Ambi-polar anomalous Nernst effect in a magnetic topological insulator

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Abstract

We report electromagnetic and thermomagnetic transport studies on a magnetic topological insulator thin film \(\text{Cr}_0.15\text{Bi}_0.85\text{Sb}_0.9\text{Te}_3\) grown by molecular beam epitaxy. The temperature and gate voltage dependence of the anomalous Hall effect exhibits the typical behavior of a quantum anomalous Hall insulator. The anomalous Nernst effect (ANE) shows a sign reversal when the Fermi level is tuned across the charge neutrality point of the surface Dirac cone. We show that the ambi-polar behavior of the ANE can be explained by the semiclassical Mott relation, in conjunction with the ambi-polar Dirac band structure.

Introduction

In a ferromagnetic (FM) metal or semiconductor, the spontaneous magnetization of the sample generates an anomalous contribution to the transverse channel of transport phenomena. The most well-known example is the anomalous Hall effect (AHE), in which an extra Hall voltage proportional to the magnetization is present even in zero magnetic field \([1, 2]\). The AHE has attracted tremendous attention in the past few decades due to its complex origin and potential applications in spintronics. Three distinct mechanisms have been proposed for the AHE. The two extrinsic ones are related to impurities, which cause side jumps or skew scatterings of itinerant electrons by spin–orbit coupling \([2–5]\). The intrinsic mechanism ascribes the AHE to the Berry-phase curvature of the occupied electronic states, which reveals the consequence of momentum space topology on transport properties \([2, 6–8]\). In general the three mechanisms take effect simultaneously in a given material, making it difficult to clarify their individual contributions \([9]\). Recently, the quantum AHE (QAHE) has been observed in a magnetic topological insulator (TI), in which a quantized Hall resistance \(R_{yx} = h/e^2\) exists even in zero magnetic field \([10–13]\). This finding not only completed the decade-long search for the last member of the quantum Hall trio \([14]\), but also unambiguously proved the intrinsic mechanism of the AHE due to the Berry-phase curvature \([15]\).

Besides the anomalous electrical transport studied in magnetic TIs, another type of magnetism-induced transport phenomenon, which is much less explored but equally interesting, is the anomalous thermoelectric or thermomagnetic effect. In a conductive material, a temperature gradient in a direction \((\nabla T_x)\) generates a longitudinal electric field \((E_x)\). The ratio \(S = E_x / \nabla T_x\) is called the thermopower or the Seebeck coefficient. In a perpendicular magnetic field \(B_y\), the moving charge carriers experience a Lorentz force perpendicular to their velocity and \(B_y\), hence generating a \(y\)-direction electric field \(E_y\). This transverse thermoelectric effect is called the Nernst effect \([16, 17]\), and an anomalous Nernst effect (ANE), namely the thermoelectric counterpart of the AHE, is available in a FM material \([9, 18]\). The ANE offers a great platform for exploring the intriguing physics of spin–orbit coupling. The unique electronic structures of a FM TI, such as the nontrivial bulk band structure, the
ambipolar Dirac-like surface states and the chiral edge states [19–21] may also bring exotic phenomena in ANE, thus creating novel applications.

In this Letter, we report electromagnetic and thermomagnetic transport studies of a magnetic TI thin film, $\text{Cr}_{0.15}(\text{Bi}_{0.1}\text{Sb}_{0.9})_{1.85}\text{Te}_3$. We found that the temperature and gate-voltage dependence of the AHE exhibits the typical behavior of a QAHE insulator. The ANE, however, shows a sign reversal when the Fermi level ($E_F$) is tuned across the charge-neutrality point (CNP) of the surface Dirac cone. We show that the ambipolar behavior of the ANE can be explained by the semiclassical Mott relation, in conjunction with the ambipolar Dirac band structure.

**Methods**

The $\text{Cr}_{0.15}(\text{Bi}_{0.1}\text{Sb}_{0.9})_{1.85}\text{Te}_3$ TI thin film with thickness of 6 quintuple layer (QL) is grown on insulating SrTiO$_3$ (111) substrate by using state-of-the-art molecular beam epitaxy. The sample growth condition is the same as that for the magnetic TI film in which the QAHE was first discovered [10]. The schematic setup of the transport measurements is shown in figure 1(a), in which the electromagnetic and thermomagnetic properties can be measured on the same sample. The magnetic TI thin film is manually scratched into a Hall-bar configuration and the electrodes are made by mechanically pressing small pieces of indium ingots onto the TI film, and then connected to gold leads. One end of the substrate is connected to a copper heat sink and a thin-film heater is mounted on the other end to produce a steady and uniform temperature gradient through the TI film. Two fine-gauge thermocouples (type E, CHROMEGA/constantan) are connected in subtractive series and thermally anchored to the substrate to monitor the temperature difference across the sample. The carrier density of the magnetic TI thin film is controlled by the applied gate voltage with the SrTiO$_3$ substrate acting as the gate dielectrics. The direction of the applied magnetic field is perpendicular to the film plane. The electromagnetic properties are measured in an isothermal condition using the delta mode of the Keithley 6221 current source plus the 2182 A nanovoltmeter. The thermomagnetic measurements are carried out in high-vacuum condition with the pressure lower than $1 \times 10^{-6}$ mbar. The dc voltages of the Nernst signals are recorded by Keithley 2182 A nanovoltmeters.

**Results and discussions**

We first measure the AHE of the 6 QL $\text{Cr}_{0.15}(\text{Bi}_{0.1}\text{Sb}_{0.9})_{1.85}\text{Te}_3$ thin film under various gate voltages ($V_g$) at the base temperature $T = 1.5$ K. As shown in figure 1(b), the magnetic-field ($\mu_0H$) dependences of the anomalous Hall resistance show square-shaped hysteresis loops with a coercive field ($H_c$) around 0.1 T. With increasing $V_g$, the anomalous Hall resistance first increases, reaches a maximum value near $V_g = 70$ V, and then decreases again. Figure 1(c) displays the $V_g$ dependence of $\rho_{xy}$ (the Hall resistance at $\mu_0H = 0$ T), which reaches a maximum value of 17.4 kΩ at $V_g = 70$ V. This gate voltage thus corresponds to the situation where the $E_F$ lies at the CNP within the energy gap at the surface-state Dirac cone opened by the FM order [10]. Both the $V_g$ dependence and the maximum $\rho_{xy}$ value are in excellent agreement with that of the original QAHE sample measured at $T = 1.5$ K (figure 4(A) in [10]). These results indicate that the magnetic TI film studied here has high quality and can achieve the QAHE at lower temperature.

To investigate the anomalous thermomagnetic transport, we measure the Nernst signal (defined as $S_{nx} = E_y/\nabla T_x$) in this magnetic TI. Figures 2(a) and (b) display the Hall effect and the Nernst effect traces.
measured at different temperatures from 5 to 40 K, respectively. At $T = 40$ K, both $S_{yx}$ and $\rho_{yx}$ traces are linear to magnetic field, which is the typical behavior of the ordinary transverse transport of charge carriers. Pronounced curvature develops at $T = 30$ K due to the magnetic field alignment of the local moments, which is characteristic of a paramagnetic metal [22]. For $T < 15$ K, the sample enters the FM phase and a square-shaped hysteresis loop starts to appear. Both transport effects exhibit the same direction of the hysteresis loop (anti-clockwise loop as indicated by the magenta arrows), and nearly identical coercivity at each temperature. The strong resemblance between the temperature dependence of the AHE and ANE in this magnetic TI suggests that the two anomalous transport effects share the same physical origin.

In contrast to the similar temperature dependence, the gate voltage dependence of the two anomalous transport effects reveal something very puzzling. Figures 3(a) and (b) display the magnetic field traces of $\rho_{yx}$ and $S_{yx}$ measured under various $V_g$ at $T = 5$ K. The CNP corresponds to $V_g$ between 55 and 70 V, when the anomalous $\rho_{yx}$ reaches the maximum level. For $V_g = -20$, 0 and 20 V, $E_F$ lies below the Dirac point so that the hole-type surface state carriers dominate the transport process. In this regime the two anomalous transport effects are highly analogous, both showing the hysteretic behavior with the same direction, and the gradual increase of anomalous signal with $V_g$. With further increase of $V_g$ towards the CNP, the anomalous $\rho_{yx}$ keeps increasing, whereas the anomalous $S_{yx}$ starts to decrease. For $V_g > 70$ V, the $E_F$ lies above the Dirac point, so that the electron-type surface state carriers dominate the transport process, and the anomalous $\rho_{yx}$ starts to decrease with increasing $V_g$. In this regime the anomalous Nernst signal first decreases to almost zero at $V_g = 100$ V, and more surprisingly, above that the anomalous $S_{yx}$ changes its sign from positive to negative. The direction of the

![](Figure2.png)

**Figure 2.** The magnetic field dependence of (a) $\rho_{yx}$ and (b) $S_{yx}$ measured at various $T$ from 5 to 40 K under $V_g = 0$ V. The magenta arrows denote the same anticlockwise direction of the anomalous Hall effect and the anomalous Nernst effect loops.

![](Figure3.png)

**Figure 3.** The magnetic field dependence of (a) $\rho_{yx}$ and (b) $S_{yx}$ under various $V_g$ measured at $T = 5$ K. The sign of the anomalous Nernst signal changes from positive (anticlockwise loop denoted by the magenta arrows) to negative (clockwise loop denoted by the blue arrows) when the thin film is tuned from hole type to electron type by gating.
ANE loops changes from anticlockwise to clockwise (as indicated by the magenta and blue arrows, respectively). Therefore, the ANE of the magnetic TI exhibit a highly unusual ambi-polar behavior when the $E_g$ is tuned across the CNP of the surface Dirac cone.

The sharp contrast between the $V_g$ dependence of AHE and ANE reveals that in the magnetic TI, the anomalous transport responses to an electric field and a temperature gradient are considerably different. Below we will show that the Mott relation, in conjunction with the ambi-polar electronic band structure of the topological surface states, give a natural explanation for the ambi-polar ANE observed here in the QAHE regime.

The Mott relation was originally derived from the Boltzmann equation for diffusive transport coefficients, in which the thermopower can be expressed as $S = \frac{-e k_B T}{2 \pi^2 \hbar^2} \cdot \frac{1}{\sigma_{xx} + \sigma_{yx}} \cdot \left( \frac{\partial \sigma_{yx}}{\partial E} \right)_{E_g} - \frac{\sigma_{xx}}{\sigma_{yx}} \cdot \left( \frac{\partial \sigma_{yy}}{\partial E} \right)_{E_g}$. In this case the Nernst signal $S_{yx}$ can be expressed as

$$S_{yx} = -\frac{\pi^2 k_B^2 T}{3e} \cdot \frac{1}{\sigma_{xx} + \sigma_{yx}} \cdot \left( \frac{\partial \sigma_{yx}}{\partial E} \right)_{E_g} - \frac{\sigma_{xx}}{\sigma_{yx}} \cdot \left( \frac{\partial \sigma_{yy}}{\partial E} \right)_{E_g}.$$ (1)

In our experiment the position of $E_g$ can be tuned by $V_g$, therefore the energy derivative of the conductivity with respect to $E_g$ can be calculated as $\frac{\partial \sigma_{yx}}{\partial E_g} = \frac{\partial \sigma_{xy}}{\partial \mu} \cdot \frac{\partial \mu}{\partial E_g} = \frac{\partial \sigma_{xy}}{\partial \mu}$. From the experimentally measured $\rho_{yx}$ and $\rho_{xx}$ values at varied gate voltages, we can calculate the $V_g$ dependent $\sigma_{xx}$ and $\sigma_{yx}$, as summarized in figure 4(a) for $\mu_0 H = 0.2$ T and $T = 5$ K. Moreover, $\partial V_g / \partial E_g$ can be estimated by using a simple Dirac-like surface band structure with linear $E$–$k$ dispersion (the contribution of the bulk carriers and the small gap of the surface band opened at the Dirac point by the magnetism can be ignored). For a TI thin film, $n_{2D} = E_g^2 / 2 \pi^2 \hbar^2 v_F^2$, where $v_F$ is the Dirac Fermion velocity and is $\sim 10^5$ m s$^{-1}$ in this system [24]. Meanwhile, $n_{2D}$ can be related to $V_g$ as: $n_{2D} = (C_g \cdot (V_g - V_D)) / \epsilon$, where $C_g$ and $V_D$ are the capacitance per unit area and the gate voltage at the Dirac point, $C_g$ can be calculated as $C_g = \varepsilon_{STO} / d_{STO}$, where $\varepsilon_{STO}$ and $d_{STO}$ are the dielectric constant and the thickness of the SrTiO$_3$ substrate. Here, $d_{STO}$ is about 0.25 mm in our experiment and $\varepsilon_{STO}$ is estimated from [25, 26]. Therefore, we obtain the relation between $E_g$ and $V_g$:

$V_g - V_D = E_g^2 / 2 \pi^2 \hbar^2 v_F^2$, and thus $\frac{\partial V_g}{\partial \mu} = \frac{1}{\hbar v_F} \cdot \sqrt{\frac{2 \pi^2 e v_F^2}{E_g}} \cdot \sqrt{\left| V_g - V_D \right|}$. Substituting it into equation (1), we obtain the anomalous $S_{yx}$ value calculated from the Mott relation, $S_{yx}^{Mott}$, which is plotted as blue solid line in figure 4(b). As can be seen clearly, $S_{yx}^{Mott}$ agrees well with the measured $S_{yx}$ at $\mu_0 H = 0.2$ T and $T = 5$ K (the red solid symbols). Most importantly, the anomalous $S_{yx}$ value changes sign from positive to negative with increasing $V_g$, consistent with the sign reversal observed experimentally. Note that the Mott relation only works
for continuous $\sigma(E)$ at low temperatures. The small quantitative deviation between theory and experiment may be caused by the discontinuity of $\sigma(E)$ around band edges and the contribution from the bulk carriers at finite temperature, which also causes a reduction of AHE from the quantized level [10].

**Conclusion**

In conclusion, we observe a sign reversal of the ANE in a magnetic TI when the Fermi level is tuned across the CNP by an external gate voltage. We show that this ambi-polar behavior of the ANE can be explained semi-quantitatively by using the Mott relation between electrical and thermal transport coefficients, in conjunction with the ambi-polar Dirac-like band structure of the topological surface states, thus is unique to magnetic TIs. These results shed important new lights on the anomalous thermomagnetic transport properties and potential applications of magnetic TIs.

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