TOPOLOGICAL INSULATORS

Engineered Magnetic Heterostructures

The combination of topological properties and magnetic order can lead to new quantum states and exotic physical phenomena. In particular, the coupling between topological insulators and antiferromagnets enables magnetic and electronic structure engineering.

Thorsten Hesjedal and Yulin Chen

Topology, a branch of mathematics that deals with smoothly deformable objects, has turned out to be of great relevance to modern physics. Phases of matter were predicted and experimentally confirmed that are protected by their built-in topological electronic structures. Topological insulators are bulk insulators with gapless, topologically protected surface states, which are not only hosting exotic quantum states, but also have the potential for new electronic and spintronic device applications, recently coined as 'topotronics'. A crucial requirement for unlocking some of their most intriguing properties and effects is the breaking of time-reversal symmetry, for instance, by magnetic doping. Now, Qing Lin He and colleagues[1] report a way of raising the magnetic ordering temperature in these materials by constructing a 'lasagne' of the magnetic topological insulator Cr:$(Bi,Sb)_2Te_3$ and the antiferromagnet CrSb to seamlessly realize proximity-coupling.

Topological insulators are a remarkable class of quantum materials with insulating bulk but gapless, Dirac-type (that is with linear dispersion) topological surface states that are robust against non-magnetic impurity scattering through the enforcement of time-reversal symmetry. These topological surface states are characterised by counter-propagating, fully spin-polarised and dissipationless conduction electron channels (see Fig. 1a). In case of magnetically ordered systems, and when time-reversal symmetry is broken, they can further host many exotic phenomena such as emergent massive Dirac fermions[2], the quantum anomalous Hall effect[3] and many other topological magnetoelectric effects[4]. Whereas random magnetic impurities open a channel for backscattering, magnetic order suppresses one branch of the spin-polarised electrons in 2D and makes the Dirac fermion acquire mass in 3D.

The quantum anomalous Hall effect was first experimentally observed in chromium-doped $(Bi,Sb)_2Te_3$ thin films – a magnetic topological insulator with a Curie temperature of mere ~15 K[3]. The quantised Hall resistance in units of h/e^2 takes integer values (as schematically shown in figure 1b) which are directly given by a topological characteristic of the band structure, called the first Chern number. As thin films of Cr-doped $(Bi,Sb)_2Te_3$ are ideally prepared by molecular beam epitaxy, experimentalists could precisely tune its chemical potential by control over the stoichiometry.

In an attempt to raise the magnetic ordering temperature of these materials, thus enabling the observation of topological phenomena at higher temperature, inspiration from ordinary ferromagnetic heterostructures and an effect known as proximity-coupling was used. In a recent paper by Moodera's group[5], room-temperature long-range order in the topological insulator Bi_2Se_3 coupled to the ferrimagnetic insulator EuS was reported. In contrast to ordinary ferromagnetic heterostructures, the coupling may be restricted to a shallow depth below the interface, and may or may not involve the topological surface state carriers to mediate the coupling between the local magnetic moments. It is therefore of utmost importance to develop the analytical tools capable of unambiguously revealing the mechanisms and properties of this buried, effectively two-dimensional magnetic systems[6].

In addition, this proximity approach brings about another advantage – a partial decoupling of the order-enhancing effect from the doping concentration in the topological insulator. As with all doped materials, dopants introduce detrimental effects such as lattice defects, and magnetically or electronically active impurities. The adverse effects of Cr-doping have been impressively visualised in a magnetic microscopy study that found weakly interacting ferromagnetic puddles giving rise to a macroscopically superparamagnetic system[7].

Using an antiferromagnet, that is an ordered magnetic system in which neighbouring spins are pointing in opposite directions, as a proximity layer is a novel approach in the context of magnetic topological insulators. Antiferromagnets and so-called artificial antiferromagnets, (engineered heterostructures where the coupling between ferromagnetic layers can be tuned), are widely used in magnetic memory applications. One of their advantages is the absence of a macroscopic magnetic moment, and thus a magnetic stray field, which makes them robust against external fields.

The work by Qing Lin He and co-workers[1] reports the realization of a superlattice of the antiferromagnet CrSb and the magnetic topological insulator Cr-doped $(Bi,Sb)_2Te_3$, combining the concepts discussed above. Both materials are well lattice-matched, leading to abrupt interfaces as shown in Fig. 2a, making CrSb (whose Néel temperature is about 700 K) one of the few antiferromagnets suited for the incorporation into functional layer structures. In this system, they demonstrate that the magnetic topological insulator can be exchange-coupled to the antiferromagnet, leading to an enhancement of the exchange field up to ~50 mT , of the Curie temperature from ~38 K to ~90 K, and the coercive field to 67 mT (for a bilayer sample, as compared to 47 mT for a single layer). Interestingly, using the antiferromagnet with its in-plane moments to pin the magnetic topological insulator at the interface, an overall parallel or antiparallel alignment of the (out-of-plane) moments of the ferromagnetic layers in a trilayer structure can be achieved, as illustrated in Fig. 2b. This is a nice example of a functional heterostructure that could be useful in engineering the quantum effects related to magnetic topological insulators.

There is no doubt that several materials challenges have to be overcome before one will be able to observe the quantum anomalous Hall effect in these proximity-coupled systems at high temperatures, however, the first steps have been made and there is more to come. In the near future, it will be important to carry out thorough magneto-transport studies, as well as angle-resolved photoemission spectroscopy (ARPES), to complete the experimental proof that the Dirac fermion got massive. As the topological surface state lives near the interface, we may see a similar surge of fascinating and surprising phenomena as with complex oxides interfaces in the recent past[8]. Emergent states are waiting to be discovered and it is time for the topological insulators to stack up.

Thorsten Hesjedal and Yulin Chen are in the Clarendon Laboratory, Department of Physics, Parks Road, University of Oxford, Oxford OX1 3PU, UK.

e-mails: Thorsten.Hesjedal@physics.ox.ac.uk; Yulin.Chen@physics.ox.ac.uk

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Images:

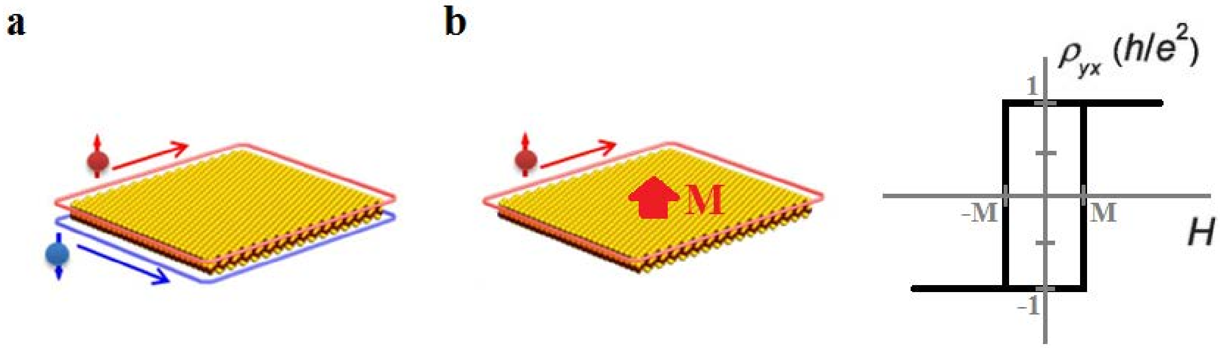

Figure 1 | **Topological surface states in a topological insulator and quantum anomalous Hall effect. a,** The topolological surface states in a topological insulator are characterised by counter-propagating, fully spin-polarised and dissipationless conduction electron channels. **b**, Quantum anomalous Hall effect in a magnetic topological insulator with magnetization M. The in-plane Hall resistivity (ρ_{xy}) becomes quantizied as shown in the right panel.

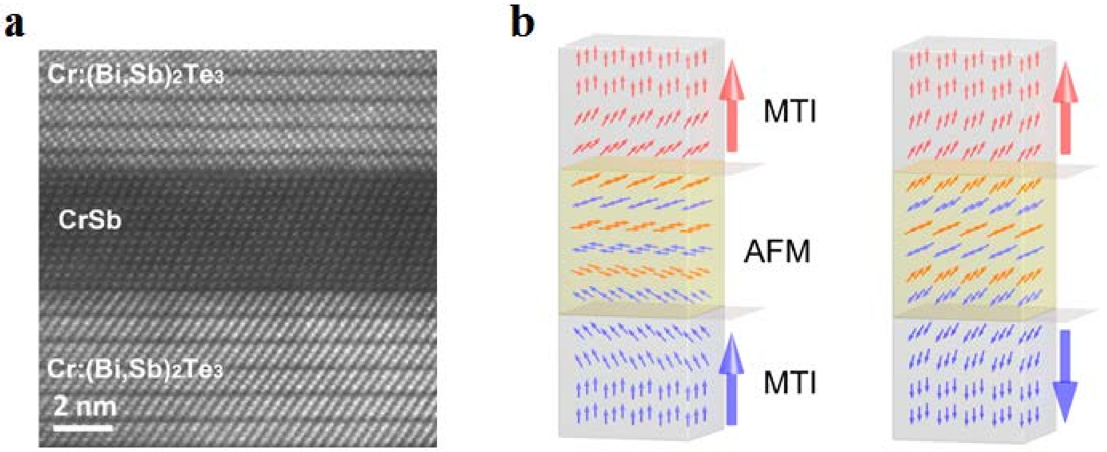

Figure 2 | **Magnetic topological insulators coupled through an antiferromagnetic layer. a,** High-resolution transmission electron microscopy image of an interfacial region of a [CrSb(4 nm)/ Cr:(Bi,Sb)$_2$Te$_3$(7 nm)]$_{n=4}$ superlattice. The antiferromagnet CrSb is almost perfectly lattice-matched to the magnetic topological insulator Cr-doped (Bi,Sb)$_2$Te$_3$. **b**, Schematic diagrams illustrating the ferromagnetic (left-hand side) and antiferromagnetic (right-hand side) coupling scenarios of two ferromagnetic topological insulator layers, mediated by an antiferromagnetic interlayer. The moments in the ferromagnetic layers are canted towards the in-plane moments of the antiferromagnet close to the interface allowing the antiferromagnetic layer to pin the magnetic moments of the topological insulator layers. Panel a adapted from ref. 1, NPG.