

Current jetting distorted planar Hall effect in a Weyl semimetal with ultrahigh mobility

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A giant planar Hall effect (PHE) and anisotropic magnetoresistance (AMR) are observed in TaP, a nonmagnetic Weyl semimetal with ultrahigh mobility. The perpendicular resistivity (i.e., the planar magnetic field applied normal to the current) far exceeds the zero-field resistivity, which thus rules out the possible origin of negative longitudinal magnetoresistance. The giant PHE and AMR are finally attributed to the large anisotropic orbital magnetoresistance that stems from the ultrahigh mobility. Furthermore, the mobility-enhanced current jetting effects are found to strongly deform the line shape of the curves, and their evolution with the changing magnetic field and temperature is also studied. Although the giant PHE and AMR suggest promising applications in spintronics, the enhanced current jetting shows the other side of the coin, which needs to be considered in future device design.

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I. INTRODUCTION

Topological (Dirac and Weyl) semimetals (TSMs) attract fast growing interests for their intriguing properties, such as extremely large nonsaturating positive magnetoresistance (XMR) [1], chiral anomaly induced negative longitudinal MR (NLMR) [2], surface Fermi arcs [3,4], etc. Chiral anomaly refers to the nonconservation of chiral charge around the Weyl nodes when the applied electric and magnetic fields are nonorthogonal ($\mathbf{E} \cdot \mathbf{B} \neq 0$). As a result of the chiral anomaly, the NLMR has been widely used to investigate and identify the TSMs [5–10]. However, recent studies indicate that the measurement of NLMR can be affected by some extrinsic effects, like ionic impurity induced scattering [11], weak localization [12], conductivity fluctuation [13], and current jetting effect [14,15]. Especially for the semimetals with high mobility (e.g., the TaP family), considerable concerns have been raised about the validity of NLMR, because the significantly enhanced current jetting effect can also induce a large NLMR [14].

Therefore, some new techniques have been tried to unveil the nontrivial nature of TSMs. These techniques include the measurements of anomalous Hall effect [16], anomalous Nernst effect [17,18], and nonlinear optical response [19].

Notably, a recently arising phenomenon, i.e., the giant planar Hall effect (PHE), has been intensively studied both theoretically [20,21] and experimentally [22–27], for its possible connection with the chiral anomaly in TSMs [22–24]. However, some studies show that the chiral anomaly induced PHE is just the angular dependence of NLMR [22,23]. The PHE measurements suffer from all the extrinsic effects that affect the measurements of NLMR, such as current jetting. Besides chiral anomaly, PHE may have other origins in various systems, including anisotropic magnetic scattering [28,29], topological surface states [30], and orbital magnetoresistance [27]. The different mechanisms are reflected as the contribution to the anisotropic resistivity $\Delta\rho = \rho_{\perp} - \rho_{\parallel}$, where ρ_{\perp} and ρ_{\parallel} are the resistivity corresponding to the (planar) magnetic field perpendicular to and parallel to the current (I), respectively. The PHE (ρ_{yx}) and related anisotropic MR (AMR, ρ_{xx}) can be expressed as [20]

$$\rho_{yx} = -\Delta\rho \sin\theta \cos\theta, \quad (1)$$

$$\rho_{xx} = \rho_{\perp} - \Delta\rho \cos^2\theta, \quad (2)$$

where θ is the angle of magnetic field with respect to current. Note that in Ref. [20] the formulations are based on the pure Weyl physics, where the $\Delta\rho$ comes only from the reduction of ρ_{\parallel} (i.e., the NLMR) while the ρ_{\perp} remains unchanged (i.e., the zero-field resistivity ρ_0). However, in the following discussion the $\Delta\rho$ has contributions from all possible origins.

In this paper, we report the observation of giant PHE and AMR in a Weyl semimetal TaP, which is not directly associated with the chiral anomaly, because the ultrahigh mobility ($\sim 10^6$ cm²/Vs [15]) prohibits the observation of a chiral anomaly induced NLMR [14,24] and the chiral anomaly may be even absent in TaP [15]. The giant PHE and AMR are

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finally attributed to the large anisotropic orbital magnetoresistance (or XMR). In addition, the mobility-enhanced current jetting effects are found to strongly deform the line shape of the curves, and their evolution with the changing magnetic field and temperature is also studied. When the current jetting effects are suppressed, in terms of the low field and reduced mobility (by increasing temperature), well-defined PHE and AMR curves are obtained. Since the XMR is always related with the ultrahigh mobility [31–33], the giant PHE and AMR and the large current jetting in TaP are understood in the same scenario. Although the former suggests promising applications in spintronics, the latter shows the other side of the coin.

II. EXPERIMENTAL METHODS

High-quality TaP single crystals were synthesized using a chemical vapor transport method. A stoichiometric mixture of Ta and P powder was first heated in an evacuated fused silica tube for 48 h at 850 °C, and then the resultant polycrystals were sealed in a quartz tube with iodine as transport agent (9 mg/cm³). Platelike single crystals can be obtained after vapor transport growth with a temperature gradient from 930 to 820 °C. The crystal structure and chemical composition were checked by single-crystal x-ray diffraction (XRD) on a Rigaku-TTR3 x-ray diffractometer using Cu K α radiation and on an Oxford Swift 3000 energy dispersive spectrometer (EDS). Magnetic susceptibility measurements were performed on a Quantum Design MPMS-3. Single crystals were polished until thin enough (around 150 μ m) for transport measurements that were taken on a Quantum Design physical property measurement system. Standard four-probe technique was used to measure the longitudinal resistivity, and Hall contacts were located on the transverse sides. Magnetic field was applied and rotated within the sample plane.

III. RESULTS AND DISCUSSION

A. Sample characterizations

The as-grown TaP single crystals are thin plates and exhibit squarelike morphology, with a typical size of $3 \times 3 \times 0.8$ mm³ [Fig. 1(a)]. The chemical composition is confirmed by EDS, as depicted in Fig. 1(b). Figure 1(c) shows the single-crystal XRD pattern, in which two sharp single crystal peaks are detected. The high quality of the single crystal is supported by the narrow full width at half maximum (FWHM, 0.08 deg) revealed in the rocking curve scan [right inset of Fig. 1(c)]. The observed peaks are in good agreement with the (00 l) diffraction of TaP with space group $I4_1md$ (no. 109), the crystal structure of which is illustrated in the left inset of Fig. 1(c). The indices also suggest that the naturally cleaved surface is the ab plane.

The obtained TaP single crystal is further characterized by the de Haas–van Alphen (dHvA) measurements and Fermi-surface analyses. Figure 2(a) presents the magnetization as a function of magnetic field ($B||c$) taken at various temperatures from 1.8 to 10 K. On a diamagnetic background, the dHvA oscillations are superimposed, starting from a field as low as 0.6 T at 1.8 K. After removing the background (represented by a polynomial), the oscillations become more pronounced (plotted against $1/B$) [Fig. 2(b)]. By performing fast Fourier

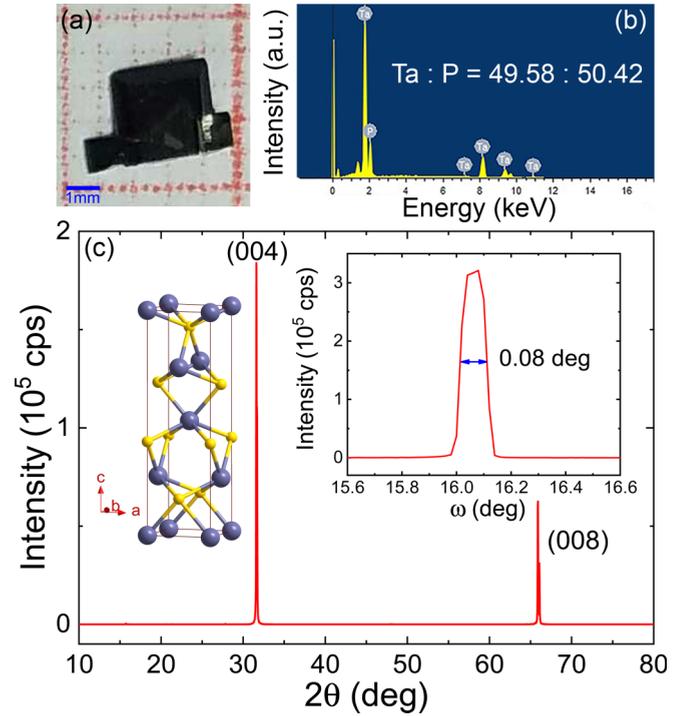


FIG. 1. (a) Optical image of the as-grown TaP single crystal. (b) EDS result of the single crystal, with atomic ratio shown in the spectroscopy. (c) Single-crystal XRD pattern taken at room temperature. Left inset: Crystal structure of TaP. Blue and yellow spheres represent Ta and P atoms, respectively. Right inset: Rocking curve scan of the [004] diffraction, showing a narrow full width at half maximum of 0.08 deg.

transformation (FFT), the frequencies of oscillations and their harmonics are retrieved, i.e., 18 T (β), 24 T (γ), 29 T (2α), and 46 T (δ) [Fig. 2(c)]. These frequencies are highly consistent with previous Shubnikov–de Haas and dHvA measurements [15,34,35], and are finally identified according to those results and band-structure calculations [15].

The nature of Weyl fermions participating in quantum oscillations (e.g., high mobility) can be revealed by quantitative analyses of dHvA oscillations. The oscillations are described by the Lifshitz-Kosevich formula [36], with the amplitude proportional to the thermal damping factor $R(T) = (\lambda m^* T / B) / \sin(\lambda m^* T / B)$, where $\lambda = 2\pi^2 k_B / e\hbar$, k_B is the Boltzmann constant, \hbar is the reduced Planck constant, and m^* is the effective mass of the carrier. Figure 2(d) shows the amplitudes as a function of temperature for all the frequencies. The fits to $R(T)$ yield effective mass for the corresponding carriers, i.e., $m_\alpha^* = 0.068 m_0$, $m_\beta^* = 0.050 m_0$, $m_\gamma^* = 0.071 m_0$, and $m_\delta^* = 0.1 m_0$ (m_0 is the mass of the free electron). Such small effective mass is always linked to steep linear bands and ultrahigh mobility. Taking the F_β branch for example, its extremal cross-section area A_F is calculated as 0.172 nm⁻², according to Onsager relation $F = (\hbar/2\pi e)A_F$. Supposing a circular cross section, a very small Fermi momentum $k_F = 0.234$ nm⁻¹ is obtained, which further leads to a large Fermi velocity $v_F = \hbar k_F / m^* = 5.4 \times 10^5$ ms⁻¹. Such a large Fermi velocity is comparable with that of NbP, which has an

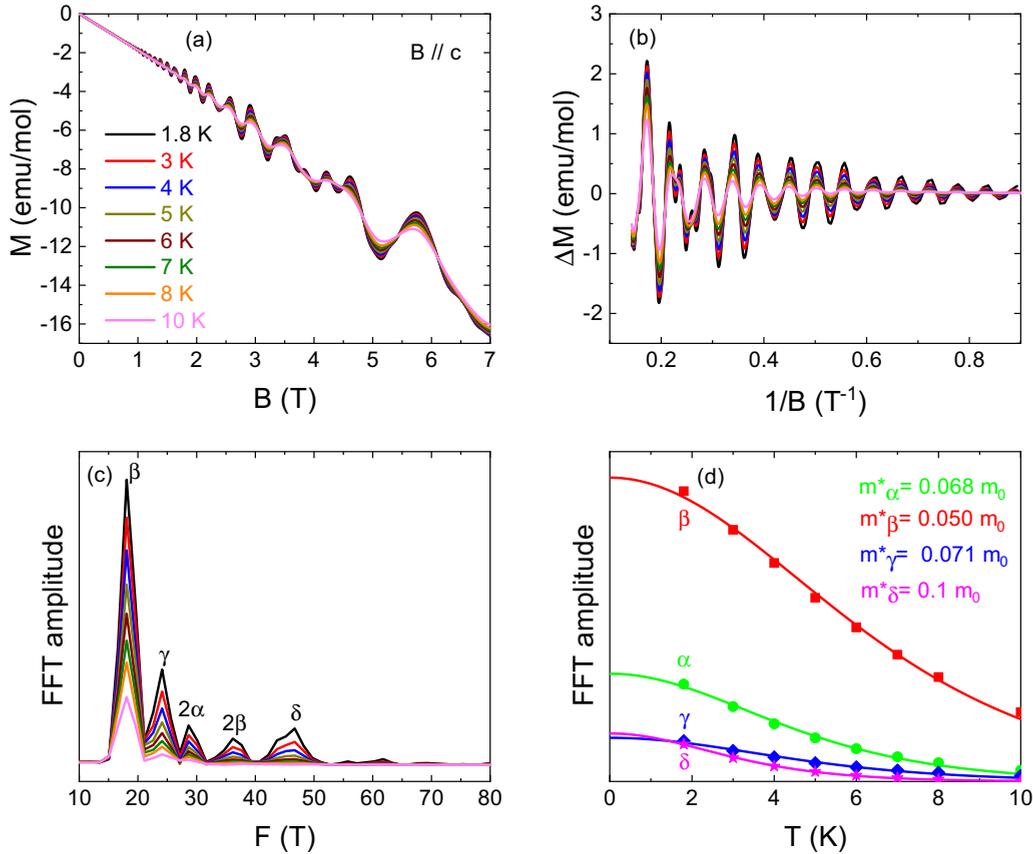


FIG. 2. (a) Magnetization as a function of magnetic field ($B \parallel c$) for TaP taken at various temperatures. (b) Oscillatory part of magnetization obtained after removing the background. (c) Fast-Fourier-transformation (FFT) spectra of the dHvA oscillations in (b). (d) Temperature-dependent FFT amplitudes of F_α , F_β , F_γ , and F_δ , fitted to the temperature damping factor R_T of the Lifshitz-Kosevich formula.

ultrahigh mobility [14], and also confirms the ultrahigh mobility in our TaP sample.

B. Giant planar Hall effect

The measurement geometry of PHE and AMR is illustrated in the inset of Fig. 3(a). The standard four-probe technique is adopted to measure longitudinal MR (ρ_{xx}), along with two Hall contacts to measure planar Hall resistivity (ρ_{yx}). Magnetic field is applied within the sample plane (ab plane) and rotates around the c axis, with an angle θ relative to the current direction. In the actual experimental setup, the magnetic field does not always perfectly lie in the sample plane. That is, a small out-of-plane field component may exist (thus a small deviation angle φ), which will result in a regular Hall resistivity. One way to eliminate this term is to average the ρ_{yx} data in positive and negative fields. Figure 3(a) shows the angular dependence of ρ_{yx} taken at 2 K under a field of 2 T, after the positive/negative operation. Another two extrinsic effects may also exist due to the possible nonsymmetrical Hall contacts. The misaligned Hall contacts will induce a small longitudinal MR in the measured Hall resistivity. One part of the additional longitudinal MR is caused by the in-plane field, which has a $\cos^2\theta$ dependence according to Eq. (2), and another part is caused by the out-of-plane field, with an approximately $\sin^2(\theta + \varphi)$ dependence. Both terms cannot be removed by data processing. However, these two effects seem

to be negligible in our measurements, as both of them are symmetrical for $\pm\theta$, which is distinctly different from the odd-function feature of the PHE curve in Fig. 3(a).

The angular dependence of ρ_{yx} has a period of 180 deg and reaches its maxima at ± 45 and ± 135 deg, both of which are consistent with the planar Hall effect. As shown in Fig. 3(a), the experimental data can be well fitted to Eq. (1), resulting in an anisotropic resistivity $\Delta\rho = 0.201$ m Ω cm. This value is comparable with that of GdPtBi [22,24] and Na₃Bi [24], and about one magnitude order larger than that of ZrTe₅ [26] and WTe₂ [25]. Figure 3(b) presents the angular dependence of ρ_{xx} , exhibiting a large planar AMR. Also, the AMR data can be fitted to Eq. (2). The fitting is roughly acceptable, except the misfit around 90 and 270 deg, which will be discussed in the next subsection. Here we focus on the possible origins of the giant PHE and AMR in TaP.

Within our knowledge scope, there are at least four possible origins of PHE and AMR in different systems.

(i) In ferromagnetic metals, the AMR and PHE originate from the interplay of the magnetic order and the spin-orbit interactions. Obviously, the PHE in TaP cannot be attributed to this mechanism, taking account of its nonmagnetic nature.

(ii) In topological insulators, the PHE and AMR arise from the topological protection mechanism through the topological surface state, in which the spin orientation and momentum are locked. The backscattering would be significantly enhanced by the magnetic field that is parallel to the current (i.e., $B \perp$

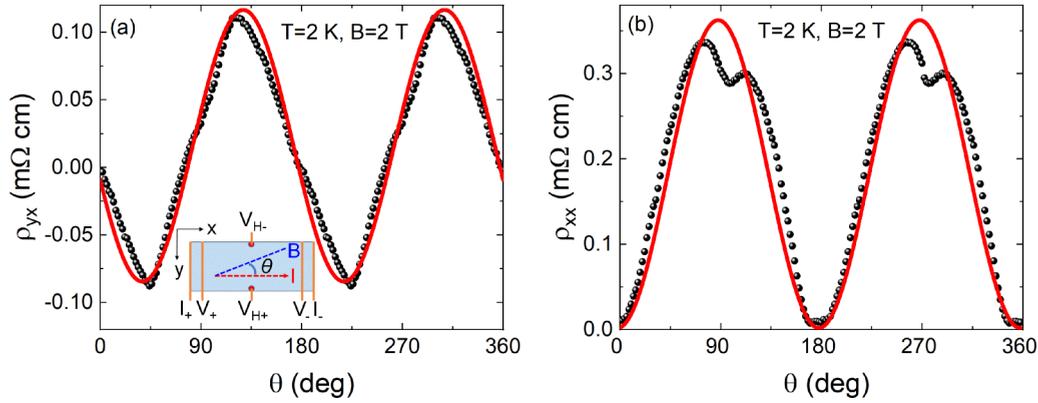


FIG. 3. Angular dependence of (a) planar Hall resistivity ρ_{yx} and (b) longitudinal MR ρ_{xx} for TaP taken at 2 K and 2 T. Red solid curves represent the fits to Eqs. (1) and (2), respectively. Inset in (a): Schematic diagram of measurement geometry.

spin orientation) and thus gives rise to an increased ρ_{\parallel} [30]. Such a condition leads to a negative $\Delta\rho$, which is hence unlikely to account for the positive $\Delta\rho$ observed in TaP.

(iii) In topological semimetals, the chiral anomaly induced NLMR is supposed to contribute to the PHE, namely, in terms of the reduced ρ_{\parallel} when magnetic field is increased. However, as stated in the Introduction, the NLMR observed in TaP can be hardly related to the chiral anomaly, due to the enhanced current jetting effect by the ultrahigh mobility. Some band-structure calculations even show that the chiral anomaly may be absent in TaP, as the Fermi surface connects pairs of Weyl points [15].

(iv) Orbital magnetoresistance arises from the asymmetric Fermi surface [37], which could in principle exist in any materials. The anisotropy of orbital magnetoresistance ($\rho_{\perp} > \rho_{\parallel}$) will definitely induce a positive $\Delta\rho$. Nevertheless, this effect is small in most cases. The giant AMR in TaP ($\rho_{\perp} \gg \rho_{\parallel}$) is attributed to the large anisotropic orbital magnetoresistance, as evidenced by the analyses below.

Figure 4(a) shows the angular dependence of ρ_{yx} taken at 2 K and various magnetic fields. Although the increasing field strongly deforms the line shape which crosses over from a sine-type function to a nearly straight line, the essential features of PHE (i.e., period in 180 deg and maxima at ± 45 and ± 135 deg) remain. Rough fittings to Eq. (1) give the anisotropic resistivity $\Delta\rho$. We may note that the $\Delta\rho$ reaches nearly 5 mΩ cm at 14 T [inset of Fig. 4(a)], which is much larger than the $\rho_{\parallel}(B=0)$ ($\sim u\Omega$ cm). That is, the giant $\Delta\rho$ is unlikely to be attributed to the NLMR (trivial or nontrivial). As is further shown in the B -dependent AMR curves [Fig. 4(b)], the ρ_{\perp} sharply rises while the ρ_{\parallel} changes much less. The large resistivity anisotropy in response to the magnetic field is the origin of the giant $\Delta\rho$. As is known, TaP is a typical XMR semimetal [34]. More and more studies suggest that the most important origin of XMR is the ultrahigh mobility that is always related with the steep linear bands [31–33]. This can be qualitatively understood in the regime of a two-band model, in which $\rho_{\perp} = [\frac{\sigma_e}{1+\mu_e^2 B^2} + \frac{\sigma_h}{1+\mu_h^2 B^2}]^{-1}$ and $\rho_{\parallel} = [\sigma_e + \sigma_h]^{-1}$ [24]. $\sigma_e = ne\mu_e$ and $\sigma_h = p\mu_h$ are the electron and hole conductivity, respectively, where n (p) and μ_e (μ_h) are the carrier density and mobility for electron (hole) carriers. For high B , we may deduce that $\Delta\rho \sim \frac{\mu_e^2 \mu_h^2 B^2}{\sigma_e \mu_h^2 + \sigma_h \mu_e^2}$.

Namely, the ultrahigh mobility can solely induce a large $\Delta\rho$. Here for TaP, the quickly increasing ρ_{\perp} with magnetic field and the resistivity plateau at low temperatures [unusually rising magnetoresistance at low temperatures, as shown in Fig. 4(d)] are consistent with the features of the XMR in TaP [34]. Hence, we finally attribute the giant PHE and AMR in TaP to the large anisotropic orbital magnetoresistance.

C. Current jetting effects

The misfit of planar AMR in Fig. 3(b) is represented by a shoulderlike or double-peak structure around 90 deg (and 270 deg), where it is supposed to be a single peak at exactly 90 deg (and 270 deg). Similar structure has been observed in GdPtBi [22,24] and Bi and Sb [38]. We attribute it to the nonuniform current distribution in the presence of magnetic field. As elucidated by Pippard [37], when B lies normal to a matchstick-shape sample, the current distribution and equipotentials are determined by the Hall angle if the sample has a Hall effect. That is, the equipotentials lie at the Hall angle to the normal of current flow, i.e., setting up an electric field along the Hall angle. The Hall angle is defined as $\tan^{-1} \omega_c \tau = \tan^{-1} \mu B$, where $\omega_c = \frac{eB}{m^*}$ is the cyclotron frequency, $\mu = \frac{e\tau}{m^*}$ is the mobility, and τ is the relaxation time. The Hall angle may be close to 90 deg when $\mu B \gg 1$. For appropriate μB , the distribution of equipotentials may exhibit double peaks near 90 deg and a dip at 90 deg. We note that this is one of the current jetting effects, i.e., field induced anisotropic mobility of conductivity (the drift of carriers normal to B is suppressed compared to the drift along B). Current jetting effect is strongly dependent upon mobility and magnetic field, and is probably unavoidable for comparably large μB . Since various current jetting effects are discussed in the present paper, we classify the $B \perp I$ case as the *Hall-angle-type* current jetting effect, and the $B \parallel I$ case as the *classical* current jetting effect.

We further note that the PHE and AMR curves are strongly deformed by the enhanced current jetting effect [Figs. 4(a) and 4(b)], via the increasing magnetic field. As discussed above, current jetting effects depend on μB . Hence, for materials with high mobility, current jetting effect could be prominent at a relatively low field. If we define B_c (inversely proportional to μ) as the onset field, above which current jetting effects become evident [24], the B_c of the TaP family

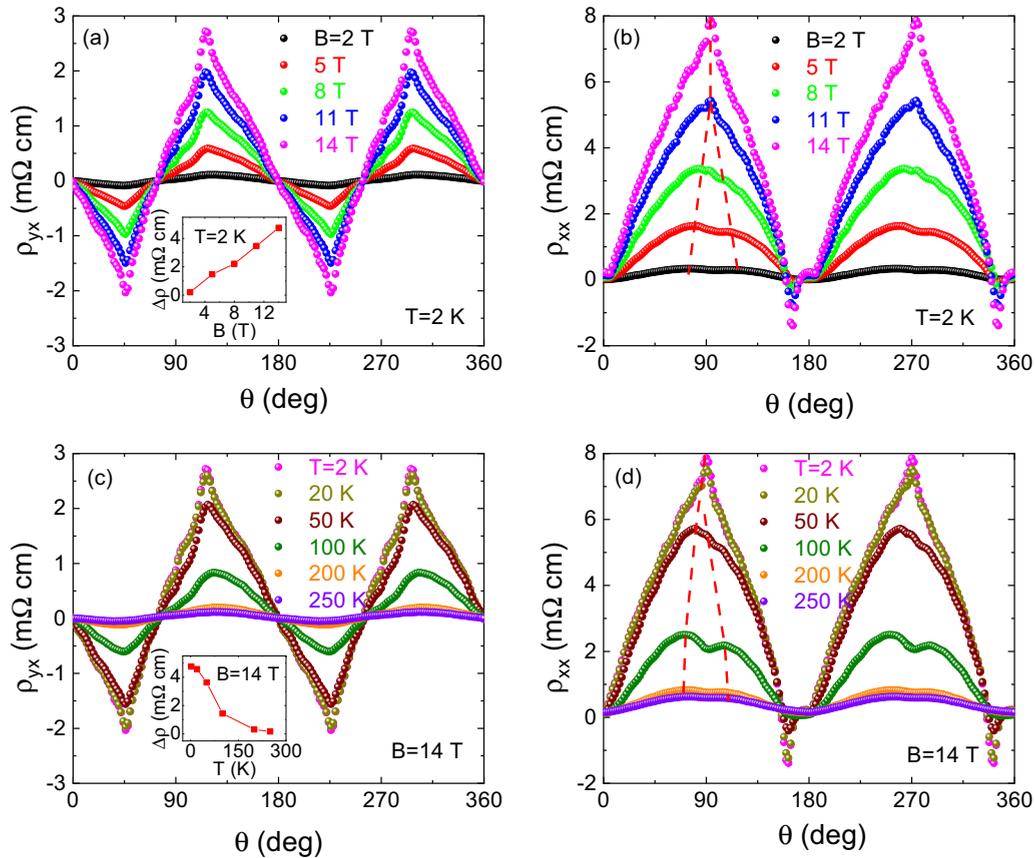


FIG. 4. Angular dependence of (a) planar Hall resistivity ρ_{yx} and (b) longitudinal MR ρ_{xx} for TaP taken at 2 K and various magnetic fields, and angular dependence of (c) ρ_{yx} and (d) ρ_{xx} taken at various temperatures and 14 T. Insets of (a) and (c): Anisotropic resistivity $\Delta\rho$ as a function of magnetic field and temperature, respectively, obtained from the fits. Dashed lines in (b) and (d) indicate the double peaks of ρ_{xx} around 90 deg.

would be very low (~ 0.4 T) because of their ultrahigh mobilities (e.g., 2.5×10^6 $\text{cm}^2/\text{V s}$ for TaP and 5×10^6 $\text{cm}^2/\text{V s}$ for NbP [14,15]). That is, current jetting effects are usually inevitable in these materials. One disaster of current jetting effect is the harm to the identification of chiral anomaly by NLMR measurements, in which a chiral anomaly induced NLMR is expected when B is applied along or slightly misaligned with the current. However, this is hardly accessed for high-mobility materials as current jetting would also cause a large NLMR [14,15]. Another extrinsic phenomenon arising from current jetting effect is the so-called negative resistivity. Such a peculiar phenomenon has been observed in bismuth (with ultrahigh mobility) [38] and NbP [14] when B is approaching the direction of current flow. As shown in Fig. 4(b), a negative resistivity also appears near 0 and 180 deg, and becomes more prominent as B increases. Finally, the negative resistivity is attributed to the classical current jetting effect, and the deformation of ρ_{yx} and ρ_{xx} curves is caused by the combination of classical and Hall-angle-type current jetting effect.

Since the onset field of current jetting effect in TaP is very low, one feasible approach to suppress the current jetting effect is to decrease the mobility by increasing temperature. Due to the enhanced thermal fluctuation, the mobility of TaP is indeed sharply reduced (e.g., from 10^6 $\text{cm}^2/\text{V s}$ at 2 K down to 10^3 $\text{cm}^2/\text{V s}$ at 150 K) [34,39]. Figures 4(c) and 4(d)

present the angular dependence of ρ_{yx} and ρ_{xx} taken at various temperatures and 14 T, respectively. It is found that, with the increasing temperature, the deformation is reduced and the curves accord with the theoretical formulas better. As shown in Fig. 5, the ρ_{yx} and ρ_{xx} curves taken at 250 K can be fitted fairly well by Eqs. (1) and (2), respectively, showing a suppressed current jetting effect. This can be understood in terms of the quickly rising B_c , as a result of the reduced mobility. The B_c of TaP should far exceed 14 T at 250 K, if we consider its mobility is almost that of Na_3Bi or GdPtBi (3000 and 2000 $\text{cm}^2/\text{V s}$ at 2 K, respectively), the B_c of which can reach as high as 30 T [24]. Also, the $\Delta\rho$ decreases quickly with the increasing temperature [inset of Fig. 4(c)], because of the reduced mobility. This is consistent with our explanation for the origin of PHE.

From Figs. 4(b) and 4(d), we can also find the evolution of Hall-angle-type current jetting effect with the changing magnetic field and temperature, as indicated by the red dashed lines. This kind of nonuniform current distribution is represented by the focusing of current flow along the direction of Hall angle, i.e., $\tan^{-1}\mu B$, when $B \perp I$. For the case with a moderate Hall angle (~ 70 – 80 deg in our measurement), the double-peak structure appears and a dip forms at 90 deg. If the Hall angle is approaching 90 deg (i.e., $\mu B \gg 1$), the double peaks may merge into a single one. Therefore, the distance of double peaks ($\Delta\theta$) relies on the scale of μB .

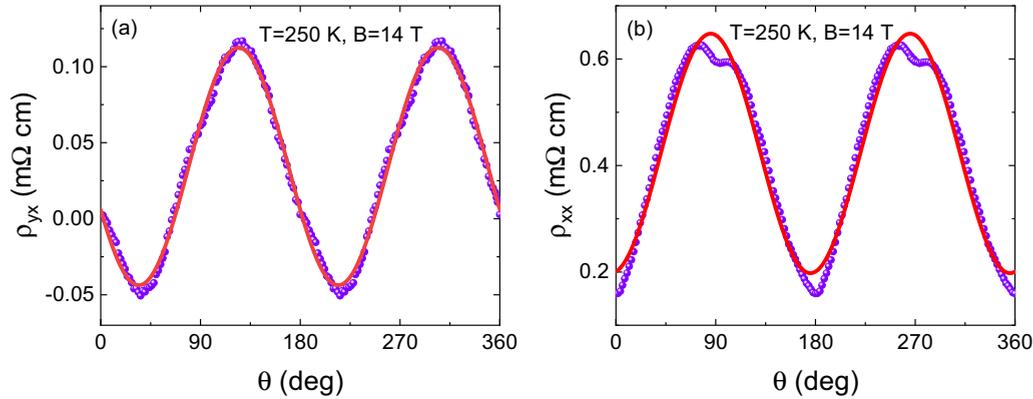


FIG. 5. Angular dependence of (a) planar Hall resistivity ρ_{yx} and (b) longitudinal MR ρ_{xx} for TaP taken at 250 K and 14 T. Red solid curves represent the fits to Eqs. (1) and (2), respectively.

No matter which is increased (μ or B), the distance will decrease, even to zero for sufficiently large μB . This explains the occurrence and evolution of double-peak structure with the changing magnetic field and temperature. We note that a similar phenomenon has been observed in GdPtBi [22,24]. Although the classical current jetting effect is unobservable in GdPtBi, the Hall-angle-type current jetting effect remains.

IV. CONCLUDING REMARKS

The NLMR induced by chiral anomaly is crucial transport evidence for TSMs. In order to obtain a conclusive and intrinsic NLMR, it is recommended to take the measurement at a high field exceeding B_Q , which pushes the chemical potential into the lowest Landau level [24]. The B_Q might be considerably high for the TaP family due to their high carrier densities (10^{18} – 10^{19} cm^{-3}) [35,40]. On the other hand, the ultrahigh mobility gives rise to a relatively low onset field of current jetting effect (B_c). Such a condition ($B_Q \gg B_c$) makes the measurement of NLMR really difficult as the current jetting effect takes effect at low fields. However, a giant PHE or AMR is observed in TaP, which comes mainly from the increased ρ_{\perp} instead of the reduced ρ_{\parallel} . The large anisotropic orbital magnetoresistance is responsible for the giant PHE.

The current jetting effect not only deforms the PHE and AMR curves for the increased μB but also leads to a double-peak structure in the AMR curves for appropriate μB . We classify these two effects of field-induced nonuniform current distribution into classical and Hall-angle-type current jetting effect, respectively. Nevertheless, the angular dependence of PHE curves (ρ_{yx}) does not change (i.e., period in 180 deg and maxima at ± 45 and ± 135 deg remain) and the altered profile is restored when μB is reduced. Our paper lays the giant PHE and AMR and the large current jetting in TaP on the same base, i.e., the ultrahigh mobility. Although the former suggests promising applications in spintronics, the latter shows the other side of the coin, which needs to be considered in future device design.

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