MATERIALS SCIENCE

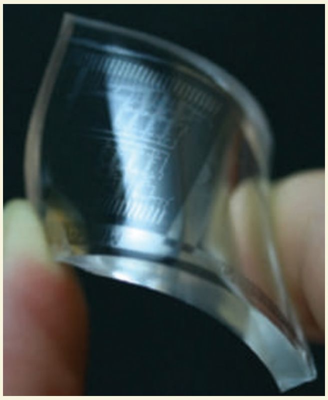
Bend, fold and stretch

It is tempting to view graphene as the material of choice for the next generation of electronic devices. The fact that it forms strong, bendable sheets — made from carbon atoms arranged in a honeycomb lattice — together with its remarkable electronic properties makes it a promising starting point for flexible electronic applications.

However, the high-performance electronic graphene devices reported so far are made from tiny, micrometre-sized pieces of graphene, obtained using a rather cumbersome method that involves peeling off layers from a larger graphite substrate. In a paper published online in *Nature,* Byung Lee Hong and his colleagues now describe an alternative and more versatile method to produce graphene films with excellent electronic properties and with large, centimetre-scale areas (K. S. Kim *et al. Nature* doi:10.1038/nature07719; 2009).

Although chemical-processing techniques already exist for producing large-area graphene material, the electronic properties of such materials have been disappointing. But Hong *et al.* have perfected an approach known as chemical-vapour deposition. In this technique, a gaseous mixture of hydrocarbons flows over heated nickel foils and breaks down into atomic carbon, which in turn rearranges into graphene. Rapid cooling of the substrate then ensures that films just a few layers thick are formed. These ultrathin films are optically transparent and have high electrical conductivity, similar to that of mechanically cleaved graphene.

The main promise of Hong and colleagues' method lies in large-area applications, notably transparent, flexible electrodes such as that pictured. Hong *et al.* show that the graphene films can be radically bent and stretched without affecting their optical and electronic properties. And crucially, with this fabrication method the graphene can be easily transferred to other materials, because the underlying nickel can simply be etched away and the graphene film picked up and placed elsewhere. In addition, nanoscale patterns can be made in the graphene films by pre-patterning the nickel substrate with standard lithography techniques.



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This combination of straightforward processing techniques and desirable properties increases the prospects of inexpensive, flexible and reliable electronic devices. Future applications, such as in photovoltaics, or as sensors and displays that are wearable or foldable, suddenly don't seem to require such a stretch of the imagination.

Liesbeth Venema

Amo and colleagues' experiment, the polariton dispersion relation (the dependence of energy on momentum) does not take the simple quadratic form that a free particle takes. This means that a pair of polaritons injected at one energy is able to scatter to one high-energy polariton state and one low-energy state, in a process known as parametric scattering[6]. The rate of scattering depends on the type of quantum statistics particles obey. Because polaritons behave as bosons and thus obey Bose–Einstein statistics, the rate of scattering goes up as the populations of the final states increase. Amo *et al.* used this property to create a small seed population in the high-energy state. This, in turn, triggered parametric scattering of polaritons from the injected energy (pump state) to a lower-energy and a higher-energy state, producing a pulse of low-energy polaritons that travelled through the microcavity, continually fed by the parametric scattering.

Previous experiments on microcavity polaritons, in which polaritons were injected (incoherently) in a range of high-energy states instead of by parametric scattering, showed that they can form a Bose–Einstein condensate[7] (BEC): a form of matter that emerges when particles obeying Bose–Einstein statistics are cooled to very low temperatures and collapse into the same lowest-energy state, behaving as a single, coherent whole. Recently, quantized vortices have also been seen[8] in these systems, a feature associated with superfluidity.

The phenomenon of superfluidity is closely related, but not equivalent, to Bose–Einstein condensation[3]. In an interacting BEC, the occupation of a single quantum state by a large fraction of bosons means that the system is described by a single quantum wavefunction that satisfies a nonlinear equation for classical waves. Ubiquitous in nonlinear physics, this equation is known as the nonlinear Schrödinger equation[9]. This equation, written in terms of the density and velocity of the condensate, has a form almost equivalent to the usual Euler equation for the dynamics of a non-viscous fluid. Thus, one has the ingredients necessary to produce many of the aspects of superfluidity, such as frictionless flow below the Landau critical velocity (Table 1).

Frictionless flow has been observed in liquid helium using moving ions as probes[10], and in BECs of dilute atoms using laser beams[11]. At subcritical velocities, the superfluid flow around such an obstacle is symmetrical fore and aft of the direction of motion, so there is no drag. This absence of drag on moving objects is known as d'Alembert's paradox. In a classical fluid, drag does arise, because viscosity breaks the fore–aft symmetry. In their experiments, Amo and co-workers observed that a cloud of polaritons passed an obstacle — a structural defect in the microcavity — without any detectable drag, realizing d'Alembert's paradox in a condensate out of thermal equilibrium. In superfluid helium and atomic BECs, the drag above the critical velocity has been attributed to the shedding of vortices around the obstacle[10]. Although no such vortices have been directly observed in the polariton experiments of Amo *et al.*, it remains plausible that drag at speeds between the critical and sound velocities could arise from vortex formation in polariton fluids.

Amo and colleagues' experiments differ from previous investigations of superfluids in several ways. Most obviously, the polaritons have a finite lifetime. But this alone need not preclude many of the regular signatures of superfluidity. Perhaps most remarkably, the linearization of the relevant part of the polariton's dispersion relation, and thus the quasiparticle's immunity to scattering from structural microcavity defects, results from the nonlinear interactions of the low-energy polaritons with the pump polaritons as well as interactions among the low-energy polaritons. By contrast, for liquid helium or cold atoms, such linearization arises entirely as a result of interactions between the low-energy particles. The question of whether such polariton fluids can be called superfluid is, to us, less interesting than investigating the properties that these out-of-thermal-equilibrium polariton fluids possess. While experiments continue apace to explore these properties, it seems better to go with the flow. ■

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