Self-Assembly of DNA into 3D Nanostructures Facilitated with caDNAno Tool

DNA has proven to be a versatile building block for the fabrication of nanostructures using bottom-up strategies. The design and self-assembly of DNA into two-dimensional, megadalton structures have been demonstrated with a strategy that uses multiple-kilobase single strands of DNA that act as scaffolds, which fold into a flat array of antiparallel helices after interacting with hundreds of oligonucleotide strands conceptualized as staples. Recently, W.M. Shih and co-researchers from the Dana-Farber Cancer Institute, Harvard Medical School, and Harvard University have extended this method to the design and fabrication of three-dimensional (3D) nanostructures that are formed as pleated layers of helices constrained to a honeycomb lattice. Shih and co-researchers designed and assembled DNA nanostructures approximating a variety of shapes with precisely controlled dimensions ranging from 10 nm to 100 nm.

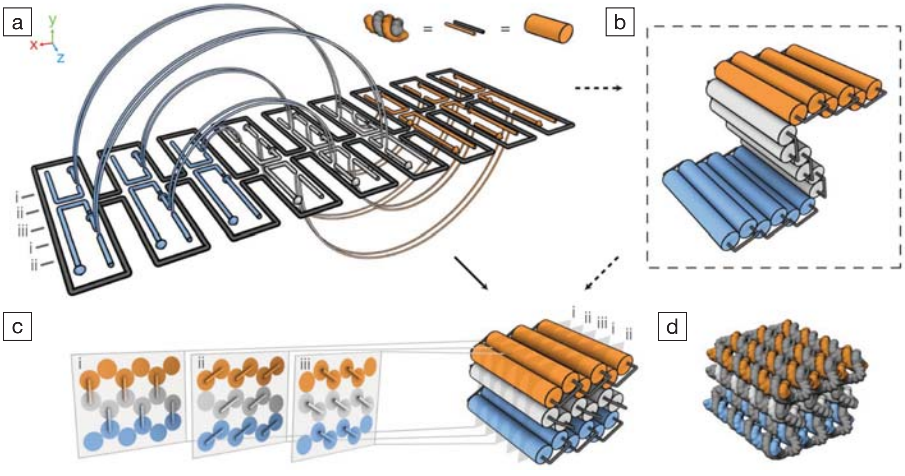

Figure 1. (a) An unrolled two-dimensional schematic of the target shape. Grey scaffold strands and orange, white, and blue staple strands form double helices that run parallel to the *z*-axis. Crossovers between adjacent helices are made with phosphate linkages, while stable crossovers (shown as semicircular arcs) bridge different layers. (b) Partial folding is illustrated with a conceptual intermediate model composed of cylinders. (c) A fully folded target shape, which also shows cross-sectional slices (i–iii) of parallel helices arranged in a honeycomb pattern in the *x-y* plane. (d) An atomistic model of the target shape. Reproduced by permission from Macmillan Publishers Ltd: *Nature* **459** (7245) (2009) p. 414, ©2009.

Shih and co-researchers described their honeycomb pleat-based assembly strategy in a letter published in the May 21 issue of *Nature* (DOI: 10.1038/nature08016; p. 414). As shown in Figure 1, double helices consisting of scaffold strands and staple strands create an unfolded, two-dimensional form of the target shape. Helices that are depicted as adjacent in the conceptual folding intermediate presented in Figure 1 are connected by a mixture of staple and scaffold crossovers, while the helices that are adjacent in the final structure but not in the conceptual folding intermediate are connected only by staple crossovers (both staple and scaffold crossovers are phosphate linkages). The researchers likened the first step in the design process to sculpting a shape from a crystalline block; unwanted DNA helices are carved away from the honeycomb lattice of antiparallel helices. Next, scaffold crossovers at a subset of allowed positions are introduced to create a singular scaffold path that visits all remaining duplex segments. Staple crossovers are then added at positions consistent with the target shape and with other structural considerations. Unpaired scaffold bases are introduced at the ends of helices to control multimerization. The researchers developed caDNAno—a design program with a graphical-user interface—to assist in honeycomb-pleated-origami design. The researchers said that, after a one-day caDNAno tutorial, inexperienced researchers will be able to generate base sequences for DNA nanostructures.

The researchers used a one-pot reaction to assemble the DNA nanostructures. A mixture of 10 nM scaffold strands (derived from the single-stranded genome of the M13 bacteriophage) and 50 nM of each oligonucleotide staple strand, together with salts and buffer, were subject to a thermal-annealing ramp followed by cooling for 80 min. from 80°C to 60°C, followed by a 173-h cooling cycle, from 60°C to 24°C. The DNA nanostructures were purified with electrophoresis and imaged using transmission electron microscopy. The researchers fabricated nanostructures approximating various 3D shapes: a monolith, a square nut, a railed bridge, a slotted cross, and a stacked cross. Programming staple strands to bridge separate scaffold strands will yield hierarchical DNA nanostructures.

The researchers said, "Three-dimensional DNA nanostructures should expand the range of possible applications with an increased range of spatial positioning that is not accessible by flat structures, including those requiring encapsulation or space-filling functionalities, as in many natural biosynthetic machines that use three-dimensional scaffolding to control assembly of complex products. Similar capabilities for synthetic machines are thus more accessible with this convenient, generalizable facility to fabricate custom-shaped three-dimensional structures from DNA."

Steven Trohalaki

Gold Nanorods Enable Five-Dimensional Optical Recording

Five-dimensional optical recording has the capability to drastically increase optical storage capacity. Current available storage techniques, such as those involving DVDs and blu-ray, only make use of two dimensions. Researchers P. Zijlstra, J.W.M. Chon, and M. Gu, at the Centre for Micro-Photonics at Australia's Swinburne University of Technology, have recently developed a single method utilizing gold nanorods that combines multiple recording domains to achieve optical recording in five dimensions. The technique combines the three spatial domains with those of polarization and wavelength to potentially increase storage capacity by orders of magnitude. The technology also has applications in encryption.

As reported in the May 21 issue of *Nature* (DOI: 10.1038/nature08053; p. 410), the new recording media based on gold nanorods allows for five-dimensional optical recording by using longitudinal surface plasmon resonance. Within a single recording layer, the gold nanoparticles were shown to have the ability to store nine information states. These nine states come from using three different wavelengths of light and three different polarization directions. Multiple recording layers may then be combined on a single disk, adding the final spatial dimension, to further increase the storage density. The size and shape of the gold nanorods provide the necessary selectivity for the five-dimensional recording process.

The gold nanorods are patterned through a photothermal reshaping process. This reshaping happens when a nanorod absorbs a laser pulse and heats above its melting temperature, which then causes the nanorod to transform into a spherical particle. The nanorods selectively absorb the laser energy depending on the wavelength and polarization of the light while the threshold for photothermal melting ensures that the writing process is confined within the focal volume of the laser. The aspect ratio and orientation of the nanorods determine the wavelength and polarization sensitivity, respectively. Recordings can be imaged nondestructively using longitudinal surface plasmon resonance mediated by two-photon luminescence. This nonlinear optical detection mechanism provides much higher angular and wavelength sensitivity compared to linear detection mechanisms used with gold nanoparticles. With the demonstrated ability to record pixel sizes close to the expected diffraction limit and in a manner free from cross-talk, this new optical recording technique has the potential to raise storage density into the terabytes for an optical disk the size of a DVD.

Charles Brooks

Graphene Nanoribbon Interconnect Resistivity Comparable to Copper

The unique properties of graphene make the material attractive for a wide range of potential electronic devices. R. Murali, K. Brenner, Y. Yang, T. Beck, and J.D. Meindl at the Georgia Institute of Technology have now experimentally demonstrated the potential for another graphene application: replacing copper for interconnects in future generations of integrated circuits. In the June issue of the *Electron Device Letters* (DOI: 10.1109/LED.2009.2020182; p. 611), the researchers provide a detailed analysis of resistivity in graphene nanoribbon interconnects as narrow as 18 nm.

"As you make copper interconnects narrower and narrower, the resistivity increases as the true nanoscale properties of the material become apparent," said Murali, a research engineer in Georgia Tech's Microelectronics Research Center. "Our experimental demonstration of graphene nanowire interconnects on the scale of 20 nm shows that their performance is comparable to even the most optimistic projections for copper interconnects at that scale. Under real-world conditions, our graphene interconnects probably already out-perform copper at this size scale." Use of graphene for these interconnects could help extend the long run of performance improvements for silicon-based integrated circuit technology.

Beyond resistivity improvement, graphene interconnects would offer higher electron mobility, better thermal conductivity, higher mechanical strength, and reduced capacitance coupling between adjacent wires.

"Resistivity is normally independent of the dimension—a property inherent to the material," Murali said. "But as you get into the nanometer-scale domain, the grain sizes of the copper become important and conductance is affected by scattering at the grain boundaries and at the side walls. These add up to increased resistivity, which nearly doubles as the interconnect sizes shrink to 30 nm."

Experimentally, the researchers began with flakes of multi-layered graphene removed from a graphite block and placed onto an oxidized silicon substrate. They used electron beam lithography to construct four electrode contacts on the graphene, then used lithography to fabricate devices consisting of parallel nanoribbons of widths ranging over 18–52 nm. The three-dimensional resistivity of the nanoribbons on 18 different devices was then measured using standard analytical techniques at room temperature.

The best of the graphene nanoribbons showed conductivity equal to that predicted for copper interconnects of the same width. Because the comparisons were between non-optimized graphene and optimistic estimates for copper, the researchers suggest that performance of the new material will ultimately surpass that of the traditional interconnect material.

Though one of graphene's key properties is reported to be ballistic transport—meaning electrons can flow through it without resistance—the material's actual conductance is limited by factors that include scattering from impurities, line-edge roughness, and from substrate phonons—vibrations in the substrate lattice.

Use of graphene interconnects could help facilitate continuing increases in integrated circuit performance once feature sizes drop to approximately 20 nm, which could happen in the next five years, Murali said. At that scale, the increased resistance of copper interconnects could offset performance increases, meaning that without other improvements, higher density would not produce faster integrated circuits.

"This is not a roadblock to achieving scaling from one generation to the next, but it is a roadblock to achieving increased performance," he said. "Dimensional scaling could continue, but because we would be giving up so much in terms of resistivity, we wouldn't get a performance advantage from that. That's the problem we hope to solve by switching to a different materials system for interconnects."

Stream of Sand Behaves like Water

H.M. Jaeger, J.R. Royer, and colleagues from the University of Chicago have demonstrated that dry granular materials such as sands, seeds, and grains have properties similar to liquid, forming water-like droplets when poured from a given source. The finding could be important to a wide range of industries that use "fluidized" dry particles for oil refining, plastics manufacturing, and pharmaceutical production.

Researchers previously thought dry particles lacked sufficient surface tension to form droplets like ordinary liquids.

"Previous studies of granular streams were able to detect clustering by performing experiments in vacuum and were able to establish that the clustering was not caused by the drag from the ambient air," said Jaeger, a professor in the university's Materials Research Science and Engineering Center. "However, the cause of the clustering remained a mystery."