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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

Wilson Yeung-Sy Su^{1,2}, Victor Chien-Pin Lu², Chii-Bin Wu¹, Jyh-Shyang Wang¹, Ji-Lin Shen¹ & Kuan-Cheng Chiu¹✉

Temperature ($T = 40 \sim 300$ K) dependence of Hall-effect analysis on the dual Si- δ -doped AlGaAs/InGaAs/AlGaAs quantum-well (QW) structures with various space layer thicknesses ($t_s = 5, 10$ and 15 nm) was performed. An interesting hysteresis behavior of electron sheet concentration [$n_{2D}(T)$] was observed for $t_s = 10$ and 15 nm but not for $t_s = 5$ 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 t_s ($= 5 \text{ nm} \leq 2.5 s$, 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 n_{2D} , and hence no hysteresis curve was observed. Finally, effects from t_s 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 AIoT¹. In particular, the two-dimensional electron gas (2DEG) in Si- δ -doped III-V quantum-well (QW) channel possesses high electron mobility (μ_n), high thermal stability, and low noise, and hence is widely adopted as the active layer for high speed and high sensitivity electronic devices^{2–6}. In contrast to the homogeneous bulk-doped structure^{7–9}, 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 dopants¹⁰. Furthermore, the single Si- δ -doping (modulation doping with single Si-doping plane)^{11–16} in the barrier layer with appropriate space layer thickness (t_s) 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 t_s , see Fig. 1) can afford nearly a similar electron concentration in the active channel with low induced internal

¹Department of Physics and Center for Nanotechnology, Chung Yuan Christian University, Chung-Li District, Taoyuan 32023, Taiwan. ²Conary Enterprise CO., LTD, Industry Accelerator and Incubation Center, Chung Yuan Christian University, Chung-Li District, Taoyuan 32023, Taiwan. ✉email: kcchiu@cycu.edu.tw

Figure 1. (a) Cross-sectional view of the Si-δ-doped QW structure adopted in this work. (b) Schematic band diagram nearby QW of the structure.

electric field due to the symmetric distribution of Si-δ-dopants and hence provide an even higher μ_n due to the further reduction of scattering effects^{17–19}.

For Si-doped Al_xGa_{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 sites²⁰ 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 μ_n than GaAs. In InGaAs system, the increase of indium percentage will enhance μ_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 data²⁶, 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. The

Figure 2. (a) Configuration of the cross-like micro-Hall element. (b) I - V characteristics for a micro-Hall sample with $t_s = 5$ nm.

Figure 3. $N_{Si}(y)$ measured from dynamic SIMS for a dual Si- δ -doping profile with $t_s = 5$ nm.

values of $t_s = 5, 10$, and 15 nm were chosen. The temperature ($T = 40 \sim 300$ K) dependent Hall-effect analyses were conducted, and the electron sheet concentration $n_{2D}(T)$ and electron mobility $\mu_n(T)$ in the active channel were deduced. Then, the T -dependent charge carriers transport across the space layer together with the effects of t_s on $n_{2D}(T)$ and $\mu_n(T)$ 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 $N_{Si}(y)$ in-depth distribution for sample with $t_s = 5$ nm was checked by dynamic secondary ion mass spectrometer (SIMS). As shown in Fig. 3, the asymmetric distribution of $N_{Si}(y)$ with respect to the center of each doping profile (at $y_\delta = \pm 11$ 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 distribution²⁷ with short enough standard deviation s ,

$$N_{Si}(y) = (N_{2D}/(2\pi s^2)^{1/2}) \times \exp[-(y - y_\delta)/s]^2/2] + N_0, \quad (1)$$

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 $N_{2D} = (1.40 \pm 0.07) \times 10^{12}$ cm⁻² and $s = 2.00 \pm 0.13$ 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 $2 \times N_{2D} = (2.80 \pm 0.14) \times 10^{12}$ cm⁻² and this parameter was held as a constant

Figure 4. $n_{2D}(T)$ measured from Hall-effect analysis for samples with $t_s = 5, 10$, and 15 nm under decreasing- (∇) and then increasing- T ($\blacktriangle$) measurements. The magnitude of the error-bar estimated from the measurement is less than the size of the symbol.

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., $t_s \geq 5$ s) such that $N_{Si}(y)$ can be reasonably regarded as a δ -doping profile, but for $t_s = 5$ nm (≤ 2.5 s) the actual distribution of $N_{Si}(y)$ 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- δ -doping profile as Fig. 3 except t_s varied from $5, 10$, to 15 nm. The electron sheet concentrations n_{2D} ($= I_x B_y / q V_H$) of these samples measured from Hall-effect analysis with decreasing- and then increasing- T modes (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 $\mu_n(T)$, the following arguments are proposed.

Shallow donors versus deep DX centers. In our samples, the AlGaAs barrier layers (except at the δ -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- δ -doping layers. The Si dopants (N_{Si}) in AlGaAs barrier layer can act either as shallow donors (N_{SD} with $E_{SD} = E_C - 5.8$ meV) or as deep DX centers (N_{DD} with $E_{DD} = E_C - 145$ meV)²². Based on the model mentioned above²⁵, the ratios of $N_{SD}/N_{Si} = 0.3$ and $N_{DD}/N_{Si} = 0.7$ were calculated for $Al_{0.3}Ga_{0.7}As$. As shown in Fig. 4 and from the Gaussian fit, the total sheet concentration of Si atoms from dual δ -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 $n_{SD} \sim 0.3 \times 2 \times N_{2D} = (0.84 \pm 0.04) \times 10^{12} \text{ cm}^{-2}$. 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 $n_{DD} = n_{2D} - n_{SD}$. 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 statistics²⁸ with

$$f(T, E_{DD}) = 1 / [1 + \exp((E_{DD} - E_F)/kT)], \quad (2)$$

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} , $f(E_{DD})$, 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- δ -doped heterojunction QW the electrons are transferred to the QW region while the ionized donors remain in the δ -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 ΔV across the space layer. Fur-

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

Table 1. Associated parameters for evaluating $E_{DD} - E_F$ at each Si- δ -doping layer and ΔV 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 $(2.80 \pm 0.14) \times 10^{12} \text{ cm}^{-2}$. 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 $n_{DD} = n_{2D} - n_{SD}$.

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.

thermore, a symmetric band diagram was assumed for simplicity for a dual and symmetric δ -doped layers^{17–19} 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 $n_{2D} = n_{SD} + n_{DD}$ is assumed as mentioned above. Accordingly, the values of F within the capacitor ($= \sigma / \epsilon_0 \epsilon_r$, where the dielectric constant $\epsilon_r = 12.24$ is taken for $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ²⁹) and ΔV across t_s were calculated for $t_s = 5$, 10, and 15 nm, separately. These data at $T = 300 \text{ K}$

Figure 6. (a) $f(T, E_{DD})$ and (b) $\Delta V(T)$ evaluated for Hall samples with $t_s = 10$ and 15 nm.

are also listed in Table 1. By taking the conduction band offset of 0.415 eV for the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ QW heterojunction³⁰, the simplified conduction band diagrams for various t_s are depicted as Fig. 5b. Based on these band diagrams derived from this simplified scheme, E_F locates reasonably far away from E_C at the Si- δ -doped layer, which suggests that the conductivity was dominantly by the 2DEG in the active channel for our samples with moderate Si-dopants ($N_{2D} = 1.40 \times 10^{12} \text{ cm}^{-2}$). Only for very high Si-doping such that E_F is very close to E_C , the parallel conductivity over the doped layers should be taken into account.

Origin of hysteresis curves of $n_{2D}(T)$ for $t_s = 10$ and 15 nm. As demonstrated in Fig. 5, the hysteresis curves of $n_{2D}(T)$ observed for $t_s = 10$ and 15 nm in Fig. 4 could be understood as followings. In general, if electrons generated and recaptured from their donor states involve only one activation energy (as in the uniform homogeneous bulk-doped sample) and if the relaxation time is short enough, then as long as the thermal equilibrium is nearly reached, no hysteresis curve will be observed for decreasing- and increasing- T measurements. In this work, the time for the system stayed at each T before Hall-effect measurement was much larger than the relaxation time expected. Therefore, more than one activation energy associated with the charge carriers transfer were required to account for the hysteresis curves observed in Fig. 4. During a decreasing- T measurement from 300 to 280 K, the electrons in active QW channel (with energy around E_F) even though encounter a large activation barrier ($E_{A1} = 216$ meV for $t_s = 15$ nm as depicted in Fig. 5b) to return the donor states in Si- δ -doped layer, with a thermally assisted tunneling the transfer of electrons from active QW channel to the δ -doping layer can be rather efficient and then $n_{2D}(T)$ decreased with decreasing T (i.e., more DX levels become occupied, the probability of $f(T, E_{DD})$ increased and $\Delta V(T)$ decreased). However, as T decreased from 280 to 200 K, with less thermally assisted tunneling the excess electrons are then persistently confined in the active 2D channel, $n_{2D}(T)$ and the corresponding $f(T, E_{DD})$ and $\Delta V(T)$ all remained constant as shown in Fig. 6. As T further decreased from 200 to 40 K, the value of F induced by the non-equilibrium extra space-charges would now assist the electrons transfer from active channel to δ -doped layers, thus $n_{2D}(T)$ dropped again and the occupied probability of DX levels, i.e., $f(T, E_{DD})$, started to increase and $\Delta V(T)$ 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_{SD} and thus n_{2D} was very close to n_{SD} (see Fig. 4), hence $f(T, E_{DD})$ remained nearly 100% and $\Delta V(T)$ 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 ($E_{A2} = q\Delta V = 95 \sim 117$ meV for $t_s = 15$ nm at $T = 150 \sim 280$ K, see Fig. 6b). Therefore, $n_{2D}(T)$ and $\Delta V(T)$ 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 $\Delta V(T) (= F \cdot t_s)$ acted differently for these two samples. Furthermore, as displayed in Fig. 4, the hysteresis curves ended at $T \sim 280$ 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 $T = 280 \sim 300$ 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

Figure 7. $\mu_n(T)$ measured from Hall-effect analysis for samples with various t_s under decreasing T (∇) and then increasing T ($\blacktriangle$) 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.

in Fig. 3 was the culprit. For $t_s = 5 \text{ nm} = 2.5 \text{ s}$, the actual distribution of $N_{Si}(y)$ near active QW (for $y = -11$ to -6 nm and 6 to 11 nm in Fig. 3) acted as a specific form of “modulation doping” with strong gradient toward QW channel and could not be regarded as an ideal δ -doping. Meanwhile, the band bending up as illustrated in Fig. 5a can shift E_{DD} (corresponding to the Si DX levels in $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barrier layer with energy of $E_C - E_{DD} = 145 \text{ meV}$) above E_F . Therefore, those electrons from DX centers located in the vicinity close to QW with energy around E_F can hop through these DX centers and fall into the QW channel. Based on the data at low enough $T = 40 \text{ K}$ as depicted in Fig. 4, n_{2D} ($\cong 1.23 \times 10^{12} \text{ cm}^{-2}$) for $t_s = 5 \text{ nm}$ was higher than n_{2D} ($\cong 0.84 \times 10^{12} \text{ cm}^{-2}$, dominated by n_{SD}) for $t_s = 10$ and 15 nm by 46% [$= (1.23 - 0.84)/0.84$]. The percentage of the extra electrons released from DX centers in this specific “modulation doping” was estimated around 20% [$= (1.23 - 0.84) \times 10^{12} / (2 \times N_{2D} \times 0.7)$]. These electrons persistently confined within the active QW channel not only enhanced the total values of n_{2D} but also compensated the T -dependence of n_{2D} from the typical DX centers as mentioned above. Thus $n_{2D}(T)$ for $t_s = 5 \text{ nm}$ turned out to be relatively weak T -dependence with respect to decreasing- and increasing- T modes and hence no hysteresis curve was observed.

Effects of t_s on the T -dependence of electron mobility. The T -dependence of electron mobility $\mu_n(T)$ deduced from Hall-effect analysis on samples with various t_s ($= 5, 10$ and 15 nm) is demonstrated in Fig. 7. For $T = 40 \text{ K}$ 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 $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ active channel (from $y = -6$ to $+6 \text{ nm}$ as shown in Fig. 5a) could further reduce μ_n . In viewing of these two factors, the sample with $t_s = 15 \text{ nm}$ possessed a highest $\mu_n(40 \text{ K}) = (5.41 \pm 0.02) \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ among these three types of samples. With increasing T , μ_n decreases dramatically due to phonon scattering in the active channel. Nevertheless, $\mu_n(300 \text{ K})$ for all dual and symmetric Si- δ -doped AlGaAs/InGaAs/AlGaAs QW samples fabricated by this work still possessed relatively high values of $(6.43 \pm 0.06) \times 10^3$, $(7.17 \pm 0.16) \times 10^3$ and $(7.76 \pm 0.03) \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ 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 $N_{2D} = 1.40 \times 10^{12} \text{ cm}^{-2}$ and $s = 2.0 \text{ nm}$ were obtained for each profile. Next, $n_{2D}(T)$ and $\mu_n(T)$ 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 $t_s = 10$ and 15 nm but not for $t_s = 5 \text{ nm}$. 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 $T = 40 \text{ K}$ the lowest value of $n_{2D} = 0.84 \times 10^{12} \text{ cm}^{-2}$ 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 $t_s = 5 \text{ nm}$ (i.e., $t_s \leq 2.5 \text{ s}$), the actual distribution of $N_{Si}(y)$ 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 n_{2D} , and hence no hysteresis curve was observed. Finally, the effects of t_s on $\mu_n(T)$ 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 environments²⁰ 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- δ -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_s . (3) The active layer was fabricated by $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ with thickness $t_A = 12 \text{ nm}$. (4) After an undoped $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ space layer with thickness t_s , the second symmetric Si- δ -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/Au³¹ 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 $t_s = 5 \text{ nm}$ 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- δ -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 system³² on the cross-like sample with 4 numbered terminals as depicted in Fig. 2, and the linear I_x - 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 $I_x = 1.0 \text{ mA}$ applied between terminals $1 \leftrightarrow 3$ under a perpendicular $B_y = 5.0 \text{ kG}$, 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_x , V_{H2} was obtained similarly. Next, I_x was switched from terminals $1 \leftrightarrow 3$ to $2 \leftrightarrow 4$, and by repeating the above procedures V_{H3} and V_{H4} across terminals $1 \leftrightarrow 3$ were obtained again. Finally, by reversing the direction of the B -field and following the same procedures, $V_{H5} \sim V_{H8}$ 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 obtained²⁴ and the carrier concentration $n_0 = 1/qR_H$ was calculated. Furthermore, for resistivity measurement, the van 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 ρ of the sample was evaluated. From n_0 and ρ , the averaged value of μ_n 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 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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Author contributions

W. Y.-S. designed and outsourced the samples. W. Y.-S. and V. C.-P. performed Hall-effect analysis. W. Y.-S., C.-B., J.-S., J.-L., and K.-C. analyzed the data. C.-B., J.-S., and J.-L. are the Co-PI. K.-C. is the PI, conducted the project and wrote the manuscript. All of the authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to K.-C.C.

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