A Little Bit About Nanotechnology

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Defining Nanotechnology

A nanometer is small. Very small. To be precise, a typical sheet of paper is 100,000 nanometers thick. Nearly 50 years ago, Richard Feynman gave a famous speech [1] in which the idea of nanotechnology was first envisioned. In it, he famously asked, “What would happen if we could arrange the atoms one by one the way we want them?” It took thirty years for microscopes to be developed that allowed that groundbreaking vision to be realized, allowing scientists to both see and manipulate matter at the atomic scale [2]. In 1999, President Clinton launched the National Nanotechnology Initiative – the first large-scale U.S. government investment in nanoscale science, engineering, and technology – a program whose budget has already tripled to roughly $1.5B per year.

Despite this rapidly growing field filled with enormous promise, not to mention vast public and now private investment, even the basic definition of nanotechnology is still heavily debated. A number of widely varying definitions can be found depending on where one searches. For example, a quick Google search reveals enormous variations in something as simple as the size range that should fall under the label “nano,” from 0.1-100 nm to 1-1000 nm (in other words, two orders of magnitude of variation). If we turn to the Press for a definition, we may find descriptions of nanotechnology such as, “the science of invisibly tiny things,” [3] while marketing firms may call it, “the technology of the minuscule,” [4]. Moving on to Hollywood for the answer, one would find that nanotechnology is the stuff that created the Incredible Hulk and was also the main professional focus of Spiderman’s nemesis (the Green Lantern was a “Nanotechnologist”).

Of course, there are many more serious and useful definitions of nanotechnology than these [5]. A simple working definition that I like, and one that appears to be gaining mounting consensus, is that *nanotechnology is the purposeful engineering of matter at scales of less than 100 nanometers to achieve size-dependent properties and functions*. The central points of a good nanotechnology definition are all represented in this concise statement, namely that: (1) it is purposeful (not nano by accident), (2) the size scale is less than 100 nanometers, and (3) it involves properties that are size-dependent.

The Nanotech Promise

According to much of the information one reads, in printed news articles, on web sites, and even in many science journals, nanotechnology holds the key to: meeting global energy needs with clean solutions, providing abundant clean water globally, increasing the health and longevity of human life, maximizing the productivity of agriculture, making powerful information technology available everywhere, and even enabling the development of space. The market for nanotechnology-based products, it is predicted by many, will be in the trillions within a mere decade, and nearly every sector of the economy will be impacted [6]. And yet, when one surveys the products based on nanotechnology that are available today, we do not come away with such an impressive picture, unless skin cream, longer-lasting tennis balls, and slightly more stain-resistant pants are going to change the world. So, an important question one might ask is: "Is all of this promise real, or is it just a lot of hype to get attention and funding?" The answer, of course, is "Yes…to both questions."

What's so Special about "Less than 100 nm"?

There are a number of reasons why "less than 100 nm" is so technologically exciting, although in the interest of brevity I will highlight only a few of the key ones here, and leave it to the reader to investigate these and others in greater detail elsewhere. The important consequence of each of these reasons is that they offer the scientific and engineering communities completely new ways of tuning the properties of materials and devices.

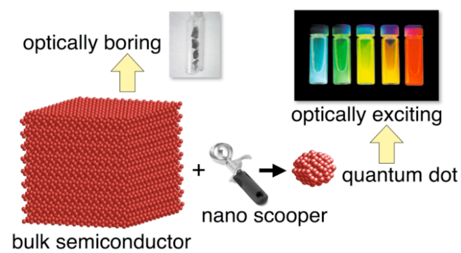

Fig. 1. Change and control of optical properties of a bulk material "going nano."

<u>Quantum Effects</u>

One of the most important attributes of nanoscale materials is the fact that it is possible for the quantum mechanical properties of matter to dominate over bulk properties. One example of this is in the change in the optical properties, for example in the photoemission, of many semiconductor materials as they "go nano." Figure 1 illustrates how, when we take a material whose optical properties may be considered uninteresting, simply by changing its size to the nanoscale we can control the color of the material, completely opening up to variation this once rigid attribute of the material. This effect is due to something known as quantum confinement.

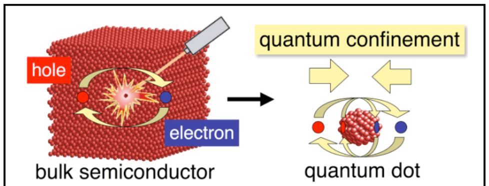

Fig. 2. Illustration of quantum confinement, in which an electron and hole in an optically excited state are squeezed.

The cartoons in Figure 2 illustrate the basic concept of quantum confinement. When light shines on a material, it can excite an electron (negative charge), which leaves behind a hole (positive charge). In this example, the electron and hole are bound together and stay a certain distance apart. When the material is shrunk so far down in size that this electron-hole pair is "squeezed," then we have a physical confinement of the excited state. This very quantum mechanical effect is precisely what leads to the changes in the color of the material.

<u>Surface Area</u>

Another key reason the nano size regime is special is because of the dramatic increase in the surface-to-volume ratio. As illustrated in Figure 3, when the size of building blocks gets smaller, the surface area of the material can increase even while the volume remains the same. This effect occurs at all length scales, but what makes it unique at the nanoscale is that the properties of the material become strongly dependent (read: "controllable") on the surface of the material, since the amount of surface is now at the same level as the amount of bulk. In fact, in some cases such as fullerenes or single-walled nanotubes, the material is *entirely* surface. The fact that the surface to volume ratio is so large opens entirely new possibilities for applications in catalysis, filtering, and new composite materials, to name only a few.

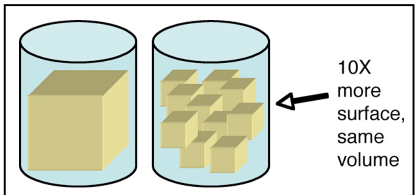

Fig. 3. Example of how surface area increases while volume stays fixed.

Convergence of Length Scales

The nanoscale happens to be the size regime of the fundamental building blocks of biology. Thus, we are now capable of making and controlling materials that are at the same length scale as biology and medicine. In Figure 4, one can see that the sizes of the same optically tuned nanoparticles discussed above lie in precisely the size range of DNA and typical proteins. This convergence of length scales means that nanostructures can be functionalized [7] in such a way to interact with biological elements, leading for example, to revolutionary possibilities for medical imaging, drug delivery, and repairing genes. Indeed, the emergent fields of nano-biology and nano-medicine are where some of the most exciting nanotechnology discoveries (and, in parallel, concerns) may originate.

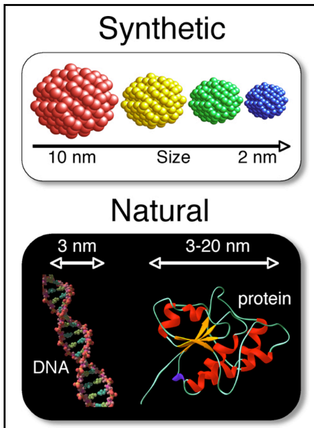

Fig. 4. Illustration of the convergence of length scales between what we can make and the fundamental building blocks of life.

Nature Already "Does Nano"

In nature, there are numerous examples of nanotechnology-based systems, already highly optimized through millions of years of evolutionary development. Three examples of what nature can do are shown in Figure 5. The inner ear of a frog (left) has nanomechanical cantilevers that measure deflections as small as 3 nm due to sound. The male silk moth (middle) can detect, with single-molecule precision, the pheromones of a female moth emitted up to 2 miles away. The eye of an ant (right) uses nanoscale features to greatly enhance its visual sensitivity. Recently, the wings of a butterfly were shown to be intricately colorful because of nanoparticles that act as a photonic crystal.

These are only a few of the countless examples of how nature employs nanotechnology in different ways (of course, with the most important one to us being the human body itself, which contains billions of nanoscale machines!). It is both fascinating and humbling to observe that, despite all of the phenomenal technological advances in nanoscale synthesis and characterization, in most cases we are still unable to build nanotechnology-based devices that even come close to rivaling nature.

Fig. 5. Nature already does nano quite well.

Possible Applications Using Nanotechnology

As I've already mentioned, there are numerous, vastly differing potential applications that will benefit from the use nanotechnology. In some cases, this benefit will mean an incremental improvement in a well-established process, for example in the increase in strength-to-weight of a material that uses carbon nanotubes as opposed to the current "carbon fibers." In other cases, the benefit will mean the ability to do something an order of magnitude (or more) better than previously, where "better" is of course dependent on the application; for example a sensor based on a nanomechanical resonator may achieve the same levels of sensitivity, but require one tenth the power to operate (or the other way around, or both, etc.). Below I give a few examples of the latter type of application, namely ones that could provide revolutionary advantages over present-day technologies, in two distinct areas: detection and energy.

<u>Detection</u>

If we could detect molecules with the same level of sensitivity, selectivity, and energy efficiency of the silk moth, we'd be able to dramatically improve a vast array of crucial national and international needs, from homeland security to environmental monitoring to – yes, you guessed it, oil. There are already some very promising sensors that are based on nanotechnologies, which offer one or more of the following attributes: smaller size and greater portability, better sensitivity (to parts per trillion thus far in some cases), and ultra-low power consumption. Most of this work is still "in the Lab" but some small companies are already beginning to sell nanotech sensors, for example one company [8] sells field effect transistor (FET)-based sensors that employ carbon nanotube networks as the transducer.

At the Center of Integrated Nanomechanical Systems at U.C. Berkeley, research groups are developing several different nano-technologies for sensing that are based on completely different concepts, allowing one to understand which approach is most suitable for a given application. For example, in addition to FET devices, sensors based on nanomechanical resonators have been fabricated and shown to be capable of measuring mass all the way down to the attogram (that's very little stuff: there are one thousand billion attograms in a single speck of dust). Just as in a frog's ear, one can also measure (either optically or electronically) the deflection of a nano-sized cantilever as a response to something attaching to it. In these cases, the cantilever can be coated so that it is chemical highly selective.

It is important to keep in mind that the development of a new sensor by itself is not sufficient for a new device, which also requires the integrated on-board electronics, new software to run, power source, and some form (preferably wireless) of data communication. Although nanotechnology is not pervasive (yet) in the oil industry, there are clear opportunities and needs for the development of selective, possibly mobile, and ultra-small sensors. The nano-tech based sensors currently under development may well find numerous applications in these areas, particularly for enhanced underground detection and imaging.

Energy

The impact of nanotechnology on both energy generation and storage is likely to be enormous, and certainly both the private (e.g., venture groups) and public (e.g., Department of Energy) are "betting big" on this possibility with massive recent investments. The most prominent areas of research in employing nanotechnology for energy include: the development of cheaper solar cells; new low-water consumption plants for biofuels; photo-electro-chemical cells that could efficiently convert sunlight into hydrogen; higher energy density and faster charging batteries; and of course, the old favorite, hydrogen storage. None of these technologies is in any way new; rather, the new excitement that has clearly been generated is a result of the fact that nanotech-based solutions could lead to much cheaper and more efficient applications of these technologies.

By way of providing one small example in this vast space of possibility, I will briefly discuss nanotechnology in the area of photovoltaics (PV), which is the conversion of sunlight directly into energy. Until now PV has been dominated by solid state junction devices, mostly made of silicon in its crystalline form. Enormous advances have been made to steadily improve the efficiencies of these devices over the past 30 years, with single-crystal silicon cells at 25% power conversion and multi-junction cells approaching 40% power conversion [9]. Yet, in order for solar energy to become a truly viable alternative to carbon-based fuels, it must also become cost-competitive, and despite these substantial advances in efficiency and cost, solar energy is still at least 10 times more expensive per kilowatt-hour than coal, gas, or oil.

Recently, a new generation of PV cells, based on nanoscale materials, has received enormous attention because of its potential to dramatically reduce the cost of solar cell energy. These new opportunities arise from major advances in the ability to control the optical, electronic, and structural properties of inorganic and organic materials at the nanometer scale. There are a number of examples of such possible future solar cells, which can have fundamentally different photon-to-electron conversion mechanisms. One class of nanomaterials-based photovoltaics – that based on hybrid organic/inorganic systems – is considered to be a leading candidate for future-generation cells. Even though the concept for these cells is less than a decade old, extensive research efforts [10] and even several major start-up companies are focused on developing practical, low-cost devices.

Challenges of Using Nanotechnology

It is true that major experimental advancements over the past several decades have made the ability to create, manipulate, and measure atomic-scale phenomena nearly routine; nevertheless, there are numerous scientific challenges that must be addressed in order for this burgeoning field to live up to the high promise and potential that nanotechnologies might offer, such as the few examples described above. All of these challenges require the confluence of disparate disciplines for the continuation of the current outstanding pace of progress, particularly in the areas of synthesis, characterization, engineering, and simulation, which I briefly highlight below.

- *Synthesis.* The main challenge in all synthesis techniques is the amount to which key characteristics can be controlled during the synthesis process.
- *Characterization*. One of the greatest challenges of the nanoscale development community is that they are essentially operating in a “blind” mode since present characterization techniques are slow, very expensive, and may require low temperature conditions to operate effectively.
- *Engineering*. The fabrication and assembly of nanoscale components requires the expertise of an engineer combined with a kind of “renaissance” understanding of the chemistry, physics, and biology of the nanoscale. Nanoengineering should be a (new) major at all Universities.
- *Simulation*. The challenge in the simulation of nanotechnologies lies in understanding how to simulate measurable quantities of the full device (for example, its current) while maintaining the appropriate level of accuracy for the regions of the device where quantum effects may dominate.

The institutions engaged in nanoscience research must develop strategies for how to best make inroads toward overcoming these scientific challenges in order to maximize our progress and accelerate innovation.

Brief Comments on the Ethical Position

At this time, little information is known regarding both the toxicity and the potential exposure risks of nanotech-based devices. As with any scientific advance, we must balance the possible benefits of nanoscience research with possible harm. I believe that it is indeed incumbent upon nanoscience research to proceed with caution. However, nanoscience research is self-regulating, peer reviewed, and by nature a field where claims have to be backed by evidence. There is quite a bit of caution already built in to the culture and discipline of nanoscience research, such that scientists are not hasty to make pronouncements or move *recklessly* toward technological innovation.

Since nanotechnology is highly likely to positively impact some of the most pressing problems facing our world – from cleaning our drinking water to maximizing our energy efficiencies to stemming global warming to finding new cures for diseases – the potential rewards are so great that we must press ahead, even urgently, with nanoscience research, keeping mindful throughout of the need to balance benefit against risk.

References

[1] R. P. Feynman, "There's plenty of room at the bottom," presentation at the American Physical Society Conference at Caltech, California (1959).
[2] see, for example, D. M. Eigler and E. K. Schweizer, *Nature* **344**, 524-526 (1990).
[3] "How super-cows and nanotechnology will make ice cream healthy," telegraph.co.uk, August 20, 2005.
[4] Babolat, Inc., in their marketing description of the "NS" line of tennis racquets.
[5] for example, the National Nanotechnology Initiative maintains a web site rich with information at www.nano.gov.
[6] These sorts of statistics are typical in reports on the topic produced, e.g., by Lux Research (and many others).
[7] The term "functionalization" in this context means changed in some way to stick to something else – it's kind of the nanoglue that bridges one nano-thing to another or to something larger (a macro-thing).
[8] While there are several examples of such companies, I'll give the Berkeley spin-off, Nanomix, Inc., which also happens to have the best nano web address around: www.nano.com.
[9] The National Renewable Energy Laboratory tests the real efficiencies of all different types of solar cells and periodically publishes them, e.g., in "Best Research-Cell Efficiencies," 2002.
[10] see, e.g., a 2005 DOE report, "Basic Research Needs for Solar Energy Utilization," which can be found on their web site.