

extracting a substrate from a phage solution and controlling the rate of deposition, researchers mediated the phages' self-assembly into a thin-film surface composed of quasi-ordered phage bundles.

In the presence of a chemical vapor, the spacing between the bundles changes; this expansion or contraction alters the coherent scattering of the incident light and, consequently, the surface's structural color. Using an iPhone app that analyzes the color change on an RGB scale, researchers can confirm the presence of a toxin and estimate its concentration.

When composed of wild-type M13 phage, the sensor displayed characteristic responses to humidity changes and vola-

tile organic compounds. However, the sensor also demonstrated selectivity and specificity for molecules with lower vapor pressures, like many explosives and environmental toxins. They engineered a phage surface sensitive to TNT, a common explosive, by modifying the phage to display a TNT-binding peptide motif. As TNT vapor concentration increased, the binding of TNT to the substrate induced structural changes in the phage bundles and a color change of the material.

A key advantage of Lee's design over other colorimetric sensors is the viewing-angle independent coloration of the phage bundles. This color fidelity, combined with the simplicity of

fabrication and portability, makes these sensors powerful and practical tools for detecting toxins.

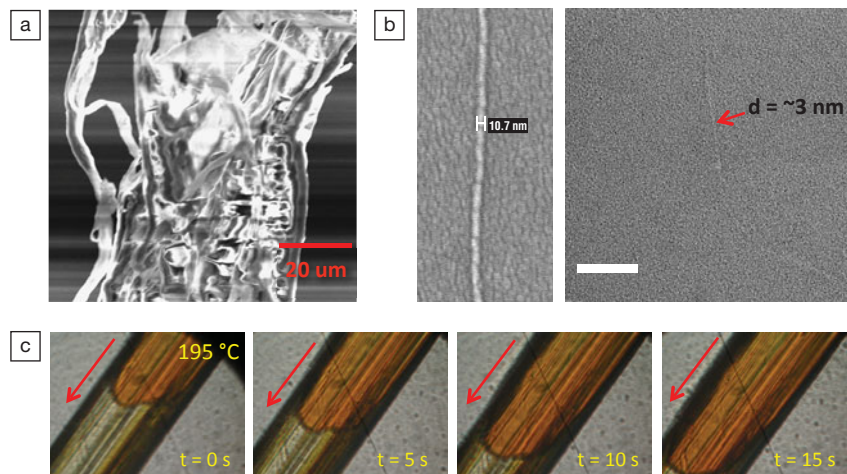
Marya Lieberman studies self-assembly of biomolecules at the University of Notre Dame. "Though the stability, reproducibility, and interferences still need to be characterized, this is a really clever way to translate a chemical interaction on the nanometer scale into a visual output on the centimeter scale. When a sensor can be read visually, it cuts the cost of making the sensor and makes it more practical for field use," Lieberman said.

**Laurel Hamers**

**Light converts monomers into large single-crystal linear polymers**

A beaker left in the sunlight has brought the world an unusual class of polymer crystals. A research team based at the University of California at Los Angeles and at Santa Barbara reports in the January 14 issue of *Science* (DOI: 10.1126/science.1245875, p. 272) the quantitative conversion of a class of monomers into large single-crystal linear polymers after exposure to visible light. "This is fascinating because they have a monomer that can undergo a topochemical polymerization to generate enormous [1.5 cm long] single crystals with exceedingly long polymers that are highly oriented," said Paula Hammond of the Massachusetts Institute of Technology. In a topochemical polymerization, monomers are pre-assembled into their approximate end positions, with reaction initiated by heat or light.

"Growth of a polymer crystal is really a pain. What [first author] Letian [Dou] found is a way to trigger the reaction, make everything very simple, and it takes just an hour," said Yang Yang of UCLA, one of the corresponding authors. Fred Wudl (UCSB), the other corresponding author, said, "In general, when anyone does an organic photochemical reaction in the solid state, the



(a) Conventional polymer by mechanical exfoliation versus (b) single-crystal polymer by mechanical exfoliation. Note the entanglement of the conventional polymer. (c) Reversibility: under heating the polymer (yellow) reverts to monomer (orange).

product absorbs more than the starting material, and in the same region [of the spectrum, blocking further reaction].... This is probably the first case where a quantitative solid-solid reaction has been observed."

The researchers found that orange-colored crystals of alkylcarboxylate-substituted bis(indene)dione monomers faded and became insoluble when exposed to sunlight or to light from a sodium lamp. X-ray diffraction analysis determined the structure of the resulting polymeric single crystals. R-factors similar to those of the monomer crys-

tals demonstrated a surprising absence of amorphous regions within the polymer. The identity of the alkylcarboxylate side chains is important to the reaction, with 6- and 8-carbon linear alkyl groups maintaining the monomers at the appropriate distance and orientation to permit topochemical polymerization, while smaller or branched alkyl-containing monomers failed to polymerize. The yellow polymer crystals revert at 195°C to orange monomer crystals, which are re-polymerized with light.

"The reversibility is interesting, and is certainly not the case with the diacety-

lenes,” said Hammond. “This could be compelling if you are able to manipulate them into new orientations and arrangements and re-polymerize.”

If the polymerization is photochemically reversible it could lead to micro-lithography applications, Wudl said. Photopolymerization of concentrated monomer solution and of spin-cast thin films led to tiny, disordered crystals.

Kirk Fields (UCSB) investigated the

tensile stress–strain properties of the single crystal of the highly oriented linear polymer, observing individual strands sliding relative to each other. Dou was able to isolate single unentangled polymer chains by mechanical exfoliation and examine them microscopically. “From the fundamental study point of view it is also interesting to have a single 1D [one-dimensional] polymer chain. It’s the synthesis of a new compound and a new chemical reaction

under visible light,” said Dou.

The research team is looking into mechanical applications for the polymers, such as reinforcement for lightweight armor, and expanding the crystal-forming polymer family by functionalizing the alkyl chains for several potential applications. “The beauty [of this work] is that since we published this, other scientists can now work on these materials and this reaction,” said Yang.

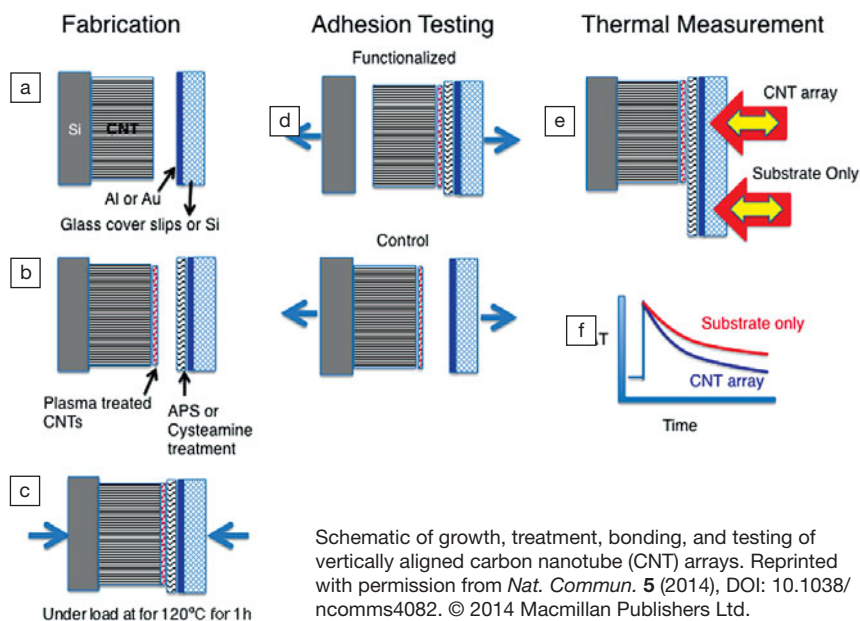
**Jen Gordon**

### Thermal interface resistance of CNT arrays reduced by factor of six

The carbon nanotube (CNT) is a promising thermal material whose potential has yet to be fully realized. While CNTs show excellent thermal conductivity, interfacial resistance between the CNTs and other components in thermal conduction systems limits their overall contribution. A research team at the Lawrence Berkeley National Laboratory has now reduced the thermal interface resistance of carbon nanotube/metal thin-film systems by a factor of six by covalently bonding the CNTs to amine groups on the metal surface.

“People tend to think that covalently-bonded organic molecules like polymers are not good conductors—but the carbon–carbon bonds in graphite and diamond are quite good conductors,” said researcher D. Frank Ogletree. “Molecular Dynamics models predicted that covalent bonds bridging a CNT-Si interface would improve thermal conductivity. Our work was a real-world attempt to duplicate that theoretical concept.”

As reported in the January 22 issue of *Nature Communications* (DOI: 10.1038/ncomms4082), Ogletree, N. Ravivikar from Intel, R. Prasher, formerly of Intel, and their colleagues grew vertically aligned CNTs on silicon wafers by chemical vapor deposition. Separately, they evaporated aluminum or gold onto glass microscope cover slips to create thin films. They exposed the nanotubes to air plasma, removing any amorphous carbon layers and creating carboxylate



groups at the ends of the CNTs. The Al thin film was exposed to aminopropyltrialkoxy-silane to create amine groups on its surface, while the gold gained amine groups through exposure to cysteamine. The CNTs were pressed against the thin films and heated, forming covalent bonds.

The resulting systems achieved thermal interface resistances of 0.6 and 0.8  $\text{mm}^2\text{-K/W}$  ( $\pm 0.2$ ) for the aluminum and gold systems, respectively. This was almost a sixfold reduction compared to the control system of mechanically joined CNTs and Al or Au thin films that were not covalently bonded. The total thermal interface resistance of materials currently used in state-of-the-art semiconductor devices is 5–10  $\text{mm}^2\text{-K/W}$ .

“This is a significant achievement with an approach that appears simple to

implement,” said Bara Cola, an expert in thermal materials at Georgia Institute of Technology. However, he highlights that work remains to be done. “The effective thermal conductivity of the CNT arrays must exceed recently reported values of 2–4  $\text{W/mK}$  before they can be considered as solder or conductive epoxy replacements, and the adhesive strengths of this system will have to be increased by 10- to 100-fold. But the authors’ approach is a significant advancement toward these goals.”

If these challenges are overcome and thermal interface resistances are kept this low in commercial applications, the world may see CNT arrays become the thermal material of choice for heat management systems of the future.

**Benjamin Scheiner**