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# News & views

**Materials science**

## A layered electron sieve infused with molecules

**Xi Ling**

A simple method for incorporating molecules into the gaps of stacked semimetallic materials through immersion offers an efficient way of filtering electrons, which could be useful for information-storage technologies. **See p.902**

An extraordinary thing happens when electrons pass through a material made of chiral chemical species, which have a handedness that distinguishes them from their mirror image. The spin of each electron (its intrinsic angular momentum) determines whether it can pass through the material: electrons in 'spin-up' states might be favoured, whereas those in 'spin-down' states might be blocked, or vice versa. This effect is known as chiral-induced spin selectivity[1,2] and it is useful for spintronics – the spin counterpart to electronics – in which information is stored in an electron's spin as well as its charge. Chiral molecules provide particularly high spin selectivity, but they are difficult to integrate into solid-state spintronic devices. On page 902, Qian and colleagues[3] report a simple, effective technique for introducing chiral molecules between the layers of systems known as van der Waals materials, in which sheets comprising one or a few layers of covalently bonded atoms are stacked together.

Chiral-induced spin selectivity has been explored in other solid-state systems, such as inorganic crystals[4], chiral organic–inorganic perovskite materials[5] and self-assembled chiral molecular films[6]. But such materials often lack structural uniformity, resulting in low spin selectivity across large areas of a sample, which in turn limits the material's potential applications. By inserting chiral molecular layers into the gaps of a van der Waals material (a process called intercalation), Qian *et al.* formed 'superlattices', consisting of alternating 2D atomic monolayers and highly ordered chiral molecular layers (Fig. 1), which mitigate the problems with homogeneity. These superlattices provide a platform for exploring chiral-induced spin selectivity in solid-state devices.

There have been many reports of intercalating species into van der Waals materials in the past few decades[7]. Even in the case of achiral species – which can be superimposed on their mirror image – such inclusions modify the way that the electrons in the layers of these materials behave and interact with each other. Superlattices can therefore be used as a means of making structures or phases of matter, or tuning material properties – with applications in energy-storage systems and superconductors, for example. Whether a species can be intercalated into a van der Waals gap depends on the size of the species and the way it interacts with the layers.

Qian *et al.* used three different semimetallic van der Waals materials as hosts: tantalum disulfide in two distinct phases, and titanium disulfide. Although the chiral molecules they used (the right- and left-handed forms of α-methylbenzylamine) are much larger than the gaps between layers in these materials, the intercalation happens harmoniously because of a unique interaction between the molecules and the layers. It occurs through a straightforward process, in which the host material is simply immersed in a pure liquid of the chiral molecules at the relatively mild temperature of 65 °C. Intercalation is complete after just 2 days in the case of titanium disulfide and one form of tantalum disulfide, whereas the second form needs 28 days to fully intercalate.

To demonstrate that the molecules were indeed in the gaps, the team used material-characterization techniques, including X-ray diffraction, atomic force microscopy and scanning transmission electron microscopy. They observed that the gaps in the superlattice were larger than those in the original material. Intriguingly, the crystal structure of the 2D layers was not affected by the intercalation, and the molecules were highly organized, thus forming high-quality superlattices with the

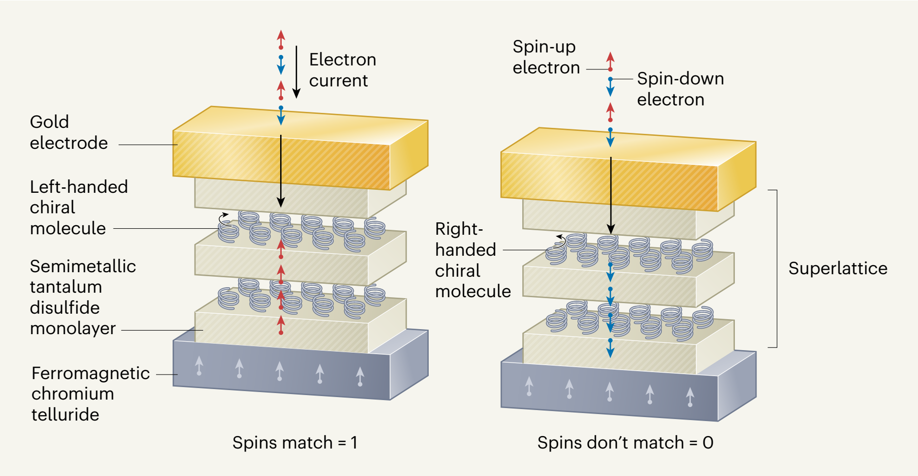

**Figure 1 | A molecular 'superlattice' for filtering electrons.** Qian *et al.*[3] introduced molecules between layers of semimetallic tantalum disulfide of single-atom thickness. This superlattice material filters out electrons that have a particular intrinsic angular momentum (spin, which can be up or down), depending on the chirality, or handedness, of the molecules. The superlattice's high spin selectivity was demonstrated with a device in which it was sandwiched between a gold electrode and a plate of chromium telluride, which exhibits ferromagnetism – a state in which spins are aligned parallel to each other. A current of electrons injected into the gold electrode was filtered by the superlattice and produced a high current (not shown) if the spin direction of the electrons matched that in the ferromagnet. In practical spintronic devices, this high current could correspond to the '1' state used in memory storage, whereas a low current arising from mismatched spins would be the '0' state.

intrinsic properties of both the 2D layers and the chiral molecules.

One common way to characterize the left- and right-handed forms of chiral molecules is circular dichroism spectroscopy, which measures the difference in the absorbance of left- and right-circularly polarized light by the molecules. The van der Waals hosts that Qian and colleagues studied are achiral, so they showed no such difference in absorbance. However, the authors could clearly see that the difference in the absorbances of the superlattices followed those of the chiral molecules exactly. And superlattices containing left- and right-handed molecules showed circular dichroism responses with opposite signs. These results suggest that the chiral molecules were successfully incorporated into the van der Waals hosts.

To showcase the spin selectivity of this new class of material, the team fabricated a solid-state device known as a spin tunnelling junction, which is the building block of the modern hard-disk drive. In a conventional spin tunnelling junction, an electrical insulator of nanometre thickness is separated by two electrodes exhibiting ferromagnetism, a state in which spins are aligned parallel to each other. Usually, a current does not flow through such an insulator, but because it is so thin, the quantum-mechanical properties of the electrons in the current can allow them to tunnel through the insulator.

The intensity of this tunnelling current depends on the alignment of electron spins in the two electrodes, which can be controlled by an external magnetic field or by an external spin current. When the spins are parallel, the tunnelling current is high; when the spins are antiparallel, the tunnelling current is low. In contrast to conventional electronics, in which the current is controlled only by electric charge, the device controls the current through the interplay of the electrons' charge and spin.

In Qian and colleagues' design, the spin tunnelling junction is a vertical structure comprising their intercalated superlattice, sandwiched between a ferromagnetic chromium telluride plate of nanometre thickness on the bottom and a gold electrode on top (Fig. 1). The chiral molecules in the superlattice filter out electrons with a particular spin state from a current injected into the gold electrode, and they do so multiple times because the superlattice has many layers.

A high current is measured if the spin state that emerges from the superlattice aligns with that of the electrons in the chromium telluride; otherwise the current is low. The authors changed the orientation of spins in the ferromagnet with an external magnetic field and observed the expected switch between high- and low-current states, which could correspond to the '0' and '1' states for spintronic applications. The large difference they measured between the two current extremes suggests that their material has high spin selectivity – around 60 times higher than most other solid-state devices exhibiting the same chiral-induced filtering effect.

There are still some challenges to be addressed before Qian and colleagues' superlattices can be used in spintronic devices. One issue is that the multilayer structure increases the electrical resistance of the devices, resulting in small current signals. This could potentially be addressed by experimenting with the abundant family of van der Waals materials and the large section of chiral molecules to modify the alignment of the energy bands accessible to the electrons, thus increasing the current. Experimenting with different chiral molecules might also boost the spin selectivity to an even higher level than that reported by the authors. However, the formation of the superlattice depends on the interaction between the molecules and the 2D layers, as does the quality of the resulting material, so every combination is not guaranteed to be obtained with the team's simple approach. Tuning the thickness of the superlattice might help to find a good balance between maintaining high spin selectivity and a large current signal.

The authors used an external magnetic field to switch the spin orientation in the ferromagnetic material of their spin tunnelling junction, but practical applications would require that this switching be controlled with an electrical spin current. They also operated it at around 10 kelvin, but room temperature would be preferable in practice. Future work therefore needs to identify a robust ferromagnetic material that could make this possible, and it remains to be seen whether the device's performance will still be high under these conditions. Nevertheless, Qian *et al.* have created a material platform with impressive spin selectivity, offering exciting prospects for future spintronic devices.

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Microbiology

# Bacterial envelope built to a peptidoglycan tune

**Michaël Deghelt & Jean-François Collet**

How a bacterium coordinates the assembly of its outer layers, and couples the formation of this envelope to cell growth and division, is not fully understood. Assessing the role of peptidoglycan molecules provides some answers. **See p.953**

A classification system in use since the end of the nineteenth century groups bacteria as either Gram-positive or Gram-negative. This sorting system depends on the level of microbial permeability to an exterior dye, a characteristic influenced by the properties of structures that form bacterial outer layers and are termed the cell envelope. This envelope has many essential roles in enabling bacteria to function and survive. On page 953, Mamou *et al.*[1] report evidence that sheds light on a long-standing mystery about how the cell envelope of Gram-negative bacteria is constructed.

Gram-negative bacteria have a particularly complex cell envelope that contains an inner and an outer membrane (Fig. 1). Between these two membranes is a space, called the periplasm. This contains a thin mesh of peptidoglycan, which consists of chains of sugars (glycans) connected by short peptides.

The composition of the outer membrane is unusual. Most biological membranes contain a bilayer of phospholipid molecules, whereas the outer membrane of Gram-negative bacteria is an asymmetric bilayer with phospholipids for the inner layer and lipopolysaccharide molecules making up the outer layer[2].

The proteins embedded in the outer membrane also exhibit striking properties. Similar to those found in the outer membrane of organelles such as mitochondria, these proteins arise from a structure called a β-sheet, which folds into a barrel shape (termed a β-barrel). These folded proteins often contain a central pore, and some such proteins enable nutrients to enter the cell. All the components of the various envelope layers are made in the