Anisotropic planar Hall effect in the type-II topological Weyl semimetal WTe_2

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The giant planar Hall effect arising from a chiral anomaly, and that is related to the Berry curvature, has been predicted but never observed in nonmagnetic type-II Dirac/Weyl semimetals. Here, we report an observation of the anisotropic planar Hall effect in type-II Weyl semimetal WTe_2 . Interestingly, we observe a chiral-anomaly-induced sinusoidal angular-dependent planar Hall effect when the electric field is parallel to the tilting direction of Weyl cone, i.e., the b axis of WTe_2 . The planar Hall effect amplitude is linearly dependent on the magnetic fields and decreases gradually as the temperature increases across the topological phase transition temperature. Our observations clearly reveal the footprints on transport from the chiral anomaly feature in type-II Weyl semimetals.

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I. INTRODUCTION

The Weyl fermions, in condensed matter, refer to the electrons that exist near the linear dispersive band crossing [1]. One of important and unusual phenomenon in Weyl semimetals is the chiral anomaly, which refers to the nonconservation of the number of particles with a given chirality [2]. A negative longitudinal magnetoresistance is usually considered to be a typical feature of Weyl semimetals when the applied magnetic field is parallel to the electric field [3–6]. Compared to the predicted magnetic Weyl semimetal with broken time-reversal symmetry, nonmagnetic Weyl semimetals with a broken inversion symmetry, such as TaAs [7], Na_3Bi [8,9], and $\text{W}(\text{Mo})\text{Te}_2$ [1], have received considerable attention, because the chiral-anomaly-induced negative longitudinal magnetoresistance in the nonmagnetic Weyl semimetals exclude the possibility of spin-dependent phenomena. However, other effects, such as current jetting and the Knudsen effect [10–12], also result in a negative magnetoresistance that prevents the validation of the Weyl nature of materials using transport methods. Nevertheless, the planar Hall effect (PHE) in nonmagnetic Weyl semimetals that we recently proposed can be an indication of the Weyl nature, through transport properties [13–16].

The PHE refers to the Hall resistance when the magnetic field is coplanar with, instead of transverse to the longitudinal and Hall electric fields. In Weyl semimetals, the nontrivial Berry curvature in the momentum space, not the magnetization in magnetic materials, produces the planar Hall resistance [13,14]. In type-II Weyl semimetals, the band crossing of electron pockets and hole pockets is tilted. More interestingly, PHE appears to behave quite differently in type-II

Weyl semimetals than it does in type-I ones [14]. The planar Hall resistivity in type-I and type-II Weyl semimetals are quadratically and linearly dependent on the magnetic field, respectively [14]. Since the prediction of theoretical work, the giant PHE has been observed in several Dirac/type-I Weyl semimetals, such as ZrTe_5 , and GdPtBi [17–20]. Although several studies report observing a chiral-anomaly-induced PHE in type-II Dirac/Weyl semimetals, e.g., VAl_3 and WTe_2 [21,22], the strong orbital magnetoresistance (OMR) in type-II Weyl makes it challenging to know, with certainty, the real physical origin of the observed PHE [23].

In this work, we investigate the anisotropic PHE in type-II Weyl semimetal WTe_2 , with an electric field along and normal to the tilting direction of the Weyl cone. We find that the planar Hall resistivity, together with the electric field along the tilting direction (b axis), are linearly dependent on the magnetic field, with an angular dependence of $\sin\varphi$ (where φ is the tilt angle between the current and magnetic field), consistently with theoretical predictions. Across the topological phase transition temperature (~ 70 K) in WTe_2 , the amplitude of the chiral-anomaly-induced PHE decrease when increasing the temperature.

II. RESULTS AND DISCUSSION

To make the Hall bar devices with a current flow along different directions, we first identify the in-plane crystal orientation of chemical vapor transport grown WTe_2 flakes (from HQ graphene, see more details in Supplemental Material Note 1), using polarized Raman spectroscopy. The intensity of the Raman spectra collected with a crystal orientation either parallel or normal to the laser polarization direction are significantly different, especially for the peaks A_1^8 (~ 130 cm^{-1}) and A_1^2 (~ 212 cm^{-1}) [24,25], as shown in Fig. 1(a). Through the angular-dependent A_1^8 and A_1^2 peaks, we can identify the

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FIG. 1. (a) Typical optical image of WTe₂ devices. The scale bar is 10 μm. The thickness of the device is 18.4 nm. (b) Typical polarized Raman spectra with the laser polarization direction along the *a* and *b* axes of WTe₂. Magnetic field dependence of longitudinal magnetoresistance at 2 K, with current along the *a* axis (c) and *b* axis (d) of WTe₂. As the increase of deviation between the current and magnetic field, the negative magnetoresistance in (d) vanishes quickly. (e) Raw SdH oscillations with current along the *a* and *b* axes (*T* = 30 mK). (f) FFT spectra of SdH oscillations with current along the *a* axis (e) and *b* axis (f) of WTe₂. The arrow indicates the Weyl orbit quantum oscillation.

in-plane crystal orientation [24,25] and then fabricate the Hall bar devices (see more details in Supplemental Material Figure S1) [26]. Figure 1(b) shows the optical image of typical WTe₂ Hall bar devices (18.4 nm), with a current flow along both directions.

According to previous studies [1,5,6,27], the Weyl points in WTe₂ sits along the *Y* axis (*b* axis). To investigate the chiral anomaly-related phenomena, we must be certain that the Fermi level is close to the Weyl points in our WTe₂ devices [6], because the the Weyl points of the bulk WTe₂ are ~60 meV away from the Fermi level [1]. We first measure the longitudinal magnetoresistance (*B*//*E*) in both devices. Figures 1(c) and 1(d) show the longitudinal magnetoresistance. Clearly, the magnetoresistance ratio is always positive

for the *B*//*E*//*a* axis, but negative for the *B*//*E*//*b* axis under strong magnetic fields (*B* > 6 T), and with a quadratic field dependence [28]. As the increase of deviation between the current and magnetic field, the negative magnetoresistance vanishes quickly. Since the chiral Landau levels (*n* = 0) are essential to the negative MR, this observed scenario is consistent with the chiral-anomaly-induced negative magnetoresistance in Weyl semimetals. The chiral Landau levels are missing when *B* is normal to the Weyl cone tilting direction, but still exist when *B* is parallel to the Weyl cone tilting direction [29]. According to the calculations on WTe₂, the Weyl cone is tilted along the *Y* direction (*b* axis) [1,27]. Therefore, a negative longitudinal magnetoresistance is expected [Fig. 1(d)]. The Fermi arc-related quantum oscillations

FIG. 2. (a) Angular dependence of planar Hall resistivity of WTe_2 , with current along the a axis (a) and b axis (b), under a magnetic field of 14 T and at 2 K. Solid lines give the angular fittings of $\sin\varphi$ and $\sin 2\varphi$ terms. Raw data of angular dependent planar Hall resistivity at various magnetic fields with current along the a axis (c) and b axis (d). Fitted planar Hall resistivity amplitude of $\sin\varphi$ (e) and $\sin 2\varphi$ (f) terms as a function of the magnetic field, with current along the a and b axes. Solid lines give the linear and quadratic fitting for $\sin\varphi$ (e) and $\sin 2\varphi$ (f) terms, respectively.

in flakes with thicknesses no more than the mean free path, the so-called “Weyl orbit,” are one more evidence of the location of the Fermi level [6,10,30–33]. According to the Weyl point separation in WTe_2 , the Weyl orbits should vanish near ~ 80 T, for a current along the a axis, but remain along the b axis [6]. To uncover the anisotropic Weyl orbits, we measure the quantum oscillations in both devices at 30 mK. Figure 1(e) shows the raw data for Shubnikov–de Haas (SdH) oscillations with current along both directions (see more SdH information in Supplemental Material information Fig. S2). From the fast Fourier transformation (FFT) of the quantum oscillations [Fig. 1(f)], we can readily see the difference between the a - and b -axis devices. The strong difference in amplitude of SdH oscillations along both directions comes from the anisotropic mobility [34]. The frequencies near 120 T are from the bulk electrons’ Fermi surfaces of WTe_2 [34]. However, we cannot resolve the Weyl orbit frequency ($F_S = E_F k_0 / e\pi v_F$) near 80 T in the a -axis WTe_2 device. Nevertheless, the potential Weyl orbit frequency, ~ 80 T, in the b -axis Hall bar, is clearly detected, as indicated by the arrow in Fig. 1(f). These features enable us to further investigate the chiral-anomaly-induced PHE in type-II Weyl semimetals.

Figures 2(a) and 2(b), respectively, give the angular dependent planar Hall resistivity with the current flowing along a and b axes ($B = 14$ T), where measurements are carried out simultaneously on devices fabricated out of the same flake. Notably, the planar Hall resistivity is composed of both $\sin\varphi$ and $\sin 2\varphi$ terms. We separate the contributions of $\sin\varphi$ and $\sin 2\varphi$ terms by fitting the angular dependent planar Hall resistivity, as shown by the solid lines in Figs. 2(a) and 2(b). The fitting equation is

$$\rho_{xy}^{\text{planar}} = A_1 \sin(\varphi + \varphi_1) + A_2 \sin(2\varphi + \varphi_2) + C, \quad (1)$$

where C gives the longitudinal resistivity offset due to the Hall bar geometric mismatch. According to previous theoretical studies, the chiral-anomaly-induced PHE for E away from the tilting direction of Weyl cones will give rise to a $\sin 2\varphi$ angular dependence [14]. At the same time, OMR will generate a $\sin 2\varphi$ angular dependence in PHE [17,23]. Chiral-anomaly-induced PHE for the case of E /tilting direction of Weyl cone (b axis) will also result in a $\sin\varphi$ term [14]. Although the magnetic field is rotating in plane during the measurement of PHE, the slight out-of-plane components of the external magnetic fields will inadvertently introduce Hall signals in the measurements, resulting in a $\sin\varphi$ behavior [17,19]. The phase shifts φ_1 and φ_2 in Eq. (1) are necessary to compensate the nonzero initial angle due to the slight misalignment (see more phase angle explanation in Supplemental Material Note 2). According to previous investigations, the carrier density of semimetallic WTe_2 is approximately 10^{19} cm^{-3} [34], which results in a non-negligible normal Hall effect [26]. Figures 2(a) and 2(b) clearly show that the $\sin\varphi$ term of E // b axis in the angular dependent planar Hall resistivity is significantly larger than that of the E // a axis. The simultaneous measurements on devices out of the same flake convince us that the difference of the $\sin\varphi$ term between E // a axis and E // b axis configurations should have another physical origin. (See the isotropic normal Hall effect with E // a axis and E // b axis in Supplemental Material information Fig. S3).

According to theoretical predictions, in the case of the E /tilting direction of Weyl cone (b axis), the planar Hall conductivity [$\sigma_{xy} = -\rho_{xy}/(\rho_{xx}^2 + \rho_{xy}^2)$] will be linearly proportional to the external magnetic field, whereas the planar Hall conductivity will be quadratically dependent on the magnetic field, when E is unparallelled to the tilting direction of the Weyl cone [14]. Figures 2(c) and 2(d) show $\rho_{xy}^{\text{planar}} - \varphi$ curves,

FIG. 3. Measured in-plane anisotropic longitudinal resistivity of WTe₂ ($t = 18.4$ nm), under various magnetic fields, and at 2 K, (a) $E//a$ axis; (b) $E//b$ axis. Extracted longitudinal resistivity as a function of the magnetic field, (c) $E//a$ axis; (d) $E//b$ axis. The solid lines give the best fittings of $\rho_{\perp}$.

under various magnetic fields ($T = 2$ K), with current along the a and b axes, respectively (see more data in Supplemental Material Fig. S4) [26]. The contributions of $\sin\varphi$ and $\sin 2\varphi$ terms can be extracted from the raw data using similar sinusoidal fittings. The amplitude of the $\sin\varphi$ term [Fig. 2(e)] linearly depends on the magnetic field for E along both a and b axes. Since the Weyl cone in WTe₂ tilts mainly along the Y directions, the $\sin\varphi$ term induced by chiral-anomaly-induced PHE for the E along the a axis is expected to be zero. We infer that the observed $\sin\varphi$ term for $E//a$ axis in Fig. 2(e) should originate from a normal Hall effect due to out-of-plane magnetic field components. Nevertheless, the $\sin\varphi$ term for $E//b$ axis is almost four times greater than that for $E//a$ axis, strongly indicating the existence of a chiral-anomaly-induced PHE in type-II Weyl semimetal WTe₂ when $E//$ tilting direction of Weyl cones (b axis).

Both OMR and chiral-anomaly-induced PHE for E away from the tilting direction of Weyl cones will follow the $\sin 2\varphi$ angular dependence on the planar Hall resistivity. Meanwhile, the magnetic field dependence of the $\sin 2\varphi$ term is approximately quadratic [14,23]. Figure 2(f) clearly shows that the amplitude of the $\sin 2\varphi$ term, with current along the a axis, is only smaller by one third than that along the b axis. Ideally, the $\sin 2\varphi$ term, with current along the b axis, should be zero, if only the chiral-anomaly-induced PHE contributes to the measured signals. This indicates that the OMR presumably dominates, in this highly anisotropic WTe₂ [23]. At the exception of the highly anisotropic carrier mobility [34], the nonlinear Hall effect in this highly anisotropic crystals were also demonstrated by second harmonic generation, which

is driven by the broken inversion symmetry and the Berry curvature dipole [35–37].

To further demonstrate the existence of a significantly strong OMR in WTe₂, we directly measure the angular dependence of longitudinal resistivity, with current along the a and b axes, as shown in Figs. 3(a) and 3(b). Notably, all the $\rho_{xx} - \varphi$ curves ($T = 2$ K) follow the $\sin 2\varphi$ relation, no matter in which direction the current flows. The unexpected feature is the $\sin 2\varphi$ dependence, with current along the b axis. According to the chiral-anomaly-induced PHE theory in type-II Weyl semimetals, the $\rho_{xx} - \varphi$ curve will have a $\sin\varphi$ dependence for $E//$ tilting direction of Weyl cone [14]. However, we can hardly see the $\sin\varphi$ feature in the curves with the $E//b$ axis [Fig. 3(b)]. We speculate that the $\sin 2\varphi$ -dependent OMR in WTe₂ probably is dominant in the longitudinal resistivity. To uncover more details, we plot the longitudinal resistivities $\rho_{\parallel}$ and $\rho_{\perp}$ as a function of the magnetic field ($T = 2$ K), as shown in Figs. 3(c) and 3(d), respectively. Clearly, $\Delta\rho = \rho_{\perp} - \rho_{\parallel}$ mainly originates from the enhancement of $\rho_{\perp}$, as the magnetic field increases. In both cases, the field dependence of $\rho_{\perp}$ can be fitted to a power law function, i.e., $\rho_{\perp} \propto B^{1.57}$ and $\rho_{\perp} \propto B^{1.46}$ for the $E//a$ and $E//b$ axes, respectively. Both MR follow subquadratic field dependence [38], and the power exponents are quite close to those observed in other systems [20,21,23]. Previous work showed that the mobility in WTe₂ was highly anisotropic [34], resulting in a highly anisotropic conductivity ($\sigma = ne\mu$) and a strong anisotropic magnetoresistance in WTe₂. This dominant OMR ($\sin 2\varphi$) could account for the absence of chiral-anomaly-induced anisotropic MR ($\sin\varphi$) in the longitudinal resistivity of WTe₂.

FIG. 4. Measured angular dependence of planar Hall resistivity of WTe_2 at different temperatures ($B = 14$ T), (a) $E//a$ axis; (b) $E//b$ axis; (c) Temperature dependence of planar Hall resistivity amplitude ($\sin \phi$ term $\rho_{xy}^{\text{chiral}}$) in WTe_2 with current along different directions. (d) Temperature dependence of planar Hall resistivity amplitude difference between the b axis and a axis. It decreases for temperature higher than 100 K.

After observing a linear field dependence of the planar Hall resistivity, we felt motivated to investigate PHE in WTe_2 at different temperatures, to further elucidate the physical origin of the $\sin \phi$ term in the b -axis device [Fig. 2(e)]. Figures 4(a) and 4(b) show the angular-dependent planar Hall resistivity, with current along both directions, at different temperatures ($B = 14$ T). Using the sinusoidal fitting shown in Figs. 2(a) and 2(b), we extract and subsequently plot the temperature dependence of the $\sin \phi$ -term amplitude in the planar Hall resistivity, along both directions [Fig. 4(c)]. The $E//a$ axis component almost stays unchanged for $T > 100$ K, whereas the $E//b$ axis component decreases continuously. However, the $\sin \phi$ -term component of the $E//b$ axis is always greater than that of the $E//a$ axis. We subtract the $E//a$ axis data from $E//b$ -axis data to eliminate the influence of the out-of-plane Hall effect, as shown in Fig. 4(d). The $\rho_{xy}^b - \rho_{xy}^a$ should be directly related to the highly anisotropic chiral anomaly in type-II Weyl semimetals because of the Fermi arc in WTe_2 being mainly along the Y axis. Most strikingly, we find that $\rho_{xy}^b - \rho_{xy}^a$ remains largely unchanged for $T < 100$ K, but decreases continuously as the temperature increases up to 100 K. The critical temperature (50–100 K) in Fig. 4(d) is consistent with the topological phase transition temperature in WTe_2 (chemical vapor transport WTe_2 : ~ 70 K) previously reported, due to the slight expansion of the lattice [39]. For temperatures above 70 K, the Weyl cone is gapped, and the Fermi arc and chiral anomaly in WTe_2 disappear gradually, resulting in a reduction of the chiral-anomaly-

induced PHE in WTe_2 . To further validate our observations and analysis (Fig. 4), we measure more devices of different thicknesses ($t = 14.4, 27.0$ nm) [26]. Both samples show the same features as those reported in Figs. 2 and 4, i.e., a planar Hall resistivity of the $E//b$ axis higher than that of $E//a$ axis, and a critical transition temperature within the range of 50–100 K [39]. Our observations demonstrate the presence of a chiral-anomaly-induced $\sin \phi$ angular dependent PHE in type-II Weyl semimetals, for the $E//\text{tilting}$ direction of Weyl cones. On the contrary, one may notice that it is very difficult to extract the $\sin \phi$ term MR with the $E//b$ axis, which could be ascribed to the fact that the longitudinal anisotropic magnetoresistance (AMR) ratio is highly anisotropic for current along a and b axes. When the magnetic field of 14 T is rotating in the ab plane (Fig. 3), the AMR ratios $[(\rho_{\max} - \rho_{\min})/\rho_{\min}]$ with current along the a and b axes are 1.1% and 2.6%, respectively, indicating clearly the anisotropy. Thus, we cannot use the same subtraction method to extract the $\sin \phi$ angular dependent MR, induced by the chiral anomaly, from the measured planar Hall effect. In a theoretical work by Nandy *et al.* [14], only the anisotropic longitudinal MR induced by chiral anomaly was estimated by ignoring the strong orbital magnetoresistance. Actually, this strong orbital magnetoresistance and anisotropic AMR ratio hinders us detecting and extracting the $\sin \phi$ term MR with $E//b$ axis in longitudinal configuration (ρ_{xx}).

Compared to the previous PHE work in other type-II Weyl semimetal systems, i.e., VAl_3 and $\text{W}(\text{Mo})\text{Te}_2$ [21–23], we

analyzed PHE in more detail with the electric field along and normal to the tilting direction of Weyl cone. Their works did not give the clear direction of current in samples. Normally, bulk $\text{W}(\text{Mo})\text{Te}_2$ has a needle shape along the a axis [34]; therefore, we can speculate that, in bulk $\text{W}(\text{Mo})\text{Te}_2$, the current is applied along the a axis, resulting in a $\sin 2\varphi$ -angular-dependent PHE without any type-II Weyl feature [14]. On the other hand, the strong OMR also prevents the observation of a $\sin\varphi$ -angular-dependent PHE [23]. In our experiments, we carefully define the direction of the electric field, and find our observations in WTe_2 to agree with predictions for type-II Weyl semimetals.

III. CONCLUSIONS

To conclude, we observed a highly anisotropic PHE in type-II Weyl semimetal WTe_2 . When E is parallel to the tilting direction of the Weyl cone of type-II Weyl semimetals, the planar Hall resistivity is linearly dependent on the

magnetic field, and the PHE decreases fast, for temperatures over the topological phase transition. Taken together with our observations of a chiral-anomaly-induced longitudinal negative magnetoresistance and Weyl orbit quantum oscillations, our results shed light on the chiral anomaly of transport in type-II Weyl semimetals, and its underlying mechanisms.

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