atoms accumulating at lower temperatures. They find that the binding energy for xenon on a nanotube is 30% lower than for xenon on graphite, and explain this difference in terms of reduced van der Waals interactions (due to the surface of the nanotube being curved and containing only one layer of carbon atoms, whereas graphite is flat and contains several layers of carbon atoms).

The movement of atoms and molecules along the nanotube is a double-edged sword. For researchers building mechanical mass spectrometers it is one more potential source of noise and error (although it might be possible to modify the carbon lattice to create trapping sites that will stop this movement and improve performance). However, the fact that atoms can move on the surface, combined with the extraordinary mass resolution that is available, means that surface scientists will be able to study a wide variety of processes and phenomena — such as nucleation processes in thin-film growth and the dynamics of monolayer formation — at the level of single atoms and single-adsorption sites. ❐

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NANOELECTRONICS

Nanotubes throw their heat around

A direct current flowing through a carbon nanotube on a substrate heats the substrate but not the nanotube, and it may be possible to exploit this phenomenon in the thermal management of nanoelectronic devices.

Amin Salehi-Khojin, Wei Zhu and Richard I. Masel

When carbon nanotubes and graphene are described as attractive electronic materials, it is usually because of their high carrier mobilities[1,2] and atomic-scale dimensions, which are characteristics expected to aid efforts to reduce the size of electronics[3,4]. However, the potential impact of such carbon nanostructures for thermal management — arguably an equally important challenge facing the electronics community — is less clear. Writing in *Nature Nanotechnology*, John Cumings and co-workers at the University of Maryland, College Park report that they have discovered a surprising new facet of charge transport in one dimension: a direct current passing through a carbon nanotube can heat the substrate under the nanotube, but leave the nanotube itself cool[5].

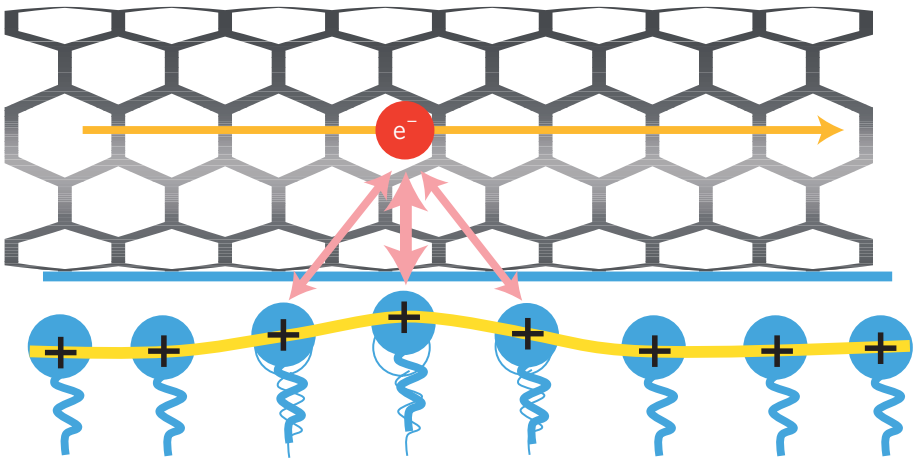

Figure 1 | A possible model for substrate heating by a direct current flowing through a nanotube. Atoms at the surface of the substrate (blue) experience a time-varying electric field with each electron (red) passing through a nanotube (grey). Because of their close proximity to the electron, the atoms are displaced from their equilibrium positions (outlines) even though they are neutral, and are subject to a spring-like restoring force (blue wavy lines). This interaction also slows the electron down.

The Maryland researchers overcame significant experimental difficulties to prove that this effect, which they call remote Joule heating, was occurring. First they prepared and deposited pristine nanotubes, to avoid defects that would otherwise create thermal hotspots. Second, they minimized the effect of contact resistance by increasing the area of overlap between the nanotube and the metal contact relative to that between the nanotube and the substrate. This was important because the low thermal and electrical resistivities of carbon nanotubes would cause the electrode contacts to dominate resistivity data. Finally, the researchers used a technique called electron thermal microscopy (EThM) to measure the temperatures of their nanotube, substrate and contacts. This technique overcomes the spatial resolution limits of infrared imaging techniques by using an electron microscope to monitor nanoscale metallic indium islands as they change from solid to liquid (and back again) in response to local temperature fluctuations[6]. The key result of this careful experimentation and analysis was the observation that the substrate underneath the nanotube and between the metallic contacts heated up before the nanotube or the contacts, suggesting extremely effective thermal transport from the nanotube to the substrate.

This means that most of the energy dissipation in electronic devices based on carbon nanotubes can be made to occur in the substrate, opening new possibilities for thermal management in these systems.

But, the data also reveal the price to be paid: the transfer of energy to the substrate introduces a drag on charge carriers, reducing their mobility, and forcing a trade-off between thermal management and mobility. Moreover, because the properties of the substrate will affect the degree of remote Joule heating, these properties will need to be carefully controlled if remote Joule heating is to be successfully leveraged for thermal management.

On first blush, the transfer of heat from a cold nanotube to a hot substrate seems odd, and vaguely in contradiction with the second law of thermodynamics. However, the energy is transferred from energetic electrons passing through the nanotube, and not from the nanotube itself. A rough analogy is the operation of an induction oven, in which an alternating current passing through a conductor leaves the conductor cool, while heating a metal substrate to over 1,000 °C. In both cases, energy is transferred when time-varying electric fields couple with the vibrational and electronic modes of the substrate.

The analogy to the induction oven is not exact, however, because Cumings and co-workers used direct, rather than alternating current. A direct current produces a constant magnetic and electric field, which does not lead to energy radiation. Surprisingly, at the nanoscale, even a direct current is able to transfer energy to a remote substrate. This is consistent with previous work showing that direct current travelling through a nanotube can transfer energy to adsorbates[7].

However, at this point, the mechanism of the direct-current energy transfer is not clear. A model[8] suggests that atoms at the surface of the substrate feel a force with each passing electron, so that a time-varying electric field is associated with even a direct current (Fig. 1). This effect is absent in macroscopic systems, because field variations are weaker at large distances, and the interactions of many electrons with a substrate sum to zero.

This model, however, does not give a quantitative explanation of remote Joule heating. Future modelling work will need to make this a goal, and take into account the inhomogeneous heating of the nanotubes[9–13]. It is now up to the research community to develop such models, and to incorporate this potentially important process into new tools for device design. ❐

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MOLECULAR JUNCTIONS

Interference comes into view

An atomic force microscope with a gold-coated tip can be used to directly observe quantum interference in molecular monolayers adsorbed on gold substrates.

Richard J. Nichols and Simon J. Higgins

Wave-interference phenomena can be beautiful, technologically important and scientifically informative. A remarkable example of interference at the nanoscale is the observation of standing electronic waves around defects on an otherwise flat metal surface with a scanning tunnelling microscope[1]. Related interference effects can also occur when electrons flow through molecules placed between metal contacts, often with surprising results.

Consider, for example, a thought experiment in which atomically sharp metal contacts are placed at three positions around a benzene ring (Fig. 1a). One might think that the flow of charge from contact A to contact B (the *meta* position) would be higher than that from A to C (the *para* position) because the contacts are closer and the tunnelling current should decrease exponentially with distance. However, it has been shown theoretically that electronic transmission around the Fermi energies of the contacts is suppressed for the *meta* geometry[2]. Furthermore, higher conductance values have been observed experimentally for rod-like molecules connected to metal contacts through the *para* position, compared with those connected through the *meta* position[3]. This counter-intuitive behaviour can be explained through the phenomenon of quantum interference[4].

Quantum interference is of particular relevance to molecular electronics because it could be used to control the operation of molecular devices at the level of the wavefunction. Manipulation could be achieved either through chemical design or by electrostatic gating with a third terminal. However, despite clear theoretical evidence for quantum interference in molecular junctions, direct observation of such phenomena has been elusive. Now, writing in *Nature Nanotechnology*, Sense Jan van der Molen and colleagues at Leiden University, the University of Groningen and the Technical University of Denmark report direct experimental evidence for destructive quantum interference in molecular monolayers sandwiched between two gold contacts[5].

Three of the key molecules used by van der Molen and colleagues are shown in Fig. 1b. AQ-DT has an anthraquinone group at its centre, and the thiol groups at both ends are used to connect the species to the gold electrodes. AQ-MT differs only in that there is no thiol group at one end, so a phenyl group connects the molecule to the top electrode. AC-DT, on the other hand, has an anthracene group at its centre and thiol groups at both ends. The difference between the anthracene and anthraquinone groups is that the former can be represented as a system of alternating single and double carbon–carbon bonds (that is, it is conjugated), whereas the latter contains two consecutive single carbon–carbon bonds in