Quantized chiral edge conduction on domain walls of a magnetic topological insulator

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Electronic ordering in magnetic and dielectric materials forms domains with different signs of order parameters. The control of configuration and motion of the domain walls (DWs) enables nonvolatile responses against minute external fields. Here, we realize chiral edge states (CESs) on the magnetic DWs of a magnetic topological insulator. We design and fabricate the magnetic domains in the quantum anomalous Hall state with the tip of a magnetic force microscope and prove the existence of the chiral one-dimensional edge conduction along the prescribed DWs through transport measurements. The proof-of-concept devices based on reconfigurable CESs and Landauer-Büttiker formalism are realized for multiple-domain configurations with well-defined DW channels. Our results may lead to the realization of low-power-consumption spintronic devices.

The theoretical prediction and experimental discovery of two- and three-dimensional (3D) topological insulators (TIs) triggered the recent emergence of a wide variety of topological quantum materials and topologically nontrivial phenomena (1, 2). Topological phases are characterized by integer indices defined in the bulk electronic state, whereas gapless quasiparticle excitations appear at the boundary of topologically distinct phases, realizing the bulk-edge correspondence. For example, in a 2D electron system under magnetic field, the quantum Hall effect (QHE) is characterized by the filling factor of Landau levels, and the corresponding number of chiral edge states (CESs) appear at the sample edge. Such CESs have been experimentally detected not only at the sample edge (3, 4) but also at the boundary of different filling factors, e.g., in-plane p-n junctions of graphene formed with local gating under fixed magnetic field (5–7).

Topological phases are further enriched by the notion of spontaneous symmetry breaking. In the quantum anomalous Hall state under zero magnetic field (I, 2, 8), the spontaneous magnetization induces the CESs at the sample edge as well as at the domain walls (DWs). The quantum anomalous Hall effect (QAHE) has recently been observed in 3D TI (Bi$_{1−x}$Sb$_x$)$_2$Te$_3$ thin films doped with magnetic ions, Cr (9–13) or V (14), which have perpendicular magnetic anisotropy. When the Fermi energy is tuned within the magnetization-induced mass gap, the Hall conductance $\sigma_{xy}$ is quantized to $+e^2/h$ or $-e^2/h$, which evidences the occurrence of QAHE with the formation of the CES at the sample edges. Here, the QAHE is characterized by a topological number called a Chern number; the Chern number ($C = +1$ or $−1$) and the chirality of the CES can be controlled by the magnetization direction ($M > 0$ or $M < 0$) (15). Furthermore, because the Chern number must discontinuously change at the DW between up and down magnetic domains, the CES is expected to appear also at the DW (Fig. 1A and B) (1, 2). Notably, the position of the CES, in contrast to those at the sample edge (3, 4, 9–14) or at the local gate boundary (5–7), can potentially be manipulated via domain control by external fields such as local magnetic field, current-induced spin-orbit torque (16, 17), or optical illumination (18). Thus, a localized electronic channel based on the CES can be constructed in a reconfigurable manner. Here, in contrast to the previous approaches to probe the CES via naturally formed controllable DWs (19, 20), the quantized conductance of the CES is clearly probed in a controllable way using a technique based on magnetic force microscopy (MFM).

Magnetic TI thin films, Cr-doped (Bi$_{1−x}$Sb$_x$)$_2$Te$_3$ are grown on InP substrates (Fig. 1C), where Cr modulation doping stabilizes the QAHE up to about 1 K (12, 13). Figure 1D shows the MFM image taken at 0.5 K in noncontact mode (15), visualizing naturally formed multidomain structure with up (red) and down (blue) magnetization and DWs (whitish regions) in between. Bubble and stripe domain patterns are observed (fig. S1), typical for a thin film with perpendicular magnetic anisotropy (21). Here, we use the stray field from the MFM tip (fig. S2) to write the magnetic domain with an arbitrary shape, as follows. We first set the respective magnetizations of the MFM tip and the sample in opposite directions (fig. S3). Then, we scan over the sample inside the dashed frame in Fig. 1E in contact mode (15) under a small magnetic field of 0.015 T (< the coercive field of the TI film $B_{c15}$). As can be seen in the MFM image taken in noncontact mode (Fig. 1F), the magnetization direction is reversed only in the scanned area, meaning that the above procedure is effective for domain writing (15). By applying this writing technique to Hall-bar devices, we facilitate the electrical detection of the CES.

Figure 2 shows the magnetic field dependence of the transport properties. For transport measurements, ac current $I$ is injected from current contact 5 to current contact 6 and voltages $V_i$ are measured at voltage contacts $i = 1$ to 4, respectively. The resistance between contact 1 and contact 4, defined as $R_{14}$, is $V_1 - V_4/I$. In the single-domain states (Fig. 2A), the Hall resistance is $|R_{14}| = |R_{23}| = 25.1 \text{ k}\Omega$ ($-h/e^2 = 25.8 \text{ k}\Omega$), with low residual longitudinal resistance of $R_{12} = R_{34} = 1.8 \text{ k}\Omega$ at $T = 0.5 \text{ K}$; this signifies the occurrence of QAHE. The sign of the Hall resistance is reversed at around $B_{c15} \approx 0.6 \text{ T}$, reflecting the change of the magnetization direction and hence of the Chern number. In the multidomain state around $B_{c15}$ the longitudinal resistance has a peak. The symmetric resistance values $R_{13} = R_{24} = R_{14}$ in the Hall-bar shape are typical behavior in QAHE (9–14).

To observe the chiral edge conduction on a single DW, the left-up–right-down domain structure is prepared with a domain writing technique by MFM (Fig. 2B, upper left schematic). Here, the Hall resistance at the left (right) side $R_{12} (R_{34})$ is $\pm h/e^2$ ($-h/e^2$), corresponding to the magnetization direction. From the measured values of $R_{13}$ ($R_{24}$) and the correspondence between $R_{12}$ and the domain structure (fig. S1), it can be confirmed that the desired domain structure is prepared. $R_{12}$ and $R_{34}$ are no longer equal to each other: $R_{12}$ takes a high value of $-2h/e^2$, whereas $R_{34}$ is almost zero, in stark contrast to Fig. 2A, where $R_{13} = R_{24}$ and $R_{14} = R_{34}$. When a magnetic field is applied, the resistance values revert to those of the single-domain state, confirming the magnetic domain origin of the resistance values in the left-up–right-down domain structure. The values of $2h/e^2$ and $0h/e^2$ for the longitudinal resistance are explained by the following physical picture: At the DW of a magnetic TI in QAHE, two CESs are predicted to travel in the same direction (black arrows in Fig. 2B) owing to the discontinuous change in the Chern number between up and down domains (1, 2). The two parallel channels intermix and equilibrate with each other across the DW (5–7, 15), according to the potentials downstream from the DW become equal so that $R_{12} \bowtie$ becomes zero. In contrast, $R_{12}$ becomes twice the von Klitzing constant, $2h/e^2$, because only half of the electrons injected from the current contact 5 would be ejected to the other current contact 6. The reversal of the relationship between $R_{13}$ and $R_{24}$ ($R_{12}$ and $R_{34}$) in the right-up–left-down domain structure (Fig. 2C) is caused by the chirality inversion of the CES. Therefore, these observations evidence the existence of the CES at the DW.

To further confirm the existence of the CES at the DW, we study the dependence of the transport...
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Fig. 1. Magnetic domain writing by MFM in a magnetic topological insulator. (A) Illustration of CESs (black arrows) at the magnetic DW of a magnetic TI. \( M > 0 \) and \( M < 0 \) indicate upward (red) and downward (blue) spontaneous magnetization, respectively. (B) The surface band structures corresponding to the magnetic structures. When the magnetization points perpendicular to the film, exchange interaction opens up the mass gap. At the DW between up and down magnetic domains, two gapless CESs appear because of the discontinuous change of the Chern number from \( C = +1 \) to \( -1 \). (C) Schematics of the Cr modulation-doped magnetic TI. BST and Cr-BST stand for \((\text{Bi}_1-x\text{Sb})_2\text{Te}_3\) and \(\text{Cr}_y(\text{Bi}_{1-x}\text{Sb})_2\text{Te}_3\), respectively, where the nominal compositions are \( x \approx 0.2 \) and \( y \approx 0.74 \). (D) Magnetic domain structure of the naturally formed multidomain state around the magnetization reversal point at \( B = 0.059 \) T. The measurement is performed using MFM in noncontact mode. The color scale shows the resonance frequency shift \( \Delta f \), where the red and blue colors correspond to up and down domains, respectively. The color scale corresponds to a 0.50-Hz span from red to blue. The scanned area is 1.5 \( \mu \text{m} \) by 1.5 \( \mu \text{m} \). (E) Illustration of the domain-writing procedure using MFM in contact mode. The stray field from the MFM tip reverses the magnetization direction of the sample, as shown in the enlarged circle (the red lines represent the stray field). (F) Magnetic domain structure after the domain-writing procedure in (E). The magnetization direction is reversed only within the dotted line frame (0.75 \( \mu \text{m} \) by 0.75 \( \mu \text{m} \) area) scanned in contact mode. Finite contrast in single-domain regions originates from the spatial inhomogeneity of nonmagnetic forces such as electrostatic forces.

Fig. 2. Observation of chiral edge conduction on a magnetic DW. (A) Magnetic field dependence of the Hall resistance \( R_{13} = R_{24} \) and the longitudinal resistance \( R_{12} = R_{34} \) at \( T = 0.5 \) K. The upper illustrations show the corresponding magnetization configurations and the chirality of CES. Current is injected from contact 5 to contact 6, and voltage is measured at contacts 1 to 4. The multidomain state in the upper middle is just a schematic view, and the actual size of the domain (typically \(~200 \) nm) is much smaller than the device size (several tens of \( \mu \text{m} \)). (B) Transport properties of the left-up–right-down domain structure (upper left) and the subsequent magnetic field dependence. See fig. S4 for the illustration of the left-up–right-down domain structure overlaid on an image of a real device. (C) Transport properties of the left-down–right-up domain structure (upper left) and the subsequent magnetic field dependence. Upon the nearly continuous drive of the DW, the Hall resistance \( R_{13}(R_{24}) \) in Fig. 3C changes from \(-\hbar/e^2 \) to \(+\hbar/e^2 \) at the corresponding voltage contacts. Interestingly, \( R_{24} \) has a peak at \(-2\hbar/e^2 \) only when the DW is in between the two contacts, consistent with the consideration from the chiral edge conduction along the DW. When the DW reaches the right-side end, the resistance values reflect the single domain state. The DW position dependence is also clearly demonstrated in the control experiments (fig. S5).

The CES width can be estimated from the resistance transition width in Fig. 3C. If the CES width were narrow enough, the Hall resistance properties on the position of the DW (Fig. 3C). As the tip scans over the device from left to right (Fig. 3A), the magnetization direction is reversed little by little from down (blue) to up (red), and accordingly the DW changes its position; the DW position \( (x) \) is defined as the distance measured from the left contact 5 edge, as shown in Fig. 3B.
R_{13} would take a constant value when the DW position is away from the voltage contacts 1 and 3. However, this is not the case in the actual experiment. We attribute this behavior to the finite width of the CES at the DW; if the CES has some spatial distribution, it starts to affect the electrical potential and Hall resistance even when the DW is not on the voltage contacts. Here, we tentatively fit a part of the resistance value R_{13} with an exponential function of the DW distance away from the voltage contacts 1 and 3: The fitting procedure gives the CES width to be approximately 5 μm, much larger than DW width itself judged from the MFM image in Fig. 1F (15). In the multdomain state, the CES width is much larger than the typical domain size of ~200 nm (Fig. 1D), so that conduction occurs through the tunneling between the multiple CESs (22–24), leading to the continuous change of resistance as observed in Fig. 2A. Therefore, writing a large magnetic domain is crucial for the observation of the CES at the DW in the present device.

Finally, we show the proof-of-concept experiments of CES-based electronic devices. We write various domain patterns by the MFM tip and measure the transport properties (Fig. 4A). In the case of the ideal chiral edge conduction, one can calculate the resistance using the Landauer-Büttiker formalism (25), as shown by the horizontal solid bars. Because of the dissipationless 1D nature of the CES, the resistance value is determined just by the relative positions of the DWs, independent of the actual size of the device. Although there are some deviations caused by the finite CES width and the Hall-bar size, the experimental values show good agreement with the ideal values. Importantly, in contrast to the cases of the QHE (3–7), these states are reconfigurable within a single device. Further demonstrations are displayed in Fig. 4B and C, presenting the possible device operation with two-terminal resistance. The behaviors are qualitatively different depending on the DW configuration: When the DWs connect the current contacts (Fig. 4B), the resistance decreases with an increasing number of DWs. In contrast, when the DWs connect the sample edges (Fig. 4C), the resistance increases with an increasing number of DWs. This is consistent with the Landauer-Büttiker formalism (25), because the ideal resistance is quantized to R_{3g} = h/(N+1) e^2 in the former case and to R_{3g} = (N+1) h/e^2 in the latter case, where N is the number of DWs. This behavior means that the CES works as a conductive channel when it connects the two current contacts, whereas it works as an edge channel reflector between the CES at the sample edges when it connects the two sample edges. The qualitative difference originates from the chiral nature of the CES and is clearly distinct from conductive DWs driven by different physical origins (26–29)—for example, those found in ferroelectric insulators (26, 27) or magnetic insulator with all-in-all-out magnetic order (28, 29).

The present discovery, combined with the recent spintronic developments based on the large spin-orbit torque caused by the spin-momentum locking of the surface state of TI (16, 17), would enable all-electrical control of the mobile DW and the CES, potentially leading to low power-consumption CES-based logic and memory devices (26, 30–32) and quantum information processing (2, 33, 34) in the future.
REFERENCES AND NOTES

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SUPPLEMENTARY MATERIALS

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A magnetic tip reconfigures edge states
Topological phases of matter are characterized by invariants such as Chern numbers, which determine their global properties. On the boundary of two domains with different Chern numbers, chiral edge states are expected to form. Yasuda et al. engineered such states in samples of a quantum anomalous Hall material by creating magnetic domains using the tip of a magnetic force microscope. The existence of chiral edge states along the domain walls was confirmed with electrical transport measurements. The ability to reconfigure and manipulate these states may improve spintronics.
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