Quantum Hall Effect in a CVD-Grown Oxide

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Abstract

Two-dimensional electron systems (2DES) are promising for investigating correlated quantum phenomena. In particular, 2D oxides provide a platform that can host various quantum phases such as quantized Hall effect, superconductivity, or magnetism. The realization of such quantum phases in 2D oxides heavily relies on dedicated heterostructure growths. Here we show the integer quantum Hall effect achieved in chemical vapor deposition grown Bi_2O_2Se - a representative member of a more accessible oxide family. A single or few sub-band 2DES can be prepared in thin films of Bi_2O_2Se, where the film thickness acts as the sole design parameter and the sub-band occupation is determined by the electric field effect. This new oxide platform exhibits characteristic advantages in structural flexibility due to its layered nature, making it suitable for scalable growth. The unique small mass distinguishes Bi_2O_2Se from other high-mobility oxides, providing a new platform for exploring quantum Hall physics in 2D oxides.

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The Quantum Hall effect (QHE), known for its quantized Hall conductance in the units of $\frac{e^2}{h}$, is a fascinating quantum phenomenon that has been actively explored in two-dimensional electron gases (2DEG) and beyond[1,2]. Achieving this macroscopic quantum state typically begins with a meticulous preparation of 2DEG systems pursuing high enough carrier mobility to ensure Landau quantization and sufficiently large potential fluctuations to localize the conduction within the channel width. In traditional semiconductors like Si and GaAs[3], this is often realized by preparing artificial structures like two-dimensional (2D) quantum wells using advanced thin-film technologies, an approach that allows precise control of defects and doping concentrations.

In more recent years, oxides have emerged as an alternative platform capable of realizing both integer and fractional quantum Hall effects[4–7]. Being chemically robust, oxides are promising candidates for constructing stable heterostructures. Physically, 2DEGs based on oxides further introduce interesting possibilities where mobile carriers can be chosen from bands composed mainly of s- and p-orbitals, such as in ZnO, or from d-orbitals as in SrTiO$_3$. Therefore, transport properties benefit from high mobility[8], leading to quantum Hall states, as well as electron correlation effects[7,8]. This facilitates interaction-driven quantum phenomena like magnetism and superconductivity, which can seamlessly interface with the QHE[9,10]. Despite the structural stability and flexibility in hosting various quantum phases in oxide 2DEGs, in comparison to traditional semiconductors, achieving the quantum Hall effect in oxides is constrained by intrinsic factors. Notably, the effective carrier mass of typical oxide 2DEGs is considerably larger, typically falling in the range of 0.3 ~ 1 m_0, where m_0 is the free electron mass. For example, when searching for quantum Hall effects in the extensively studied interfaces and heterostructures of SrTiO$_3$, the relevant carrier density covers sub-bands coming from the anisotropic Ti, $3d_{xy}$ and $3d_{yz}/3d_{xz}$ orbitals, having masses of ~0.7 and 10 m_0, respectively[11]. Consequently, despite achieving ultrahigh quality—where the mobility of thin film SrTiO$_3$[8,7] surpasses that of bulk single crystals—quantizing edge states remains a challenge due to the heavy electrons.

The recently discovered Bi$_2$O$_2$Se offers the potential to provide an easy solution to the challenges of quantized transport in oxides. Bi$_2$O$_2$Se is a bismuth-based oxychalcogenide, which is synthesized by widely accessible and scalable chemical vapor deposition (CVD)[12–14]. Bi$_2$O$_2$Se single crystals are constructed by sharing a Se layer between two Bi-O layers (see Fig. 1a), lacking a distinct Van der Waals (VdW) gap. Although not cleavable as 2D materials, physically, Bi$_2$O$_2$Se is a layered semiconductor with an indirect bandgap of ~ 0.8 eV and the transition is from X to Γ points of the Brillouin zone. The highly dispersive parabolic Γ pocket of the conduction band originates mainly from the p-orbitals of Bi, leading to a low effective mass of $m^* = 0.14\ m_0$[15]. As carriers mainly navigate within the Bi-O layer in the crystal structure, the electrical transport is effectively encapsulated by the Se layer, essentially forming a buried interface. Consequently, Bi$_2$O$_2$Se is insensitive to reactions in ambient conditions and adsorptions as contaminants. This stands in sharp contrast to other prominent systems

based on 2D materials, such as black phosphorous[16], where encapsulation as heterostructures is essential to either protect air-unstable materials from reactions or isolate the sensitive surface from contaminations. Moreover, in contrast to conventional semiconductors and oxides, the structural flexibility inherent in layered compounds offers distinct advantages. The layered structure facilitates the incorporation of oxide layers with diverse properties[17], thereby enabling the introduction of additional quantum states, such as superconductivity[18]. Our demonstration of the quantum Hall effect (QHE) in Bi_2O_2Se showcases the potential of this oxide system for readily accessing the quantum Hall state. This opens avenues for further exploration of quantum transport and the development of devices on a resilient oxide platform capable of hosting various quantum phases.

In this paper, we demonstrate that the integer quantum Hall effect can be achieved in CVD-grown Bi_2O_2Se samples of 6 to 30 nm in thickness. In contrast to the layered quasi-2D systems in bulk form, such as transition metal dichalcogenides (TMDs)[19], the Fermi surface of bulk Bi_2O_2Se is a 3D ellipsoid[20]. Although the highest mobility has reached $\sim 10^4 - 10^5$ cm^2 V^{-1}s^{-1} [20–22] and carrier concentrations as low as $10^{18} - 10^{19}$ cm^{-3} in bulk single crystals, the QHE in 2D Bi_2O_2Se has remained elusive. In our study, we demonstrate that by introducing quantum confinement to form a 2DEG, the QHE is readily observed in samples with one or two orders lower mobility (~1000 cm^2 V^{-1}s^{-1}), making Bi_2O_2Se an excellent candidate for oxide quantum electronics.

Shubnikov-de Haas oscillation in Bi₂O₂Se field-effect transistors

The Bi_2O_2Se crystal, as shown in Fig. 1a, has unit cells in a so-called 2D zipper structure[20,23], where the chalcogen plane is shared between two neighboring covalently-bonded bismuth-oxide layers. Isolating Bi-O layers randomly unzip the single Se layer between two newly formed surfaces[20,23]. Once cleaved, the half-covering Se top layer is reconstructed, forming high-density defects. Therefore, we study the as-grown Bi_2O_2Se crystals directly from CVD synthesis. Fig. 1b shows our typical field-effect transistor (FET) device, gated by 300 nm thick SiO_2 as the gate dielectric. The thickness of each Bi_2O_2Se channel was extracted from atomic force microscopy (AFM) imaging preceding the device fabrication (Extended Data Fig.1).

All as-grown flakes measured are intrinsically conducting at room temperature. For flakes thicker than ~30 nm, finite bulk conductivity persists down to 4.2 K (Fig. 1c). The subsequently measured transfer characteristics of flakes show distinct thickness dependences. The thick flakes (32 and 60 nm) are intrinsically metallic, where the high conductivities ($\sigma_s \approx 1$ and 0.01 S at 4.2 K, respectively) show no or little response to field-effect gating. When a magnetic field B is applied to thick flakes with high conductivity (*e.g.* the 32 nm sample), the magnetoresistance (MR) varies, with conventional metallic behavior, as $\sim B^2$ (Fig. 1d). The electron concentrations of the different samples determined from the slope of the Hall resistance (Fig. 1e) are in the range of $10^{19} \sim 10^{20}$ cm^{-3}, consistent with typical values expected for a degenerately doped semiconductor.

On the other hand, the conductivity of thinner samples is significantly reduced (inset of Fig. 1c) and becomes vanishingly small below V_{th}, the threshold voltage. The overall Hall response increases with the decrease in thickness (Fig. 1e) indicating lower carrier densities induced in thinner samples. Nevertheless, metallic states, having σ_s higher than $\frac{2e^2}{h}$, can be quickly switched on at $V_G > V_{th}$. The gradual decrease of the ON state conductivity upon thinning down (Fig. 1c) is accompanied by a vanishing $\sim B^2$ behavior in the MR (Fig. 1d). Meanwhile, on top of a slowly varying MR background, we observe prominent Shubnikov-de Haas (SdH) oscillations in all measured samples (Fig. 1d and Extended Data Fig. 2). As a finer detail, rich beating patterns, notable in thick samples (*e.g.* 60, 32, and 26 nm), gradually disappears in thinner samples. The variation of oscillation frequency based on thickness can be captured by comparing the fast Fourier transform (FFT) spectra of the SdH signal as a function of $\frac{1}{B}$. Illustrated in Fig. 1f, a wide spectrum, containing frequency components spanning from 100 to 300 T, undergoes characteristic changes with decreasing thickness. Physically, the SdH frequency B_F is directly linked to the area enclosed by the electron orbits on the Fermi surface $\mathcal{A}_k(E_F)$ described by the semiclassical relation, $B_F = \frac{\hbar}{2\pi e}\mathcal{A}_k(E_F)$, where $\hbar$ is the reduced Plank's constant, and e is the elementary charge. The presence of multiple frequencies is therefore attributed to distinct electronic pockets $\alpha_{1,2,\cdots,i}$. The SdH oscillation patterns, stretching to higher frequencies with the increase of thickness, can be categorized into three main groups. Beginning with the simplest single distinct component α_1 in samples thinner than 12 nm (Fig. 1f), it progresses to the intermediate thickness range of 26 and 19 nm, exhibiting two components α_1 and α_2, and further extends to three or more oscillation frequencies in thick samples (32 and 60 nm).

Despite its layered crystal stacking, bulk Bi$_2$O$_2$Se still has a typical 3D Fermi surface with significant dispersion along $\Gamma - Z$ direction of the Brillouin zone (BZ)[15]. Using the generic relation, $m_z^* = \hbar^2 \left(\frac{d^2E}{dk_z^2}\right)^{-1}$, at the bottom of the conduction band, the effective mass out of B-O plane (k_z along $\Gamma - Z$) yields $m_z^* = 0.34\,m_0$ [20,24]. The substantial k_z dispersion sets the Bi$_2$O$_2$Se apart from conventional VdW semiconductors, where the k_z dispersion is much weaker. As typical m_z^* values can well exceed m_0 in conventional VdW materials, a pronounced layer degree of freedom with intrinsic quasi-2D electronic states can already appear in the bulk. In contrast, a 2D state in Bi$_2$O$_2$Se has to be built by quantizing the dispersion along k_z direction.

At 4.2 K, we estimate the thermal de Broglie wavelength $\lambda_D = \sqrt{\frac{2\pi\hbar^2}{m_\perp^* k_B T}}$ of the conduction electrons to be 62.4 nm. Since the electrons in Bi$_2$O$_2$Se are highly delocalized, the extended wavefunction in the out-of-plane direction renders the dispersion of electrons susceptible to the sample thickness. In the case of electron motion along the *z*-direction restricted by the crystal boundaries, the energy spectrum becomes quasi-continuous, $E = E_i + \frac{\hbar^2 k_\parallel^2}{2m_\parallel^*}$, where $k_\parallel$ is an in-plane wavevector. The E_i

quantizes as $E_{1,2...i}$, where the energy separation $\Delta E_{i,i+1} = E_{i+1} - E_i$ is determined by the specific shape of the confining potential [1,3]. Using the simplest well-type potential, the energy spacing reduces to $\Delta E_{i,i+1} = \left(\frac{\hbar^2 \pi^2}{2m_{\perp}^*}\right)\frac{2i+1}{d^2}$, where d is the quantum-well width (Fig. 1g). In Bi$_2$O$_2$Se flakes thinner than the characteristic length λ_D, quantization leads to the formation of concentrically arranged 2D sub-bands. We label the energy at the bottom of each sub-band as E_i, as illustrated in the simplified sub-band structure in Fig. 1g.

Quantum Hall effect in a two-dimensional electron gas

Based on the quantization scheme discussed above, the critical prerequisite for realizing the QHE is to form a 2DEG with sufficiently large sub-band separation. Therefore, we choose the sample thickness as the only device parameter and focus on thin samples below ~15 nm. In these thicknesses, where the estimated 2D sub-band separation can well exceed the thermal broadening ($\Delta E_{i,i+1} \gg k_B T$ at 4.2 K), we can then use the gate voltage V_G to adjust the Fermi level near the bottom of conduction band and selectively occupy the lowest sub-band ($i = 1$) of the 2DEG[1].

Applying a strong magnetic field perpendicular to this 2DEG can further quantize the energy spectrum as

$$E = E_1 + \left(l + \frac{1}{2}\right)\frac{\hbar eB}{m_{\parallel}^*} + m_s g^* \boldsymbol{\mu_B} \cdot \boldsymbol{B}, \qquad (1)$$

where $l = 0, 1, 2, \cdots$ is the Landau level (LL) index, $m_s = \pm\frac{1}{2}$ is the spin quantum number, g^* the Landé factor (see also Supplementary Note 1 and 6), and μ_B the Bohr magneton. Fig. 2a shows a set of MRs measured at 1.34 K up to 35 T for various electron concentrations in an 11 nm sample. When B is higher than ~25 T and carrier concentrations n_{2D} is tuned $< 3.8\times10^{12}$ cm^{-2}, the SdH oscillation develop into a QHE with a small residual ρ_{xx} and a well-quantized plateaus in ρ_{xy} at even integer fractions of $R_K = \frac{h}{\nu e^2}$, where $\nu = 2, 4, 6\cdots$, are the filling factors corresponding to the lowest filled LL of the bottommost E_1 sub-band (Fig. 2b). Contributions from the next sub-band, E_2, becomes increasingly noticeable in the SdH oscillations at $n_{2D} > 5.02\times10^{12}$ cm^{-2}, where multicomponent oscillations initiate at $B > 15$ T (see Supplementary Note 3).

We proceed with further characterization of our device by extracting crucial parameters that enable QHE. Fig. 2c shows the n_{2D} and mobility μ_H, extracted from Hall effect measurements (see Supplementary Note 2). Here, the electron concentration follows a linear dependence with gate voltage over a wide range of V_G as $\Delta n_{2D} = \frac{\varepsilon_0 \varepsilon_r}{e d_{ox}}\Delta V_G$, where ε_0 is the permittivity of a vacuum. The SiO$_2$ gate capacitor used in our device has a thickness $d_{ox} = 300$ nm and a dielectric constant $\varepsilon_r = 3.87$. For the thin Bi$_2$O$_2$Se device μ_H peaks around ~2200 cm^{2}V^{-1}s^{-1} at $n_{2D} \approx 3.5\times10^{12}$ cm^{-2} and saturates at higher

concentrations. The μ_H then drops rapidly toward a percolation limit below the critical density n_c[25] (see Supplementary Note 2).

The amplitude of the primary SdH oscillations α_1 exhibits a pronounced temperature dependence (Extended Data Fig.3), which can be described by the Lifshitz-Kosevich equation $R_T = \frac{\lambda T}{\sinh(\lambda T)}$. By using $\lambda = \frac{2\pi^2 k_B}{e\hbar B} m_c$, we can extract the cyclotron mass, m_c. Two distinct electronic states with $n_{2D} = 6.94$ and 1.62×10^{12} cm^{-2} display different rates of amplitude decay as a function of T (Extended Data Fig.4), yielding $m_c \approx 0.27$ and $0.13m_0$, respectively. Cyclotron masses m_c extracted at different carrier concentrations n_{2D} (Fig. 2e), demonstrate an overall tendency to decrease towards the band edge. Notably, the smallest $m_c = 0.13m_0$ obtained from the SdH is in good agreement with the reported values of m^*, measured at the band edge of Bi$_2$O$_2$Se crystals[20,23,24].

Sub-band splitting in a confined electron system

We further investigate the 2D sub-bands in all other flakes thinner than 15 nm, by analyzing the dependence of the primary SdH oscillation frequency B_F as a function of n_{2D}. The relationship between B_F and V_G for different thicknesses is established from standard fan diagrams. The frequency of oscillation in resistivity is a function of the density of carriers n_{SdH} as $B_F = \frac{\phi_0 n_{SdH}}{g_s \Delta_i}$, where ϕ_0 is the magnetic flux quantum, and $g_s \Delta_i$ are spin and sub-band degeneracies. As shown in Fig. 3a, n_{2D} and B_F/ϕ_0 follow a linear relationship, with $g_s \Delta_i = 2$ up to a characteristic carrier density n_0, determined individually for each given thickness. The $g_s \Delta_i = 2$ factor originates from the single spin-degenerate sub-band Δ_1 situated at the Γ point of the first BZ[15]. The factor also aligns well with the even integer fractions observed from the Hall plateaus (Fig. 2b). With the increase in n_{2D}, an abrupt change of linear dependence between n_{2D} and B_F/ϕ_0 is universally observed when $n_{2D} > n_0$, for each given thickness. For example, in the 11 nm sample, the slope is nearly doubled at $n_{2D} > n_0 \sim 3.5\times10^{12}$ cm^{-2}. This abrupt change is caused by a doubling of the sub-band index, $\Delta_i = 1 \rightarrow 2$, in the density of states $D(E) = g_s \Delta_i \frac{m_\parallel^*}{2\pi\hbar^2}$ when the Fermi level enters the higher sub-band E_2.

Considering the first two sub-bands of a quantum well with an infinite potential wall, the energy separation is given by $\Delta E_{1,2} = \frac{3\hbar^2\pi^2}{2m_\perp^*} \frac{1}{d^2}$. To raise E_F from E_1 to E_2, we can calculate the required additional carriers as $n_e = D(E)(E_2 - E_1) = \frac{3}{2}\left(\frac{m_\parallel^*}{m_\perp^*}\right)\frac{1}{d^2}$, which is proportional to a mass anisotropy ratio $\sim \frac{m_\parallel^*}{m_\perp^*}$, and inversely proportional to sample thickness $\sim \frac{1}{d^2}$. We find that the thickness dependence of the onset carrier density n_0 can be well described by the quantum well model (Fig. 3b), with $m_\parallel^*/m_\perp^* = 0.24/0.3$. It is worth noting that, although the free-electron analysis (Fig. 3c) does not consider the sophisticated shape of the quantum well caused by the interplay between sample thickness and electric

confinement potential, this straightforward model can already be used as a guide to select a proper d value as the sole design parameter for CVD-based Bi_2O_2Se when applying it to QHE devices.

Landau level structure at high magnetic field

We now turn to the high field regime, where the Landau levels can be well resolved. By simultaneous measuring ρ_{xx} and ρ_{xy} as a function of V_G (Fig. 4a) at a field of 30 T, pronounced QHE plateaus are observed at $\rho_{xy} = \frac{h}{ve^2}$, where the integer filling factor v undergoes successive changes by multiples of 2 each time the Fermi level crosses a Landau Level (LL). The plateaus in ρ_{xy} are accompanied by equidistantly spaced minima in ρ_{xx} with a separation of ΔV_G ~21 V, this spacing further supports the notion that $g_s\Delta_i = 2$. Considering additional n_{2D} accumulated by ΔV_G (Fig. 4a), we can calculate the filling required to occupy individual LL as $(\alpha\Delta V_G) = g_s\Delta_i B/\phi_0$, when we choose $\alpha = 7.13\times10^{12}$ cm^{-2} and $g_s\Delta_i = 2$.

The sequential filling of Landau levels significantly changes at $V_G \geq 70$ V, where n_{2D} starts to exceed n_0 for the 11 nm thick sample. The inset of Fig. 4a shows this change in the filling pattern in σ_{xy} at different magnetic fields. For the sequence of $\sigma_{xy} = N\left(\frac{2e^2}{h}\right)$, where N is the total number of LLs crossed, the filling alters at 15 and 22.5 T when the sub-band degeneracy incriminator increases from $\Delta_i = 1 \rightarrow 2$. Namely, the interval doubles at $N = 5$ from 1, 2, 3, 4, 5 to 7, 9, 11 (See also Extended Data Fig.5 and 6). This doubling of LL degeneracy disappears at larger cyclotron energy $\hbar\omega_c$ (30 T), where the filling reverts to the 1, 2, 3, 4, 5 sequence. The change in the filling pattern can be explained by the reconstructed sub-band alignment between E_1 and E_2 as shown in Fig. 4b or from the reconstructed Landau fan diagram (see Supplementary Note 5). Here, at $B = 15$ T, the energy separation is $\Delta E_{1,2} \approx 4.8\ \hbar\omega_c$, therefore, the zeroth LL of the second sub-band $l_2 = 0$ is closely aligned in energy with the fifth LL of the first sub-band $l_1 = 5$. Whereas, at $B = 30$ T, the $\Delta E_{1,2}$ becomes $\approx 2.4\ \hbar\omega_c$, hence, the $l_2 = 0$ LL aligns in between $l_1 = 2$ and 3 (Extended Data Fig.7). The additional carrier required to reach E_2 can be estimated as $n_e = 2.4\frac{eB}{\pi\hbar} = 3.48\times10^{12}$ cm^{-2} (Supplementary Note 5), which is closely agrees with the n_0 obtained from Fig. 3b.

Conclusions

In summary, we have successfully demonstrated the QHE in the one or two-subband 2DEG of a CVD–grown oxide – Bi_2O_2Se. Despite its inherent 3D electronic structure, we found that samples thinner than the λ_D can function as field-effect transistors. The gated Bi_2O_2Se conforms to a simple quantum well model based on the free electron approximation, with the layer thickness serving as the sole device design parameter. Due to its inherently small effective mass compared to typical high-mobility oxides, the QHE effect in Bi_2O_2Se can be observed even in samples with very low mobilities, offering significant flexibility for utilizing the quantum Hall effect in oxide materials. The flexible

layered structure of this new oxide family and its unique small mass makes it a promising platform for exploring the versatile quantum Hall effect in oxide materials.

Methods

Crystal growth

Single crystals of Bi_2O_2Se were grown using conventional chemical vapor deposition (CVD) on *f*-mica substrates. Two powder-based precursors, Bi_2O_3 and Bi_2Se_3, were vaporized at high temperatures in a multizone tube furnace and carried by an Ar flow in a quartz tube downstream to the mica substrates, which were held at lower temperatures. The growth process was conducted in an under-pressure environment of ~400 Torr. The high temperatures used to evaporate sources were raised to 620 °C at a rate of 25 K/min. The isotherm for CVD growth was held for 40 minutes. The growth is terminated by a natural cooling[12].

Device fabrication

Single crystals of Bi_2O_2Se with uniform morphology ranging from 6 to 60 nm in thickness were carefully chosen for device fabrication. Square-shaped flakes, having 20-40 μm in lateral size, were selected and transferred using a polybisphenol carbonate (PC) adhesive layer, which can be dissolved in chloroform within 20 minutes. The AFM topography of transferred samples on SiO_2/Si^{++} substrates is shown in Extended Data Fig.1. All AFM scans were conducted right after the PC-assisted transfer from the mica. We used conventional e-beam lithography to fabricate the Hall-bar devices. As shown in the inset of each AFM micrograph, the contacts to the devices consist of Pt/Au electrodes, with a thickness of 5/35 nm.

Transport measurements

The low-temperature electrical transport was measured in a He-4 cryostat. We use standard lock-in amplifiers (SR-860) to probe the transport in a four-probe configuration. The carrier concentration of the Hall-bar device is tuned by gating through a 300 nm dielectric layer of thermally grown SiO_2. A Keithley 2611B source meter was used to apply the DC gate bias.

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Fig. 1| Crystal structure and electronic properties of Bi₂O₂Se thin films.

a, Side view of the Bi₂O₂Se bilayer. The single crystal is bonded via a chalcogen atomic plane interlaced between layers of covalently bonded bismuth-oxide. **b,** Optical micrograph of a 10 nm thick Bi₂O₂Se device and its atomic force microscopy (AFM) image before fabrication. The scalebar is 5 µm. **c,** Sheet conductivity σ_s as a function of gate voltage V_G at $T = 4.2$ K. Samples with different thicknesses d are labeled with different colors. We use the same color scheme throughout the whole paper to trace the different thicknesses. The dashed line marks the quantum conductance $\frac{2e^2}{h}$. *Inset* shows the σ_s for the saturation conductivity, namely the "ON" states, as a function of device thicknesses. **d** and **e** Shubnikov-de Haas oscillations (SdH) of Bi₂O₂Se flakes in the "ON" state **(c)** and the corresponding Hall effect. The data is plotted by taking the symmetric $\frac{1}{2}[R_{xx}(+B) + R_{xx}(-B)]$ and antisymmetric $\frac{1}{2}[R_{xy}(+B) - R_{xy}(-B)]$ components of longitudinal and transverse resistance, respectively. **f,** Fast Fourier transform (FFT) spectra of the SdH oscillation in the inverse magnetic field domain $1/B$. **g,** Schematic structure of sub-bands configuration of the electronic pocket located at Γ point of the first Brillouin zone of Bi₂O₂Se starting from a thick sample to its thin counterpart (*top to bottom*). The bottom of each sub-band is indicated as $E_{1,2,\cdots,i}$, where i is a sub-band index. Dashed lines mark the thermal broadening energy at 4.2 K.

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Fig. 2| Shubnikov-de Haas oscillations and quantum Hall effect.

a, Symmetric component of longitudinal resistivity ρ_{xx} of a 11 nm Bi_2O_2Se flake at carrier concentrations n_{2D} ranging from 1.33 to 8.43×10^{12} cm^{-2}. The magnetic field dependences of ρ_{xx} are offset for clarity. The short horizontal bars, marking $\rho_{xx} = 0$ for each curve, are color-coded accordingly , and the height of all scale bars is 2 kΩ. From shortest to longest, three scale bars correspond to carrier density ranges up to 1.61, 3.80, and 8.43×10^{12} cm^{-2}, respectively. The resistance minima are labeled as v corresponding to different filling factors. **b,** Hall effect ρ_{xy} measured at $T = 1.36$ K simultaneously with ρ_{xx} shown in panel **(a)**. Dashed lines mark the position of even fractions of the von Klitzing constant $R_K = \dfrac{h}{ve^2}$, where $v = 2, 4, 6, 8\cdots$. Plateaus observed at even integer filling factors correspond to filled spin-split Landau Levels (LLs) of the Γ – band (*see inset*). **c,** Concentration of induced electrons n_{2D} (*left axis*) and Hall mobility μ_H (*right axis*) as a function of gate voltage V_G. The solid line and the filled circles correspond to the two data sets, obtained from varying the carrier concentration at magnetic field $B = 2$ T and vice versa. The dashed line is a fitting to a capacitor model of SiO_2 gate dielectric (300 nm). **d,** The decay of the amplitude of the SdH oscillation as a function of temperature. We plot two exemplary states measured at 30 Tesla, having $n_{2D} = 1.61$ and 6.94×10^{12} cm^{-2}. The Lifshitz-Kosevich fittings to the data (solid lines) yield $m_c \approx 0.13$ and 0.27 m_0, respectively. **e,** Cyclotron mass m_c/m_0 extracted at different electron concentrations for two different samples 11 nm (*pink dot*) and 10 nm thick (*blue dot*).

Fig. 3| Quantum confinement in thin films.

a, Hall effect carrier concentration n_{2D} is plotted as a function of B_F/ϕ_0, where B_F is extracted from the SdH oscillation. The n_{2D} values are color-coded for different thicknesses. The black dashed line is a fitting with the LL degeneracy factor $g_s\Delta_i = 2$. The colored dashed lines guide the deflections from the degeneracy factor $g_s\Delta_i = 2$ to 4 at different critical Hall carrier densities n_0, for different thicknesses. **b,** Critical carrier concentration n_0, marking the onset of occupying the second sub-band as a function of sample thickness. **c,** Confinement potential tuned by the gate voltage for two different thicknesses. The thinner sample acquires greater sub-band splitting energy between E_i and E_{i+1}.

Fig. 4| Quantum Hall effect in 2DEG.

a, Longitudinal ρ_{xx} and Hall resistivity ρ_{xy} as a function of applied gate voltage at 30 T and T = 1.32 K. The sample is 11 nm thick. At 30 T, the LLs are periodically spaced in ΔV_G up to ~70 V. Considering that the oscillations sequentially appear at $\Delta V_G \approx 21\,V$ ($B = 30\,\text{T}$) and the relation between LL occupation and LL energy separation is $(\alpha \cdot \Delta V_G) = g_s \Delta_i \cdot B/\phi_0$, we obtain $g_s = 2$. Above $\sim 70\,V$, the oscillation period rearranges due to populating a higher sub-band $\Delta_i = 1 \rightarrow 2$. *The inset* shows transverse conductivity σ_{xy}, in the units of $\frac{2e^2}{h}$, plotted versus the measured Hall carrier density at 15, 22.5, and 30 T, respectively. **b,** Schematic picture of the sub-band alignment in a magnetic field of 15 (*top*) and 30 T (*bottom*) at the highest accessed occupation. The sub-bands are shifted horizontally for clarity. The LL index is denoted as l, unfilled levels are semitransparent.