New theory explains electronic and thermal behavior of nanotubes

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Researchers at the University of Illinois at Urbana-Champaign have made an important theoretical breakthrough in the understanding of energy dissipation and thermal breakdown in metallic carbon nanotubes. Their discovery will help move nanotube wires from laboratory to marketplace.

The remarkable electrical and mechanical properties of metallic carbon nanotubes make them promising candidates for interconnects in future nanoscale electronic devices. But, like tiny metal wires, nanotubes grow hotter as electrical current is increased. At some point, a nanotube will burn apart like an element in a blown fuse.

“Heat dissipation is a fundamental problem of electronic transport at the nanoscale,” said Jean-Pierre Leburton, the Gregory Stillman Professor of Electrical and Computer Engineering at Illinois and co-author of a paper published in the Dec. 21 issue of the journal *Physical Review Letters*. “To fully utilize nanotubes as interconnects, we must characterize them and understand their behavior and operating limits.”

Up to now, no coherent interpretation had been proposed that reconciled heat dissipation and electronic transport, and described thermal effects in metallic carbon nanotubes under electronic stress, said Leburton, who is also a researcher at the Beckman Institute for Advanced Science and Technology, at the Micro and Nanotechnology Laboratory and at the Frederick Seitz Materials Research Laboratory. “Our theoretical results not only reproduce experimental data for electronic transport, they also explain the odd behavior of thermal breakdown in these nanotubes."

For example, in both theory and experiment, the shorter the nanotube, the larger the current that can be carried before thermal breakdown occurs. Also, the longer the nanotube, the faster the rise in temperature as the threshold current for thermal heating is reduced.

In nanotubes, heat generated by electrical resistance creates atomic vibrations in the nanostructure, which causes more collisions with the charge carriers. The additional collisions generate more heat and more vibrations, followed by even more collisions in a vicious cycle that ends when the nanotube burns apart, breaking the circuit.

"Short nanotubes can carry more current before burning apart because they dissipate heat better than longer nanotubes," Leburton said. "Although the entire nanotube experiences resistance heating, the electrical contacts at each end act as heat sinks, which in short nanotubes are relatively close to one another, leading to efficient heat removal."

This phenomenon also explains why the highest temperature always occurs in the middle of the nanostructure, Leburton said, "which is the furthest point away from the two ends, and where burning occurs in longer nanotubes under electrical stress."

In another important finding, Leburton and his colleagues have revised the common belief that charge carriers go ballistic in short metallic nanotubes having high currents. Researchers had previously thought that charge carriers traveled from one terminal to the other like a rocket; that is, without experiencing collisions.

"We have shown that the high current level in short metallic nanotubes is not due to ballistic transport, but to reduced heating effects," Leburton said. "Owing to their large concentration, the charge carriers collide efficiently among themselves, which prevent them from going ballistic. Even in short nanostructures, the current level is determined by a balance between the attractive force of the external electric field and the frictional force caused by the nanotube thermal vibrations. The collisions among charge carriers help the energy transfer to the nanotubes which results in heat dissipation."

Co-authors of the paper are Leburton, electrical and computer engineering professor Andreas Cangellaris and graduate student Marcelo Kuroda.

Source: University of Illinois at Urbana-Champaign

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