A dual-gate InSb nanosheet field-effect device is realized and is used to investigate the physical origin and the controllability of the spin–orbit interaction in a narrow bandgap semiconductor InSb nanosheet. We demonstrate that by applying a voltage over the dual gate, efficiently tuning of the spin–orbit interaction in the InSb nanosheet can be achieved. We also find the presence of an intrinsic spin–orbit interaction in the InSb nanosheet at zero dual-gate voltage and identify its physical origin as a build-in asymmetry in the device layer structure. Having a strong and controllable spin–orbit interaction in an InSb nanosheet could simplify the design and realization of spintronic devices, spin-based quantum devices, and topological quantum devices.

**RESULTS AND DISCUSSION**

Dual-gate InSb nanosheet device

The dual-gate device studied in this work is made from a free-standing, single-crystalline, zincblende InSb nanosheet on an n-doped silicon (Si) substrate covered by a 300-nm-thick layer of silicon dioxide (SiO₂) on top, using standard nanofabrication techniques (see “Methods”). Figure 1a shows a scanning electron microscope (SEM) image of the device and the measurement circuit setup. Figure 1b shows a schematic view of the layer structure of the device. The InSb nanosheet in the device is grown InSb nanowires, including field-effect transistors, single- and double quantum dots, and semiconductor–superconductor hybrid quantum devices. Among the most influential, pioneer developments are the topological superconducting quantum devices made from InSb nanowires, in which zero-energy modes, a signature of Majorana fermions, can be conveniently performed and thus topological quantum computations can be designed and realized. It could be inevitable to move from single-nanowire structures to multiple-nanowire and two-dimensional (2D) planar quantum structures. Recently, high-quality InSb/InAlSb heterostructured quantum wells and free-standing InSb nanosheets have been achieved by epitaxial growth techniques. In comparison with InSb/InAlSb quantum wells, the free-standing InSb nanosheets have advantages in direct contact by metals, including superconducting materials, in easy transfer to different substrates, and in convenient fabrication of dual-gate structures. With use of free-standing InSb nanosheets, lateral quantum devices, such as planar quantum dots, have been successfully fabricated. A most intriguing perspective of these layered materials is to build topological superconducting structures from them, in which Majorana fermions and parafermions can be created and manipulated, enabling a different route of developments towards topological quantum computation technology. A desired ingredient in constructing topological superconducting states from such a semiconductor nanostructure is strong SOI (with a few 100 nm or shorter in spin–orbit length and about 100 µeV or larger in spin–orbit energy) possessed in the material. Comprehensive studies of SOI have been carried out for InSb nanowires and quantum wells. However, a desired study of SOI and, in particular, its controllability has not yet been carried out for free-standing InSb nanosheets, although it is highly anticipated that such a study would lead to great advancement in the developments of spintronics, quantum-dot based spin–orbit qubits, and topological quantum computation technology.
contacted by four stripes of Ti/Au (contact electrodes). The n-doped Si substrate (contacted by a thin gold film at the bottom) and the SiO₂ layer are employed as the bottom gate and the gate dielectric. The top gate is made from a Ti/Au film with a layer of hafnium dioxide (HfO₂) as the top-gate dielectric. The nanosheet has a width of ~550 nm and a thickness of ~30 nm (estimated based on the calibrated contrast in the SEM image). The separation between the two inner Ti/Au electrodes is 1.1 μm.

Figure 1d shows a horizontal line cut of Fig. 1c (bottom-gate transfer characteristics) at a temperature of \( T = 1.9 \) K. In the measurements, a 17-Hz AC current \( I \) of 100 nA is applied through the two outer electrodes, and the voltage drop \( V \) between the two inner electrodes is recorded and is then converted to the conductance through \( G = \frac{I}{V} \). The red and yellow solid lines denote the constant conductance contours of \( \approx 9 \) and \( \approx 5 e^2/h \), respectively. The conductance fluctuations superimposed on the transfer curves are reproducible and arise from universal conductance fluctuations (UCF). Overall, the top gate shows a strong coupling to the InSb nanosheet, while the bottom gate shows a relatively weak coupling to the nanosheet. The former is in accordance with the fact that a short distance between the top gate and the nanosheet and a high dielectric material (HfO₂ in this case) are employed in the device. From Fig. 1b, one can infer that an electric field stretching perpendicularly through the InSb nanosheet can be present and can be tuned by a voltage applied over the two gates (dual-gate voltage).

The carrier density in the InSb nanosheet can be estimated from the measured transfer characteristics. Here, we extract the carrier density, at a fixed top-gate voltage of \( V_{TG} = 0 \) V, from

\[
\frac{V_{BG}}{C_0} = \frac{V_T}{C_{gs}} - \frac{V_{BG}}{C_{gs}} = \frac{V_{BG}}{d} = \frac{V_{BG}}{300 \text{ nm}},
\]

where \( n \) denotes the elementary charge and \( C_{gs} = \frac{C}{A} \) is the unit area capacitance between the bottom gate and the nanosheet with \( \varepsilon_0 \) being the vacuum permittivity, \( \varepsilon = 3.9 \) the dielectric constant of SiO₂, and \( d = 300 \) nm the thickness of SiO₂. In the above relation, \( \frac{V_{BG}}{C_0} \) is the threshold voltage at which the conductance \( G \) goes to zero. In our case, to extract the
threshold, a line fit to the measured $G - V_{BG}$ curve in Fig. 1d is made (see Supplementary Fig. 1a). Then by extending the fitting line to intersect the horizontal axis, we obtain $V_{BG}^h$. In this way, we have estimated out a carrier density of $n = 7.2 \times 10^{11}$ cm$^{-2}$ at $V_{BG} = -5$ V and $V_{TG} = 0$ V, at which the measured conductance takes a value of $G = 9e^2/h$. Note that along the red contour line in Fig. 1c, the measured conductance stays at the same value of $G = 9e^2/h$ and thus the carrier density in the nanosheet stays, to a good approximation, at the same value of $n = 7.2 \times 10^{11}$ cm$^{-2}$. Similarly, the yellow contour line in Fig. 1c displays the measurements at a conductance of $G = 5e^2/h$ and a carrier density of $n = 4.3 \times 10^{11}$ cm$^{-2}$ in the nanosheet. The electron mobility in the nanosheet is estimated from $\mu = \sigma/n e$, where $\sigma = e/h$ is the sheet conductivity with $L$ being the channel length (i.e., the distance between the two inner contact electrodes, 1.1 μm in this device) and $W$ being the channel width (i.e., the width of the nanosheet, 550 nm in this device). Since the conductance is approximately a linear function of $V_{BG}$ and the same is for the electron density in the nanosheet, the same electron mobility of $\mu = 6000$ cm$^2$/V s$^{-1}$ in the nanosheet is extracted at both $G = 9e^2/h$ and $G = 5e^2/h$. The electron mean free path in the nanosheet can be estimated from $L_e = \frac{\hbar}{e} \sqrt{\frac{2m}{\pi n}}$, where $\hbar = \frac{h}{2\pi}$ with $h$ being the Planck constant, giving $L_e \sim 84$ nm at $n = 7.2 \times 10^{11}$ cm$^{-2}$ ($G = 9e^2/h$) and $L_e \sim 65$ nm at $n = 4.3 \times 10^{11}$ cm$^{-2}$ ($G = 5e^2/h$). A larger value of $L_e$ obtained at the higher electron density could be due to screening of scattering by electrons in the nanosheet. For comparison, it is worthwhile to note that the Fermi wavelength can be estimated as $\lambda_F = \sqrt{2\pi/n} \sim 30$ nm at the carrier density of $n = 72 \times 10^{11}$ cm$^{-2}$, which is close to the thickness of the nanosheet. Thus, only one or few 2D electron subbands in the InSb nanosheet are occupied and the InSb nanosheet is dominantly a 2D electron system. The same analysis based on the top-gate transfer characteristics should give the similar estimations for the carrier density and the mobility at the same setting of $V_{BG}$ and $V_{TG}$. According to this, we have extracted a value of $e \sim 6.5$ for the dielectric constant of the top-gate dielectric HfO$_2$ using the $G - V_{TG}$ curve shown in Fig. 1e and the carrier densities extracted through the $G - V_{BG}$ curve (see Supplementary Note 1 for detail).

Quantum transport characteristics of the InSb nanosheet

In a quantum diffusive device, the electron transport can be characterized by a set of transport length scales, including phase coherence length ($L_p$), SOI length ($L_{SOI}$), and mean free path ($L_e$). In order to determine all these lengths in the InSb nanosheet, we have performed detailed magnetotransport measurements for the dual-gate InSb nanosheet device at low magnetic fields. Figure 2a shows the measured magnetoconductance, $\Delta G = G(B) - G(0)$, at different $V_{BG}$ with top-gate voltage set at $V_{TG} = 0$ V. Here, the magnetic field $B$ is applied perpendicular to the nanosheet. It is seen that the measured magnetoconductance displays a peak in the vicinity of $B = 0$, i.e. the weak antilocalization (WAL) characteristics. The WAL arises from quantum interference in the presence of strong SOI and gives a positive quantum correction to the conductance at zero magnetic field. It is also seen that at $V_{BG} = 0$ V, a well-defined WAL peak is observed, but the peak becomes less pronounced as $V_{BG}$ decreases.

For a 2D diffusive system, the low-field magnetoconductance is well described by the Hikami–Larkin–Nagaoka (HLN) quantum interference theory. Assuming that the electron transport in the InSb nanosheet is in the 2D diffusion regime, the quantum corrections to the low-field magnetoconductance is given by

$$\Delta G(B) = -\frac{e^2}{2\pi} \left[ \frac{1}{2} \left( \Psi\left(\frac{3}{4}\right) + \frac{1}{2} \right) + \frac{1}{2} \left( \Psi\left(\frac{5}{4}\right) + \frac{1}{2} \right) \right]$$

where $\Psi(x)$ is the digamma function. Three subscripts, φ, SO, and e, in the above equation denote inelastic dephasing, spin–orbit scattering, and elastic scattering processes, respectively. $B_{SO}$ are the characteristic fields for the three scattering mechanisms and are given by $B_{SO} = h/(4eL_{SOI})$. The measured low-field magnetoconductance data at different $V_{BG}$ shown in Fig. 2a are fitted to Eq. (1) using $L_p$, $L_{SOI}$, and $L_e$ as fitting parameters (see further detail in "Methods"). The black solid lines in Fig. 2a are the results of the fits.

Figure 2b shows the extracted $L_p$, $L_{SOI}$, and $L_e$ in the InSb nanosheet from the fits at $V_{TG} = 0$ V as a function of $V_{BG}$. As shown in Fig. 2b, $L_p$ is strongly dependent on $V_{BG}$, while $L_{SOI}$ and $L_e$ show weak $V_{BG}$ dependences and stay at values of $L_{SOI} \sim 130$ nm and $L_e \sim 80$ nm. Here, we note that the extracted $L_e \sim 80$ nm is in good agreement with the values extracted above from the gate transfer characteristics. The weak $V_{BG}$ dependence of $L_e$ arises from the fact that at the low temperature we have considered, $L_e$ is primarily given by the distribution of scattering centers, such as charged impurities and lattice defects, in the conduction InSb channel and the dielectric SiO$_2$ layer, as well as at the InSb–SiO$_2$ interface, and the distribution of scattering centers should be insensitive to a change in the gate voltage in the range we have considered. The $L_{SOI}$ also shows a weak $V_{BG}$ dependence because it primarily depends on the perpendicular electric field penetrates the InSb nanosheet, which is only weakly dependent on $V_{BG}$ when the InSb nanosheet is at open conduction state. At $V_{BG} = 0$ V (a high carrier density case), the extracted $L_p$ reaches to $\sim 530$ nm.
As $V_{bG}$ sweeps from 0 to $-13$ V, $L_D$ decreases rapidly to $\sim 180$ nm, indicating that the dephasing is stronger at a lower carrier density. The physical origin of this increase in $L_D$ with increasing carrier density is that, at this low temperature, the dephasing arises predominantly from electron–electron interaction with small energy transfers, in the form of electromagnetic field fluctuations generated by the motions of neighboring electrons (the Nyquist dephasing mechanism$^{44}$), and such fluctuations get to be diminished at a higher carrier density and thus an increased bottom-gate voltage due to stronger charge screening. It is worthwhile to emphasize that $L_D$ is one order of magnitude larger than the thickness of the nanosheet. This, together with the fact that the typical Fermi wavelength $\lambda_F \sim 30$ nm is close to the thickness of the nanosheet, supports our assumption that the transport in the nanosheet is of a 2D nature. In addition, the extracted $L_D \sim 80$ nm is one order of magnitude smaller than the distance between the two inner contact electrodes, indicating that the transport in the nanosheet is in the diffusion regime.

There are several possible mechanisms responsible for the spin relaxation process in the nanosheet. One is the Elliot–Yafet mechanism$^{45,46}$, i.e., the spin randomization due to momentum scattering. In the Elliot–Yafet mechanism, the spin relaxation length can be estimated out as$^{39,47}$

$$
L_{SO,XY} = \frac{\hbar}{\sqrt{2} S} \frac{E_F}{E_F} L_F \left( \frac{\epsilon_F + \Delta_C(\epsilon_F + 2\Delta_C)}{\Delta_C(\epsilon_F + \Delta_C)} \right) \geq 500 \text{ nm}
$$

using the bandgap $E_g = 0.23$ eV, the Fermi energy $E_F = \frac{h^2}{2m^*} \leq 50$ meV (with $n \leq 7.2 \times 10^{11}$ cm$^{-2}$), bulk spin–orbit gap $\frac{\Delta SO}{m^*} \sim 0.8$ eV, and the mean free path $L_e \sim 80$ nm. The estimated $L_{SO,XY}$ is much larger than the experimentally extracted value of $L_{SO} \sim 130$ nm. Therefore, the Elliot–Yafet mechanism does not play a key role in our system. Another one is the D'yakonov-Perel' mechanism$^{49}$, which considers the spin precession between scattering events. Since the InSb nanosheets used in our device is a zincblende crystal and the current flow would take along a $<111>$ or a $<110>$ crystallographic direction$^{27}$, the Dresselhaus SOI$^{50}$ would be either absent or negligible$^{51}$. Based on the above analyses, we expect that the Rashba SOI$^{52}$ is the primary cause of spin relaxation in the InSb nanosheet. This expectation is also consistent with our designed device structure with an enhanced structural asymmetry. Hence we can obtain a Rashba spin–orbit strength of $\alpha_R \sim 0.42$ eV$A$ according to $L_{SO} = \frac{\hbar^2}{m^* \alpha_R}$, where $m^* = 0.014 m_0$ denotes the effective mass of electrons in InSb with $m_0$ being the free electron mass. The spin–orbit energy can be determined as $E_{SO} = \frac{m^* \alpha_R^2}{2\hbar^2} \sim 160$ µeV in the InSb nanosheet. In comparison with most commonly employed III–V narrow bandgap semiconductor nanostructures with a strong SOI, the extracted spin–orbit strength of $\alpha_R \sim 0.42$ eV$A$ in our InSb nanosheet from the low-field magnetotransport measurements shown in Fig. 3 is smaller than but comparable to the values of 0.5–1 eV$A$ found in InSb nanowires$^{53}$, but is significantly larger than the values of $\sim 0.16$ eV$A$ found in InAs nanowires$^{53}$. In addition, our extracted spin–orbit strength in the InSb nanosheet is an order of magnitude larger than the values reported previously for InSb and InAs quantum wells$^{41,54}$. Thus, the extracted $\alpha_R \sim 0.42$ eV$A$ in our InSb nanosheet corresponds to a strong SOI found in a III–V narrow bandgap semiconductor nanostructure.

Tuning the SOI in the InSb nanosheet by dual-gate voltage
The SOI of the Rashba type is tunable by applying an electric field perpendicularly through the InSb nanosheet. Such an electric field can be achieved and tuned by a voltage $V_D$ applied over the dual
gate. For example, with $V_{TG}$ being set at 0 V, we could sweep $V_{BG}$ to gradually change $V_D$ and thus the electric field through the nanosheet. However, as we showed above, sweeping $V_{BG}$ only also tunes the carrier density in the nanosheet. To demonstrate the manipulation of SOI solely via the vertical electric field in the nanosheet, the carrier density in the nanosheet ought to be fixed. In the present work, this is achieved by performing magnetotransport measurements along an equal conductance contour line, in which the carrier density in the nanosheet approximately stays at a constant value, but the dual-gate voltage, $V_D = V_{TG} - V_{BG}$, is tuned continuously. Figure 3a shows magnetoconductance traces measured along a contour line of $G = 9e^2/h$ (the red contour line in Fig. 1c) at several values of $V_D$. It is seen that all the measured magnetoconductance traces show the WAL characteristics. To extract the transport length scales as a function of $V_D$, we fit these measured magnetoconductance traces to Eq. (1). The black solid lines in Fig. 3a show the results of the fits. Figure 3b displays the characteristic transport lengths $L_{vr}$, $L_{SO}$, and $L_{D}$ extracted from the fits. It is shown that $L_{vr}$ stays at a constant value of ~460 nm, independent of $V_D$. This is in good agreement with the fact that $L_{vr}$ is mainly influenced by carrier density and temperature, but not by an electric field applied perpendicular to the nanosheet. The same is also true for $L_{vr}$ which is found to stay at a value of ~85 nm. However, $L_{SO}$ shows a strong dependence on $V_D$. As seen in Fig. 3b, $L_{SO}$ is monotonically increased from ~130 to ~390 nm as $V_D$ changes from ~2 to 11 V, indicating that the SOI strength becomes weaker as $V_D$ moves towards more positive values. Figure 3c shows the magnetoconductance traces measured along a constant conductance contour line of $G = 5e^2/h$ (the yellow contour line in Fig. 1c) at varying $V_D$ from ~4.4 to 10.7 V. Again, the WAL characteristics are observed in the measurements. The black solid lines in Fig. 3c show the fits of the measurements to Eq. (1) and Fig. 3d shows the transport lengths extracted from the fits. Again, it is seen that with varying $V_D$, $L_{vr}$ stays at a value of ~340 nm and $L_{D}$ stays at a value of ~78 nm, i.e., both are independent of $V_D$. However, $L_{SO}$ is seen to increase from ~130 to ~270 nm as $V_D$ is tuned from ~4.4 to ~10.7 V. Our results presented in Fig. 3 clearly demonstrate that the SOI in the InSb nanosheet of our dual-gate device can be effectively tuned by applying a voltage over the dual gate without a change in the carrier density in the nanosheet. The achieved change in $L_{SO}$ from 130 to 390 nm corresponds to a change in the spin–orbit strength from 0.42 to 0.14 eVÅ and a change in the spin–orbit energy from 160 to 18 μeV.

We have also performed the dual-gate voltage $V_D$ dependent measurements of the transport characteristics lengths $L_{vr}$, $L_{SO}$, and $L_{D}$ in the InSb nanosheet along the constant conductance contour lines of ~2.6 and ~1.1e^2/h, and an efficient tuning of SOI in the nanosheet by the dual-gate voltage $V_D$ is again observed (see Supplementary Note V). All the results presented in the present section (and in Supplementary Fig. 5) manifest that the SOI in the InSb nanosheet in a dual-gate structure can be efficiently tuned by a voltage applied to the dual gate at largely different but fixed carrier densities of the nanosheet.

Band diagram and intrinsic Rashba SOI in the InSb nanosheet

It is important to emphasize that the experimentally extracted Rashba spin–orbit length $L_{SO}$ is small, indicating a strong SOI, even at $V_D = 0$ V. This seemingly unexpected observation however reveals the presence of an intrinsic structural asymmetry even in the absence of a voltage difference between the top and bottom gates due to band offsets appeared in the HfO₂-InSb-SiO₂ heterostructure. To show this, the energy band diagram in the vertical direction is simulated using commercially available software COMSOL. The simulation is mainly based on Poisson’s equations and takes the material parameters of HfO₂, InSb, and SiO₂, including bandgaps, dielectric constants, electron effective masses, and electron affinities, as inputs (see Supplementary Table I for material parameters). Figure 4a displays the simulated energy band diagram of the HfO₂-InSb-SiO₂ structure at $V_D = 0$ V (with $V_{TG} = V_{BG} = −0.33$ V) and carrier density $n = 7.2 \times 10^{11}$ cm⁻² in the InSb nanolayer. The conduction band and the valence band edges exhibit a noticeable bending even at $V_D = 0$ V, illustrating the presence of an intrinsic structure asymmetry in the InSb nanosheet. Figure 4b shows a zoom-in view of the simulated conduction band edge in the InSb nanosheet at three values of $V_D$. The green, blue, and red solid lines represent the conduction band edges at $V_D = 0$, −2 (with $V_{BG} = −0.46$ V and $V_{BG} = 1.54$ V), and 11 V ($V_{BG} = −0.4$ V and $V_{BG} = −10.6$ V), respectively, and the carrier density of $n = 7.2 \times 10^{11}$ cm⁻² in the InSb nanosheet. With pushing the dual-gate voltage from $V_D = 0$ V to $V_D = −2$ V, we can see that the band bending becomes stronger, indicating an enhanced structural asymmetry and thus a stronger Rashba SOI. On the contrary, by moving from $V_D = 0$ V to $V_D = 11$ V, we compensate the band bending towards a nearly flat band, leading to a reduced asymmetry in the structure and a weaker Rashba SOI. These simulated results are fully in line with the experimental observations. Based on the simulations, the strength of the vertical, effective mean electric field in the InSb nanosheet can be estimated. It is found that the field strength gradually increases when changing from $V_D = 11$ V to $V_D = −2$ V (see Supplementary
by atomic layer deposition. Finally, a Ti/Au (5/90 nm in thickness) metal deposition is subsequently annealed in situ to form Ag nanoparticles. Thin films are deposited on top of InAs nanowires on a Si (111) substrate. The growth process starts by depositing a thin layer of Ag on the Si substrate in an MBE chamber. The InSb nanosheets are grown on top of InAs nanowires by abruptly switching the group-V source from As to Sb and with an increased Sb flux. High-quality, free-standing, single-crystalline, pure zincblende phase InSb nanosheets used in this work are grown by molecular-beam epitaxy (MBE) on top of InAs nanowires on a Si (111) substrate. The growth process starts by depositing a thin layer of Ag on the Si substrate in an MBE chamber. The film is subsequently annealed in situ to form Ag nanoparticles. Thin InAs nanowires are then grown with these Ag nanoparticles as seeds. The InSb nanosheets are grown on top of the InAs nanowires by abruptly switching the group-V source from As to Sb and with an increased Sb flux. High-resolution transmission electron microscopy and scanning electron microscopy analyses show that the as-grown InSb nanosheets are of high-quality, pure zincblende phase, single crystals and are up to several micrometers in sizes and down to ~10 nm in thickness. For further details about the growth process and structural properties of our MBE-grown InSb nanosheets, we refer to ref. [27].

**METHODS**

**Material growth**

High-quality, free-standing, single-crystalline, pure zincblende phase InSb nanosheets used in this work are grown by molecular-beam epitaxy (MBE) on top of InAs nanowires on a Si (111) substrate. The growth process starts by depositing a thin layer of Ag on the Si substrate in an MBE chamber. The InSb nanosheets are grown on top of the InAs nanowires by abruptly switching the group-V source from As to Sb and with an increased Sb flux. High-resolution transmission electron microscopy and scanning electron microscopy analyses show that the as-grown InSb nanosheets are of high-quality, pure zincblende phase, single crystals and are up to several micrometers in sizes and down to ~10 nm in thickness. For further details about the growth process and structural properties of our MBE-grown InSb nanosheets, we refer to ref. [27].

**Device fabrication**

For device fabrication, the InAs nanowires are mechanically transferred from the growth substrate onto an n-doped Si substrate covered with a 300-nm-thick layer of SiO2 on top. The Si and SiO2 layers are later used as a global bottom gate and its dielectric. After transferring, contact electrodes are fabricated on selected nanosheets with a thickness of ~30 nm via a combined process of electron-beam lithography (EBL), electron-beam evaporation (EBE) of a Ti/Au (5/90 nm in thickness) metal bilayer, and lift off. We note that before the metal evaporation, the exposed areas on the InSb nanosheets are chemically etched in a de-ionized water-diluted (NH4)2S2O8 solution to remove the surface oxide and to subsequently passivate the fresh surface. After the contact electrode fabrication, a 20-nm-thick HfO2 dielectric layer is deposited on the sample by atomic layer deposition. Finally, a Ti/Au (5/90 nm in thickness) metal bilayer top gate is fabricated on each device by the combined process of EBL, EBE and lift off. As indicated in the schematic shown in Fig. 1a, the top gate covers the entire InSb nanosheet as seen in Fig. 1a and as indicated in the schematic shown in Fig. 1b.
Gate transfer characteristics and magnetotransport measurements Low-temperature transport measurements of the fabricated devices are carried out in a PPMS cryostat equipped with a uniaxial magnet. The InSb nanosheet conductance is measured in a four-probe configuration to eliminate the impact of the contact resistances using a lock-in technique, in which a 17-Hz AC excitation current $I = 100 \text{nA}$ is supplied between the two outer electrodes and the voltage drop $V$ between the two inner contact electrodes is recorded. The nanosheet channel conductance $G$ is obtained numerically from $G = IV$. For this work, the results of the measurements obtained from a representative device as shown in Fig. 1a are presented. The measurements are carried out with magnetic fields applied perpendicular to the nanosheet plane at temperatures of $T = 1.9–20 \text{K}$.

Fitting of the measured magnetoconductance data to the HLN formula
To extract the characteristic transport lengths of $L_p$, $L_S$, and $L_d$ in the InSb nanosheet, the measured data are fitted to Eq. (1), based on the least-squares method, using both the “curve_fit” function in the SciPy package written in Python and the non-linear fit program in the Origin software for crosscheck. The two fitting procedures give almost the same results. The fitting bounds are set in order to make the corresponding length scales vary in a reasonable range. For example, we set the fitting bound of $L_d$ as $L_d \leq 200 \text{ nm}$. The range of magnetic fields $B$ is chosen to be $|B| \leq 20 \text{ mT}$ in all the fittings presented in this work in order to make the low-field condition of Eq. (1) satisfied.

Band diagram simulation
To simulate the energy band diagrams of the HfO_2–InSb–SiO_2 heterostructure in the device, Poisson’s equations are solved using commercially available program COMSOL in compliance with the boundary conditions of the system. An effective one-dimensional model with three sections representing three different materials, HfO_2, InSb, and SiO_2, is considered. Material properties employed in the simulation, include bandgaps, dielectric constants, electron effective masses, and electron affinities, are listed in Supplementary Table 1. The carrier density in the InSb nanosheet and the boundary conditions used in the simulation are acquired from the experiments. We first show the different degrees of band bending, i.e., the different degrees of asymmetry, when various voltages are applied to the top and bottom gates (Fig. 4 and Supplementary Fig. 3a). The carrier density distribution inside the InSb layer can also be calculated (see Supplementary Fig. 3c). It is seen that the carrier density is non-uniformly distributed, consistent with the conduction band bending profile obtained. The quantitative analysis of the asymmetry is carried out from the calculated effective electric field strength inside the InSb layer shown in Supplementary Fig. 3b.

DATA AVAILABILITY
The data supporting the findings of this study are available within the article and its Supplementary Information file. Additional data including simulation codes are available from the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

H.Q.X. conceived and supervised the project. Y.C. and S.H. fabricated the devices and carried out the transport measurements. D.P. and J.Z. grew the materials. J.X. and L.Z. participated in the device fabrication and measurements. Y.C. performed the band diagram simulations. Y.C., S.H., and H.Q.X. analyzed the data and wrote the manuscript with contributions from all authors. All authors contributed to the discussion of the results and the interpretation of the data acquired.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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