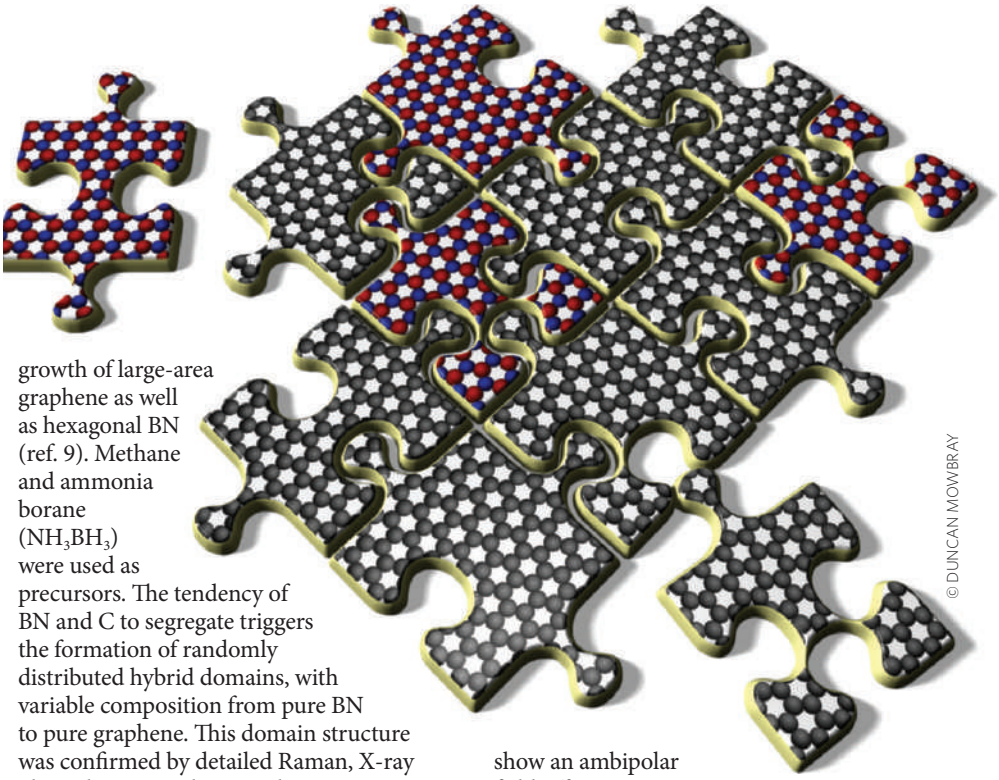
HYBRIDIZED GRAPHENE

Nanoscale patchworks

Patching carbon and boron nitride nanodomains emerges as an efficient way to engineer bandgaps in graphene, opening a new avenue for optoelectronic devices.

Angel Rubio



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Carbon is arguably the element that best represents the emergence of new phenomena and properties when dimensionality or size are reduced. Fullerenes[1], nanotubes[2], nanoribbons and graphene[3] can be considered as the pieces available in the carbon-only 'Lego' of nanoscience, all of which show excellent electronic, mechanical and thermal properties. Combining carbon with its neighbouring atoms in the periodic table (boron and nitrogen) increases enormously the number of pieces available, offering a host of different BCN configurations. Soon after the discovery of nanotubes in the 1990s[1] it was predicted theoretically that other inorganic BCN nanostructures could be formed[4,5], and such predictions were fulfilled almost immediately[6], thereby supporting the emergence of the field of BCN-nanostructured-based materials[7]. Well over a decade after these first results, Ci *et al.*[8] now report in *Nature Materials* a systematic route to synthesize two-dimensional (2D) BCN hybrid structures consisting of a patchwork (or jigsaw) of BN and C nanodomains, unveiling just a part of the largely unexplored BCN-rich phase diagram. These results are particularly valuable in terms of the potential electronic applications of graphene, as they provide a hitherto unexplored route to induce and engineer the bandgap of this 2D material, as opposed to other approaches such as chemical doping or lateral size reduction.

BCN nanostructures show a rich variety of physical properties and numerous possible technological applications in the fields of nano-electronics, optical devices, field emission, catalysis and lubrication. They are highly resistant to chemical degradation and oxidation whereas their mechanical and electronic properties can in principle be tuned by varying the contents of each of the three elements. Unfortunately, however, BCN systems are much harder to synthesize than their carbon counterparts, and are therefore much less studied.

Ci *et al.*[8] provide an elegant solution to this problem in two dimensions through the use of a thermal catalytic chemical vapour deposition method. They used a copper substrate that is known to favour the growth of large-area graphene as well as hexagonal BN (ref. 9). Methane and ammonia borane (NH_3BH_3) were used as precursors. The tendency of BN and C to segregate triggers the formation of randomly distributed hybrid domains, with variable composition from pure BN to pure graphene. This domain structure was confirmed by detailed Raman, X-ray photoelectron and energy-loss spectroscopy, and high-resolution transmission microscopy demonstrates that the samples consist of mainly two or three layers. The atomic ratio can be controlled by changing the experimental conditions of pressure, temperature and gas concentration, although in all cases B and N appear in a 1:1 ratio. The C content can be changed from as little as 10% to nearly 100%. The work constitutes only the first step to show that these structures can indeed be grown in only a few atomic layers, down to the single-layer limit.

The new hybrid structures show optical and electronic transport properties that are different to those of pure graphene and hexagonal BN. Electrical measurements on the samples show that the conductivity increases with increasing C concentration (with a lowest nominal resistance of 10^{-3} Ω cm), implying that the electric properties of the films can be tuned from insulating to highly conducting. In addition, the temperature reduction of the measured resistance clearly demonstrates the semiconducting nature of the films. Remarkably, the new BCN layers show an ambipolar field-effect transistor behaviour similar to that of graphene, with an electron and hole mobility ranging between 5–20 $cm^2\ V^{-1}\ s^{-1}$, which is about four orders of magnitude smaller than that of graphene. This result supports the presence of BN and C domains instead of a stacked structure, and it is consistent with first-principles studies performed by the authors of ref. 8.

The realization of hybrid layered structures opens the path towards having 2D and one-dimensional (rolled layer) heterostructures with new properties dictated by their structure and composition. Looking at BN in an otherwise perfect graphene structure, many fundamental issues could be answered through careful studies of these new few-layer materials. These issues include: (1) the transition from a weak to strong Anderson localization regime in two dimensions as a function of the density of BN domains (acting as long-range scattering centres); (2) the possible appearance of edge states localized at the BN/C interface that could be spin-polarized (or not) and lead to half-metallicity (as predicted for some graphene[10] and BCN ribbons[11]; and (3) the possibility of

using voltage to tune the optical and lasing devices based on BN (ref. 12). The work by Ci *et al.* will help the development of an entirely new and exciting field for both basic physics and optoelectronic applications of low-dimensional BCN materials. By changing the processing conditions one should be able to find other stable or metastable phases with different relative compositions (that is, $B_xC_yN_z$) and dimensionality (from clusters to nanotubes to molecular solids and three-dimensional structures). ❐

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FERROELECTRICS

A new spin on spintronics

The use of a ferroelectric tunnel junction to control the spin polarization of adjacent magnetic electrodes promises a new approach to the use of interface effects for low-power-consumption spintronic devices.

R. Ramesh

The ever-increasing demand for faster, smaller and non-volatile electronics is pushing the limits of present semiconductor-based information processing and storage systems. Convoluting this development towards smaller device sizes is the fact that power-consumption requirements are increasing as transistor sizes shrink to the sub-100-nm regime. All of these point to the desperate need to have ultralow-power electronics for both information processing and storage. In the past decade, dramatic advances have been made on both fronts, namely the emergence of spintronics as a totally different approach to information processing, using the spin of the electron as the fundamental quantum of information, as well as the emergence of several low-power, non-volatile, information-storage technologies[1]. One of the manifestations of the spintronics approach is to use a spin current to create a 'spin torque' that can be subsequently transferred to a magnetic element, such as a domain wall[2] (Fig. 1). However, this requires the passage of significant amounts of electrical current, typically of the order of several tens of milliamperes. These currents can be extremely prohibitive in terms of energy consumption. Thus, it would be highly desirable to explore pathways that would allow the control of the magnetic state of the ferromagnet using electric fields instead of currents. Writing in *Science*, Vincent Garcia and co-workers[3] now present an exciting new development in this direction by demonstrating low-power control of magnetoresistance across a ferroelectric tunnel junction with ferromagnetic electrodes.

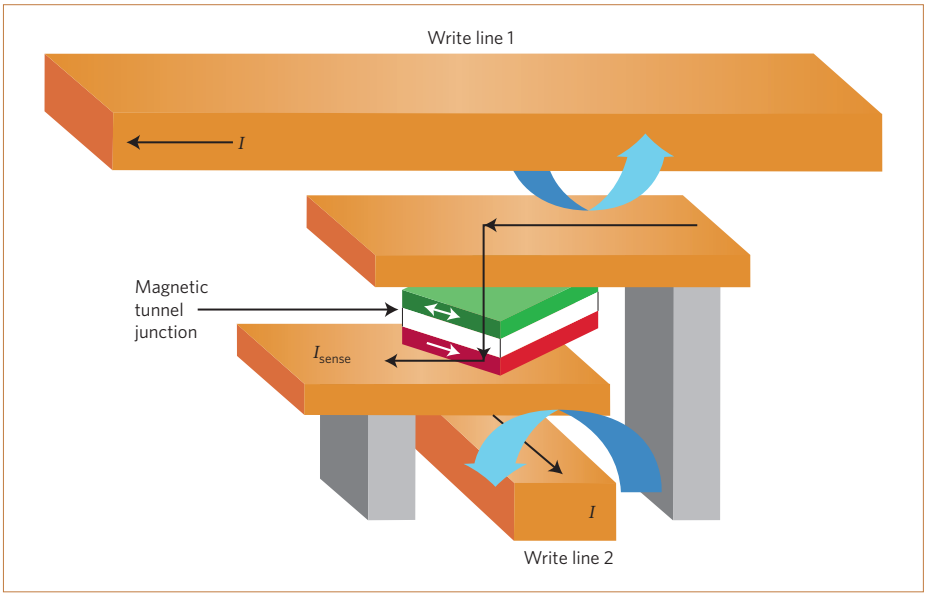

Figure 1 | Electric control of magnetism in a storage device. In magnetic random-access memory, an electric current I is used to apply a magnetic torque (blue arrows) that switches the magnetization (white arrows) in one layer (green) with respect to a layer with a fixed magnetization (red). I_{sense} denotes the sensing current. Figure adapted from ref. 1.

There has been a considerable amount of research activity recently that is directly aimed at exploring magnetism with electric fields. Clearly, the use of the latter necessitates the use of insulators because free charge carriers would otherwise screen the applied electric fields. One tantalizing possibility is one that involves the use of multiferroics (such as antiferromagnetic ferroelectrics) in contact with a ferromagnet as a pathway to control the ferromagnetic state. Ferromagnetic layers in contact with an antiferromagnet exhibit an interfacial magnetic coupling, termed as exchange bias coupling. If such an antiferromagnet is a magnetoelectric multiferroic, then in principle the interface coupling can be controlled and manipulated by the application of an electric field. The rudiments of this approach has been demonstrated through imaging of the magnetic state[4] and by means of low-temperature magnetotransport studies[5].

An alternative approach is to use a ferroelectric layer as a tunnel barrier between