GRAPHENE

Quantum information on chicken wire

The ability to build electronic structures from graphene sheets has progressed significantly. Two theoretical studies suggest that graphene nanostructures could be used for quantum information processing.

Vladimir Fal’ko
Is in the Physics Department of Lancaster University, Lancaster LA1 4YB, UK.
e-mail: v.falko@lancaster.ac.uk

Graphene — the name by which a single atomic sheet of graphite is known — is a remarkable material. Not only is this atomically thin film chemically and structurally stable, but it is also conductive. In 2004, Geim and co-workers’ developed techniques to separate individual graphene flakes from pyrolitic graphite crystals to produce the first graphene-based field-effect transistor. This led to the discovery by several groups that the charge carriers in graphene behave as if they were effectively massless — prompting great excitement over the possibilities this presents for exploring new physics and new applications alike. Two theoretical studies in this issue continue this exploration to propose graphene device structures with unexpected functionality. The first, on page 172 by Rycerz and colleagues, suggests that graphene valley-like electronic bands could be exploited in a similar manner to the way in which spin is used in the emerging field of spintronics. This report, as well as the second, on page 192, by Trauzettel and colleagues, suggests how to build an array of solid-state qubits using graphene nanoribbons.

The unique electronic band-structure of graphene was predicted well before a single sheet was successfully isolated. Graphene is a gapless semiconductor whose Fermi level is located near the points in its electronic structure where its conduction and valence bands touch. These degenerate points, known as Dirac points, are located in the corners of graphene’s hexagonal Brillouin zone of this material. Owing to the 120° rotational symmetry of the honeycomb lattice, these define two valleys at different points in momentum space, in which carriers can move. Moreover, the conical shape of the dispersion relation near the bottom of each valley means that the energy of carriers travelling within them varies linearly with their momentum — as if they were massless — according to a Dirac-type hamiltonian, $\mathbf{p}\cdot\mathbf{\alpha}$. The 2x2 Pauli matrices, $\mathbf{\alpha}$ in this hamiltonian, describe the amplitudes of the electronic wave function with respect to two triangular sublattices within the overall honeycomb structure. A consequence of this is that graphene’s charge carriers are ‘chiral’, so that the contribution of each sublattice to a carrier’s wavefunction depends on the direction in which it propagates. This property is responsible for the unusual sequencing of plateaus observed in measurements of the quantum Hall effect.

When a voltage is applied to the gate of a graphene field-effect transistor, the carrier density in a graphene sheet can be varied continuously from p-type (hole) to n-type (electron) conduction. This behaviour could be useful for building networks of p- and n-type regions within a single graphene sheet, by applying voltages to individual electrodes in an array of split gates. Such a device would offer the appealing possibility of creating electron (or hole) puddles, similar to lateral quantum dots in conventional semiconductor structures. Would this enable the spin state of electrons populating each puddle/dot to be controlled? And if the dots were close enough to couple these spins by exchange interaction, would it be possible to form a network of coupled spin qubits? In turns out, however, that the p–n junctions envisaged to form such qubits leak charge considerably. When a conduction-band electron in an n-type region is incident perpendicular on an interface with a p-type region, the probability that it will transmit through the interface and into the valence band on the p-type side is exactly one. This makes it impossible to form a conventional-type quantum dot — one that accommodates a well-defined number of confined electrons — inside an infinite graphene sheet.

Both Rycerz et al. and Trauzettel et al. show that such difficulties can be overcome by forming devices along narrow strips of graphene — so-called nanoribbons — rather than in the middle of a large sheet. For this to work, the edges of these strips must be terminated in a very particular way — they must have either an ‘armchair’ or a ‘zig-zag’ structure. In the case of a nanoribbon that has armchair edges, both sublattices of graphene’s hexagonal structure will be terminated equally on both sides. This causes the amplitude of the two-component wavefunction of graphene’s charge carriers to be zero at the edges, and results in the emergence of a gap — whose value is inversely proportional to the ribbon’s width — in the spectrum of propagating electronic modes. Trauzettel et al. suggest this could enable individual carriers to be localized by a sequence of electrodes placed along a graphene nanoribbon. Applying a voltage to these electrodes forms a series of barriers along the ribbon. The regions between these barriers represent quantum dots capable of accommodating individual qubits on a graphene nanoribbon. Barrier electrodes (blue) spaced along a nanoribbon of graphene with armchair edges, define quantum dots that can accommodate individual charge carriers (coloured spheres) on the regions between. The direction of the electronic spin (coloured arrows) of the carrier on a given dot represents a single spin qubit. A second set of gate electrodes (red) underneath these regions enables the coupling between qubits to be controlled. (Image used with permission of Guido Burkard.)
charge carriers, and the spin on each dot can be used to represent individual qubits (see Fig. 1). Moreover, with a second array of gate electrodes under each qubit, their calculations suggest it should be possible to control the exchange coupling between each qubit — a system that could eventually be used for quantum computation.

Conversely, if the edges of a graphene nanoribbon are terminated with a zig-zag structure, the amplitudes of Bloch states are not necessarily zero on both sublattices. In this case, the spectrum of propagating electronic modes in the ribbon does not develop a gap, whereas the chiral nature of graphene charge carriers means that carriers travelling in different directions along such a ribbon must do so in different valley states. Consequently, a current driven in one direction along such a nanoribbon will be carried by electrons in one valley, whereas current driven in the opposite direction will be carried by electrons in the other. Rycerz et al. suggest that the ability to differentially populate — or polarize — the valley states of graphene could be used to represent information, in the same way that charge is used in digital electronics, or spin in the putative field of spintronics. To this end, they set out to demonstrate how two rudimentary ‘valleytronic’ devices might be constructed. The first, a valley filter, is nothing more than a quantum point contact that completely polarizes the valley states of a zig-zag-edged graphene nanoribbon by injecting current in one direction only. The second, a valley valve, consists of two point contacts in series — one acting as a polarizer and the other as an analyser — which allows current to flow in one direction (and thus one valley) but prevents it from flowing in the other (and thus the other valley) depending on the relative bias applied to each of two gates situated over each contact. Moreover, a pair of valley valves can be manipulated electronically to operate as a quantum dot, thus becoming a building block for a chain of coupled qubits similar to that proposed by Trauzettel et al.

The significance of both proposals will not be truly known until attempts are made to realize them in real working devices. Although both groups have attempted to anticipate the difficulties that might arise, it is of course impossible to take account of an unforeseen hurdle. Even if others manage to manufacture qubits proposed by Trauzettel et al., one may wonder what would be their scalability to a practically useful array. Indeed, owing to the one-dimensional geometry of graphene nanoribbons, their use may be practically limited by similar issues to those that limit the scalability of nanotube electronics. But there may even be solutions to this. In bilayer graphene, for example, a transverse electric field opens a gap between the conduction and valence bands that can be controlled by pairs of top and bottom gates. This could enable similar ideas to be adapted to the formation of 2D quantum dot arrays on such bilayer sheets. But here too, only time, and experiments, will tell.

References