Temperature-dependent charge-carrier transport between Si-δ-doped layers and AlGaAs/InGaAs/AlGaAs quantum well with various space layer thicknesses measured by Hall-effect analysis

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Temperature (T = 40 ~ 300 K) dependence of Hall-effect analysis on the dual Si-δ-doped AlGaAs/InGaAs/AlGaAs quantum-well (QW) structures with various space layer thicknesses (tS = 5, 10 and 15 nm) was performed. An interesting hysteresis behavior of electron sheet concentration [n2D(T)] was observed for tS = 10 and 15 nm but not for tS = 5 nm. A model involving two different activation barriers encountered respectively by electrons in the active QW and by electrons in the δ-doped layers is proposed to account for the hysteresis behavior. However, for small enough tS (= 5 nm ± 2.5 s, where s = 2.0 nm is the standard deviation of the Gaussian fit to the Si-δ-doped profile), the distribution of Si dopants near active QW acted as a specific form of “modulation doping” and can not be regarded as an ideal δ-doping. These Si dopants nearby the active QW effectively increase the magnitude of n2D, and hence no hysteresis curve was observed. Finally, effects from tS on the T-dependence of electron mobility in active QW channel are also discussed.

Motivated by the progress of artificial intelligence and internet of things (AIoT), an intense effort has been devoted to the fabrication and characterization of sensors and actuators to quickly detect and response the variations in the physical world. Among them, the Hall magnetic sensors fabricated from semiconductors are mostly used in contact-less sensors for linear and angular position, velocity and angular frequency, electrical current, etc., and play an important role in the era of AIoT. In particular, the two-dimensional electron gas (2DEG) in Si-δ-doped III–V quantum-well (QW) channel possesses high electron mobility (μn), high thermal stability, and low noise, and hence is widely adopted as the active layer for high speed and high sensitivity electronic devices. In contrast to the homogeneous bulk-doped structure, the uniform modulation doping in barrier layers of III–V QW structure can supply charge carriers in the undoped active channel with high mobility due to less scattering from ionized dopants. Furthermore, the single Si-δ-doping (modulation doping with single Si-doping plane) in the barrier layer with appropriate space layer thickness (tS) can offer effectively more 2DEG than the uniform modulation doping. As compared to the single Si-δ-doping, the dual and symmetric Si-δ-doping (modulation doping with two planes of Si evenly separating into two sides of the active channel with appropriate tS, see Fig. 1) can afford nearly a similar electron concentration in the active channel with low induced internal
electric field due to the symmetric distribution of Si-δ-dopants and hence provide an even higher $\mu_n$ due to the further reduction of scattering effects$^{17-19}$.

For Si-doped Al$_x$Ga$_{1-x}$As fabricated by metal organic chemical-vapor deposition (MOCVD) processes under As-rich environments, the Si dopants (with concentration $N_{Si}$) usually occupy the group III sites$^{20}$ and act either as shallow donors ($N_{SD}$, with donor level $E_{SD} = E_C - 5.8$ meV) for normal substitution or as deep DX centers ($N_{DD}$, with $E_{DD} = E_C - 145$ meV) for broken-bond configurations$^{12,21-24}$, where $E_C$ is the conduction band edge.

Assume that $N_{SD} + N_{DD} = N_{Si}$, the ratio of $N_{DD}/N_{Si}$ changes with Al mole fraction $x$: for $x < 0.20$, $N_{DD}/N_{Si} = 0$; and for $0.20 < x < 0.40$, $N_{DD}/N_{Si}$ increases continuously with $x^{25}$. Although this relation is deduced from a homogeneous Si-bulk-doped structure, it still holds in the Si-δ-doping layer due to the similar occupation behaviors of Si atoms in the group III sites as long as the concentration of Si-dopants is below degenerate doping. To achieve a good confinement of 2DEG in the active channel, $x = 0.3$ is commonly chosen. Accordingly, with high enough temperature, the thermal activation of charge carriers released from DX centers and the transport of carriers across space layer between Si-δ-doped layer and active QW layer should be carefully characterized because both of them play a crucial role in the performance of the devices fabricated.

As depicted in Fig. 1, an undoped In$_{0.15}$Ga$_{0.85}$As was chosen as the active layer because it possesses a higher $\mu_n$ than GaAs. In InGaAs system, the increase of indium percentage will enhance $\mu_n$, but it also enhances the lattice constant and reduces the bandgap. The enhancement of lattice constant in InGaAs increase the lattice mismatch between InGaAs active layer and AlGaAs barrier layer which will deteriorate the quality of the sandwiched active layer. The reduction of bandgap can induce the noise from thermally generated electron–hole pairs as the device is operating at high temperature. Based on the published data$^{26}$, a compromise of 15% was chosen.

Here, a dual and symmetric Si-δ-doped Al$_{0.3}$Ga$_{0.7}$As/In$_{0.15}$Ga$_{0.85}$As/Al$_{0.3}$Ga$_{0.7}$As QW structure as depicted in Fig. 1 was fabricated to be used as the core-element in the micro-Hall magnetic sensors as shown in Fig. 2.

![Cross-sectional view of the Si-δ-doped QW structure adopted in this work.](image1)

![Schematic band diagram nearby QW of the structure.](image2)
values of $t_S = 5, 10, \text{ and } 15 \text{ nm were chosen. The temperature } (T = 40 \sim 300 \text{ K}) \text{ dependent Hall-effect analyses were conducted, and the electron sheet concentration } n_{2D}(T) \text{ and electron mobility } \mu_n(T) \text{ in the active channel were deduced. Then, the } T\text{-dependent charge carriers transport across the space layer together with the effects of } t_S \text{ on } n_{2D}(T) \text{ and } \mu_n(T) \text{ are discussed.}

Results and discussion

Dynamic SIMS measurement. The Si-δ-doping in both sides of active layer provides the 2DEG in active channel, so at first the characteristics of the doping profile $N_S(y)$ in-depth distribution for sample with $t_S = 5 \text{ nm}$ was checked by dynamic secondary ion mass spectrometer (SIMS). As shown in Fig. 3, the asymmetric distribution of $N_S(y)$ with respect to the center of each doping profile (at $y_\delta = \pm 11 \text{ nm}$) can be understood as that the thermal energy caused by the primary ions bombardment could drive some in situ Si dopants to diffuse back. Therefore, an extra tiny residues were added to the falling edge of the δ-doping profile as compared to the leading edge. Therefore, by taking the leading edge into account only, one of the Si-δ-doping profiles as depicted in Fig. 3 can be modeled as a Gaussian distribution with short enough standard deviation $s$,

$$N_S(y) = \frac{N_{2D}/(2\pi s^2)^{1/2}}{\sqrt{2\pi}} \times \exp\left[-(y - y_\delta)^2/s^2\right] + N_0,$$

where $N_{2D}$ is the Si sheet concentration and $N_0$ is the background. From a least squared fit to these dual Si-δ-doping profiles, the averaged values of $N_{2D} = (1.40 \pm 0.07) \times 10^{12} \text{ cm}^{-2}$ and $s = 2.00 \pm 0.13 \text{ nm}$ were obtained, and the two fitted Gaussian profiles were rather symmetric. The total sheet concentration of Si atoms from these dual δ-doping layers was equal to $2 \times N_{2D} = (2.80 \pm 0.14) \times 10^{12} \text{ cm}^{-2}$ and this parameter was held as a constant
for the samples fabricated with various \( t_s \) in this work. Although the magnitude of \( s = 2 \) nm was small enough for \( t_s = 10 \) and 15 nm (i.e., \( t_s \geq s \)) such that \( N_d(y) \) can be reasonably regarded as a \( \delta \)-doping profile, but for \( t_s = 5 \) nm (\( s \leq 2.5 \) s) the actual distribution of \( N_d(y) \) as depicted in Fig. 3 in the narrow regions close to active channel (for \( y = -11 \) to \( -6 \) nm and 6 to 11 nm) as well as the tiny amount of Si atoms penetrated into the active region (from \( y = -6 \) to \( +6 \) nm) cannot be neglected and their effects on the magnitude of \( n_{2D} \) and on the transport properties will be addressed later.

Electron sheet concentrations \( n_{2D}(T) \) from Hall-effect analysis. Three types of samples are focused in this study with similar structure as Fig. 1a and identical Si-\( \delta \)-doping profile as Fig. 3 except \( t_s \) varied from 5, 10, to 15 nm. The electron sheet concentrations \( n_{2D} = (1, B_i/qV_H) \) of these samples measured from Hall-effect analysis with decreasing- and then increasing-\( T \) measurements (for \( T \) between 40 and 300 K) are depicted in Fig. 4. For \( t_s = 5 \) nm, \( n_{2D}(T) \) varied slightly with \( T \), but for \( t_s = 10 \) and 15 nm, \( n_{2D}(T) \) varied drastically and exhibited an interesting hysteresis behavior. Besides, at 40 K, \( n_{2D} \) for \( t_s = 5 \) nm was 46% higher than \( n_{2D} \) for \( t_s = 10 \) and 15 nm. To explain the hysteresis behavior of \( n_{2D}(T) \) and the effects of \( t_s \) on \( n_{2D}(T) \) and \( \mu(T) \), the following arguments are proposed.

Shallow donors versus deep DX centers. In our samples, the AlGaAs barrier layers (except at the \( \delta \)-doping layers) and InGaAs active channel were undoped, the surface states were passivated by InGaP, and the intrinsic carrier concentrations from these III–V compounds were small enough to be neglected, so the measured \( n_{2D}(T) \) was assumed dominantly from the dual Si-\( \delta \)-doping layers. The Si dopants \( (N_s) \) in AlGaAs barrier layer can act either as shallow donors \( (N_{SD} \) with \( E_{SD} = E_F - 5.8 \) meV) or as deep DX centers \( (N_{DD} \) with \( E_{DD} = E_F - 145 \) meV)\(^{22} \). Based on the model mentioned above\(^{25} \), the ratios of \( N_{SD}/N_{S} = 0.3 \) and \( N_{DD}/N_{S} = 0.7 \) were calculated for Al\(_{0.7}\)Ga\(_{0.3}\)As. As shown in Fig. 4 and from the Gaussian fit, the total sheet concentration of Si atoms from dual \( \delta \)-doping layers was \( 2 \times n_{2D} \). Thus, 30% of the Si dopants (acted as shallow dopants) became nearly completely ionized at \( T = 300 \) K, and contributed a sheet electron density \( n_{2D} \sim 0.3 \times 2 \times N_{2D} = (0.84 \pm 0.04) \times 10^{12} \) cm\(^{-2} \). As depicted in Fig. 4, this value coincided with the lowest value of \( n_{2D} \) observed for samples with \( t_s = 10 \) and 15 nm at \( T = 40 \) K, i.e., in such situations \( n_{2D} \) was composed of the electrons completely ionized from shallow donors \( (n_{SD}) \). Therefore, for \( t_s = 10 \) and 15 nm, the measured values of \( n_{2D} > n_{SD} \) at high \( T \) suggests that electrons partially ionized from the DX centers \( (n_{DD}) \) must be taken into account, which gives \( n_{DD} = n_{SD} - n_{SD} \). From the ratio of \( n_{DD}(0.7 \times 2 \times N_{2D}) \), which equals the unoccupied probability \( [1 - f(T, E_{DD})] \) of electrons at \( E_{DD} \), then the occupied probability for electrons at DX centers, \( f(T, E_{DD}) \), can be evaluated from Fermi–Dirac statistics\(^{28} \) with

\[
f(T, E_{DD}) = 1 / \left[ 1 + \exp((E_{DD} - E_F)/kT) \right],
\]

where \( E_F \) is the Fermi energy level and \( kT \) is the thermal energy. Accordingly, the energy difference of \( E_{DD} - E_F \) can also be estimated. For samples with various \( t_s \), the associated parameters \( (n_{2D}, n_{SD}, n_{DD}, f(E_{DD}), \text{ and } E_{DD} - E_F) \) are listed in Table 1 for \( T = 300 \) K.

Simplified band diagrams modelling by two back-to-back capacitors. Unlike homogeneous bulk-doped materials, where the electrons and ionized donors appear in the same spatial location, for Si-\( \delta \)-doped heterojunction QW the electrons are transferred to the QW region while the ionized donors remain in the \( \delta \)-doped layers\(^{11–19} \). Because of the separation of charges, a model consisted of two back-to-back capacitors was chosen to calculate the internal transverse electric field \( (F) \) and electric potential difference \( \Delta V \) across the space layer. Fur-
thermore, a symmetric band diagram was assumed for simplicity for a dual and symmetric δ-doped layers as depicted in Fig. 5a. In such a case, the capacitor has a positive surface charge density $+\sigma = q \times (n_{SD} + n_{DD})/2$ from ionized Si donors located at one of the δ-doping layers and a negative surface charge density $-\sigma = -q \times n_{2D}/2$ accumulated by electrons at one edge of the active QW channel, and $n_{2D} = n_{SD} + n_{DD}$.

Table 1. Associated parameters for evaluating $E_{DD} - E_F$ at each Si-δ-doping layer and $\Delta V$ across $t_s$ for samples with various $t_s$ at 300 K. The total sheet concentration of Si atoms from dual δ-doping layers was fixed at (2.80 ± 0.14) × 10^{12} cm^{-2}. Note that $n_{2D}$ was taken from Hall-effect analysis (see Fig. 4), $n_{SD}$ was taken from SIMS analysis and estimated by information based on Ref.25, and $n_{DD} = n_{2D} - n_{SD}$.

| $t_s$ (nm) | $n_{2D}/2$ (10^{12} cm^{-2}) | $n_{SD}/2$ (10^{12} cm^{-2}) | $n_{DD}/2$ (10^{12} cm^{-2}) | $f(E_{red})$ | $E_{red} - E_F$ (meV) | $F$ (10^4 V/cm) | $\Delta V$ (mV) |
|-----------|-----------------------------|-----------------------------|-----------------------------|--------------|----------------------|-----------------|------------|
| 5         | 0.631 ± 0.001               | 0.42 ± 0.02                 | 0.21 ± 0.02                 | 78.4 ± 1.6%  | −33 ± 2              | 9.32 ± 0.01    | 47         |
| 10        | 0.559 ± 0.005               | 0.42 ± 0.02                 | 0.14 ± 0.02                 | 85.6 ± 2.7%  | −45 ± 6              | 8.27 ± 0.07    | 83         |
| 15        | 0.548 ± 0.001               | 0.42 ± 0.02                 | 0.12 ± 0.02                 | 87.6 ± 2.7%  | −50 ± 6              | 8.09 ± 0.01    | 121        |

Figure 5. (a) Simplified conduction band diagram deduced from the dual Si-δ-doping layers based on two back-to-back capacitors at 300 K. (b) Comparison of the corresponding band diagrams for samples with $t_s = 5, 10, and 15$ nm.
The simplified conduction band diagrams for various $n_{SD}$ with a thermally assisted tunneling the transfer of electrons from active QW channel to the δ-doping layer can be rather efficient and then $n_{2D}$. On the other hand, during an increasing-$T$ measurement from 300 to 280 K, the electrons in active QW channel (with energy around $E_F$) started to increase and Δ$V(T)$ across the capacitor reduced. At $T = 40$ K, $f(T, E_{DD})$ reached nearly 100%, and in this situation $n_{2D}$ was totally dominated by the completely ionized shallow donors ($n_{SD}$). On the other hand, during an increasing-$T$ measurement from 40 to 150 K, the electrons thermally released from DX centers in Si-δ-doping layer were rather small as compared with $n_{3D}$ and thus $n_{2D}$ was very close to $n_{3D}$ (see Fig. 4), hence $f(T, E_{DD})$ remained nearly 100% and Δ$V(T)$ kept as a constant (see Fig. 6). For $T$ increased from 150 to 280 K, the thermally released electrons from DX centers to conduction band in AlGaAs become noticeably and by a longitudinal applied bias these electrons then transferred to the active channel efficiently due to a small activation barrier ($E_{A2} = q^2V = 95 ~ 117$ meV for $t_s = 15$ nm at $T = 150 ~ 280$ K, see Fig. 6b). Therefore, $n_{2D}(T)$ and Δ$V(T)$ increased while $f(T, E_{DD})$ decreased with increasing $T$. Because of these different activation barriers encountered with respect to decreasing- and increasing-$T$ modes ($E_{A1}$ versus $E_{A2}$), a $T$-dependent hysteresis on $n_{2D}(T)$ was resulted as shown in Fig. 4 for $t_s = 10$ and 15 nm. Besides, based on the model of two back-to-back capacitors, the values of $F$ for these two samples were nearly alike due to the good match of $n_{2D}(T)$ as shown in Table 1 and Fig. 4. Hence, as depicted in Fig. 6, $f(T, E_{DD})$ followed the same trend while Δ$V(T)$ ($= F(t_s)$) acted differently for these two samples. Furthermore, as displayed in Fig. 4, the hysteresis curves ended at $T = 280$ K for these two samples. Note that the occupied probability for electron at DX center is related to an energy difference of $E_{DD} - E_F$. As listed in Table 1, the magnitudes of $E_{DD} - E_F$ were nearly comparable to $kT$ for $T = 280 ~ 300$ K. With the support of thermally assisted tunneling and a longitudinal applied bias, the transfer of electrons through the space layers became reversible. Because of the upper limit of our cryostat, no further experimental data are provided for $T > 300$ K.

Effects from non-ideal Si-δ-doped profiles for $t_s = 5$ nm. As also illustrated in Fig. 4, the fact of no hysteresis curve of $n_{2D}(T)$ observed for small $t_s = 5$ nm suggests that the non-ideal Si-δ-doped profiles as shown
were obtained for each profile. Next, the two Si dopant-profiles were rather symmetric and N_{2D} of (6.43 ± 0.06) × 10^{3}, (7.17 ± 0.16) × 10^{3} and (7.76 ± 0.03) × 10^{3} cm^{-2} V^{-1} s^{-1} for Si-δ-doped AlGaAs/InGaAs/AlGaAs QW samples fabricated by this work still possessed relatively high values of μ_n, high value of n_{SD} is one of the important figures of merit for high sensitivity magnetic sensor.

Effects of t_S on the T-dependence of electron mobility. The T-dependence of electron mobility μ_n(T) deduced from Hall-effect analysis on samples with various t_S (= 5, 10 and 15 nm) is demonstrated in Fig. 7. For T = 40 K with less phonon scattering, μ_n is very sensitively dependent on the Coulombic scattering from the ionized Si-donors located at δ-doped layers separated by t_S from the active channel. In addition, the very small amount of Si dopants entered into the In_{0.15}Ga_{0.85}As active channel from y = −6 to +6 nm as shown in Fig. 5a could further reduce μ_n. In viewing of these two factors, the sample with t_S = 15 nm possessed a highest μ_n (40 K) = (5.41 ± 0.02) × 10^{4} cm^{2} V^{-1} s^{-1} among these three types of samples. With increasing T, μ_n decreases dramatically due to phonon scattering in the active channel. Nevertheless, μ_n (300 K) for all dual and symmetric Si-δ-doped AlGaAs/InGaAs/AlGaAs QW samples fabricated by this work still possessed relatively high values of (6.43 ± 0.06) × 10^{4}, (7.17 ± 0.16) × 10^{4} and (7.76 ± 0.03) × 10^{4} cm^{2} V^{-1} s^{-1} for t_S = 5, 10 and 15 nm, respectively. A high value of μ_n is one of the important figures of merit for high sensitivity magnetic sensor.

Conclusion
In this work, dual and symmetric Si-δ-doped AlGaAs/InGaAs/AlGaAs QW structures of various t_S (= 5, 10 and 15 nm) were fabricated and characterized. At first, from a Gaussian fit on the dynamic SIMS data for the dual Si-doping profile, the two Si dopant-profiles were rather symmetric and N_{2D} = 1.40 × 10^{12} cm^{-2} and s = 2.0 nm were obtained for each profile. Next, n_{2D}(T) and μ_n(T) in the active QW channel of these samples were measured from Hall-effect analysis with decreasing- and then increasing-T modes. Interesting hysteresis curves of n_{2D}(T) were observed for t_S = 5 and 15 nm but not for t_S = 10 nm. Because of the charge separation for the Si-δ-doped AlGaAs/InGaAs/AlGaAs QW structure, a simplified energy-band diagram based on two back-to-back charged capacitors was proposed to explain these phenomena. Due to the different activation barriers encountered respectively by electrons in the active QW and by electrons in the δ-doped layers during decreasing- and then increasing-T modes, a hysteresis on n_{2D}(T) was obtained for t_S = 10 and 15 nm. Besides, at T = 40 K the lowest value of n_{2D} = 0.84 × 10^{12} cm^{-2} observed for samples with t_S = 10 and 15 nm indicates that in such situations n_{2D} was composed of the electrons completely ionized from shallow donors (n_{SD}) which agrees well with the results from the proposed model based on experimental SIMS data. However, for small enough t_S = 5 nm (i.e., t_S ≤ 2.5 s), the actual distribution of N_D(y) near QW could not be regarded as an ideal δ-doping. The amount of Si atoms nearby the active QW channel acted as a specific form of ‘modulation doping’ and effectively increased the level of the error-bar estimated from the measurement is less than the size of the symbol.

Figure 7. μ_n(T) measured from Hall-effect analysis for samples with various t_S under decreasing T (▲) and then increasing T (▼) measurements. The inset enlarges the corresponding values near room temperature. The magnitude of the error-bar estimated from the measurement is less than the size of the symbol.
of \( n_{2D} \), and hence no hysteresis curve was observed. Finally, the effects of \( t_1 \) on \( \mu_c(T) \) for these three structures were also addressed.

**Methods**

**Fabrication of the epi-structure.** The epi-layers of the Hall sample on a semi-insulating GaAs substrate depicted in Fig. 1 were fabricated by MOCVD under As-rich environments in the following steps. (1) At first, 5 nm InGaP and 10 nm GaAs buffer layers were deposited sequentially, followed by 10 pairs of 6 nm AlAs and 6 nm GaAs superlattice layers, and another 10 nm GaAs buffer layer to release the strain resulted from lattice mismatch. (2) After deposition of an undoped 55 nm \( \text{Al}_0.3\text{Ga}_0.7\text{As} \) barrier layer, the first Si-\( \delta \)-doping layer with sheet concentration of \( 1.4 \times 10^{12} \, \text{cm}^{-2} \) was achieved by injection a high SiH \(_4\) doping flow and followed by an undoped \( \text{Al}_0.3\text{Ga}_0.7\text{As} \) space layer with thickness \( t_2 \). (3) The active layer was fabricated by In\(_{0.2}\text{Ga}_{0.8}\text{As} \) with thickness \( t_3 = 12 \, \text{nm} \). (4) After an undoped \( \text{Al}_0.3\text{Ga}_0.7\text{As} \) space layer with thickness \( t_2 \), the second symmetric Si-\( \delta \)-doping layer was repeated, then followed by a 60 nm undoped \( \text{Al}_0.3\text{Ga}_0.7\text{As} \) barrier layer. (5) Finally, a passivation layer of 5 nm InGaP was deposited on top of the Hall element to reduce the effects from surface states and acted as an etching stopping layer (ESL). For ohmic contact with the active channel, after capped with 15 nm Si-doped GaAs cap layer, the standard ohmic contact were applied by adding a metal layer series of AuGe/Ni/Au \(^{31} \) of total thickness 350 nm, thermally driven to make a contact with the QW active channel, and finalized with a Ti/Au bonding pad. The dimensions of the cross-like micro-Hall element as illustrated in Fig. 2 were \( 420 \times 420 \, \mu\text{m}^2 \), with channel width \( W = 115 \, \mu\text{m} \) and length \( L = 350 \, \mu\text{m} \). According to the \( I-V \) characteristics for a micro-Hall sample with \( t_2 = 5 \, \text{nm} \) as depicted in Fig. 2b, the charge transport properties along the active channels exhibited a good ohmic contact behavior and a nice symmetry.

**Characterization.** The characteristics of the Si-\( \delta \)-doping in-depth distribution were first verified by dynamic mode of secondary ion mass spectroscopy (SIMS, outsourced by EAG Laboratories). Then the Hall-effect analysis was conducted by a Keithley 7065 system on the cross-like sample with 4 numbered terminals as depicted in Fig. 2, and the linear \( I_1-V_x \) characteristics in each active channel between terminals 1 \( \leftrightarrow \) 3 and 2 \( \leftrightarrow \) 4 were confirmed for \( I_x < 8 \, \text{mA} \), respectively. With a steady current \( I_1 = 1.0 \, \text{mA} \) applied between terminals 1 \( \leftrightarrow \) 3 under a perpendicular \( B_1 = 5.0 \, \text{kG} \), the Hall voltage across terminals 2 \( \leftrightarrow \) 4 were consecutively measured for ten times and averaged to give the value of \( V_{H1} \). By reversing the direction of \( I_1 \), \( V_{H1} \) was switched from terminals 1 \( \leftrightarrow \) 3 to 2 \( \leftrightarrow \) 4, and by repeating the above procedures \( V_{H2} \) and \( V_{H3} \) across terminals 1 \( \leftrightarrow \) 3 were obtained again. Finally, by reversing the direction of the \( B \)-field and following the same procedures, \( V_{H1} \sim V_{H2} \) were measured correspondingly. From the combination of these eight measurements to compensate the offset voltage due to any asymmetry of the cross-like Hall sample, the Hall coefficient \( R_h \) was obtained \(^{24} \) and the carrier concentration \( n_0 = 1/qR_h \) was calculated. Furthermore, for resistivity measurement, the von der Pauw model was adopted with a current applied between terminals 1 and 2 and the voltage measured across terminals 3 and 4. By switching the direction of the current and then rotating the sequence of the contact terminals, again a total of eight measurements were taken separately, and the averaged resistivity \( \rho \) of the sample was evaluated. From \( n_0 \) and \( \rho \), the averaged value of \( \mu_c \) in the active 2DEG channel was estimated. The temperature \( T \) of the sample during the Hall-effect analysis was controlled by a cryostat system. The cooling or heating rate was set at 2.0 K \text{ min}^{-1} for each \( \Delta T = 20 \, \text{K} \), and then the system stayed at each \( T \) for 10 min to allow the sample to reach near equilibrium before Hall-effect measurement. The period for one set of Hall-data acquisition at each \( T \) took another 15 min.

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