OPTOMECHANICAL SYSTEMS

Hot electrons but cool vibrations

The electronic degrees of freedom in semiconductor membranes provide an innovative new way of cooling mechanical motion.

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One might expect that exciting the electrons in a piece of semiconductor by shining a laser on it would simply heat it up. However, a rather more interesting outcome can be achieved if the semiconductor is fashioned into a thin membrane. As Koji Usami and colleagues now report in *Nature Physics*[1], although the excited electrons do cause local heating of the semiconductor, they can also produce a dramatic cooling down of the mechanical vibrations of the membrane. This apparently paradoxical result is achieved through a subtle interplay between the light and the mechanical motion, which is carefully tuned by incorporating the membrane into an optical cavity.

A pair of parallel mirrors set a fixed distance apart form a cavity that supports optical modes whose frequencies are determined by the cavity length. When this cavity is driven by a laser at a frequency close to that of one of these optical modes, a large number of photons can build up inside. In an optomechanical system, such as the device studied by Usami *et al.*, one mirror of the cavity is flexible, acting as a mechanical resonator that can be displaced by forces arising from the photons in the cavity[2,3]. The change in momentum when light is reflected provides one such force[2–5], but light that is absorbed by the mirror causes local heating that then generates mechanical stress, which can also deflect the resonator[6].

A key feature of optomechanical systems is the dynamical behaviour that follows from the coupling between the movable mirror and the light[2,3]. The resonator is displaced by forces generated by the light, changing the cavity length and hence its mode frequencies; this translates into a change in the number of photons in the cavity (as the laser driving the cavity is now closer to or further away from resonance) and hence a change in the force generated. Crucially, it takes a finite amount of time for the force produced by the light to respond to mechanical motion. The delayed response means that a component of the force on the resonator depends on how fast it is moving. This velocity-dependent part of the force can damp out the thermal fluctuations in the resonator's motion, in effect cooling it down.

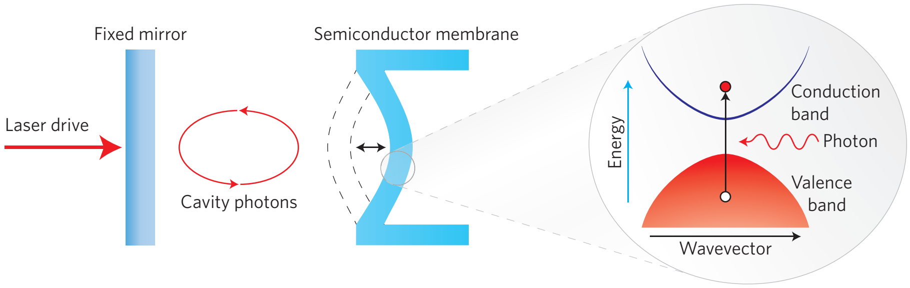

Figure 1 | Schematic view of the optomechanical system. Usami *et al.*[1] use a semiconductor membrane combined with a fixed mirror to form an optical cavity. Driving the system with a laser whose frequency is close to one of its normal modes leads to a build-up of photons inside the cavity. When the photon energy matches (or exceeds) the semiconductor bandgap, a cavity photon can excite an electron from the valence band to the conduction band, creating an electron–hole pair, which in turn leads to a mechanical force.

Usami and co-workers now take a new approach to optomechanics[1] by exploiting electrical degrees of freedom inside the mechanical resonator[7]. In their work, a thin semiconductor membrane acts as one of the mirrors in a cavity. They see a strong response only when the wavelength of the light they shine on the mirror matches the semiconductor's bandgap so that electron–hole pairs are excited (Fig. 1). The electron–hole pairs generate a mechanical force on the membrane in two ways. First, a mechanical stress is generated electrically because the excitation of electrons from the valence band to the conduction band changes the lattice spacing[8] (the valence band electrons bind the lattice more tightly). Second, the membrane heats up because electrons and holes recombine non-radiatively, generating a mechanical stress as the lattice expands. However, the lifetime of the electron–hole pairs excited in this device is so small (<50 ps)[1] that there could never be enough around to generate significant stress electrically. On the other hand, there is clear evidence that the heating effect plays a dominant role, as the membrane's motion takes 10 ms to respond to changes in the laser drive, which is close to the time for heat to diffuse across the membrane.

By driving the cavity with plenty of laser power, Usami *et al.* generated enough damping from excited electrons to cool the membrane from room temperature to 4 K. Recent progress in optomechanics has been so rapid that this level of cooling by itself is no longer remarkable[4,5], although it is still impressive for a first experiment. Usami *et al.* predict that they could cool the membrane much further using an improved cavity geometry[9] and by employing the electrical force produced by excited electrons, although this would require a much longer electron–hole pair lifetime. Fortunately, there is scope for increasing the lifetime by engineering the composition of the membrane. For example, the excited electrons could be confined within a thin quantum well inside the membrane.

Ultimately though, the damping force arising from the light in cavity optomechanics can only cool a resonator down to a level set by fluctuations in the force itself[2,3]. For the radiation-pressure force, and for thermally generated stress, the fluctuations are known to be small enough to enable cooling of a resonator almost to its quantum-mechanical ground state[4,5,10,11]. Whether the electrical stress generated by electron–hole pairs in devices like the one by Usami *et al.* will also allow mechanical vibrations to be cooled practically all the way to the quantum ground state remains an interesting open question. However, even if excited-electron cooling proves unable to achieve this, the work of Usami *et al.* provides a fascinating preview into what might be possible when the mechanical resonator in an optomechanical device is an optically active semiconductor. Given the extraordinary richness of semiconductor physics, it seems likely that a whole range of exciting new experiments will follow. ❐

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References

1. Usami, K. *et al. Nature Phys.* http://dx.doi.org/10.1038/nphys2196 (2012).
2. Kippenberg, T. J. & Vahala, K. J. *Science* **321,** 1172–1176 (2008).
3. Marquardt, F. & Girvin, S. M. *Physics* **2,** 40 (2009).
4. Teufel, J. D. *et al. Nature* **475,** 359–363 (2011).
5. Chan, J. *et al. Nature* **478,** 89–92 (2011).
6. Höberger Metzger, C. & Karrai, K. *Nature* **432,** 1002–1005 (2004).
7. Okamoto, H. *et al. Phys. Rev. Lett.* **106,** 036801 (2011).
8. Matsuda, O., Tachizaki, T., Baumberg, J. J. & Wright, O. B. *Phys. Rev. B* **71,** 115330 (2005).
9. Thompson, J. D. *et al. Nature* **452,** 72–75 (2008).
10. De Liberato, S., Lambert, N. & Nori, F. *Phy. Rev. A* **83,** 033809 (2011).
11. Restrepo, J., Gabelli, J., Ciuti, C. & Favero, I. *C. R. Phys.* **12,** 860–870 (2011).