Quantum oscillations in correlated insulators of a moiré superlattice

Le Liu1,2, Yanbang Chu1,2, Guang Yang1,2, Yalong Yuan1,2, Fanfan Wu1,2, Yiru Ji1,2, Jinpeng Tian1,2, Rong Yang1,3, Kenji Watanabe4, Takashi Taniguchi5, Gen Long3, Dongxia Shi1,2,3, Jianpeng Liu6,7, Jie Shen1,2,3, Li Lu1,2,3, Wei Yang1,2,3*, and Guangyu Zhang1,2,3*

1 Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
2 School of Physical Sciences, University of Chinese Academy of Sciences, Beijing, 100190, China
3 Songshan Lake Materials Laboratory, Dongguan 523808, China
4 Research Center for Functional Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
5 International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
6 School of Physical Sciences and Technology, ShanghaiTech University, Shanghai 200031, China
7 ShanghaiTech Laboratory for Topological Physics, ShanghaiTech University, Shanghai 200031, China

* Corresponding authors. Email: wei.yang@iphy.ac.cn; gyzhang@iphy.ac.cn

Abstract

Quantum oscillations (QOs) are ubiquitous in metal due to the Landau quantization of cyclotron motion in magnetic field, while they are generally absent in an insulator. Here, we report an observation of QOs in the valley polarized correlated insulators of twisted double bilayer graphene (TDBG). The anomalous QOs are best captured in the magneto resistivity oscillations of the insulators at $v = -2$, with a period of $1/B$ and an oscillation amplitude as high as 150 kΩ. The QOs can survive up to ~10K, and above 12K, the insulating behaviors are dominant. The QOs of the insulator are strongly D dependent: the carrier density extracted from the $1/B$ periodicity decreases almost linearly with $D$ from -0.7 to -1.1V/nm, suggesting a reduced Fermi surface; the effective mass from Lifshitz-Kosevich analysis depends nonlinearly on $D$, reaching a minimal value of $0.1m_e$ at $D = -1.0V/nm$. Similar observations of QOs are also found at $v = 2$, as well as in other devices without graphite gate. We interpret the $D$ sensitive QOs of the correlated insulators in the picture of band inversion. By reconstructing the inverted bands in a toy model with the measured effective mass and Fermi surface, the density of states calculations of Landau levels agree qualitatively with the observed QOs in the insulators. While more theoretical understandings are needed in the future to fully account for the anomalous quantum oscillations in this moiré system, our study suggests that TDBG is an excellent platform to discover exotic phases where correlation and topology are at play.
Introduction

Quantum oscillations (QOs) of conductance are widely observed in mesoscopic devices. For metals in a magnetic field ($B$), QOs are usually revealed in the Shubnikov-de Haas oscillations (SdHOs) of conductance with a period of $1/B$ due to the Landau quantization of the Fermi surface; for insulators, however, SdHOs are in principle not expected, due to the absence of Fermi surface. Surprisingly, QOs have been observed in Kondo insulators (SmB$_6$ and YbB$_{12}$), InAs/GaSb quantum wells, and more recently in the insulating state of WTe$_2$. To explain the anomalous QOs, various mechanisms are proposed, including the conventional picture with band inversion, in which the finite density of state (DOS) in the gap oscillates with $B$ due to the broadening of quantized Fermi surfaces away from gaps, unconventional Landau quantization of neutral Fermions, and trivial external capacitive mechanism due to the DOS in the gate electrode. However, the strong debates impede the reaching of consensus. Noted that, despite the material differences, these insulators share one common feature, i.e. the insulating gaps are small and resulted from band hybridizations. Inversely, one might ask: is it possible to reproduce the QOs in an insulator with a given band hybridization? This is important, as it might provide a feasible method to extend the family of the insulators with QOs, and moreover to unveil the mystery behind.

Twisted double bilayer graphene (TDBG), a highly tunable moiré flat band system that hosts correlated insulators, offers another opportunity to unveil the puzzling anomalous QOs. The bands in TDBG include flat moiré conduction bands and more dispersive moiré valence band and remote bands, allowing versatile band hybridizations. Besides, perpendicular electrical displacement field ($D$) could in-situ change the on-site energy between layers and in turn modify nonlinearly the moiré bandwidths as well as the gaps separating different bands, enabling the facile tuning of Coulomb interactions. Moreover, there is a rich interplay of spin, valley, and Coulomb interaction that results in isospin competition with different polarized ground states of the correlated insulators at half fillings. As demonstrated in TDBG, it could have a phase transition from metal or spin polarized correlated insulator to valley polarized correlated insulator by increasing $D$. Thus, TDBG provides a versatile playground for tuning electron correlation and band hybridizations. However, the QOs in the correlated insulators of TDBG as well as other twisted multilayer moiré systems have not been explored.

Here, we report an observation of QOs in the correlated insulators of TDBG. We will firstly focus on the valley polarized correlated insulator at $v$ = -2 in the TDBG device with a graphite gate, and demonstrate the QOs in the insulator from the observation of the resistivity oscillations as a function of $1/B$. Then, we reveal that the insulating QOs are strongly $D$-field dependent, distinctly different from $D$ insensitive SdHOs of the Bloch electrons in the magnetic field. We also demonstrate the universality of the insulating QOs at $v$ = 2 as well as in other devices without graphite gate. Lastly, we interpret the $D$ sensitive QOs of the correlated insulators in the picture of band inversion, which agrees well with our numerical DOS calculations of Landau levels in the inverted band toy model by using the measured effective mass from Lifshitz-Kosevich analysis of the insulating QOs amplitudes and Fermi surface from the $1/B$ periodicity.

The QOs of the valley polarized insulator at $v$ = -2

The twisted double bilayer graphene (TDBG) samples are prepared by using the ‘cut and stack’
method\textsuperscript{38}, and the details of device information are presented in Ref. 24\textsuperscript{24}. These devices have a dual gate configuration (devices D1 and D2 (D3) with a graphite (Si) bottom gate and gold top gate), which allows independent tuning of the carrier density $n$ and $D$. Here, $n = (C_{BG}V_{BG} + C_{TG}V_{TG})/e$ and $D = (C_{BG}V_{BG} - C_{TG}V_{TG})/2\varepsilon_0$, where $C_{BG}$ ($C_{TG}$) is the geometrical capacitance per area for bottom (top) gate, $e$ is the electron charge, and $\varepsilon_0$ is the vacuum permittivity. The filling factor is defined as $\nu = 4n/n_s$, corresponding to the number of carriers per moiré unit cell. Here, $n_s = 4/A \approx 8\theta(\sqrt{3}a^2)$, where $A$ is the area of a moiré unit cell, $\theta$ is twisted angle, and $a$ is the lattice constant of graphene.

In the following, we focus on the magneto transport of the valley polarized correlated insulators at $\nu = -2$ in device D1 with twisted angle of 1.38°. All measurements are done at $T = 1.8K$, unless stated otherwise.

Figure 1a shows a color mapping of longitudinal resistance $R_{xx}(\nu, B)$ at a displacement field of $D = -0.94V/nm$. The valley polarized correlated insulator at $\nu = -2$ is developed at finite magnetic field due to orbital Zeeman effect\textsuperscript{24}. Away from the insulator, Landau levels (LLs) are observed fanning out from $\nu = -2$ with $\nu_{LL} = \pm1, \pm2, \pm3, \pm4, \pm5, \pm6$, indicating the presence of both electron-like and hole-like Fermi surfaces and a fully lifted degeneracy of spin and valley in the moiré valence band at such a high $D$. While these observations are in line with previous report\textsuperscript{24}, however, the alternating color changes between red and white at $\nu = -2$ in Fig. 1a suggest resistance oscillations as a function of $B$.

The unexpected quantum oscillations are better presented in the plot of $R_{xx}(B)$ in Fig. 1b, with a nontrivial oscillation amplitude as high as 150 kΩ at around 6T. The resistance oscillates periodically with $1/B$, as shown in Fig. 1c. By tracing the position of oscillation peaks and valleys, we obtain a frequency of $B_f \sim 13.3$T. These oscillations are very sensitive to the temperature, and they are barely visible at $T = 13K$ as shown in Fig.1d. A full temperature dependence of the oscillations at $\nu = -2$ is depicted in Fig. 1e, where the negative and the positive sign of $dR/dT$ indicate insulator (blue) and metal (red), respectively. Thus, the observation of resistance oscillations at $\nu = -2$ is indeed a manifestation of quantum oscillations in insulator, distinct from SdHOs in metals.

The $D$ dependence of insulating QOs

The resistive QOs of the insulator at $\nu = -2$ are observed over a wide range of $|D| > 0.6V/nm$, as shown in the color mapping of $R_{xx}(D, B)$ at $T = 100$ mK in Fig. 2a. In particular, these QOs emerge as a series of fans at $|D|$ from 0.7 to 1.1 V/nm, which is reminiscent of the Landau fan diagram with varied carrier density. By performing FFT of Fig. 2a, the periodicity of these QOs, $B_f$, scales linearly to the change of $D$, indicated by the orange dashed line in Fig. 2b. Besides, the QOs of the insulator are also vividly shown as the periodic resistance peaks at $\nu = -2$ with $B = 3T$ in Fig. 2c. Lastly, the QOs are vanishing at around $|D| \sim 1.17V/nm$ and then reentrant up on further increasing the $|D| > 1.2V/nm$; however, the oscillating pattern at $|D| > 1.2V/nm$ is seemingly antisymmetric compared to those at $|D| < 1.2V/nm$, suggesting a pi phase change.

Compared to the resistive QOs at $|D| > 0.6V/nm$, metallic QOs are also observed at a lower displacement field ($|D| < 0.6V/nm$), with QOs frequency of $B_f \sim 46$T that is independent on $D$. The $B_f \sim 46$T matches well with commensuration of $\Phi/\Phi_0 = 1$ for moiré superlattices with a twisted angle of 1.38°. Here $\Phi = BS$ is the magnetic flux through a superlattice cell with an area of $S$, and $\Phi_0 = h/e$ is magnetic flux quantum. We attribute these QOs at $|D| < 0.6V/nm$ to the Brown-Zak oscillations (BZOs, a feature of the Hofstadter butterfly) at $\Phi/\Phi_0 = p/q$\textsuperscript{39}, where $p$ and $q$ are co-prime integers. The
transition from metallic BZOs to insulating QOs at around \( v = -2 \) is better revealed in the Landau fan diagram at different \( D \) in Extended Data Fig. 2. Such BZOs with \( B_f \approx 46 \text{T} \) are also clearly visible at the remote valance band (\( v < -4 \)) in Landau fan diagrams at \( D = -0.94 \text{V/nm} \) in Extended Data Fig. 1, where the drastic difference of oscillating periodicity is revealed in the comparison between BZOs and resistive QOs. Thus, the electrical field tunable QOs in the valley polarized correlated insulator are distinctly different from BZOs.

Note that the QOs of the insulator at \( v = -2 \) have also been observed in other two devices, D2 of \( \theta = 1.21^\circ \) with a metal top gate and a graphite back gate (Extended Data Fig. 6), and D3 with \( \theta = 1.26^\circ \) with a metal top gate and a heavy doped Si back gate (Extended Data Fig. 7). Similar to D1, the resistive QOs and the \( D \) tunable low oscillation frequency \( (B_f < 20 \text{T}) \) are different from the BZOs. Besides, the observations in both graphite and non-graphite gate devices indicate that the resistive QOs cannot be induced by capacitive mechanism\(^{18} \) of graphite DOS at high magnetic fields.

**Calculated DOS in a toy model with inverted bands**

In the following, we will try to attribute the QOs of the insulator at \( v = -2 \) to a toy model with inverted bands, as shown in Fig. 3a. As demonstrated, the \( v = -2 \) insulators are valley polarized\(^{24} \). The potential energy difference between two valley subbands \( K \) and \( K' \) is gradually increased due to the orbital Zeeman effect and Coulomb interaction, described by the formula \( \Delta E = 2g_\mu_B B + E_c \), where \( g \), \( \mu_B \), and \( E_c \) are effective g factor, Bohr magneton, and Coulomb interaction energy, respectively. Suppose the Zeeman splitting energy is not enough to open a gap between two subbands in weak magnetic field, the two subbands will overlap as shown in Fig. 3(a), where the size of overlap almost depends on \( E_c \). In flat band case, intervalley coherent (IVC) order plays an important role and opens a hybridization gap, which has been proved in the Hartree-Fock calculation in TDBG\(^{24} \). As shown in Extended data Fig. 3, the bandwidth of the valance band gradually decreases when \( U \) increases from 40meV to 80meV, according with \( D \) from -0.6 to -1.2V/nm in experiment, suggesting effectively enhanced Coulomb interaction energy \( E_c \). Hence, we have built a phenomenological electric field tunable inverted band model up to now.

By doing quantitively analysis, we could obtain effective mass \( m^* \) and oscillating carrier density \( n \) from QOs of the insulator. Similar to the SdHOs in metals, the temperature dependence of QOs in the insulator are found following the Lifshitz–Kosevich formula: \( \Delta R = R_{xx}(T) - R_{xx}(T = 13 \text{K}) \sim kT/sinh(kT) \), where \( k = 2\pi^2 k_B m^*/(heB) \). Here, \( k_B \), \( m^* \), \( h \), and \( e \) are Boltzmann constant, effective mass, reduced Planck constant, and electron charge, respectively. The obtained \( m^* \) from QOs of the insulator varies from 0.1 to 0.15\( m_e \) (\( m_e \) is electron mass) in the oscillation region, decreasing with the increase of \( |D| \) at first and then rising rapidly after reaching the minimum value close to \( D = -1 \text{V/nm} \), as shown in Fig. 2c. In the same way, one could obtain \( m^* \) for both SdHOs and QOs of the insulator at \( D = -0.94 \text{V/nm} \) in Fig. 1f. In addition, the extracted oscillating carrier density \( n \) is shown as an orange line in Fig. 2e, via \( B_f = A\Phi_0/(2\pi)^2 = n\Phi_0/s \), where \( A \) is the enclosed area of inverted bands without hybridization\(^{11} \) and \( s = 2 \) is the spin degeneracy of valley polarized subbands.

Then, we could further calculate the Landau levels spectrum based on the inverted band hypothesis and the experimental values of gap size \( \Delta \), \( m^* \), and oscillating carrier density \( n \). Fig. 3a shows a reconstructed band structure of the moiré valence band at \( D = -0.94 \text{V/nm} \), with \( m_K = 0.15m_e \) and \( m_K' \).
\[ m_h/0.8, \Delta \sim 1.6 \text{meV}, n \sim 6.5 \times 10^{11}/\text{cm}^2. \] 

The resulted Landau levels spectrum in inverted band systems are shown in the top panel of Fig. 3b. Even though in the absence of LLs, there is a finite low energy DOS in the gap that oscillates periodically with \( 1/B \), matching well with our experimental data in the bottom panel of Fig. 3b. Moreover, the toy model establishes a close relationship between the size of the enclosed Fermi surface and \( D \), as the latter governs the size of band overlap \( \delta \mu \) (details in methods).

The resulted calculations in Fig. 3c indeed predict a change of QOs periodicity as a function of \( |D| \), in good agreement with our observation in Fig. 2a.

Discussions and outlook

While the model can well explain the data at a \( |D| \) from 0.7 to 1.1 V/nm, it fails to account for the observations at \( |D| \geq \sim 1.2 \text{V/nm} \). This discrepancy lies in the over-simplified toy model and might suggest a more complicated band structure when Coulomb interaction plays an important role. The QOs of insulators are vanishing at \( |D| \sim 1.2 \text{V/nm} \) as the carrier density in enclosed area decreases. At around \( D = -1.24 \text{V/nm} \) and \( B = 9 \text{T} \), a new insulating state develops at \( v = -3 \) (Fig. 4a) with a large \( g \) factor of \( \sim 11.5 \) (Fig. 4b), suggesting a valley polarized insulator. Prominent LLs with \( v_{LL} = 0, +1, +2 \) appear at \( v = -2 + \delta \) (electron like) while there are only \( v_{LL} = -6, -8 \) Landau levels alternately showing up at \( v = -2 - \delta \) (hole like). This asymmetry pattern suggests two subbands with different dispersions: the hole-type band becomes flatter than the electron-type band, which suppresses the development of Landau levels and induces a correlated gap at \( v = -3 \) in the hole-type band. These observations suggest an enhanced Coulomb interaction at high \( D \), in agreement with the reduced bandwidth of the valance band from \( U = 40 \) to \( 80 \text{meV} \) in Extended Data Fig. 3. This argument is further supported in the similar yet weaker QOs at \( v = 2 \) in Extended Data Fig. 5, where moiré conduction bands are flatter compared to the moiré valence bands. Also noted, the real systems might acquire phases as \( D \) changes, as shown in Extended Data Fig. 4; however, phase changes are not included in the toy model.

Lastly, we briefly discuss the other possible interpretation like the neutral Fermi surfaces existing in gaps\(^{15-17} \). The valley polarized insulator at half fillings in TDBG, together with trigonal moiré superlattice and spin unpolarized, is a possible system with frustrated magnetic interactions, and thus is a potential candidate for hosting quantum spin liquid states\(^{40, 41} \). In this exotic picture, the total resistance is the sum of bosonic charge insulator (non-oscillating) and fermionic spinon (oscillating). To testify the neutral Fermion picture, however, conventional charge transport in our work and others falls short, and experimental techniques that could distinguish the charge transport and spin transport are highly demanded. Anyway, being an electric field tunable system, TDBG is an excellent platform to study the oscillations in an insulator. The evolution of valley polarized subbands from band inversion to complete separation suggests abundant correlation-driven behaviors and emerging topological phases in field-tunable TDBG systems. While most of the QOs in the correlated insulators are captured in the phenomenological model of the inverted bands with hybridizations, more theoretical and experimental investigations are needed in the future to better understand the insulating QOs in TDBG and other moiré systems as well.
Methods

Transport measurements. The low temperature magneto-transport measurements are performed in a helium-4 cryostat (base temperature ~ 1.8K) and an Oxford dilution refrigerator (base temperature ~ 10mK). We measure the four terminal longitudinal resistance $R_{xx}$ and Hall resistance $R_{xy}$ using the lock-in amplifier SR830/LI5650 with a frequency of 10~35Hz. Excitation currents $I = 10nA$ with a large series resistance 100MΩ or excitation voltages $V = 200uV$ with a 1/1000 divider are used in our measurements.

Band structure calculations. We calculate the band structure of AB-BA stacked TDBG with a twisted angle $\theta = 1.38^\circ$ using the continuum model\textsuperscript{27, 42}. The interlayer coupling terms are set as $u_{AA} = 80meV$, $u_{AB} = 100meV$ (A, B correspond to sublattice indices) due to the relaxation effect. Electric field tunable interlayer asymmetry potential is

$$V = \begin{pmatrix}
\frac{3}{2}U \hat{1} & 0 & 0 & 0 \\
0 & \frac{1}{2}U \hat{1} & 0 & 0 \\
0 & 0 & -\frac{1}{2}U \hat{1} & 0 \\
0 & 0 & 0 & -\frac{3}{2}U \hat{1}
\end{pmatrix},$$

where $U$ is the interlayer potential energy difference.

Inverted band model. We calculate the inverted band structure using a toy model in Ref. 11\textsuperscript{31}. The Hamiltonian is

$$\begin{pmatrix}
\frac{\hbar^2 k^2}{2m_k} - \mu_k & V \vec{k} \cdot \vec{\sigma} \\
V \vec{k} \cdot \vec{\sigma} & -\frac{\hbar^2 k^2}{2m_{k'}} - \mu_{k'}
\end{pmatrix},$$

where $m_k = 0.15m_e$ and $m_{k'} = m_k/\alpha$ are effective mass of K and K' valley subbands, respectively. $\alpha = 0.8$ corresponds to the heavier hole-like subband in our model. $\delta\mu = \mu_K - \mu_{K'} = k(D + D_b)$, determined by the electric displacement field $D$, shows the size of overlap of two bands. Here $k \approx 58.386$, $D_b \approx 1.26$ are extracted from experimental results. $V$ corresponds to the size of hybridization gap. $\sigma = (\sigma_x, \sigma_y)$ are Pauli matrices. Landau levels spectrums and density of states are calculated with the formula in Ref. 11. We ignore the dynamic change of band overlap with the increase of $B$ in our toy model because of the small Zeeman split energy relative to the large size of band overlap, which is reasonable in optimal oscillation region of $D$ from -0.7 to -1.1 V/nm.

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Author contributions

W.Y. and G.Z. supervised the project; W.Y., L.L. designed the experiments; L.L., Y.C. fabricated the devices and performed the magneto-transport measurement with assistance from G.Y; L.L. calculated the band structure and Landau level DOS; K.W. and T.T. provided hexagonal boron nitride crystals; W.Y., L.L., and G.Z. analyzed and interpreted the data; W.Y. and L.L. wrote the paper with the input from all the authors.

Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is provided online.

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Fig. 1 | Quantum oscillations of \( v = -2 \) insulators. a, Landau fan diagram at \( D = -0.94 \text{V/nm} \) and \( T = 1.8 \text{K} \). b, Line cuts at \( v = -2 \) shown in a. c, \( R_{xx} \) versus \( 1/B \) at \( v = -2 \). Inset, oscillation index versus \( 1/B \). Blue triangles correspond to the position of oscillation peak and valley. The Orange line corresponds to the linear fitting. d, Landau fan diagram at \( D = -0.94 \text{V/nm} \) and \( T = 13 \text{K} \). e, First order derivative of \( R_{xx}(T) \) as a function of \( B_{\perp} \) and \( T \) at \( v = -2 \). f, Effective mass of SdHO and quantum oscillations of insulators shown in a.
Fig. 2 | Electric field tunable quantum oscillations. a, $R_{xx}$ as a function of $D$ and $B_{\perp}$ at $\nu = -2$ and $T = 100\text{mK}$. b, Fast Fourier transform (FFT) of a. Amplitude is magnified 25 times in a range of $D = 0$ to $-0.6\text{V/nm}$. The orange dash line is a linear fitting along the amplitude peak. c, Dual gate mapping at $B_{\perp} = 3\text{T}$ and $T = 30\text{mK}$. The yellow line is a line cut along $\nu = -2$. d, $\Delta R$ versus $1/B$ at different temperature. Inset, L-K fitting of the oscillation amplitude. e, Effective mass and carrier density versus $D$ at $\nu = -2$. Error bars of effective mass are estimated from the least square method. The orange shadow corresponds to the uncertainty of carrier density calculated from FFT results.
Fig. 3 | **Oscillation in hybridization gaps of inverted band systems.** a, Hybridized inverted Band calculated by a toy model. The orange (blue) line corresponds to the energy band in valley K(K’). b, Top, calculated Landau levels spectrum with 1/B. Bottom, calculated low energy DOS in gap (black line) and measured $\sigma_{xx}$ at $v = -2$ and $D = -0.94$V/nm (red line). c, Calculated DOS spectrum as a function of $D$ and $B_\perp$.

Fig. 4 | **$v = -3$ valley polarized insulators in the strong correlation region.** a, $R_{xx}$ as a function of $v$ and $D$ at $B_\perp = 9$T and $T = 1.8$K. $D^\ast$ corresponds to the electric displacement field in which the $v = -3$ correlated insulator shows up. b, Top, $R_{xx}$ as a function of $v$ and $B_\perp$ at $D = -1.24$V/nm. Bottom, thermal activation gaps versus $B_\perp$. $g \approx 11.49$ is extracted from linear fitting. c, Landau fan diagram at $D = -1.24$V/nm.
Extended Data Figure

Extended Data Fig. 1 | Wannier diagram at \( D = -0.94 \text{V/nm}. \) The red arrow corresponds to Brown-Zak oscillation. The black arrow corresponds to quantum oscillations of insulators. Right figure, line cuts of the two types of oscillations shown in left figure.

Extended Data Fig. 2 | Landau fan diagram at different \( D. \) a, c, g, \( R_{xx} \) as a function of \( v \) and \( B_{\perp} \) at \( D = 0, -0.47 \) and \(-0.94 \text{V/nm}. \) b, d, h, Schematics Landau levels shown in a. (C, \( v \)) = (10, 4/5), (1, 7/2) at \( D = -0.47 \text{V/nm} \) are possible charge density wave states. (2, 2) at \( D = -0.94 \text{V/nm} \) is the Chern insulator. e, f, Enlarged view of \( R_{xx} \) and \( R_{xy} \) at \( D = -0.47 \text{ V/nm}. \) Blue lines correspond to (10, 4/5), (1, 3) and (1, 7/2) states.
Extended Data Fig. 3 | Calculated band structures and density of states. **a**, Band structures at different interlayer potential energy with a twisted angle $\theta = 1.38^\circ$. Red (blue) region corresponds to the first moiré conduction (valance) band. **b**, Bandwidth of first moiré valance and conduction bands versus U. **c**, Density of states of the first moiré valance band at different U.

Extended Data Fig. 4 | Berry phase extracted from quantum oscillations index at $v = -2$. We calculated berry phase by fitting different numbers of oscillation peak and valley due to $D$ dependence of numbers of index. There are at least four indices in the whole range of $D$. 
Extended Data Fig. 5 | Quantum oscillations at $v = 2$. a, $R_{xx}$ as a function of $D$ and $\Phi/\Phi_0$ at $v = 2$. b, Line cuts at $D = 0.88\text{V/nm}$ shown in a. c, $\Delta R_{xx}$ versus $1/B$. Here the smooth polynomial background is subtracted. Inset, oscillation index versus $1/B$.

Extended Data Fig. 6 | Quantum oscillations of $v = -2$ insulators in device D2. a, $R_{xx}$ as a function of $D$ and $B_\perp$ at $v = -2$ and $T = 100\text{mK}$. b, Fast Fourier transform (FFT) of a. Amplitude is magnified 10 times in a range of $D = 0$ to $-0.6\text{V/nm}$. c, Magnified figure of b. Black and red lines correspond to the linear fitting of the first and second order FFT peaks of quantum oscillations, respectively. d, Line cuts at $D = -0.66\text{V/nm}$ shown in a. e, $\Delta R_{xx}$ versus $1/B$ at different temperature. Here $\Delta R = R(T) - R(T = 8\text{K})$. Inset, L-K fitting of the oscillation amplitude. f, Carrier density versus $D$ at $v = -2$. The orange shadow corresponds to the uncertainty of carrier density calculated from FFT results.
Extended Data Fig. 7 | Quantum oscillations of ν = -2 insulators in device D3. a, \( R_{xx} \) as a function of \( D \) and \( B_\perp \) at \( ν = -2 \) and \( T = 1.8\)K. b, Line cuts at \( D = -0.71\)V/nm shown in a. c, \( \Delta R_{xx} \) versus \( 1/B \) at different temperature. Here \( \Delta R = R(T) - R(T = 7\)K). Inset, L-K fitting of the oscillation amplitude.