Realization of the Haldane Chern Insulator in a Moiré Lattice

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Primary CNF Tools Used: Zeiss Supra SEM, Nabity Nanometer Pattern Generator System (NPGS), SC4500 Odd/Even-Hour Evaporator, Autostep i-line Stepper, Hamatech Wafer Processor Develop, Heidelberg Mask Writer - DWL2000, Photolithography Spinners, Dicing Saw - DISCO

Abstract:

The Chern insulator displays a quantized Hall effect without Landau levels. Theoretically, this state can be realized by engineering complex next-nearest-neighbor hopping in a honeycomb lattice — the so-called Haldane model [1]. We realize a Haldane Chern insulator in AB-stacked $MoTe_2/WSe_2$ moiré bilayers, which form a honeycomb moiré lattice with two sublattices residing in different layers [2]. We show that the moiré bilayer filled with two holes per unit cell is a quantum spin Hall insulator with a tunable charge gap. Under a small out-of-plane magnetic field, it becomes a Chern insulator with a finite Chern number because the Zeeman field splits the quantum spin Hall insulator into two halves of opposite valley — one with a positive and the other a negative moiré band gap. We also demonstrate experimental evidence of the Haldane model at zero external magnetic field by proximity coupling the moiré bilayer to a ferromagnetic insulator.

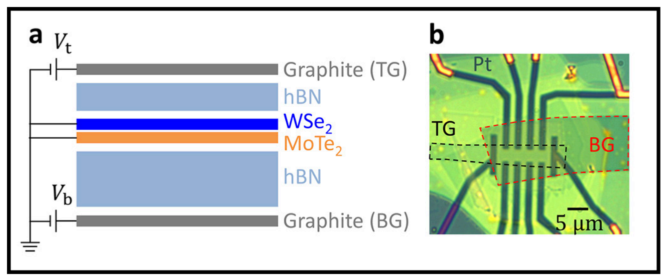


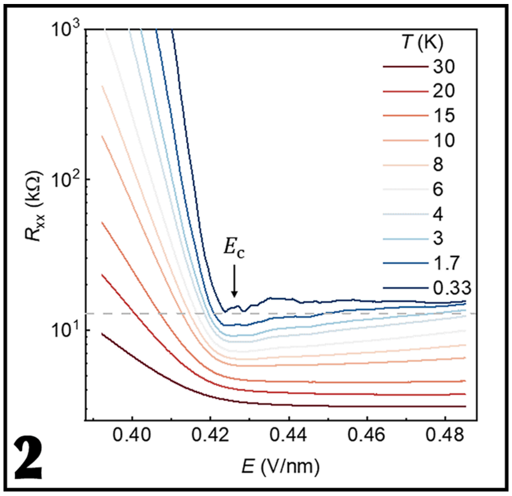
Figure 1: a, Device schematics. b, Optical microscope image of a dual-gated device. The scale bar is 5 μm.

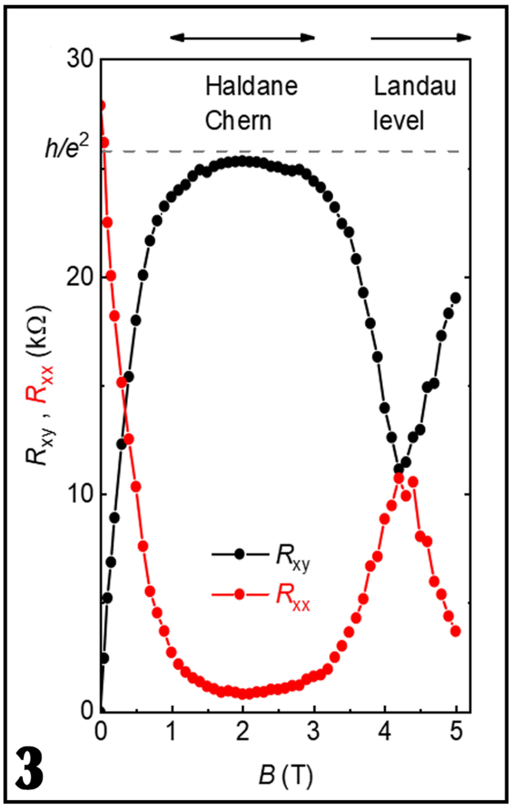
Summary of Research:

When a two-dimensional electron gas is exposed to high magnetic fields, it forms Landau levels, and quantized Hall conductance is observed [3]. Researchers aim to achieve a quantum Hall state without external magnetic fields, known as a Chern insulator [1]. These insulators have been realized in a few materials, such as magnetic topological insulators and moiré materials. A proposed method involves transforming a quantum spin Hall (QSH) insulator into a Chern insulator through magnetic interactions [4].

In this study, we use AB-stacked $MoTe_2/WSe_2$ moiré bilayer, which is a new QSH insulator with a tunable charge gap and unique spin-valley-layer locking. By applying an out-of-plane magnetic field or proximity coupling to a ferromagnetic insulator, the material transitions into a Chern insulator. This transformation is facilitated by valley-dependent magnetic interactions and Zeeman energies. We demonstrated that an out-of-plane magnetic field of about 1 Tesla or proximity coupling can induce this transition. We investigated the transport properties of these bilayers, showing the emergence of a nearly quantized Hall resistance for the Chern insulator state at specific electric and magnetic field conditions. The results support the realization of a Haldane Chern insulator and suggest a new method for creating Chern insulators through tunable band inversion and magnetic proximity effects.

Figure 1 shows the schematic and optical image of a device. We fabricated dual-gated $MoTe_2/WSe_2$ devices using a layer-by-layer dry-transfer technique. We deposited 5-nm Pt contacts on hBN by standard electron-beam lithography and evaporation, followed by another step of electron-beam lithography and metallization to form a bilayer of 5-nm Ti and 40-nm Au to connect the thin Pt contacts on hBN to pre-patterned electrodes.





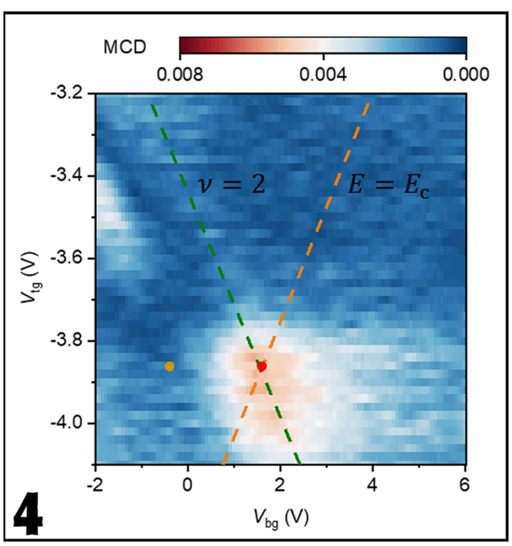


Figure 2 shows the electric-field dependence of R_{xx} at $v = 2$ and temperature $T = 0.33$-30 K. The resistance shows a minimum near E_c and distinct behaviors on two sides of E_c. Below E_c, R_{xx} decreases as E approaches E_c; and at a fixed field, R_{xx} diverges as T decreases. This is a typical response of an insulator with a diminishing band gap towards E_c. Above E_c, R_{xx} plateaus, and the value saturates around 15 kΩ ≈ 1.16 $h/2e^2$ at 0.33 K. The nearly quantized R_{xx} plateau suggests the emergence of a QSH insulator for $E > E_c$, where E_c corresponds to the quantum critical point for band inversion.

Figure 3 is the magnetic-field dependence of R_{xy} and R_{xx} to show this transition from the QSH insulator to the Haldane Chern insulator. The Hall resistance increases sharply from 0 at $B = 0$ T, plateaus between 1 T and 3 T, and displays non-monotonic field dependence for $B >$ 3 T. The plateau value (≈ 25.4 kΩ) is within 2% of the quantized Hall resistance, h/e^2. Concurrently, R_{xx} drops sharply with increasing field and remains small (< 1 kΩ) between 1 T and 3 T. Hence, when we set E near the band inversion critical point, a moderate magnetic field between 1 T and 3 T is sufficient to induce the Chern state.

Figure 4 shows the gate voltage dependence of the spontaneous magnetic circular dichroism (MCD) of a $CrBr_3$-$MoTe_2$/WSe_2 device, where the $CrBr_3$ is a ferromagnetic insulator. The observed MCD hot spot demonstrates spontaneous time reversal symmetry breaking near the band inversion critical point. This is consistent with the emergence of an exchange field from the magnetic proximity effect at the $CrBr_3$-$MoTe_2$/WSe_2 interface. Similar to the external magnetic field, the proximity exchange field splits the QSH insulator near band inversion to the Haldane model.

Conclusion and Future Steps:

We have realized a Haldane Chern insulator in AB-stacked $MoTe_2$/WSe_2 moiré bilayers. Our study presents a generic route to realizing Chern insulators through tunable band inversion and magnetic proximity coupling. The demonstrated large exchange field has the potential to stabilize a large-gap Chern insulator. Future transport studies with improved electrical contacts are required to further establish the Haldane physics under zero magnetic field.

References:

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[2] Li, T., et al. Nature 600, 641-646 (2021).

[3] Klitzing, K. V., Dorda, G., and Pepper, M. Phys. Rev. Lett. 45, 494-497 (1980).

[4] Liu, C., et al. Quantum Wells. 101, 146802 (2008).

Figure 2, top: Electric-field dependence of R_{xx} *at* $v = 2$ *at different temperatures. Figure 3, middle: Magnetic-field dependence of* R_{xx} *and* R_{xy} *at* $v = 2$ *and* $E = E_c$*. The lines are guides to the eye. The Hall resistance is nearly quantized at* h/e^2 *(dashed line) between 1 T and 3 T. It is divided into the low-field (Haldane Chern) and high-field (Landau level) regimes. Figure 4, bottom: Spontaneous MCD of the* $CrBr_3$*-*$MoTe_2$*/*WSe_2 *device as a function of the top and bottom gate voltages. The dashed lines denote constant filling factor* $v = 2$ *(green lines) and constant electric field* $E = E_c$ *(orange lines).*