# Exploring New Science Through Nanoscale Integration

S. Tom Picraux

To fully realize the promise of nanotechnology one must incorporate nanoscale building blocks into functional systems that connect to the micro- and macroscale world. This process is called integration. While every materials scientist appreciates the important role integration has played in the advance of *technology*, the significance of integration as a driver of *scientific discovery* is often overlooked. I submit that nanoscience has entered a particularly fruitful period in materials research, where nanoscale integration is leading the way to exciting advances in basic scientific understanding.

Integration's role in advancing technology is easy to understand. In electronics the integrated circuit (IC)[*] combined devices together on a single chip to revolutionize the electronics industry from low power complementary logic which enabled electronic watches in the 1970s to today's silicon chips with billions of devices driving computational power not previously imagined.

In biotechnology, recently developed DNA microarrays[†] simultaneously measure the expression of 10s of thousands of genes, with applications ranging from forensics to monitoring genetic predisposition to diseases. However, the IC also led to new scientific concepts, from manipulation of single charges on surfaces to charge collection-based imaging devices. And while still at an early stage, microarrays are revolutionizing the biosciences by providing the means to interrogate the complex genetic control of biological functions.

Just as the new functionalities enabled by integrated circuits and DNA microarrays have led to new concepts, the integration of nanoscale materials and structures is anticipated to lead to new scientific understanding and to enable the design of new functionalities not previously envisioned. The fundamental questions underlying integration go beyond the complex engineering of known solutions; they lead to new discoveries and new science.

Nanoscale integration involves assembling diverse nanoscale materials across length scales to design and achieve new properties and functionality.[‡] This process of integration extends from the synthesis of individual heterostructured building blocks that combine new combinations of materials, to the assembly of these building blocks into composite structures, and finally to the formation of complex functional systems (see Figure 1). At each stage, size-dependent properties, the influence of surfaces in close proximity, and a multitude of interfaces all come into play. Whether the final integrated structure is motivated by an objective of coherent electrons in a quantum computing approach, reduction in phonon transport for high efficiency thermoelectrics, or a new molecular recognition approach for bio-sensing, the combined effects of size, surfaces, and interfaces will be critical and will introduce opportunities for new science. In essence, the objective is to combine the novel functions available through nanoscale structuring to achieve unique multifunctionalities not available in bulk materials.

What are some of the questions that emerge from the process of nanoscale integration and that will lead to new scientific knowledge? These questions go beyond a single system or materials area. They include, for example, how can one control interactions between nanostructures to

- assemble nanoscale building blocks into specific structures?
- control energy transfer and transport across interfaces?
- design interactions within assembled structures to achieve new properties?

These high level questions are not only important to the advancement of nanotechnology, they also serve to drive research and to advance the understanding of the complex phenomena and multifunctional properties that emerge from the integrated structures.

As an example, in photonics there is currently much effort in plasmonics and

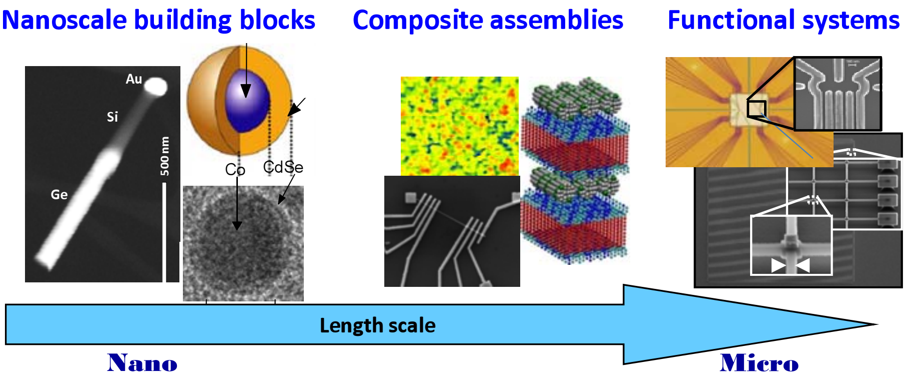

Figure 1. Nanoscale integration involves assembling diverse nanoscale materials across length scales—from individual building blocks to composite assemblies and functional systems—to design and achieve new properties and functionality. Illustrated for nanoscale building blocks are (left) a Si-Ge axial heterostructured nanowire and Co–CdSe core–shell nanoparticle; for composite assemblies (center) semiconducting nanowire with metal contacts, a nanocomposite and a lipid bilayer model; and for functional systems (right) a nanomechanical oscillator array system and a nanoelectronics structure for manipulating single charges.

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[*] J.S. Kilby, "Miniaturized Electronic Circuits" (U.S. Patent 3,138,743, filed February 6, 1959; issued June 1964); R. Noyce, "Semiconductor Device-and-Lead Structure" (U.S. Patent 2,981,877, filed July 30, 1959; issued April, 1961).

[†] M. Schena, D. Shalon, R.W. Davis, P.O. Brown, *Science* **270**, 467–470 (1995).

[‡] See, for example, F. Qian, Y. Li, S. Gradec, H.-G. Park, Y. Dong, Y. Ding, Z.L. Wang, and C.M. Lieber, *Nature Matls.* **7**, 701 (2008); N. Nuraje, I.A. Banerjee, R.I. MacCuspie, L. Yu, and H. Matsui, *J. Amer. Chem. Soc.* **126**, 8088 (2004).

metamaterials to understand and control the response of nanoscale conducting structures on dielectrics, to allow one to localize, manipulate, and control electromagnetic energy in integrated systems. Essential to this area is a fundamental understanding of energy transfer. The objective is to control and exploit the interactions between nanoscale structures to tune, propagate, and otherwise exploit electromagnetic energy. For instance, achieving local propagation of plasmonic excitations with gain is of great interest. Likewise, functional structures that allow active switching or modulation of terahertz radiation are receiving much attention. In both cases a broad understanding of the interactions and transfer of electromagnetic energy between nanostructures is paramount. One seeks to design these structures to achieve specific electromagnetic response functions for sensing, cloaking, and information processing.

In a second area, the electrical and thermal transport through nanowires is strongly influenced by their surfaces and interfaces. Transport across the nanowire interfaces is central to understanding and exploiting heterostructured materials combinations, strain-induced band structure modification, and the role of surface tailoring and electrical contact behavior in achieving new properties and functionality. Recently, radial nanowire *p-n* structures are being explored for charge separation in a new approach to solar cells. As a second illustration, surface modification and heterostructuring of nanowires to decouple electrical and thermal transport, and greatly reduce thermal transport through phonon scattering is of much interest to achieve new ultra-efficient thermoelectric materials.

In a third area, biological systems in nature are greatly admired for their ability to self-assemble structures from simple building blocks which then carry out well-defined and complex functions. These structures are often also able to reconfigure themselves based on their environment and may self-repair their structures when damaged. It is one of the quests of nanoscience to establish the principles and practical methods for designing interactions between self-assembling structures to similarly achieve given specific functionalities.

In understanding these fascinating questions posed by the interactions between nanomaterials upon integration, we will inevitably learn to understand and exploit the resulting unique properties. The scientific challenges in nanoscale integration are great and the promise of new understanding even greater.

Material Matters is a forum for expressing personal points of view on issues of interest to the materials community.

*__S. Tom Picraux__ is chief scientist at the Center for Integrated Nanotechnologies, a Department of Energy (DOE) National Nanoscale Science Research Center located at Los Alamos and Sandia National Laboratories. He served as the president of the Materials Research Society in 1993. He is also past division chair of the American Physical Society's Materials Physics Division and recipient of DOE's prestigious E.O. Lawrence Award for his research on materials.*

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## RESEARCH/RESEARCHERS

### Fabricated Diamond Nanowires Serve as a Source of Single Photons

Secure communication with new technologies, such as quantum cryptography, require development of robust light sources that emit one photon at a time on demand. The incorporation of fluorescent dyes, quantum dots, and carbon nanotubes into devices has been explored, but none have shown a combination of a high, single-photon flux with stable, room-temperature operation. Luminescent centers in diamond have recently been considered as a stable photon source, in particular, nitrogen-vacancy (NV) centers, which are point defects containing a substitutional nitrogen atom located adjacent to a neutral carbon vacancy. However, these luminescent centers, which form naturally during crystal growth or by ion implantation afterwards, suffer from low photon out-coupling in the case of bulk diamond. Recently, however, M. Lončar of Harvard University and co-researchers have shown that NV centers in diamond nanowires emit single photons, producing a photon flux 10 times greater than by bulk diamond devices while using 10 times less power.

As reported in the March issue of *Nature Nanotechnology* (DOI: 10.1038/NNANO.2010.6; p. 195), the team used a top-down nano-fabrication approach, using electron-beam lithography and reactive-ion etching to create a large array of vertically oriented nanowire antennas in a single-crystal diamond substrate. The nanowires are ~200 nm in diameter and ~2 mm tall with smooth sidewalls. The etching process mechanically isolates individual NV centers, which, because they are embedded randomly in the devices, minimizes background fluorescence. The researchers used a homebuilt, laser scanning, confocal microscope to scan large arrays of devices and identify those with high count rates. The nonclassical nature of light emitted from a single color center embedded within a single nanowire, that is the emission of one photon at the time, was confirmed by monitoring photon statistics. Strong photon antibunching was observed, demonstrating that coupling between one NV center and the nanowire antenna is dominant over all other background sources.

The researchers used three-dimensional finite-difference time-domain (FDTD) calculations to model the devices and show that NV centers in nanowire antennae perform better as single-photon sources than those in bulk diamond by allowing for an order of magnitude more efficient excitation and by facilitating collection of emitted photons with an objective lens. The researchers said, "Further fundamental studies of the properties of an NV center in diamond nanostructures will facilitate their integration into more complex photonic quantum information devices, in which more advanced functions such as increasing the photon production rate by means of the Purcell effect will allow devices operating at even higher count levels and lower powers."

Along with Lončar, the research team included T.M. Babinec, M. Khan, Y. Zhang, and J.R. Maze of Harvard, B.J.M. Hausmann of Harvard and Technische Universität München, and P.R. Hemmer of Texas A&M University.

STEVEN TROHALAKI