CAVITY OPTOMECHANICS

Mechanical memory sees the light

A nanomechanical beam coupled to an optical cavity can be operated as a non-volatile memory element.

Garrett D. Cole and Markus Aspelmeyer

Digital photonic logic has long been seen as a candidate to replace existing electronic integrated circuits. The main impetus for pursuing this approach, which is also known as 'all-optical computing', was, and still is, the prospect of combining ultrahigh-speed and high-bandwidth computing with a direct interface to advanced optical communications. The problem has been that various technological obstacles — including the weak interactions between photons in existing nonlinear materials, the large footprint of circuit elements and the lack of an efficient optical memory — have allowed low-cost and high-speed electronic approaches to computing to remain dominant. And although tremendous progress in optoelectronic systems, notably in silicon-based photonics combined with conventional integrated circuits, has brought hybrid solutions to the fore, all-optical computing remains an unfulfilled dream. However, developments in the field of cavity optomechanics may be about to change that. Writing in *Nature Nanotechnology*, Hong Tang and co-workers at Yale University report that they have made the first non-volatile nanomechanical memory cell that is operated exclusively by light[1].

The use of mechanical logic goes back to the earliest computing devices and the work of Schickard, Pascal, Leibniz, Babbage and others from the seventeenth to nineteenth centuries. Mechanical devices were also the driving force behind the first large-scale computational efforts of the twentieth century, such as the Zuse Z1, Z2 and Z3 machines in Germany and the Harvard Mark I and II machines in the United States, before being displaced by purely electronic solutions. Today, mechanics is experiencing a renaissance through micro- and nanomechanical devices, including the demonstration of mechanical transistors for operation in harsh environments[2], a high-density mechanical memory[3], and a variation on the Parametron approach to logic processing[4] (which was rendered obsolete by the transistor). Tang and co-workers complement these developments by demonstrating a purely optical approach to reading and writing data to a non-volatile nanomechanical memory.

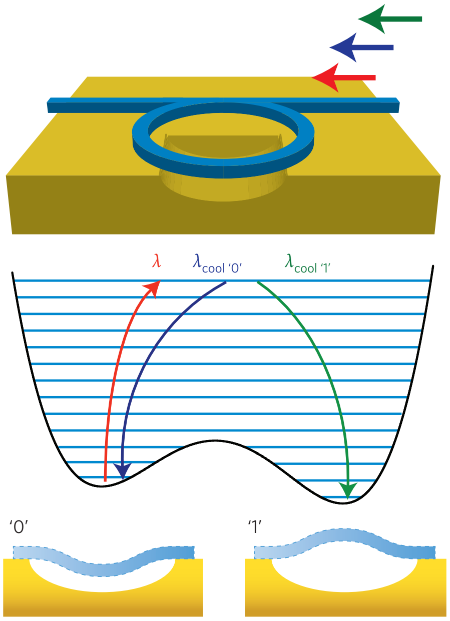

Figure 1 | The nanomechanical beam in the Yale experiment exhibits a slight buckle, which means that it is either in an up ('1') or a down ('0') state when it is at rest (bottom). These two states correspond to the minima in a double-well potential (centre). The beam is also coupled to an optical cavity (top) and it can be excited into a high-amplitude state when this cavity is pumped by a laser (red arrow) with the correct wavelength (λ). When the pump laser is switched off the beam can be returned to either the up or down state by sending a second laser (green and blue arrows) with the appropriate wavelength into the cavity.

The work at Yale builds on recent advances in cavity optomechanics, which has emerged as a new interface for light–matter interactions. The basic idea is to transfer momentum between photons confined within an optical cavity and mechanical devices that are either inside or part of the cavity[5]. Photons in the cavity are converted into phonons in the mechanical device, and vice versa. Rapid progress in this nascent field recently culminated in the use of optical forces to cool micro- and nanoscale mechanical oscillators into their quantum ground state of motion[6,7].

The cavity in the Yale experiment is a race-track-shaped ring resonator and it is fabricated from a silicon-on-insulator wafer. A 10-μm-long portion of the waveguide has been under-etched to form a suspended single-crystal silicon nanomechanical beam with a mass of 1 pg and a fundamental resonance frequency of 8 MHz. When light propagates along the waveguide, optical near-field effects cause the nanomechanical beam to experience an optical gradient force in the direction of the substrate[8]. This constitutes the fundamental optomechanical interaction between the cavity and the nanobeam.

Rather than focusing on cooling mechanical systems, Tang and co-workers used optical forces to amplify the motion of the nanobeam by detuning the light incident on the cavity to a frequency that is slightly higher than the resonance frequency of the cavity. When illuminating this 'blue sideband', only those photons that deposit energy into the mechanical oscillator (and excite phonons) will be able to enter the cavity efficiently. In other words, the cavity resonantly enhances the generation of phonons by off-resonant 'drive' photons. By operating their device with a spectrally broad cavity, in what is known as the unresolved-sideband regime, a single photon can generate several phonons at a time while still remaining resonant with the optical cavity. This allowed Tang and co-workers to drive the nanobeam into the high-amplitude regime, with the amplitude of the oscillations exceeding 300 nm (which means that about 10^{12} phonons have been created).

In contrast to previous studies[9], the high-amplitude regime involves distinctly nonlinear optomechanical interactions. However, the Yale experiment has an additional twist in that the nanomechanical beam is inherently bistable: owing to a built-in compressive strain in the device layer of the silicon-on-insulator stack, the nanobeam buckles and can be found in one of two stable positions. These buckled 'up' and 'down' positions can be considered as the mechanical analogues of '1' or '0'. From a fundamental physics point of view, these two states correspond to two widely separated minima in a double-well potential (Fig. 1).

The non-volatile optomechanical memory works as follows. The optically driven phonon-amplification process described above is strong enough to overcome the energy barrier that separates the two stable mechanical positions. Once the nanobeam is excited, preferential optical cooling at the 'red sideband' (that is, the frequency of the drive laser is slightly lower than the resonance frequency of the cavity) allows the nanobeam to be selectively steered back into one of the two stable states, hence concluding the write cycle. The read-out process is also all optical, and relies on the fact that the resonance frequency of the cavity–nanobeam system depends on whether the nanobeam is buckled up or down.

The work of Tang and co-workers is a promising first step towards the all-optical operation of mechanical logic elements. Although the energy cost of each data operation is significantly higher than for modern CMOS (complementary metal oxide semiconductor) devices (~10 μJ compared with ~1 pJ), enhancing the optomechanical coupling rate should lead to substantial reductions in the energy consumption, with the ultimate limit being operation in the single-photon regime. Furthermore, along with proposals for optomechanical signal processing[10], this work represents one of the first technological applications within the field of cavity optomechanics.

Finally, in terms of fundamental physics, the mechanical nonlinearity inherent in the Yale device offers a new versatility for optomechanical devices, for example, allowing researchers to generate non-classical states of mechanical motion and generating quantum entanglement, analogous to entangled states of light. Moreover, the double-well structure might even permit the study of novel quantum effects, such as the quantum tunnelling of macroscopic objects. Although this is indeed a far-off prospect, the rate of progress in cavity optomechanics suggests that it may well be possible. ❐

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NANOELECTRONICS

Shuttle transport for single electrons

A surface acoustic wave can be used to remove a single electron from a quantum dot, drag it along a nanowire, and deposit it in a second quantum dot.

Markus Kindermann

The goal of gaining control over single electrons in solids is the driving force behind much research in contemporary physics, and today it is possible to confine and manipulate single electrons in quantum dots and other semiconductor nanostructures in a controlled way. Now, writing in *Nature*, two independent groups of researchers — one a collaboration between groups in France, Germany and Japan[1], and the other based in the UK[2] — report a new level of control by describing how single electrons can be transferred between two quantum dots.

The most exciting potential application of the single-electron shuttles developed by the groups is a quantum computer — a machine that exploits a subtle parallelism inherent in quantum mechanics to perform certain computations with unprecedented speed. One promising way to make a quantum computer is to encode one bit of quantum information — called a qubit — in the intrinsic angular momentum (or spin) of a single electron confined in a quantum dot[3]. However, the qubits need to be able to interact and communicate with each other, and this is where a single-electron shuttle becomes useful.

Transporting a single electron is a challenging task. The traditional way of moving electrons is through wires, but even in nanowires the electrons have to swim in a sea of many other electrons. This electron sea actually has an important role in moving electrons from A to B: the presence of so many electrons means that the Pauli exclusion principle boosts the momentum of most of them. This can give some electrons enough kinetic energy to overcome the almost inevitable peaks in the electric potential inside the wire, which allows them to make it through to the other end of the wire. However, for certain applications, such as a quantum computer, this mode of transport is not acceptable. Instead, one wants to be able to move a specific electron — for example, an electron

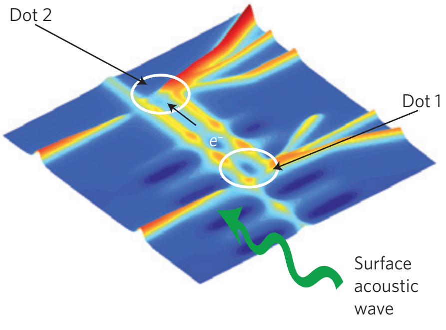

Figure 1 | The potential-energy landscape seen by an electron in the experiment by Ford and co-workers[2]. The red regions correspond to the metal electrodes that define the quantum dots, and the nanowire between them, in a two-dimensional electron gas in a GaAs/AlGaAs heterostructure. The effect of the surface acoustic wave (green arrow) on the potential-energy landscape near the first quantum dot is also visible. Figure courtesy of Robert McNeil.