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Nanotechnology: promises and challenges for tomorrow*

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Nanotechnology is based on the ability to create and utilize materials, devices and systems through control of the matter at the nanometer scale. If successful, nanotechnology is expected to lead to broad new technological developments. The efficiency of energy conversion can be increased through the use of nanostructured materials with enhanced magnetic, light emission or wear resistant properties. Energy generation using nanostructured photovoltatics or nanocluster driven photocatalysis could fundamentally change the economic viability of renewable energy sources. In addition, the ability to imitate molecular processes found in living organisms may be key to developing highly sensitive and discriminating chemical and biological sensors. Such sensors could greatly expand the range of medical home testing as well as provide new technologies to counter the spread of chemical and biological weapons. Even the production of chemicals and materials could be revolutionized through the development of molecular reactors that can promote low energy chemical pathways for materials synthesis.

Although nanotechnologies hold great promise, significant scientific challenges must be addressed before we can convert that promise into a reality. A key challenge in nanoscience is to understand how nano-scale tailoring of materials can lead to novel and enhanced functions. Our laboratory, for example, is currently making broad contributions in this area by synthesizing and exploring nanomaterials ranging from layered structures for electronics/photonics to novel nanocrystalline catalysts. We are even adapting functions from biological molecules to synthesize new forms of nanostructured materials.

New light emitting materials are made possible by nanostructuring semiconducting materials. The Vertical Cavity Surface Emitting Laser (VCSEL) developed at our laboratories uses layered quantum well structures to produce highly efficient, low power light sources. Key to achieving high efficiency and optical control is the quantum confinement that results from designing and building materials with chemically distinct layers that are on the order of 10nm thick.

Three-dimensional nanomaterials offer new opportunities for tailoring optical, magnetic and chemical properties of materials. Our laboratory has developed unique chemical synthesis approaches that allow one to produce highly uniform nanoclusters of metals, oxides, and semiconductors. In this new class of nanocluster materials, size becomes a variable that can be used to "tune" properties. Quantum confinement can be used to tune the optical properties of nanoclusters. In addition, we have shown that the nanoscale effects can be used to control the chemical properties of these materials[1]. We are currently developing MoS_2 nanocrystals to photocatalyze the oxidation of alkyl chloride environmental contaminants. Our studies show that 3nm diameter crystals promote photo-oxidation using only visible room light.

Borrowing from the biological toolbox, we are synthesizing new metal/oxide nanocomposites by incorporating tin-porphyrin electron-transfer mediators into mesoporous silica structures. Porphyrins are important bio-molecules used to carry out various reactions in living organisms. We have found that these same bio-molecules are capable of reducing metal salts from solution to form metal particles as small as 3-4nm in diameter. Light

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activation of the porphyrin chemistry allows us to lithographically control the formation of these unique nanomaterials.

Our examples thus far have focused on the nanomaterial themselves. In many cases, the development of nanoscience and technology is needed to enable the performance of larger scale devices. For example, silicon-based micromachines show great promise for applications including navigation, communications, and inertial and chemical sensing. A key challenge for micro-scale technology is to develop the ability to reduce or eliminate adhesion and wear. Just as macroscale devices utilize microscale lubricants and coatings, the development of microscale devices demands nanoscale solutions. We are exploring the application of single-layer molecular coatings that dramatically reduce interfacial adhesion and improve the mechanical performance of MEMS devices. The early success in this area opens many new questions concerning the mechanical and chemical stability of nanoscale surface treatments.

In many ways, the successful development of nanotechnology will hinge on our ability to characterize materials and their properties at the nanoscale. Scanning Probe Microscopes (SPM) and Electron Microscope Characterization instruments provide unique capabilities for diagnosing nano-scale materials and processes. This rapidly developing area of instrumentation is providing atomic-level microscopies, advanced spectroscopies, and real-time monitors of molecular processes. We are making substantial contributions to this growing field with developments such as the Atom Tracking Microscope, the Interfacial Force Microscope, and the use of high resolution transmission electron microscopy (TEM) with energy filtered imaging and multivariate statistical analysis (MSA) of spectrum images from energy dispersive x-ray spectrometry. The Atom Tracking Microscope[2] allows us visualize the actual motion of atoms and molecules to better understand the dynamics and stability of nanostructures. The Interfacial Force Microscope[3] is providing new capabilities to probe the mechanical chemical, optical and magnetic properties of nanoscale materials. Electron Microscope characterization provides information on the structure, both morphology and crystallography, and compositional information either through point-by-point analysis or full spectrum images with state of the art mass spec analysis . Of course, high-end computing must be used as an equal partner with experiment if we hope to advance nanoscience and technology in a timely and cost-effective manner. Here, advances both in machine speed and new algorithm development are allowing us to simulate and predict complex material behavior.

The promise of nanotechnology is generating a worldwide rush of excitement. New characterization and imaging tools that allow us to observe and manipulate the nanoscale world are responsible for much of this enthusiasm. It is clear as we look to the future that the transformation of nanoscience into revolutionary new technologies will rely on continued breakthroughs and developments in this area.

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