Nanoelectromechanical Systems

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Nanoelectromechanical systems are evolving, with new scientific studies and technical applications emerging. Mechanical devices are shrinking in thickness and width to reduce mass, increase resonant frequency, and lower the force constants of these systems. Advances in the field include improvements in fabrication processes and new methods for actuating and detecting motion at the nanoscale. Lithographic approaches are capable of creating freestanding objects in silicon and other materials, with thickness and lateral dimensions down to about 20 nanometers. Similar processes can make channels or pores of comparable dimensions, approaching the molecular scale. This allows access to a new experimental regime and suggests new applications in sensing and molecular interactions.

Microelectromechanical systems (MEMS) have been studied for decades (*1, 2*), with interest increasing recently because of growing commercial applications. Arrays of micromechanical mirrors for optical crossbar switches, for example, recently caused a stir in the optical communications industry. Figure 1 shows an array of state-of-the-art tilting mirrors from Lucent Technologies, where the diameter of the mirrors is ~0.4 mm (*3*). Similar technologies have been used in projection displays with an array of metal mirrors used to modulate light beams (*4*). Ink-jet printers, using control of fluid jets, represent a major use of micromachined integrated electromechanical systems (*5*). Accelerometers, used as sensors for deploying automobile air bags, are also in wide use (*6*), and a range of MEMS sensors and actuators are in various stages of development (*7*). Many of the devices in practical use today are made with silicon-based fabrication technology, because of the well-developed methods created for use by the microelectronics industry. Typical dimensions of MEMS devices are in the several micrometers to hundreds of micrometers range. The importance of MEMS technology is not so much the size, but rather the use of planar processing technologies, related to those used in the fabrication of electronic integrated circuits, to simultaneously "machine" large numbers of relatively simple mechanical devices in an integrated fashion.

Nanoelectromechanical systems, or NEMS, are characterized by small dimensions, where the dimensions are relevant for the function of the devices. Critical feature sizes may be from hundreds to a few nanometers. New physical properties, resulting from the small dimensions, may dominate the operation of the devices, and new fabrication approaches may be required to make them. Microelectronics fabrication technologies are driving relentlessly to manufacture smaller transistors packed with increasing density on integrated circuit chips. The economic driving forces for this miniaturization are strong and have driven transistor minimum feature sizes down to the 100-nm regime [see, for example, (*8*)]. The miniaturization of commercial electronics has been taking place with an allied physics-motivated study of electron transport and magnetic properties of mesoscopic and nanoscale devices. The nanoscale studies often involve a wider range of materials and higher spatial resolution fabrication processes than the silicon microelectronics processes. Similar advanced fabrication processes can be exploited to further miniaturize electromechanical systems to bring us into the regime of NEMS. The new class of NEMS devices may provide a revolution in applications such as sensors, medical diagnostics, displays, and data storage. NEMS devices will enable experiments on the structure and function of individual bimolecules. The initial research in science and technology related to nanomechanical systems is taking place now in a growing number of laboratories throughout the world.

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Freestanding Nanostructures

One class of NEMS devices consists of freestanding or suspended mechanical objects in the tens of nanometers range. These devices can be fabricated by a combination of electron beam lithography and etching to remove the material beneath the lithographically fabricated object. Kwong and others, for example, fabricated freestanding metal wires with widths down to 50 nm (*9*). This approach was used to isolate thin metal wires from bulk phonons associated with the substrate. Creating a two-dimensional pattern in a thin film and undercutting it to make a released structure has come to be known as "surface micromachining" (*10*). Surface micromachining primarily has been used with silicon-related materials and larger structures. It is the combination of this machining approach with high-resolution lithography that creates a basic method of NEMS fabrication. A schematic of this type of fabrication process is shown in Fig. 2. The pattern is defined by a scanned focused beam of electrons that is driven under computer control to trace a desired pattern over the surface. The standard lithographic approach uses ultraviolet light to expose a resist layer, but diffraction limits the resolution of this process. Electron beams with energies in the keV range are not limited by diffraction. The electrons alter the chemical character of the resist layer that is typically a thin polymer formed on the surface by a spinning process (*11*). The chemically modified resist is selectively dissolved to create a polymer template for etching, or another form of transfer, of the pattern into the substrate (*12, 13*). The regions under the structures that are to be released can be either defined by another lithography step or undercut by an isotropic etch that is timed to release only the thin isolated features. In most cases, the nanomechanical devices remain attached to a larger support attached to the substrate, but the same approach can be used to fabricate completely released free-floating structures. A related micromachining approach with electron beam lithography to create movable mechanical systems has been used with bulk single-crystal silicon wafers (*14*). The electron beam approach is flexible because the beam can be scanned in any desired pattern to create objects of nearly any connected two-dimensional pattern.

Scanning electron micrographs of several structures made by the approach described above are shown in Fig. 3. Figure 3, A and B, shows tilting mirrors where the mirror width is ~2 μm, with the supporting wires as small as 50 nm in width (*15*). These are ~200 times smaller than the MEMS mirrors shown in Fig. 1. The mirrors can be driven in resonance by ac electric fields that stimulate a range of oscillatory modes of the device. The electric fields are created by ac voltage applied across the electrode on the substrate and the electrode on the moving element as

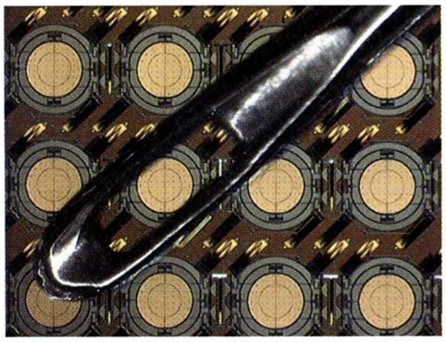


Fig. 1. Optical micrograph of a portion of a Lucent Technologies mirror array, with a sewing needle for scale (*3*).

shown in Fig. 2. Figure 3C shows an array of single-crystal silicon wires of varying length (*16*). The resonant frequency of these wires varies with the length, analogous to a musical instrument. When set in motion by an electric field, the rods will resonate at their eigenfrequencies, where the frequencies in this case are in the radio frequency range. The resonant frequency of a doubly clamped beam is

$$f_0 = \frac{(4.730)^2}{2\pi}\frac{1}{l^2}\sqrt{\frac{EI}{\rho A}} \qquad (1)$$

where l is the length of the beam, ρ is the density, E is Young's modulus, A is the cross-sectional area, and I is the moment of inertia. The ~2-μm wire, for example, has a resonant frequency of ~400 MHz. The same kind of structures can be made of deposited amorphous and polycrystalline materials by similar approaches. Figure 3D shows a mesh structure that forms an oscillating mirror as part of a Fabry-Perot device, where the motion is detected by optical interference changes as the mirror moves (*17*). Because the mesh features are smaller than the wavelength of light, the optical properties of the mesh create an effective refractive index formed by this subwavelength grating. This demonstrates the possibility of designing optical properties of structures by nanofabrication that differ from the bulk properties of the material. Reed and others used a lithographic approach to create fine silicon wires followed by a chemical etch to further reduce the width of the silicon wires (*18*). In this way, they made silicon suspended wires 20 nm in diameter in which they observed shifts in plasmon frequencies as observed by electron energy loss spectroscopy.

Generating Movement in Rigid Nanosystems

For very small structures, both the induction of motion and the detection of motion are challenges. All of the moving devices discussed in the previous paragraph were actuated by applied electric fields and observed by optical interference or angular deflection of a laser beam. This is perhaps the most direct method for actuation and observation of small-scale motion, and it can be used for a variety of experimental devices. Both static displacements and resonant motion can be readily actuated in this way. Other methods can be used to induce and observe nanoscale motion of NEMS. Lorentz forces have been used to drive small conducting beams (*14*), with alternating current passing through a conducting wire in a strong transverse magnetic field to drive motion. The induced electromotive force, or voltage, can be detected as a measure of the motion. This method requires a fully conducting path and works well, for example, with a beam clamped at both ends. Piezoelectric elements and bilayers of differential thermal expansion, mounted on the moveable elements, have been used to actuate MEMS devices. For resonant systems, secondary actuation also works well for nanoscale systems, by using piezoelectric or other actuation to oscillate the supports of resonant NEMS devices. Electron tunneling is a very sensitive method that can detect subnanometer motion by the exponential dependence of the electron tunneling current with the separation between tunneling electrodes (*19*). For widespread commercial applications, miniaturization and integration of the entire system will be desirable.

A new method has been recently demonstrated, which uses a scanning tunneling microscope (STM) as an actuator combined with a scanning electron microscope to detect the motion (*20*). This approach provides capabilities that are important for exploring oscillatory mode structure at a scale much finer than that obtainable by laser Doppler techniques. Electron micrographs of a STM tip and a silicon nitride cantilever are shown in Fig. 4, left. An ac voltage applied to the piezoelectric axial drive of the tip imparts a localized drive to the mechanical system. By observing interaction of the focused electron beam with the moving oscillator, a measure of the motion can be obtained. The STM could also be used to image surface nanostructure and correlate surface structure with mechanical response and losses. This also

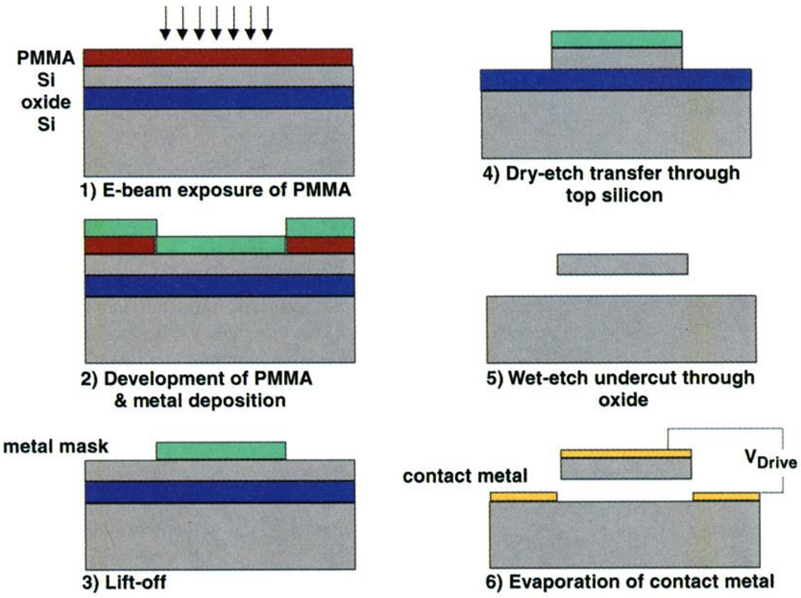


Fig. 2. Schematic of surface micromachining approach used to nanofabricate NEMS devices. The pattern shapes are created by a scanning electron beam (E-beam) exposing a polymeric polymethylmethacrylate (PMMA) resist. The motion may be actuated by applying a voltage (V_{Drive}) between the electron on the moving element and the electrode on the substrate.

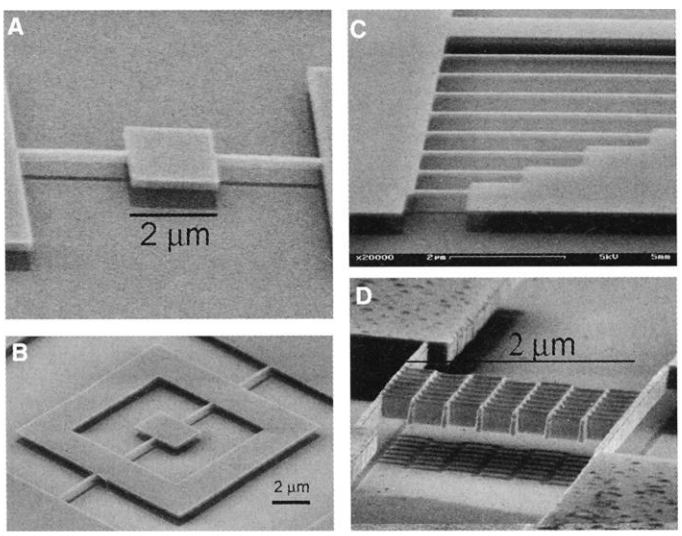


Fig. 3. Electron micrograph of NEMS objects fabricated in single-crystal silicon by using electron beam lithography and surface micromachining. **(A)** A torsional oscillator from (*15*), **(B)** a compound torsional oscillator, **(C)** a series of silicon nanowires from (*16*), and **(D)** an oscillating silicon mesh mirror from (*17*).

could be the basis for making tunable NEMS oscillators.

Smaller mechanical systems allow for the measurement of small forces, and similarly, NEMS systems can be actuated by small forces. The possibility of fabricating engineered structures that can interact and probe material at the molecular level opens exciting possibilities. Scanning probe microscopes such as STMs and atomic force microscopes have entered this regime. NEMS is a more general technology that, in addition to imaging, can be engineered for various uses. The motivations for miniaturizing mechanical systems also include applications such as ultrahigh-density data storage (*21*) or high-frequency device components for wireless communications (*22*). As the device size shrinks, the surfaces become a dominant feature of the objects, and the mechanical dissipation associated with surfaces becomes more important. These issues drive materials-related studies of NEMS systems.

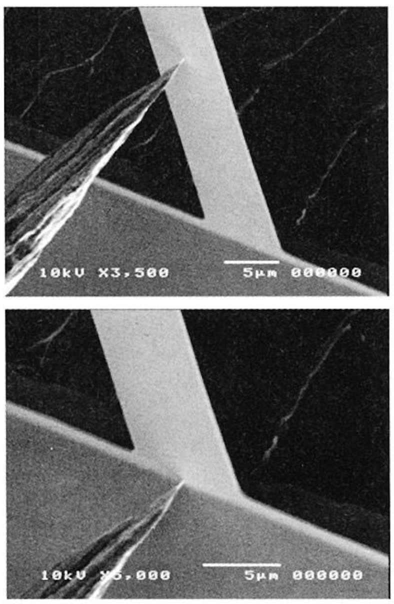
Small and thin mechanical devices can have very small force constants and could in principle be used to detect forces resulting from small magnetic fields. Sidles suggested that mechanical oscillators could be used to directly detect the magnetic forces of a single spin in a magnetic resonance system, potentially creating a molecular resolution magnetic resonance imaging system (*23*). Rugar and others described an experimental system employing a resonant mechanical cantilever to detect the oscillatory magnetic fields of a small (~30 ng) paramagnetic sample (*24*). Cantilevers for detecting magnetic force could be further miniaturized, and research is under way in several laboratories to increase the sensitivity of such experiments (*25*). Biomechanical forces have been measured by arrays of deflecting cantilevers (*26*).

Nanomechanical oscillators can be used for highly sensitive detection of adsorbed mass. The concept of using shift in resonant frequency of macroscopic quartz oscillators to measure mass change is a well-established technology for measuring deposited film thickness. Microfabricated resonant systems functioning in air using electrical or optical readout can detect mass changes on the order of 1 pg (*27, 28*). A bacterium, for example, has a mass of ~1 pg, and its adherence to a cantilever can be detected by the resonance shift of a vibrating cantilever. An electron micrograph of an *Escherichia coli* O157:H7 bacterium on a silicon nitride cantilever is shown in Fig. 5. The cantilever is coated with a layer of antibodies to this bacteria so the binding is specific to this strain of pathogen (*27*). It is apparent that the size of the cell is comparable to the size of the fabricated cantilever. The resonant frequency shift of this single cell can be detected with the cantilever vibrating in air. By creating even smaller vibrating devices of the type described above and by operating in reduced pressure environment, attograms of mass change should be detectable (*27, 28*). This is a clear advantage of reduction in size of the mechanical devices.

Nanomechanical resonant systems can oscillate at high frequencies and can be used as radio frequency devices. A device similar to that shown in Fig. 3A, for example, can operate as a resonator in the 1- to 10-MHz region, with quality factors on the order of 10^3, and exhibit nonlinear mechanical properties even at very small amplitude. The measured and calculated translational response of a simple single-crystal NEMS oscillator is shown in Fig. 6 (*15*). The asymmetric resonant response is a signature of nonlinear terms in the equation of motion of the oscillator. These effects become evident, even at amplitudes as small as 10 to 15 nm. Such behavior can be harnessed to create parametric oscillators and possibly could be used to create highly sensitive resonant force and mass sensors.

Nanofluidics

Many chemical, biological, and biophysical processes and experiments take place in liquid environments. Therefore, a class of NEMS devices of considerable importance is nanofluidic systems, with critical dimensions comparable to relevant length scales in fluid environments. These length scales include diffusion lengths of nanoparticles and molecules, molecular size, and the electrostatic screening lengths of ionic conducting fluids. Microfluidics is now accepted as technologically important for miniaturized chemical processing systems. Micro total analytical systems (μTAS) or "lab-on-a-chip" systems use microfabricated fluid systems primarily to transport liquids in channels on the order of tens to hundreds of micrometers [see, for example, (*29*)]. Nanofluidic systems may have critical dimensions on the order of hundreds to a few nanometers. In addition to hydrostatic pressure, electric fields in ionic conducting fluids can be used to drive and control the flow of liquid or motion of individual molecules. Electroosmotic flow or electrophoretic motion of charged molecules can be controlled by applied electrostatic potentials and controlled channel geometry and surface charge (*30*). Chou and van Oudenaarden and Boxer (*31*) described systems, for example, where structure dimensions are comparable to diffusion lengths of single-molecule systems. In an asymmetric diffusion array device, these groups could dynamically sort molecules by rectification of the size-dependent Brownian motion of the molecules. Han and Craighead were able to sort large DNA molecules by creating structures smaller than the radius of gyration of the molecules (*32–34*). These systems have molecular transport effects imposed by the fabricated dimensions. Exploiting NEMS technology for single-molecule detection, analysis, and utilization should be a unique capability of NEMS systems.



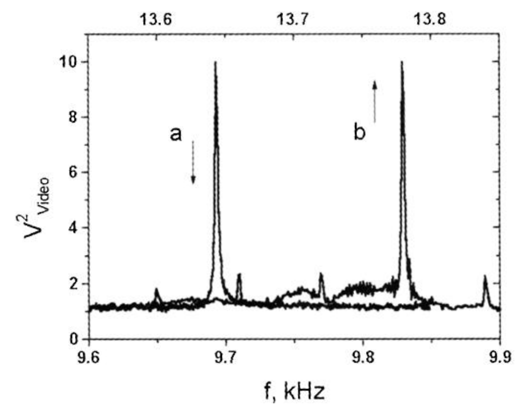


Fig. 4. (**Left**) Scanning electron microscope (SEM) images of a STM actuated cantilever device with the STM tip in two positions [from (*20*)]. The motion of the cantilever is measured by the modulation of the secondary electron current by the moving cantilever. (**Right**) The graph shows the measured resonant response of the cantilever, as a function of driving frequency f plotted as the square of the ac voltage signal from the video (secondary electron) detector of the SEM (V^2_{Video}). Curve a is the response of the cantilever with the STM tip near the base (lower left image), and curve b is the response with the driving STM tip closer to the free end of the cantilever (upper left image).

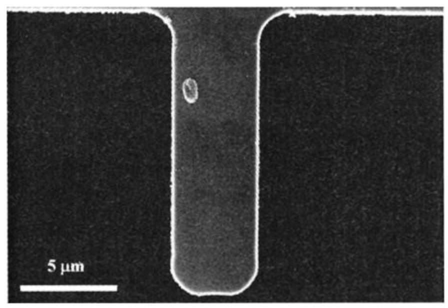


Fig. 5. Scanning electron micrograph of a single *E. coli* bacterium on an antibody-coated silicon nitride cantilever oscillator (*27*).

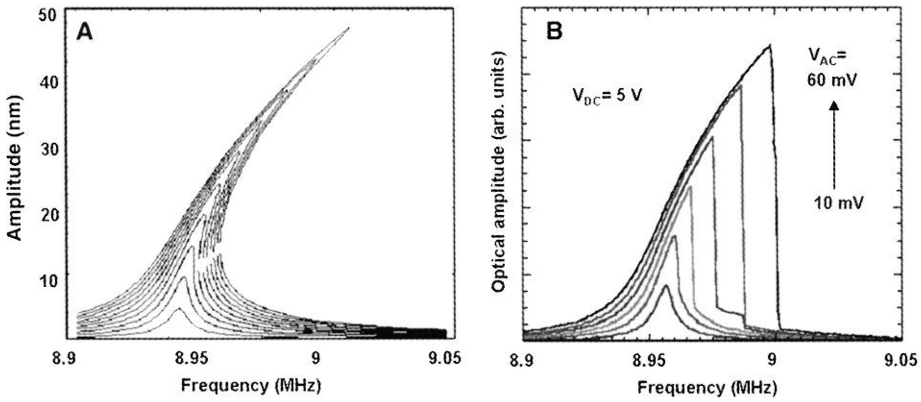


Fig. 6. (**A**) Model and (**B**) experimentally observed translational resonant motion of a NEMS oscillator similar to that in Fig. 3A, where the motion is observed by optical modulation of a laser due to optical interference. The family of curves shows the response of the system for increasing driving force. The curves show the onset of nonlinear mechanical responses with displacements on the order of 10 nm. Data and calculations are from (*15*).

Methods to create nanometer-scale channels include the use of sacrificial layer removal approaches, related in concept to the methods for fabricating the suspended moving mechanical structures, with similar electron beam lithography and directional etching processes (Fig. 7). In this case, a tube can be created by fabricating a "wire" of an etchable material, and rather than removing the underlying support to free the structure, one can encapsulate the wire in a nonetching material and selectively remove the wire to leave a tube. This can be applied to a range of material systems, with the smallest ones to date in silicon nitride and silicon dioxide (*35–37*). This approach has been used to create the asymmetric lateral diffusion arrays described above and entropic recoil separation systems for dynamic sorting of polymers by deformability and length (*38*). The ability to integrate electrically controllable processes in nanofluidic systems is a powerful approach that increases the functionality of devices to a level approaching that of integrated electronic devices.

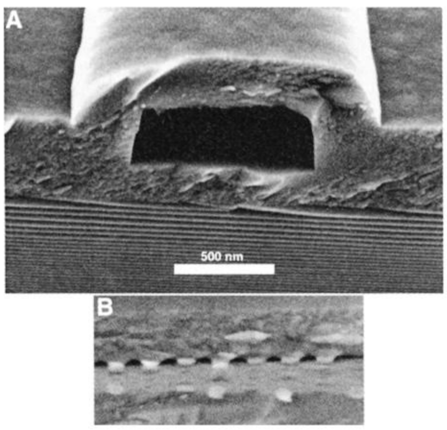


Fig. 7. (**A**) A scanning electron micrograph showing a fluidics structure fabricated with the sacrificial layer removal technique. (**B**) A micrograph of a row of 100-nm passages shown on the same scale.

Future Directions

The ability to fabricate mechanical structures with arbitrary geometries in a range of materials provides new abilities for experimentation at the nanoscale and the possibility of devices that interact with individual molecules. Carbon nanotubes are marvelous nanostructures that are being widely explored and may have interesting mechanical properties (*39*). NEMS systems that are defined by lithographic approaches are approaching the dimensions of carbon nanotubes, but can be formed in a range of materials and integrated with electronic and optical systems to create highly functional devices. Interfacing to naturally occurring functional molecules such as receptor molecules, membrane pores (*40*), motor molecules (*41*), and other functional molecular systems presents exciting new possibilities. NEMS structures can be fabricated and surface chemistry can be patterned (*42*) at the nanoscale to interface to molecular systems, combining the power of biochemistry with engineered devices. The studies described here suggest the technologies that can be used to create a revolutionary new class of devices. One can anticipate that, in a decade or so, we may be seeing a prevalence of NEMS devices at the level one now finds MEMS systems. With functional NEMS devices, we anticipate highly functional sensors, noninvasive medical diagnostic devices, and ultrahigh-density data storage systems. The basic studies of fabrication approaches and the science of nanoscale systems are taking place now.

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