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Home   Search   Register   Login

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Features: February 2001

Back to ⬆ Volume 14 Issue 2

Nanoelectromechanical systems face the future

A host of novel applications and new physics could be unleashed as microelectromechanical systems shrink towards the nanoscale.

Author:
Michael Roukes

Further Reading

In the late 1950s visionary physicist Richard Feynman issued a public challenge by offering $1000 to the first person to create an electrical motor "smaller than 1/64th of an inch". Much to Feynman's consternation the young man who met this challenge, William McLellan, did so by investing many tedious and painstaking hours building the device by hand using tweezers and a microscope (figure 1).

Figure 1

McLellan's motor now sits in a display case at the California Institute of Technology and has long since ceased to spin. Meanwhile, in the field that Feynman hoped to incite, the wheels are turning - both figuratively and literally - in many university and corporate laboratories, and even on industrial production lines. Indeed, the field of microelectromechanical systems (MEMS), which became firmly established in the mid-1980s, has now matured to the point where we can be rather blasé about the mass production of diminutive motors that are hundreds of times smaller than McLellan's original. Along the way the MEMS community has developed some truly intriguing products - from digital projectors that contain millions of electrically driven micromirrors to microscale motion sensors that sit in cars ready to deploy airbags (figure 2).

Figure 2

A whole new realm of interconnected microsensors and instruments is emerging from the minds and laboratories of the scientists and engineers engaged in this research. Their devices are being assigned to a myriad of remote outposts, from the depths of the sea and the Earth's crust, to the far-flung regions of space and distant planets. Moreover, the robustness and low cost of such remote microsensors are helping to provide an avalanche of information about our physical surroundings.

MEMS represent the marriage of semiconductor processing to mechanical engineering - at a very small scale. And it is a field that has grown enormously during the past decade. Numerous companies - from the semiconductor giants to fledgling start-ups - are all now scrambling for a piece of the action at the microscale. Yet very little has been done with MEMS at sizes below one micrometre. This stands in striking contrast to the recent developments in mainstream microelectronics where

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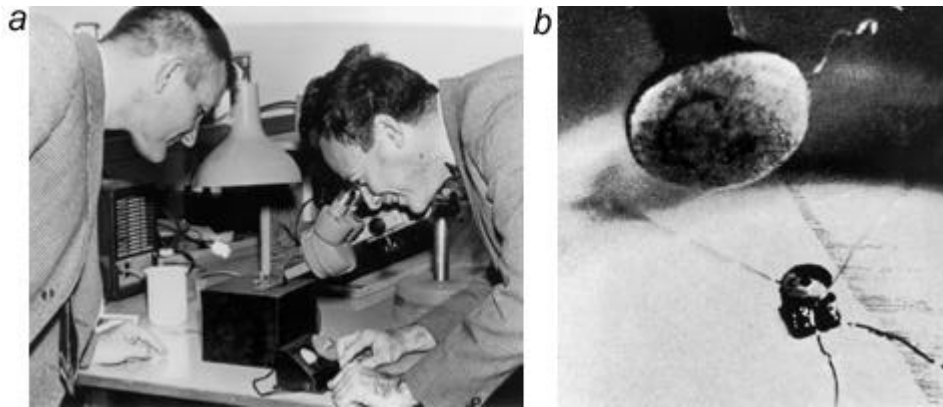
Features: February 2001
Feynman's challenge

Figure 1. (a) Richard Feynman viewing the micromotor built by William McLellan (left) who won the challenge to build the first motor smaller than 1/64th of an inch. (b) The motor, 3.81 mm wide, photographed under an optical microscope. The huge object above it is the head of a pin. (Picture credit: Caltech Archives)

Back to ⬤ Article

PhysicsWeb

News
Physics World
Buyer's Guide
Reviews
Web links
Calendar
PhysicsJobs
TIPTOP
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Features: February 2001
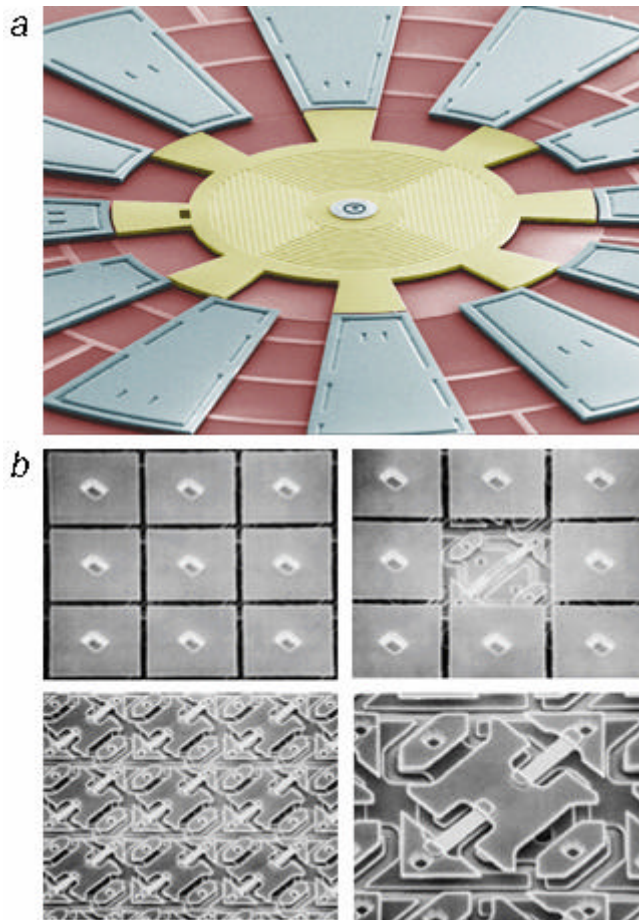
A wealth of applications

Figure 2. Micromachining now enables a huge variety of micromechanical devices to be mass- produced. (a) A MEMS electrostatic micromotor fabricated from silicon. (b) The individual mechanical micromirrors at the heart of the Texas Instruments Digital Light Processor. (Picture credit: Texas Instruments, M Mehregany/Case Western Reserve University)

Back to ⬢ Article

chips are now mass-produced with features as small as 0.18 microns. Indeed, SEMATECH - a think-tank for a consortia of semiconductor companies in the US - predicts that the minimum feature size will shrink to 70 nm by 2010.

In the face of these achievements, and the advances they are expected to bring to mainstream electronics, the time is ripe for a concerted exploration of nanoelectromechanical systems (NEMS) - i.e. machines, sensors, computers and electronics that are on the nanoscale. Such efforts are under way in my group at Caltech, and in several others around the world. The potential payoffs are likely to be enormous and could benefit a diverse range of fields, from medicine and biotechnology to the foundations of quantum mechanics. In this article I highlight a few of the most exciting promises of NEMS, and the challenges that must be faced to attain them.

## What is an electromechanical system?

One of the earliest reported electromechanical devices was built in 1785 by Charles-Augustin de Coulomb to measure electrical charge. His electrical torsion balance consisted of two spherical metal balls - one of which was fixed, the other attached to a moving rod - that acted as capacitor plates, converting a difference in charge between them to an attractive force. The device illustrates the two principal components common to most electromechanical systems irrespective of scale: a mechanical element and transducers.

The mechanical element either deflects or vibrates in response to an applied force. To measure quasi-static forces, the element typically has a weak spring constant so that a small force can deflect it by a large amount. Time-varying forces are best measured using low-loss mechanical resonators that have a large response to oscillating signals with small amplitudes.

Many different types of mechanical elements can be used to sense static or time-varying forces. These include the torsion balance (used by Coulomb), the cantilever (now ubiquitous in scanning probe microscopy) and the "doubly clamped" beam, which is fixed at both ends. In pursuit of ultrahigh sensitivity, even more intricate devices are used, such as compound resonant structures that possess complicated transverse, torsional or longitudinal modes of vibration. These complicated modes can be used to minimize vibrational losses, in much the same way that the handle of a tuning fork is positioned carefully to reduce losses.

The transducers in MEMS and NEMS convert mechanical energy into electrical or optical signals and vice versa. However, in some cases the input transducer simply keeps the mechanical element vibrating steadily while its characteristics are monitored as the system is perturbed. In this case such perturbations, rather than the input signal itself, are precisely the signals we wish to measure. They might include pressure variations that affect the mechanical damping of the device, the presence of chemical adsorbates that alter the mass of the nanoscale resonator, or temperature changes that can modify its elasticity or internal strain. In these last two cases, the net effect is to change the frequency of vibration.

In general, the output of an electromechanical device is the movement of the mechanical element. There are two main types of response: the element can simply deflect under the applied force or its amplitude of oscillation can change (figure 3). Detecting either type of response requires an output or readout transducer, which is often distinct from the input one. In Coulomb's case, the readout transducer was "optical" - he simply used his eyes to record a deflection. Today mechanical devices contain transducers that are based on a host of physical mechanisms involving piezoelectric and magnetomotive effects, nanomagnets and electron tunnelling, as well as electrostatics and optics.
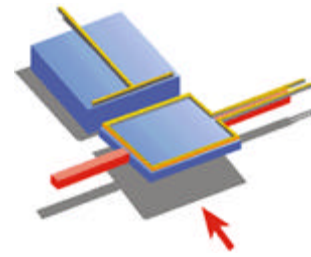
Figure 3

The benefits of nanomachines
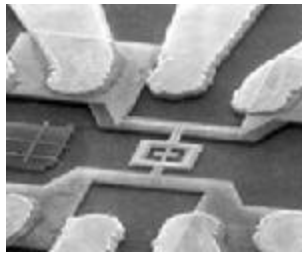
Figure 4

Nanomechanical devices promise to revolutionize measurements of extremely small displacements and extremely weak forces, particularly at the molecular scale. Indeed with surface and bulk nanomachining techniques, NEMS can now be built with masses approaching a few attograms (10^{-18} g) and with cross-sections of about 10 nm (figure 4). The small mass and size of NEMS gives them a number of unique attributes that offer immense potential for new applications and fundamental measurements.

Mechanical systems vibrate at a natural angular frequency, w_0, that can be approximated by $w_0 = (k_{eff}/m_{eff})^{1/2}$, where k_{eff} is an effective spring constant and m_{eff} is an effective mass. (Underlying these simplified "effective" terms is a complex set of elasticity equations that govern the mechanical response of these objects.) If we reduce the size of the mechanical device while preserving its overall shape, then the fundamental frequency, w_0, increases as the linear dimension, l, decreases.

Underlying this behaviour is the fact that the effective mass is proportional to l^3, while the effective spring constant is proportional to l. This is important because a high response frequency translates directly to a fast response time to applied forces. It also means that a fast response can be achieved without the expense of making stiff structures.

Resonators with fundamental frequencies above 10 GHz (10^{10} Hz) can now be built using surface nanomachining processes involving state-of-the-art nanolithography at the 10 nm scale (see box). Such high-frequency mechanical devices are unprecedented and open up many new and exciting possibilities. Among these are ultralow-power mechanical signal processing at microwave frequencies and new types of fast scanning probe microscopes that could be used in fundamental research or perhaps even as the basis of new forms of mechanical computers.

A second important attribute of NEMS is that they dissipate very little energy, a feature that is characterized by the high quality or Q factor of resonance. As a result, NEMS are extremely sensitive to external damping mechanisms, which is crucial for building many types of sensors. In addition, the thermomechanical noise, which is analogous to Johnson noise in electrical resistors, is inversely proportional to Q. High Q values are therefore an important attribute for both resonant and deflection sensors, suppressing random mechanical fluctuations and thus making these devices highly

sensitive to applied forces. Indeed, this sensitivity appears destined to reach the quantum limit.

Typically, high-frequency electrical resonators have Q values less than several hundred, but even the first high-frequency mechanical device built in 1994 by Andrew Cleland at Caltech was 100 times better. Such high quality factors are significant for potential applications in signal processing.

The small effective mass of the vibrating part of the device - or the small moment of inertia for torsional devices - has another important consequence. It gives NEMS an astoundingly high sensitivity to additional masses - clearly a valuable attribute for a wide range of sensing applications. Recent work by Kamil Ekinci at Caltech supports the prediction that the most sensitive devices we can currently fabricate are measurably affected by small numbers of atoms being adsorbed on the surface of the device.

Meanwhile, the small size of NEMS also implies that they have a highly localized spatial response. Moreover, the geometry of a NEMS device can be tailored so that the vibrating element reacts only to external forces in a specific direction. This flexibility is extremely useful for designing new types of scanning probe microscopes.

NEMS are also intrinsically ultralow-power devices. Their fundamental power scale is defined by the thermal energy divided by the response time, set by Q/w_o. At 300 K, NEMS are only overwhelmed by thermal fluctuations when they are operated at the attowatt (10^{-18} W) level. Thus driving a NEMS device at the picowatt (10^{-12} W) scale provides signal-to-noise ratios of up to 10^6. Even if a million such devices were operated simultaneously in a NEMS signal processor, the total power dissipated by the entire system would still only be about a microwatt. This is three or four orders of magnitude less than the power consumed by conventional electronic processors that operate by shuttling packets of electronic charge rather than relying on mechanical elements.

Another advantage of MEMS and NEMS is that they can be fabricated from silicon, gallium arsenide and indium arsenide - the cornerstones of the electronics industry - or other compatible materials. As a result, any auxiliary electronic components, such as transducers and transistors, can be fabricated on the same chip as the mechanical elements. Patterning NEMS so that all the main internal components are on the same chip means that the circuits can be immensely complex. It also completely circumvents the insurmountable problem of aligning different components at the nanometre scale.

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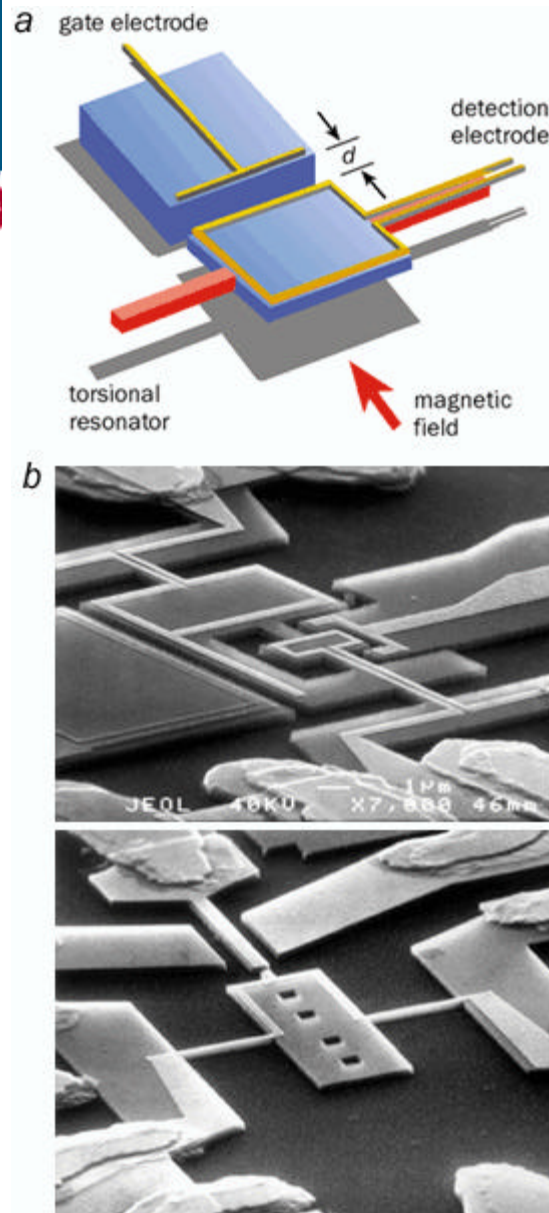
NEMS in action

Figure 3. (a) At the heart of the electrometer is a mechanical resonator made of silicon-on-insulator that rotates when a radio-frequency current is passed through the loop-shaped gold electrode in the presence of a strong magnetic field. The resulting torsional motion generates an electric field that is measured by the detection electrode. When a charge is placed on the gate electrode, the resulting electric field

alters the frequency with which the resonator rotates. (b) First- and second-generation mechanical electrometers built at Caltech. (Picture credit: A N Cleland/Caltech, E A Henriksen/Caltech)

Back to ⬤ Article

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News
Physics World
Buyer's Guide
Reviews
Web links
Calendar
PhysicsJobs
TIPTOP
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Features: February 2001
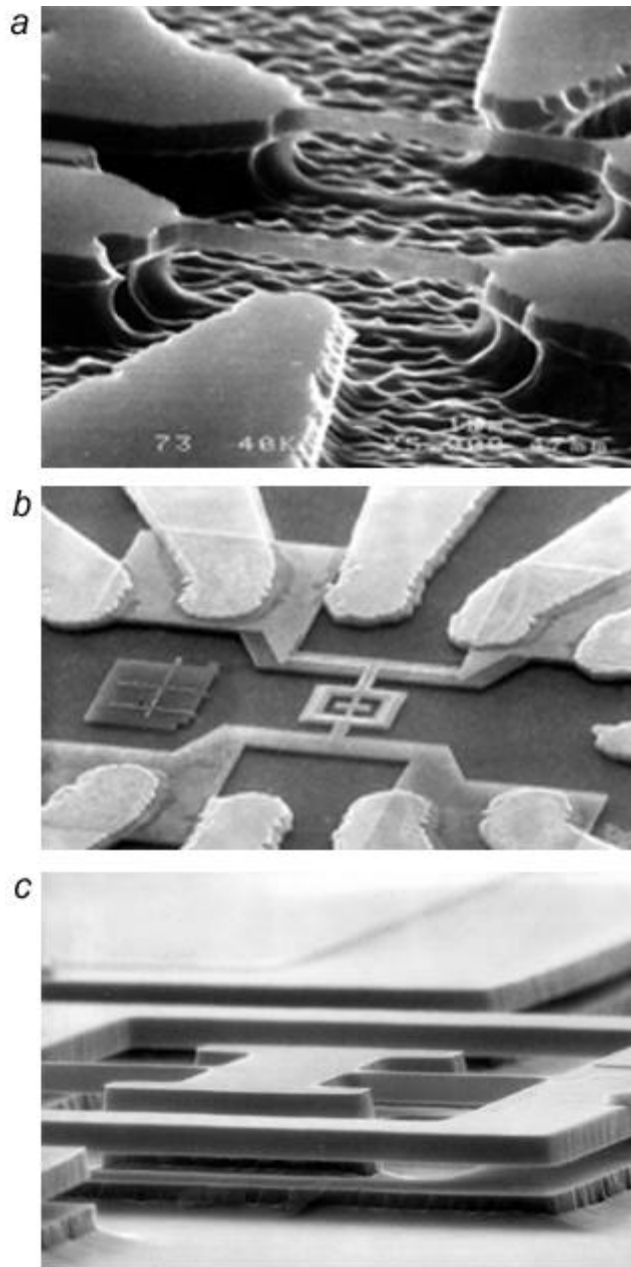# Clean lines in semiconductors

Figure 4. Continued improvements in nanofabrication processes have led to progressively more ideal structures. (a) An early (and rather rough) doubly clamped beam "carved" from a silicon wafer. (b) A compound torsional resonator made from silicon-on-insulator, and (c) a "clean" example made from gallium arsenide that is

used to measure minute forces at high frequencies. (Picture credit: A N Cleland/Caltech, A N Cleland/Caltech, M J Murphy and D A Harrington/Caltech)

Back to ⬢ Article

How to make MEMS and NEMS
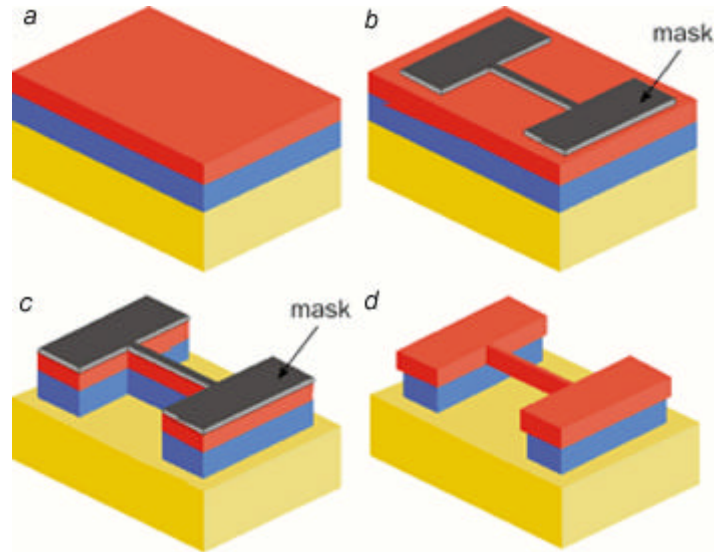
Over the past six years, at my lab and elsewhere, new techniques have been developed for patterning freely suspended 3-D semiconductor structures. These techniques apply to bulk silicon, epitaxial silicon and silicon-on-insulator heterostructures, as well as to systems based on gallium arsenide and indium arsenide.

(a) In its simplest form, the procedure begins with a heterostructure that contains structural (red) and sacrificial layers (blue) on a substrate (yellow). (b) Masks on top of this substrate are patterned by a combination of optical and electron-beam lithography, followed by a thin-film deposition processes. The resulting mask (black) protects the material beneath it during the next stage. (c) Unprotected material around the mask is then etched away using a plasma process. (d) Finally, a local chemically selective etch step removes the sacrificial layer from specific regions to create freely suspended nanostructures that are both thermally and mechanically isolated.

In typical devices this entire procedure might be repeated several times and combined with various deposition processes to give complicated mechanical nanostructures. The flexibility of the process allows complex suspended structures with lateral dimensions down to a few tens of nanometres to be fabricated. Moreover, complex transducers can be incorporated for control and measurement purposes. Epitaxial growth means that the thickness of the layers can be controlled with atomic precision. In principle, the fabricated devices can be just a few layers thick.

Challenges for NEMS

Processes such as electron-beam lithography and nanomachining now enable semiconductor nanostructures to be fabricated below 10 nm. It would appear that the technology exists to build NEMS. So what is holding up applications? It turns out that there are three principal challenges that must be addressed before the full potential of NEMS can be realized: communicating signals from the nanoscale to the macroscopic world; understanding and controlling mesoscopic mechanics; and developing methods for reproducible and routine nanofabrication.

NEMS are clearly very small devices that can deflect or vibrate within an even smaller range during operation. For example, the deflection of a doubly clamped beam varies linearly with an applied force only if it is displaced by an amount that typically corresponds to a few per cent of its thickness. For a beam 10 nm in diameter, this translates to displacements that are only a fraction of a nanometre. Building transducers that are sensitive enough to allow information to be transferred accurately at this scale requires reading out positions with a far greater precision. A further difficulty is that the natural frequency of this motion increases with decreasing size. So the ideal NEMS transducer must ultimately be capable of resolving displacements in the 10^{-15}-10^{-12} m range and be able to do so up to frequencies of a few gigahertz. These two requirements are truly daunting, and much more challenging than those faced by the MEMS community so far.

To compound the problem, some of the transducers that are mainstays of the micromechanical realm are not applicable in the nanoworld. Electrostatic transduction, the staple of MEMS, does not scale well into the domain of NEMS. Nanoscale electrodes have capacitances of about 10^{-18} farad and less. As a result, the many other, unavoidable parasitic impedances tend to dominate the "dynamic" capacitance that is altered by the device motion.

Meanwhile optical methods, such as simple beam-deflection schemes or more sophisticated optical and fibre-optic interferometry - both commonly used in scanning probe microscopy to detect the deflection of the probe - generally fail beyond the so-called diffraction limit. In other words, these methods cannot easily be applied to objects with cross-sections much smaller than the wavelength of light. For fibre-optic interferometry, this breakdown can occur even earlier, when devices are shrunk to a fraction of the diameter of the fibre.

Conventional approaches thus appear to hold little promise for high-efficiency transduction with the smallest of NEMS devices. Nonetheless, there are a host of intriguing new concepts in the pipeline. These include techniques that are based on integrated near-field optics, nanoscale magnets, high-electron-mobility transistors, superconducting quantum interference devices and single-electron transistors - to name just a few. Discussion of these topics is, unfortunately, beyond the scope of this article (see Roukes in further reading).

The role of surface physics

One of the keys to realizing the potential of NEMS is to achieve ultrahigh quality factors. This overarching theme underlies most areas of research, with the possible exception of non-resonant applications. However, both intrinsic and extrinsic properties limit the quality factor in real devices. Defects in the bulk material and interfaces, fabrication-induced surface damage and adsorbates on the surfaces are among the intrinsic features that can dampen the motion of a resonator.

Fortunately, many of these effects can be suppressed through a careful choice of materials, processing and device geometry. Extrinsic effects - such as air resistance, clamping losses at the supports and electrical losses mediated through the transducers - can all be reduced by careful engineering. However, certain loss mechanisms are fundamental and ultimately limit the maximum attainable quality factors. These processes include thermoelastic damping that arises from inelastic losses in the material.

One aspect in particular looms large: as we shrink MEMS towards the domain of NEMS, the device physics becomes increasingly dominated by the surfaces. We would expect that extremely small mechanical devices made from single crystals and

ultrahig-purity heterostructures would contain very few defects, so that energy losses in the bulk are suppressed and high quality factors should be possible.

For example, Robert Pohl's group at Cornell University, and others, has shown that centimetre-scale semiconductor MEMS can have Q factors as high as 100 million at cryogenic temperatures. But my group at Caltech has shown repeatedly over the past seven years that this value decreases significantly - by a factor of between 1000 and 10 000 - as the devices are shrunk to the nanometre scale. The reasons for this decrease are not clear at present. However, the greatly increased surface-to-volume ratio in NEMS, together with the non-optimized surface properties, is the most likely explanation.

Figure 5

This can be illustrated by considering a NEMS device fabricated using state-of-the-art electron-beam lithography. A silicon beam 100 nm long, 10 nm wide and 10 nm thick contains only about 5×10^5 atoms, with some 3×10^4 of these atoms residing at the surface. In other words, more than 10% of the constituents are surface or near-surface atoms. It is clear that these surface atoms play a central role, but understanding exactly how will take considerable effort. My group and others - at IBM's Almaden Research Center, Stanford University, the University of California at Santa Barbara and Cornell University, all in the US, together with Ludwig-Maximilians University in Munich, Germany - are currently exploring this crucial issue (figure 5).

Ultimately, as devices become ever smaller, macroscopic mechanics will break down and atomistic behaviour will emerge. Indeed, molecular dynamics simulations, such as those performed by Robert Rudd and Jeremy Broughton at the Naval Research Laboratory in Washington DC on idealized structures just a few tens of atoms thick, would appear to support this idea.

Back to ● Volume 14 Issue 2

Page ○ 1 ● of 2
Article ● 8 ● of 10

PhysicsWeb

News
Physics World
Buyer's Guide
Reviews
Web links
Calendar
PhysicsJobs
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Features: February 2001
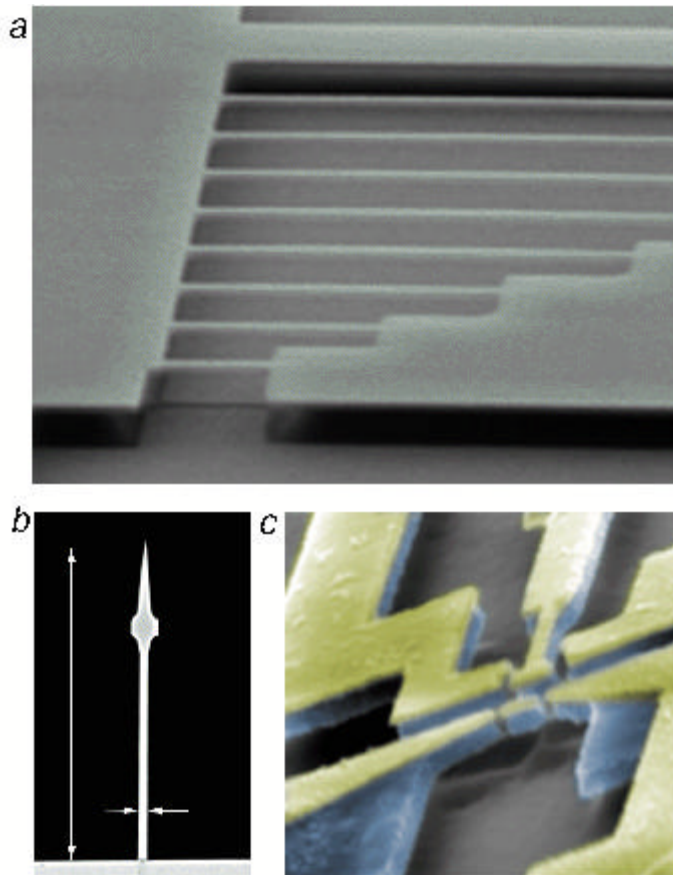
Suspended NEMS devices

Figure 5. (a) A series of parallel silicon beams fabricated by Harold Craighead and co-workers at Cornell University. Each beam resonates at a slightly different frequency. The highest frequency measured in an individual beam of this type is 380 MHz. (b) An ultrathin cantilever - width 5 μm and height 260 μm - developed by a collaboration between researchers at Stanford University and IBM's Almaden Research Center. The deflection of such a cantilever has been used to measure forces at the attonewton (10^{-18} N) scale. (c) A device built at Ludwigs-Maximilians University that is used to shuttle individual electron charges between electrodes. (Picture credit: H Craighead/Cornell University, R Blick/LMU, T Kenny/Stanford University and D Rugar/IBM260)

Back to ⬢ Article

PhysicsWeb

| Home | Search | Register | Login |

PhysicsWorld

: February 2001

Back to ⬤ Volume 14 Issue 2

Nanoelectromechanical systems face the future (page 2)

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Further Reading

Towards routine manufacture at the nanoscale

NEMS must overcome a final important hurdle before nanoscale machines, sensors and electronics emerge from industrial production lines. Put simply, when we combine state-of-the-art processes from two disparate fields - nanolithography and MEMS micromachining - we increase the chances that something will go awry during manufacturing. Fortunately, sustained and careful work is beginning to solve these problems and is revealing the way to build robust, reliable NEMS. Given the remarkable success of microelectronics, it seems clear that such current troubles will ultimately become only of historical significance.

But there is a special class of difficulties unique to NEMS that cannot be so easily dismissed. NEMS can respond to masses approaching the level of single atoms or molecules. However, this sensitivity is a double-edged sword. On the one hand it offers major advances in mass spectrometry; but it can also make device reproducibility troublesome, even elusive. For example, at Caltech we have found that it places extremely stringent requirements on the cleanliness and precision of nanofabrication techniques.

Some applications of NEMS

Ultimately, NEMS could be used across a broad range of applications. At Caltech we have used NEMS for metrology and fundamental science, detecting charges by mechanical methods and in thermal transport studies on the nanoscale (see Schwab _et al._ in further reading). In addition, a number of NEMS applications are being pursued that might hold immense technological promise.

In my opinion, most prominent among these is magnetic resonance force microscopy (MRFM). Nuclear magnetic resonance was first observed in 1946 by Edward Purcell, Felix Bloch and their collaborators, and is now routinely used for medical imaging. The technique exploits the fact that most nuclei have an intrinsic magnetic moment or "spin" that can interact with an applied magnetic field. However, it takes about 10^{14}-10^{16} nuclei to generate a measurable signal. This limits the resolution that can be attained in state-of-the-art magnetic resonance imaging (MRI) research laboratories to about 10 μm. Meanwhile, the typical resolution achievable in hospitals is about 1 mm.

One would assume then that the detection of individual atoms using MRI is only a distant dream. However, in 1991 John Sidles of the University of Washington at

Seattle proposed that mechanical detection methods could lead to nuclear magnetic resonance spectrometry that would be sensitive to the spin of a single proton. Achieving this degree of sensitivity would be a truly revolutionary advance, allowing, for example, individual biomolecules to be imaged with atomic-scale resolution in three dimensions.

Magnetic resonance force microscopy (MRFM) could thus have an enormous impact on many fields, ranging from molecular biology to materials science. The technique was first demonstrated in 1992 by Dan Rugar and co-workers at IBM's Almaden Research Center, and was later confirmed by Chris Hammel at the Los Alamos National Lab in collaboration with my group at Caltech, and others.

Like conventional magnetic resonance, MRFM uses a uniform radio-frequency field to excite the spins into resonance. A nanomagnet provides a magnetic field that varies so strongly in space that the nuclear-resonance condition is satisfied only within a small volume, which is about the size of atom. This magnet also interacts with the resonant nuclear spins to generate a tiny "back action" force that causes the cantilever on which the nanomagnet is mounted to vibrate. For a single resonant nucleus, the size of this force is a few attonewtons (10^{-18} N) at the most. Nonetheless, Thomas Kenny's group at Stanford, in collaboration with Rugar's group at IBM, has demonstrated that such minute forces are measurable.

By scanning the tip over a surface, a 3-D map of the relative positions of resonating atoms can be created. Although Rugar and co-workers detected a signal from some 10^{13} protons in their early experiments, the sensitivity still exceeded that of conventional MRI methods.

In another area of research, Clark Nguyen and co-workers at the University of Michigan are beginning to demonstrate completely mechanical components for processing radio-frequency signals.

With the advent of NEMS, several groups are investigating fast logic gates, switches and even computers that are entirely mechanical. The idea is not new. Charles Babbage designed the first mechanical computer in the 1820s, which is viewed as the forerunner to the modern computer. His ideas were abandoned in the 1960s when the speed of nanosecond electronic logic gates and integrated circuits vastly outperformed moving elements. But now that NEMS can move on timescales of a nanosecond or less, the established dogma of the digital electronic age needs careful re-examination.

To the quantum limit - and beyond

The ultimate limit for nanomechanical devices is operation at, or even beyond, the quantum limit. One of the most intriguing aspects of current nanomechanical devices is that they are already on the verge of this limit. The key to determining whether NEMS are in this domain is the relationship between the thermal energy, $k_B T$, and the quantity hf_0, where k_B is the Boltzmann constant, h is the Planck constant, f_0 is the fundamental frequency of the mechanical resonator and T is its temperature.

When the temperature of the device is low and its frequency is sufficiently high that hf_0 greatly exceeds $k_B T$, then any thermal fluctuations will be smaller than the intrinsic quantum noise that affects the lowest vibrational mode. In this limit, the mean square amplitude of the vibration can be quantized and can only assume values that are integral multiples of $hf_0 Q/2k_{eff}$. A full exploration of this quantum domain must

wait for crucial technological advances in ultrasensitive transducers for NEMS that will enable us to measure tiny displacements at microwave frequencies.

In spite of this significant challenge, we should begin to see signs of quantum phenomena in nanomechanical systems in the near future. Even the first NEMS resonators produced back in 1994 operated at sufficiently high frequencies that, if cooled to 100 mK, only about 20 vibrational quanta would be excited in the lowest fundamental mode. Such temperatures are readily reached using a helium dilution refrigerator. So the question that comes to mind is whether quantized amplitude jumps can be observed in a nanoscale resonating device? If so, one should be able to observe discrete transitions as the system exchanges quanta with the outside world. At this point, the answer to the question seems to be that such jumps should be observable if two important criteria can be met.

The first is that the resonator must be in a state with a definite quantum number. In general, transducers measure the position of the resonator, rather than the position squared. The continual interaction between such a "linear transducer" and the quantum system prevents the resonator from being in a state characterized by a discrete number of quanta. Transducers that measure the position squared were discussed in 1980 by Carlton Caves, now at the University of New Mexico, and co-workers at Caltech in a pioneering paper on quantum measurements with mechanical systems (see Caves in further reading). And it now seems possible to transfer their ideas to NEMS.

The second criterion is more problematic. The transducer must be sensitive enough to resolve a single quantum jump. Again, ultrahigh sensitivity to displacements is the key needed to unlock the door to this quantum domain. A simple estimate shows that we must detect changes in the mean square displacement as small as 10^{-27} m^2 to observe such quantum phenomena. Is it possible to achieve this level of sensitivity? My group at Caltech has recently made significant progress towards new ultra-sensitive transducers for high-frequency NEMS - and we are currently only a factor of 100 or so away from such sensitivity.

In related work, last year Keith Schwab, Eric Henriksen, John Worlock and I investigated the quantum limit, where $hf_0 >> kT$, for the first time in thermal-transport experiments using nanoscale beams fabricated from silicon nitride (figure 6). As the smallest features on the devices are scaled down in size, the energy spacing between the phonons - the quanta of vibrational energy - increases. When the temperature is lowered, fewer and

Figure 6

fewer of these modes of vibration (or phonons) remain energetically accessible. Effectively, this means that most of them cannot participate in thermal transport. Indeed, in a beam that is small enough, only four phonon modes can transport energy between the system and its surroundings.
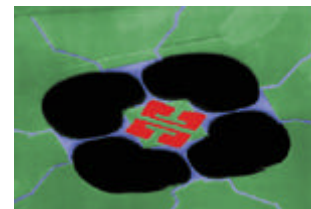
We found that the thermal conductance in this regime becomes quantized. In other words, each phonon mode that transports energy can only provide a maximum thermal conductance given by $\frac{1}{4}k^2 T/6h$. Quantum mechanics thus places an upper limit on the rate at which energy can be dissipated in small devices by vibrations.

In spite of the complications encountered at the quantum level, the rewards in terms of intriguing physics will be truly significant. Force and displacement measurements at this limit will open new horizons in science at the molecular level, new devices for quantum computation, and the possibility of being able to control the thermal transport by individual phonons between nanomechanical systems or between a

system and its environment.

Once we have passed into this realm of quantum mechanics, the division between quantum optics and solid-state physics becomes increasingly blurred. Many of the same physical principles governing the manipulation of light at the level of individual photons will come into play for both the mechanical and thermal properties of nanoscale systems.

Future outlook

NEMS offer unprecedented and intriguing opportunities for sensing and fundamental measurements. Both novel applications and fascinating physics will undoubtedly emerge from this new field, including single-spin magnetic resonance and phonon counting using mechanical devices. To take full advantage of these systems we will have to stretch our imaginations, as well as our current methods and "mindsets" in micro- and nanoscale science and technology.

But there remains a gap between today's NEMS devices that are sculpted from bulk materials and those that will ultimately be built atom by atom. In the future, complex molecular-scale mechanical devices will be mass-produced by placing millions of atoms with exquisite precision or by some form of controlled self-assembly. This will be true nanotechnology. Nature has already mastered such remarkable feats of atomic assembly, forming molecular motors and machinery that can transport biochemicals within cells or move entire cells.

Clearly, for us to attain such levels of control and replication will take sustained effort, involving a host of laboratories. Meanwhile, in the shorter term, NEMS are clearly destined to provide much of the crucial scientific and engineering foundation that will underlie future nanotechnology.

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Back to ⬤ Volume 14 Issue 2

Page ⬤ 2 ○ of 2
Article ⬤ 8 ⬤ of 10

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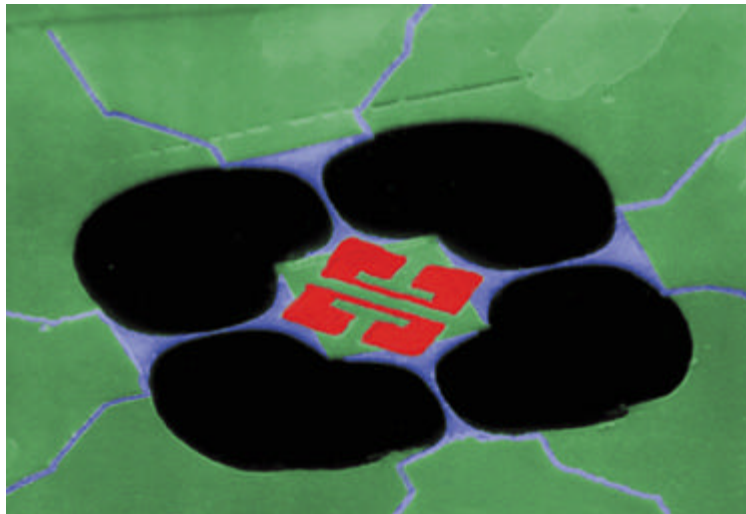: February 2001

NEMS meet quantum mechanics

Figure 6. A suspended mesoscopic thermal transport devices that recently enabled the first measurement of the quantum of thermal conductance. The device is surrounded by thin phonon waveguides and consists of a thin silicon-nitride membrane at the centre that is supported by the thin phonon waveguides. (Picture credit: K Schwab, EA Henriksen/Caltech)

Back to ⬣ Article