NIRT: Technologies, Architectures and Performance Analysis for Nanoelectronics

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PIs: **André Dehon**[1], **Charles M Lieber**[2], **John E Savage**[3]
[1]California Institute of Technology, [2]Harvard University, [3]Brown University

Introduction and Objectives

Forty years ago Gordon Moore predicted exponential growth in the density of electronic circuits, a forecast that has been realized. A concomitant of this remarkable achievement is that design and manufacturing costs have increased dramatically. We are approaching a tipping point at which either exponential growth in density will cease or new technologies and methods of assembly will emerge that will allow continuing progress at reasonable cost. Our research program is predicated on the proposition that new materials of nanometer-sized dimensions and assembled in new ways will supplement and replace conventional lithography-based wires and devices. Our goal is to understand and address problems that stand in the way of achieving this objective. More specifically, we seek to a) develop low-dimensional nanoelectronic materials that can be self-assembled into large-scale circuits, b) create and analyze models for directed self-assembly of such circuits with particular focus on crossbars, c) explore large-scale nanoelectronics-based architectures for efficient computation, and d) incorporate knowledge thus acquired into advanced undergraduate and early graduate instruction.

Crossbars

Important advances have been made in creating **nanowires** (NWs) with diameters as small as a few nanometers and lengths ranging from microns to millimeters. It has been shown that large numbers of parallel NWs can be placed on chips. Undifferentiated NWs can be deposited using nanoimprint lithography and nanostamping. Differentiated NWs can be grown, mixed randomly, and deposited on a chip fluidically.

Small NWs have been assembled into **crossbars**, two orthogonal sets of parallel wires separated by a layer of switchable material. **Self-assembled molecular layers** (SAMs) have been developed whose electronic state can be switched by a large electric field and sensed, but not changed, by a smaller electric field. Molecules at crosspoints formed by pairs of orthogonal NWs are set or read by activating one NW in each set of parallel NWs. This requires that they be addressable by a small number of meso-scale wires (MWs). Small crossbars have been devised that both store and retrieve data and emulate logic circuits. Experiments and analysis indicate that large numbers of NWs can be assembled into crossbars with densities one to two orders of magnitude greater than predicted for 22 *nm* photolithography, the currently best possible.

Decoders

Three approaches have been proposed to enable small numbers of MWs to address many NWs. The first two work with undifferentiated NWs. The **randomized contact decoder** scatters particles randomly between NWs and MWs at right angles, thereby making switches at the point of contact controlled by MWs. A NW is conducting only when all its switches are open. The **randomized mask decoder** interposes lithographically defined high-K dielectric regions, many of which are randomly placed, between MWs and NWs. The dielectric intensifies the MW electric field and thus disables NWs exposed to it. A NW is conducting only when none of the MWs associated with its overlapping regions have electric fields. In both cases the randomized placement of materials gives a distinct identity to identical NWs. Clearly, there is no guarantee that every NW will be given a unique address by these methods. Instead conditions must be set to ensure that with high probability the number of addressable NWs is large.

The third decoder, the **encoded NW decoder**, is used to control differentiated NWs. Fields on MWs at right angles to NWs cause their lightly doped regions to turn off. Because the assembly process is stochastic, it is impossible to predict in advance the number of NW encodings appearing on a chip. Instead, one sets the conditions so that many occur with high probability.

Encoded NW decoders have been developed for **axially** and **radially encoded NWs**. Axially encoded NWs are grown from seed catalysts using chemical vapor deposition from a gaseous mixture that contains impurities to dope the NWs. Along their axis NWs are lightly and heavily doped. Radially doped NWs are encoded by adding differentially etcheable shells to a previously grown, lightly doped NW core.

Both axially and radially encoded NWs are controlled by exposing one or more lightly doped NW region to an electric field on a MW that causes the NW to lose its conductivity. Axially encoded NWs are decoded by placing them under MWs. If NW doped regions are aligned with MWs and their encodings match applied fields, they conduct; otherwise they do not. Radially encoded NWs are decoded by removing shells under MWs through etching. Etching sequences define types of decoder, some of which use more MWs than others but require fewer NW types. Several methods of encoding differentiated NWs have been developed.

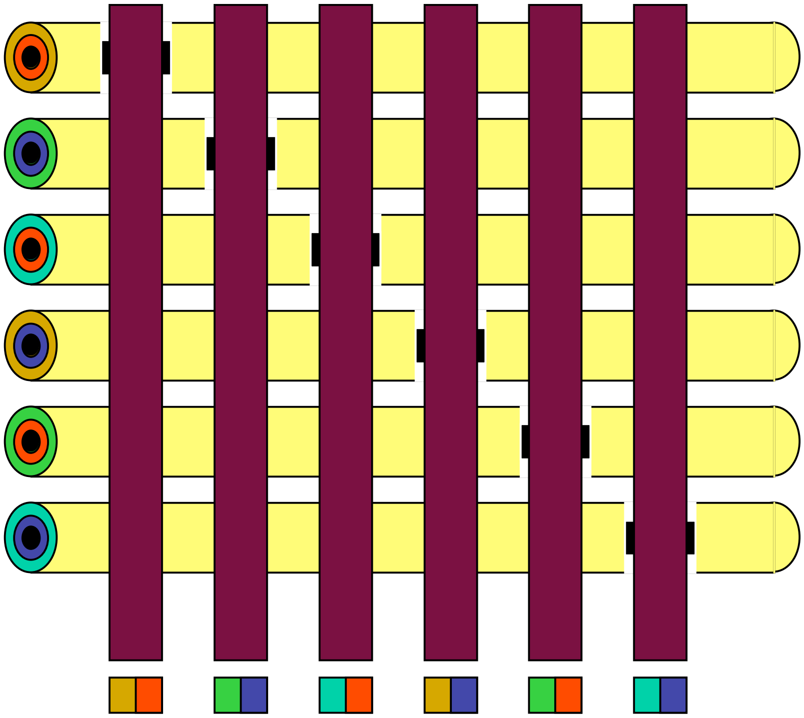
Differentiated NWs will be assembled on a chip using the Langmuir-Blodgett fluid-based method. This method aligns NWs in parallel through fluid flow. NWs are then transferred to a chip. Repeating the process at right angles creates a crossbar. In between NWs a switchable SAM layer is deposited.

Fluidic assembly does not guarantee end-to-end alignment of NWs, and misalignment of axially encoded NW doped regions can lead to ambiguous control of NWs. Furthermore, the transitions between lightly and heavily doped regions on axially encoded NWs are gradual, occuring over a distance comparable to their diameter, and this further complicates control of axially encoded NWs. These problems don’t arise with radially encoded NWs.

Research Results

During the last year we have made significant progress in three areas. First, we have modeled and analyzed the randomized mask-based decoder [2]. When lithography is used to position dielectric regions, the uncertainty in the location of these regions relative to the pitch of NWs is very large when small NWs are used. Our analysis shows that hundreds more MWs may be needed to control NWs than the minimum number required when the placement of dielectric regions is deterministic and precise. Consequently, this decoding method may be impractical.

Second, we have introduced and analyzed a variety of strategies for converting external binary addresses to internal NW addresses in a crossbar assembled from differentiated NWs [3]. Two strategies appear to be most effective. Both assume that NWs in each dimension of a crossbar are organized into small contact groups containing 10 to 20 NWs. The first strategy requires that with high probability at least half the NWs in each contact group have different encodings. The second requires that each NW encoding appear in at least *p* contact groups, where *p* is a significant fraction of the number of groups. The superiority of these addressing strategies has been demonstrated through analysis. Our subsequent Monte Carlo experiments (not yet published) show that the second strategy generates at least 500 different addresses from a population of 1,000 addresses with probability 0.99 when only 10-20 NW encodings are used. A third strategy, which exploits all available addresses, generates approximately 75% of all available addresses under the same conditions. However, it requires a significantly larger address-translation circuit.



The third area addressed this year was the introduction of radially encoded NWs as well as the development of methods of decoding them [4]. (The figure at left shows a simple decoder.) Radial encoding has important advantages vis-à-vis axial encoding that outweigh the disadvantage of somewhat larger NW diameters. Since the diameter of radially encoded NWs grows with the number of NW types, it is important that a large fraction of available NWs be addressable with as few as 12 different encoding types. We believe that radial NW encoding has great promise for the realization of nano-crossbars.

The first two research topics were addressed by the Brown PI and his students. The second received input from the Caltech PI. The third is the result of collaboration among all NIRT team members. Knowledge acquired through this project is being taught at Brown University in a graduate level course, *Introduction to Nanocomputing,* in the fall of 2005.

References

[1] For further information about this project send email to **<John_Savage@brown.edu**
[2] Analysis of a Mask-Based Decoder, Eric Rachlin, John E. Savage, and Benjamin Gojman, Procs. IEEE Computer Society Annl. Symp. on VLSI, A. Smailagic and N. Ranganathan (Eds.), May 11-12, 2005, pp. 6-13.
[3] Evaluation of Design Strategies for Stochastically Assembled Nanoarray Memories[4], Benjamin Gojman, Eric Rachlin, and John E. Savage, ACM JETC, Vol. 1, No. 2, pp. 73-108, July 2005.
[4] Radial Addressing of Nanowires, John E. Savage, André DeHon, Charles M. Lieber, and Yue Wu, submitted to ACM JETC.