NANOELECTRONICS

Flat transistors get off the ground

The presence of a large bandgap means that a single layer of molybdenum disulphide can be used to make field-effect transistors with high on/off ratios and reasonably high mobilities.

Frank Schwierz

Over the past four decades, performance improvements in semiconductor electronics have been driven by 'scaling' or reducing the dimensions of field-effect transistors. Today, logic chips contain billions of silicon-based metal–oxide–semiconductor field-effect transistors (MOSFETs) with gate lengths of just 20–30 nm, and devices made from compound semiconductors such as gallium arsenide or indium phosphide have enabled radio-frequency (RF) circuits to operate at frequencies of several hundred gigahertz.

Unfortunately, the scaling of field-effect transistors (FETs) is expected to reach fundamental limits in the near future, so researchers are busy searching for alternative device concepts. One option is to explore entirely new physics with, for example, spin transistors or single-electron devices. Another route is to stick with the FET concept and introduce new materials. Transistors in which the channel that connects the source and drain electrodes is made of graphene — a single layer of carbon atoms — are expected to be scalable beyond the limits of silicon MOSFETs and should also be able to compete successfully with conventional RF devices in low-power high-frequency applications[1–3]. Now, in *Nature Nanotechnology*, Andras Kis and co-workers at the EPFL in Switzerland report that they have made MOSFETs with another flat material, namely molybdenum disulphide[4] (Fig. 1). This raises an intriguing question: could MoS_2 be a serious competitor for graphene?

In addition to the source and drain electrodes, a FET also contains a gate electrode that is used to control the conductivity of the channel by means of the electric field effect. The channel material in a FET is usually a semiconductor and it needs to meet a number of requirements. First, it must be possible to switch off the device — otherwise it is useless for digital logic — which means that the semiconductor used to make the channel should, preferably, have a bandgap of ~0.4 eV or more. Second, to obtain high power gain, the drain current should saturate as the voltage applied across the source and drain electrodes is increased. This is particularly important for RF transistors. Third, short-channel effects must be suppressed, otherwise the performance of the transistor will be degraded. It has been shown that short-channel effects can be reduced if the channel and the gate dielectric (the layer between the gate electrode and the channel) are very thin. Fourth, and finally, a high carrier mobility in the channel is needed to increase the switching speed of the transistor.

Graphene shows very high mobilities and is extremely thin, but a large area of pristine graphene does not have a bandgap, so it does not meet the first of these requirements[1,2]. A gap can be opened by making graphene nanoribbons just a few nanometres wide, and excellent switch-off

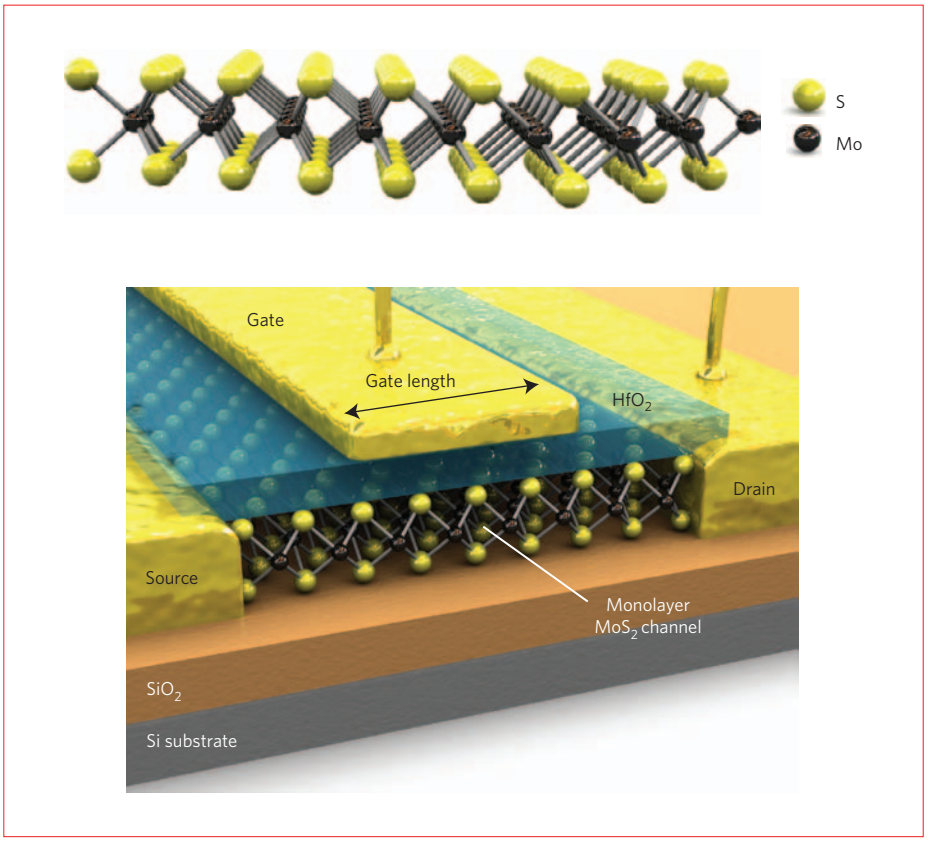

Figure 1 | Single layers of MoS_2 have a large bandgap, which is needed to make transistors for various applications. Top: A single layer of MoS_2 is a few ångströms thick and consists of molybdenum atoms (black) sandwiched between two layers of sulphur atoms (yellow). Schematic (not to scale) of the MOSFET devices made by Kis and co-workers[4]: the channel is a layer of MoS_2 that is 1.5-μm long and 4-μm wide; the gate length is 500 nm. The source, drain and gate electrodes are made of gold, and hafnium dioxide (transparent layer) is used as the gate dielectric and also to boost the mobility of the channel. The devices are fabricated on silicon dioxide on silicon substrates.

has been observed in such nanoribbons in the lab[5], but at present it is not possible to manufacture large numbers of devices containing such narrow nanoribbons. Moreover, the gap opening observed in the lab was accompanied by a dramatic reduction of the mobility.

Monolayer MoS_2 is composed of one layer of molybdenum atoms sandwiched between two layers of sulphur atoms (Fig. 1), so it is only a little thicker than graphene and is much thinner than the channel regions of conventional FETs. However, even more exciting is the fact that monolayer MoS_2 is a semiconductor with a bandgap of 1.8 eV, compared with 1.1 eV for silicon. Moreover, just as graphene can be mechanically exfoliated from graphite, monolayer MoS_2 can be exfoliated from commercially available MoS_2 crystals and then transferred to oxidized silicon wafers. Indeed, the Manchester group that first exfoliated graphene in 2004 also reported the exfoliation of monolayer MoS_2 in 2005[6], but the observed mobilities were small.

Initially, the mobilities measured by the EPFL researchers were also very low, but by depositing hafnium dioxide on top of the MoS_2 monolayer, they were able to increase the mobility to more than 200 $cm^2\ V^{-1}\ s^{-1}$. Although this is much lower than the mobilities measured in compound semiconductor devices, it is comparable to the values reported for silicon MOSFETs and graphene nanoribbons. Kis and co-workers also fabricated MoS_2 MOSFETs with a gate length of 500 nm that had excellent switch-off characteristics.

The EPFL team proposes to go beyond the classical MOSFET design and exploit a phenomenon known as interband tunnelling to make MoS_2 devices for ultra-low-power logic applications. A less revolutionary option would be to explore MoS_2 devices for RF applications. Provided the bandgap and thinness of the MoS_2 monolayer translate into good current saturation, these devices should offer both high RF current and power gains, and a correspondingly high cutoff frequency and maximum frequency of oscillation. Large-area graphene MOSFETs with cutoff frequencies of 100–300 GHz have been reported[7], but the maximum oscillation frequency for these devices is rather low.

By fabricating the first transistor with a single-layer channel made from a flat material other than graphene, the EPFL team has made significant progress, but it is still only a first step towards useful MoS_2 transistors and many challenges remain. Compared with graphene technology, which itself is still exotic, MoS_2 processing is in an embryonic stage. Moreover, and this is crucial for the acceptance by the semiconductor industry, a wafer-scale preparation scheme (which is, in principle, already available for graphene[8,9]) has yet to be developed for MoS_2. And from the electrical point of view, it has to be proved that the ultrathin MoS_2 channel really suppresses short-channel effects and leads to good RF performance. However, enough progress has been made for us to say that yes, MoS_2 is a new competitor for graphene. ❐

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References

1. Avouris, Ph. *Nano Lett.* **10,** 4285–4294 (2010).
2. Schwierz, F. *Nature Nanotech.* **5,** 487–496 (2010).
3. Geim, A. K. & Novoselov, K. S. *Nature Mater.* **6,** 183–191 (2007).
4. Radisavljevic, B. *et al. Nature Nanotech.* **6,** 147–150 (2011).
5. Wang, X. *et al. Phys. Rev. Lett.* **100,** 206803 (2008).
6. Novoselov, K. S. *et al. Proc. Natl Acad. Sci. USA* **102,** 10451–10453 (2005).
7. Liao, L. *et al. Nature* **467,** 305–308 (2010).
8. Berger, C. *et al. J. Phys. Chem. B* **108,** 19912–19916 (2004).
9. Li, X. *et al. Science* **324,** 1312–1314 (2009).

SUPRAMOLECULAR STRUCTURES

Robust materials from weak forces

Recyclable membranes that are capable of separating nanoparticles of different sizes can be prepared from supramolecular assemblies that are held together by non-covalent bonds.

Carsten Schmuck

Everyday materials such as steel, concrete, plastics or ceramics are almost always robust and stable. The materials have to withstand external physical forces and we expect them to be held together by strong molecular forces. And traditionally these materials are indeed based on the strongest chemical forces we know. For example, ceramics are three-dimensional (3D) crystals held together by long-range electrostatic interactions, whereas the monomers in polymers are connected by covalent bonds. However, the formation of such materials is irreversible and a lot of energy is required to break them down. Therefore, the structures and properties of the materials can not adapt to changes in their surroundings. Alternatively, supramolecular chemistry[1] focuses on molecules held together by weak intermolecular forces such as hydrogen bonds, dipole–dipole interactions, aromatic interactions and solvophobic effects. Owing to the very low strength of these interactions (a few kilojoules per mole per interaction in contrast to the few hundred kilojoules per mole for covalent bonds), the formation of supramolecular systems is in most cases reversible. Furthermore, supramolecular structures can be altered by changing external parameters such as pH, temperature or solvent composition.

These properties have already been used to develop responsive materials that can, for example, adopt different structures (such as vesicles or rods) depending on solvent or pH[2]. However, the weak nature of the intermolecular forces also creates problems for any real-world application. Specifically, supramolecular materials are usually formed only under special conditions, such as in non-polar solvents and in the absence of moisture[3], and their mechanical stability is limited because even weak external physical forces can overwhelm the intermolecular forces holding them together. Therefore, it is a significant challenge to combine the mechanical stability and robustness of covalent structures with the reversibility and external switchability of supramolecular systems. Writing in *Nature Nanotechnology*, Boris Rybtchinski and colleagues at the Weizmann Institute of Science now report an elegant example of such a material: a recyclable supramolecular membrane that can be used in the size-selective separation of nanoparticles[4].

The membranes are formed from a large, flat aromatic molecule called perylene,