from the tip of the new growth straight through the substrate on which the material is growing.

Tracking the surface evolution of the material provides insight into how the structure evolves and helps researchers understand the nanostructure formation mechanism. The creation of surface pole figures was particularly important in understanding the growth of nanoblades, as the surface morphology changed greatly with time.

The surface pole figure technique was first outlined by Tang, a postdoctoral research associate in Wang's group, in a 2006 issue of *Applied Physics Letters*. In that article, surface pole figures were created for nanorod growth. The researchers are now working to analyze nanoblade growth to provide additional insight into the growth patterns of these nanomaterials.

## Researchers Look at Nanotubes Inside Living Animals

T.K. Leeuw, K.M. Beckingham, R.B. Weisman, and colleagues at Rice University have confirmed that near-infrared fluorescent imaging was capable of detecting DNA-sized, single-walled carbon nanotubes inside living fruit flies.

"Carbon nanotubes are much smaller than living cells, and they give off fluorescent light in a way that researchers hope to harness to detect diseases earlier than currently possible," said Bruce Weisman, professor of chemistry at Rice. "In order to do that, we need to learn how to detect and monitor nanotubes inside living tissues, and we must also determine whether they pose any hazards to organisms."

Researchers have studied how carbon nanotubes interact with tissues of rabbits, mice, and other animals, but Weisman and co-researcher Kathleen Beckingham, professor of biochemistry and cell biology, chose the fruit fly *Drosophila melanogaster* to attempt the detection of nanotubes inside a living animal.

In the study, published in the September issue of *Nano Letters* (p. 2650; DOI: 10.1021/nl0710452), fruit fly larvae were raised on a yeast paste that contained carbon nanotubes. The flies were fed this food from the time they hatched throughout their initial feeding phase of 4–5 days. Fruit flies are ravenous eaters during this period and gain weight continuously until they are about 200 times heavier than hatchlings. Then they become pupae. As pupae, they do not eat or grow. They mature inside pupal cases and emerge as adult flies.

"Developmentally, the first few days of a fruit fly's life are critical," Beckingham said. "We provided larval flies with a steady diet of food that contained carbon nanotubes and checked their weight just after they emerged from their pupal cases. We found no significant differences in the adult weight of nanotube-fed flies when compared to control groups that were not fed carbon nanotubes."

The nanotube-fed larvae also survived to adulthood just as well as the control group.

Using a custom-built microscope, the team aimed a red laser beam into the fruit flies. This excited a fluorescent glow from the carbon nanotubes as they emitted near-infrared light of specific wavelengths. The researchers were then able to use a camera to view the glowing nanotubes inside living flies. Videos constructed from these images showed peristaltic movements in the digestive system.

When the researchers removed and examined tissues from the flies, they found the near-infrared microscope enabled them to see and identify individual nanotubes inside the tissue specimens. The highest concentration of nanotubes was found in the dorsal vessel, which is analogous to a main blood vessel in a mammal. Lesser concentrations were found in the brain, ventral nerve cord, salivary glands, trachea, and fat. Based on their assays, the team estimates that only about 1 in 100 million nanotubes passed through the gut wall and became incorporated into the flies' organs.

The researchers said that the "apparent biocompatibility of single-walled carbon nanotubes shown here supports their promise for the development of novel biomedical applications."

## Researchers Probe a "Quantum Paramagnetic" Spin State

A team of international researchers that includes researchers has found experimental evidence of a highly sought-after type of arrangement of atomic magnetic moments, or spins, in a series of materials. Their work, one of few studies of this particular spin state that has been postulated as a possible underlying mechanism for high-temperature superconductivity, may eventually serve as a test of current and future theoretical models of exotic spin states.

At the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) and the Hahn-Meitner Institute in Berlin, Germany, the researchers used intense beams of neutrons to probe a series of antiferromagnets, materials in which each spin cancels another, giving the material a net magnetic field of zero. The results, described in the August 26 posting of *Nature Materials* (DOI:10.1038/nmat1986), revealed evidence of a rare and poorly understood "quantum paramagnetic" spin state, in which neighboring spins pair up to form "entangled spin singlets" that have an ordered pattern and enable the material to weakly respond to an outside magnetic field (i.e., become paramagnetic).

The antiferromagnets used in this work are composed mainly of zinc and copper and are distinguished by their proportions of each, with the number of copper ions determined by the number of zinc ions. At the atomic level, the material is formed of many repeating layers. The atoms of each layer are arranged into a structure known as a kagome lattice, which is a pattern of triangles laid point-to-point whose basic unit resembles a six-point star.

Researchers have been studying antiferromagnets with kagome structures for the last 20 years because they suspected these materials harbored interesting spin structures. But good model systems, like the zinc/copper compounds used by this group, had not been identified.

At the NCNR, the researchers determined how varying concentrations of zinc and copper and varying temperatures affected fluctuations in the way the spins are arranged in these materials. Using a neutron spectrometer at the Hahn-Meitner Institute, they also investigated the effect of external magnetic fields of varying strengths. The group uncovered several magnetic phases in addition to the quantum paramagnetic state and were able to construct a complete phase diagram as a function of the zinc concentration and temperature. They are planning further experimental and theoretical studies to learn more about the kagome system.

This work was led by S.-H. Lee at the University of Virginia. The other participating institutions are the University of Fukui in Japan and the Technical University of Berlin.

## Use of Electric Field and Nanoscale Nozzle Achieves Significant Resolution in E-Jet Printing

By combining electrically induced fluid flow with nanoscale nozzles, researchers J.-U. Park and J.A. Rogers of the University of Illinois, Urbana-Champaign (UIUC), S.J. Kang of the Korea Research Institute of Standards and Science, and their colleagues at the UIUC Center for Nanoscale Chemical Electrical Mechanical Manufacturing Systems have established new benchmarks for precision control and resolution in jet-printing processes.

"We have invented methods for an electrohydrodynamic jet (e-jet) printing



https://doi.org/10.1557/mrs2007.182 Published online by Cambridge University Press

process that can produce patterns and functional devices that establish new resolution benchmarks for liquid printing, significantly exceeding those of established ink-jet technologies," said John Rogers, a Founder Professor of Materials Science and Engineering, and corresponding author of an article published in the October 1 issue of *Nature Materials* (p. 782; DOI: 10.1038/nmat974).

This type of e-jet printing could be used for large-area circuits, displays, photovoltaic modules and related devices, and other application possibilities in security, biotechnology, and photonics, Rogers said.

"As an industrial process, this work opens up the possibility for low-cost and high-performance printed electronics and other systems that involve materials that cannot be manipulated with more common patterning methods derived from microelectronics fabrication," said Placid Ferreira, the Grayce Wicall Gauthier Professor of Mechanical Science and Engineering, the director of the center and a key member of the team.

Unlike conventional ink-jet printers, which use heat or mechanical vibrations to launch liquid droplets through a nozzle, e-jet printing uses electric fields to pull the fluid out. Although the concept of electric-field induced flow is not new, the way the research team has exploited this phenomenon with nanoscale nozzles and precision control of electric fields to achieve unprecedented levels of resolution is an important advance.

The researchers' e-jet printing head consists of a gold-coated microcapillary nozzle (with a diameter as small as 300 nm) mounted on a computer-controlled mechanical support. An organic, Teflon-like coating on the gold ensures the ink flows cleanly out the nozzle toward the target. Tiny droplets of ink eject onto a moving substrate to produce printed patterns. Lines with widths as narrow as 700 nm, and dots as small as 250 nm, can be achieved in this fashion.

As a demonstration of electronic device fabrication by e-jet printing, thin-film transistors that use aligned arrays of single-walled carbon nanotubes as the semiconductor and e-jet-printed source and drain electrodes were printed on flexible plastic substrates. The transistors were fully operational, with properties comparable to similar devices fabricated with conventional photolithographic methods.

The team also demonstrated that e-jet printing could be extended to a variety of functional organic and inorganic inks, including suspensions of solid objects (such as nanoscale silicon rods) with resolutions again extending to the submicron range.

Because the nozzles are routed directly to ink reservoirs, e-jet printing has the capability to deliver large ink volumes to a surface and offers the ability to perform preprocessing on the inks before printing, Rogers said.

## Efficient Electronic Devices Obtained through Molecular-Level "Contamination"

One way to improve something is to "contaminate" it slightly. For example, the modern electronics industry is based on the practice of taking a relatively "pure" semiconductor, such as silicon, and purposely introducing small amounts of "impurities" into it. It is these impurities that enable the conductance of electricity through the semiconductor and, thus, allow control over the electronic properties of the material. Recently, a group of scientists at the Weizmann Institute of Science led by D. Cahen, together with C. Chan of Princeton University and their colleagues, implemented this technique in the field of molecular electronics. Their work was reported in the June 20 issue of the *Journal of the American Chemical Society* (p. 7494; DOI: 10.1021/ja071960p).

Molecular electronics is based on single molecules or on layers that are no more than one molecule thick. The problem with using these monolayers for electronic purposes is that they form a delicate system that is hard to manipulate precisely, and until recently, it was unclear whether it was even possible to dope them.

The current research demonstrates, however, that such "contamination" is indeed possible.

The first stage involves cleaning the molecular layer of its defects through long processes of drying, cleaning, and removing oxygen. In this case, the researchers used simple organic molecules, that is, $CH_2–(CH_2)_{12}–CH_3$ hydrocarbon chains (similar to octane found in petrol), which are electrically insulating. Electrical transport measurements through $Si–CH_2–(CH_2)_{12}–CH_3$//Hg junctions demonstrated that the layers acted as ideal insulators. Characterization of the resulting "clean" surface showed that, although the resulting molecular system included unavoidable impurities to a certain degree, those impurities did not dictate the system's electrical behavior.

To dope the clean surface, the scientists irradiated it with UV light or weak electron beams. As a result, chemical changes occurred within the system: double (as opposed to single) chemical bonds were created between the carbon atoms that assemble into the molecular chains that make up the molecular layer. It is these bonds that ultimately influence electronic transport through the molecules (see figure).

Cahen said, "The method that we have developed allows us to start working with a system that is made up of a uniform layer of 'pure' molecules, which dominates the structure's overall electrical properties.

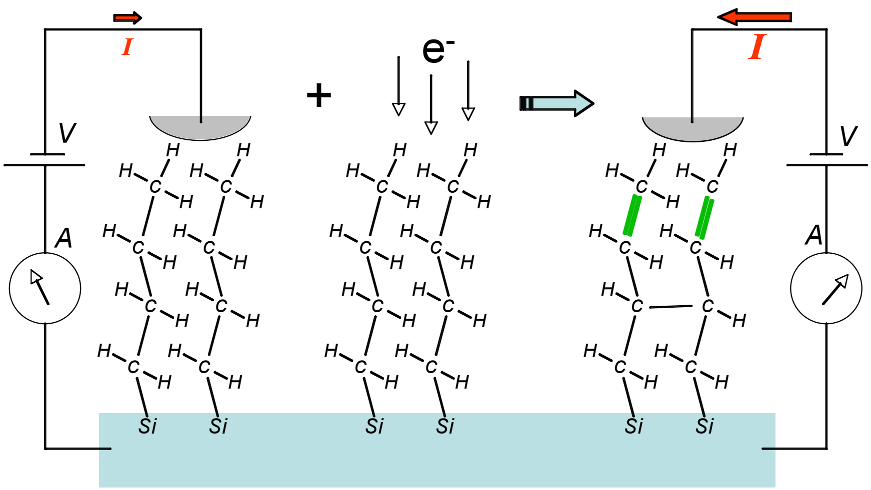


Figure 1. A single layer of chains of hydrocarbons (molecules with hydrogen, H, bound to carbon, C) on a surface of silicon (light blue). Exposing the molecules to a weak beam of electrons (center) causes chemical changes (loss of some hydrogen atoms), creating double bonds between carbon atoms (right, green). As a result, the material's electronic transport properties change, changing the mechanism of transport and increasing the electric current by a factor of 10–100.