FOREWORD

Nanomaterials science

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The nanometer regime covers the transition from condensed matter behavior to atomic and molecular properties and thus is a very rich but also very demanding area in materials science. Close to the condensed matter side, properties and functions might still very well be scalable, whereas close to the atomic and molecular side, the scalability is mostly lost. Properties and functions change qualitatively or quantitatively by orders of magnitude when the dimensions become smaller than a critical size in the nanometer range. Examples are the ballistic regime for electron or spin transport at dimensions below the mean free path, near-field effects in scanning near-field optical microscopy and quantum wells when the dimensions are below an appropriate wavelength, novel electronic, mechanical, and chemical properties when the number of bulk atoms becomes smaller than that of surface atoms, quantum conduction, and Coulomb blockade. Thus, by going below a certain size, an abundance of novel properties and functions are at one’s disposal, or, in other words, we can functionalize materials simply by reducing their size to the nanoscale.

The key to the future lies in the functions that we give to materials, not just in finding ‘novel functional materials’. This catch expression in many materials science programs and initiatives of the past two decades sounds great, but it is not what really counts. All materials are functional in one way or another and, therefore, all new materials are ‘novel functional materials’. Certainly, finding new materials is always an important part of progress, but we should also focus on the much larger domain of novel functions that we can give to existing or modified materials. A good example is semiconductors: they are fifty or more years old and their properties are very well known, but they were not of widespread interest and use until the transistor changed their destiny into being the central material in the information technology revolution. Interfaces gave them their functions, and shaping them into ever-smaller functional components made them indispensably omnipresent as transistors—produced in billions per person and per year—and they are no doubt the rulers of today’s technical world.

The semiconductor and transistor serve as an inspiring example of functionalizing materials. The developments of microelectronics profited very much from scalability, that is, the properties and functions do not change significantly with size. Therefore, every step toward smaller dimensions was a technical and commercial challenge with risks well under control. The transition to the nanoscale, however, is discontinuous. Examples of this transition are the local probe methods that exploit the mechanically controlled proximity to the object under consideration and that have become indispensable as microscopes and as measuring and modifying tools, the size of molecular components that are much smaller than the smallest possibly achievable transistor, the properties and functions of materials below a critical size as mentioned above, the continuum properties versus discrete ones, and novel concepts inspired by living nature. Those novel concepts include growing circuits first and building the active components at the nodes afterwards and measuring weak by weak, small by small, and many by many. It is these discontinuous steps that make the nanoscale different, not just smaller. They pose exciting challenges, open great opportunities and nearly unlimited possibilities, but they also carry serious technical, commercial, environmental, and health risks.
The nanoscale is also a great opportunity for materials science in general. Materials science is interdisciplinary \textit{per se}. A materials scientist should have a reasonable understanding of physics, chemistry, engineering, and more recently, also biology. Certainly one can always team up with representatives from other disciplines and forge collaborations. However, an effective team can only emerge from a common understanding of the respective languages and problems. The lack of such an understanding is the Achilles’ heel of so many collaborations. Despite the intrinsic interdisciplinary nature, materials science has split into various segments according to the type of material, for example, metals, organic, inorganic, biological, molecular, and so on. Each of them leads an independent life with little understanding for the others. This segmentation has made materials science lose, to an undesirable extent, its all-embracing mission for science and technology. There are laudable efforts to reunite different branches of materials science into comprehensive institutions; examples are NIMS in Tsukuba and IMR at Tohoku University, but institutions alone do not make the day. The nanoscale provides an excellent opportunity for scientists. The nanoscale was the bifurcation point where disciplines split and developed their own disciplinary views and language. This was the necessary core for the tremendous developments of science. Technology always had to rely on broader views. Now, disciplines merge again at the nanoscale, which will hopefully bring back to materials science much of what was lost over recent decades.

It is difficult to delimit the nanodomain using general criteria since everything consists of atoms that are roughly a third of a nanometer in size, as is their distance from each other in condensed matter. In most cases, the individual addressabilities of nanostructures, properties, and processes are important. Atoms emerged from the anonymity as members of an ensemble; they have become our partners as individuals. As upper limits for nano, we might agree on 100–200 nm in object size and 1–10 nm in accuracy for local positioning, measuring, modifying, and controlling processes. The lower limit is open; a hundredth of a nanometer in positioning and measuring is nothing extraordinary. As a reviewer, I would accept a very interesting and daring research proposal, even if it interprets ‘nano’ somewhat too generously. After all, we want to promote top-class research and not average research just for the sake of ‘nano’.

Interfaces, material growth at given nano positions, shaping materials to a given nanosize and form, and bistability are key elements for functionalizing materials.

\textbf{Interfaces}

The role of interfaces is rapidly increasing in science and technology. The number of interfaces increases with the square of the number of phases of materials. Even if the majority of them are impractical or useless, they are still much more abundant than the materials themselves, and they are the key to new functions. Think of the simple ‘mechanical’ interface responsible for the lotus effect where wetting is prevented by the rapidly changing surface curvature due to nanoparticles. Think of all the connections of a nanometer-sized area between very different materials, for example, for electron or spin transport. Think of the delicate interfaces that protect nanofunctional units from the environment but allow for communication of various types with other nanocomponents or with the macroscopic world. The solid–liquid interface plays a special role here. For me, it is the interface of the future, both for local growth and removal of nm$^3$ quantities and for working with biological specimens requiring a liquid environment. Interfaces are the ‘faces of action’ and nanoscale materials science will be, to a great extent, ‘interface science’. There is no need to change the name; attentive awareness suffices.
Material growth at given nano positions
This is the second central challenge in nanoscale materials science, but maybe still a futuristic one. We have heard much about the extraordinary properties of carbon nanotubes. They do a great job in certain applications, like tips of scanning tunneling and atomic force microscopes or nanoinjection needles or as bundles for electron emission or electron transport. As single carbon nanotubes of various lengths in complex micro- and nano-electronic circuits, however, they have to be grown at given positions, which is still problematic. Another example concerns the assembly scenario for electronics, components like sensors, actuators, and nano-systems. Macromolecular chemistry is producing highly functional macromolecules, but, eventually, they have to be produced and assembled at given positions.

Shaping materials to a given nanosize and form
In the field of micro- and nanoelectronics, shaping semiconductors, many oxides, and selected metals down to 20–100 nm dimensions is standard. In nanomechanics, however, other materials might be more appropriate and better suited for a given task. In other cases, finishing procedures might be impossible or too time-consuming for large numbers of them. Components for counting electrons—more elegant and smaller than today’s single-electron transistors—or adjustable holes for counting atoms and molecules will eventually be badly needed because of the $1/\sqrt{N}$ fluctuations in the properties and measurements at a small $N$, for example, $N$ dopants in nanosize transistors or $N$ electrons in very short current pulses.

Bistable components
Bistable components, which do not require electrical currents, are aimed at reducing local energy dissipation and faster startup of personal computers. Magnetoresistive and ferroelectric random access memory (MRAMS and FRAMS) devices are the first attempts to use them in circuits. I am not aware of reported switching times that are considerably faster than a few nanoseconds, as required in today’s storage. This is too slow for memory and much too slow for possible logic devices based on two-terminal bistable components. Bistable molecules, a mechanical switch, might be a valid and sufficiently fast alternative, certainly with all the challenges mentioned above.

I have mentioned just a few obvious examples of the involvement of materials science in the new world of nanodimensions. However, for materials scientists, the sky is the limit.

The thoughts given above are partly reflected in the lectures that I have recently given in Japan. It is my pleasure to thank my colleagues for the mutual understanding and hospitality that I always experience in Japan.