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 microlithography 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.

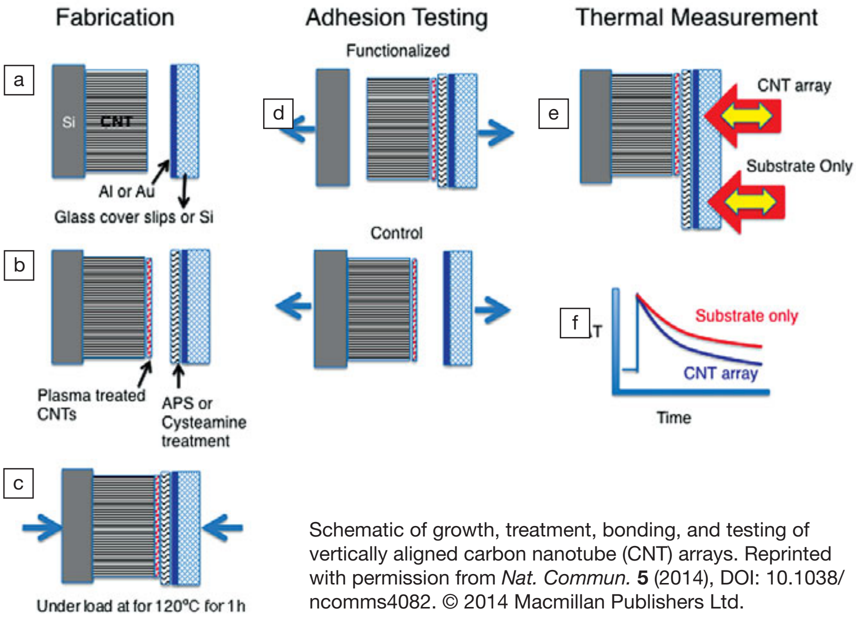
Jen Gordon

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. Raravikar 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 aminopropyl-trialkoxy-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.



Schematic of growth, treatment, bonding, and testing of vertically aligned carbon nanotube (CNT) arrays. Reprinted with permission from *Nat. Commun.* **5** (2014), DOI: 10.1038/ncomms4082. © 2014 Macmillan Publishers Ltd.

The resulting systems achieved thermal interface resistances of 0.6 and 0.8 mm^2-K/W (+/–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 mm^2-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 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

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