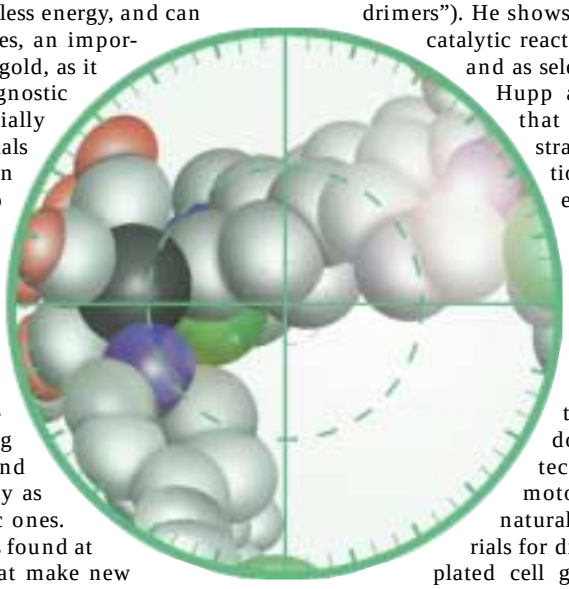
Emerging Nanoscience and Functional Artificial Nanoarchitectures

by Joseph T. Hupp

Nanoscience and nanotechnology—not so long ago only futuristic, speculative ideas—are now vibrant real areas of scientific research and engineering development. The excitement, and the private and public investment to back it, comes from nothing less than the promise of revolutionary advances in medicine, communications, and other areas of contemporary technology. Why? The most obvious idea is that miniaturization—ultimately, to the nanometer scale—makes things faster. Electrons, photons, and everything else used by machines to coordinate their own movement and function, can get there sooner if they have less distance to traverse. Miniaturization also makes things cheaper. Small devices require less energy, and can be made from less stuff than big ones, an important consideration if the stuff is, say, gold, as it is in some of the nanoscale bio-diagnostic technologies now being commercially developed. Less obvious is that materials comprising of these devices, when reduced in scale from large to small to truly tiny or nanoscopic, can begin to behave in fundamentally different ways: solids turn to liquid, opaque substances become transparent, and forgotten physical forces like dispersion interactions dominate interactions between tiny objects, leading to remarkable self-organizational and self-ordering behavior. Indeed, nanoscale objects and materials almost never behave simply as scaled down versions of macroscopic ones. The new behavior and new properties found at the nanoscale are a large part of what make new nanotechnologies possible.



Nanotechnology becomes viable, of course, only when desired nanoscale objects can be intentionally and reproducibly made. Here again there is an obvious notion and a not so obvious one. The obvious one—and one that has considerable appeal—is to chisel down large things until they are small. The tools here are parallel/lithographic (electron beams and soft X-rays) as well as serial (etching with STM tips, and so on). The less obvious approach—but one that also has great appeal—is to start from the bottom and build up. That the second approach is important is good news for chemists: In some sense the central business of chemistry is to make things, and the things chemists most often make are molecules—objects or building blocks typically featuring dimensions ranging from a few nanometers to a few tenths of a nanometer. Perhaps more to the point, molecule-derived and molecule-functionalized materials permit an extraordinary range of functions to be built into nanoarchitectures: chemical recognition and transport, catalytic chemical processing, environment-responsive electronic and ionic conduction, light emission, electrical power generation, bio-affinity, and so on. New materials and new architectures—devised in a bottom-up, molecular fashion—can be engines for the invention of new and better nanoscience and the development of new and better nanotechnology.

Many of the architects of new nanoscience and nanotechnology (*e.g.*, condensed-matter physicists, molecular biologists, chemists, chemical engineers, electrical engineers, and others) further recognize that the action often is at physical interfaces—and interfaces, of course, are the domain of the electrochemist. It will be exciting to see over the next few years just how far, and in what ways, electrochemists take molecule-derived materials in the development of functional nanoarchitectures. What follows are three representative reports that emphasize nanostructured materials construction and function, from a molecular perspective. Feldheim describes molecule-organized nanoscale metallic structures that display, among other things, quantized charging behavior and single-electron conductivity. These exotic behaviors, which are absent for microscale structures, illustrate and illuminate emerging concepts in the field of molecular electronics. Crooks describes 2-D assemblies of nanoscale 3-D polymers – very well-defined (monodisperse) hyper-branched or dendritic polymers ("dendrimers"). He shows how these can be used as nanoscale catalytic reactors, as gates for molecular transport, and as selective receptors for chemical sensing. Hupp and Nguyen describe soft materials that are constructed using the design strategies of supramolecular coordination chemistry. These materials feature extraordinary nanoscale porosity—a property that makes them suitable for sieving, selective chemical sensing, and enzyme-like chemical catalysis.

Participants in this exciting field will recognize that the reports indeed are only representative, not comprehensive. Missing are descriptions of molecule-labeled quantum-dot technology, biomolecule-derived technology (*e.g.* ATP-driven flagellar motors for propelling tiny manmade and naturally occurring objects; nanoscale materials for disease diagnostics, gene therapy, templated cell growth and "human repair;" membranes containing nanometer-wide protein pores for stochastic sensing and identification of single molecules; etc.), nanoscale light-emitting diode assemblies, self-replicating and self-repairing assemblies, ultra small electronic and ionic conductors based on carbon nanotube and fullerene technology, nanostructured materials for light-to-electrical energy conversion ("artificial leaf" technology), and a host of other demonstrated or emerging nanoscale molecular materials applications. Also missing are descriptions of equally exciting non-molecular, nanostructured materials, including a tremendous variety of templated materials comprising nanoscale tubes and cylinders for catalysis, transport, chemical sensing, and electrochemical energy storage; periodic structures for an extraordinary number of emerging photonics applications; and so on. It will be exciting to see which of the many new nanoscience and nanotechnology ideas ultimately succeed in enhancing the quality of human life and which of the successful technologies comprise applications of fundamental electrochemical processes or phenomena. ■

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