Nanotechnology: Understanding How Small Solutions Drive Big Innovation

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1. What is nanoscience and nanotechnology?

The prefix "Nano" derives from the Greek word νᾶνος and means dwarf. In fact, nanotechnology is the manipulation, design and fabrication of the very small. More specifically, nanotechnology can be defined as control over the structure of matter at the nanoscale and nanoscience is concerned with the particular laws of nature that govern this regime. With that said, humans have no good intuition to truly grasp the smallness of the nanoscale. A nanometer as a billionth of a meter is hard to visualize because we lack meaningful comparison with objects of our daily-life experience. When we think of something small we may have length scales such as the diameter of a red blood cell or a human hair in mind. However, these objects can easily be imaged by an ordinary optical microscope. As the prefix "micro" in microscope suggests, objects that can be imaged with an optical microscope are of the order of a micron (about 6 micron diameter for a red blood cell and 50 micron of a human hair) in size or bigger. The nanometer (nm) is three orders of magnitude smaller than the micron (one thousandth of one micron) and thus about 10 000 times smaller than a red blood cell. It is therefore more appropriate to look for comparison on a molecular scale. The length of 1nm is roughly equivalent to about 5 atoms next to each other. With this in mind one can understand that a technology operating on a scale from 1 to 100 nm allows us to fabricate devices, with potentially complex function, which are just a fraction of a human blood cell in size and could be used for example as functional components traveling in our bloodstream while monitoring and actively improving our health (Feynman's dream of "swallowing the doctor").

Nanotechnology has been envisioned with remarkable accuracy by Nobel Prize laureate Richard P. Feynman in his celebrated Caltech talk from 1959 entitled "There's plenty of room at the bottom" where he sketched the technological possibilities of functional systems engineered at the molecular scale.

> "There's Plenty of Room at the Bottom",
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> *R.P. Feynman, reprint of J. Microelectromech. Sys. 1, 60 (1992).*

2. Emerging material properties at the nanoscale

Feynman's vision was ahead of the technology of his time when he asked the inspiring question: "What would happen if we could arrange the atoms one by one the way we want them?". - His vision is still a guiding principle. Today we have the technological capabilities to image and manipulate structures at the nanoscale. Consequences of this achievement can hardly be overstated when considering the particular aspect that all physical properties of matter are determined by the underlying atomic structure. That means, if we can manipulate the atomic structure of matter, we are able to design all its properties at will limited only by our imagination and the constraints determined by the fundamental laws of quantum physics. A simple but effective example of the application of the structure-property correlation is seen when successively reducing the dimensions of a three dimensional bulk specimen such as a metallic block. Every physical property such as conductivity has a characteristic length scale which separates regimes such as diffusive and ballistic transport of electrons. When preparing films of a material with a thickness below the characteristic length scale, the material becomes essentially two-dimensional. Similarly one can create one-dimensional nanowires, and zero dimensional nanodots. As a rule, each dimensional transition is accompanied by qualitative changes in the electronic structure of the material with far reaching consequences on electrical, optical, mechanical, thermal, and magnetic properties. Prominent examples are the tunable and dramatically altered optical and electrical properties of gold nanoparticles with applications ranging from catalysis to therapeutic agent delivery or the use of optimized magnetic nanoparticles for cancer treatment via magnetic hyperthermia. The relation between structure on the nanoscale and material properties is the domain of nanophysics and governed by the laws of quantum mechanics although some important applications of nanoparticles arise from the simple fact that the surface to volume ration of a particle increases with decreasing diameter. However, in order to truly design material properties one has to understand and utilize the fundamental principles of quantum mechanics in a synergetic approach of theory and experiment.

A new quality is added to materials design when fabricating nanostructures from more than a single element. This is realized for example in the form of artificial multilayers which combine materials "A" and "B" through modern deposition techniques (such as molecular beam epitaxy, pulsed laser deposition and atomic layer deposition) in ways conventional chemistry does not allow. At the interface of such heterostructures new material properties can emerge which are neither present in A nor in B. Here the whole is more than the sum of its parts. Emergent interface phenomena pave the way to design materials with functions not known from traditional bulk synthesis. Because in nanostructures the number of interface atoms can be a sizable fraction of the total number of atoms, interface effects often dominate the material properties of heterolayers.

More than 40 years ago, Nobel laureate Herbert Kroemer from UC Santa Barbara coined the celebrated phrase "the interface is the device". Today, researchers such as the interdisciplinary teams at the

University of Nebraska routinely design and utilize interface properties for new functions critical for example to advance information technology.

"The interface is the device"

H. Kroemer's Nobel lecture, December 8, 2000, Quasi-electric fields and band offsets: teaching electrons new tricks

3. Complex nanostructures and nanotechnology

Today scientists and engineers are armed with unprecedented and continuously evolving characterization, fabrication, and computational tools. The former include scanning probe microscopy enabling imaging and bottom-up fabrication where atoms are actively arranged into nanostructures. The bottom-up technique is complemented by molecular self-assembly where molecules with tailored intermolecular interaction can create a self-organized nanopattern which can serve, e.g., as templates for further fabrication steps. Various lithography techniques form the backbone of the top-down approach. Here structuring of functional nanostructures such as transistors and memory cells are carved from a macroscopic block or thin film of matter. These experimental tools are accompanied by powerful computational approaches with techniques which start from quantum mechanical first principles and implement, e.g., density functional theory to simulate the properties of materials and nanostructures. We truly stand on the shoulders of giants such as Binnig and Rohrer who have been awarded with the Nobel Prize in Physics in 1986 for their design of the scanning tunneling microscope. It jumpstarted the field of scanning probe microscopy with spectacular pioneering nanoscientific achievements such as the fabrication of quantum corrals where individual atoms are actively arranged in ring-type structures. These structures reveal the interference pattern of electron waves just as predicted by quantum mechanics. Kohn and Sham (Nobel Prize in Chemistry in 1998) paved the way for computational chemistry and Watson, Crick and Wilkins (1962 Nobel Prize in Medicine) discovered the molecular structure of DNA and its significance for information transfer in living material. The work of these pioneers makes physics, chemistry and biology fundamental pillars of nanotechnology and exemplifies that nanotechnology is truly an interdisciplinary field.

The exiting race that led to the decoding of the double helix structure of DNA shows how fundamental discoveries such as Röntgen's X-rays lead to transformative breakthroughs in other fields of science. This process is continuing today for example in the field of neuroscience. The exploding increase of knowledge about the human brain became possible through modern imaging techniques most notably magnetic resonance imaging (MRI). Advances in fields such as neuroscience should no longer be considered independent from nanotechnology. It is at the interface between those scientific frontiers where future transformative breakthroughs will most likely happen. Nanotechnology is expected to play a key role in detecting and fighting brain diseases. The smallness of nanoparticles allows them to circumvent the blood-brain barrier, penetrate cell membranes, and interact with biomolecules. Nanoparticles are also used to drastically increase the contrast in tissue-specific MRI images. At the same time, advances in understanding of the human brain are expected to have major impact on information technology for example through the modern field of neuromorphic computation where spintronic nanostructures serve as artificial neurons. It is the creative application of modern tools and findings in an interdisciplinary approach which makes the realization of Feynman's dream feasible.

Synergy between experimentation and computation allows for systematic progress faster than ever before. An important role play advances in computational quantum physics and quantum chemistry and the ability to model on multiple length and time scales (multiscale modeling) ranging from the nanoscale all the way up to the device and circuit scale. The role of computational tools to systematically guide experimentation has been identified and its use is substantially fostered through President Obama's Materials Genome Initiative.

4. Grand challenges, vision of the future and current research

Virtually all of the national and global challenges can at least in part be addressed by advances in nanotechnology. Although the boundary between science and fiction is blurry, it appears reasonable to predict that the transformative power of nanotechnology can rival the industrial revolution. Nanotechnology is expected to make major contributions in fields such as

- Information Technology
- Medical applications
- Energy
- Water supply with strong correlation to the energy problem
- Smart materials
- Manufacturing

It is perhaps one of the major transformative powers of nanotechnology that many of these traditionally separated fields will merge. For example, the use of nanotechnology in medical applications doesn't have to be and most likely will not be limited to monitor and maintain health. Merging of molecular biology and information technology in nanotechnological applications has the potential to expand human's physical and cognitive potential as well as life expectancy far beyond today's limits. Nanotechnology will without question continue to strive in the near future through obvious applications such as better computers and more powerful cellphones, but it will not be limited by these rather conventional advances. If we chose to do so, nanotechnology may very well become an integral part of human existence and an integral part of many of the objects surrounding us which in turn might allow us to interact with our environment in radically new ways. One of the goals that appear within reach is the possibility to give non-biological materials properties known from biological entities such as self-repair and replication.

In all areas affected by nanotechnology, changes will most likely not be incremental but have the potential to radically transform our lives in ways that are hard to imagine. The lack to appropriately extrapolate the technological progress originates from the fact that human intuition is ill-prepared to understand the potential of exponential growth. Typically, we extrapolate linearly. Information technology, today one of the forefronts of nanotechnology, is perhaps the prime example where linear extrapolation fails and we can witness the effects of exponential growth in accordance with Moore's law

(Gordon Moore co-founder of Intel Corp.). It states that the performance-to-cost ratio of major components in information technology doubles about every 18 months. Moore's law holds now for more than half a century and can be extended up to a century if vacuum tube technology and mechanical calculators are included. Moore's law applies remarkably well for microelectronic components and data storage technology such as magnetic hard disc drives (HDD).

IBM's HDD from 1956 had a capacity of less than 5MB, was as big as two refrigerators, and weighed about two tons. In 2006 the HDD of a typical laptop computer could store 20-100 GB and shrunk to the size of a deck of cards. This is a 100 million time increase in the information stored per area of magnetic material and an even bigger increase in the performance-to-cost ratio.

The improvement of magnetic storage media depends on numerous breakthroughs in nanotechnology. Examples are the reduction in the size of magnetic grains which constitute a bit, and the discovery of the giant magneto resistance (GMR) effect in nanostructured magnetic thin film multilayers (awarded with the Nobel Prize in Physics in 2007 by Albert Fert and Peter Grünberg). Today grain sizes of HDD media are only a few nm in diameter making the material science of magnetic recording a true nanoscience. The discovery of the scalable GMR effect allowed for a qualitatively new way to read the magnetic stray-fields of ever smaller magnetic bits replacing the magnetic induction of small pick-up coils which show a rapid decrease in the signal-to-noise ratio when scaled down. It is often stated that the computing power of a modern cellphone is higher than all of NASA's computers in 1969 combined. This is another manifestation of Moore's law in the field of integrated electronic circuits. Both examples show that the transformative power of information technology, in case Moore's law holds for a few additional decade, is hard to comprehend.

The continuation of Moore's exponential growth in performance-to cost is not self-evident. After all, Moore's "law" is not a law of nature. There are various energy related challenges which collide with the demands for miniaturization and ever faster processing of information. Those challenges require a common solution through nanotechnology. Exponential progress has been achieved over the decades by making transistors ever smaller without changing the basic principle of CMOS technology. Today, fundamental limits dictated by phenomena such as quantum tunneling demand for radically different solutions. There are at least two energy aspects that challenge progress in information technology. The ongoing miniaturization of transistors and the increasing clock-speed of computers give rise to power dissipation. Insulating barriers are no longer effective on the nanoscale. With decreasing thickness of the gate insulator of a field-effect transistor, electrons can tunnel through the barrier and electric leakage currents rise dramatically. As a result heat production increases. Heat is not only wasteful but also detrimental to the electronic components. Latest by 2005 it became clear that business as usual meaning continuation of scaling down CMOS electronics to ever higher transistor densities without conceptual innovations will lead to power densities inside a computer's CPU comparable to the surface of the sun. In addition, the energy demand for technologies such as modern cloud computing is growing at a staggering rate. Extrapolating this rate 10 years into the future reveals that a multiple of today's entire electricity production will be necessary just to satisfy the energy demand of cloud computing.

"If scaling continues at present pace, by 2005, high speed processors would have power density of nuclear reactor, by 2010, a rocket nozzle, and by 2015, surface of sun."

Patrick Gelsinger Intel Corporation Microprocessors of the New Millennium: Challenges, Opportunities, and New Frontiers ISSCC 2001

Advances in nanotechnology are mandatory to continue growth according to Moore's law or progress even faster with new device concepts combining, e.g., memory and logical function to achieve what is known as "More than Moore". Latest by 2020 today's approach to scale down CMOS circuits comes to a hold while clock-speed is already stagnating for years. The US industry is very well aware of challenges and opportunities for information technology and sponsors national research programs for example in the field of spintronics. My group and I are privileged to be involved in two such programs. The Center for NanoFerroic Devices (CNFD) is sponsored by the Nanoelectronics Research Initiative (NRI) and the National Institute of Standards and Technology (NIST). CNFD is a partnership of investigators from six academic institutions: University of Nebraska-Lincoln (UNL), University of California at Irvine (UCI), University of Wisconsin-Madison (UWM), University at Buffalo, SUNY (UB), University of Delaware (UD), and Oakland University (OU). UNL serves as lead institution. The second program is the Center for Spintronic Materials, Interfaces, and Novel Architectures- C-SPIN. Here 32 experts from 18 universities collaborate and are sponsored (overall funding $31M) through one of several STARnet programs funded through the Semiconductor Research Corporation with member organizations such as IBM, Intel, Micron, Applied Materials, GLOBALFOUNDRIES, Raytheon Company, Texas Instruments Incorporated, United Technologies Corporation and government participation through the Defense Advanced Research Projects Agency (DARPA).

Research in the field of spintronics specifically targets at nanotechnological solutions for energy related limitations of information technology inherent to today's CMOS based electronics. Spintronics is an approach to process and store information by utilizing the spin degree of freedom of electrons rather than their charge alone. Today's electronic devices rely on the control of electric currents through electric fields and their coupling to the electron's charge. Spintronics allows us to utilize the quantum mechanical electron spin in addition to charge with multiple advantages. The collective order of interacting spins in nanomagnets is inherently non-volatile. That means non-volatile memory function is relatively easily implemented in spintronic devices allowing for innovations such as instant-on technology which eliminates the booting procedure of a computer. Moreover, there are multiple strategies to switch magnetic state variables virtually in the absence of electric currents solely by voltage or at least strongly supported by voltage. This means spintronic devices have the potential to solve the problem of energy consumption and overheating of processor cores due to the absence or strong reduction of electric currents and their accompanying heat production through Ohmic losses.

Nanotechnological solutions can be found in diverse and rather unexpected applications allowing for advanced energy efficiency, electric power generation and more. For example, nanotechnology is used to optimize permanent magnetic materials with a large range of transformative applications such as lightweight headphones, powerful and lightweight electrical motors used in unmanned aerial vehicles, generators in wind turbines and many more. All of them rely on modern permanent magnets with their unprecedented high energy product. At the University of Nebraska for instance there is a substantial effort to find alternatives to rare earth permanent magnets such as NdFeB or SmCo with the help of nanotechnology. The need to reduce the use of rare earth materials becomes obvious when considering for instance that a 2MW wind turbine contains about 800 pounds of rare earth minerals. Rare earth minerals are primarily mined in China creating unwanted dependencies, high costs, and significant pollution.

For similar reasons we use nanotechnology to create prototype materials with applications in near room temperature magnetic refrigeration. 36% of the electrical energy consumed by US households is used for heating, ventilation and cooling (DOE Energy Information Administration). Therefore, a sizable increase in the efficiency of cooling technology is a potentially big part of the solution to the energy crisis. The magnetocaloric effect forms the basis of such an energy efficient and environmentally friendly cooling technology. Magnetic refrigeration is based on the phenomenon that a magnetic material increases its temperature when exposed to a magnetic field and lowers its temperature when the magnetic field is removed. This phenomenon can be utilized in a refrigeration cycle in close analogy to gas compression refrigeration. We use nanotechnology as an effective tool in materials design. On the macroscopic level one has to tailor the response of the magnetization of a material on temperature and fields. The structure-property relation underlying the success of nanotechnology allows us to tune microscopic parameters such as the quantum mechanical exchange to systematically realize the desired macroscopic properties. Optimizations, which are necessary for a breakthrough of this technology, include again the elimination or rare earth materials. Moreover, nanotechnology opens the possibility to eliminate the need for magnetic fields replacing them by electric fields in artificial multiferroics materials. This approach gave rise to my pending patent on refrigeration through voltage-controlled entropy change and has promising applications in miniaturized cooling devices useful for instance in night-vision goggles.

5. Impact on society and economy

The outlined examples provide a glimpse into the transformative power of nanotechnology. It is important to realize that advances in one field, such as information technology, will in turn advance fundamental aspect of nanoscience for instance in the important field of friction and lubrication on the atomic scale (the domain of nanotribology). Those insights enable ever more sophisticated nanotechnological machines and tools for imaging and fabrication which in turn accelerates our understanding and ability to master engineering on the nanoscale. This upward spiral makes extrapolation difficult and most likely leads to an underestimation of progress and its impact on society and economy.

Nanotechnology will gradually but at a fast rate become ever more important for the fabrication of consumer products. As outlined, a hallmark of nanotechnology will be its potential to include all sciences. Interdisciplinarity will become a key quality for innovation. This has important implications for the education of the workforce. A basic understanding of nanotechnology and the sciences it is based on will be of increasing importance and decide about competitiveness of the industry. Already today research consortia such as the Semiconductor Research Corporation (SRC) are extremely interested to be in close contact with the nation's graduate students for instance via meetings such as Techcon 2014. Here students working in SRC sponsored programs interact face-to-face with industry leaders, e.g., during poster presentations. SRC certainly understands the importance to compete for the best of the next generation of engineers and scientists.

Nanotechnology will very likely come with a large number of opportunities enriching our lives but it will also create new challenges for example those that accompany an unprecedented increase in life expectancy of the population. For the US economy it remains important to stay ahead of the technological development because one can expect a separation into mass products and nanotechnological products which require a high level of research and development. Successful competition with other nations, which certainly understand the importance of nanotechnology as well, requires a constant financial effort through industry and government participation especially in high risk and fundamentally oriented long-term research. It requires the constant attention and support of policy makers, and constant improvement in the education of the workforce and the general public.