LA-UR- 09-06247

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Title: Nanoscale integration is the next frontier for nanotechnology

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Intended for: MRS Bulletin

MRS Bulletin
Material Matters submission
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Nanoscale integration is the next frontier for nanotechnology

Nanoscale integration of materials and structures is the next critical step to exploit the promise of nanomaterials. Many novel and fascinating properties have been revealed for nanostructured materials. But if nanotechnology is to live up to its promise we must incorporate these nanoscale building blocks into functional systems that connect to the micro- and macro-scale world. To do this we will inevitably need to understand and exploit the resulting combined unique properties of these *integrated nanosystems*. Much science waits to be discovered in the process.

Nanoscale integration extends from the synthesis and fabrication of individual nanoscale building blocks, to the assembly of these building blocks into composite structures, and finally to the formation of complex functional systems. As illustrated in Figure 1, the building blocks may be homogeneous or heterogeneous, the composite materials may be nanocomposite or patterned structures, and the functional systems will involve additional combinations of materials. *Nanoscale integration involves assembling diverse nanoscale materials across length scales to design and achieve new properties and functionality.* 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 system involves coherent electrons in a quantum computing approach, the combined flow of phonons and electrons for a high efficiency thermoelectric micro-generator, or a molecular recognition structure for bio-sensing, the combined effects of size, surface, and interface will be critical. In essence, one wants to combine the novel functions available through nanoscale science to achieve unique multi-functionalities not available in bulk materials.

Perhaps the best-known example of integration is that of combining electronic components together into very large scale integrated circuits (VLSI). The integrated circuit has revolutionized electronics in many ways, from exploiting field-effect transistor devices and low power complementary logic to enable the electronic watch and hand calculator in the 1970's, to today's microprocessors and memories with billions of devices and a computational power not imagined a few decades ago. The manipulation of charges on a chip, the new concepts in combining devices for logic functions, and the new approaches to computation, information processing, and imaging have all emerged from Kilby and Noyce's simple concept of integrating devices on a single chip.[1] Moving from hard to soft materials, a second more recent example of integration is the DNA microarray.[2] These microarrays, with up to millions of elements in a planar array that can be optically read out, can simultaneously measure the expression of 10's of thousands of genes to study the effects of disease and treatment, or screen for single nucleotide polymorphisms for uses ranging from forensics to predisposition to disease. While still at an early stage, microarrays have revolutionized biosciences by providing the means to interrogate the complex genetic control of biological functions. Just as integrated circuits and microarrays have led to completely new functionalities and performance, the integration of nanoscale materials and structures is anticipated to lead to new performance and enable the design of new functionalities not previously envisioned. The fundamental questions underlying integration go beyond just complex fabrication or the engineering of known solutions; they lead to new discoveries and new science.

The scientific challenges around *nanoscale integration* necessitate the development of new knowledge that is central to the advance of nanotechnology. To move forward one must address key science questions that arise in nanoscience integration and go beyond a single system or materials area. New science and discoveries especially await around three questions. *How does one:*

1. Control energy transfer and other interactions across interfaces and over multiple length scales?
2. Understand and control the interactions between nanoscale building blocks to assemble specific integrated structures?
3. Design and exploit interactions within assembled structures to achieve new properties and specific functionalities?

These high level questions can serve to drive research, and to advance understanding of the complex phenomena and multifunctionality that may emerge from integration. For example, in photonics there is considerable effort 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 such as in the field known as metamaterials. Essential to this area is a fundamental understanding of energy transfer across multiple length scales (question 1 above). The objective is to control and exploit these interactions between nanoscale structures to tune, propagate, and otherwise exploit electromagnetic energy (question 3). Locally propagating plasmonic excitation energy with controlled loss (or gain), and switching or modulating terahertz radiation are examples where a broad understanding of these integration questions are paramount. One seeks to design these structures to achieve specific electromagnetic response functions for sensing, cloaking, and information processing. As a second example, the electrical and thermal transport through nanowires is strongly influenced by surfaces and interfaces. Interactions across nanowire interfaces are central to understanding and exploiting heterostructures, strain, and surface tailoring to achieve new properties and functionality. Examples include radial nanowire heterostructures being explored for charge separation in photovoltaics for a new generation of solar cells and surface modification of nanowires to reduce phonon flow for ultra-efficient thermoelectric materials. In short the challenges of nanoscale integration are great, but the promise of new advances is enormous. It's a frontier worth engaging.

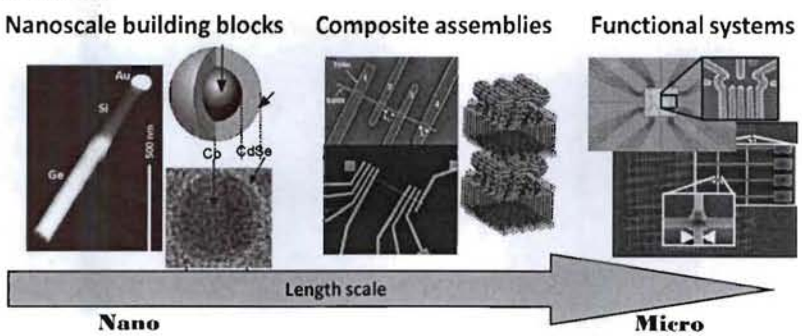

Fig. 1 Nanoscale integration involves assembling diverse nanoscale materials across length scales—from individual building blocks to composite structures to functional systems—to design and achieve new properties and functionality. Illustrated for nanoscale building blocks (left) are a Si-Ge axial heterostructured nanowire and Co/CdSe core shell nanoparticle, for composite assemblies (center)

semiconducting nanowires with metal contacts and a composite membrane structure, and for functional systems (right) a nanoelectronics system for manipulating single charges (top) and a nanomechanical array (bottom).

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[1] Jack S. Kilby, patent filed February 6, 1959, "Miniaturized Electronic Circuits", (issued June 1964); Robert Noyce, patent filed July 30, 1959, "Semiconductor Device-and-Lead Structure" (issued April, 1961).
[2] See, for example, Schena M, Shalon D, Davis RW, Brown PO (1995). "Quantitative monitoring of gene expression patterns with a complementary DNA microarray". *Science* **270**: 467–470.