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Nanomechanics weighs in

Nano-scale devices can measure masses with a precision of one attogram, which is three orders of magnitude better than the previous record

From **Nickolay Lavrik** and **Panos Datskos** at the Oak Ridge National Laboratory, Oak Ridge, TN, US

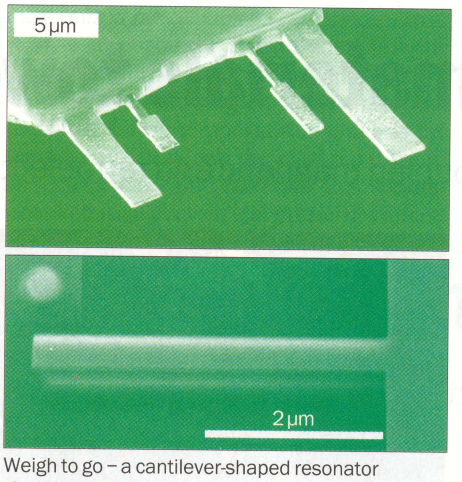
We tend to associate mass with the quantity or size of an object. At the microscopic scale, however, mass measurements are a powerful tool that can provide information about the molecular and atomic composition of an object. While measurements of macroscopic masses traditionally rely on the fact that the gravitational force is directly proportional to the mass of the object, the Earth's gravitational field is too weak to produce reliable measurements of the force in the case of molecular-scale objects.

A better way to measure the mass of a microscopic sample is to quantify the sample's inertia as it is forced into motion. This is the principle behind mass spectroscopy, in which the trajectory of an ionized particle in a strong electromagnetic field provides a precise measure of the particle's inertia, and therefore a measure of its mass. Mass spectroscopy is able to distinguish ionized particles that differ by a single atomic-mass unit – about 1.66×10^{-27} kg, or 1.66 yoctograms. However, many researchers have pondered whether a less complex and more versatile measurement technique could be devised that has a similar level of sensitivity.

Harold Craighead and co-workers at Cornell University in the US have now built a mechanical device that suggests such an alternative could eventually be possible. Following the basic idea of placing particles in a strong field, they studied how the inertia of a nanoelectromechanical cantilever changed when it was loaded with small masses. As heavier objects were added the oscillation frequency of the device decreased, which enabled the Cornell team to measure the mass of a particle with a precision of one attogram (10^{-18} g). This is three orders of magnitude more sensitive than the previous record (R Ilic *et al.* 2004 *J. Appl. Phys.* at press).

Mass oscillation

Nanoelectromechanical devices (NEMS) are tiny structures that have mechanical degrees of freedom. They can be batch fabricated in a similar way to electronic chips, and a typical NEMS device used for mass measurements looks a bit like a diving board. This structure resonates at a frequency that is precisely defined by its stiffness, mass and geometry. Any additional mass that is added to the suspended portion of the device tends to slow down this oscillatory motion.



Weigh to go – a cantilever-shaped resonator shrunk to the nano-scale tends to oscillate at a characteristic frequency in the radio-frequency range. This resonance frequency decreases slightly when a small mass is attached to the resonator, and this has allowed researchers at Cornell University to attain a record-breaking mass sensitivity of 10^{-18} g, or 1 attogram.

In 1992 researchers at Simon Fraser University in Canada demonstrated for the first time that such resonators can be used to detect masses less than 0.5 ng. Michael Roukes of the California Institute of Technology and co-workers developed NEMS devices further with the goal of detecting masses in the femtogram regime (see *Physics World* February 2001 pp25–31). These studies showed that the sensitivity of NEMS devices could reach the level of a single atomic-mass unit. Recently Roukes and co-workers also demonstrated attogram-mass sensitivity, although their experiments were performed in an ultrahigh vacuum and at cryogenic temperatures (arXiv.org/abs/cond-mat/0402528).

A useful rule of thumb in the NEMS mass-detection business is that the smallest theoretically detectable mass roughly corresponds to a millionth of the mass of the cantilever. This reflects the fact that the smallest meaningful change in the resonance frequency of a nanomechanical device at room temperature is limited by thermal noise. While predictions of very high sensitivity using nanomechanical resonators have abounded in the literature, experimental NEMS that can operate under "normal" ambient conditions have clearly lagged behind the theory. It appears that approaching the theoretical limit is a very challenging experimental task.

One of the main reasons for this is the difficulty in reading-out the NEMS data. The frequency of nanomechanical resonators is generally determined by reflecting a laser off the resonator. As a result, reading-out the data becomes increasingly complicated as the widths of the resonators become smaller than the wavelength of visible light. While UV lasers with smaller wavelengths could be used, they tend to be less experimentally friendly than visible lasers and much more expensive.

The operation of mass-sensitive NEMS also needs to be optimized, which involves a difficult trade-off between several factors. For instance, thicker and stiffer resonators are less susceptible to thermal noise, but they are also more difficult to read-out because they tend to oscillate with smaller amplitudes and at higher frequencies. Resonators as thin as 50 nm and just several microns wide offer a reasonable compromise between the requirements of mass sensitivity and suitability for an optical read-out.

In 2003 the present authors took all these requirements into account and used a technique called focused ion milling to carve tiny slivers out of much larger commercially available silicon cantilevers (top figure). The result was a number of lightweight resonators that could undergo readily measurable changes in resonance frequency when they were loaded with a few femtograms of an organic material (2003 *Appl. Phys. Lett.* **82** 2697–2699).

New order

Craighead and co-workers have now taken the optimization of NEMS for mass detection to new levels. Using their extensive experience with nanofabrication techniques, and by experimenting with various types of NEMS devices, the Cornell team has managed to improve the limit of mass detection by three orders of magnitude compared with our group's previous world best. The resonators were made of silicon, were 4 µm long and 0.5 µm wide, and had a suspended mass of less than one nanogram (bottom figure). This allowed the researchers to achieve attogram-mass sensitivity, which is consistent with the rule of thumb of approximately one millionth of the mass of the resonator. Despite this minute mass, the devices were still large enough to accommodate a very convenient optical read-out.

Attogram-sensitive NEMS have immediate applications for novel chemical and biological sensors. Real-time trace analysis of highly hazardous agents, such as toxins, explosives and pathogens, may finally become possible without the need for expensive instrumentation, and this would allow hazardous agents to be detected before dangerous amounts of them accumulate. Such devices could also be used to detect large protein molecules, and to differentiate between individual viruses simply by weighing them. In short, an attogram-sensitive NEMS is an excellent addition to the toolkit of any scientist interested in studying interactions at the level of individual molecules.

To improve the sensitivity of mass-detecting NEMS still further, we will have to rely on even smaller resonators. But Craighead and co-workers have good reason to be optimistic. They have built a variety of NEMS devices with features as small as 20 nm, including the world's smallest guitar (see *Physics World* December 2003 p3).

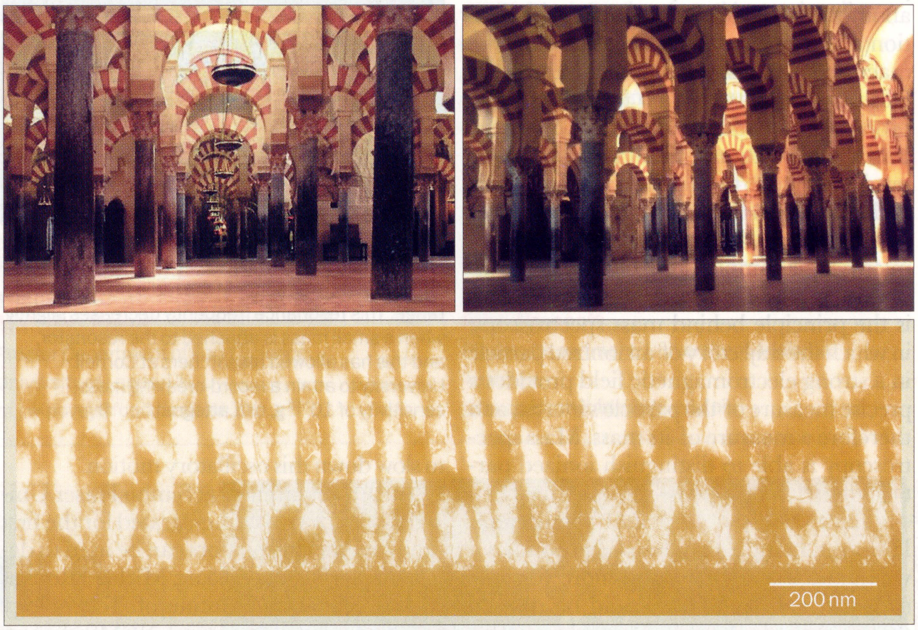
The next milestone in nanoelectromechanical mass detection is achieving zeptogram (10^{-21} g) sensitivity, which will prove whether nanomechanical mass spectroscopy is feasible. We anticipate this prize will attract even more researchers to join the mass-sensitive NEMS community in the next few years.

Multiferroic materials tower up

Tiny structures with strongly coupled magnetic and ferroelectric properties could make it big

From **Nicola A Spaldin** in the Materials Department, University of California, Santa Barbara, CA, US

For generations humans have been engineering pillars that have more than one function. The giant stone pillars of the 9th-century Cordoba Mosque in Andalusia, Spain, for example, provide both structural stability and aesthetic appeal. Now researchers in the US have built pillar structures at the nanometre scale that combine two markedly different functions: magnetism and ferroelectricity. The technological importance of these 21st-century nanopillars could be as far reaching as that of the ancient building techniques used in Andalusia.



Pillars of strength – like the stone pillars in ancient architecture (such as those in the Cordoba Mosque in Spain), which have both structural and aesthetic appeal, materials built from arrays of nanopillars can combine magnetic and ferroelectric properties. An image obtained using atomic force microscopy shows the nanopillars of such a multiferroic material from the side.

Magnetic materials are ubiquitous, from the huge transformer cores in electrical power sub-stations to the tiny magnetic particles that are used to store data on our computer disks. The widespread applications of magnets stem from two basic properties. First, they have a spontaneous magnetic moment, which enables magnetic flux to be concentrated in transformers. Second, the orientation of the magnetism can be switched back and forth by an applied magnetic field, and can therefore be used for data storage.

Similarly, ferroelectric materials have a spontaneous *electric* polarization, the direction of which can be switched with an applied electric field. In fact, the "ferro" part of the name arises because their electrical properties are similar to the magnetic properties of iron-based magnetic materials; most, however, are not ferrous in the sense that they contain iron. Ferroelectrics are used to make capacitors with high dielectric constants, and also have applications in non-volatile data storage and sonar.

Combining strengths

Materials that are both magnetic and ferroelectric are called multiferroics, and they are very appealing from a technological point of view. In addition to all the properties of their parent phenomena, multiferroics can also display magneto-electric coupling: in other words a magnetic field can affect the material's electrical properties, and vice versa. This coupling could be harnessed to make novel devices such as magnetically tuneable dielectrics, electrically controlled ferromagnetic resonance devices, or three-way transducers. Furthermore, the fundamental physics of multiferroics is rich and fascinating.

There is, however, one rather significant drawback: robust magnetic ferroelectrics do not yet exist. Although there is no physical law that prevents magnetism and ferroelectricity from co-existing in a single compound, my group in Santa Barbara has recently shown that there are practical obstacles to making a multiferroic material.

Our calculations reveal that the covalent-bond formation that promotes ferroelectricity tends to disfavour magnetism. Factors that promote magnetic properties, on the other hand, disfavour ferroelectric properties. And although we have been able to predict the existence of materials that have indeed turned out to be ferromagnetic and ferroelectric, we have not been able to design materials that are suitable for building actual devices.

Haimei Zheng of the University of Maryland and colleagues in the US have now adopted a different approach, which I believe is much more promising for producing useful magneto-electric multiferroics. Instead of trying to produce a single compound, they grow a closely interwoven composite material from magnetic cobalt ferrite ($CoFe_2O_4$) and ferroelectric barium titanate ($BaTiO_3$). To do this, the team used a well established growth technique called pulsed vapour deposition, in which an oxide target containing the correct ratios of barium, titanium, cobalt and iron is bombarded with a laser. This releases atoms from the target that fortuitously self-assemble into nanometre-sized 3D pillars of cobalt ferrite within a barium titanate matrix (H Zheng *et al.* 2004 *Science* **303** 661–663).

Composite multiferroics have been developed before, mostly by layering thick chunks