Lessons in Nanotechnology from
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NANOTECHNOLOGY AND ITS IMPLICATIONS FOR SOCIETY

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Great strides are being made worldwide in our ability to assemble nanoscale building blocks to create advanced nanostructured materials and devices with novel properties and functionalities. This rapidly growing effort has been accelerated in the past few years by research funding from the U.S. National Nanotechnology Initiative (NNI)[1] and similar national and international efforts around the world. A brief perspective of nanotechnology and its implications for society in the coming years is presented, which is based upon thoughts and conclusions drawn from our work in the U.S. National Science Foundation (NSF) Nanoscale Science and Engineering Center (NSEC) for Directed Assembly of Nanostructures at Rensselaer. The opportunities and major challenges facing the worldwide nanotechnology research community, industry, and government in moving forward are very briefly considered.

The area called nanotechnology really encompasses nanoscale science, engineering, and technology. It is fundamentally based upon the understanding and control of matter at dimensions between about 1 nm and 100 nm, the range of length scales in which unique phenomena enable novel applications owing to confinement effects on all material properties in sufficiently small bits of matter and the exceedingly large surface or interface areas of nanoscale building blocks, such as nanoparticles, nanotubes, and nanolayers. The field has been enabled to its present extent by changes of focus in, and the confluence of interests among, the three core disciplines of physics, chemistry, and biology. In all three of these disciplines over the past few decades, the focus has changed toward phenomena at the nanoscale, with the developing understanding that control of size, atomic and molecular arrangements, and morphology in this regime can offer new opportunities for integrating physical laws, biological principles, and chemical properties to create novel materials, devices, and systems. It is this confluence of interests and activities that makes the field of nanotechnology today so exciting.

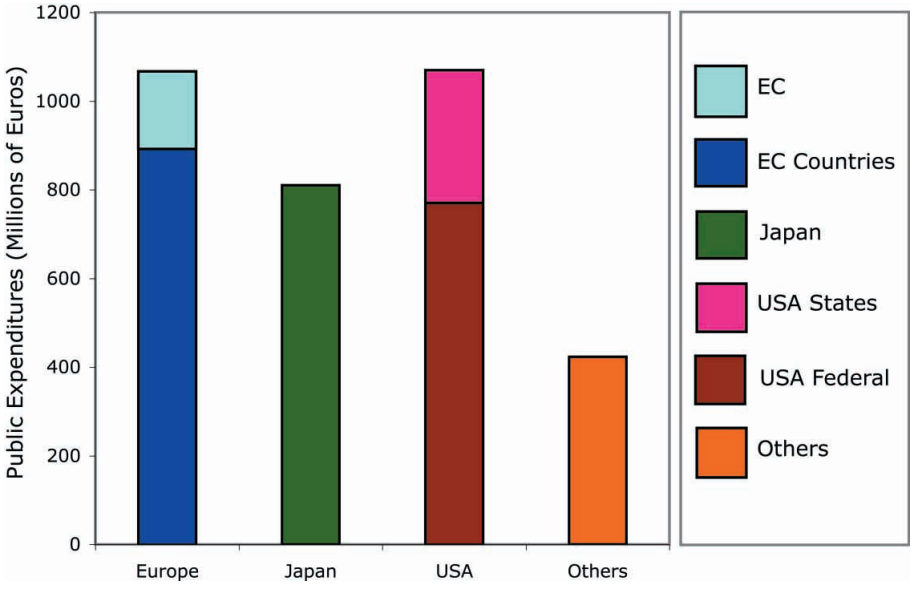

FIGURE 1 - Worldwide public funding for nanotechnology during 2003 is presented in millions of Euros (funding not normalized for purchasing power)[5].

Significant investments in nanotechnology research are now being made that range around $1 billion annually each in the U.S., Europe, and Japan, with somewhat less investment in the rest of the world, as shown in Figure 1. Many of these investments were encouraged by the NNI begun in 2001 during the final term of U.S. President Bill Clinton that resulted from a series of studies [2, 3] carried out under the sponsorship of the NSF and other funding agencies. This initiative, and others like it around the world, is often justified in terms of international competitiveness and the potential economic value of nanotechnology markets worldwide, projected by the NSF to be about $1 trillion annually, give or take a factor of two, by 2010[4]. The extraordinary breadth of this expected economic value should be derived from such areas as materials production, nanocomposites for transportation vehicles and other applications, goods and services, components, materials and devices for computing and communications, and pharmaceuticals, which supports such justification. Indeed, it is certainly likely that nanotechnology in the future will impact our daily lives in a multitude of ways. Many examples exist even today such as giant magnetic resistance devices, sunscreens, sports equipment, and nanocomposite plastics, for example.

The eventual and likely societal implications of the responsible development of nanotechnology are potentially very broad and very deep.

They will include: our greatly increased ability to understand nature and the possibility to create new avenues to educate people about the world in which they live; a wide range of new and improved products and services; better health care and quality of life; more efficient use of natural resources through greater manufacturing efficiency; food and energy sufficiency; sustainable development; and improved national and international security. These latter three areas are the overriding global issues for the world today and, as such, deserve further description here.

Food and energy sufficiency will be enabled and enhanced by effective and inexpensive water purification, widespread food source supervision and management, new energy efficient systems, and new and improved alternate energy sources. Our progress toward a condition of sustainable development will be very positively impacted by more efficient manufacturing with minimal waste, decreased raw material use, and reduced environmental contamination. Improved national and international security will be enhanced through better threat detection, communication, and intervention, but it should also certainly be reduced in need by more global manufacturing, greater dispersion of workforces worldwide, balanced trade and market development, and greater availability of health services. Responsible development and use of nanotechnology can offer the opportunity to find solutions to all of these issues in the coming decades.

The examples presented in my talk* from our recent research results included a number of investigations of functional nanoscale and nanostructured materials that may potentially find commercial use in structural, electrical, environmental, and biomedical applications. Many of these and more can be found in the references on the website for our NSEC[6]. In this brief summary, I will not repeat them here, but rather focus on the opportunities that I have already cited and the challenges facing the world as we move forward trying to take advantage of nanotechnology.

Indeed, there are significant challenges that will need to be met and overcome, by the worldwide scientific research community, by the technological and industrial community, and by the general lay public and their governmental bodies, if we are to reach the lofty goals and successes envisioned for nanotechnology. The scientific research community will need to continue learning pathways from physics, chemistry, and biology to create and assemble organic and inorganic nanoscale building blocks into useful

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hybrid materials, devices, and systems. The technological and industrial community will need to develop robust and potentially massively parallel methods for the creation of such hierarchical materials, devices, and systems for a wide range of applications to serve society. And the general lay public and their governmental bodies will need to understand the value of helping to solve the truly grand challenges facing society worldwide (energy, clean water, health, etc.) and have the resolve to move forward toward their solution. In this regard, it will be very important and necessary to educate the public and their representatives to become science literate to allow them to make technologically informed decisions.

While these challenges will certainly need to be overcome in the future, we have already made progress in the field. We are now able to create a wide variety of nanoscale building blocks worldwide through a number of chemical, physical, and biological pathways. We are also learning how to assemble these building blocks into useful nanostructured materials and devices. Hierarchical nano-micro-macro systems are being created and society is already beginning to benefit from nanoscience and nanotechnology and its applications through the involvement of industry. However, it is really still early in the development of nanotechnology and there is much more to come!

REFERENCES

1. See *www.nano.gov*
2. *Nanostructure Science and Technology*: World Technology Evaluation Center (WTEC) Panel Report on R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices, R.W. Siegel, E. Hu, and M.C. Roco, eds. (Kluwer, Dordrecht, 1999).
3. *Nanotechnology Research Directions*, M.C. Roco, R.S. Williams, and P. Alivisatos, eds. (Kluwer, Boston, 2000).
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5. *European Industrial Research*, December 2003 (European Commission, Brussels).
6. See *www.nano.rpi.edu*

Discussion

L.L. Hench: Intellectual property and venture capital availability are important issues in bringing a new technology, such as nanotechnology, to the marketplace. Please summarize your opinion as to the status of these issues at this time with regard to nanotechnology developments.

R.W. Siegel: You are correct that these are important issues. Intellectual property (IP) needs to be well secured so that investments can have some likelihood of return and venture capital needs to be made available for bringing new technology to the marketplace and to the benefit of society. Generally, IP in nanotechnology is now being sought around the world, but venture capital is not always readily available. The U.S. certainly now leads in this regard, but the U.K. is rapidly advancing and Europe and Japan, as well as other developed countries, are realizing more and more how important this availability is and are seeking new avenues for making venture capital more available.

J. Lafait: What is the superiority of ZnO over TiO_2 in the domain of ultraviolet applications for purifying instruments, water, etc.?

R.W. Siegel: The relative superiority of these two oxide materials for commercial applications, such as those you have mentioned, lies not only in technical issues associated with their properties, but also with the economics of their production in usable forms. Which is superior for a given application will depend upon both of these issues and the results of a commercial cost/benefit analysis.

Yu.D. Tretyakov: You've described quite a lot in nanotechnology and nanomaterials development in your talk. What do you consider as some sort of priorities in your own research?

R.W. Siegel: I am now involved in quite a wide range of research, but the area that I find most intellectually challenging at present, which will very likely be the most important in the long range, is working to understand the fundamental interactions between biomolecules, such as proteins, and nanostructures. It is already clear that such interactions have great importance in nature, and they may eventually be used to create new materials and devices, but we have very little knowledge now about them. It will certainly be fun to learn more.