application, in return, opens virgin territory that raises the future worth of metallic glasses themselves. Indeed, broadening the scope of critical applications for metallic glasses is a key challenge facing the metallic-glass research community today. This interdisciplinary advance[7] is thus a timely and welcome stimulus for both fields.   ❑

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CARBON NANOTUBES

Not that slippery

Friction measurements on carbon nanotubes show a remarkable anisotropy, the origin of which can be traced to the activation of specific deformation modes of energy dissipation.

Ruben Perez

Sliding friction is one of the oldest problems in physics and materials science. Almost every aspect of everyday life involves the contact of two solid surfaces, and the effort to minimize the energy lost during their relative displacement has occupied some of the brightest minds in history, including Leonardo da Vinci. Understanding the fundamental origin of friction has become an even more pressing challenge with the miniaturization of moving components in many commercial products, including computer-disk heads and the microelectromechanical systems that trigger the airbags in our cars. Carbon nanotubes (CNTs) are one of the most promising building blocks to scale these devices down to the nanometre scale. On page 876 of this issue, Lucas *et al.*[1] explore the tribological properties of CNTs, and show that friction forces are different when sliding a nanosized tip parallel or perpendicular to the CNT axis. With the aid of molecular-dynamics simulations, they are able to identify the microscopic dissipation mechanism responsible for this anisotropic behaviour and its connection with some fundamental properties of the nanotubes, such as their chirality.

The old, simple empirical laws that govern friction at the macroscopic scale are the result of the collective behaviour of the many different asperities that define the real contact area between two rough surfaces. Modern nanotribology aims to explore the 'single asperity' level relevant
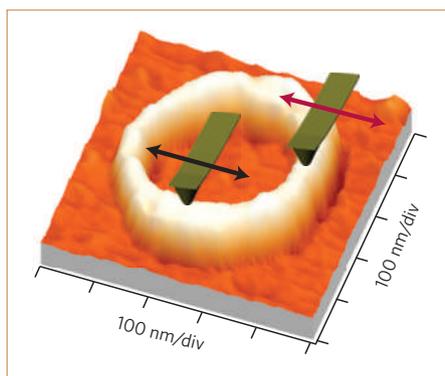

Figure 1 | Schematic of the experiment, showing the AFM topography of a 7 nm nanotube and the scanning direction of the AFM tip parallel (black arrow) or perpendicular (red arrow) to the nanotube axis.

for nanometre-scale junctions[2,3]. The atomic force microscope (AFM) is the tool of choice for measuring the normal and lateral forces during the sliding of the nanometre-radius tip of the AFM on a given surface. Lucas *et al.* follow this approach to determine the friction properties of multiwall CNTs deposited on a silicon substrate (Fig. 1). Their measurements confirm that the simple linear relationship (that we learn at school) between the friction force and the applied load is replaced by a two-thirds power-law dependence at these nanometre-scale contacts. More surprisingly, they found that, for nanotubes with radii

smaller than 10 nm, friction forces are different when the tip slides parallel or perpendicular to the CNT axis. The shear strength, which is the proportionality factor between the friction force and the contact area, can be as much as three times larger for the transverse sliding for a CNT with a radius of 4 nm.

In the absence of wear (that is, no permanent damage of the tip and/or sample), friction arises from the transfer of collective translational kinetic energy into nearly random heat motion. Understanding the fundamental microscopic mechanisms involved in this process is one of the great challenges in nanotribology. Mechanical energy can be directly converted into vibrations of the surface and tip atoms in the contact. These vibrations are expected to be damped by energy transfer to bulk phonon modes, and by electronic excitations of charge carriers (for example, the creation of electron–hole pairs in metals, the creation of electronic surface states that are charged and then discharged on release of the stress, and tip-induced hopping of trapped charges).

Recent experiments that focus on the control of one of these possible mechanisms have shown the dependence of friction force on carrier concentration in silicon p–n junctions[4], and the effect of changes in the mass of the surface atoms (and thus, in their vibrational properties)[5]. Differences in friction between single and bilayer graphene films have been related to a dramatic difference in electron–phonon

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coupling[6]. From the theoretical side, molecular-dynamics simulations of coaxial CNTs in relative motion have shown a large enhancement of friction that can be attributed to the excitation of phonons with group velocity close to the sliding velocity[7].

Molecular-dynamics simulations have been also used by Lucas et al.[1] to address the remarkable friction anisotropy revealed by their experiments. Even with the fastest computers available, the smallest sliding velocities that can be achieved in the simulations are still orders of magnitude larger than those demonstrated in the experiments, which prevents the realistic simulation of the energy transfer. Nevertheless, these simulations have a key role in the identification of the soft vibrational mode that is responsible for the enhanced energy dissipation found when sliding perpendicular to the nanotube axis.

In the absence of adhesion with the substrate, the nanotube would naturally roll with no energy cost when kicked perpendicular to its axis. The interaction turns this tendency into a low-frequency oscillation, a soft mode[8], that can be easily excited by lateral pushing by the tip (Fig. 2). The simulations show that the coupling of the tip displacement and this 'hindered rolling' mode depends on an intrinsic property of the nanotube — its chirality. In non-chiral nanotubes, these modes are only active during transverse sliding, leading to a friction anisotropy (the ratio of transverse to longitudinal friction) of 20; nanotube chirality favours the coupling between the longitudinal and transverse displacements,
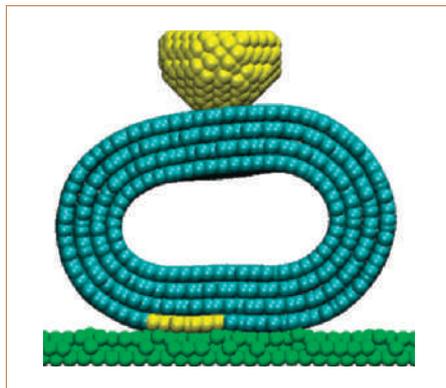

Figure 2 | Simulated cross-sectional view showing nanotube deformation during the sliding of the AFM tip perpendicular to the nanotube axis. The yellow dots on the underside of the nanotube represent the fixed atoms during the attempted rolling induced by the lateral pushing of the tip.

reducing the friction anisotropy to a value of two to three.

These soft lateral deformations and the accompanying friction anisotropy should be present in different situations involving nanotubes made from carbon and other inorganic materials, such as boron nitride and tungsten disulphide. Understanding how friction at the nanometre scale is quantitatively affected by the contact geometry, adhesion forces, contaminants and atomic-scale defects is the next challenge. The friction forces measured by Lucas et al.[1] on silicon substrates are two orders of magnitude larger than the

values found for CNTs sliding on graphite, and three to four orders larger than forces between the walls of CNTs during pulling experiments. Dynamic operation modes for the AFM, which can achieve atomic resolution, have already contributed to the quantitative understanding of tip–sample interaction and energy dissipation. A combination of force-spectroscopy experiments with first-principles simulations have identified a dissipation channel associated with the properties of a single atomic contact, and have provided a detailed atomistic description of the process[8]. Recent extensions of this technique to map the three-dimensional surface force field with picometre and piconewton resolution[9,10] promise to open a new avenue for the characterization and understanding of friction at the atomic scale. ❐

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ORGANIC ELECTRONICS

Electrical contacts

Further achievements in the realm of organic and molecular electronics — even at the level of device applications — requires greater understanding of the materials at a fundamental level. This insight can only come with input from researchers in several disciplines working together on the materials from different perspectives.

Natalie Stingelin

The discovery by Stokes that certain organic molecules[1], particularly conjugated species, display interesting fluorescence properties fuelled scientists' curiosity towards organic matter. These materials promise new features and characteristics that are difficult — if not entirely impossible — to achieve with their inorganic counterparts. This is because of the wealth of molecular structures that are

accessible and the variety of processing methodologies that can be applied to these often 'plastic like' materials. Indeed, a suite of fabrication tools is available that can be used to control the final solid-state microstructure and, therefore, the optoelectronic properties of these compounds. Furthermore, large-area and roll-to-roll manufacturing methods can be applied to produce the materials on a

large scale. At present, these technologies are attracting significant interest for developing products based on organic field-effect transistors, light-emitting diodes and photovoltaic cells. Already, a high number of different device designs and structures have been constructed with organic conjugated materials; and it is easy to envisage entirely new architectures being created in the future. However, for this to be