Researchers exploring spintronics in graphene

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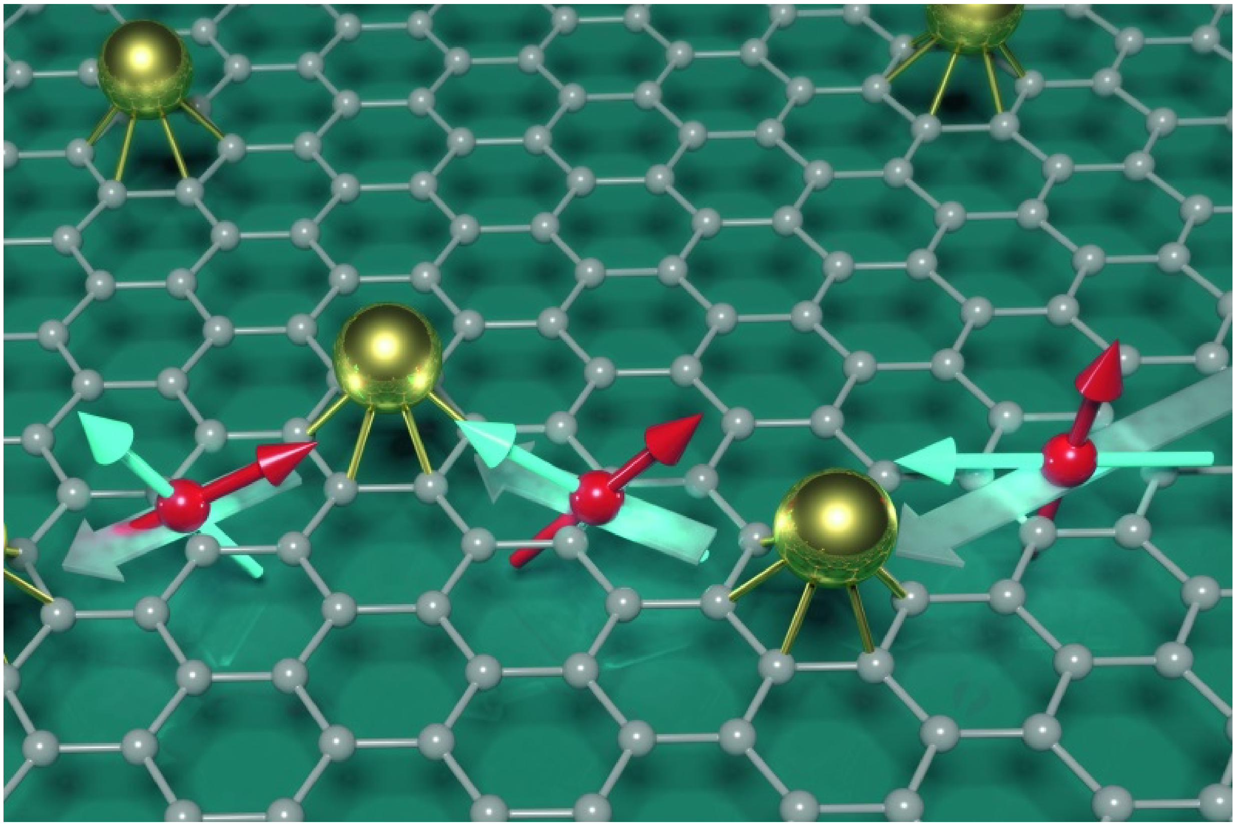

Illustration of electron spin in a graphene lattice. Credit: Bart van Wees

Electronics is based on the manipulation of electrons and other charge carriers, but in addition to charge, electrons possess a property known as spin. When spin is manipulated with magnetic and electric fields, the result is a spin-polarised current that carries more information than is possible with charge alone. Spin-transport electronics, or spintronics, is a subject of active investigation within Europe's Graphene Flagship.

Spintronics is the study and exploitation in solid-state devices of electron spin and its associated magnetic moment, along with electric charge. Some consider the topic esoteric, given the conceptually challenging quantum physics and chemistry that underpins it, but the same was once said of what today is mainstream electronics. The reality is that spintronics is a maturing field of applied science and engineering, as well as fascinating pure science in its own right.

Electron spin and quantum logic

Before looking at spintronics in graphene, it is worth noting that spintronics is already established in one critical area of digital electronics, namely data storage.

Spin can be thought of as the rotation of the electron around its own axis. It is a form of intrinsic angular momentum, and can be detected as a magnetic field with one of two orientations: up and down. Combine these magnetic orientations with the on/off current states in binary logic, and we have a system of four states, with the two magnetic orientations forming a quantum bit, or qubit.

In computing technology terms, four states rather than two provides for higher data transfer speeds, increased processing power and memory density, and added storage capacity. Electron spin provides an additional degree of freedom to store and manipulate information.

The read heads of modern magnetic hard drives exploit the spin-related effects known as Giant Magnetoresistance (GMR) and Tunnel Magnetoresistance (TMR). In GMR devices, two or more layers of ferromagnetic materials are separated by a spacer. When the magnetisation vectors of the magnetic layers are aligned, the electrical resistance is lower than when the vectors are in the opposite sense. A device based on such a configuration is known as a spin valve. In TMR, electron transport is achieved by quantum mechanical tunnelling of the particles through an insulator separating ferromagnetic layers.

In both cases, the result is a magnetic field sensor that may be used to read data magnetically encoded on hard drive platters. And not only hard drives. Two types of computer memory – Magnetoresistive Random Access Memory and racetrack memory – also exploit electron spin.

Spin transport in graphene

Graphene, an atomic monolayer of graphitic carbon, is a promising material for spintronics applications owing to its capacity for room-temperature spin transport over relatively long diffusion lengths of several micrometres. Graphene also has high electron mobility, and a tuneable charge carrier concentration.

Interest in room-temperature spin transport in graphene goes back to 2007, with experiments performed by the research group of Groningen University physicist and leading Graphene Flagship scientist Bart van Wees. A discussion of that first practical demonstration of spin transport, together with a detailed technical overview of graphene spintronics in theory and practice, can be found in an article published last year in the academic journal *Nature Nanotechnology*. One of the review authors is Regensburg-based flagship scientist Jaroslav Fabian.

The van Wees group experiments and subsequent studies showed a relatively low spin injection efficiency of around 10%, which was attributed to either a conductance mismatch between the ferromagnetic metals and graphene, or other contact-related effects. Considerably higher efficiencies were achieved by using magnesium oxide thin films as the tunnel barrier.

Further approaches were also employed, including pinhole contacts across an insulating barrier, transparent contacts, in which the ferromagnetic electrodes are in direct contact with the graphene layer, and the use of non-magnetic metals such as copper. In the case of tunnelling across an insulating barrier, the largest magnetoresistance measured was 130 ohms, corresponding to a spin injection efficiency of over 60%.

Moving from small-scale studies to investigations of spin transport in large-area graphene is a key step toward enabling graphene spintronics at the integrated-circuit wafer scale. The focus here has been on spin transport in suspended graphene layers, and graphene deposited on hexagonal boron nitride (hBN) substrates. As the technology progresses, longer spin lengths and lifetimes are observed, and a practical example of such a graphene-hBN heterostructure will be discussed in a follow-up article.

Making graphene magnetic

Creating magnetic order in graphene, which in its pristine state is a strongly diamagnetic material, is a major challenge. Nonetheless, inducing magnetic moments in graphene is of vital importance if the material is to be used in spintronics. The hope is to have a tuneable magnetism through doping or functionalisation of graphene. This could be achieved through defects in the material's hexagonal crystal structure, or the influence of adsorbed atoms on its surface.

Hydrogenated graphene is a benchmark case for graphene magnetism, with hydrogen atoms chemically absorbing onto graphene in a reversible manner. This creates an imbalance in the crystal lattice, inducing a magnetic moment. Another interesting adatom is fluorine, which bonds to carbon, transforming graphene into a wide-gap insulator. As with hydrogen, fluorine can be reversibly chemisorbed on graphene.

"Graphene is a promising material for spintronics, given that its spin properties can not only be tailored, but indeed defined by what adatoms and other 2d materials you combine with it," says Fabian. "Once the right materials are identified – and this is what we are investigating in the flagship – a path opens towards specific technological applications."

A missing carbon atom, or vacancy in graphene's structure, creates a spin-polarised electron density by stripping four electrons from the bands, three of which form 'dangling bond' states. Two of these dangling bonds contribute magnetic moments, but direct evidence of the predicted π-magnetism is missing.

Extending spin lifetime

Maximising spin lifetime is critical when it comes to applications of graphene spintronics. Theory predicts lifetimes of around a microsecond for pristine graphene, whereas experiment shows values ranging from tens of picoseconds to a few nanoseconds. Only with nanosecond lifetimes and longer will spin transport in graphene prove useful in real-world applications. The more than two orders of magnitude discrepancy is a serious concern, and it suggests that the source of spin relaxation is of extrinsic origin, such as impurities, defects or ripples in the graphene studied.

Spin lifetimes of a few nanoseconds have been observed experimentally for graphene spin valves on silicon dioxide substrates with tunnelling contacts, but with pinhole contacts the measured lifetimes are only a fraction of a nanosecond. Contact-induced spin relaxation is a significant factor. This can be minimised by improving the quality of the contacts, and making the distance between ferromagnetic electrodes much larger than the bulk graphene spin-relaxation length.

Despite numerous theoretical studies, the origin of spin relaxation in graphene is little understood. Two mechanisms have been put forward to explain experimental trends. Both have their origins in metal and semiconductor spintronics, and they each rely on spin-orbit coupling and momentum scattering. Spin-orbit coupling is the interaction of an electron's spin with its motion, which leads to shifts in the particle's atomic energy levels as a result of the interaction between the spin and the magnetic field generated by the electron's orbit around the atomic nucleus.

The problem is that neither of the proposed spin relaxation mechanisms work. Both predict microsecond lifetimes, yet experiments show a few nanoseconds at best. The only mechanism that agrees with experiment for both single and bilayer graphene is based on resonant scattering by local magnetic moments. This model was proposed by Fabian's research group in Regensburg.

What recent studies indicate is that electron mobility is not the limiting factor for spin lifetime, and scattering between charged particles and impurities is not primarily responsible for spin relaxation in graphene. That said, determining the primary source of spin relaxation remains an important challenge for graphene researchers. Identifying it should help raise spin lifetime in graphene towards the theoretical limit, which will have important implications for both basic science and technological applications.

Future directions

In the conclusion to their Nature Nanotechnology review, Fabian and his colleagues consider graphene in spin-transfer torque-based logic devices that use spins and magnets for information processing. Spin-logic devices are now part of the International Technology Roadmap for Semiconductors, with a view to their inclusion in future computers.

Examples of spin-logic devices include rewritable microchips, transistors, logic gates, magnetic sensors and semiconductor nanoparticles for quantum computing. These and other opportunities for graphene-based spintronics are discussed in the recently published "Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems". The roadmap was developed within the framework of Europe's Graphene Flagship – an international academic/industrial consortium, part-funded by the European Commission, devoted to the development of graphene and other layered materials.

Spintronics may be a relatively young field of research and development, but in recent years we have seen significant progress toward long spin lifetimes and diffusion lengths in graphene and related materials. Graphene Flagship researchers are at the heart of this worldwide effort.

More information: "Graphene spintronics," *Nature Nanotech*. 9, 794 (2014); DOI: 10.1038/nnano.2014.214

"Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems," *Nanoscale* 7, 4598 (2015); DOI: 10.1039/C4NR01600A

Provided by Graphene Flagship

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