectively on the colloidal surface.

Evaluation referring to our definition of Nanotechnology:

The nanoeffect is clearly given by the change of the behavior of the electron/hole pairs due to the fact that the semiconducting nanoparticles are smaller than the space charge layer. Consequently, this example fulfills the definition as a particular interface effect (see 4.1).

Application:

The photocatalytic activity of titanium results in thin coatings of the material exhibiting self cleaning and disinfecting properties under exposure to UV radiation (Antimicrobial Coatings). These properties make the material a candidate for applications such as medical devices, food preparation surfaces, air conditioning filters, and sanitary ware surfaces.

References:

Bems B., Jentoft F.C., Schlogl R., *Appl Catal B-Environ*, 1999, 20, 155

Kisch H., Macyk W., *Chemphyschem*, 2002, 3, 399

Vautier M., Guillard C., Herrmann J.M., *J. Catal.*, 2001, 201, 46

5.2.35 Defusion Systems (E6)

Cell of the table: Thermodynamic properties of boundary surfaces

Explanation:

Phenomena of spontaneous formation of regular or irregular structures are widely spread in nature. Typical examples could be found in biology, but also in physics, meteorology and chemistry. Pattern formation can also occur in the nanometer scale to the intermolecular interactions and interactions between molecular systems and solid substrates. From a mathematical and physical point of view, the systems could be described as activator-inhibitor type reactions which can be treated via a system of non linear reaction defusion equations. Through formation of nanometer scale structures by self organization using this mechanism, the conventional limitations of sequential writing or projection lithography could be partially overcome. Thus, by following the biological approach, small structures with specific macroscopic cooperative functions can be generated.

Evaluation referring to our definition of Nanotechnology:

This effect is not essentially depending on the size of a system and so does not fulfill our definition of Nanotechnology.

Applications:

Applications range from the formation of dot and antidot structures on surfaces up to the formation of linear or two dimensional structures over large areas by means of wetting instabilities. Thus, surface modifications and surface structures can be generated without local manipulation and lithographic techniques. These structures can then be used as a basis for new optical and electronic devices as well as templates for the generation of moulds and micro stamps as well as templates for the directed growth of biological cells. The latter aspect can also be considered to be useful for biocompatible surfaces.

References:

Astrow Y., Ammelt E., Purwins H.-G., *Phys. Rev. Lett.*, 1997, 78, 3129

Bode M., Purwins H.-G., *Physica D*, 1995, 86, 53

Gleiche M., Chi L.F., Fuchs H., *Nature*, 2000, 403, 173

5.2.36 Self-Organized Complex Patterns; Phase Separated Block Copolymers (G6)

Cell of the table: Ability for self assembly of boundary surfaces

Explanation:

Block copolymers are macromolecules like chains which consist of different parts made of different molecular building blocks. These sub-chains can be chemically tailored that a particular sub-chain prefers to be surrounded by chains made of the same building block. This organization of macromolecules can result in very regular patterns in nanoscale dimensions in two dimensions on surfaces and in three dimensions in materials (Hamley 2003). The regularity of the structure allows for physical effects (optical properties) that are typical for periodic nanoscale structures. The figure below shows two structures that have been made by phase separation of a diblock copolymer (Park et al. 1997).

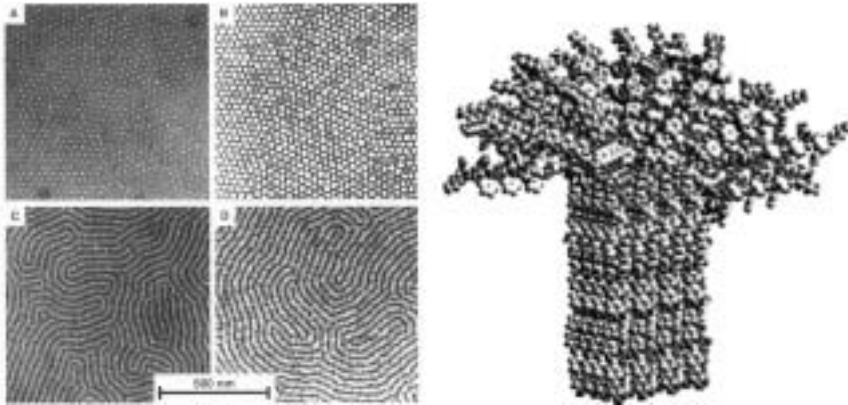


Figure: *Left side: TEM picture of a surface structure made by a diblock copolymer. Both surface structures have been used as lithographical masks resulting in the structures on the right side (Park et al. 1997). Right side: Schematic representation of the mushroom shaped object formed by a diblock copolymer (Stupp et al. 1997).*

In another approach, these phase separation effects have already been used for the engineering of nanoscale objects, like the mushroom shaped objects from Stupp et. al. (1997), shown in the figure above on the right side.

Evaluation referring to our definition of Nanotechnology:

The selective recognition of a limited number of sub-chains in a polymer strand, which results in a phase separation, is taking place in an ordered manner on a molecular level. Consequently, this example fulfills our definition as an interaction of a limited number of constituents (see 4.1).

Application:

The potential applications of such materials are manifold. Their use as lithographical mask has already been demonstrated in the figure above. Large antireflection surfaces have been prepared by phase separation as well. An envisaged application of nanoscale objects is their use as artificial body compatible polymers for surfaces of prostheses.

References:

Hamley I.W., *Angew. Chem. Int. Ed. Engl.*, 2003, 24, 1692

Park M., Harrison C., Chaikin P.M., Register R.A., Adamson D.H., *Science*, 1997, 276, 1401

Stupp S.I., LeBonheur V., Walker K., Li L.S., Huggins K., Keser M., Amstutz A., *Science*, 1997, 276, 384

6 Miniaturization, New Materials and Nanotechnology – Challenges for Technology Assessment

6.1 Overview

Projects conducted by the Europäische Akademie are interdisciplinary in nature. They aim at bringing together scientific expertise from different fields in order to improve science's capability to deal with societal consequences of the scientific and technological advance. Technology Assessment has been developed as a means to bundle scientific knowledge about the consequences of technology and to focus this knowledge to the needs of society to allow for "rational" – in the sense of knowledge-based as well as ethically reflected (Grunwald 2000a) – decisions about the future course of development.

The objective of this chapter is to develop a framework for Technology Assessment dealing with questions related to the topic of miniaturization in the field of materials research. To be able to do so requires introducing some basic approaches to and experiences from Technology Assessment (part 1). In part 2 some relations between materials research and Technology Assessment are explained, based on earlier work of the Europäische Akademie (Harig/Langenbach 1999). Part 3 is dedicated to some ideas how Technology Assessment could be used in the field of Nanotechnology.

6.2 Technology Assessment as Research for Giving Advice

Technology Assessment is oriented to the scope of social problems and challenges related to upcoming inventions and innovations in science and technology. Impacts and consequences of technology, political and societal ways of dealing with them, potentials for contributions to societal problem-solving and innovation policy as well as implementation conditions of technology are the classical fields of Technology Assessment. Technology Assessment shall provide knowledge as a basis for acting and decision-making concerning technology and its implementation in society (Grunwald 2002). The need for integrative and interdisciplinary research on the impact and consequences of technology results from the manifold of mutual interdependencies between technology and society as well as from the

necessity for integrated and coherent political and societal judgement in preparing decisions.

Technology Assessment has always been understood as a contribution to shaping technology from the societal perspective. In the beginning, it was a question of providing the U.S.-Congress with scientific advice, in order to make better informed processes of parliamentary decision-making possible. The effects of technology – as was the aim – should, as far as possible, be known in advance, in order to optimize the basis for decision-making. This has been and is still being done today in two different manners. Technology Assessment as an early warning should contribute to ensuring that – by means of precautionary political action – the potential hazards it warned about either don't become reality, or are at least minimized (highly impressive case studies from the past 100 years where such early warnings have been missing or failed can be found in Harremoes et al. 2002). Technology Assessment as early detection of the chances of technology is supposed to put society in a position to recognize the undiscovered potentials of a technology, and to make the best possible use of them.

The mission of Technology Assessment is, in both cases mentioned, to improve society's – normally: political – possibilities for deciding about the future path of technology and the embodiment of technology into society. It does this by providing information about the consequences of technology, by assisting society in the evaluation and judgment of this information, by initiating and promoting societal communication about technology, by supporting conflict management and by working out action strategies.

Technology Assessment was originally conceived as providing scientific advice for political decision-making (cp. the history of the Office of Technology Assessment OTA at the U.S. Congress, Grunwald 2002, ch. 5). This was done in the conviction that the state would be able to direct technology development actively. Today, however, the state is seen more as a moderator of societal decision-making processes, being only part of the game (except of its decisive role in creating legitimization, cp. Grunwald 2000a, chap. 3) than as a central instance of direct steering. Instead, we now presuppose a decentralized development of technology, which is divided among many societal areas, stakeholders and social groups. In modern, spe-

cialized society marked by functional differentiation and the division of labor, the contributions of various actors and of the various societal groups (engineers, users, managers, politicians, etc.) to the development of technology also differ. At various points in the complex decision-making processes which lead to new technical products or systems, they contribute to determining the final characteristics of the result (Grunwald 2000a, 2002):

- The state influences technology development in at least four points: (1) as a buyer and user of technology (including materials used) on a large scale, (2) as a direct initiator and contractor for technology development (for instance, large-scale infrastructure, and for military purposes), (3) as a sponsor of science and technology via public funding agencies, as well as of corresponding initiatives promoting technology for economic reasons, and (4) as a regulatory body (tax legislation, liability law, guaranteeing data protection and intellectual property rights, setting environmental and safety standards etc.). The most important fields for new materials and Nanotechnology may be, at the moment, the public sponsorship of new developments and the regulatory level.
- The economy (engineers, designers, management) intervenes in the development of technology by means of concrete research and development, through the manufacture and sale of technical products, systems and services, as well as through strategic corporate decisions, marketing and advertisement. If new technologies and new materials shall be introduced to the marketplace their role is decisive. At this level the rules of competition and economic success are dominating the activities – there is no obligation to acknowledge something like the “common good” or ethical values beyond accepting and observing the regulatory standards and the socially valid rules of making business.
- The consumers, the buyers and users of technology, decide on the acceptance of technology and of technology-based services at the marketplace. Further, they can take part in dialogues in market research on the development of future technologies, or in participative Technology Assessment on the political development of technology.

- Active citizens and non-government organizations can also exert influence within the framework of a “civil society“ (cp. the “Brent Spar” action of Greenpeace some years ago).²⁶

The chances for Technology Assessment to support decision-making will vary from case to case. Whether it is a question of assessing the impact of new materials on the natural environment or of determining the probabilities for getting products successfully into the marketplace; whether the question of the consequences of new materials for human health or for the national economy are on the agenda: respectively different societal actors take part, and influence technology development by different means. The tasks and objectives for Technology Assessment depend in individual cases on the type and extent of the co-operation involved in this process. Technology Assessment has to be designed conceptually and methodologically in different ways, according to its concrete subject and the circle of addressees.

The group of addressees and the subject matter correlate: both are determined by the specific question to be treated. Whoever should or wants to be advised in shaping the technical world determines which questions are asked: for instance, whether it is a matter of analysis of the political or legal frameworks for the development of technology, of assessing a product’s possible effects, of research on market conditions, or of secondary or tertiary side effects of technology and eventual regulatory needs. Such a broad spectrum of Technology Assessment as an advice for the development and use of new technologies and materials exists and may be used in order to investigate and reflect the technological paths towards future society.

Like a coin, Technology Assessment also has two sides: provision of knowledge by means of research on technology and on its effects including ethical reflection on the one hand, and societal communication on questions of evaluation, acceptance and of setting priorities on the other. Both aspects

²⁶ This is a good example for the influence of NGOs and the Public; it is, however, a bad example with respect to the role of knowledge. Some months after the intensive debate, it came out that the initial plan of Shell to sink Brent Spar would have been probably the ecologically better way.

are indispensable for shaping technology though their respective roles and their relative importance may vary from case to case. It is imperative not only to take into consideration the best knowledge which the various scientific disciplines can provide, but also to hold a broad societal dialogue about the purposes of development, about visions of a future society, about the desirability, acceptability and reasonableness of technological innovations. In the concrete realization of these ideals, a number of experiences have been made in Technology Assessment in the past decades, and these experiences have to be taken into account:

Technology and society are by no means isolated from one another but interact in multiple ways. We are surrounded by technology, and live in a “technological milieu“, as Michael Schwarz put it (Schwarz 1992). There is a “co-evolution” of technology and society (Bijker et al. 1987);

There is no strict separation between knowledge and values; both are inter-related: the production of knowledge depends on the preceding decisions made as regards relevance or evaluations (Funtowicz/Ravetz 1993). Societal values and norms are challenged by new technologies, and possibly altered; technology can be accepted by society, even if it at first conflicts with values – if just these values are changed by technology;

Our course into the future society always has – in spite of all of our ex ante deliberations on the consequences of technology – experimental aspects and has to deal with considerable uncertainties. As Boris Groys once expressed it in a radical notion: “You basically never know in advance whether a technological innovation will stabilize present society, or ruin it“ (Groys 1997).

What follows as an essence out of all these experiences is, in fact, that shaping future technology can’t be done in the form of one-dimensional planning for a predetermined goal, and that with guaranteed success. What is feasible, however, is that there are numerous possibilities for understanding the co-shaping of technology and society as a learning process: as a societal process, in which the objectives of this co-determination and options for its realization are discussed, in which scientific knowledge and ethical orientation find consideration, and in which the shape of future society gradually,

step by step, becomes recognizable (Grunwald 2000b) – showing a deep-going analogy to the process character of sustainable development (Kopfmüller et al. 2001, chap. 8).

Shaping technology in the sense of a continuous process of learning, with the opportunity of learning from practical experience as well – and then to use this experience to modify practice is the only way not to leave the evolution of technology to its own devices, but – in a well-reflected and scientifically informed process – to take part in directing it. Technology Assessment is, in this sense, a medium for learning, inasmuch as the development of technology and of the corresponding societal frameworks is critically discussed. Far beyond its original function as advice in preparation for decision-making, Technology Assessment is confronted with many further responsibilities: namely, to assist societal learning processes regarding the development, the societal introduction and the later consequences of technology on a scientific basis, and thereby to contribute to promoting less formal procedures of opinion formation in the preliminary stage of decision-making also. In this case, terms such as a learning regulation by the state, monitoring the effects of development measures, finding indicators for conditions or changes, procedures of collective learning, distinguishing learning processes from mere fashionable changes, and the question of translating the results of these learning processes into practice are fundamental.

In this sense, we have to distinguish between at least three different levels of learning:

- On the cognitive level, it is a question of learning new information about the effects of technology, fields of application, acceptance, of the users' behavior on the market, etc.
- On the normative level, the framework conditions stand in the foreground: it is a question of bringing regulations up to date, of new procedures for managing conflicts, and, lastly, of a learning refinement of ethical sensitivity and of values.
- On the level of the societal self-understanding, questions of the perception and acceptance of risk, of expectations concerning the future are important for the relation between society and technology.

On all of these levels, Technology Assessment can provide or improve the preconditions for broadening the leeway for options in technology-relevant societal decisions by means of social learning. In the quasi-experimental situation it is urgent to make the inherent uncertainties of knowledge transparent, to make possible an open discussion on how to deal with these uncertainties and with the unavoidable risks they bring about. The risks then have to be weighed against those of other options for the future, and against the respective foreseeable opportunities.

In elaborating on the relation between Technology Assessment and societal processes of learning, it is decisive to avoid the misconception that exclusively technology shows progress while society does not. There are not only scientific and technical innovations but also societal ones, for example new institutional mechanisms of dealing with certain problems. The foundation of ministries for environmental protection is such an institutional innovation as well as some recently established cross-cutting institutions in the field of sustainable development.

The societal options for dealing with technology, for learning and for integrating technology are also developed further, in a way of co-evolution with technology. In the field of road traffic, for example, there have not only been technical innovations since the days of Daimler and Benz but also social innovations like laws and regulations for road traffic, road traffic management activities, emergency services and medical treatment of accident victims, a highly specialized insurance industry, and traffic courts deciding in cases of conflict. If such lessons learned in the field of “societal innovation“ are overlooked, then either utopian or apocalyptic visions rear their heads, such as those expressed in the recent debate on a possible supremacy of machines over humans (Bill-Joy-discussion). Obviously, one arrives at visions of horror if one extrapolates the technical potentialities over decades, and then compares them to today’s societal possibilities for coping with them. This, however, is an obvious fallacy, because it completely ignores the possibility of societal learning concerning the dealing with technology.

Because Technology Assessment draws attention to and supports opportunities for learning with regard to the societal embodiment of technology,

one-sided, naive, “irrational“ or obstructive positive or negative utopias of the type mentioned can be criticized and avoided, and the opportunities of new technologies can be better utilized.

6.3 Technology Assessment and Materials Research

The possibility of a miniaturization of technology depends considerably on the properties of the materials used. Materials research and the search for new materials and ways of processing them are, consequently, to be taken into account in talking about miniaturization.

Research on new materials is an important pre-requisite for a lot of innovative technologies. New materials are decisive in many fields of scientific and technological advance as well as for achieving societal needs. The close relation between societal needs and the importance of new materials as cross-cutting and basic inputs for a manifold of applications have been leading to the situation that materials research is one of the main areas of public research funding. Projects in materials research and lines of materials development are frequently embedded into national or European research programs. Main overall objectives to be met by those programs are (Harig/Langenbach, chap. 6):

- To contribute to global technological competitiveness by making new materials and processes available for new technical systems and products;
- To contribute to economic welfare in national economies. The availability of new materials is a key factor for many technological developments with high impact on the economy;
- To contribute to a more sustainable way of dealing with natural resources by enhancing the resource productivity of the materials used, to decrease the need for large energy and mass flows by miniaturization, and to minimize negative impacts of materials induced emissions to the environment;
- To increase the capabilities of SMEs to introduce innovative ideas on new materials and their processing successfully to the marketplace – facing the difficulty that the rather extended diffusion times of 10–15 years are

related to high risks of investment which usually cannot be taken by SMEs without support.

- To enhance the performance of the innovation system(s) by promoting cooperation and synergy effects, by fastening technology transfer and by ensuring more coherence and effectiveness in funding;
- Technology Assessment mostly deals with the innovations promised by materials research, not with the inventions concerning materials or processes directly. This is due to the fact that inventions at the scientific level do not have an immediate and direct impact on society. The impacts on society are arising as soon as ideas for innovation are expected or are coming out from the scientific inventions. In this way, Technology Assessment in the field of materials research is interested;
- in the (economic, social and political, sometimes cultural) circumstances under which inventions might lead to innovations;
- in the specific kind of innovations expected in the respective case;
- in the consequences which might be expected to occur if those innovations are entering society and change the need for natural resources, the amount and composition of emissions, but also consumption and production patterns, economic issues, deployment, access to social resources, lifestyle and culture there;
- but also in the conditions which are determining the success of the innovation at the marketplace.

Using the following distinction allows classifying material innovations either as (1) materials for substitution or (2) materials for system innovations.²⁷

(1) New materials frequently shall substitute traditional materials in available products or systems. The objective of the substitution may be to

²⁷ In the field of Nanotechnology, this distinction also can be applied (see part 3 of this chapter). Often, there is a third area mentioned consisting of the more futuristic aspects of Nanotechnology (Fleischer 2002). However, it has still to be clarified and illustrated to which extent this distinction really contributes to Nanotechnology Assessment.

increase the quality of the products (for example durability and stability), to improve the economic efficiency, to increase the competitiveness of the products, to reduce weight (in the automobile or airplane sector) or to reduce environmental impacts. New materials are in competition with traditional ones, including the respective processing. Main criterion for the success of the substitution is often the cost/benefit relation. But also societal framework conditions like safety or environmental standards are relevant for the expectability of the success of substitutions. Political conditions and measures, furthermore, may be forcing materials substitutions (like in the case of CFC)²⁸, they may be promoting specific substitutions but they also may be obstacles (cases studies for each case are to be found in Harremoes et al. 2002). Technology Assessments dealing with such substitution processes have to take into account all of these heterogeneous aspects.

(2) Beyond the level of substitution, new materials often are a *conditio sine qua non* for the development of completely new technical products and systems (Socher et al. 1994b, S. 23). New materials are, in combination with the respective processing, “enabling” technologies. The innovation, in such cases, would not have been possible without the inventions coming from materials research. This also applies if the “enabling” invention at the side of the materials involved vanishes in an economic consideration – because the value added coming directly from the materials may be only a small portion of the value added coming from the entire innovative system or product – or in the public perception because customers often are only interested in the new properties available but not in the reasons why they became available (Harig/Langenbach 1999, ch. 2.2.3). An important objective of the scientific disciplines involved in materials research is to implement appropriate boundary conditions so that – beyond the “substitution“

²⁸ These chemicals are an excellent example in which way the assessment of materials may vary dependent on knowledge and technological capabilities available. They have been introduced because of their inertness in the narrow human environment – in contrast to other chemicals serving the same purposes (butan derivatives) which have been recognized to be a danger to human health in the case of coming in contact with food (Freisetzung). Nowadays, where there are much better possibilities to prevent such cases, and where it has been recognized that CFCs are not inert in the upper atmosphere, the assessment looks different and such chemicals are used to replace CFCs.

of traditional by new materials – there are chances to provide new materials and respective processes as “enabling technologies”. Obviously, there is high risk involved because the fields of application are not so clearly defined as if a specific substitution would be the objective. Situations of competition can arise which can be investigated and assessed in advance only to a high degree of uncertainty. Corresponding tasks for Technology Assessment are related to support such complex decision-making processes, for example in the field of public funding of such activities but also concerning the question how to shape political and societal framework conditions in a way that innovations are enabled or promoted (Socher et al. 1994, Harig/Langenbach 1999).

Technology Assessment (TA) studies in the field of materials research and related innovations have to be designed in a way different from, for example, studies concerning spaceflight technologies. In both cases mentioned above it is not the materials directly which have an impact on the environment or on the society (which then could be a subject to be investigated in Technology Assessment). Instead, the products and systems with materials being only a part of them will cause impacts. Therefore, Technology Assessment always has to take into account the relation between new materials and their expected role in future products and systems.

The concrete design of a TA study on the societal impacts of new materials depends on the very case. The following classes have been identified in previous work (Harig/Langenbach 1999):

Material-oriented assessments select specific developments from materials research as point of departure, such as innovative developments in certain material classes or in the related processing (for example, IPTS 1996a). They aim at identifying and assessing the impacts and consequences (typically in the contraposition of chances and risks) of the selected developments in various application areas. Roughly speaking, studies in this direction are following the “technology push” approach.

Application-oriented assessments choose technical products and systems as points of departure. They are dedicated, on the one hand, to the functional requirements of technical products and systems with respect to new materi-

als (for example, IPTS 1996b), and, on the other hand, on the impacts and consequences of the respective products and systems for society. They also deal with questions which new materials or new material properties should be developed in order to satisfy those needs, starting from an analysis of societal needs (demand-pull approach).

Context-oriented assessments focus on the societal (economic, social and political) contexts and boundary conditions which are relevant for materials research, the use of new materials and the chances for innovation by new materials. Most prominent topics are agenda-setting and priority-setting in public funding of materials research, the research infrastructure and legal and economic framework conditions (Socher et al. 1994).

These types of TA studies with different perspectives on new materials open a broad field for investigation and assessment.

6.4 Nanotechnology Assessment

Currently there is large enthusiasm that nanoscale science and Nanotechnology could become the next society-transforming wave of knowledge and innovation (3rd industrial revolution²⁹). Nanotechnology has to do with miniaturization because technological manipulation becomes available at the nanoscale. Accordingly, the issues on the relation between Technology Assessment and miniaturization mentioned above also can be applied in this field. But due to the definition chosen by the authors of this book (see chapter 4.1) Nanotechnology must not be characterized by miniaturization only. It has to do with newly appearing effects on the nanoscale. Therefore, it may be expected that even more and different aspects of Nanotechnology may be of interest in Technology Assessment.

Before elaborating a little bit more about such relations it shall be made clear that Nanotechnology is an ideal case for investigation and reflection

²⁹ One should be, however, rather precautionary in talking about current or future “revolutions“. What development might be denoted as a revolution is being decided upon in the time after that development. The demarcation of something as a revolution always happens from an ex post perspective.

by Technology Assessment. Because Nanotechnology is still in a very early developmental phase, it is the appropriate target for building an interdisciplinary prototype model for Technology Assessment accompanying and consulting the scientific and technological work as well as giving advice concerning the interface between Nanotechnology and society. Reflexive and socially responsive research influencing the further course of development seems to be possible – in contradiction to many cases of technology development where reflection and impact research came too late. With several experiences of Technology Assessment having come too late, it is a request of almost all present concepts of doing Technology Assessment as early as possible (Rip et al. 1995, Grunwald 1999, BMBF 2001) – in spite of the undoubted fact that the knowledge available in such early phases will be limited, incomplete and uncertain (Collingridge 1980). Nanotechnology seems to be an ideally suitable field of research to implement that conceptual idea and to learn more about it by practice.

The idea of Technology Assessment as accompanying research, reflection and communication about the “societal side” of Nanotechnology is supported by a further, more general observation. Experiences with public opposition to new technologies such as nuclear power, genetically modified food, and stem cell research, show that early and open communication about chances and risks could be an appropriate approach to prevent societal positions becoming fundamentalistic. As a consequence of the combination of this relation with the desire and necessity to utilize benefits derived from new technologies to a large extent, it may be argued for new approaches aiming at enhanced linkages between technology development, innovation processes and social goals. The innovation system itself should, for its own optimization, be aware of the broader social context within which the innovation is occurring. Reflexiveness should better be integrated into the innovation process from its earliest stages, before resource streams and institutional designs become reified, and before Nanotechnology products are changing society. In this way, Nanotechnology assessment (NTA) should cooperate very closely with Nanotechnology research, in order to help the innovation system to integrate other social values besides those valid at the economic marketplace.

The following structural fields of Technology Assessment on Nanotechnology can be separated, as has been regarded in the recent discussion on NTA (Fleischer 2002):

- NTA on the substitution of traditional materials, building-blocks or processes by Nanotechnology based inventions and applications. Substitutions are showing impacts on material flows, on the need for input resources and energy, on emissions (cp. the ongoing discussion on possibly toxic properties of nanoparticles), but also on the value added chains and the economic growth. The investigation of such impacts of Nanotechnology and their societal consequences may be subject of NTA, as well as possible response strategies dealing with such impacts.
- NTA on novel products, systems and processes which will (possibly or probably) be enabled by Nanotechnology (Nanotechnology as “enabling technology”, Fleischer 2002). This course of research might focus on certain fields of application (information/communication, media, military, medical technologies, biotechnology, food and nutrition, energy conversion technologies etc.) and will ask for societal impacts and consequences as well as for response strategies and measures. The issues to be dealt with will depend on the very case. Generally, the entire spectrum of Technology Assessment applies.
- NTA on the structure of Nanotechnology research: Nanotechnology is brought forward by a large community of researchers in publicly funded research institutions and universities but also in industry. Public funding has reached a considerable order of magnitude, nationally and internationally. Agenda-setting and priority defining in research funding often require, among taking into account the aspects of scientific originality and curiosity, to be aware of the future societal demand for problem-solving by Nanotechnology research and of the future contexts in which that technologies could be implemented. NTA could provide pieces of such “future knowledge” as well as methods and approaches how to gain that knowledge (technology foresight).
- NTA on the relation between Nanotechnology and the public: Nanotechnology is, up to now, perceived in society as a highly innovative research

field. Sometimes problems are discussed (Bill-Joy-debate), but there is still no serious resistance but a very positive overall appreciation in the public. NTA could carefully observe the relation between Nanotechnology and the public in order to provide an “early-warning function” in the case that the above mentioned situation would change.

Obviously, these fields of possible NTA studies are very different from each other and will, accordingly, require different methodical and conceptual approaches. On the other hand, it is possible to structure NTA in a way not following the structural setting but focussing on the more thematic questions to be dealt with. Such fields of questions are

- The dimension of scientific and technological advance: What can be said about the direction and the speed of the nanotechnological advance? When will specific capabilities in Nanotechnology be available? What can be said about the timescales of research, development, production and diffusion? Are there “break-throughs” to be expected? This type of NTA consists of, depending on the respective design, technology foresight (scenario-oriented) or forecasting (more predictive).
- The dimension of economic growth: How does Nanotechnology influence the economic growth? Are the rather high expectations justified? What are the (economic, political and social) factors determining the contribution of Nanotechnology to the national and global economy? Are there obstacles and how should they be dealt with? This type of NTA is very close to the economic innovation research (see chapter 7).
- The dimension of sustainability: in which way does Nanotechnology influence the relevant rules of the sustainability postulate (Kopfmüller et al. 2001)? How are the consumption of resources (materials and energy) and the emission of waste influenced? Are there toxic effects on humans or the environment? Is it possible to shape Nanotechnology in a way that sustainability goals may be reached (Fleischer 2003)? Such questions will have to be dealt with in concrete case studies focussing on specific nano developments for specific applications (for example, by investigating material flows and providing life cycle assessments). It will, however,

not be sensible to perform a sustainability assessment of Nanotechnology per se (Fleischer 2003).

- The dimension of ethical questions: Which moral problems or conflicts are touched by Nanotechnology, if any? Which type of ethical inquiry is adequate in such conflicts? Can there be an “early warning” concerning such moral questions allowing society to prepare itself for dealing with them? Beyond the ethical questions included in terms like sustainability (“future ethics”), the most virulent ethical questions may occur in Nanobiotechnology and in medical applications of Nanotechnology.
- The dimension of future models of mankind and society: Positive and negative utopias of future applications of Nanotechnology are, on the one hand, touching ethical questions (see above). However, they go beyond them and include presupposed changes of self-images of humans (concerning, for example, the border between humans and technical artifacts) and of future models of society. Anthropological questions arise as well as new discussions in the cultural sciences.

Summarizing, it may be stated that Nanotechnology is becoming a new and highly important subject area of Technology Assessment. A lot of questions will have to be answered in the next years. At the time being, the structures of NTA are still not been fixed but they will evolve throughout the next years. Some proposals concerning this process have been forwarded in this paper and will, hopefully, influence this ongoing process.

7 Commercial Potential of Nanotechnology – A First Look

Nanotechnology has become a buzzword, comparable to the upcoming of the Internet. The ‘nanotech hype’ becomes obvious in a study published by the US-based venture capital firm luxcapital in which it was found that mentions of the term ‘Nanotechnology’ in the press had increased by 2000 % between 1995 and 2002 (luxcapital, 2003). Because of its potentially large impact on many industries, Nanotechnology is widely considered to be a revolutionary technology that could obliterate business models and restructure vast parts of the economy (BMBF, 2002; CMP Cientifica, 2002; luxcapital, 2003).

The world market for Nanotechnology in 2001 was estimated to be worth EUR 54 billion (Nano Business Alliance, 2001; DG-Bank, 2001). The total Nanotechnology market can be broken down into nanoparticles and composites (23% of the total Nanotechnology market in 2001), ultra-thin layers (44%), measuring and analyzing nanostructures (24%), ultraprecision processes of surfaces (6%) and lateral nanostructures (3%). The total market is expected to grow by 15%–17% p.a. leading to a total market value of EUR 220 billion in 2010 (DG-Bank, 2001). Nanoparticles and composites are forecasted to relatively grow faster compared to the other four areas of Nanotechnology (DG-Bank, 2001). According to the more optimistic forecast of the Nano Business Alliance, the market volume of EUR 220 billion will already be reached by 2005 and will have passed US\$ 1 trillion in 2015 (Nano Business Alliance, 2001). The significant difference between both forecasts is caused by deviating definitions of Nanotechnology. Whereas one forecast focuses mainly on materials and systems (DG-Bank, 2001), the other estimate includes all products that are affected by Nanotechnology (Nano Business Alliance, 2001).

These estimates exemplify that many forecasts on the market potential of Nanotechnology are hardly comparable because they use different definitions and/or classifications of Nanotechnology. A further breakdown of the field ‘nanoparticles and composites’ reveals that 95% of this market is taken by established nanotech products such as pigments, catalysts and dispersions. ‘New’ nanotech products such as ‘new’ nanoparticles and

nanocomposites only had a market share of less than 5% in 2001 (DG-Bank, 2001). It is forecasted that the absolute sales volume of 'new' nanoparticles and nanocomposites will double to US\$ 900 million until 2005; however, the overall share in the total segment of nanoparticles and nanocomposites will remain constant at approximately 5% (Ebenau, 2002). These numbers show that a narrow focus on 'new' nanomaterials would ultimately lead to a lower market forecast for these areas of Nanotechnology and that the relative market impact of Nanotechnology may be relatively minor. According to an estimation of Business Week, the market for 'pure' nanotech products such as "buckyballs, nanotubes and new nanomaterials is still small potatoes", having a total value of US \$50 million in 2001 (Business Week, 2002). Some venture capitalists argue that many of the young nanotech firms have not been able to establish an attractive business model with significant growth potential yet. Thus, sales are low and many of these firms have remained niche players so far (Business Week, 2002; WGZ-Bank, 2002). It is estimated that large incumbents will eventually be the main beneficiaries of Nanotechnology because of a need for scale and large capital resources, especially in the fields of materials and electronics (Ebenau, 2002; luxcapital, 2003). VCs see the best short-term investments opportunities in the area of tools and long-term ones in the area of devices and Nanobiotechnology (luxcapital, 2003).

Very optimistic market forecasts based on a rather broad view of Nanotechnology explain why Nanotechnology has attracted great attention in the public and private sector (BMBF, 2002; CMP Cientifica, 2002; luxcapital, 2003). Figure 1 summarizes some key indicators of recent activities in the field of Nanotechnology. Increasing venture capital funding, the growing number of start-up businesses and private research and development (R&D) and patenting activities indicate that private companies and investors see a significant business opportunity in the field of Nanotechnology.

Table: *Some Key Figures about Recent Activities in Nanotechnology*
(luxcapital, 2003)

- Over US\$ 3 billion international R&D investment in Nanotechnology in 2003; significant share of corporate R&D in Nanotechnology
- Significant and increasing government funding for Nanotechnology: the US has spent more than US\$ 2 billion since 2000; Japan increased government funding from US\$ 120 million in 1997 to US\$ 750 million in 2002; the EU plans to spend US\$ 1 billion between 2002 and 2006 for Nanotechnology.
- Venture capital investment in Nanotechnology amounts to US\$ 900 million since 1999, with US\$ 386 million invested in 2002.
- Venture capital investment in Nanotechnology is growing faster relatively to other industrial sectors. While total venture capital investment declined between 2002 and 2001, venture capital investments in Nanotechnology increased by 251% in electronics, by 211% in industrial products and by 313% in sciences/Nanobiotechnology.
- The number of Nanotechnology patents has been growing significantly; many large corporations (e.g. IBM and Samsung as the top two patentees) are among the most active patentees.
- More than 700 companies are involved in Nanotechnology.

Existing market forecasts are based on the assumptions that Nanotechnology will enable a variety of applications across many industries (BMBF, 2002; CMP Cientifica, 2002; luxcapital, 2003). Tools, materials, devices, techniques for building nanoscale structures, electronics and information technology and life sciences have been identified as the main areas of commercial applications of Nanotechnology (CMP Cientifica, 2002). Within 10 years, the market potential of Nanotechnology in the area of materials is estimated to reach US\$ 340 billion and US\$ 300 billion both in electronics and for integrated circuits (CMP Cientifica, 2002, p. 14 and p. 19). Further, 50% of the multi-billion pharmaceutical industry is forecasted to rely on Nanotechnology within 10 years (luxcapital, 2003, p. 21). These seems to

be the most attractive markets for nanotech products as far as volume is concerned.

A fundamental problem of these enthusiastic forecasts about the market potential of Nanotechnology is that they are often based on the assumption that applications based on Nanotechnology will eventually replace existing technologies and thus capture large shares of an existing market. Very optimistic market estimates for Nanotechnology are simply based on forecasts for already existing markets assuming that the entire or large shares of the future market will belong to nanotech products. This type of forecast faces the fundamental problem of determining Nanotechnology's share in the value chain of the respective products. Only the share of nanotech products in the relevant value chain could be used as a meaningful indicator for the commercial value of Nanotechnology. These estimates are further highly problematic because they disregard important technological and economic aspects that can have a significant impact on Nanotechnology's future market potential:

Nanotechnology is, despite some major scientific breakthroughs, still in its infant stages of technological development (BMBF, 2002; CMP Cientifica, 2002; luxcapital, 2003; WGZ-Bank, 2002). One may argue that the most part of Nanotechnology is still in a form that is considered to be Nanoscience. Science solves theoretical questions, creates explanations and discovers new things; it is a way of knowing. By contrast, technology applies science to produce things and solve practical problems; it is a way of doing (Brockhoff, 1999). Thus, it still is very uncertain in many areas of Nanotechnology whether the technological objectives will eventually be achieved in the predicted time frame and whether these technologies will finally lead to commercially viable products on the market. Further, advances in complementary technologies, e.g. manufacturing technologies, are required in order to apply Nanotechnology in marketable products. Reliable and efficient manufacturing technologies are, e.g., very important in the semiconductor industry, an important target market of Nanotechnology. These technical uncertainties are not taken into account in existing market forecasts of Nanotechnology.

Market estimates for Nanotechnology further disregard the occurrence of significant improvements of existing technologies. However, R&D into existing technologies may improve their performance so that they offer higher added value to customers than Nanotechnology. In addition, other technologies may be developed in the future which may have significant technological and commercial advantages over Nanotechnology. In both scenarios, the market forecasts for applications based on Nanotechnology would have to be reduced.

A superior technology may not necessarily become an innovation. A product innovation is defined as the successful introduction of an invention on the market in the innovation management literature (Brockhoff, 1999; Hauschildt, 1997). Success is usually measured in commercial terms, as e.g. by sales, market share or profits generated from the innovation. A process innovation is the successful introduction of a new process, e.g. a new manufacturing process, within the firm. Success, again, is measured in commercial terms, as e.g. by cost savings achieved by the new manufacturing process. It is important to recognize that technical success is a necessary but not a sufficient requirement for an innovation (Brockhoff, 1999; Hauschildt, 1997).

The attractiveness of a technology must therefore not only be assessed according to technical criteria (Brockhoff, 1999). A superior technology may be very expensive to develop and/or to manufacture which results in a price disadvantage of the final product compared to competing technologies or products. If the market is not willing to pay the higher price, the technologically superior product will fail commercially. It is – based on the present technological knowledge – argued that Nanotechnology may be too expensive for some of the envisioned applications (CMP Cientifica, 2002; Ebenau, 2002). If this is the case, the respective market estimates need to be reduced.

The most important success factor of a product innovation is its advantage relative to existing products as recognized and valued by the customer (Ernst, 2002; Montoya-Weiss/Calantone, 1994). A technology that is superior from a technical standpoint may fail in the market because the customer does not recognize the benefit of the technology or is not willing to

pay a higher price for the more expensive technology. Due to a lack of customer acceptance, the technology fails in the market and can therefore not be called an innovation. A commercially successful technology must either offer additional benefits to the customer that justify higher prices or it must deliver the same functionality as existing technologies or products at a lower price. In both instances, the added value to the customer is higher for the innovation than for the existing product. Nanotech products will only be successful from a commercial perspective, if they will offer a higher added value to customers than competing products.

This very brief discussion leads to the conclusion that a sound estimation of the commercial potential of Nanotechnology requires much more than just an assessment of technological opportunities. It has been pointed out that technological uncertainties, competing technologies and complementary technological developments need to be assessed as well. Moreover, economic aspects, particularly the identification of the relative advantage of a product based on Nanotechnology compared to competing products, must be assessed. The present discussion of Nanotechnology's market potential seems to be highly technology-driven assuming that technological superiority will automatically be transformed into commercial success. This may not be the case as discussed above which casts doubts on the validity of existing estimates of Nanotechnology's market potential.

Because Nanotechnology is in an early stage of development, it is difficult to achieve a sound assessment of its commercial potential with an acceptable level of effort. The commercial assessment becomes even more difficult for entirely new products based on Nanotechnology (BMBF, 2002). In the early stages of Nanotechnology, the potentially high opportunities should motivate first R&D investments. The more scientists and engineers understand about Nanotechnology and start progressing from basic research to applied research and finally to the development of marketable products, the more they should focus on a proper commercial assessment which goes beyond the technical dimension of evaluation. This ultimately requires a thorough analysis of market requirements and the inclusion of competing and complementary technologies. The biggest challenge for companies, VCs and governments is to identify the most promising areas of

application for Nanotechnology in this process and to focus R&D efforts accordingly on these areas while at the same time consequently terminating those developments that are unpromising. Professional R&D portfolio management has been identified as an important success factor of innovations (Ernst, 2002) and must therefore become a core and indispensable part of future R&D in Nanotechnology.

References

- Arnall A H (2003) *Future Technologies, Today's Choices Nanotechnology, Artificial Intelligence and Robotics; A technical, political and institutional map of emerging technologies*. Greenpeace Environmental Trust.
- Bijker WE, Hughes TP, Pinch TJ (eds) (1987) *The Social Construction of Technological Systems. New Directions in the Sociology and History of Technological Systems*. Cambridge (Mass.)/London
- Bachmann G (1998) *Innovationsschub aus dem Nanokosmos*. VDI-TZ, Düsseldorf
- BMBF – Bundesministerium für Bildung und Forschung (2001) *Innovations- und Technikanalyse*. Berlin.
- BMBF (2002) *Standortbestimmung: Nanotechnologie in Deutschland*.
- Brockhoff K (1999): *Forschung und Entwicklung. Planung und Kontrolle*. 5th edition, Munich.
- Business Week (2002) *The Tech Outlook: Nano Technology*. Spring edition (Vol. 50).
- CMP Cientifica (2002) *Nanotech – The tiny Revolution*, Madrid.
- Collingridge D (1980) *The Social Control of Technology*. New York.
- Datta S (1995) *Electronic Transport in Mesoscopic Systems*. Cambridge University Press, 1-2.
- DG-Bank (2001) *Im Fokus. Nanotechnologie in der Chemie*, Frankfurt a.M.
- Ebenau A (2002) *Enorme Märkte für kleinste Teilchen*, BASF, Ludwigshafen.
- Enzyklopädie (1997) *Enzyklopädie Philosophie und Wissenschaftstheorie*, hg. von J. Mittelstraß, Stuttgart, Band 1.

- Etc group (2002) *No small matter! Nanotech Particles Penetrate Living Cells and Accumulate in Animal Organs*. ETC Group Communiqué Issue 76.
- Etc group (2003) *The Big Down. Atomtech: Technologies Converging at the Nanoscale*.
- Ernst H (2002) *International Journal of Management Reviews*, Vol. 4, No. 1, 1-40.
- Fleischer T (2002) *Technikfolgenabschätzung – Theorie und Praxis*, Nr. 3/4, 11. Jahrgang, 111-122.
- Fleischer T (2003) *Technikgestaltung für mehr Nachhaltigkeit: Nanotechnologie*. In: Coenen R, Grunwald A (eds) *Nachhaltigkeitsprobleme in Deutschland. Analysen und Wege ihrer Bewältigung*. Edition Sigma, Berlin, 415-432.
- Fromherz P (2002) *ChemPhysChem*, 3, 276-284.
- Funtowitz S, Ravetz J (1993) *The Emergence of Post-Normal Science*. In: Schomberg R von (ed) *Science, Politics and Morality*. London.
- Janich P (1997) *Kleine Philosophie der Naturwissenschaften*. München.
- Groys B (1997) *Technik im Archiv. Die dämonische Logik technischer Innovation*. Jahrbuch Technik und Gesellschaft 9. Frankfurt am Main, 15–32.
- Grunwald A (ed) (1999) *Rationale Technikfolgenbeurteilung. Konzeption und methodische Grundlagen*. Berlin.
- Grunwald A (2000a) *Technik für die Gesellschaft von morgen. Möglichkeiten und Grenzen gesellschaftlicher Technikgestaltung*. Frankfurt am Main.
- Grunwald A (2000b) *Technology Policy Between Long-Term Planning Requirements and Short-Ranged Acceptance Problems. New Challenges for Technology Assessment*. In: Grin J, Grunwald A (eds) *Vision assessment: shaping technology in 21st century society. Towards a repertoire for Technology Assessment*. Heidelberg et al., 99–148.

- Grunwald A (2002) *Technikfolgenabschätzung – eine Einführung*. Berlin.
- Harig H, Langenbach Ch (eds) (1999) *Neue Materialien für innovative Produkte*. Heidelberg et al.
- Harremoës P, Gee D, MacGarvin M, Stirling A, Keys J, Wynne B, Guedes Vaz S (eds) (2002) *The Precautionary Principle in the 20th century. Late Lessons from early warnings*. EARTHSCAN, London.
- Hess H, Vogel V (2001) *Reviews in Molecular Biotechnology* 82, 67-85.
- Hess H, Howard J, Vogel V (2002) *Nanoletters* 2, 113-116.
- IPTS – Institute For Prospective Technological Studies (ed) (1996a) *The Increasing Use of Aluminium: Prospects and Implications*. EUR 17284 EN. Seville.
- IPTS – Institute For Prospective Technological Studies (ed) (1996b) *The Car of the Future, the Future of the Car*. EUR 17277 EN. Seville.
- Kopfmüller J, Brandl V, Jörissen J, Paetau M, Banse G, Coenen R, Grunwald A (2001) *Nachhaltige Entwicklung integrativ betrachtet. Konstitutive Elemente, Regeln, Indikatoren*. Berlin.
- Mittelstraß J (1974) *Die Möglichkeit von Wissenschaft*. Frankfurt: Suhrkamp.
- Monticelli DM (2002) *Die Renaissance der Analog-Technik*. Elektroniknet.de
- Moore GE (1965) *Cramming more components onto integrated circuits*. Electronics, Volume 38, Number 8, April 19.
- Luxcapital (2003) *The Nanotech Report 2003*, New York.
- Hauschildt J (1997) *Innovationsmanagement*, 2nd edition, Munich.
- National Science Foundation (2001) *Social Implications of Nanoscience and Nanotechnology*, Washington.
- Rip A, Misa T, Schot J (eds) (1995) *Managing Technology in Society*. London.

- Schwarz M (1992) *Technology and Society: Dilemmas of the Technological Culture. Technology and Democracy, Proceedings of the 3rd European Congress on Technology Assessment*. Copenhagen, 30–44.
- Socher M, Rieken Th, Baumer D (1994a) *Neue Werkstoffe. Endbericht*. TAB-Arbeitsbericht Nr. 26. Bonn.
- Spencer Brown G (1979) *Laws of Form* (Neudruck). New York.
- WGZ-Bank (2002) *Mikro- und Nanotechnologie. Branchenreport aus Sicht des Kapitalmarktes*, Düsseldorf.

List of Authors

Dr. Michael Decker

Studied physics (minor subject economics) at the university of Heidelberg, 1992 diploma, 1995 doctorate with a dissertation on temperature measurements in high pressure combustion by laser-induced fluorescence of molecular oxygen at the university of Heidelberg, 1995–1997 scientist at the German Aerospace Center (DLR) in Stuttgart, 1997–2002 member of the scientific staff of the Europäische Akademie GmbH. He was coordinator of the project “Robotics. Options of the replaceability of human beings“ and coordinates the project “Technology Assessment between Method and Impact“ and the study group “Miniaturization and Material Properties“. Since 2003 he is member of the scientific staff of the Institute for Technology Assessment and System Analysis (ITAS) at the Research Center Karlsruhe.

Main research areas: TA of robotics and Nanotechnology, comparison of TA-methods and interdisciplinary research.

Postal address: Institut für Technikfolgenabschätzung und Systemanalyse, Forschungszentrum Karlsruhe, Postfach 3640, 76021 Karlsruhe.

E-mail: Michael.Decker@ITAS.FZK.DE

Professor Dr. Holger Ernst

Professor of business administration, particularly for technology and innovation management, director of the Center for Entrepreneurship and director of the Biopharma Management Center (BMC) at the WHU – Otto Beisheim Graduate School of Management, Vallendar, Germany. He studied business administration at the University of Kiel, Germany and the University of Illinois at Urbana-Champaign, U.S.A. He received a degree in business administration (1992) and his Ph.D. (1996) from the University of Kiel. His main research interests lie in the fields of technology and innovation management, Intellectual Property management, new product development, entrepreneurship and e-business. He has published articles in leading US journals in this field such as *Journal of Engineering and Technology Management* and *IEEE Transactions on Engineering Management* and

European journals such as *International Journal of Management Reviews*, *Research Policy*, *R&D Management*, *Technovation*, *Zeitschrift für Betriebswirtschaft* and *Zeitschrift für betriebswirtschaftliche Forschung*. He consults a variety of private and public organizations in the area of technology, patent and innovation management. He teaches regularly in the WHU executive programs.

Postal address: WHU – Otto Beisheim Graduate School of Management, Burgplatz 2, 56179 Vallendar, Germany

E-mail: hernst@whu.edu

Professor Dr. Harald Fuchs

is a Full Professor of physics at the University of Muenster, Germany, and also the Scientific Director of the Center of Nanotechnology (CeNTech) in Muenster. His research focuses on nanoscale science and Nanotechnology, ranging from atomic force microscopy to nanostructure fabrication. He has published some 200 scientific articles in top journals and, in 1994, was awarded the Philip Morris Research Prize “Challenge Future“. He is currently a member of various scientific organizations including the German Academy Leopoldina. Furthermore, he is a cofounder for several nanotech companies, including nanoAnalytics and Sunyx, and has trained many postdoctoral fellows from countries all over the world.

Postal address: Physikalisches Institut, Westfälische Wilhelms-Universität Wilhelm-Klemm-Str. 10, 48149 Münster, Germany

E-mail: fuchsh@uni-muenster.de

Internet: <http://www.uni-muenster.de/Physik/PI/Fuchs/>

Dr. Werner Grünwald

studied physics at the universities Munich and Stuttgart. 1968 diploma, 1973 dissertation on “Determination of the Nitrogen content in extremely purified Niobium by hot extraction in Ultra High Vacuum“. Joined Corporate R&D in Robert Bosch Company in 1973, active as project leader in different fields. 1980 Head of Thick Film Technology Group with focus on the development of exhaust gas sensors and processes and methods for the

production of electronic circuits. Since 1982, concerned with technology monitoring as Senior Consultant in the staff of Corporate R&D.

Postal address: Robert Bosch GmbH, Dep. BFV2, PO Box 10 60 50, D-70049 Stuttgart ; (will retire at the end of 2003)

E-Mail: werner.gruenwald@de.bosch.com

Private: Römerweg 8, D-70839 Gerlingen;

E-mail: gruenwaldwerner@aol.com

Professor Dr. Armin Grunwald

studied physics at the universities Münster and Cologne, 1984 diploma, 1987 dissertation on thermal transport processes in semiconductors at Cologne university, 1987–1991 software engineering and systems specialist, studies of mathematics and philosophy at Cologne university, 1992 graduate (Staatsexamen), 1991–1995 scientist at the DLR (German Aerospace Center) in the field of Technology Assessment, 1996 vice director of the Europäische Akademie Bad Neuenahr-Ahrweiler, 1998 habilitation at the faculty of social sciences and philosophy at Marburg university with a study on culturalist planning theory. Since October 1999 director of the Institute for Technology Assessment and systems analysis (ITAS) at the research center Karlsruhe and professor at the university of Freiburg. Since 2002 also director of the Office of Technology Assessment at the German Bundestag (TAB). Since 2003, in addition, speaker of the Helmholtz program “Sustainable Development and Technology”. Working areas: theory and methodology of Technology Assessment, ethics of technology, philosophy of science, approaches to sustainable development.

Postal address: Institute for Technology Assessment and Systems Analysis, Research Center Karlsruhe, P.O. box 36 40, 76021 Karlsruhe, Germany.

E-mail: grunwald@itas.fzk.de

Professor Dr.-Ing. Heinrich Hofmann

graduated as engineer in foundry technology at Duisburg (D) and engineer in Materials Science at the Technical University at Berlin, he got his PhD in Material Science with a thesis prepared at the Powder Metallurgy Laboratory at the MPI in Stuttgart in the materials science area. From 1983 until

1985 he worked as senior scientist at the Powder Metallurgy Laboratory, at the Max-Planck-Institute Metal Science in Stuttgart. In 1985 he begins as senior researcher and later as leader of inorganic materials research at the R&D center of Alusuisse-Lonza Services AG, at Neuhausen-am-Rheinfall. In 1993 he joins the EPFL (Swiss Federal Institute of Technology) as extraordinary Professor and Director of the Powder Technology Laboratory (LTP) at the Department of Materials science and engineering. His research area includes synthesis of inorganic powders, their characterization and surface modification, as well as processing and sintering. He is mainly concerned with the synthesis of nanostructured materials based on nanoparticles and the modification of surfaces with nanoparticles using colloidal methods. The fields of application of such materials are medical and biological, (drug delivery, hyperthermia, cell separation, biosensors), electronics and sensors.

Postal address: Ecole Polytechnique Fédéral Lausanne, Institut des Matériaux,

MX-D, CH-1015 Lausanne

E-mail: Heinrich.Hofmann@epfl.ch

PD Dr. Marcel Mayor,

Studied chemistry at the university of Berne (Switzerland), 1991 diploma, 1995 dissertation on vitamin B12 derivatives with peripheral ion complexation sites. 1995–1996 Postdoc fellow of the Swiss National Science Foundation with Prof. Jean-Marie Lehn in the Laboratoire de Chimie Supramoléculaire, Université Louis Pasteur in Strasbourg (France) working on the design and synthesis of reducible cryptatium compounds. 1996–1997 Scientist in the Laboratoire de Chimie Supramoléculaire, Université Louis Pasteur in Strasbourg investigating molecular wires. 1997–1998 Maître de Conférence invité at the Collège de France in Paris and at the Laboratoire de Chimie Supramoléculaire, Université Louis Pasteur in Strasbourg. Since 1998 Scientist and group manager at the Institute for Nanotechnology at the Forschungszentrum Karlsruhe GmbH, Karlsruhe. Working areas: correlation between chemical structure and electronic trans-

port properties of molecules, supramolecular assemblies and nanostructures; nanoscale objects with tailored physical properties.

Postal address: Institute for Nanotechnology at the Forschungszentrum Karlsruhe GmbH, P.O. box 36 40, 76021 Karlsruhe, Germany.

Email: marcel.mayor@int.fzk.de

Dipl.-Ing. Wolfgang Rathgeber

studied electrical engineering at the universities of Erlangen, Campinas (Brazil) and Valencia (Spain). 1998 diploma. 1999–2003 scientist at the Institute of Radio Frequency Engineering and Radar Systems of the German Aerospace Center (DLR) in Oberpfaffenhofen. Since 2003 member of the scientific staff of the Europäische Akademie, managing the project “Nanomaterialien, Nanodevices, Nanocomputing. Standortbestimmung und Perspektiven“. Mr. Rathgeber is currently pursuing a Ph.D. degree in the area of Radar Signal Processing at the university of Karlsruhe.

Postal address: Europäische Akademie zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen Bad Neuenahr-Ahrweiler GmbH, Wilhelmstr. 56, 53474 Bad Neuenahr-Ahrweiler

E-mail: wolfgang.rathgeber@dlr.de

Professor Dr. Günter Schmid

studied chemistry at the University of Munich. He received his diploma in 1962 and his Doctor's Degree in inorganic chemistry in 1965, both at the University of Munich. In 1966 he moved to the University of Marburg where he finished his habilitation on metal-boron compounds in 1969. In 1971 he got a professorship in Marburg. From 1975–1976 he was Dean of the Chemistry Department in Marburg. In 1977 he followed the call on the chair for inorganic chemistry at the University of Essen, where he is still working. In Essen he was acting as a Dean of the Chemistry Department from 1987-1988. From 1988 until 1992 he was a member of the rectorate of the university where he was responsible for the research affairs. Professor Schmid's scientific main interests include the synthesis and investigation of large transition metal clusters and colloids. The generation of three-, two- and one-dimensional arrangements of nanoparticles with respect to

their use as quantum dots in future nanoelectronic devices is presently in the focus of his research activities. Professor Schmid published ca. 350 original papers. He acted as editor of two books on nanosciences. He is a member of various editorial boards of international journals. In 2003 he received the highly ranked Wilhelm-Klemm Award from the German Chemical Society for his contributions on the field of nanosciences.

Postal address: Universität GH Essen, Fachbereich 8, 45117 Essen

E-mail: guenter.schmid@uni-essen.de

Professor Dr. Ulrich Simon

studied chemistry at the University of Essen and obtained his diploma in 1990. 1992 dissertation on electronic quantum properties of ligand stabilized nanoparticles. 1999 habilitation on charge transport phenomena in nanoporous solids. 2000 Full Professor of inorganic chemistry and electrochemistry at the Aachen University of Technology (RWTH Aachen, Germany). 2002 Chairman of the interdisciplinary “Forum Life Sciences” of the RWTH Aachen. His awards include the Gottschalk-Diedrich-Baedeker prize in 1993 and the 1998 ADUC-Jahrespreis for habilitands.

The main interests of his current research are the synthesis, the characterization and the electrical properties of nanostructured materials. This includes aspects of molecular electronics, biomolecular diagnostics and combinatorial research on sensor materials.

Postal address: Institut für Anorganische Chemie der RWTH Aachen, Professor-Pirlet-Str. 1, D-52056 Aachen, Germany,

E-mail: ulrich.simon@ac.rwth-aachen.de

Dipl.-Chem. Daniel Wyrwa

studied chemistry at the University of Essen, 2001 diploma. Since 2002 PhD-student and co-worker in the group of Prof. Dr. G. Schmid at the Institute for Inorganic Chemistry in Essen and scientific assistant in the study group “miniaturization and material properties” of the Europäische Akademie GmbH. Working area of the PhD: Nano-structuring of metal surfaces for heterogeneous catalysis.

Postal address: Institute for Inorganic Chemistry, University of Essen,
45117 Essen, Germany.

E-mail: daniel.wyrwa@uni-essen.de

Previous Publications of the *Graue Reihe*:

- 1 Carl Friedrich Gethmann, Armin Grunwald, Technikfolgenabschätzung: Konzeptionen im Überblick, 9/96, 2. Aufl. 7/98
- 2 Carl Friedrich Gethmann, Umweltprobleme und globaler Wandel als Thema der Ethik in Deutschland, 9/96, 2. Aufl. 10/98
- 3 Armin Grunwald, Sozialverträgliche Technikgestaltung: Kritik des deskriptivistischen Verständnisses, 10/96
- 4 Technikfolgenbeurteilung der Erforschung und Entwicklung neuer Materialien. Perspektiven in der Verkehrstechnik. Endbericht zum Vorprojekt, Arbeitsgruppe Neue Materialien, 1/97
- 5 Mathias Gutmann, Peter Janich, Zur Wissenschaftstheorie der Genetik. Materialien zum Genbegriff, 4/97
- 6 Stephan Lingner, Carl Friedrich Gethmann, Klimavorhersage und -vorsorge, 7/97
- 7 Jan P. Beckmann, Xenotransplantation. Ethische Fragen und Probleme, 7/97
- 8 Michael Decker, Perspektiven der Robotik. Überlegungen zur Ersetzbarkeit des Menschen, 11/97
- 9 Carl Friedrich Gethmann, Nikolaj Plotnikov, Philosophie in Rußland. Tendenzen und Perspektiven, 5/98
- 10 Gerhard Banse (Hrsg.), Technikfolgenbeurteilung in Ländern Mittel- und Osteuropas, 6/98
- 11 Mathias Gutmann, Wilhelm Barthlott (Hrsg.), Biodiversitätsforschung in Deutschland. Potentiale und Perspektiven, 11/98, 2. Aufl. 4/00
- 12 Thorsten Galert, Biodiversität als Problem der Naturethik. Literaturreview und Bibliographie, 12/98
- 13 Gerhard Banse, Christian J. Langenbach (Hrsg.), Geistiges Eigentum und Copyright im multimedialen Zeitalter. Positionen, Probleme, Perspektiven, 2/99
- 14 Karl-Michael Nigge, Materials Science in Europe, 3/99

- 15 Meinhard Schröder, Stephan Lingner (eds.), *Modelling Climate Change and its Economic Consequences. A review*, 6/99
- 16 Michael Decker (Hrsg.), *Robotik. Einführung in eine interdisziplinäre Diskussion*, 9/99
- 17 Otto Ulrich, „Protection Profile“ – Ein industriepolitischer Ansatz zur Förderung des „neuen Datenschutzes“, 11/99
- 18 Ulrich Müller-Herold, Martin Scheringer, *Zur Umweltgefährdungsbeurteilung von Schadstoffen und Schadstoffkombinationen durch Reichweiten- und Persistenzanalyse*, 12/99
- 19 Christian Streffer et al., *Environmental Standards. Combined Exposures and their Effects on Human Beings and their Environment (Summary)*, 1/00
- 20 Felix Thiele (Hrsg.), *Genetische Diagnostik und Versicherungsschutz. Die Situation in Deutschland*, 1/00, 2. Aufl. 2/01
- 21 Michael Weingarten, *Entwicklung und Innovation*, 4/00
- 22 Ramon Rosselló-Mora, Rudolf Amann, *The Species Concepts in Prokaryotic Taxonomy*, 8/00
- 23 Stephan Lingner, Erik Borg, *Präventiver Bodenschutz. Problemdimensionen und normative Grundlagen*, 9/00
- 24 Minou Bernadette Friele (Hrsg.), *Embryo Experimentation in Europe*, 2/01
- 25 Felix Thiele (Hrsg.), *Tierschutz als Staatsziel? Naturwissenschaftliche, rechtliche und ethische Aspekte*, 2/01
- 26 Vitaly G. Gorokhov, *Technikphilosophie und Technikfolgenforschung in Russland*, 2/01
- 27 Chris W. Backes, *Klimaschutz in den Niederlanden*, 3/01
- 28 G. Hanekamp, U. Steger (Hrsg.), *Nachhaltige Entwicklung und Innovation im Energiebereich*, 7/01
- 29 Thomas Christaller, Michael Decker (Hrsg.), *Robotik. Perspektiven für menschliches Handeln in der zukünftigen Gesellschaft. Materialienband*, 11/01

- 30 Selgelid, Michael, Societal Decision Making and the New Eugenics, 4/02
- 31 Irrgang, Bernhard, Humangenetik auf dem Weg in eine neue Eugenik von unten?; 2/02
- 32 Meinhard Schröder et al., Climate Prediction and Climate Precautions, Executive Summary, 06/02
- 33 Ulrich Steger et al., Sustainable Development and Innovation in the Energy Sector. Executive Summary, 2/03
- 34 Carl Friedrich Gethmann, Stephan Lingner, Zukünftige Klimaänderungen als Herausforderung für die deutsche Wirtschaft, 7/03