Opportunities in topological insulator devices

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Abstract | Topological insulators (TIs) hold promise as a platform for unique quantum phenomena. However, realizing these phenomena experimentally requires sophisticated devices. In this Technical Review, we discuss four topics of particular interest for TI devices: topological superconductivity, quantum anomalous Hall insulators as a platform for exotic phenomena, spintronic functionalities and topological mesoscopic physics. We also discuss the status and technical challenges in fabricating TI devices to address new physics.

Chiral Majorana fermions
Fermionic particles that are their own antiparticles, arising as a 1D gapless edge mode, as expected in a proximitized quantum anomalous Hall insulator.

Topological qubits
A quantum system incorporating Majorana zero modes that allows quantum computation based on non-abelian exchange statistics to enable ‘digital’-like gate operation, as opposed to ‘analogue’-like conventional qubits.

Majorana zero modes (MZMs)
Localized bound states having a self-conjugate property, which can be viewed as an emergent Majorana particle obeying non-abelian exchange statistics.

After more than ten years of research on them, the understanding of topological insulator (TI) materials is very advanced. They are characterized by a nontrivial $Z$ topology of their bulk electronic wave functions, which leads to the appearance of topologically protected Dirac surface states. The most important property of the topological surface states is the spin-momentum locking, which lifts the spin degeneracy and dictates the spin orientation in relation to the momentum $k$. In fact, this property makes TIs a promising platform for topological superconductivity or spintronic devices. The next step is to use TIs as a platform for devices that realize useful topological phenomena, such as the emergence of chiral Majorana fermions, topological qubits that use Majorana zero modes (MZMs) or topological magneto-electric effects in the axion insulator state. In addition, the mesoscopic physics of the topological states of matter is a rich realm, but it has been largely left unexplored. Hence, TI devices provide promising opportunities for discoveries.

TIs have been characterized experimentally using transport measurements, angle-resolved photoemission spectroscopy, scanning tunnelling microscopy, scanning tunnelling spectroscopy, magneto-optical spectroscopy and ultra-fast optics measurements, among others. The spectroscopic experiments are useful for understanding how the topological electronic structures depend on energy, momentum, space, time and spin. Conversely, transport measurements are suitable for probing the low-energy physics that occurs at the Fermi level, such as quantum oscillations, superconductivity or quantum Hall effects. Employing device fabrication allows the targeted design of transport experiments and provides a tuning knob for systematic measurements or to manipulate the electronic states at will.

Although it is clear that TI devices would be useful for the exploration of unique topological phenomena, it is important to note that almost all known TI materials are much less robust against device fabrication processes compared with typical semiconductor materials, such as Si or GaAs. In addition, the functionally active part of TIs is the surface states and the bulk conduction should be suppressed as much as possible. As a result, it is important to apply techniques specifically tuned for TI devices. Such techniques have been reasonably well developed and various kinds of TI devices are being fabricated, allowing for observations of interesting phenomena peculiar to TIs.

In this Technical Review, we discuss important themes to be addressed using TI devices. They include realization of topological superconductivity, topological phenomena based on quantum anomalous Hall (QAH) insulators, spintronic functionalities of TIs and topological mesoscopic physics. After these physics discussions, technical challenges in TI devices are discussed and suggestions are made for the realization of these expectations.

Selected phenomena in TI devices
Besides the basic devices used for characterizations (Fig. 1a), TI devices are made to realize the conditions required for interesting quantum phenomena and/or to address the peculiar properties expected for TIs. Devices that combine TIs with a superconductor or a ferromagnet (or both) are of particular interest because of their prospect for applications in quantum computing or spintronics. Here, we discuss the physics behind these expectations. Analysis of TI/superconducting devices is discussed in Box 1.

Topological superconductivity
Topological superconductivity is a broad concept for superconductors characterized by some non-trivial topological invariant. Although much of the recent attention on topological superconductivity is due to its relevance to topological quantum computing, it is...
Interesting quantum phenomena deriving from the peculiar properties of topological insulators (TIs) can be observed in TI devices. Fabrication of such devices should take into account the special challenges these materials pose for fabrication.

In proximity to a conventional superconductor, TIs can realize a topological superconducting state hosting Majorana zero modes, representing the main ingredient for topological quantum computing, in which TIs can potentially have an advantage over semiconductor platforms.

By magnetically doping a TI, the quantum anomalous Hall effect can be observed if the Fermi level is tuned into the magnetic exchange gap and chiral edge states arise that are expected to turn into chiral Majorana edge states if superconductivity is induced by the proximity effect.

The spin-momentum-locked surface states of a TI are potentially useful for spINTRonic applications due to their current-induced spin polarization that interacts with ferromagnetic electrodes.

Quantum confinement in mesoscopic-sized TI nanowires leads to the formation of a peculiar Dirac subband structure, which can be modified by magnetic and electric fields to open extended topological phases within which Majorana zero modes are expected if proximitized by a superconductor.

Fabricating devices based on TIs and interfacing them with ferromagnets or superconductors requires well-tuned processes in order to preserve and control the surface state properties.

Useful to note that not all topological superconductors are useful for this purpose. For example, a spinful chiral $p$-wave superconductor (for which Sr$_3$RuO$_4$ is a candidate) is not suitable. The key ingredient for topological quantum computing is an isolated MZM: when isolated, this mode is pinned to zero energy and can be viewed as a half of an electron, because it requires two MZMs to accommodate an unpaired electron in the topological superconductor. This situation, in turn, means that the information carried by an electron can be stored non-locally in two MZMs that are spatially well separated, which gives an advantage in protecting the quantum information when MZMs are used for encoding a qubit. Another, more fundamentally important, advantage of a qubit based on MZMs is the possibility to perform a topologically protected gate operation, known as ‘braiding’. Typically, a Majorana qubit consists of four MZMs and a braiding operation exchanges two of the four MZMs. One such braid changes the qubit state $|0\rangle$ into an equal superposition of $|0\rangle$ and $|1\rangle$ states, which is equal to a $\pi/2$ rotation of the qubit state on the Bloch sphere. Moreover, two braids bring the $|0\rangle$ state into the $|1\rangle$ states, which is a $\pi$ rotation of the qubit state. Theoretically, the result of these one-bit gate operations performed via braiding depends only on the number of braiding and has no timing error, which is why it is called topological quantum computing.

Importantly, for the electron condensate to become a topological superconductor capable of hosting MZMs, it needs to be spin-non-degenerate, the property often called ‘spinless’. Such a spinless situation is realized when electrons are spin-polarized and only one spin subspace is relevant to the low-energy physics. The ferromagnetic state in a half-metal naturally satisfies such a condition. In addition, the spin-momentum-locked surface states of TIs are also spinless. The advantage of the TI surface states is that the spin is antiparallel between electrons with momentum $k$ and $-k$, which makes it easy to induce Cooper pairing between these surface electrons by using the superconducting proximity effect from a conventional $s$-wave superconductor. Still, the spinless nature of the surface state makes it possible to use a simple unitary transformation to map the superconducting state induced in the TI surface to the spinless chiral $p$-wave state. This state is a prototype of a topological superconducting state hosting a MZM in the vortex core. Note that the superconducting TI surface is time-reversal-invariant and one needs to break the time-reversal symmetry (by threading a vortex, for example) to generate MZMs.

Because MZMs in vortex cores are difficult to access and manipulate in devices, experiments have been performed on TI-based Josephson junctions. Unless one makes a trijunction, MZMs cannot be generated in a Josephson junction. Nevertheless, TI-based Josephson junctions can still host dispersive Majorana bound states; a necessary but not sufficient condition to distinguish these from the usual Andreev bound states is the $4\pi$-periodic dependence on the phase difference between the two superconducting electrodes. The $4\pi$-periodicity manifests itself most prominently in the AC Josephson effects, either in the form of missing first Shapiro step upon microwave irradiation or halving of the emitted microwave frequency upon dc voltage application. One should keep in mind, however, that an apparent $4\pi$-periodicity can be observed due to excited quasiparticles or Landau–Zener tunnelling. Hence, the Josephson junction experiments can only provide indirect support to the realization of topological superconductivity.

After the proposal by Liang Fu and Charles Kane, it was recognized that a spinless band structure similar to that in a TI surface can be engineered in a spin–orbit-coupled semiconductor (such as InAs) by combining a Rashba-type band splitting and a Zeeman energy gap. By engineering such spinless bands in a 1D semiconductor nanowire and by employing the superconducting proximity effect, MZMs can be generated at the ends of the nanowire, even though doing so requires a large magnetic field. This 1D semiconductor platform has been considered to be the main contender for topological quantum computing and many high-profile experiments have been reported. However, unambiguous evidence for MZMs has not been obtained and it was recently pointed out that the density of impurities should be $\sim 10^{15}$ cm$^{-3}$ or lower to realize a Majorana qubit; this figure is about 100 times lower than the current state of the art.

In this regard, it was recently proposed that, taking the unavoidable disorder into account, TI nanowires could be a more promising platform for generating robust MZMs. In that proposal, a lifting of the degeneracy by a combination of an electric field (produced by a gate) and a moderate magnetic field provides the spinless band in a reasonably wide energy window on the order of 10 meV. In this case, the quantum confinement of the TI surface states to create a peculiar subband structure plays a key role, besides the fact that a 1D topological superconductor naturally hosts MZMs at the ends without the need to create vortices. Nevertheless, the bulk-insulating TI nanowires that are currently available...
are compensation-doped, which leaves charged impurities that cause fluctuations of the Coulomb potential. It has been predicted that the impurity density should be ~$10^{18}$ cm$^{-3}$ or lower to realize a Majorana device with TI nanowires, because only in such nanowires the fluctuations of the Coulomb potential would remain smaller than the energy window for the spinless band. (Note that the analytic estimate in Fig. 1 shows that, for impurity density $\gtrsim 10^{18}$ cm$^{-3}$, the subband features are completely smeared in the transport properties of a nanowire. However, gate-voltage-dependent resistance oscillations reflecting the subband gaps have been experimentally observed, suggesting that the impurity density in TI nanowires may actually be lower than this threshold.)

Quantum anomalous Hall insulators

The QAH effect is similar to the quantum Hall effect but can be achieved without requiring a strong magnetic field to induce the formation of Landau levels; instead, it arises from the quantized Berry curvature of the occupied states. This quantization happens when the Fermi level is tuned to the magnetic exchange gap that is opened at the charge neutrality point (Dirac point) of the TI surface states in the presence of ferromagnetic order. The QAH effect can be realized in thin films (thickness $\lesssim 10$ nm) of bulk-insulating TI material (Bi$_{1-x}$Sb$_x$)$_2$Te$_3$ doped with Cr or V to induce ferromagnetism. It can also be achieved in thin exfoliated flakes of MnBi$_2$Te$_4$. In the QAH effect, the Hall conductance $\sigma_{xy}$ is quantized to $e^2/h$ and the longitudinal conductance $\sigma_{xx}$ vanishes.

The ferromagnetic TI that shows the QAH effect is called a QAH insulator, because the ‘bulk’ of the 2D surface states are gapped and only the 1D chiral edge states carry the electric current. The physics of these chiral edge states is itself an interesting subject to study. For example, chiral edge states appear at the magnetic domain boundaries in a QAH insulator and can be moved by manipulating the magnetic domains using, for example, the tip of a magnetic force microscope. In addition, the $\sigma_{xx}$ = 0 state is extremely unstable against electric current, which is an indication of an intricate interaction between the edge states and the bulk states. Furthermore, this interaction leads to a large non-reciprocal transport through the edge states.

In a QAH insulator, the magnetization needs to be parallel in the top and bottom surfaces. By making the magnetization of the two surfaces to be antiparallel, one can realize an axion insulator, in which the whole system (bulk and edge) is gapped. According to theory, such an axion insulator presents interesting topological magneto-electro effects. For example, a charge polarization will induce bulk magnetization, with the proportionality coefficient given by the fine structure constant $a = e^2/\hbar c$.

When a QAH insulator is in contact with a conventional s-wave superconductor, the combination of electron doping from the superconductor to the QAH insulator surface and the superconducting proximity effect is expected to lead to a time-reversal-symmetry-breaking topological superconductivity. In a QAH insulator, the magnetization needs to be parallel in the top and bottom surfaces. By making the magnetization of the two surfaces to be antiparallel, one can realize an axion insulator, in which the whole system (bulk and edge) is gapped. According to theory, such an axion insulator presents interesting topological magneto-electro effects. For example, a charge polarization will induce bulk magnetization, with the proportionality coefficient given by the fine structure constant $a = e^2/\hbar c$.

Fig. 1 | TI device fabrication. a | Top-gated Hall bar device fabricated from a molecular-beam-epitaxy-grown thin film. The dashed line indicates the edge of the etched Hall bar structure underneath the gate metal. b | Optical contrast of thin exfoliated flakes. The flake marked by a blue arrow and shown in a magnified view (box framed blue) is less than 20 nm thick and, thus, appears half-transparent. On its left edge, the thickness is larger, indicated by a brighter colour. In dark-field microscopy (inset), the edge of thin flakes is less apparent than that of thicker flakes. A dense array of prefabricated markers (corners of the image) is useful for precise alignment. c | Process of transferring a topological insulator (TI) film from an Al$_2$O$_3$ growth substrate to a Si/SiO$_2$ substrate for dual-gating, following the process in Fig. 1. TI, topological insulator; PMMA, poly(methyl methacrylate). Part a, image courtesy of Gertjan Lippertz and Alexey Taskin. Part b, image courtesy of Linh Dang.
1D edge modes that have Majorana character, namely, the modes are self-conjugate. In quantum field theory, a self-conjugate particle is its own antiparticle and it is the decisive character of the original Majorana fermions conceived by Ettore Majorana as a model for neutrinos. In this sense, one may say that this 1D edge mode realizes chiral Majorana fermions. Therefore, proximity-induced superconductivity in a QAH insulator is of particular interest in Majorana physics and there are already experimental works along this line. However, the generation of chiral Majorana fermions remains controversial.

Chiral Majorana fermions are dispersive fermionic quasiparticles that cannot themselves be used for topological quantum computing. Nevertheless, a phase boundary in the chiral Majorana edge state is a zero mode and can be used for braiding. Such a phase boundary is created when a vortex crosses the edge state. Interestingly, this zero mode has charge $e/2$ and is carried by the 1D edge mode. A Majorana qubit based on this type of MZM is conceivable and would belong to the ‘flying qubit’ category, which has the obvious advantage of allowing quantum information to be transported over macroscopic distances. The braiding experiment in this case requires a rather complex device set-up and time-resolved measurements. Although challenging, such an experiment would be interesting. A different approach for generating MZMs has also been proposed, namely, to use gating to define 1D channels in a QAH insulator proximity-coupled to a superconductor.

**Spintronic functionalities**

The spintronic functionalities of TIs arise naturally from the spin–momentum locking of the surface states. One can induce spin polarization by generating an electric current in the surface; the orientation of the spin polarization is controlled by the direction of the current. Note that the induced spin polarization in the TI surface is primarily confined within the surface plane, but the third-order hexagonal warping term in the surface Hamiltonian gives rise to an out-of-plane spin component, which can be useful for using TIs as a controllable spin source.

In the diffusive transport regime, the mechanism of current-induced spin polarization is the Edelstein effect — the electric current creates an imbalance in the electron population on a spin-polarized Fermi surface, resulting in the dominance of one spin orientation on average. The extent of the imbalance depends inversely on the electron scattering rate. Hence, cleaner surfaces create larger spin polarizations.
Size quantization
Discretization of the quantum-mechanical eigenenergies due to spatial confinement.

Kramers degeneracy
The ever-present double degeneracy of eigenstates of a fermionic system that is time-reversal invariant.

The gap at the Dirac point and the spin degeneracy changes depending on the induced spin polarization on the TI surface. A pictorial explanation of this principle can be found in Ref. 46. Note that, owing to the negative charge of electrons, the magnetization on the TI surface is antiparallel to the current-induced spin polarization. This sign difference has sometimes caused confusion in data interpretation, such as in Ref. 47.

It is useful to mention that, even though the helical spin polarization of the Dirac surface states changes sign across the Dirac point, the current-induced spin polarization is not expected to change sign. This is because, for a given $k$, not only the spin but also the Fermi velocity change sign upon crossing the Dirac point. These two sign changes cancel each other in the Edelstein effect and lead to the same spin polarization. Nevertheless, if Rashba-type surface states are created by a surface band bending and coexist with the topological surface states, their competition might lead to a sign change in the current-induced spin polarization upon gating, leading to a ‘spin transistor’ operation.

Although controlling spin polarization via current is appealing, the efficiency of spin generation on the TI surface is inherently low in the diffusive transport regime, as is always the case with the Edelstein effect for spin generation. In this regard, there is an interesting possibility for TIs to dramatically increase the spin generation efficiency: in the ballistic transport regime, spin-momentum locking means that 100% spin polarization is expected in theory. Hence, TI-based nanodevices to pursue this avenue would be valuable. It should be mentioned, however, that TI nanowires may not be suitable for this purpose, because the 1D bands formed in TI nanowires are spin-degenerate, as explained below. A magnetic flux can lift the spin degeneracy but it may cause a problem in spin detection. Also, the mean free path of currently available TI nanowires is ∼100 nm and true ballistic transport has not been achieved; as long as the transport is diffusive, the Edelstein effect is the relevant mechanism for spin generation, even in 1D nanowires.

Topological mesoscopic physics
Another interesting direction in TI device research is mesoscopic physics in TIs. In this regard, the size quantization in TI nanowires leads to a gap opening and the formation of spin-degenerate subbands\(^{46-50}\). The gap at the Dirac point and the spin degeneracy of the subbands can be manipulated by a magnetic flux $\Phi$ threading along the nanowire. The 1D bands formed in a TI nanowire are indexed by the angular momentum quantum number $\ell$. In the presence of $\Phi$, the energy dispersion is given by

$$E_\ell(k) = \pm \hbar v_F \sqrt{k^2 + \left(\frac{\ell - (\Phi/\Phi_0)}{R}\right)^2}$$

where $v_F$ is the Fermi velocity, $R$ is the wire radius and $\Phi_0 = h/e$ is the flux quantum. The Berry phase that arises from the spin-momentum locking causes $\ell$ to take half-integer values $\pm \frac{1}{2}, \pm \frac{3}{2}, \ldots$, causing the 1D band to be gapped in zero field. The realization of this peculiar subband structure in TI nanowires was recently confirmed by observing gate-voltage-dependent resistance oscillations$^6$.

In Eq. 1, the flux $\Phi = \Phi_0/2$ cancels $\ell = 1/2$ and gives rise to a non-degenerate gapless band — this band is
spinless, which makes it eligible for hosting MZMs when superconductivity is induced. The dependence of this subband structure on $\Phi$ leads to Aharonov–Bohm (AB)-like oscillations in the nanowire resistance\(^{44,49,50}\) when the magnetic field is applied along the nanowire. For example, in an ideal case in which the Fermi level $E_F$ is located at the Dirac point, the density of states (DOS) at $E_F$ is zero when $\Phi = n\Phi_0$, with $n = 0, \pm 1, \ldots$, whereas the DOS becomes finite at $E_F$ when the gap is closed at $\Phi = (n + \frac{1}{2})\Phi_0$. This periodic change in the DOS at $E_F$ is the mechanism of the AB-like oscillations in TI nanowires. Therefore, when $E_F$ is gate-tuned to the bottom of one of the subbands, the AB-like oscillations are predicted to show a $\pi$ phase shift. This phase shift as a function of gate voltage has been observed\(^{10,24}\), although the measured phase shift was quite irregular.

Tuning the 1D band structure, including its spin degeneracy, would lead to more exotic mesoscopic effects. For example, applying an electric field by gating, thereby, breaking inversion symmetry, has been theoretically shown to lift the double degeneracy of subbands in zero magnetic field. Further lifting the Kramers degeneracy with a moderate magnetic field produces a band structure that is particularly suitable for hosting MZMs in the presence of unavoidable disorder\(^1\), as discussed above. Even without the Majorana context, the interplay between the Berry phase and various types of symmetry breaking in TI nanostructures offers a testing ground for mesoscopic physics and quantum transport, including nonreciprocal response\(^{53}\).

**Fabrication of TI devices**

In the fabrication of TI devices, there are three main challenges: realizing and preserving the insulating bulk, simultaneously protecting and accessing the surface states and controlling and manipulating the surface states. Key points for fabrication are summarized in BOX 2.

**Realizing and preserving the insulating bulk**

The excitement about devices based on TIs is based on the peculiar properties of their conducting surface states. The contribution of surface states can be enhanced not only by using thin films and exfoliated flakes to achieve a large surface-to-bulk ratio but also by tuning the material growth such that the chemical potential lies within the bulk band gap. Owing to naturally occurring self-doping, most TI compounds — such as the binary tetradymite $\text{Bi}_2\text{Se}_3$, $\text{Bi}_2\text{Te}_3$, or $\text{Sb}_2\text{Te}_3$ — conduct in their bulk. Nevertheless, the experimental challenge to realize a truly insulating bulk has been overcome by ‘compensation’ of dopants, which can be achieved, for example, in the solid solution of tetradymite compounds having opposite types of naturally occurring carriers\(^1\). Two widely used materials belong to this class: $\text{Bi}_2\text{Se}_{1-y}\text{Te}_y\text{Sb}_x$ (hereafter called BST)\(^44\) for thin films and $\text{Bi}_{x}\text{Sb}_{1-x}\text{Te}_2\text{Se}_3$ (called BSTS) for bulk crystals\(^8\).

Bulk-insulating BST thin films can be grown using molecular beam epitaxy (MBE) by the tuning of flux ratios and growth temperatures\(^44\). Because the growth proceeds in the van der Waals epitaxy mode\(^1\), epitaxy does not require matching the lattice constant of the substrate. Whereas silicon wafers are compatible with well-established industry tools and allow for epitaxial growth of BST\(^44\), sapphire ($\text{Al}_2\text{O}_3$) wafers tend to give better film qualities\(^5\).

Thanks to the layered structure and weak van der Waals bonds of 3D TIs of the tetradymite family, another route to obtain high-quality bulk-insulating TIs for device fabrication is to exfoliate melt-grown bulk crystals of BSTS into thin flakes (FIG. 2a). A major advantage of flakes over thin films is the flexibility in the choice of substrates on which to exfoliate. Conducting substrates coated with an insulating dielectric, such as doped Si coated with SiO$_2$, can be used for simple realization of a gate. For device fabrications based on exfoliated flakes, it is helpful to use prefabricated substrates patterned with an array of markers for coordination in lithography (FIG. 1b). In the crucial thickness range of 5–30 nm, the thickness of exfoliated flakes can be judged by optical microscopy, based on the shade of the flake in the bright field and the contrast of its edge in the dark field (FIG. 1b).

A major benefit of devices is the possibility of gate-tuning the chemical potential, but the large DOSs coming from conducting bulk would lead to screening, thereby, preventing any efficient tuning, spoiling this benefit. Therefore, it is crucial to retain the insulation of the bulk upon fabrication by not heating the sample too much during the resist baking or depositions of metals and dielectrics, so that the chemical composition of the TI remains intact. For example, in the cases of BST films and BSTS flakes, the maximum process temperature is 120°C.

**Protecting and accessing the surface states**

It is important to note that ambient atmosphere oxidizes the surface of BST and BSTS. The oxidation dynamics depends on the chemical composition of the TI material and its surface morphology\(^27,18\). For strongly terraced MBE thin films, surface oxidation is more relevant than it is for exfoliated flakes that are almost atomically flat. Oxidation causes electron doping, but, besides that, there has been no evidence that oxidation degrades the electron mobility in the surface states\(^9\) — most likely, the surface states just migrate beneath the oxide layer without experiencing enhanced scattering. In this sense, the oxide layer protects the surface states.
However, the oxide layer poses a problem upon taking ohmic contacts or inducing superconductivity through a metal or superconductor deposited on the surface. Thus, the oxide layer has to be removed by etching before metallizing. Note that, after the etching, sizeable oxidation typically occurs within minutes to hours at ambient conditions, so the air exposure of the device under fabrication needs to be minimized. A common strategy is to avoid oxidation by capping films in situ or immediately after the growth, with minimal air exposure. As a capping layer for BST, tellurium layer grown in situ in a MBE chamber or Al₂O₃ layer grown in situ by electron beam evaporation or sputtering or ex situ with atomic layer deposition have proven successful. Depositing a thin layer of aluminium and letting it oxidize to form Al₂O₃ is less suitable, as aluminium forms alloys with TIs.

For making electrical contacts, it is necessary to remove any kind of capping layer right before metallization. In this case, plasma etching, even if performed in situ, is not a preferred option, because the etch rate of the tetradymite TIs even at low ion energies is large compared with the capping materials. Thus, even a slight over-etch of the capping layer can quickly remove the whole TI underneath. Larger selectivity is achieved by wet etching, for example, by using aluminium etchant (type D, Transene) for Al₂O₃ removal. Because oxidation occurs immediately after removing the capping layer in the crucial interfacial areas if the device is exposed to air, it is helpful to use a suitable vacuum transfer box or perform a gentle in situ cleaning procedure prior to further fabrication.

Because BST and BSTS are chemically not very stable, for the fabrication of their devices, established semiconductor-based fabrication processes need to be reconsidered, starting with the choice of process chemicals. Solvents like acetone and isopropyl alcohol can be used safely and do not degrade the properties of the TI. However, common developers for photolithography should be employed without heating the TI material too much, even though a high-quality gate dielectric often requires high-temperature growth; in this regard, SiNₓ grown by hot-wire chemical vapour deposition, Al₂O₃ grown by atomic layer deposition and flakes of hexagonal boron nitride transferred onto TI flakes have proved useful.

Inducing a superconducting gap. The surface states of TIs can be manipulated by interfacing them with a superconductor or a ferromagnet. One can open a superconducting gap in the TI surface states by using the superconducting proximity effect, but doing so requires careful optimization of the interface between the TI and a superconductor to realize a robust superconducting gap. To ensure that the TI surface is free from residual oxides or adsorbates upon deposition of a superconducting layer, successive in situ deposition of a superconductor onto a freshly grown TI thin film is a possibility. However, an epitaxial growth of a superconductor compatible with post-fabrication of nanodevices has not been achieved. In an ex situ process, interface cleaning can be performed by gentle (reactive) ion etching and dilute acid treatment. In addition, in situ plasma cleaning at low energies (<90 eV) can help to prepare pristine surfaces, but the ion energy and milling time should be tuned carefully to avoid surface
Degradation. In this context, atomic hydrogen cleaning, which has been successfully applied to semiconductor–superconductor interfaces\(^{47,48}\), could be an interesting alternative, although there has been no report on its application for TIs at lower substrate temperatures.

Besides physically cleaning the interface, the choice of the proximitizing superconductor material and/or the adhesion layer material is crucial for achieving a high interface transparency (Table 1). Not all common superconductor materials can be used directly on top of TI materials, owing to potential alloying with the TI, for example, among the popular superconductor materials, aluminium alloys with BST and BSTS\(^{62}\). Thus, it is often necessary to first coat the TI with an adhesion layer that also acts as a diffusion barrier. Platinum and titanium are commonly used for this purpose.

**Interfacing with ferromagnets.** Ferromagnets in contact with the TI surface offer two types of functionalities. One is the breaking of time-reversal symmetry in the TI surface states through the ‘magnetic proximity effect’ and the opening of a magnetic exchange gap at the Dirac point. The other is spintronic functionalities, either to detect the spin polarization on the TI surface or even to present magnetization switching due the spin–orbit torque exerted from the TI\(^{46}\). Insulating ferromagnets are used for the magnetic proximity effect, whereas metallic ferromagnets are used for spintronic devices.

Among the ferromagnetic insulators, EuS grown on Bi\(_2\)Se\(_3\) has been used to induce magnetism by the proximity effect. At magnetic domain boundaries, chiral currents have been detected\(^{49}\). Further, ferromagnetism was induced in the TI surface even at room temperature\(^{50}\). In addition, the magnetic proximity effect is a cleaner way to induce ferromagnetism in the TI surface states than magnetic doping because it maintains a high carrier mobility, and the QAH effect has recently been achieved by interfacing the ferromagnetic insulator Zn\(_{1-x}\)Cr\(_x\)Te to BST\(^{70}\). For efficient magnetic proximity effects, using MBE to realize epitaxial interfaces is crucial\(^{70,71}\).

As already mentioned, in spintronic devices based on TIs, ferromagnets are used as a spin–voltage detector to probe the current-induced spin polarization in the spin-momentum-locked surface states\(^{46,47}\); for this purpose, ferromagnetic metals must be employed, preferably half-metals. Thermally evaporated permalloy is commonly used for this purpose. For spin-voltage detection, a non-ohmic, high-resistance contact is preferred to compensate for the impedance mismatch at the interface, and a tunnel barrier is typically inserted in between the TI and the ferromagnet to enhance the spin voltage. For TIs, Al\(_2\)O\(_3\) or MgO is often used as the tunnel barrier material.

Current-induced spin polarization can be used to switch the magnetization of a ferromagnetic metal in direct contact with the TI surface. Such devices use spin–orbit torque, which requires a good metallic contact. The first demonstration of the switching operation was performed in a epitaxially grown bilayer of BST and ferromagnetic Cr-doped BST\(^{72}\). A very efficient spin–orbit torque switching has been reported\(^{73}\) for a device based on Bi\(_{0.9}\)Sb\(_{0.1}\) and MnGa.

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**Table 1 | Materials used for interfacing with a topological insulator**

| Material            | Adhesion layer | Deposition method                      | Comment                                      |
|---------------------|----------------|----------------------------------------|----------------------------------------------|
| Niobium (Nb)        | –              | UHV sputtering                         | SC, great adhesion, high T\(_c\), no epitaxy\(^{76}\) |
| Aluminium (Al)      | Ti, Pt         | Preferred: e-beam evaporation; alternative: thermal evaporation | SC, good transparency, considerable ageing if not capped\(^{18,27}\) |
| Vanadium (V)        | Ti             | e-beam evaporation                     | SC, self-formed upon deposition of Pd (REF.\(^{77}\)) |
| PdTe\(_2\)          | –              | HV sputtering of Pd                    | SC, difficult to deposit\(^{18,79}\)          |
| Tungsten (W)        | –              | FIB                                    | SC, difficult to deposit\(^{18,79}\)          |
| Lead (Pb)           | –              | Thermal evaporation                    | SC, unpopular material for microfabrication\(^{53,54}\), topological proximity effect\(^{46}\) |
| EuS                 | –              | MBE                                    | FM insulator, epitaxial growth on Bi\(_2\)Se\(_3\) (REF.\(^{79}\)) |
| Zr\(_{1-x}\)Cr\(_x\)Te | –              | MBE                                    | FM insulator, epitaxial growth on BST to achieve QAH effect\(^{11}\) |
| Permalloy (Fe\(_{50}\)–Ni\(_{50}\)) | –              | Thermal evaporation                    | FM metal, used for spin detection\(^{46}\) |
| Cobalt (Co)         | –              | Thermal/e-beam evaporation             | FM metal, used for spin detection\(^{47}\) |
| Iron (Fe)           | –              | e-beam evaporation/MBE                 | FM metal, used for spin detection\(^{47}\) |
| MgO                 | –              | e-beam evaporation/MBE                 | Insulator, tunnel barrier for spin detection\(^{47}\) |
| Al\(_2\)O\(_3\)      | –              | ALD is preferred                       | Insulator, used for capping and tunnel barrier, chemically removable\(^7\) |
| Tellurium (Te)      | –              | MBE                                    | Insulator, capping BST film in the MBE chamber, removable by heating\(^9\) |
| Selenium (Se)       | –              | MBE                                    | Insulator, capping Bi\(_2\)Se\(_3\) film in the MBE chamber, removable by heating\(^9\) |

ALD, atomic layer deposition; BST, (Bi\(_{1-x}\)Sb\(_x\))\(_3\)Te; FIB, focused ion beam; FM, ferromagnetic; HV, high vacuum; MBE, molecular beam epitaxy; QAH, quantum anomalous Hall; SC, superconducting; UHV, ultra-high vacuum.
Inducing a size quantization gap in nanowires. As discussed above, when a 3D TI is made into a nanowire, the size quantization effect causes the Dirac surface states to acquire a gap and split into spin-degenerate subbands. For a nanowire of diameter $R \approx 30 \text{ nm}$, Eq. 1 gives the quantization gap $\Delta_{\text{NW}}(=h\nu_{\text{F}}/R)$ on the order of 10 meV. Suitable nanowires can be obtained in various ways. Vapour–liquid–solid growth yields TI nanowires of a few micrometres in length and of consistent morphology5,6 (Fig. 3a). Hydrothermal synthesis7 or exfoliation of bulk crystals8 can also result in thin TI nanoribbons. The approach of etching a continuous thin film into desired nanowires (or a network of them) promises much design freedom; nanowires with carrier mobilities retained from the pristine film can be obtained by a combination of dry ion etching and wet etching9,10 (Figs 3b,3b). In addition, the ‘selective area growth’ method (Fig. 3c) of pre-patterning a substrate with a growth mask for subsequent epitaxy allows for complex device designs and can additionally be extended to employ in situ deposition of superconductors by using suspended growth masks9,10,12.

Conclusion
TI devices offer opportunities for fundamental discoveries, in particular, in the areas of Majorana physics, topological magneto-electric effects, spintronics and topological mesoscopic physics. Currently, the factors that hold research back are mostly related to materials: the quality of the interface to a superconductor or a ferromagnet should be improved, preferably by finding combinations to allow for epitaxial interface and a high electronic transparency; furthermore, the properties of the TI material itself should be improved for reduced Coulomb disorder and a higher surface carrier mobility. Because epitaxial interface preparation usually requires in situ successive growths of the upper and bottom layers, developing a suitable nanofabrication technology for devices involving such an epitaxial interface is also important — doing so requires either a post-growth etching process or an in situ nanostructuring process to be combined with the growth11.

An important practical issue is that of reproducibility. In the case of TI devices, there are three main sources that affect the reproducibility of the results: interface cleanliness, level of bulk insulation and distribution of Coulomb disorder. The first two issues can be improved with a tighter control of the fabrication process but the last one is uncontrollable and unavoidable in strongly compensated TIs. In this regard, it would be desirable to find a new TI material that is bulk-insulating without compensation.

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