Linear and quadratic magnetoresistance in the semimetal SiP

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Multiple mechanisms for extremely large magnetoresistance (XMR) found in many topologically nontrivial/trivial semimetals have been theoretically proposed, but experimentally it is unclear which mechanism is responsible in a particular sample. In this article, by the combination of band structure calculations, numerical simulations of magnetoresistance (MR), Hall resistivity and de Haas-van Alphen (dHvA) oscillation measurements, we studied the MR anisotropy of SiP, which is verified to be a topologically trivial, incomplete compensation semimetal. It was found that as magnetic field, $H$, is applied along the a axis, the MR exhibits an unsaturated nearly linear $H$ dependence, which was argued to arise from incomplete carriers compensation. For the $H \parallel [101]$ orientation, an unsaturated nearly quadratic $H$ dependence of MR up to $2.20 \times 10^5\%$ (at 2 K, 9 T) and field-induced up-turn behavior in resistivity were observed, which was suggested due to the existence of hole open orbits extending along the $k_x$ direction. Good agreement of the experimental results with the simulations based on the calculated Fermi surface (FS) indicates that the topology of FS plays an important role in its MR.

I. INTRODUCTION

Since magnetoresistance (MR) has a great potential in applications such as hard drives and magnetic sensors, the search for new materials with large MR has attracted much attention in the past decades. Though the well-known giant magnetoresistance (GMR) in magnetic multilayers and the colossal magnetoresistance (CMR) in perovskite manganites have been widely explored, recent discoveries of the materials with XMR up to $10^6\%$ rekindled the enthusiasm for MR research. XMR has been observed in elements and compounds, such as Bi, graphite, $\alpha$-Ga, Dirac semimetal Na$_3$Bi, and Cd$_3$As$_2$, Weyl semimetals of TaAs family, WTe$_2$, and $\beta$-WP$_2$, transition metal dipnictides such as TPa$_2$ ($T$ = Ta and Nb, Pn = P, As and Sb), $\alpha$-WP$_2$, rock salt rare earth compound LaBi/Sb, and others.

Several mechanisms have been proposed to explain the XMR found in these semimetals including topologically nontrivial or trivial materials. Nontrivial band topology inducing linear band dispersion is believed to be responsible for the linear field dependent MR such as in Cd$_3$As$_2$. The classical carrier compensation scenario can be used to explain the non-saturating quadratic dependence of MR such as in WTe$_2$. An angle-resolved photoemission spectroscopy (ARPES) measurement on WTe$_2$ confirmed that the temperature dependent band structure is consistent with the MR measurements, thus giving evidence to support the carrier compensation theory. However, although LaBi shows nearly perfect carrier compensation, the magnitude of MR is much smaller, which is believed to be caused by the electron and hole mobility mismatch. Recent ARPES results on MoTe$_2$, which has a crystal structure identical to that of WTe$_2$, illustrated that the net size of hole pockets is larger than the net size of electron pockets, indicating the compensation mechanism is invalid for the non-saturating XMR of MoTe$_2$. YSb lacks topological protection and perfect electron-hole compensation, but also exhibits XMR behavior. A small difference between the concentrations of electrons and holes will lead to saturation of MR at high magnetic field such as in Bi and graphite. Zhang et al. showed that MR has a quadratic relation in weak magnetic field, but saturates in high field if the FS is closed and the saturation value is determined by the difference in charge carrier concentrations. The other mechanism attributes the XMR to open-orbit trajectories of charge carriers driven by Lorentz force under magnetic field as a result of non-closed Fermi surface (FS). Experimentally, it is difficult to identify which mechanism is responsible for MR in a particular sample. It is necessary to make a clear connection between experimental observations and theoretical models.

SiP$_2$ crystallizes in a cubic pyrite-type structure with space group $Pa\bar{3}$, and was recently discovered to be a promising negative electrode material for Li- and Na-ion batteries due to its outstanding capacity. In contrast to the isostructural NiP$_2$, PtP$_2$, or pyrite itself (FeS$_2$) being semiconductors, SiP$_2$ is characterized as a semimetal with nearly filled Brillouin zone. To un-
understand its semimetal character, the electronic structure of SiP$_2$ had been calculated. It was suggested by Bachhuber et al. that a flat band segment occurs between the $\Gamma$ and X point, resulting in no gap formed.

In this article, we have successfully grown high-quality SiP$_2$ crystals, measured their longitudinal resistivity with various magnetic field orientations, Hall resistivity, de Haas-van Alphen (dHvA) oscillations occurring on isothermal magnetization and calculated its band structure. The results show SiP$_2$ is a topologically trivial and incomplete compensation semimetal. It was found that the MR exhibits remarkable anisotropy. As $H$ is applied in a axis, a non-saturating linear field dependence of MR with relatively small value (596% at 2 K, 9 T) occurs. While $H$ is applied in [101] direction, MR (2172% at 2 K, 9 T) exhibits a non-saturating quadratic $H$ dependence. The mechanisms of the two types MR will be discussed.

II. EXPERIMENTAL METHODS AND CALCULATIONS

Single crystals of SiP$_2$ were grown by a chemical vapor transport method. High purity Si and P powder were mixed in the mole ratio 1 : 2, then sealed in an evacuated silica tube with PBr$_5$ producing enough Br$_2$ as a transport agent. The quartz tube was placed in a tube furnace with a temperature gradient of 1200 °C to 800 °C for one week. The black shiny SiP$_2$ crystals were obtained at the cool end of the silica tube. A single crystal with dimensions of $1 \times 1 \times 0.15$ mm$^3$ and crystalline cleavage surface (200) [see in Fig. 1(b)] was selected for transport and magnetic measurements. The crystal structure was determined by X-ray diffraction (XRD) measurements using a PANalytical diffractometer. The powder XRD pattern is shown in Fig. 1(c), which confirms that SiP$_2$ crystallizes in a pyrite-type structure. The fit to XRD data yields the lattice parameters: $a = b = c = 5.704(9)$ Å (weight profile factor $R_{wp} = 9.96\%$ and the goodness-of-fit $\chi^2 = 0.9229$). A standard four-probe method was used for electrical resistivity measurements on a Physical Property Measurement System (Quantum Design, PPMS-9 T). The magnetization measurements were performed on a Magnetic Property Measurement System (Quantum Design, MPMS-7 T).

Meanwhile, we performed numerical simulations based on the Boltzmann transport theory and first-principles calculations that can be compared with the results of experimental measurements. The band structure is calculated using the generalized gradient approximation within the VASP package. The Fermi surface and transport calculation are performed with WannierTools package which is based on the maximally localized Wannier function tight-binding model constructed by using the Wannier90 package.
Within the relaxation time approximation, the band-wise conductivity tensor $\sigma$ is calculated by solving the Boltzmann equation in presence of an applied magnetic field as [36, 54, 55],

$$\sigma^{(n)}_{ij}(B) = \frac{e^2}{4\pi} \int d\mathbf{k} \tau_n \mathbf{v}_n(k) \mathbf{v}_n(k) \left( -\frac{\partial f}{\partial \varepsilon} \right) \varepsilon = \varepsilon_n(k), \quad (1)$$

where $e$ is the electron charge, $n$ is the band index, $\tau_n$ is the relaxation time of $n$th band that is assumed to be independent on the wavevector $\mathbf{k}$, $f$ is the Fermi-Dirac distribution, $\mathbf{v}_n(k)$ is the velocity defined by the gradient of band energy,

$$\mathbf{v}_n(k) = \frac{1}{\hbar} \nabla_k \varepsilon_n(k), \quad (2)$$

and $\mathbf{v}_n(k)$ is the weighted average of velocity over the past history of the charge carrier,

$$\bar{\mathbf{v}}_n(k) = \int_{-\infty}^{0} dt \, e^{-\tau_n} \mathbf{v}_n(k(t)). \quad (3)$$

The orbital motion of charge carriers in applied magnetic field causes the time evolution of $k_n(t)$, written as,

$$\frac{d\mathbf{k}_n(t)}{dt} = -\frac{e}{\hbar} \mathbf{v}_n(k_n(t)) \times \mathbf{B} \quad (4)$$

with $k_n(0) = k$. The total conductivity is the sum of band-wise conductivities, i.e. $\sigma_{ij} = \sum_n \sigma^{(n)}_{ij}$, which is then inverted to obtain the resistivity tensor $\hat{\rho} = \sigma^{-1}$.

### III. RESULTS AND DISCUSSIONS

In order to explore the role of the Fermi surface topology in MR, we calculated the band structure and FS of SiP$_2$, as shown in Fig. 1(d) - (g). The FS is composed of two hole pockets near the $\Gamma$ point of P-3p character and four electron pockets located at the R point of Si-3s character, exhibiting three dimensional (3D) nature. The existence of both hole and electron pockets of the FS is consistent with SiP$_2$ being a semimetal and the calculation results reported by Bachhuber et al. [42]. In addition, it should be pointed out that no crossing between the conduction and valence bands emerges in the calculated band structure and all FS sheets have zero Chern number, indicating that SiP$_2$ is a topologically trivial semimetal.

Figure 1(h) shows the temperature dependence of resistivity, $\rho(T)$, measured with current $I$ along the $b$ axis and at both magnetic field $\mu_0H = 0$ T and 9 T applied along the $a$ axis, respectively. At $\mu_0H = 0$ T, the resistivity decreases monotonously with decreasing temperature above 15 K, and reaches a minimum at 15 K [see Fig. 1(h), inset], then increases slightly at low temperature.

We suggest that the emergence of minimum at $T = 15$ K in $\rho(T)$ may result from the well-known weak localization effect (WLE) [56–58], which arises from the carriers backscattered coherently by randomly distributed disorder existing in the crystals, and had been used to explain a similar behavior in some oxides, such as SrRuO$_3$ [59] and LaNiO$_3$ [60] thin films. As discussed by Herranz et al. [59, 60], we fitted the $\rho(T)$ data at lower temperatures by using the equation [59, 60]:

$$\rho(T) \sim T^{\alpha} \rho_{0}$$

Figure 2. (a) Temperature dependence of resistivity measured at various magnetic fields applied along the $a$ axis. (b) The normalized MR vs. temperature under various magnetic fields. The inset is MR as a function of temperature. (c) MR of SiP$_2$ measured under different temperatures with the field along the $a$ axis. (d) Kohler scaling analysis on the MR data, the solid red line indicates the fitting of Kohler’s rule with $m = 1.2$. Typical cross-sections of the FS of SiP$_2$ in $k_x - k_y$ plane corresponding to (e) $k_z = 0$, (f) $k_z = 0.2\pi/a$, (g) $k_z = 0.5\pi/a$. The solid red line indicates the fitting of Kohler’s rule with $m = 1.2$. Typical cross-sections of the FS of SiP$_2$ in $k_x - k_y$ plane corresponding to (e) $k_z = 0$, (f) $k_z = 0.2\pi/a$, (g) $k_z = 0.5\pi/a$. Red and green dashed lines highlight the closed hole and electron orbits, respectively.
simpler FS, and provides a clearer platform for studying another minimum at $\theta = 90^\circ$, also crystallizing in cubic structure, SiP. Compared with Cu crystal, a representative material, the FS projected onto the plane perpendicular to current $I$ has a fourfold symmetry, i.e. $\rho(\theta) = \rho(\theta + \pi/2)$, the resistivity grows quickly from a minimum at $\theta = 0^\circ$ ($H \parallel a$ axis) to a maximum at $\theta = 45^\circ$ [$H \perp (101)$ plane], and then decreases rapidly to another minimum at $\theta = 90^\circ$ ($H \parallel c$ axis), which is consistent with the cubic structure of SiP$_2$ crystal. As we know, the resistivity anisotropy reflects the symmetry of the FS projected onto the plane perpendicular to current. Compared with Cu crystal, a representative material [30], also crystallizing in cubic structure, SiP$_2$ has a simpler FS, and provides a clearer platform for studying MR mechanism based on FS topology. In order to reveal the physics underlying the MR anisotropy, we measured both the field and temperature dependencies of resistivity for the magnetic field orientations corresponding to extrema points marked by A and B in Fig. 1(j).

As $H$ is applied along the $a$ axis [$\theta = 0^\circ$, the A point in Fig. 1(j)] with a minimum resistivity relative to other orientations, the $\rho(T)$ measured at various fields is shown in Fig. 2(a). Although the resistivity is remarkably enhanced by magnetic field at lower temperatures, the field-induced up-turn was not observed, which is a typical behavior for many trivial or nontrivial semimetals with XMR [28, 61, 62]. The normalized MR, with the conventional definition $MR = \frac{\Delta \rho}{\rho(0)} = [\frac{\rho(H) - \rho(0)}{\rho(0)}] \times 100\%$, has the same temperature dependence at different magnetic fields [see Fig. 2(b)], excluding the existence of a magnetic field-dependent gap. Figure 2(c) shows the MR as a function of field at various temperatures. The MR reaches 596% at 2 K and 9 T, and does not show any sign of saturation up to the highest field in our measurements. The MR can be described by the Kohler scaling law [61, 63]:

$$MR = \frac{\Delta \rho_{xx}(T, H)}{\rho_0(T)} = \alpha \left(\frac{\mu_0 H}{\rho_0(0)}\right)^m$$  \hspace{1cm} (6)

As shown in Fig. 2(d), all MR data from 2 to 100 K collapse onto a single line plotted as MR $\sim H/\rho(0)$ curve, with $\alpha = 56.4$ ([$\mu\Omega$ cm]/T)$^{1.2}$ and $m = 1.2$ obtained by fitting, indicating that MR has a nearly linear field dependence. To understand this nearly linear magnetic field dependence, we plot the representative orbits in Fig. 2(e) - (h). The circular orbits in Fig. 2(e) and the orbits in Fig. 2(f) - (h) can be attributed to closed electron (in green) and hole (in red) orbits. But the square like orbits [indicated by the green dashed line in Fig. 2(e)] are more complex, since they originate from joining the hole pocket fragments in the adjacent periodic replicas of the Brillouin zone. However, these square like orbits are electron orbits rather than hole orbits, since they enclose filled states. Therefore, the perfect compensation between the electron and hole charge carriers is altered upon applying magnetic field oriented along the $a$ axis ($\theta = 0^\circ$). The incomplete compensation induces the departure of resistivity from the ideal parabolic to nearly linear scaling.

On the other hand, for this particular magnetic field orientation, incomplete compensation of the two kinds of charge carriers was confirmed by the Hall resistivity measurements. As shown in Fig. 3(a), the non-linear field dependence of Hall resistivity, $\rho_{xy}(H)$, measured at various temperatures with $H \parallel a$ axis, indicates its multi-band behavior. We fitted the Hall conductivity data [see Fig. 3(b)] by using the two-band model given by [63]:

$$\sigma_{xy} = -\frac{\rho_{xy}}{\rho_{xx}^2 + \rho_{xy}^2} = eB\left[\frac{n_1\mu_{1}^2}{1 + \mu_{1}^2 B^2} - \frac{n_2\mu_{2}^2}{1 + \mu_{2}^2 B^2}\right]$$  \hspace{1cm} (7)

$$\rho_{xx} = \frac{1}{\sigma_{xx}} = eB\left[\frac{n_1\mu_{1}^2}{1 + \mu_{1}^2 B^2} + \frac{n_2\mu_{2}^2}{1 + \mu_{2}^2 B^2}\right]$$  \hspace{1cm} (8)

$$MR = \frac{\Delta \rho_{xx}(T, H)}{\rho_0(T)} = \alpha \left(\frac{\mu_0 H}{\rho_0(0)}\right)^m$$  \hspace{1cm} (9)
1.8. Typical cross-sections of the FS of SiP

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the (101) plane. The horizontal axis corresponds to the dashed lines indicate open orbits along the
direction while the vertical axis is parallel to [10 \bar{1}]. (b) Normalized MR versus temperature at various magnetic fields. The inset is MR as a function of temperature at first, reaches a maximum, 1.74 × 10^4 cm^2 V^{-1} s^{-1}, at 10 K, then drops, while the \( \mu_e \) changes with temperature, also having a maximum near 10 K. It is important that \( \mu_e \) is obviously larger than \( \mu_h \) in the whole temperature range, such as \( \mu_e = 1.53 \times 10^4 \) cm^2 V^{-1} s^{-1}, \( \mu_h = 0.28 \times 10^4 \) cm^2 V^{-1} s^{-1} at 2 K, shown in Fig. 3(d). In our SiP crystals, the cooperative action of a substantial difference between electron and hole mobility and a moderate carrier compensation might contribute to the MR, similar to the case reported by He et al. \[35\] for YSb, which also lacks topological protection and perfect electron-hole compensation.

As \( H \) is applied along the [101] direction \( [\theta = 45^{\circ}] \), the B point in Fig. 1(j) with a maximum MR, the \( \rho(T) \) measured at various fields is shown in Fig. 4(a). The resistivity is remarkably enhanced by magnetic field at lower temperatures, and the field-induced up-turn was observed, in contrast with that observed for the \( H \parallel a \) axis, but similar to that in most materials with XMR. The normalized MR also has the same temperature dependence at various fields, as shown in Fig. 4(b). Figure 4(c) displays the MR as a function of magnetic field at various temperatures, which reaches 2172% at 2 K and 9 T, three times larger than that for the \( H \parallel a \) axis, and does not show any sign of saturation too. The MR can be described by the Kohler scaling law in Eq. (2) [see Fig. 4(d)] with the fitting parameters \( \alpha = 68.4 \) (\( \mu \Omega \) cm/T)^{1.8} and \( m = 1.8 \). The nearly quadratic field dependence of MR and the field-induced up-turn behavior are the common characteristics for most topologically non-trivial/trivial semimetals with XMR, such as WTe\(_2\) [61], \( \alpha \)-WP\(_2\) [29], \( \beta \)-WP\(_2\) [18, 20] and \( \alpha \)-Ga\(_2\) et al., which is usually attributed to the perfect electron-hole compensation. However, it is obvious that this condition is not satisfied in our SiP crystals. We check the topology of the FS projected onto the plane perpendicular to [101], as plotted in Fig. 4(e) - (h) for different planes. It is clear that the hole open orbits extending along the \( k_x \) direction emerge. We believe that MR \( \propto H^{1.8} \) for this magnetic field orientation is due to the existence of these open orbits, as discussed by Zhang et al. \[36\] for cubic Cu crystals. From the above results, we conclude that the linear MR for \( H \parallel a \) axis is attributed to incomplete carriers compensation, while the quadratic MR for \( H \parallel [101] \) results from the existence of hole open orbits.

Figure 5 shows our numerical simulation results for the resistivity anisotropy and the magnetic field dependence of MR by combining the FS discussed above with the Boltzmann transport theory approach based on the semiclassical model and the relaxation time approxima-

where \( n_h \) (\( n_e \)) and \( \mu_h \) (\( \mu_e \)) are the hole (electron) carrier concentrations and mobilities, respectively. The obtained \( n_h \) (\( n_e \)) and \( \mu_h \) (\( \mu_e \)) as a function of temperature are plotted in Fig. 3(c) and Fig. 3(d), respectively. It was found that \( n_h \) increases with decreasing temperature while \( n_e \) varies less with temperature. It is obvious that

\( \mu_h \) is larger than \( \mu_e \) in the whole temperature range, such as \( \mu_h = 1.62 \times 10^{20} \) cm^{-3} and \( \mu_e = 3.22 \times 10^{19} \) cm^{-3} at 2 K, implying the incomplete compensation of both carriers. Such \( n_h \) (\( n_e \)) values are similar to that in most semimetals, but higher than that in Dirac semimetals Cd\(_3\)As\(_2\) [12], Na\(_3\)Bi [10]. The \( \mu_e \) increases with decreasing temperature at first, reaches a maximum, 1.74 \( \times 10^4 \) cm^2 V^{-1} s^{-1}, at 10 K, then drops, while the \( \mu_h \) changes with temperature, also having a maximum near 10 K. It is important that \( \mu_e \) is obviously larger than \( \mu_h \) in the whole temperature range, such as \( \mu_e = 1.53 \times 10^4 \) cm^2 V^{-1} s^{-1}, \( \mu_h = 0.28 \times 10^4 \) cm^2 V^{-1} s^{-1} at 2 K, shown in Fig. 3(d). In our SiP crystals, the cooperative action of a substantial difference between electron and hole mobility and a moderate carrier compensation might contribute to the MR, similar to the case reported by He et al. \[35\] for YSb, which also lacks topological protection and perfect electron-hole compensation.
Figure 5. (a) Calculated anisotropy of resistivity $\rho_{||c}$ for magnetic field rotated in the $a-c$ plane agrees well with experiment results in Fig. 1(j). (b) Magnetoresistivity MR as a function of the magnitude of magnetic field for the four directions indicated by $\theta$. The resistivity at $\theta = 45^\circ$ is scaled by a factor of 0.25 in order to make this curve visible.

It is clear that the calculated anisotropy of resistivity for $H$ rotated in the $a-c$ plane agrees well with the measuring results shown in Fig. 1(j). The calculated magnetic field dependence of MR also exhibits a linear behavior [see Fig. 5(b)], as $H$ oriented along the $a$ axis ($\theta = 0^\circ$), i.e., MR has $H^{1.0}$ scaling. Moreover, in case there is a misalignment of the $H$ relative to the $a$ axis, our calculations for $H$ tilting by a small angle, such as from $\theta = 3^\circ$ to $\theta = 6^\circ$, show that the magnetic field dependence of MR changes from $H^{1.1}$ to $H^{1.4}$, as shown in Fig. 5(b). All these calculated MR results for SiP$_2$ crystal, including the MR $\propto H^{1.9}$ [see Fig. 5(b)] for $H$ applied in [101] direction ($\theta = 45^\circ$), are well consistent with the experimental results discussed above, which indicates that the topology of FS plays the crucial role in its MR.

Finally, in order to obtain additional information on the electronic structure, we measured the dHvA quantum oscillations in the isothermal magnetization, $M(H)$, for SiP$_2$ crystal up to 7 T for $H \parallel a$ axis orientation. As shown in Fig. 6(a), clear dHvA oscillations starting from 2 T in $M(H)$ curves indicate low effective masses of charge carriers. After subtracting a smooth background from the $M(H)$ data at each temperature, the periodical oscillations are visible in 1/H up to 18 K. As an example, Figure 6(d) shows the $\Delta M$ at 2 K as a function of 1/H. From the fast Fourier transformation (FFT) analysis, we have derived four basic frequencies $F_\alpha$ (59.3 T), $F_\beta$ (81.7 T), $F_\gamma$ (251.1 T) and $F_\delta$ (610.8 T), respectively [see Fig. 6(b)], which may correspond to the small hole or electron pockets in FS. In general, as discussed by Hu et al. [64, 65] for ZrSiX ($X = S, Se, Te$), the oscillatory magnetization for the 3D metals can be described by the Lifshitz-Kosevich (LK) formula $[66]$ with the Berry phase $[67]$

$$\Delta M \propto -B^{2} R_T R_D R_S \sin[2\pi(F/B - \gamma - \delta)]$$

where $R_T = \alpha T \mu/B \sinh(\alpha T \mu)$, $R_D = \exp(-\alpha T D \mu/B)$ and $R_S = \cos(\pi g \mu/2)$, $\mu$ is the ratio of effective cyclotron mass $m^*$ to free electron mass $m_0$, the spin $g$-factor $g = 2$ for free electron. $T_D$ is the Dingle temperature, and $\alpha = (2\pi^3 k_B m_0)/h^2$. The oscillation of $\Delta M$ is described by the sine term with a phase factor $-\gamma - \delta$, in which $\gamma = \frac{1}{2} - \frac{\phi_B}{2\pi}$ and $\phi_B$ is the Berry phase, the phase shift $\delta = \pm 1/8$ for 3D system. The effective cyclotron masses $m^*$ for each frequency [see Table I] were obtained from the fit to the temperature dependent FFT amplitudes by the thermal damping factor $R_T$, as shown in Fig. 6(c). Then we used the obtained $m^*$ and $F$ values to fit the entire oscillation spectra [see Fig. 6(d)], and obtained the $T_D$ and $\phi_B$ values (see Table I). For example, the $T_D = 9.88$ K for $F_\alpha$, the corresponding quantum relaxation time $\tau_Q = \hbar/2\pi k_B T_Q = 1.23 \times 10^{-13}$ s, the quantum mobility $\mu_Q = e\tau_Q/m^* = 0.123 \times 10^4$ cm$^2$ V$^{-1}$ s$^{-1}$.

It is important to distinguish the $\mu_Q$ from the transport mobility $\mu_t$ derived from Hall measurements. $\mu_Q$ is sensitive to all angle scattering processes while classical $\mu_t$ is only susceptible to the large angle scattering, thus $\mu_t$ is usually larger than $\mu_Q$. The Berry phase is the key
The LL fan diagram. For directly from the multi-band fit to the LK formula or feature of Dirac fermions that can be determined either as $0.032 \pi$ is away from a similar property to the oscillations, the minima of $\Delta$ near the Fermi level reaches a minimum, and in dHvA two adjacent LLs, where the density of state (DOS) should be assigned when the Fermi level lies between index fan diagram. Generally, the integer LL indices extracted the corresponding Berry phase from the LL band, as shown in Fig. 6(f). Take $\alpha$ band as an example, the extrapolation of linear fit in the LL fan diagram yields an intercept $n_0 = -0.1225$, which corresponding to a Berry phase $\phi_B = 2\pi(-0.1225 \pm 1/8)$, and the slope of the linear fit is $59.22$ corresponding to the frequency $[64, 65]$. As shown in Table I, all the four bands have a similar property to the $\alpha$ band, whose Berry phase is away from $\pi$, indicating the SiP$_2$ is a topologically trivial semimetal.

### IV. CONCLUSION

In summary, it was found that, as magnetic field is applied along the $a$ axis, the MR exhibits a non-saturating linear $H$ dependence and no field-induced up-turn behavior in resistivity emerges. The incomplete compensation of carriers was considered to be the dominant mechanism of LMR. For the $H \parallel [101]$ orientation, a non-saturating quadratic $H$ dependence of MR and field-induced up-turn in resistivity were observed. We argue that the existence of hole open orbits on the FS is the dominant mechanism for MR along this direction. Good agreement of the experimental results of MR with the simulations based on the FS calculated in SiP$_2$ indicates that the topology of FS plays the crucial role in the magnetotransport properties.

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| Table I. Oscillation parameters of SiP$_2$ |
| Parameters | $F_\alpha$ | $F_\beta$ | $F_\gamma$ | $F_\delta$ |
|------------|------------|------------|------------|------------|
| Frequency (T) | 59.3 | 81.7 | 251.1 | 610.8 |
| $m^*/m_0$ | 0.175 | 0.216 | 0.309 | 0.268 |
| $T_B$ (K) | 9.88 | 2.42 | 2.97 | 6.74 |
| $\tau_\phi$ (ps) | 0.123 | 0.5 | 0.407 | 0.179 |
| $\mu_Q$ (cm$^2$/Vs) | 1230 | 4074 | 2321 | 1179 |
| $\phi_B +1/8$ (LK) | $0.032\pi$ | $0.573\pi$ | $1.072\pi$ | $0.772\pi$ |
| $\phi_B -1/8$ (LK) | $-0.467\pi$ | $0.073\pi$ | $0.573\pi$ | $0.272\pi$ |
| slope | 59.22 | 81.84 | 249.85 | 608.58 |
| intercept | -0.123 | 0.183 | 0.123 | 0.151 |
| $\phi_B +1/8$ (LL) | $0.01\pi$ | $0.617\pi$ | $0.495\pi$ | $0.552\pi$ |
| $\phi_B -1/8$ (LL) | $-0.495\pi$ | $0.117\pi$ | $-0.005\pi$ | $0.052\pi$ |
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