Graphene opens up to new possibilities on SiC

Structures made up of a few or even single layers of carbon in hexagonal sheets (graphene) have exciting possibilities for electronics. Until recently, these structures have been measured to have zero bandgap putting them on the border line between metal and semiconductor. Now, a positive gap has been found for graphene layers on silicon carbide, pushing the material into the semiconductor domain.
Dr Mike Cooke reports.

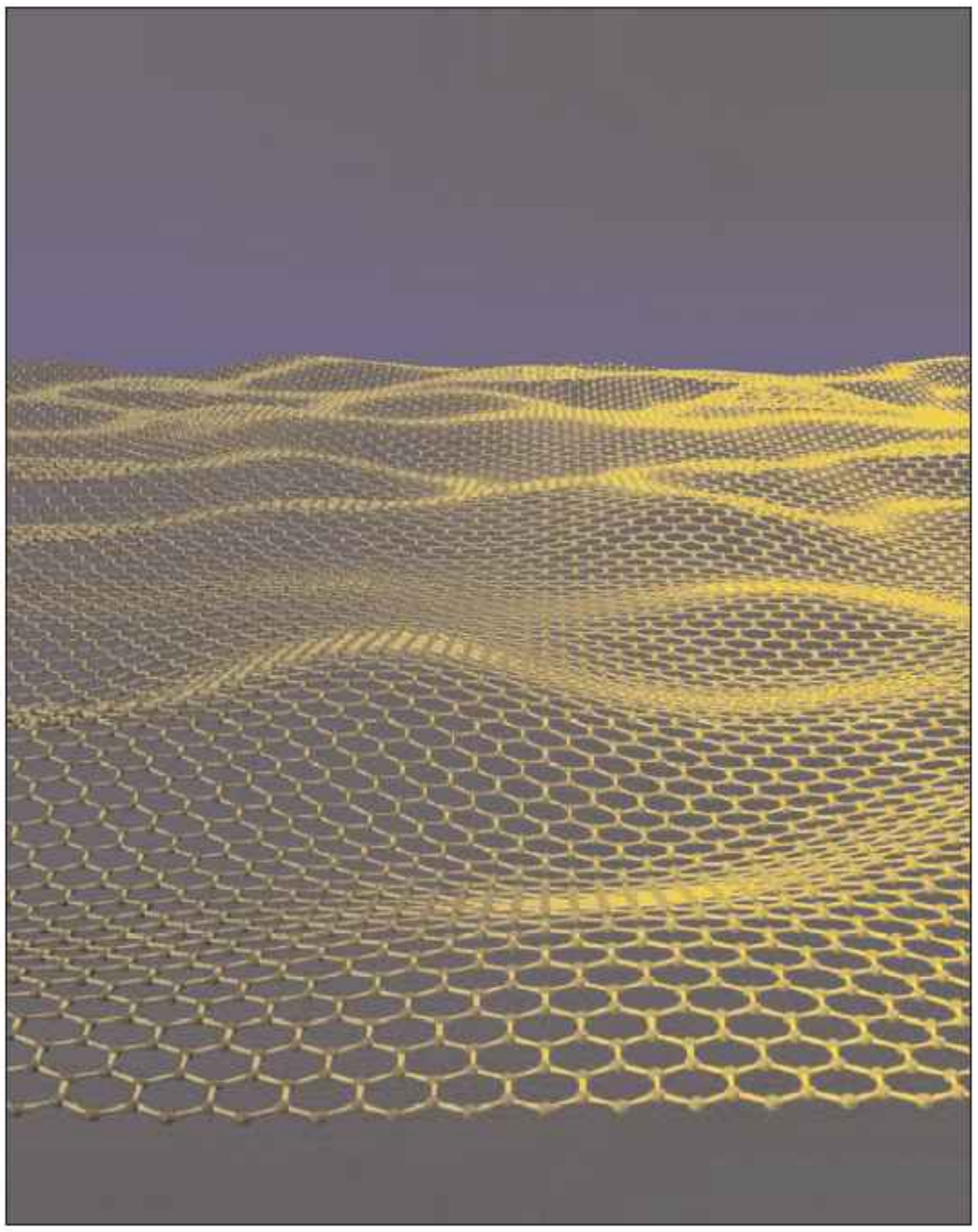

Figure 1. Artistic impression of a graphene sheet by Jannik Meyer, Max Planck Institute for Solid State Research, Germany.

When physicists started producing flakes of single- and few-layer graphene from graphite in 2004 [1], it was contrary to theoretical expectations that said two-dimensional structures would not be thermodynamically stable. At the same time, the electronic structure of single-layer graphene was found to have the form of the relativistic Dirac equation (with zero effective mass) where the 'speed of light' is 10^6m/s rather than $3x10^8$m/s. The 'spin' of the graphene 'Dirac' equation is in addition to the usual angular-momentum spin and is related to there being two carbon atoms per unit cell in the hexagonal 'chicken-wire' lattice (see Figure 1).

This behavior gives single-layer graphene a zero energy gap, putting it on the border between a metal and an insulator. Multiple layers of graphene have overlapping conduction and valence bands, giving these materials semi-metal electronic behavior.

While this behavior could create experimental analogues of difficult-to-access high-energy physics theoretical structures such as two-dimensional quantum electrodynamics and, it has been suggested, string theory, as well as opportunities for interconnects and normally-on transistors (using electric-field-induced band gaps), for practical use of graphene in transistors one really needs normally-off transistors, as provided by semiconductor (positive band-gap) materials to produce integrated circuits.

So it is with some excitement that one reads of the development of epitaxial graphene layers with positive band gaps deposited on silicon carbide substrates [2], reported by US and Spanish scientists at the universities of California-Berkeley, California-Santa Cruz and Boston, the Georgia Institute of Technology, the US Lawrence Berkeley National Laboratory and Instituto de Ciencia de Materiales de Madrid in Spain. The graphene layers are produced by thermal decomposition of a Si-terminated n-type SiC wafer surface.

The researchers have measured a band gap of the order of 0.26eV. This gap reduces as the number of layers increases and closes beyond four layers. For bilayer graphene the gap is given as 0.14eV, and for a trilayer it is 0.066eV (Figure 2). The scientists theorize that the gap is the result of sublattice symmetry breaking from the graphene–substrate interactions.

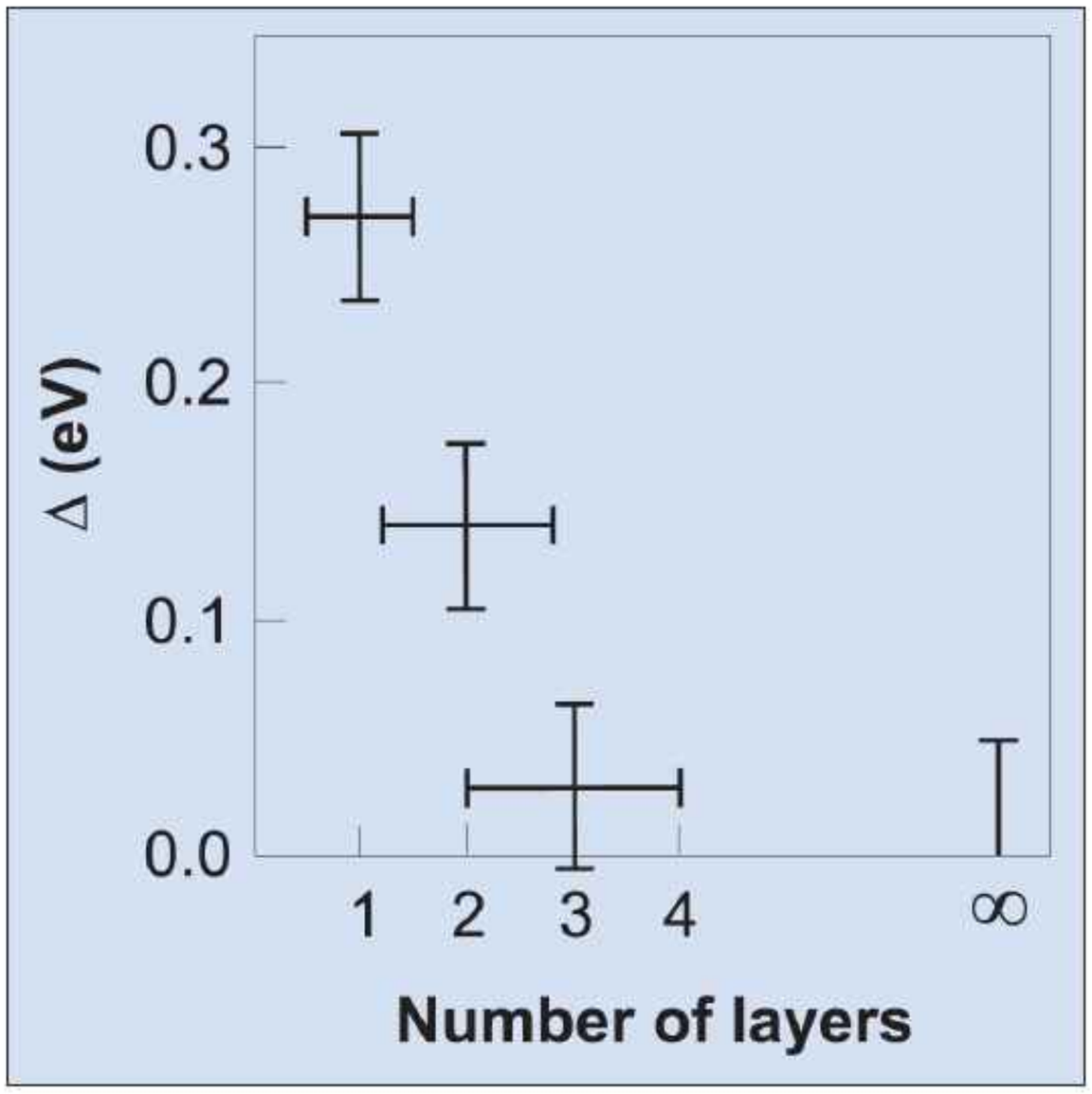

Figure 2. Induced gap of graphene on SiC versus the number of layers.

Electron energy (EDC) and momentum (MDC) distribution curves found using angle-resolved photoemission spectroscopy (ARPES) were used to derive dispersion relations near the band gap (Figure 3). The ARPES measurements were carried out at the Advanced Light Source (synchrotron) at Lawrence Berkeley.

The gap can be seen within the Dirac model as giving the electron a small effective mass — small enough so that, away from the gap, the dispersion relation becomes linear (as for the zero gap case) rather than quadratic (as for normal 'non-relativistic' fermions in semiconductors); see Figure 4.

The EDC peaks are broad, giving finite photoemission in the gap. Why the peaks are so broad and how this would affect attempts to construct devices are important unanswered questions. The article's authors point out that ARPES measurements tend to underestimate transport lifetimes by up to two orders of magnitude. As one approaches the Fermi level, the peaks become sharper (indicating longer lifetimes), giving hope for device applications.

The position of the Fermi level is such that the graphene layers are usually electron doped. Among the next key steps for this research is to attempt hole doping or to apply a gate voltage to move the Fermi level into the gap. The researchers also plan to investigate layers on other substrates in the hope of controlling the gap.

The researchers prefer a model where symmetry breaking occurs between the two sublattices making up the hexagonal graphene structure due to interaction with the SiC crystal surface structure. Previously, attempts to create a band gap in graphene have

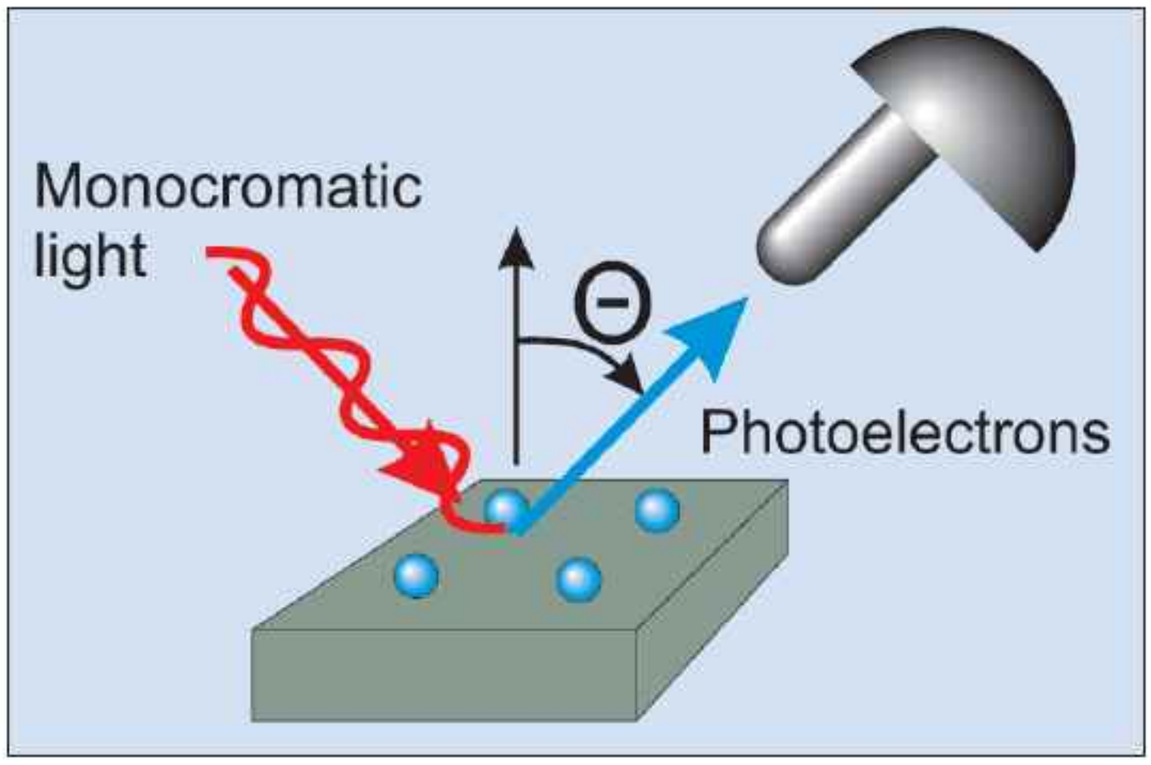

Figure 3. Schematic of angle-resolved photoemission spectroscopy (ARPES).

involved complex sculpting of nanostructures (dots, ribbons, combinations of monolayer and bilayer regions, etc.).

Scientists from the University of Manchester (UK) and the Institute for Microelectronics Technology in Chernogolovka (Russia) first isolated and studied graphene sheets of carbon by drawing graphite across a surface and searching among the fragments on a silicon dioxide coated wafer with an optical microscope [1, 3]. A silicon dioxide layer of around 300nm gives the best contrast to search for graphene fragments. A 5% difference in the layer thickness significantly reduces the contrast. However, such manual search techniques are best suited to the patient researcher; industrialists will want repeatable, mass production.

Since the first studies on graphene, it has since been produced on silicon carbide, non-crystal substrates, in liquid suspension and as suspended membranes. Also, other 'two-dimensional' (2D) materials have also been found constructed of boron nitride and of a half-layer of the high-temperature superconductor, bismuth strontium calcium copper oxide (BSCCO).

Thermal decomposition of hexagonal (6H) SiC crystals is the main alternative to the 'exfoliation' of the Manchester group. Dr Claire Berger, a researcher into graphene on SiC based both at Institut Néel of the Centre National de la Recherche Scientifique (CNRS) in France and Georgia Tech in the USA, comments: "In our process by thermal decomposition of SiC, graphene covers the entire sample of millimeter size. There is no size limitation in principle. Graphene grows over terraces like a carpet and so extends over very long distances. The terraces we talk about correspond essentially to the SiC substrate local miscut, and are of the order of several hundreds of nanometers. We use commercial SiC from Cree. We start with a 3-inch wafer that we dice into rectangles 3mm x 4mm or so to fit in our measurement and tool setup."

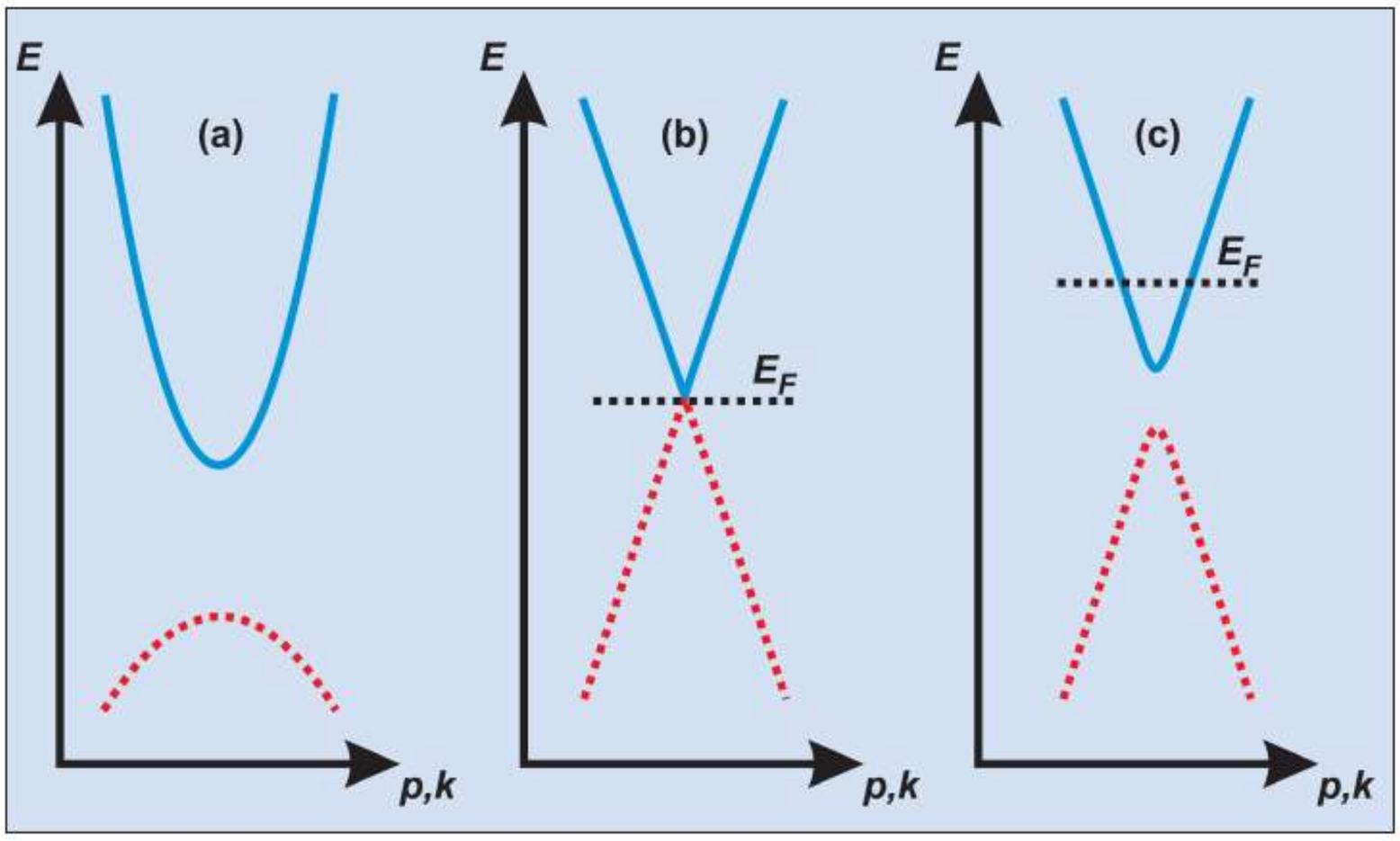

Figure 4. Form of energy–momentum dispersion near a gap in (a) normal semiconductor, (b) single layer graphene, (c) 1–3 layer graphene on SiC. While the Fermi level in graphene is at the cross-over point, on SiC the level is in the conduction band, giving electron conduction in the material.

The first graphene-based transistor was made at the same time as the material's discovery [1], and other groups have since reproduced the result (for example, Georgia Institute of Technology growing the graphene on silicon carbide substrates, [4]). But these graphene transistors were very 'leaky'. If such high leakage rates continued, this would limit possible applications and rule out use in computer chips and other electronic circuits needing a high density of transistors.

Graphene mobilities of up to 30,000cm^2/V-s have been measured at 300K ('room temperature'). Silicon mobilities are around 1500cm^2/V-s and decrease rapidly with the doping levels being used in today's semiconductor devices. Alternative high-mobility channels are being sought for CMOS transistors, and graphene is one possibility. While mass production of controllable graphene layers still seems some way off, results such as producing a positive gap in graphene could draw interest from academic and industrial researchers and accelerate the pace of development. ■

References

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