NEMS

All you need is feedback

In the past, nanoelectromechanical resonators have been passive devices that required external oscillators to keep them working, so the development of a self-sustaining resonator powered only by a d.c. voltage is a major advance.

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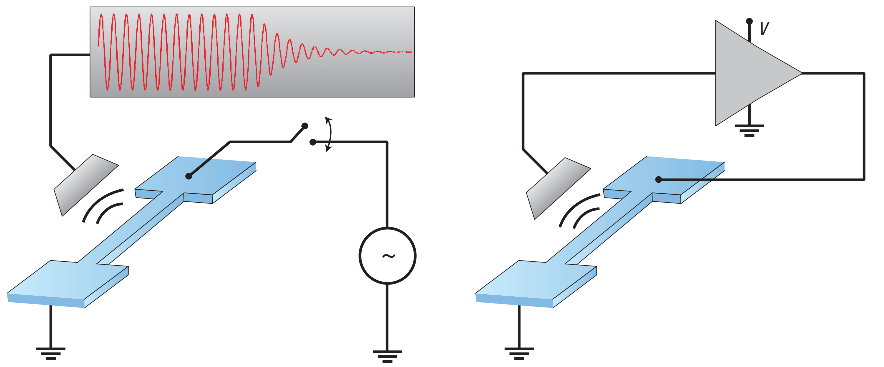

Figure 1 Most nanoelectromechanical resonators require an external oscillator, such as an applied a.c. voltage, to compensate for losses. However, if this external oscillator is disconnected, the nanoelectromechanical resonator will gradually stop oscillating (left). By exploiting a sophisticated electronic feedback loop that includes an amplifier (grey triangle), Michael Roukes and co-workers at Caltech were able to make a self-sustaining nanoelectromechanical oscillator that did not require an external oscillator (right).

Almost all electronic devices — from wristwatches to radios to computers — rely on electrical oscillators in some way. However, all oscillators are prone to losses, so it is necessary to keep adding energy to keep them oscillating. The most intuitive way to do this is to use feedback: take a small fraction of the output of the oscillator, amplify it and then, somehow, feed this amplified signal back into the oscillator circuit without disturbing its overall balance too much. This approach to building self-sustaining oscillator circuits is also used in other kinds of devices such as lasers. On page 342 of this issue, Philip Feng, Christopher White, Ali Hajimiri and Michael Roukes at Caltech report the first example of a self-sustaining nanoelectromechanical oscillator[1]. Such devices could have applications in sensing, precision timekeeping and communications.

The Caltech device is basically a nanoscale bridge made of silicon carbide that resonates at roughly 428 million cycles per second, which is in the ultrahigh frequency (UHF) band. The device is similar to a simple mass-and-spring system: an a.c. voltage from an external oscillator applies a sinusoidal force to the system, causing energy to move back and forth between the potential energy of the spring and the kinetic energy of the mass. In every cycle, however, a small fraction of energy is lost to friction or by radiation to the surroundings, with the size of this loss depending on the quality factor of the resonator. The external oscillator is needed to replenish these losses, and the oscillations start to fade away if the external oscillator is switched off (Fig. 1).

Previously, most nanoelectromechanical resonators relied on external oscillators. In some cases, the frequency of the external oscillator was swept around the mechanical resonance, which allowed information about the mass of the resonator[2], the energy losses[3] and so forth to be extracted from the frequency response. In other cases, phase-lock techniques were used to build frequency-tracking circuits that could measure very small masses and forces[4].

In the Caltech experiment, the external oscillator is no longer needed because the energy that sustains the oscillations comes solely from a d.c. power supply (Fig. 1). Oscillations can be started by a small disturbance in the circuit, such as a thermal 'kick', and if the feedback system is well tuned, only oscillations at the desired frequency are sustained. When the resonator is running in a steady state, its mechanical oscillations are first converted into electrical oscillations by an electromechanical transducer and then amplified. These electrical oscillations are converted back into an oscillating mechanical force by another transducer, which is applied to the resonator to compensate for all the energy losses. The key to sustaining the oscillations is to tune the phase and amplitude around the feedback loop very accurately so that the mechanical force is applied at the correct time and with the right phase.

The Caltech group had to surmount a number of technological challenges to get its self-sustaining nanoelectromechanical oscillator to work. The nanoscale bridge at the centre of the resonator moves by only ~1 nm at most, so an ultrasensitive transducer is needed to convert the motion into electrical signals. They use a magnetomotive transducer, which relies upon Faraday's law to generate an electromotive force on the moving bridge in a magnetic field, but even then the signal is buried in a huge background. Roukes and co-workers have spent over a decade painstakingly developing sophisticated techniques to overcome such challenges, and all this work has paid off in the new device.

Even at its development stage, the nanoelectromechanical oscillator can compete with state-of-the-art oscillators in terms of stability and spectral purity. The frequency of a perfect oscillator does not change, and all its oscillatory energy is focused at a single frequency. The frequency of a real oscillator, however, fluctuates in short time intervals, and can drift over longer periods of time. These imperfections are usually caused by external agents, such as amplifiers and/or fundamental physics[5]. Electrical engineers have developed intuitive measures for quantifying the performance of oscillators in both the time and frequency domains. Measurements of the Allan deviation (which is a measure of performance in the time domain[6]) and the phase noise (frequency domain[7]) suggest that there is still room for improvement. At present the performance of the Caltech device is limited by the electrical noise in the feedback circuit, but it should be possible to reduce this noise until the random thermal motion of the bridge dominates.

Nanoelectromechanical systems are already used to measure extremely small masses and forces: these measurements rely on a resonator oscillating at a very stable frequency so that a small change in the resonant frequency caused by, for example, a molecule landing on the resonator, can be readily detected. One day it may be possible to go a step further and actually measure time itself by counting the 'ticks' of an ultrastable nanoelectromechanical oscillator.

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ENVIRONMENTAL NANOTECHNOLOGY

Nanomaterials clean up

Membranes made of manganese oxide nanowires can be used to selectively absorb oil from water through a combination of superhydrophobicity and capillary action.

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On 24 March 1989, the Exxon Valdez ran aground in Alaska, releasing nearly 11 million US gallons of crude oil and killing approximately 250,000 seabirds, 3,000 sea otters and 250 bald eagles, despite intense remediation efforts. This incident emphasized the need for materials that can effectively separate oil and water and thus be used to clean up oil spills. Because the separation of oil and water is an interfacial challenge, certain properties of nanomaterials — such as high surface-to-volume ratios, and our ability to make surfaces that are either hydrophilic (water-loving) or hydrophobic (water-hating) — may provide solutions to this problem[1]. Indeed, it is now possible to make surfaces that switch between hydrophilic and hydrophobic behaviour on demand[2,3].

On page 332 of this issue, Francesco Stellacci of MIT and co-workers have translated such nanomaterial concepts into practice[4]. Taking advantage of the nanoscale self-assembly of inorganic nanowires, they have created non-woven membranes with controllable surface properties. These potassium manganese oxide nanowires are each about 20 nm in diameter and assemble into bundles that can be several hundreds of micrometres long resulting

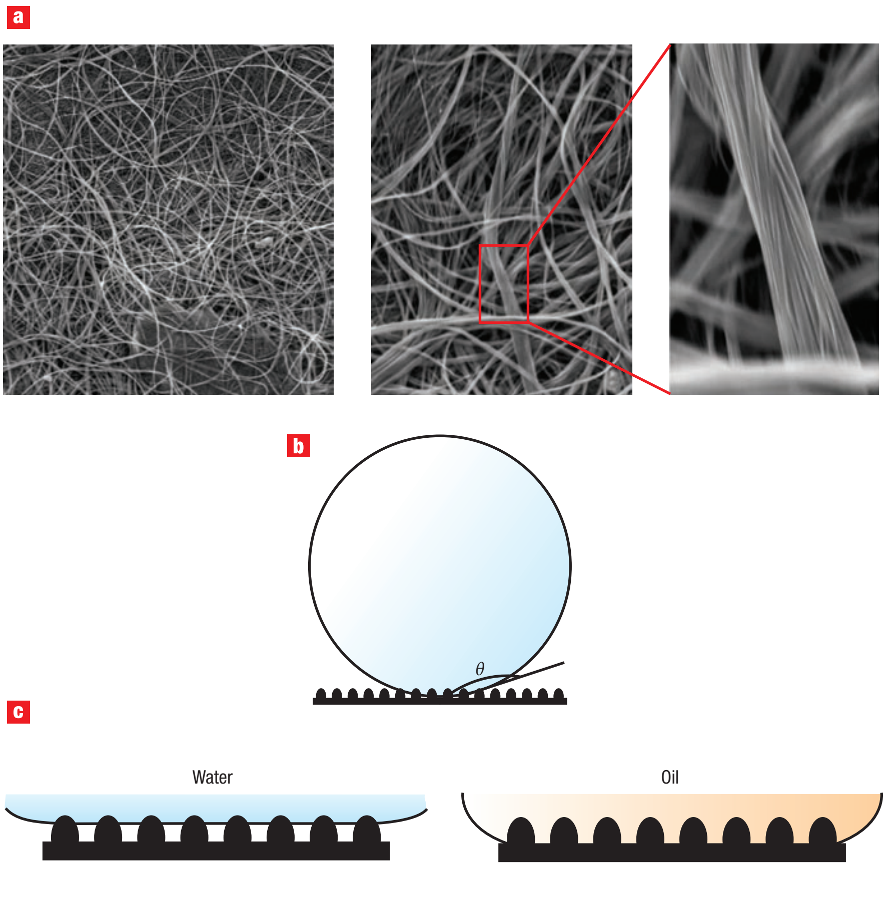

Figure 1 The properties of nanomaterials make them ideal candidates for use in oil/water separation[4]. **a**, The mesh of nanowires provides a porous structure with high surface-to-volume ratio and is shown with increasing magnification from left to right. **b**, The contact angle, θ, quantifies the wetting behaviour of a material and is a measurement of the angle between the surface and liquid/vapour interface. **c**, The membrane surface displays heterogeneous wetting when in contact with water (left) but homogeneous wetting for oil (right).