the polarization of the ferroelectric layer downwards (to the LSMO), which placed the device in a high resistive state (off) by increasing the height of the tunnelling barrier (Fig. 1b). Negative voltages oriented the polarization upwards, which lowered the tunnelling barrier (Fig. 1a) and put the device into a low resistive state (on). The ratio R_{off}/R_{on} had a value of ~100, which is remarkably high and corresponds to a giant tunnel electroresistance effect of 10,000% at room temperature. The memory can be read with a voltage as low as 100 mV.

Garcia and co-workers argue that the temperature dependence of the measured electroresistance shows that quantum tunnelling is responsible for the current through the BTO layer. However, although they clearly demonstrate the influence of the ferroelectric polarization on the current, they cannot completely exclude the possibility that electrochemical reactions at the interfaces also have a role. Ruling out these other effects will require complementary structural data together with further experiments to investigate what is happening at the interfaces.

One of the major advances reported by Garcia and co-workers is the demonstration of memory programming with short (10 ns) voltage pulses, 3 V in amplitude, and the high reproducibility of the results in a large number of samples. The ferroelectric tunnel junctions show the potential for devices with a low program energy per bit, with experimental values of less than 10 fJ per bit in 50 nm devices: this is less than the typical values for existing flash and phase-change RAM memories (which are in the picojoule to nanojoule range).

These latest results represent a basic proof of concept, not a fully optimized memory cell, so a number of challenges remain, such as achieving greater control over the barrier potential and making these devices compatible with silicon substrates. However, it is also clear from this work that quantum tunnelling in ferroelectric materials at the nanoscale offers considerable scope for innovation in nanoelectronic devices. ❐

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TOPOLOGICAL INSULATORS

The surface surfaces

Circularly polarized light can isolate surface states from bulk states in topological insulators, allowing their unique properties to be probed.

Judy J. Cha and Yi Cui

Most materials are either insulators or conductors, and semiconductors straddle the divide by becoming conducting or insulating as their charge-carrier density is tuned. Recently, a new class of materials was discovered that combines these properties in a new way: called topological insulators, they have bulks that are insulating and surfaces that are conducting[1,2]. Moreover, the spin of their surface electrons is locked in a direction that is perpendicular to the direction of motion (a property known as helicity): this reduces the probability of the electrons being backscattered by surface defects and phonons, thereby lowering the surface resistivity. However, accessing these surface states unambiguously is a challenge, because defects in the bulk increase bulk conductivity, so that any current injected from external electrodes is transported through both surface and bulk states. Now, writing in *Nature Nanotechnology,* Nuh Gedik of MIT and co-workers have exploited the helicity of surface states to access and control them directly using circularly polarized light, avoiding any significant contribution from bulk conduction[3].

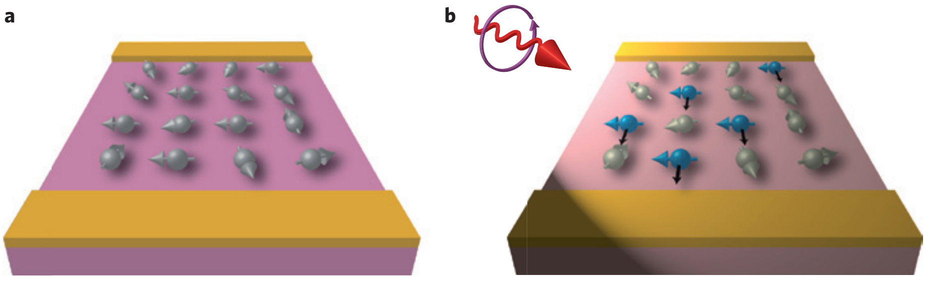

Figure 1 | Owing to helicity, circularly polarized light can generate spin-polarized surface current in topological insulators. **a**, Electrons at the surface of a Bi_2Se_3 flake (pink) have randomly oriented spins. **b**, When laser light (red arrow) that is circularly polarized (purple arrow) illuminates the flake, electrons with spins pointing to the left (blue) are preferentially excited. Because these electrons are restricted to move in one direction (black arrows), a net electron current is established and measured by two contact leads (gold).

First demonstrated in HgTe quantum well systems[4], topological insulators have turned out to be more common than expected, and include well known thermoelectric materials like Bi_2Se_3 and Bi_2Te_3. Interesting in their own right, the surface states of topological insulators are also good platforms for studying fundamental physical phenomena (such as the quantum anomalous Hall effect and Majorana fermions). Furthermore, Bi_2Se_3 and Bi_2Te_3 are layered materials, with atomically thin sheets held together by weak van der Waals forces. As a result they can be exfoliated into very thin sheets, and used to build nanometre-scale devices, potentially allowing quantum confinement effects to be combined with the surface properties of topological insulators.

These surface properties, including a unique electronic band structure and a lack of back-scattering, have been carefully studied in three-dimensional materials by surface-sensitive techniques including angle-resolved photoemission spectroscopy and scanning tunnelling microscopy[5–7]. The next challenge is to make it possible to routinely access and manipulate the surface states of topological insulators in thin-film devices. The obstacle to achieving this goal with three-dimensional topological insulators like Bi_2Se_3 and Bi_2Te_3 is the high density of charge carriers in their bulk, which arises from defects such as Se vacancies or anti-site defects (in which two atoms swap positions). This increases bulk conductivity, and mixes together bulk and surface transport characteristics. Efforts to reduce the bulk carrier contribution have included substitutional doping[8], increasing the surface-to-bulk ratio through nanostructuring[9], and electrostatic gating of nanostructured devices[10].

However, even if these techniques successfully reduce the bulk carrier contribution, the materials remain sensitive to the environment, often becoming heavily doped when exposed to air. To confirm that surface states have contributed to measured transport data, scientists look for electronic properties that are characteristic of surface states (like two-dimensional Shubnikov–de Haas oscillations and Berry's phase). However, this approach can also prove inconclusive because bulk states can form two-dimensional electron gases that mimic the behaviour of surface states.

Gedik and his colleagues — James McIver, David Hsieh, Hadar Steinberg and Pablo Jarillo-Herrero — circumvented these issues, unambiguously accessing the surface states in flakes of Bi_2Se_3 by exploiting the fact that surface states have helicity and bulk states do not. Following theoretical predictions[11,12], Gedik and co-workers illuminated flakes of Bi_2Se_3 (which were ~120 nm thick and ~5 μm long) with circularly polarized laser light to preferentially excite electrons whose spins had a particular orientation. Electrons with other orientations were unaffected. Because each spin orientation of a surface electron is uniquely associated with one direction of travel, this preferential excitation generated a spin-polarized surface current, which was measured by two contact leads. Changing the light polarization reversed the direction of the current, a clear indication that helical surface states were being probed. Surprisingly, the measured spin-polarized surface photocurrents persisted up to room temperature — another consequence of the robust nature of helical surface states of topological insulators.

This successful isolation of surface-state transport is based on the use of spin-selective optical pumping of the device, rather than electrical pumping. Measurements of transport induced by an applied voltage would result in the usual mixtures of surface and bulk transport channels. The direct optical control of spin-polarized surface currents in a topological insulator opens a host of exciting possibilities. New science may emerge from studying surface states under electrostatic gating, or with a surface energy gap opened by magnetic doping or an interface with a ferromagnet, or in superconductors. Applications may exploit the suppressed back-scattering and spin-momentum locking for quantum computing, optical spintronics and low-dissipation devices. ❐

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