

characteristics and are thus not specific enough, especially in complex mixtures. Finally, the fluidity of the lipid bilayer inside the nanopore also reduces the likelihood of pores being clogged by protein aggregates, addressing another major issue in nanopore sensing. Amyloid-beta proteins that are used as a model system were shown to translocate smoothly through the pores.

Mayer and colleagues⁷ have essentially killed four birds with one stone with the new approach. The fluid lipids have allowed specific proteins from dilute solutions to be concentrated and translocated at frequencies much higher than expected from the solution concentration and without clogging the pores.

This new technology is not restricted to improving the sensing performance of nanopore devices. The idea of being able to deliver certain molecules, say proteins or enzymes, to a well-defined location on the nanopore could also be applied to assemble particular types of molecules, supramolecular structures or more complex molecular 'machines' at or inside the nanopore⁸. This may offer interesting prospects for the design of single-molecule devices or biological/solid-state hybrid structures potentially for many devices in parallel, say on a wafer scale.

The introduction of the 'fluid-wall technology' seems to be just the beginning of an exciting new development in nanopore

research and, more generally, biological nanotechnology as a whole. □

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NANOELECTRONICS

Making light of electrons

Electrons have been channelled through graphene wires using the principles of optical guiding by fibre optic cables.

David Goldhaber-Gordon

Science and technology often rely on analogy to make progress. For example, photonic crystals are periodic materials that allow only certain wavelengths of light to propagate in them, in the same way that crystalline semiconductors allow electrons with only certain energies to move through them. Electronic counterparts of familiar optical components such as pinhole sources¹, interferometers², beam splitters and electron beam lenses^{3,4} have also been built. These advances exploit the shared wave nature of electrons and photons, and have been made possible by developments in semiconductor materials growth and nanofabrication that allow the patterning of the potential energy landscape experienced by an electron on submicrometre scales and with extremely low disorder. Now, the electron has been made to mimic the photon in a new way, courtesy of graphene. Writing in *Nature Nanotechnology*, Charles Marcus and co-workers at Harvard and Purdue University report that they have guided electrons through narrow graphene channels by exploiting the same principles by which light is guided through a fibre optic cable⁵.

Electronic waveguides (such as nanowires) typically work by creating a potential energy step that prevents mobile electrons from leaving the waveguide. However, an electronic analogue of the optical fibre has not been demonstrated. Optical fibres guide light through a core region (with a high refractive index)

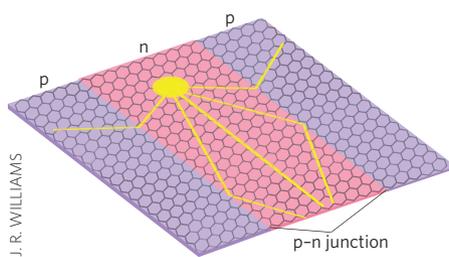


Figure 1 | Electrons from a point source (yellow circle) travel down a graphene p-n waveguide, consisting of two hole-rich areas (p) and a central, electron-rich area (n). Electrons incident on the p-n junction at glancing angles are reflected back into the n-type core, whereas those incident at larger angles escape into the p-type cladding. The unusual bend in the escaping trajectories is characteristic of a change in the sign of the index of refraction.

that is surrounded by cladding (with a lower refractive index). Light hitting the core-cladding interface bends and, for a shallow enough incident angle, is trapped in the core. This phenomenon, known as total internal reflection, allows the guiding of light over tens of kilometres without the need for signal regeneration.

Now enter graphene. In this material, it is impossible to exclude electrons from some regions of space using simple potential energy steps, so there is a motivation for examining other ways of guiding

electrons. Furthermore, the possibility of light-like guiding in graphene is somehow more obvious than it is in conventional semiconductors. This is because the relationship between the energy and wavelength of electrons in graphene is very similar to the corresponding relationship in photons, because electrons in graphene behave as if they were massless, in close analogy to massless photons. In retrospect, it is clear that light-like electron guiding could be done in conventional semiconductors as well, and perhaps that will be fruitfully explored in the coming years.

There are two possible approaches to achieve light-like guiding of electrons in graphene. First, in direct analogy to a fibre optic cable, one can construct an electronic 'cladding' with a lower density of carriers than in a corresponding 'core' to achieve so-called optical guiding. Or, more exotically, the cladding and core charge densities can be made opposite to one another, by arranging for one to carry holes and the other electrons, resulting in p-n guiding (Fig. 1). This gives the cladding an effectively negative index of refraction, a concept also borrowed from optics^{6,7}.

Marcus and collaborators simulate, then build, both types of guiding configuration in graphene wires. They focus on calculating and measuring the guiding efficiency, which is the portion of electrons injected at one end of the wire that successfully transit to the other end. A simulation of an idealized,

disorder-free gated graphene waveguide predicts that optical guiding will be 53% efficient (Fig. 2b of ref. 5), p–n guiding will be 39% efficient (Fig. S3b of ref. 5), and a combination of both approaches will be 55% efficient (Fig. S3c of ref. 5).

These calculated efficiencies are all far less than 100% because electrons coupled into the waveguide are not collimated, so some of them hit the borders of the waveguide at angles that allow escape. In other words, the waveguide's efficiency is limited by the quality of input coupling, rather than the difficulty of guiding over long distances (the waveguide is actually quite short, only 100 nm long). Fibre optic cables, too, require incoming light to be carefully shaped. The collimation required in graphene might be achieved using a p–n junction at the entrance to the waveguide^{7,8}.

The experimentally measured efficiencies were even lower — 20% at best — and in particular pure p–n guiding turned out to be much less effective than optical guiding. Why the discrepancy from the calculations? First, the electrostatically defined walls of the graphene waveguide are not perfectly straight⁹, primarily because of charged defects above or below the

graphene sheet. A given density of charges produces more potential fluctuation in the case of a p–n junction than between two n-type regions, because screening is poorer when there are few mobile charges: thus the location where carriers transition from electrons to holes meanders as one goes along the waveguide. Presumably this could be improved using recent developments in which disorder in graphene can be reduced by putting it on an atomically flat substrate with few charged defects, such as hexagonal boron nitride¹⁰.

Even with these improvements, there will be limits to how far electrons can be guided. Unlike in high-quality glass in which light can travel long distances without escaping, the same disorder that causes the borders of a graphene waveguide to meander causes today's cleanest, pristine graphene to have an electron mean free path of less than a micrometre. Thus, electrons have their directions randomized every micrometre or less, and so will eventually hit the interface nearly head-on and escape. Nonetheless, guiding electrons in a 10-nm-wide waveguide over a distance of a micrometre could be very interesting for future, reconfigurable electronics, and

the concepts demonstrated by Marcus and co-workers⁵ may be combined with other phenomena such as magnetic deflection¹¹ to further increase efficiency and guiding distance. □

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NANOELECTRONICS

A topological twist for transistors

A nanoribbon of a material with topological surface states has been used as the channel in a field-effect transistor.

Qi-Kun Xue

An ordinary insulator such as glass cannot conduct electricity because electrons are not free to move through the material, but physicists have recently discovered a special type of insulator that behaves somewhat differently. The electrons inside or in the bulk of these 'topological insulators' behave like the electrons in conventional insulators. However, topological insulators have surface states in which electrons can flow as easily as in a metal. A topological insulator can thus be thought of as a glass that is coated with a very thin (~1 nm thick) layer of metal on its surface (or along its edges for a two-dimensional topological insulator). More importantly, these surface or edge states possess exotic properties that could prove useful in applications such as error-tolerant quantum computation and low-power electronics^{1–3}.

These exotic properties result from the combined effect of spin–orbit interactions and time-reversal symmetry, and thus topological

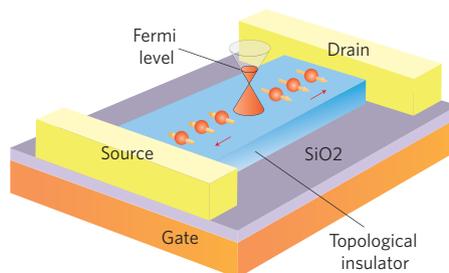


Figure 1 | A FET in which the channel is a topological insulator nanoribbon⁷. The dispersion relation of the surface electrons (that is, their energy plotted as a function of their momentum) is cone shaped, and applying a voltage to the gate electrode can move the Fermi level up or down this Dirac cone. The spins of the surface electrons (orange arrows) are also polarized, and electrons with opposite spins move in opposite directions (red arrows). This spin polarization could prove useful for low-power spintronic devices.

insulators are usually composed of heavy elements (Bi, Se, Te, Hg and so forth) because the larger nuclear charges of such elements lead to stronger spin–orbital coupling^{4–6}. Crucially, the conducting surface or edge states exist at all the surfaces or edges of a topological insulator, no matter what the crystalline orientation or atomic arrangement or other details of the surfaces/edges look like.

Photoemission experiments have shown that the surface states of several topological insulators, notably Bi₂Te₃ and Bi₂Se₃, are spin-polarized and have cone-shaped dispersion relations (see Fig. 1)^{4,6}. However, the energy gap between the conduction and valence bands in the bulk is very small, so the charge carriers in the surface states can easily be overwhelmed by charge carriers from the bulk, which makes it very difficult to explore the exotic nature of the surface states.

For topological insulators to be useful in electronic devices, it will be necessary to separate the surface states from the