concentration is in turn controlled by the type and concentration of the carbonaceous gas, and the thickness of the nickel layer. After a chemical etching of the nickel, the graphene membrane detaches and can be transferred to another substrate. This direct CVD synthesis provides high quality layers of graphene without intensive mechanical or chemical treatments.

The graphene films demonstrate excellent electronic and optical properties: a sheet resistance as low as ~280 Ω cm^{-2} (ref. 7), a carrier mobility as high as 3,700 cm^2 V^{-1} s^{-1} (ref. 7) and a 90% optical transparency[7,8]. Although these values are inferior to those obtained for a perfect single layer of graphene[1], they are nevertheless useful for applications such as flexible and transparent electrodes for solar cells and liquid crystal displays, and various high-frequency electronic and optoelectronic devices. The combination of low cost, scalability and advanced material properties displayed by the CVD approach is exceptional.

Even though the further development of large-scale CVD deposition of graphene for industrial purposes will be mostly by engineering, fundamental research will also have a part to play. Replacing the polycrystalline substrates used by the three groups with the single-crystal nickel substrates used to grow epitaxial graphene would reduce the number of defects in the samples by reducing the mismatch between the nickel and graphene lattices[11]. Another serious obstacle to CVD technology is that the large difference in the thermal expansion coefficients of nickel and graphite leads to ripple structures in the samples[7,9,10]. This will need to be overcome to achieve the planar graphene film topology required for micro-patterning of electronic devices.

The successful demonstration of large-area graphene from CVD is a promising step towards the industrial production of graphene-based electronic and optoelectronic devices. The use of large-scale CVD graphene as flexible and optically transparent electrical contacts has been demonstrated by the teams led by Hong[7] and Kong[8]. These properties are attractive for applications, including liquid crystal devices, solar cells and organic light-emission devices, where graphene may provide potentially significant advantages (in terms of carrier mobility and mechanical strength and flexibility) over conventional metal oxides.

Chen and colleagues[9] also unambiguously demonstrate that the extraordinary electronic properties of CVD graphene may be practically exploited in submicron electronic devices. These include quantum coherent devices where phase coherent electron transport is used for new device functionalities or improved performance. The scalability of CVD graphene technology may hasten the transition from processing single electronic devices — which has been demonstrated already[1,7–9] — to the production of complicated integrated circuits containing numerous active and passive graphene-based components. ❐

Alexander N. Obraztsov is in the Department of Physics, Moscow State University, Moscow 119991, Russia, and in the Department of Physics and Mathematics, University of Joensuu, PO Box 111, FI-80101 Joensuu, Finland.
e-mail: obraz@polly.phys.msu.ru; alexander.obraztsov@joensuu.fi

References

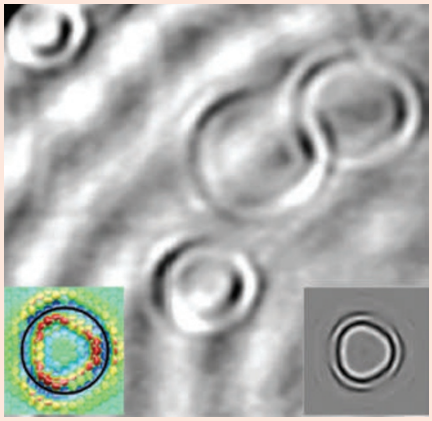
1. Novoselov, K. S. *et al. Science* **306,** 666–669 (2004).
2. Novoselov, K. S. *et al. Nature* **438,** 197–200 (2005).
3. Booth, T. J. *et al. Nano Lett.* **8,** 2442–2446 (2008).
4. Berger, C. *et al. Science* **312,** 1191–1196 (2006).
5. Eda, G., Fanchini, G. & Chhowalla, M. *Nature Nanotech.* **3,** 270–274 (2008).
6. Park, S. & Ruoff, R. S. *Nature Nanotech.* **4,** 217–224 (2009).
7. Kim, K. S. *et al. Nature* **457,** 706–710 (2009).
8. Reina, A. *et al. Nano Lett.* **9,** 30–35 (2009).
9. Cao, H. *et al.* Preprint at <http://arxiv.org/abs/0901.1136> (2009).
10. Obraztsov, A. N. *et al. Carbon* **45,** 2017–2021 (2007).
11. Grüneis, A. & Vyalikh, D. V. *Phys. Rev. B* **77,** 193401 (2008).

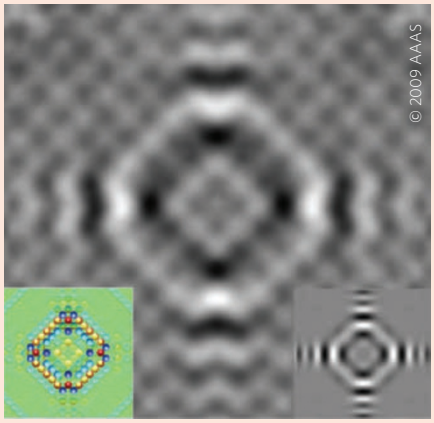
PROBE MICROSCOPY

Beneath the surface

The Fermi surface of a crystalline solid is the boundary between states that are occupied by electrons at absolute zero temperature and states that are empty at this temperature. It is usually measured in momentum space, rather than real space, by techniques such as angle-resolved photoemission spectroscopy. Now Martin Wenderoth, of the University of Göttingen, and colleagues have shown that it is possible to image the Fermi surface of a solid in real space with a scanning tunnelling microscope (STM; *Science* **323,** 1190–1193; 2009).

In a typical STM measurement an electron from the tip of the microscope tunnels into a surface and becomes a bulk electron wave with amplitude that decays with distance. If a defect atom is present beneath the surface, the electron wave can be reflected, interfering with the incoming wave to form a standing-wave pattern. When the Fermi surface is spherical, a weak interference pattern is observed at the surface. However, when the Fermi surface is not spherical, electrons can be focused along certain directions, resulting in pronounced interference patterns at the surface. These patterns reflect information about the flow of electrons in the bulk of the material, and hence the shape of the Fermi surface.





The STM image on the left is 9 nm across and shows four cobalt atoms below a copper(111) surface; the image on the right is 3.5 nm across and shows one cobalt atom below a copper(100) surface. The insets are 4 nm across and show the local electron density of states derived from the images (left insets), and from theory (right insets).

OWAIN VAUGHAN