

the (111) facets of ultraclean silver crystals as the substrate, and heated bulk crystals of extremely pure λ -(BETS)₂GaCl₄ under high-vacuum conditions so that less than a monolayer was deposited onto the substrate. Remarkably, even though the substrate was maintained at a temperature of 120 K, the BETS and GaCl₄ molecules organized into small islands of (BETS)₂-GaCl₄ structures that arranged themselves in chains to mimic the bulk crystal structure for this material (Fig. 1).

Scanning tunnelling microscopy and spectroscopy revealed the presence of (BETS)₂-GaCl₄ chains of different lengths, the unambiguous orientation of the rings in the BETS molecules perpendicular to the substrate, and the clear demonstration of nearly complete charge transfer between the BETS and GaCl₄ molecules. The surprise result was the discovery that a superconducting energy gap opens up at temperatures below ~10 K. This gap, which is a measure of the energy needed to break up a Cooper pair, was measured with scanning tunnelling spectroscopy,

and was found to be much larger with respect to the critical temperature than it is in conventional superconductors. Last, but not least, the superconducting energy gap was proportional to the length of the chain — but it still survived in chains that contained just four (BETS)₂-GaCl₄ pairs.

Encouraged by this advance we may ask many new questions. How is charge transported in these nanostructures? Can a zero-resistance state be measured in a (BETS)₂-GaCl₄ nanowire below 10 K? Can we measure the symmetry of the wavefunction describing the Cooper pairs using scanning probe methods, as has been done for high-temperature superconductors? How do magnetism and superconductivity⁷ interact in the related compound (BETS)₂-FeCl₄ at the nanoscale? And how will electric fields affect the charge-transfer properties of these materials in monolayer films in device configurations? Many of these investigations will require the availability of insulating substrates or interfaces that are as effective as Ag(111).

The work of Hla and co-workers is an example of the ways in which ultrapure materials and conditions, sometimes in combination with low temperatures, can surprise us with serendipitous discoveries that can transform a field of research, leading to new levels of scientific and technical opportunity. □

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References

1. Clark, K. *et al.* *Nature Nanotech.* **5**, 261–265 (2010).
2. Tanatar, M. A., Ishiguro, T., Tanaka, H. & Kobayashi, H. *Phys. Rev. B* **66**, 134503 (2002).
3. Uji, S. *et al.* *Phys. Rev. Lett.* **97**, 157001 (2006).
4. Brooks, J. S. in *Handbook of High Temperature Superconductivity* (eds Schrieffer, J. R. & Brooks, J. S.) 463–490 (Springer, 2007).
5. Beebe, M. *et al.* *J. Phys. Chem. B* **109**, 5207–5215 (2005).
6. Kirtley, J. R. *et al.* *Nature* **373**, 225–228 (1995).
7. Uji, S. *et al.* *Nature* **410**, 908–910 (2001).

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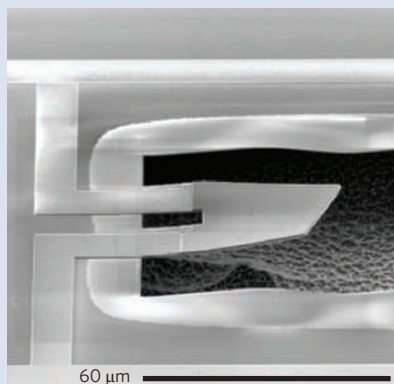
NANOMECHANICS

Welcome to the quantum ground state

A mechanical device has been cooled into its quantum ground state for the first time in a landmark experiment that could shed new light on the boundary between quantum and classical mechanics. Andrew Cleland and co-workers at the University of California at Santa Barbara (UCSB) cooled a mechanical oscillator to a temperature of 25 mK with a dilution refrigerator, and then used a superconducting quantum bit (qubit) to measure the quantum state of the device. The UCSB team was also able to create a superposition state in the qubit and transfer it to the oscillator so that the latter was both moving and not moving at the same time (*Nature* **464**, 697–703; 2010).

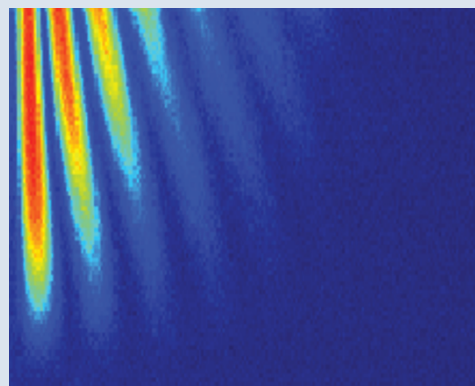
The oscillator, which was visible to the naked eye, consisted of a thin layer of aluminium nitride sandwiched between two aluminium electrodes (left). When a voltage was applied to the electrodes, the device expanded and contracted because aluminium nitride is a piezoelectric material. The oscillator — also known as a ‘quantum drum’ — was coupled to the qubit, which acted as a quantum thermometer, by a capacitor.

The temperature at which quantum effects can be observed in a mechanical



oscillator is proportional to its fundamental resonant frequency. At just over 6 GHz, the resonant frequency of the oscillator made by the UCSB team was relatively high for a mechanical device, which meant that quantum effects kicked in at the relatively high temperature of 0.1 K. Other groups are still trying to achieve the much lower temperatures needed to reach the quantum ground state in mechanical devices that have considerably lower resonant frequencies.

Reaching the quantum ground state in such an experiment involves removing all



the thermal vibrations from the system. Cleland and co-workers estimated that their oscillator contained a maximum of 0.07 phonons (the quanta of vibrational energy in a solid), which means that the probability of the oscillator being in the ground state was greater than 93%. They also transferred a single quantum excitation from the qubit to the oscillator and back again multiple times, and created coherent phonon states in the oscillator (right).

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