The Nano–Micro Interface

Bridging the Micro and Nano Worlds

Edited by
Hans-Jörg Fecht and Matthias Werner

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Preface

The key topic of this book "The Nano-Micro-Interface" (NAMIX) intends to bridge the gap between microsystem technology and nanotechnology. Micro- and nanotechnologies are becoming key technologies having a significant impact on the development of new products and production technologies for nearly all industrial branches.

This newly emerging field includes the use of nanotechnology effects to achieve a better device performance or to create completely new devices (bottom-up). The trend to a continuous miniaturization and the corresponding increase in the density of integration is a challenge to the processes and materials in use (top down). Therefore, this exciting area at the interface between the micro- and nanoworld is gaining more and more interest from the fundamental point of view as well as for industrial applications. One of the key scientific and commercial problems to be solved is the development of novel functional structures of superior performance by controlling the atomic or molecular structure on a scale between 1 and 100 nm.

Nanotechnology Comprises

- All products with a controlled geometry size of at least one functional component below 100 nanometres in one or more dimensions that makes physical, chemical or biological effects available which cannot be achieved above the critical dimension(s) ($\leq$100 nm) without a loss of performance.
- Equipment for analytical or manipulatory purposes that allows controlled fabrication, movement or measurement resolution with a precision below 100 nanometres.

According to this definition, a nanotechnology product contains at least one functional component which should fulfill one of the above-mentioned boundary conditions. Obviously, only in a few cases does such a product consist of nanoscale building blocks alone without any macroscopic element. Since the value of the nanotechnology contribution to such a product is difficult to estimate, it is only possible to consider the market price value of the end product. This has implications for the determination of the overall market size. Therefore, a “nanotechnology product” is defined as the smallest unit with a functional nanotechnology component that can be commercially sold in the marketplace. For example, the functional component of a magnetic disk drive is the read/write head that is based on the GMR (Giant Magneto Resistance) effect. However, the smallest unit that is commercially available is the magnetic disk drive and not the read/write head itself. Therefore, market figures are most often based on the market price of the smallest commercially available units with functional nanotechnology components.

Most fundamental physical properties change if the geometry size in at least one dimension is reduced to a critical value below 100 nanometres, depending on the material itself. For example, this allows tuning of the physical properties of a macroscopic material if the material consists of nanoscale building blocks with controlled size and composition. Every property has a critical length scale, and if a nanoscale building block is made smaller than the critical length scale, the fundamental physics of that property changes. By altering the sizes of those building blocks, controlling their internal and surface chemistry, their atomic structure, and their assembly, it is possible to engineer properties and functionalities in completely new ways.

Nanoparticles and nanomaterials possess radically different phenomena and behaviours, as compared to their larger scale counterparts. Such mechanisms include quantum effects, statistical time variations of properties and their scaling with structure size, dominant surface and interface interactions and absence of defects in the nanocrystals. These nanoparticles and nanomaterials have unique mechanical, electronic, magnetic, optical, and chemical properties, opening the door to enormous new possibilities of engineered nanostructures and integrated nanodevice designs, with application opportunities in information and communications, biotechnology and medicine, photonics and electronics. Examples include developments in very high-density data storage, molecular electronics, quantum dots and spintronics. Atomic or molecular units, with their well-known subatomic structure, offer the ultimate building blocks for a bottom-up, atom-by-atom synthesis and, in some cases, self-assembly manufacturing. Advanced nanostructured materials such as high purity single wall carbon nanotubes are being considered for microelectronics, sensors, thermal management for micro- and optoelectronics, and flat panel displays.

This is the first book picking up these emerging technology trends and compiling contributions from 25 authors and international research groups. It addresses the interface between micro- and nanotechnology with a strong focus on synergy effects provided by the combination of both. The book’s contributions cover the entire range of basic technology aspects with a strong focus on potential applications. Moreover, business aspects such as potential markets, roadmaps, transnational networking, and investment opportunities are some of the key topics as well.

Many users are already unknowingly using effects based on nanotechnology. A case in point is sunscreen with a high protection factor, the effect of which is based on nanocristalline titanium oxide. Nanocristalline titanium oxide provides a high protection factor without having a negative impact on the transparency and biocompatibility of the sun cream. Only through a low particle size may this effect be obtained. Another example is the Giant Magneto Resistive Effect (GMR), which is found in virtually any hard disk drive of a computer as a read/write head. The currently high storage densities may only be obtained through use of this nanotechnology effect.

The subject of Nano-Micro Interface ranges from nanomaterials through electronic to biological systems. Using nanotechnology effects in combination with microtechnology is about to open up a considerable market potential. It is remarkable in this context that the European Union, and Germany in particular, is playing an outstanding role, next to the United States and Japan, in the field of micro- and nanotechnology. Germany ranks among the top three in the world both in MST and nanotechnology. This is borne out by technology indicators as well as by the number of publications and the number of patents per country.

Applications in Microsystems

Microsystems, including microelectromechanical systems (MEMS), bioMEMS, nanoelectromechanical systems (NEMS), optical, electronic, and electrochemical microsystems, hold the promise of a new class of multifunctional devices and systems for many applications ranging from advanced computing, chemical and biological analysis/detection, drug delivery/discovery, tissue engineering, chemical and materials synthesis, to energy conversion and storage. New advanced micro-

Effects of nanomaterials and applications due to the reduced dimension.

Effects	*Applications*
Higher surface to volume ratio, enhanced reactivity	Catalysis, solar cells, batteries, gas sensors
Lower percolation threshold	Conductivity of materials
Increased hardness with decreasing grain size	Hard coatings, thin protection layers
Narrower bandgap with decreasing grain size	Opto-electronics
Higher resistivity with decreasing grain size	Electronics, passive components, sensors
Increased wear resistance	Hard coatings, tools
Lower melting and sintering temperature	Processing of materials, low sintering materials
Improved transport kinetics	Batteries, hydrogen storage
Improved reliability	Nanoparticle encapsulated electronic components

systems with integrated nanometer-scale structures and functions present a multidisciplinary challenge.

The performance of such microsystems also depends on the understanding of the properties on both the nano- and microscales. Recently, the Review Committee of the National Nanotechnology Initiative in the U.S. recommended: "Revolutionary change will come from integrating molecular and nanoscale components into high order structures... To achieve improvements over today's systems, chemical and biologically assembled machines must combine the best features of the top-down and bottom-up approaches."

An overview of the effects and applications of the reduced dimensionality of nanomaterials is listed in the table. Furthermore, the addition of nanoparticles to an otherwise homogenous material can lead to a change in the macroscopic material behaviour. Most material properties may be changed and engineered dramatically through the controlled size-selective synthesis and assembly of nanoscale building blocks.

September 2004

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III Applications

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I

Nanotechnology Research Funding and Commercialization Prospects

U.S. National Nanotechnology Initiative: Planning for the Next Five Years

Mihail C. Roco

1
Introduction

Nanoscience and nanotechnology are opening up a new era of integrated fundamental research at the nanoscale, a more coherent science and engineering education, economic nanoscale manufacturing of products, and an enabling foundation for improving human capabilities and societal outcomes in the long term. The U.S. National Nanotechnology Initiative (NNI) is a visionary program that coordinates 17 departments and independent agencies [1–5] with a total budget of U.S.$ 961 million in the fiscal year 2004. An overview of the main research and development (R&D) themes, outcomes in the first two years of the initiative, and plans for the future are presented. At least 35 countries have initiated national activities in this field, partially stimulated by the NNI vision and plans.

Priority in funding in 2004 is oriented to:
- research to enable the nanoscale as the most efficient manufacturing domain;
- innovative nanotechnology solutions to biological, chemical, radiological, and explosives detection and protection;
- development of instrumentation and standards;
- nanobiosystems;
- the education and training of a new generation of workers for the future industries;
- societal implications; and
- partnerships to enhance industrial participation in the nanotechnology revolution.

Priority nanoscale science and technology goals in the next five years are in currently exploratory areas of research (including nanomedicine, energy conversion, food and agriculture, realistic simulations at the nanoscale, molecular nanosystems), in areas transiting to technological innovation (nanostructured materials, nanoelectronics, catalysts, and pharmaceuticals, development of tools for measurement and simulation), and in areas to advance broad societal goals (such as better understanding of nature and life, increasing productivity in manufacturing, interdisciplinary education, improving human performance, and sustainable development). Societal and educational implications, including environmental research, will increase in importance in NNI as nanotechnology products and services reach the market.

Several generations of nanotechnology products are expected to evolve from relatively simple nanostructures for products such as coatings and hard metals, to active components such as nanoscale transistors, and then nanosystems with new architectures. This chapter shows how miniaturization, self-assembling from molecules up, and multiscale architectures lead to the integration of nano- and micro-components into system applications.

2
Government R&D Investments

The worldwide nanotechnology R&D investments reported by government organizations has increased more than six-fold from U.S.$ 430 million to about U.S.$ 3 billion between 1997 and 2003 (Tab. 1 and Fig. 1). At least 35 countries have initiated national activities in this field, partially stimulated by the U.S. NNI.

Scientists have opened a broad net that does not leave any major research area untouched in the physical, biological, materials, and engineering sciences. Industry has gained confidence that nanotechnology will bring competitive advantages to both traditional and emerging fields, and significant growth is noted in small businesses, large companies, and venture capital firms. The annual global impact of products where nanotechnology will play a key role was estimated in 2000 to exceed U.S.$ 1 trillion by 2015, which would require about 2 million nanotechnol-

Tab. 1 Estimated government nanotechnology R&D expenditures during 1997–2003 (in U.S.$ millions/year).

Region	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*
West Europe	126	151	179	200	~225	~400	~600
Japan	120	135	157	245	~465	~700	~810
USA [a)]	116	190	255	270	422 (465) [b)]	600 (697) [b)]	774 (862) [b)]
Others	70	83	96	110	~380	~550	~800
Total	432	559	687	825	1492	2347	2984
(% of 1997)	100	129	159	191	346	502	690

Explanatory notes: West Europe includes countries in EU and Switzerland; the rate of exchange U.S.$1 = 1.1 Euro until 2002; U.S.$1 = 1 Euro in 2003; Japan rate of exchange U.S.$1 = 120 yen in 2002; others include Australia, Canada, China, Eastern Europe, FSU, Israel, Korea, Singapore, Taiwan and other countries with nanotechnology R&D.

a) A financial year begins in the United States on 1 October of the previous calendaristic year, six months before most other countries.

b) Denotes the actual budget recorded at the end of the respective fiscal year. Estimations use the nanotechnology definition as defined in NNI [1]; this definition does not include MEMS, and includes the publicly reported government spending.