

Nanoparticle electronic architectures assembled by DNA

Richard A. Kiehl

*Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA
(E-mail: kiehl@ece.umn.edu)*

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The continued scaling of integrated circuit technology at its current Moore's Law rate could lead to circuits containing over a billion transistors with 20 nm features by the year 2015. Reaching integration levels beyond that point will require nanometer-scale devices that are too small to be manufactured or operated in the same manner as the devices of today. While the progress in electronics thus far has relied on the scaling of transistors and an increasingly complex maze of interconnecting wires, future circuitry will require a major paradigm shift involving radically different fabrication technologies, device principles, and circuit architectures. In particular, constraints on power dissipation at higher integration levels and the inherently low drive capability of small devices will mandate the use of relatively simple, ultrasmall devices laid out in highly regular arrays and interconnected locally – all done with nanometer-scale precision.

The use of DNA as a programmable scaffolding upon which nanoparticles (clusters, tubes, molecules) can precisely assemble could provide a new basis for the manufacturing of future electronic circuitry. Rather than using the techniques of current semiconductor chip manufacturing, in which features are written onto the structure by a lithographic process, this approach exploits programmed Watson–Crick base pairing for assembly on the nanoscale. It has recently been demonstrated that a set of specifically designed synthetic DNA oligonucleotides can assemble as tiles to create a two-dimensional (2D) crystal with modified surface features (Liu et al., 1999). In a similar manner, one could exploit the predictability of sticky-ended cohesion to construct DNA tiles with programmable features that serve as a scaffolding upon which electrical nanocomponents precisely assemble. This process would allow the ultra-small scale of the DNA crystal to direct the assembly with a precision limited only by the 3.4 nm periodicity of the helix rotation and the 0.34 nm



nucleotide separation. Note that in contrast to schemes for 'patterned' self-assembly, such as the strain directed process described in an earlier issue of this journal (Hung et al., 1999), the present process can truly be called a 'programmed' self-assembly since the structure is spontaneously generated according to the DNA code programmed into the synthetic strands. Thus, this approach offers both the programmability and precision needed for assembling electronic circuitry on the nanoscale.

As a step toward demonstrating this approach to manufacturing circuitry, the assembly of gold nanoparticles into linear arrays on the surface of a 2D DNA scaffolding is being investigated. A set of short DNA strands with different sequences will be assembled to form DNA-tiles that assemble into a DNA crystal. The particles will be assembled onto the DNA scaffolding by covalently attaching the gold nanoparticles to one type of strand. In our test structures, gold nanoparticles

approximately 1 nm in diameter with a 4 nm interparticle spacing will be assembled on a DNA scaffolding to form linear arrays positioned 32 nm apart. The assembly of other nanocomponents, such as clusters, nanotubes and, molecular components, onto the 2D structures should also be possible. The development of a scheme for assembling scaffolding in more intricate 2D patterns, including superlattices and aperiodic patterns, would be important for obtaining flexibility and customization in circuit design. Another important direction for future work is the extension of the scaffolding in the third dimension. Even the capability to extend the structures to a few layers of 2D crystals would be extremely useful since this would allow the programmed self-alignment of subelements, which could be exploited in the integration of nanodevices with nanowiring for biasing and signal lines.

Fundamental constraints will require a new paradigm, in which electronic devices are simple, locally interconnected, and laid out in highly regular arrays. Assuming that DNA scaffolding will allow the manufacture of regular arrays with nanoscale precision, can compatible device and circuit concepts be developed to satisfy the requirements for simplicity and local connectivity? It is intriguing that even particles as simple as gold nanoclusters can potentially provide useful device function at the nanoscale. A memory in which nanoparticles provide islands for electron storage is one example and is compatible with the periodic arrangement of particles on a DNA scaffolding. For certain memory applications, scanning probe techniques could provide a means for accessing the state of the particles without the need for long interconnects. Finding a practical scheme for information processing is a more difficult challenge since the paradigm of conventional complementary metal-oxide-semiconductor transistor circuitry is based on the virtually random interconnection between many transistors from all regions of the chip. However, simple circuits based on nanoclusters or molecules arranged in arrays might provide a means for circumventing this problem. One possible direction is through a device concept known as tunneling phase logic (Ohshima & Kiehl, 1996), in

which the Coulomb blockade effect in a nanoparticle, or possibly an analogous effect in a molecular system, is used to represent logic states by the phase of an electron tunneling process. Theoretical studies indicate that tunneling phase logic devices exhibit impulsive, neuron-like waveforms which could produce strong coupling of locally interconnected devices. Recent work shows that this mechanism can potentially be exploited in cellular nonlinear networks comprised of locally interconnected devices to realize high level information processing through nonlinear dynamics similar to those used in the brain (Yang & Chua, 2000). Such architectures circumvent the interconnect problem through their local connectivity and would provide new capabilities for information processing through methods not possible with current technology.

The combination of nanoparticle assembly by DNA scaffolding with compatible neuron-like devices and cellular network architectures could lead to machines for storing and processing information that are radically different from those of today and are manufactured by and operate on principles inspired by biological systems. While these fabrication, device, and circuit concepts are highly speculative at the present time, such a blending of ideas from the fields of nanotechnology, biotechnology, and information technology will offer many exciting possibilities for realizing revolutionary technologies in the future.

References

- Liu F., R. Sha & N.C. Seeman, 1999. Modifying the surface features of two-dimensional DNA crystals. *J. Amer Chem. Soc.* 121, 917–922.
- Hung C.-Y., A.F. Marshall, K.-K. Kim, W.D. Nix, J.S. Harris Jr. & R.A. Kiehl, 1999. Strain directed assembly of nanoparticle arrays within a semiconductor. *J. Nanoparticle Res.* 1, 329–347.
- Ohshima T. & R.A. Kiehl, 1996. Operation of bistable phase-locked single-electron tunneling logic elements. *J. Appl. Phys.* 80, 912–923.
- Yang T. & L.O. Chua, 2000. Nonlinear dynamics of driven single-electron tunneling junctions. *Int. J. Bifurc Chaos* 10, 1091–1113.