Electron transfer efficiency of Si δ-modulation-doped pseudomorphic $GaAs/In_{0.2}Ga_{0.8}As/Al_xGa_{1-x}As$ quantum wells

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In Si δ-modulation-doped $GaAs/In_{0.2}Ga_{0.8}As/Al_xGa_{1-x}As$ quantum well structures (QWs), the electrons from the ionized Si donors are initially confined in the V-shaped potential well (V-PW) formed at the position of a Si δ-doped layer. The efficiency of electrons transferring from the V-PW to the QW was investigated as a function of Si δ-doping concentration in the symmetric $GaAs/In_{0.2}Ga_{0.8}As/GaAs$ QW at 1.7 K. The electron density in the QW increases linearly with an increase of Si δ-doping concentration, while the electron transfer efficiency remains unchanged either in the dark or under the illumination. The asymmetric $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW has a relatively higher electron transfer efficiency. The effect of grading the Al mole fraction over the $Al_xGa_{1-x}As$ spacer layer on the electron transfer efficiency was also reported. © *1998 American Institute of Physics.* [S0003-6951(98)01209-1]

In comparison with (Al, Ga)As/GaAs quantum well structures (QWs), a larger conduction-band discontinuity at the heterojunction of (Al, Ga)As/InGaAs makes it possible to have a much higher electron density in the channel. A larger Γ-to-L valley energy separation in (Al, Ga)As/InGaAs induces a higher steady-state saturation velocity and a larger non-steady-state electron overshoot. Hence, the Si modulation-doped pseudomorphic (Al, Ga)As/InGaAs QWs have been widely used to fabricate high-speed electronic devices. The ensemble Monte Carlo simulation indicates that the use of a δ-doped layer in modulation-doped (Al, Ga)As/InGaAs QWs increases both the electron density and the drift velocity of electrons in the channel. They stem primarily from better electron confinement in the channel and reduced parallel conduction.[1] Those advantages are further manifested in improved device performance, particularly in the drain current drive capability and the transconductance of high electron mobility transistors.[2]

In Si δ-modulation-doped (Al, Ga)As/InGaAs QWs, the transfer of the electrons from the Si δ-doped layer to the QW substantially affects their transport and optical properties. For example, the residual electrons in the Si δ-doped layers result in undesirable parallel conductance. For a Si δ-doped layer with spatially confined distribution, the depth of the V-shaped potential well (V-PW) formed at the Si δ-doped layer is actually comparable to the conduction-band off-set of $In_{0.2}Ga_{0.8}As/GaAs$.[3] This deep V-PW prevents the electrons from completely transferring from the Si δ-doped layer into the QW. The different Si δ-doping positions relative to the well were recently investigated to find their effects on the properties of Si δ-modulation-doped (Al, Ga)As/InGaAs QWs.[4–6] A graded barrier layer was also proposed to enhance the electron transfer in Si δ-doped GaInP/InGaAs QW.[7]

In this work, the electron transfer efficiency in Si δ-modulation-doped $GaAs/In_{0.2}Ga_{0.8}As/Al_xGa_{1-x}As$ QWs was characterized by the ratio of the electron density in the QW over the Si δ-doping concentration. For the symmetric $GaAs/In_{0.2}Ga_{0.8}As/GaAs$ QW, the effect of Si δ-doping concentration on the electron transfer efficiency was investigated. The electron transfer efficiency of the asymmetric $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW with or without grading of the Al mole fraction over the $Al_xGa_{1-x}As$ spacer layer was compared with the symmetric QW.

The samples were grown at 630 °C by metal–organic vapor phase epitaxy using trimethylgallium, trimethylindium, and arsine (AsH_3) as growth precursors, and silane as a doping precursor. The substrate was semi-insulating (100) GaAs with 2° off towards [011]. The growth rate of GaAs was 2.6 μm/h with a constant V/III ratio of 200. Three different structures were schematically shown in Fig. 1. The Si δ-doped layer adjacent to the top surface [referred to as δ1 in Figs. 1(a)–1(c)] was used for good Ohmic contacts and to eliminate the effect of the surface states. δ2 is the Si δ-doped layer for modulation doping. The details of Si δ-doping were

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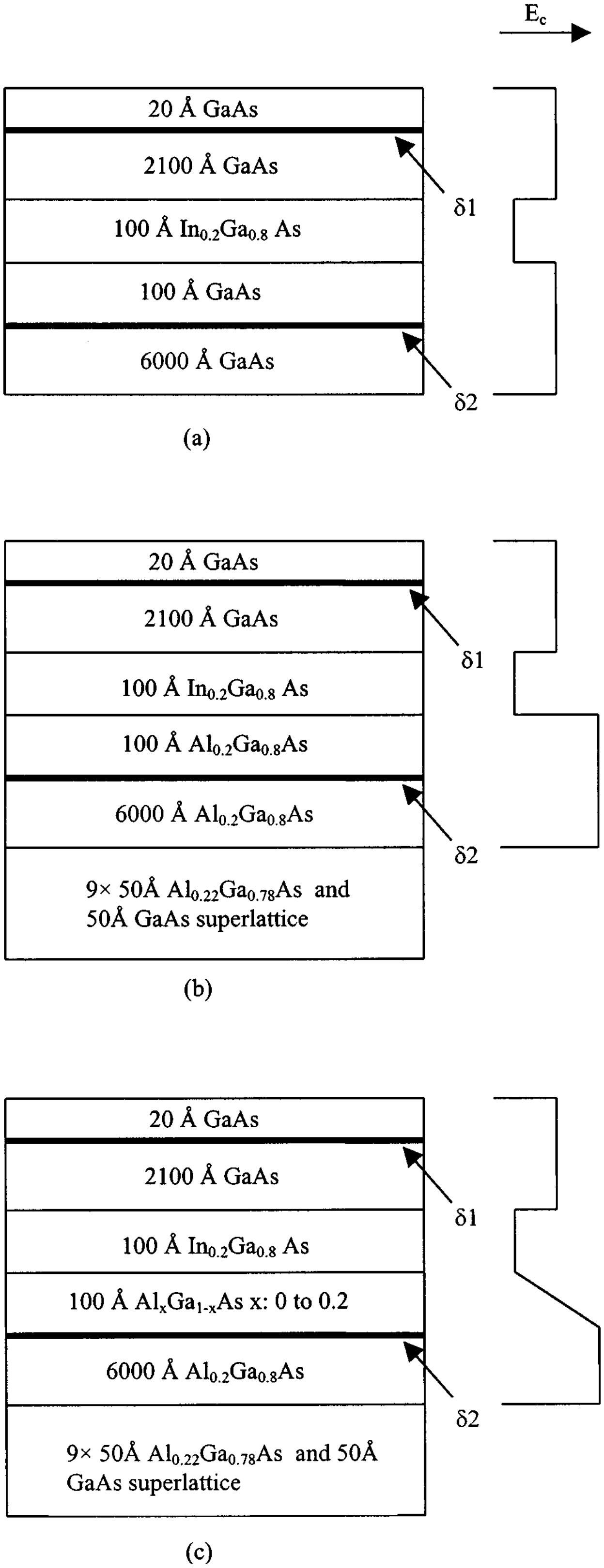

FIG. 1. Schematic diagrams of three structures used in this work: (a) the symmetric $GaAs/In_{0.2}Ga_{0.8}As/GaAs$ quantum well structure; (b) the asymmetric $GaAs/In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ quantum well structure; and (c) the asymmetric $GaAs/In_{0.2}Ga_{0.8}As/Al_xGa_{1-x}As$ with a linear grading of the Al mole fraction over the undoped $Al_xGa_{1-x}As$ spacer layer between the well and the Si δ-doped layer. The band structures of undoped QWs are also shown on the right. δ1 and δ2 indicate the positions of two δ-doped layers. δ1 with the electron density of 2.3×10^{12} cm^{-2} was used for good Ohmic contacts and to eliminate the effect of surface states.

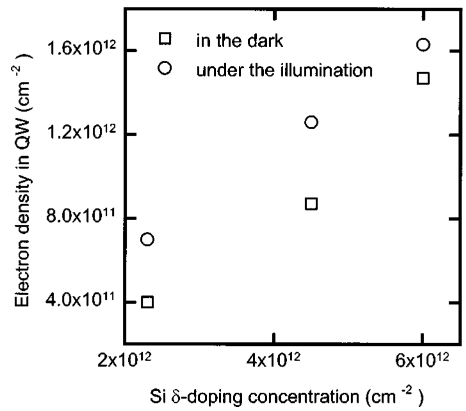

FIG. 2. The dependence of the electron density in the symmetric $GaAs/In_{0.2}Ga_{0.8}As/GaAs$ quantum well on the Si δ-doping concentration at 1.7 K.

given in a previous report.[8] Briefly, the pre-δ-doping purge time was 8 s with an AsH_3 flow rate of 15 sccm. The δ-doping time for δ2 was varied to have different Si δ-doping concentrations. The AsH_3 flow rate during the δ-doping step was 160 sccm. There was no post-δ-doping purge step. The electron profiles showed that the Si dopant memory effect was negligible. For the Si δ-doped layer with an electron density of 4.5×10^{12} cm^{-2}, the full width at the half maximum of the electron profile was about 50 Å, indicating the Si dopants are spatially confined to one or two atomic layers.[3] Magnetotransport measurements were performed over the magnetic-field range of 0–12 T in the dark or under the illumination of a red light-emitting diode at 1.7 K. Conventional Hall-effect measurements were carried out at room temperature. The samples were in the Hall bar geometry with alloyed Au–Ge Ohmic contacts.

In the symmetric $GaAs/In_{0.2}Ga_{0.8}As$ QW structure, the Si δ-doping concentration, referred to as δ2 in Fig. 1(a), was changed from 2.3×10^{12} to 6×10^{12} cm^{-2} at the GaAs spacer layer thickness of 100 Å. Figure 2 shows that the density of the two-dimensional electron gas (2DEG) in the QW increases linearly with an increase of the Si δ-doping concentration, while the electron transfer efficiency almost remains unchanged either in the dark or under illumination (see Table I). It is evident that the illumination excites some electrons from the Si δ-doped layer into the QW, which leads to a slight increase of the 2DEG density in the QW as well as the electron transfer efficiency. Besides, the electron transfer efficiency less than 30% at 1.7 K means that more than half of the electrons of the Si δ-doped layer remain in the V-PW. This results in substantial parallel conductance, as has been observed in our magnetotransport measurements. We also found that the Si δ doping at the GaAs barrier on the surface side or the substrate side of the QW does not affect the electron transfer efficiency.

The theoretical calculation shows that the energy level of the ground state in the V-PW is about 80 meV below the conduction-band edge outside of the V-PW.[3] This is comparable to the depth of the $In_{0.2}Ga_{0.8}As$ QW (about 100 meV below the conduction-band edge of GaAs). Note that most of the electrons in the Si δ-doped layer occupy the ground

TABLE I. A summary of Si δ-doping concentrations, Hall electron density, and mobility of Si δ-modulation-doped quantum well structures at room temperature; the density of 2DEGs in QWs and the electron transfer efficiency at 1.7 K. A: the symmetric GaAs/$In_{0.2}Ga_{0.8}As$/GaAs QW structure; B: the asymmetric GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ QW; and C: the asymmetric GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ QW with a linear grading of the Al mole fraction over a 100 Å $Al_xGa_{1-x}As$ spacer layer.

Structures	A			B	C
Si δ-doping concentration (cm^{-2})	2.3×10^{12}	4.5×10^{12}	6.0×10^{12}	6.0×10^{12}	6.0×10^{12}
Hall electron density (cm^{-2})	0.7×10^{12}	3.9×10^{12}	5.9×10^{12}	2.9×10^{12}	3.1×10^{12}
Hall mobility (cm^2/s V)	3375	2230	1950	3710	2400
2 DEG electron density in QW (cm^{-2})					
In the dark	0.4×10^{12}	0.9×10^{12}	1.5×10^{12}	1.8×10^{12}	1.6×10^{12}
Under illumination	0.7×10^{12}	1.3×10^{12}	1.6×10^{12}	2.2×10^{12}	1.9×10^{12}
Electron transfer efficiency					
In the dark	17%	19%	24%	29%	27%
Under illumination	30%	28%	27%	37%	32%

state.[9] With the Si δ-doped layer placed far away from the QW, and with the Si dopants being spatially confined to one atomic layer, the transfer of the electrons is greatly restricted by the potential barrier between two deep wells. In our samples, the spatial extent of the wave function of the electrons in the ground state of the V-PW is about 50 Å.[3] For the 100 Å separation between the Si δ-doped layer and the QW, the interaction of two 2DEGs is very weak, particularly between the two ground states. As a result, only the electrons occupying high subband levels in the V-PW could be possibly transferred into the QW. This led to a large amount of electrons remaining in the V-PW. However, a reduced spacer layer thickness may enhance the interaction between two 2DEGs for an increased electron transfer efficiency. At the same time, the use of a thin spacer layer may cause the distribution of the Si donors over the QW, which can significantly degrade the transport properties of 2DEGs in the QW. In the case where the Si donors are not ideally confined to one or two atomic layers, the spacer layer thickness must be carefully optimized between the electron transfer efficiency and the spatial confinement of the Si donors.

Compared to the symmetric GaAs/$In_{0.2}Ga_{0.8}As$ QW structure [see Fig. 1(a)], we found that the asymmetric GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ QW structure [see Fig. 1(b)] has a relatively higher electron transfer efficiency (see Table I). Under illumination at 1.7 K, the electron transfer efficiency is about 37%. The use of $Al_{0.2}Ga_{0.8}As$ as one side of the barriers eliminates a possible effect arising from the DX centers. The temperature-variable capacitance–voltage measurements showed that the Si δ-doped layer in GaAs or $Al_{0.2}Ga_{0.8}As$ had the same electron density over the temperature range of 300–77 K. No persistent photoconductivity effect was observed in Si δ-doped $Al_{0.2}Ga_{0.8}As$ at low temperatures. So, the increased electron transfer efficiency, as observed in the asymmetric QW, is ascribed to more electrons being transferred into the well due to the difference in the QW structure.

Using the same asymmetric QW structure as shown in Fig. 1(b), the Al mole fraction was linearly graded from 0 at the QW interface to 0.2 at the position of the Si δ-doped layer over the 100 Å thick $Al_xGa_{1-x}As$ spacer layer [see Fig. 1(c)]. The results in Table I show that the electron transfer efficiency is higher than that obtained using the symmetric QW structure but lower than that achieved using the asymmetric QW structure, either in the dark or under the illumination. This implies that the grading of the Al mole fraction over the $Al_xGa_{1-x}As$ spacer layer does not further improve the electron transfer efficiency. This does not support previous thought.[7] Explanation for these experimental findings relies on detailed calculation of the band structures of both the asymmetric QWs and the V-PW. Briefly, the use of a larger band gap of $Al_{0.2}Ga_{0.8}As$ in the asymmetric QW structure shifts the subband energy levels (including the ground-state level) in the V-PW up relative to those in the QW. Hence, the electrons even occupying the low subband levels in the V-PW could possibly be transferred into the well, which eventually increases the electron transfer efficiency.

In conclusion, at a given undoped GaAs spacer thickness, an increase of the Si δ-doping concentration increases the electron density in the symmetric GaAs/$In_{0.2}Ga_{0.8}As$/GaAs QW, while the electron transfer efficiency almost remains unchanged. Compared to the symmetric QWs, more electrons are capable of transferring from the V-PW into the QW in the asymmetric GaAs/$In_{0.2}Ga_{0.8}As$/$Al_{0.2}Ga_{0.8}As$ QWs, either in the dark or under illumination. The grading of the Al mole fraction over the undoped $Al_xGa_{1-x}As$ spacer layer in the asymmetric QW structure does not further improve the electron transfer efficiency.

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