

Engineering magnetotransport through hierarchical symmetry in Weyl semimetal superlattices

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Superlattice engineering, the introduction of periodic potentials to a material, can induce selective scattering events that modify the electrical properties of the material in predictable ways. Extending superlattice engineering to three-dimensional (3D) electronic materials can expand the tunability of their transport properties beyond traditional means such as doping. Here, we show that magnetotransport can be modified by superlattices in 3D materials based on the relative symmetry between the Fermi surface and nanostructured superlattice. We demonstrate commensuration oscillations in the ballistic transport regime of a nanostructured 3D material with the Weyl semimetal NbP. The oscillations encode information about the shared properties between the quasiparticles at the Fermi surface—including their momentum, charge, mass, and rotational symmetry—and the structure of the superlattice. These results point toward methods to engineer quantum transport in 3D electronic materials based on the mutual properties of the superlattice and Fermi surface.

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I. INTRODUCTION

Artificial superlattices exhibit properties that differ from those of their underlying constituents. This principle has helped guide the architecture of materials and devices across virtually all length scales, from mechanical metamaterials with macroscopic features [1,2] to photonic crystals [3–7] on the order of micrometers and moiré superlattices on the nanometer scale [8–13]. An important consideration in the design of superlattices is creating a periodic structure with a periodicity that matches a relevant length scale in the underlying medium. For example, in a photonic metamaterial the artificial unit cell period is typically close to the wavelengths of light it is designed to be used in. Similarly, the superlattice period in moiré materials is small enough to be close to the de Broglie wavelength of untwisted materials, resulting in strongly renormalized electronic properties.

Given the success of superlattice engineering to achieve on-demand transport properties and phases of matter in lower-dimensional electronic systems, it is natural to explore the extent to which these methods can be employed in three-dimensional (3D) materials. Currently, there are a limited number of methods to achieve precise control over a 3D material's transport properties, including applying external stimuli such as pressure, strain, or magnetic field, or chemical doping.

Thus, establishing means of controlling 3D electronic properties without chemical substitution or external stimulus is appealing. The additional diversity of phases of matter found in 3D electronic materials in contrast to low-dimensional materials presents a vast experimental phase space that superlattice engineering can be applied to.

To gain a deeper understanding of the fundamental properties of superlattices in 3D materials, we used focused-ion beam (FIB) micromachining to create nanoscale superlattices in the Weyl semimetal NbP. FIB with Ga ions is an ideal tool to create specific superlattice structures with feature sizes larger than ~ 250 nm, especially since traditional means of nanofabrication such as photo- or electron-beam lithography are challenging on 3D materials. We chose NbP as a starting material because of its long mean free path $l_{\text{mfp}} \sim 10$ μm at liquid helium temperatures arising from the well-defined Weyl nodes near the Fermi surface [14]. These carriers' long l_{mfp} exceeds the feature sizes achievable with FIB, and the well-documented properties of NbP's electronic structure make it an ideal candidate to understand how the electronic structure and superlattice spacing each affect their combined properties.

One consequence of introducing a periodic potential to an electronic system subject to a magnetic field is that the field-induced cyclotron orbit radius can become commensurate with the superlattice potential, leading to oscillations in the material's resistance [15–17]. The additional translational symmetry imposed by the superlattice splits the degeneracy of the Landau levels, yielding a complicated fractal energy spectrum in magnetic field called Hofstadter's spectrum [8,9,18–20]. Encoded in Hofstadter's spectrum is information about the quantum Hall effect [21–23], as well as other quantum transport phenomena such as Brown-Zak oscillations and geometric commensuration oscillations (COs) [24–26]. Quantum mechanically, COs correspond to oscillations in the

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superlattice-imposed magnetic miniband width as the flux is changed, leading to oscillations in the magnetic miniband conductivity that are measurable in quantum transport experiments [20,27].

Semiclassically, the commensuration oscillations correspond to cyclotron orbits that get pinned and scattered chaotically by the artificial superlattice [16,17,28,29]. The COs occur when the cyclotron orbits enclose a quantized number n of superlattice unit cells, with $na = 2r_c$. In this expression, n is an integer, a is the lattice spacing of the superlattice, $r_c = \frac{\hbar k_f}{eB}$ is the cyclotron radius, k_f is the Fermi momentum, B is the magnitude of the applied magnetic field, e is the charge of an electron, and $\hbar$ is the reduced Planck's constant. Commensuration oscillations have been observed in high-mobility two-dimensional (2D) electron systems with artificially defined superlattices on the order of tens to hundreds of nanometers, including two-dimensional electron gases in III–V compound semiconductor heterostructures [15–17,30], monolayers of graphene [25,26,31–33], surface states of a topological insulator [34], and incommensurate charge-density waves [35]. In addition to shedding light on the fundamental properties of the Hofstadter spectrum, commensuration oscillations have also been used to prove the fermionic nature of the fractional quantum Hall state [36]. The investigation of commensuration oscillations has thus far been limited to 2D materials with isotropic Fermi surfaces.

In contrast to 2D materials with isotropic Fermi surfaces, NbP has an anisotropic Fermi surface with fourfold rotational symmetry, thus providing an additional tuning parameter for its magnetotransport. This material's mean free path $l_{\text{mfp}} \sim 10 \mu\text{m}$ at liquid helium temperatures [14] is longer than the superlattice period a in our FIB milled structures, satisfying the criteria for semiclassical commensuration oscillations ($l_{\text{mfp}} > a$). By changing the rotational symmetry of the superlattice, we quench the strength of the CO peaks, demonstrating that their intensity reflects the in-plane rotational symmetry of the Fermi surface. We further introduce a chiral superlattice that has an asymmetric response to the magnetic field, dictated by the negative charge of the ballistic quasiparticles and superlattice enantiomer.

Beyond leveraging the relative symmetry between the Fermi surface and superlattice, we show the depth and breadth of fermiological information—including effective mass, Fermi momentum, and quasiparticle charge parity—reflected in the CO peaks at relatively high temperatures and low magnetic fields. The out-of-plane structure of the Fermi surface leaves a distinct signature in the dependence of the CO peaks on the angle of the applied magnetic field. The effective mass and out-of-plane Fermi surface shape are complemented by temperature- and angle-dependent Shubnikov-de Haas (SdH) measurements, showing methodological consistency but also demonstrating the wealth of information contained in the CO peaks compared to conventional quantum oscillations (QOs).

II. MATERIALS AND METHODS

A. NbP crystal growth

Polycrystalline NbP powder was synthesized by reacting Nb powder (99.9% purity) and red phosphorus pieces

(99.999% purity) in an evacuated silica tube for 48 h at 800 °C. Single NbP crystals were then grown from this powder through a chemical transport reaction using iodine as the transport agent, with the source and sink set at 950 and 850 °C, respectively.

B. Device fabrication

Microstructured single crystals of NbP were shaped using a FEI Helios 600i Ga⁺ focused ion beam system, using an ion accelerating voltage of 30 kV. When patterning the superlattices, a current of 80 pA was used. The lamellae were extracted from the single-crystal samples, shaped to the desired specifications, and then placed on a prefabricated substrate within the vacuum of the FIB. These substrates consist of sputtered gold pads on top of silicon, with an insulating oxide layer in between. Contact between the gold pads and FIB device was made with the FIB platinum.

C. Magnetotransport measurements

AC electrical transport measurements were made by applying constant current along the a direction of NbP and measuring voltage along transverse and longitudinal directions with respect to the current. These measurements were done in a PPMS Dynacool cryostat with external lock-in amplifiers (MFLI, Zurich Instruments). Magnetic field was applied along the c direction unless otherwise specified.

III. MAGNETOTRANSPORT IN WEYL SEMIMETAL SUPERLATTICES

Weyl semimetals are ideal materials in which to observe commensuration oscillations because of their large mean free paths and relatively small Fermi surfaces [37]. These properties make COs observable under the constraints of superlattice periods achievable with FIB machining [38] and laboratory-based magnetic fields of a few teslas. Unlike graphene and two-dimensional electron gas (2DEG) systems, which have isotropic circular Fermi surfaces, NbP has a fourfold symmetric Fermi surface, with each pocket constituted by two slightly overlapping lobes [14,39] [Fig. 1(a)]. The noncircular nature of these Fermi pockets comes from the separation of the Weyl nodes. As the real-space cyclotron motion is related to the reciprocal-space shape of the Fermi surface, the noncircular Fermi pockets change the commensuration condition when the superlattice is aligned with the principal crystallographic directions. For example, in a square antidot lattice—like the one shown in Fig. 1(c)—the anisotropic Fermi surface of NbP heuristically leads to a modified commensuration condition

$$na = 2r_{c1} = \frac{2\hbar k_{f1}}{eB}, \quad (1a)$$

$$2ma = 2r_{c2} = \frac{2\hbar k_{f2}}{eB}, \quad (1b)$$

for $k_{f1} = 0.022 \text{ \AA}^{-1}$, $k_{f2} = 0.035 \text{ \AA}^{-1}$ [14] and m, n are integers. An example of a typical device is shown in Fig. 1(b), which has a superlattice pattern defined on one side, such that the transport can be readily compared to the device's unpatterned side. In each of our superlattice devices, the superlattice is well defined with respect to the crystallographic

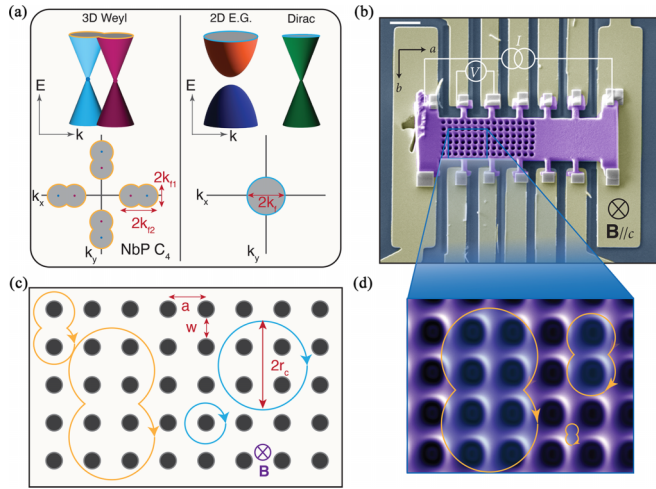


FIG. 1. Device design and commensuration principle. (a) Comparison between the electronic structures in a 3D Weyl semimetal like NbP (left) and 2D electron systems like graphene (right). The Fermi pockets of the Weyl semimetal have a characteristic “peanut shape” arising from the separation of the Weyl nodes and have two distinct Fermi momenta k_{f1} and k_{f2} , while the Fermi pockets in a 2D electron gases are isotropic with only one characteristic Fermi momentum k_f . In addition, the Fermi pockets in NbP are related to one another by the C4 symmetry of the lattice. Meanwhile, the Fermi pockets of 2DEGs are isotropic. (b) False colored scanning electron microscope (SEM) image of a Hall bar made by FIB lithography with thickness $t = 1.3 \mu\text{m}$. Devices include a region with a superlattice on the order of hundreds of nanometers and an unpatterned region used as a reference. Scale bar is $5 \mu\text{m}$. AC current is applied along the a axis of NbP, while the magnetic field is applied along its c axis. (c) Depiction of the commensuration effect. With an applied magnetic field out of plane (purple arrow), charged particles precess in the plane of the superlattice (black dots). For a material with an isotropic Fermi surface, such as graphene or a 2D electron gas, the cyclotron orbit is circular (blue). NbP has Fermi pockets with a “peanut” shape and its cyclotron orbits are shown in gold. The commensuration condition is satisfied when an integer number of superlattice unit cells are enclosed by the cyclotron orbits. (d) Magnification of an FIB defined superlattice with period $a = 730 \text{ nm}$ and three possible NbP cyclotron orbits that satisfy the commensuration condition overlaid.

axes. The commensuration oscillation conditions are depicted in Fig. 1(c), and superimposed on a magnification of the superlattice in one of our devices in Fig. 1(d). These conditions show how introducing a more complicated Fermi surface affects the commensuration oscillations. The symmetry of the Fermi surface imposes conditions on commensuration oscillations that strongly contrast with previously investigated isotropic systems.

We observe commensuration oscillations in the longitudinal resistivity of the superlattice devices for magnetic fields perpendicular to the current direction. Figure 2(a) shows an SEM image of a square superlattice device with spacing $a = 730 \text{ nm}$. The background-subtracted resistance $\Delta R = R - R_b$ displayed in Fig. 2(b) shows oscillations below $B = 1 \text{ T}$, with a broad and prominent peak near $B = 0.4 \text{ T}$. We attribute the broad dip near $B = 0 \text{ T}$ to weak antilocalization (WAL), which obscures higher harmonic CO features. Faint peaks

appear in the raw magnetoresistance $\text{MR} = 100\% \times \frac{R(B) - R(0)}{R(0)}$ [Fig. 2(c)], but the clarity of the signal in the background-subtracted resistance makes it more suitable for analysis (see Note S1 in the Supplemental Material (SM) [40]). The positions of the peaks in magnetic field compare well to those expected from Eqs. (1a) and (1b) with the Fermi momenta of the Weyl nodes and superlattice spacing $a = 730 \text{ nm}$. In contrast to the COs, which begin at magnetic fields below $B \sim 1 \text{ T}$, the QOs become prominent at fields above $B \sim 2 \text{ T}$ as shown in Fig. S6 of the SM [40]. We note that the superlattice does not significantly change the shape of the Fermi surface, as indicated by the similarity in the SdH spectra of the patterned and unpatterned sides of the devices [Fig. 2(d)]. In particular, the QOs identify the most prominent peak as coming from the pocket with area $A = 31 \text{ T}$, which corresponds to the Fermi pocket containing the electronlike Weyl nodes [14,41] whose momenta are imprinted on the COs. The CO peaks are also prominent in the second derivative with respect to field of R_b displayed in Fig. 2(e). This reveals the splitting of the $n = 1$ peak at $B = 0.4$ and 0.33 T , corresponding to the two different Fermi momenta k_{f1} and k_{f2} in Eqs. (1a) and (1b). The $n = 2$ peak near $B = 0.2 \text{ T}$ is also visible against the low-field WAL signal (inset). To confirm the validity of the heuristic commensuration conditions in Eq. (1), we fabricate four devices with different superlattice spacings, and find good agreement between the predicted CO peak positions and the lattice spacings [Fig. 2(f)]. We attribute the data points at high magnetic fields that do not fall on the theoretical lines to cyclotron orbits trapped in the interstitial sites of the superlattice.

Next, we demonstrate that changing the superlattice symmetry is an effective means of altering the commensuration effect. The Fermi surface of NbP has fourfold rotational symmetry in the xy plane due to its tetragonal crystal structure. To investigate this symmetry selection, we pattern a triangular (threefold symmetric) superlattice to see how the CO amplitude changes [Fig. 2(g)]. Indeed, we observe that the CO amplitude is quenched in the threefold symmetric superlattice [Fig. 2(h)] relative to the fourfold symmetric lattice [Fig. 2(e)]. This symmetry selection can be explained by the fact that the triangular superlattice no longer has the same underlying symmetry as the Fermi surface, and thus the commensuration condition is more difficult to satisfy. There are still some signatures of commensuration effects in the triangular superlattice, which may arise from commensuration effects in one direction, but not both. In particular, the peak at magnetic field value of $B = 0.6 \text{ T}$ [$a = 483$ and 384 nm in Eqs. (1a) and (1b), respectively] for the COs in the triangular lattice corresponds well to the cyclotron orbits being trapped in between the antidots, but not encircling them. Thus, information about the relative symmetry between the superlattice and Fermi surface is imprinted on the CO spectrum.

Notably, the CO peaks are observable at temperatures an order of magnitude higher than Shubnikov-de Haas QOs, and we use the CO temperature dependence to extract the quasiparticle mass. Conventional quantum oscillations are typically observed at low temperatures because the thermal broadening of the Fermi-Dirac distribution suppresses the magnitude of the quantum oscillations. Commensuration oscillations follow

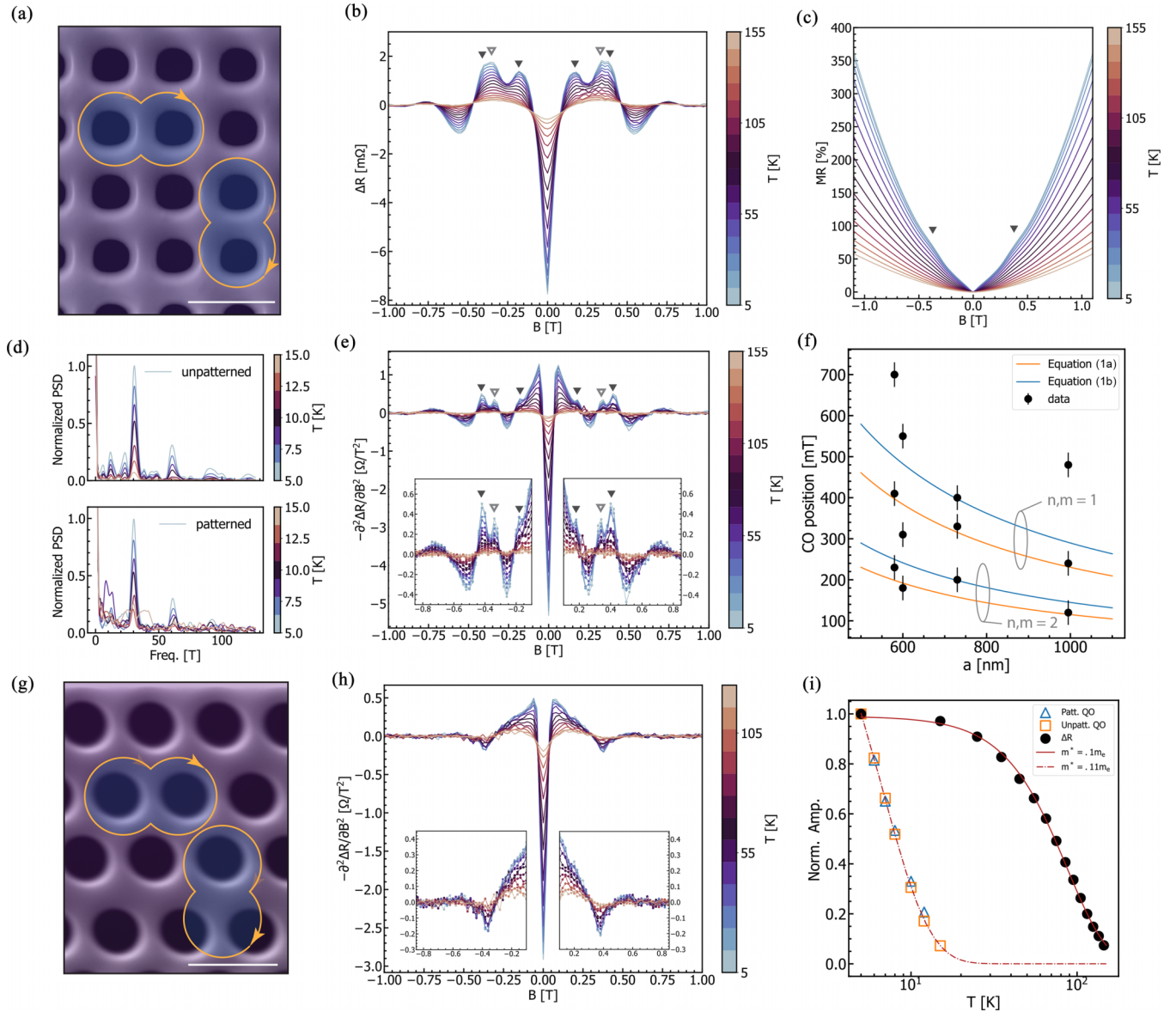


FIG. 2. Field and temperature dependence of commensuration oscillations in longitudinal resistance. (a) False colored SEM image of NbP patterned with a square superlattice, with $a = 730$ nm and thickness $t = 1.3$ μm . Yellow paths are representations of the cyclotron orbits in real space. Scale bar in bottom right is 1 μm . (b) Background-subtracted resistance $\Delta R = R - R_b$ of the same device, which more prominently shows the commensuration oscillations, indicated by solid and open gray arrows. (c) Magnetoresistance defined as $MR = 100\%(R(B)/R(0) - 1)$ of the square antidot device with superlattice spacing $a = 730$ nm measured for different cryostat temperatures between $T = 5$ K and $T = 155$ K. Solid gray arrows indicate small humps in the MR arising from commensuration. (d) Normalized Fourier amplitude of the high-field quantum oscillations for the unpatterned and patterned devices (top and bottom panels, respectively) for temperatures between 5 and 15 K. The spectra of both sides have primary peaks around 31 and 61 T, consistent with the literature [14,41]. (e) Second derivative of background-subtracted resistance ΔR in panel (b) more clearly shows the splitting of the CO peaks, as indicated by the gray arrows and shown in the insets. (f) Resistivity peak position in magnetic field for each of the four fourfold symmetric superlattice devices in this study with different superlattice spacings. Blue and orange lines indicate the $n = 1$ and $n = 2$ conditions from Eqs. (1a) and (1b). (g) False colored SEM image of NbP patterned with a triangular superlattice, with $a = 730$ nm. Yellow paths are representations of the cyclotron orbits in real space. Scale bar in bottom right is 1 μm . (h) Second derivative of background-subtracted resistance ΔR in a device with a triangular superlattice that has quenched CO features in contrast with the square device data presented in panel (e). (i) Temperature dependence of the COs (black points) and QOs (blue for patterned, green for unpatterned). Black points are extracted from ΔR ($B = 0.4$ T) in panel (b). Red line is a fit to the modified Lifshitz-Kosevich formula and extracted $m_{\text{co}}^* = 0.1m_e$.

a temperature dependence similar to the Lifshitz-Kosevich form $A = \frac{T/T_c}{\sinh(T/T_c)}$, where $T_c = \frac{\hbar e B}{2\pi^2 k_B m^*}$, but renormalized by a factor of $k_f a/2$ such that $T_c^{\text{CO}} = \frac{\hbar e B}{4\pi^2 k_B m^*} k_f a$ [42,43]. This factor reflects how the thermal smearing of the cyclotron orbits impacts the commensuration condition. The amplitude of the commensuration oscillations as a function of temperature—extracted from CO peak in ΔR at $B = 0.4\text{T}$ —is plotted in Fig. 2(e). We fit the data with the modified Lifshitz-Kosevich formula including a T -dependent scattering time [25,35,42] (which is ultimately found to be negligible; see Note S6 in the (SM) [40]) to extract the mass of the quasiparticles from the amplitude change of the commensuration oscillations. The extracted quasiparticle mass $m^* = 0.1m_e$ is in excellent agreement with the mass extracted from the QO [dashed red line in Fig. 2(e)] and literature values for NbP [14,44–46]. Notably, the QOs are visible up to $T \sim 15\text{ K}$, while the COs are visible up to $T \sim 150\text{ K}$, demonstrating both the robustness of the CO effect and how they can be used to extract the same information as the QO at more relaxed (higher T , lower B) conditions.

A. Angle dependence based on 3D superlattice and Fermi surface structure

In addition to showing that the commensuration effect depends on the relative in-plane symmetry of the superlattice and Fermi surface, we also demonstrate how the 3D geometry of the Fermi surface and the 3D superlattice structure impacts the commensuration conditions. One important property of a nanostructured superlattice in a 3D material by comparison to a 2D material is that the 3D material (NbP in this case) has an additional spatial component to its electronic structure. Following the semiclassical equations of motion for a Bloch electron in a magnetic field, the cyclotron orbit of a quasiparticle in a magnetic field is in the plane perpendicular to the applied field [47]. In typical QO measurements, this means that by changing the angle of the applied field, the frequency of the QO changes based on the change in the cross-sectional area of the Fermi surface perpendicular to the magnetic field. Thus, angle-dependent QO measurements are frequently employed to map out the full 3D shape of a material's Fermi surface.

Figure 3(a) shows the change of commensuration peaks as the field is rotated away from the z direction (out of plane relative to the superlattice). In Fig. 3(b), we plot the dependence of the $n = 1$ commensuration peaks as a function of field angle ϕ . The angular dependence of the CO peaks closely follows the $1/\cos \phi$ dependence characteristic of a cylindrical Fermi surface, as fit by the solid line. The cylindrical Fermi surface is a good approximation in NbP based on the anisotropic (but closed) Fermi surface from DFT calculations for this material [46], although we note that NbP's Fermi surface is closed. The angular dependence of the CO peaks also matches the angular dependence of the Fermi surface area, as shown in Fig. 3(c).

The angular dependence of the cyclotron orbit is imprinted on the commensuration oscillations because the radius of the cyclotron orbit in real space dictates the commensuration condition. As depicted in Fig. 3(d), the Fermi momentum

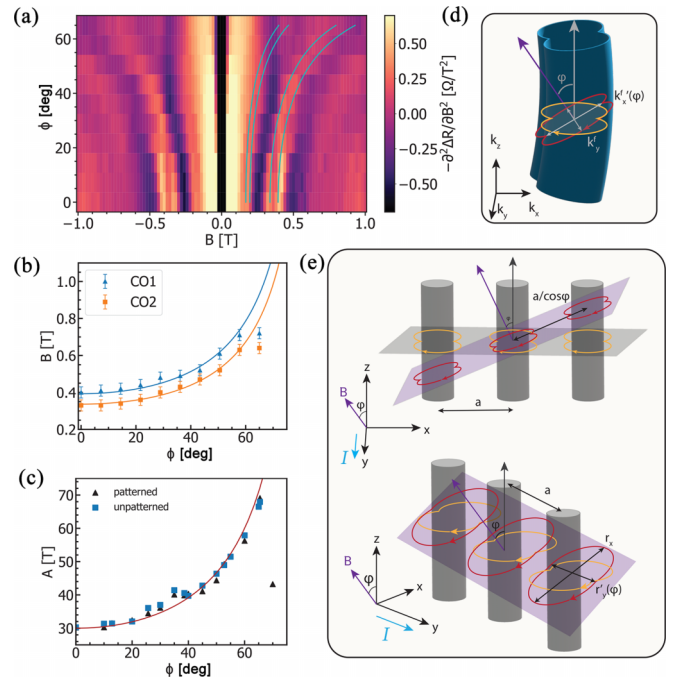


FIG. 3. Commensuration dependence on magnetic field angle. (a) Colormap of the second derivative with respect to field of the background-subtracted resistance ΔR in the square superlattice device with $a = 730\text{ nm}$ for different directions of applied magnetic field ϕ transverse to the applied current. Overlain cyan lines correspond to the $1/\cos \phi$ dependence from Eq. (2). (b) Extracted $n = 1$ CO position as a function of field angle ϕ with solid red line corresponding to fit to the CO data of $1/\cos \phi$ to Eqs. (2a) and (2b). (c) Fermi surface area extracted from the quantum oscillations on both the patterned and unpatterned sides of the device as a function of field angle. Solid red line corresponds to fit to the QO data of $1/\cos \phi$. (d) In reciprocal space, the Fermi surface cross section depends on the angle of the field. For a magnetic field in the x - z plane, the Fermi momentum along the k_x direction becomes renormalized and the Fermi momentum along the k_y direction remains unchanged, leading to a change in the cyclotron radius along the y direction in real space [Fig. 3(e), bottom]. (e) Real-space schematic of transport geometry with magnetic field applied at angle ϕ in the x - z plane, always perpendicular to the electrical current I applied along the y direction. In the plane of the field rotation (top), the superlattice spacing between the potentials is modified along the x direction, and the cyclotron radius is unchanged. In the plane perpendicular to the field (bottom), the superlattice spacing is unchanged, but the cyclotron radius in the y direction becomes modified based on the change of the Fermi surface. Yellow orbits correspond to trajectories for $\phi = 0$, whereas the red orbits indicate the trajectories once the field angle is changed.

in reciprocal space changes in the direction orthogonal to the magnetic field, confined to the plane of rotation, and acquires angular dependence $k_f(\phi)$. In real space, the cyclotron orbit changes size in the direction orthogonal to both the magnetic field and the momentum change [Fig. 3(e), bottom], while the lattice spacing remains the same. In the other direction [Fig. 3(e), bottom], the superlattice spacing acquires an angular dependence $a(\phi) = a/\cos \phi$. As a result, the

commensuration equations (1a) and (1b) become

$$B_1 = \frac{2\hbar k'_{f1}(\varphi)}{ena}, \quad (2a)$$

$$B_2 = \frac{\hbar k'_{f2}(\varphi)}{ena}, \quad (2b)$$

$$B_3 = \frac{2\hbar k_{f1}}{ena} \cos \varphi, \quad (2c)$$

$$B_4 = \frac{\hbar k_{f2}}{ena} \cos \varphi. \quad (2d)$$

We note that while the $B \sim 1/\cos(\varphi)$ angular dependence from the cyclotron radius change is clear in our data, the $B \sim \cos(\varphi)$ dependence from the superlattice spacing change is not. One reason for this discrepancy could be the decrease in CO amplitude and the higher background at low field. As the radius of the cyclotron orbit increases, the amplitude of the CO peaks decreases because of a total increase in scattering along the longer path length (larger orbit circumference) [42].

B. Asymmetric MR in a chiral superlattice

To further extend the notion of CO tunability by superlattice symmetry, we engineer a chiral superlattice with an asymmetric response to magnetic field. As shown in Fig. 4(a), the chiral superlattice breaks in-plane mirror symmetry in both the x and y directions, resulting in a designated handedness. We designed the chiral superlattice to have fourfold rotational symmetry to match the symmetry of NbP's Fermi surface. In this device, the COs show an asymmetry between the positive and negative field resistance [Fig. 4(b)]. To quantify this asymmetry, we use a rectification ratio

$$\eta = \frac{\Delta R(-B) - \Delta R(+B)}{\Delta R(-B) + \Delta R(+B)},$$

which shows a temperature-dependent peak at the commensuration condition for the chiral superlattice [Fig. 4(c)] but not for the square lattice [Fig. 4(d)]. The chirality of the boundary scattering impacts the CO peaks depending on the charge of the quasiparticles. Microscopically, this effect comes from considering that positively and negatively charged quasiparticles have cyclotron orbits with opposite direction for a given magnetic field direction [green and yellow solid orbits in Fig. 4(e), respectively]. At boundaries of the plaquette, cyclotron orbits induce chiral skipping modes. In Fig. 4(e), the drift direction is represented by the blue and red arrows for positively and negatively charged quasiparticles, respectively. Crucially, in a superlattice with a given chirality, the skipping orbit drift can either flow into a boundary or out of the chiral plaquette. When the direction of the drift is toward the boundary, the resistance is higher from increased boundary scattering. Changing the magnetic field direction or the quasiparticle charge flips the direction of the skipping orbit drift, leading to higher or lower resistance at the CO condition [Fig. 4(e), bottom]. The observed sign of the rectification ratio η corresponds to negatively charged quasiparticles interacting with the chiral superlattice [yellow orbits in Fig. 2(e)]. The charge parity displayed in the chiral superlattice device is also consistent with prior studies of NbP, which show an electronlike nature of the Weyl-fermion pocket [44].

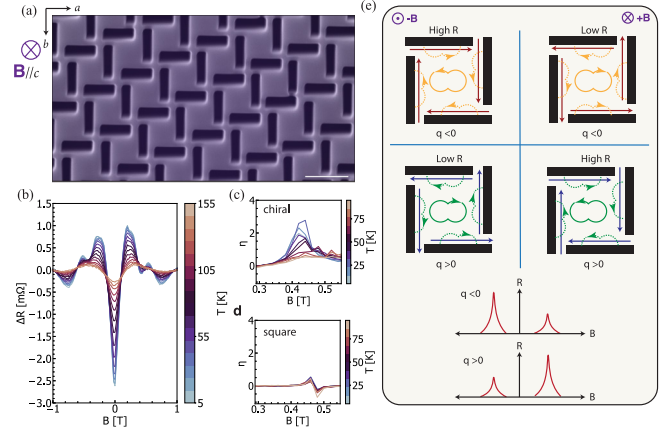


FIG. 4. Asymmetric magnetotransport in a chiral superlattice. (a) False colored SEM image of chiral superlattice with fourfold rotational symmetry. Scale bar in bottom right corner is $1 \mu\text{m}$. Positive magnetic field B points into the plane of the superlattice. (b) Background-subtracted resistance ΔR in the chiral superlattice for temperatures between $T = 5 \text{ K}$ and $T = 155 \text{ K}$. (c) Rectification ratio $\eta = \frac{\Delta R(-B) - \Delta R(+B)}{\Delta R(-B) + \Delta R(+B)}$ for the chiral superlattice shows a peak at the commensuration condition, whereas for the square lattice [panel (d)] it does not. (e) Cyclotron orbits for oppositely charged particles (yellow for negative, green for positive) are confined to chiral plaquettes at the commensuration condition. At the boundaries of the plaquettes are chiral skipping orbits (dashed lines) whose drift direction is indicated by the red and blue arrows. The relative chirality drift velocities and the boundaries lead to higher- or lower-resistance peaks, shown in the bottom for positive and negative charges, respectively. (c) First derivative with respect to field of the asymmetric resistance $\Delta R = R(-B) - R(+B)$ for the patterned and unpatterned sides of the chiral device. For the chiral pattern, there is a strong asymmetric response at low field, indicating a negative charge of the quasiparticles based on the chirality of the superlattice.

IV. CONCLUSIONS

Based on the large length scale of the lattice compared to the Fermi wavelength of NbP, our experiments are limited to the semiclassical, as opposed to quantum, regime. Consequently, the symmetry of the superlattice does not necessarily modify the wavefunction of the quasiparticles at the Fermi surface. Such a modification would be evident in the quantum oscillation spectrum, which shows the same peaks for the patterned and unpatterned devices [Fig. 2(d)]. In the quantum regime, when the superlattice modulation is on a similar order of magnitude as the Fermi wavelength, it has been observed that additional quantum oscillations become present on top of the commensuration oscillations [17]. To endow the Weyl electrons with the symmetry of the superlattice and modify their electronic structure, it may be necessary to have the superlattice modulation on a scale of tens of nanometers, matching the Fermi wavelength (for NbP, $\lambda_f \sim 20 \text{ nm}$). Achieving such small superlattice sizes remains challenging, as traditional lithographic techniques are not generally applicable to 3D structures like bulk single crystals, and the FIB technique is limited by resolution [38] at such small feature sizes.

Extending methods of engineered superlattices to 3D materials requires understanding the fundamental interactions between the superlattice and underlying electronic degrees of freedom. We have explored the properties of the Fermi surface that become imprinted on the magnetotransport of nanostructured NbP, based on the superlattice spacing and symmetry. The commensuration oscillations of resistivity in magnetic field provide detailed probe of the Fermi surface at temperatures and magnetic fields more amenable than quantum oscillations. It may be promising to combine phonon engineering [48–50] with electronic superlattice engineering in Weyl semimetals, especially given their unique thermal and thermoelectric transport properties [51–54]. As topological semimetals find more applications [55], it is attractive to consider nanostructured superlattices as a means of creating properties on demand in this novel materials class.

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The authors declare no competing interests.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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