NEMS

Putting a damper on nanoresonators

The observation of nonlinear damping in resonators made from carbon nanotubes and graphene should lead to an improved understanding of energy losses in nanomechanical devices.

J. Scott Bunch

The harmonic oscillator holds a special place in the history of science and technology, having an important role in the development of both classical and quantum physics. Examples include Galileo's pendulum, resonant electrical circuits and molecular vibrations. In micro and nanomechanical systems, the prototypical harmonic oscillator is a mechanical resonator — a beam of material that oscillates in response to an externally applied force. In an ideal world, or at least a world in which there is no dissipation of energy, the oscillations would continue indefinitely after energy had been supplied to the resonator.

In the real world, however, energy is sucked out of the system, which leads to damping and the eventual disappearance of oscillations. For many systems this damping force is found to be linearly proportional to velocity and independent of the amplitude of the oscillations. Writing in *Nature Nanotechnology*, Adrian Bachtold and co-workers describe how damping in carbon nanotube and graphene resonators follows a different paradigm — it depends strongly on the amplitude of motion[1].

Mechanical resonators are potential candidates for applications such as mass sensing, quantum motion detection and radiofrequency signal processing. Device performance improves as the resonant frequency increases and the resonator mass decreases, so researchers have developed smaller and smaller resonators over the past several decades. This has now culminated with the development of carbon nanotube and graphene resonators — the ultimate limits of 1D and 2D nanomechanical structures.

Not only are carbon nanotubes and graphene the thinnest materials in the world, they are also the stiffest and strongest, making them promising materials for a variety of mechanical applications[2,3]. However, energy losses in these atomically thin resonators are notoriously high at room temperature, so it is essential to understand and minimize the damping in these systems if we are to make the most of their remarkable potential[4].
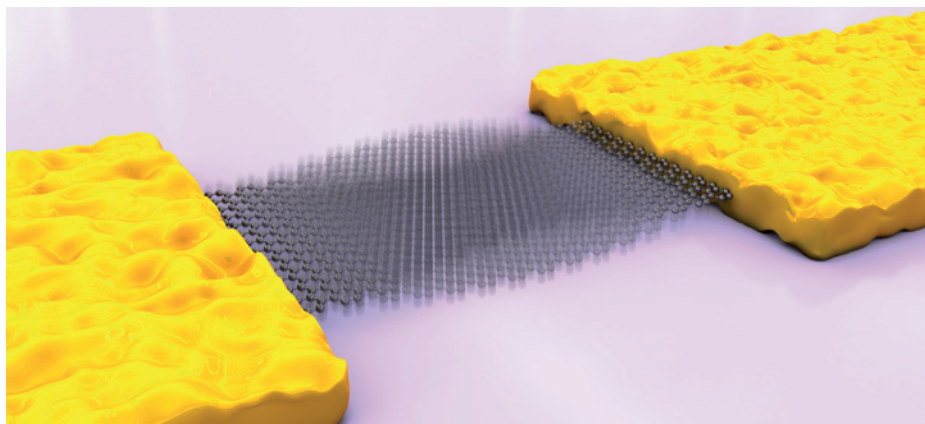
Figure 1 | Artist's impression of a graphene resonator between two metal electrodes. Nanoscale mechanical resonators could be used for applications such as mass sensing, radiofrequency signal processing and tests of quantum theory.

Bachtold and co-workers — who are based at the Catalan Institute of Nanotechnology and the Technical University of Munich — measured how the damping changed as the amplitude of the oscillations was increased for three different resonator setups: nanotubes under tensile stress; nanotubes with slack; and graphene under tensile stress (Fig. 1). In all three cases, and for a range of temperatures from room temperature down to 90 mK, they found that the damping increased with increasing amplitude of motion.

Before this work, there were theoretical results describing the importance of nonlinear dynamics on nanomechanical resonators[5], and experimental results on the first graphene resonators had suggested that nonlinear damping might have an important role[6]. The present work puts the hypothesis of nonlinear damping in carbon nanotube and graphene resonators on a firm experimental footing, and represents an important step towards understanding damping in atomically thin resonators. However, the exact physical mechanism responsible for the damping is not fully understood.

There are also practical obstacles to overcome before these nanoscale resonators can live up to their potential. Mass production of consistent and reliable devices is one challenge, although there has been significant progress in this area[7–9], and detecting and actuating their motion — especially at higher resonant frequencies — is another.

In the first experiments on nanotube resonators, the motion was detected in an electron microscope, whereas optical detection was used for the first graphene resonators[6,10]. However, both of these techniques are costly and bulky. Electrical actuation and detection is preferable, but small resonators with high resonant frequencies typically generate only small electrical signals, and this — combined with high resistances and large parasitic capacitances — makes electrical detection difficult. Bachtold and co-workers used an all-electrical electromechanical mixing technique that was developed at Cornell University for measuring carbon nanotube resonators[11] and was later applied to graphene resonators by researchers at Columbia University[12]. Direct electrical readout of a graphene resonator operating at tens of megahertz was demonstrated by the Columbia team last year using a local gate to minimize the parasitic capacitance[13].

The market for microelectromechanical systems (MEMS) is worth ~$10bn per year, and it is difficult to avoid MEMS devices in everyday life — they are found in automobiles, mobile phones and video-game controllers to name just a few applications. The most difficult challenge that carbon nanotubes and graphene face in this field is that silicon reigns supreme, just as it does in electronics. It will not be easy to displace the silicon behemoth, but the superior mechanical properties of carbon

nanotubes and graphene — they are the thinnest, stiffest, and strongest materials in the world — could be reason enough to bet on carbon. ❑

J. Scott Bunch is in the Department of Mechanical Engineering, University of Colorado, Boulder, Colorado 80309, USA.
e-mail: jbunch@colorado.edu

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IN VITRO STUDIES

Ups and downs of cellular uptake

Experiments on the uptake of gold nanoparticles by cells grown in different cell culture configurations suggest that the influence of sedimentation should be taken into account when performing *in vitro* studies.

Dominique Lison and François Huaux

*I*n vitro cell culture studies, which are commonly used in toxicological research to screen new compounds and to explore the mechanisms of toxicity, typically involve subjecting cells grown at the bottom of a culture well to a dose of test material, and measuring their response to determine the dose–effect relationship. Traditional *in vitro* assays have been primarily designed for testing soluble molecules. However, using *in vitro* assays to test nanoparticles and fibres has been problematic because solid objects do not behave the same as soluble molecules and, therefore, it has been difficult to define appropriate expressions for the dose.

Writing in *Nature Nanotechnology*, Eun Chul Cho, Qiang Zhang and Younan Xia[1] from Washington University in St. Louis report, based on experiments with upright and inverted cell cultures, that sedimentation of nanoparticles is an important determinant of cellular dose in *in vitro* cell studies. Gold nanoparticles of various shapes, sizes, surface coating, density and initial concentration were examined and those with faster sedimentation rates showed higher cellular uptake in the upright setup compared with the inverted one.

The concentration of test molecules in *in vitro* assays is normally expressed as the nominal mass dose, which is quoted in units of micrograms of chemical per millilitre of cell culture medium (μg chemical per ml). The relevant dose is more difficult to define for solids because the cellular response can be driven by various parameters, depending on the site and mechanism of action (Fig. 1a). When surface activity, such as the release of reactive oxygen species by crystalline silica
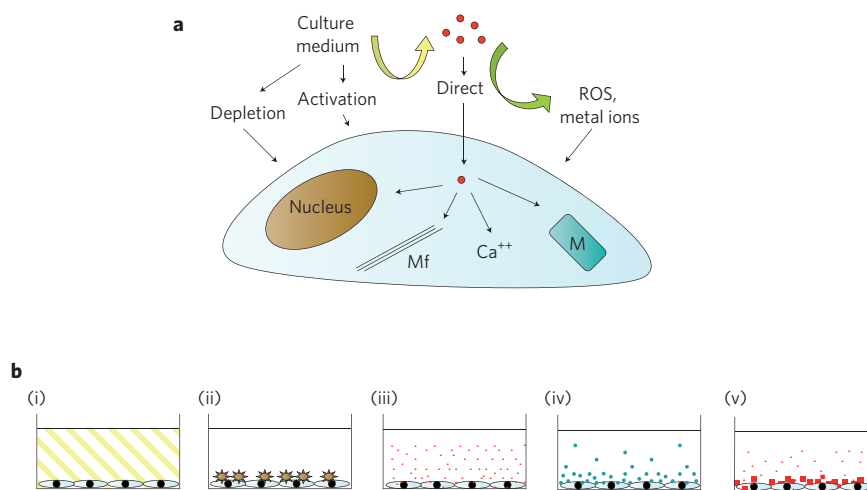
Figure 1 | The variety of ways in which solid nanoparticles interact with cells (**a**) and behave in culture medium (**b**) make it difficult to define the relevant dose for nanotoxicology studies. **a**, Nanoparticles (red circles) can act directly on targets inside cells (including mitochondria (M), calcium stores (Ca⁺⁺), microfilaments (Mf) or the nucleus), or indirectly by releasing compounds (such as reactive oxygen species (ROS) or metal ions) that damage the cells from outside, or by changing the cell culture medium in ways that influence the cellular response (by, for example, activating or depleting various constituents in the medium). **b**, When cells are exposed to toxic species in the form of soluble molecules (i), the relevant dose is the concentration of the molecules in the culture medium. However, the situation is more complex for solid particles that are not soluble. Microparticles (ii) generally sediment and rapidly come in contact with the cells. Small nanoparticles (iii) sediment less and their contact with cells is determined by diffusion and convection forces. However, larger nanoparticles (iv) settle more rapidly because of the additional influence of sedimentation forces. In most cases, nanoparticles form aggregates (v) in the culture medium, so cells are exposed to a mixture of single and aggregated nanoparticles that settle in different ways.

particles[2], is involved, the surface area of the nanoparticle per millilitre of cell culture medium (cm² particle per ml) is considered to be the appropriate expression of dose.

However, when toxicity is mediated by ions released from the solids[3], the relevant dose should be measured in units of mass of ions per millilitre of cell culture medium