Subband electron densities of Si δ-doped pseudomorphic $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures

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Magnetotransport properties of Si δ-doped pseudomorphic $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures grown by metalorganic vapor phase epitaxy have been investigated in magnetic fields up to 12 T in the dark at 1.7 K. Different δ-doping configurations, in which the same Si δ-doped layer was placed at different positions with respect to the $In_{0.2}Ga_{0.8}As$ well, have been studied to clarify their effect on subband electron densities in the well. Very high electron densities of $>4\times10^{12}$ cm^{-2} were obtained when placing a Si δ-doped layer at the well center or the well–barrier interface. We found that one subband was occupied in the well-center-doped structure, but when the Si δ-doped layer was at the well–barrier interface, the second subband in the well became occupied. The electron density of Si δ-modulation-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures, in which the cap barrier or the buffer barrier was Si δ doped, was in the order of $<1.2\times10^{12}$ cm^{-2}. The Si δ doping in both of the barriers led to an increase of the electron density by almost a factor of 2. Owing to an incomplete transfer of the electrons from the Si δ-doped layers to the well, parallel conduction was observed in the Si δ-modulation-doped structures. © *1997 American Institute of Physics.* [S0003-6951(97)03026-X]

Si-modulation-doped (Al,Ga)As/GaAs heterostructures have been widely used to fabricate high performance high electron mobility transistors. At room temperature, the mobility of quasi-two-dimensional electron gas confined at the heterojunction is limited by optical phonon scattering.[1] The improvement of the channel conductivity relies on an increase of the electron density. The electron density in (Al,Ga)As/GaAs heterostructures is fundamentally limited to $\sim1\times10^{12}$ cm^{-2}.[2] By comparison, much greater electron densities can be achieved in Si-modulation-doped pseudomorphic InGaAs/GaAs heterostructures owing to larger conduction-band discontinuity. A larger Γ-valley to L-valley energy separation in InGaAs also gives rise to a higher steady-state saturation velocity and larger non-steady-state electron overshoot.[3] Those advantages have made Si-modulation-doped InGaAs/(Al,Ga)As heterostructures increasingly attractive in high-speed electronic devices.[4–6]

Si δ doping has been used to improve electrical transport properties of modulation-doped (Al,Ga)As/GaAs and InGaAs/(Al,Ga)As heterostructures. Ensemble Monte Carlo simulation indicates that the use of a δ-doped layer not only increases the channel electron density but also the channel drift velocity.[7] Recently, different δ-doping configurations, in which Si δ-doped layers were placed at different positions, with respect to the InGaAs well,[4–6,8] have been used to optimize device structures. There have been a few reports on the subband electronic structure of molecular beam epitaxy grown Si δ-doped InGaAs/(Al,Ga)As heterostructures,[9–12] but differences in growth conditions and layer structures, i.e., the composition and thickness of $In_xGa_{1-x}As$ wells, make it impossible to clarify the effect of different δ-doping configurations. In this work, magnetotransport measurements were used to study subband electronic structures of Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures with different δ-doping configurations. In those heterostructures, the same Si δ-doped layer(s) was (were) placed at different positions with respect to the $In_{0.2}Ga_{0.8}As$ well, while the basic $In_{0.2}Ga_{0.8}As/GaAs$ heterostructure, such as well composition and thickness, was kept identical.

Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures were grown in low-pressure (76 Torr) metalorganic vapor phase epitaxy (MOVPE) at 630 °C. The precursors included trimethylgallium (TMGa), trimethylindium (TMIn), and 100% AsH_3. The carrier gas was H_2 and the doping precursor was 500 ppm SiH_4 diluted in H_2. The growth rate was 2 μm/h for GaAs and 1.2 μm/h for $In_{0.2}Ga_{0.8}As$. The (100) oriented with 2° off towards the (110) semi-insulating GaAs wafers were used as substrates. The details of Si δ doping have been previously described.[13] The sheet electron density of a Si δ-doped layer in GaAs used in this work was 4.5×10^{12} cm^{-2} for the full electron profile width at the half-maximum of ~50 Å. Magnetotransport measurements were performed over the magnetic-field range of 0–12 T in the dark at 1.7 K. The samples were in Hall bar geometry with alloyed Au–Ge Ohmic contacts.

The positions [(A)–(E)] of Si δ-doped layer(s) in the $In_{0.2}Ga_{0.8}As/GaAs$ heterostructure are schematically shown in Fig. 1. Those positions can be briefly described as follows: (A) at the well center; (B) at the well–barrier interface; (C) in the GaAs cap barrier layer 100 Å away from the interface; (D) in the GaAs buffer barrier layer 100 Å away from the interface; and (E) in both the GaAs cap and buffer barrier layers with the 100 Å spacer layer between the δ-doped layer and the interface. The traces of longitudinal resistivity (ρ_{xx}) as a function of magnetic field (B) are shown in Fig. 2. Clearly, different δ-doping configurations produce distinct traces in the shape. The fast Fourier transform analysis (FFT) was applied to the traces shown in Fig. 2, and the results are

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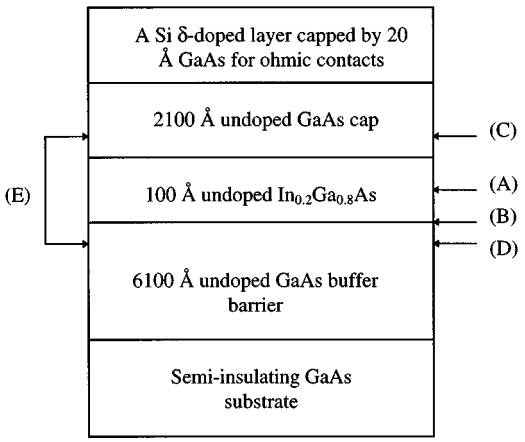

FIG. 1. A schematic diagram of the Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructure. The arrows indicate the positions of the Si δ-doped layer(s) in the structure: (A) at the well center; (B) at the well–barrier interface; (C) in the GaAs cap barrier layer 100 Å away from the interface; (D) in the GaAs buffer barrier layer 100 Å away from the interface; and (E) in both the GaAs cap and buffer barrier layers with the 100 Å spacer layer between the δ-doped layer and the interface.

presented in Fig. 3. The subband electron densities are summarized in Table I.

It can be clearly seen in Figs. 3(A) and 3(B) that compared to the one subband occupation in the well-center Si δ-doped heterostructure (A), the well–barrier-interface-doped heterostructure (B) has two subbands occupied. Those results are consistent with the self-consistent calculation based on similar structures, except there is a discrepancy in the subband electron densities.[9] The total electron density of the well–barrier-interface-doped heterostructure is 4.2×10^{12} cm^{-2}, which is greater than that (4.0×10^{12} cm^{-2}) of the well-center-doped one. This slight difference has been ascribed to a possible change of Si δ doping concentration when the δ doping was conducted on different nongrowing surfaces of GaAs (the well–barrier-interface doped) and $In_{0.2}Ga_{0.8}As$ (the well-center doped). Another possibility could be due to the different effect of a Si δ-doped layer at those two different positions on the subband electronic structure of the well.[9] Comparing to the electron density of a Si δ-doped layer in GaAs (4.5×10^{12} cm^{-2}), it is believed that most of the electrons are electrically active when the Si δ-doped layer is placed at the well center or the well–barrier interface.

When a Si δ-doped layer is placed in the barrier, the structure becomes modulation doped. The electron density of Si δ-modulation-doped heterostructures ($<2.1\times10^{12}$ cm^{-2}) is much lower than that of the well-doped (well center or well–barrier interface) heterostructures ($\sim4\times10^{12}$ cm^{-2}), as well as the electron density of the Si δ-doped layer itself. This means that when the Si δ-doped layer(s) is (are) located in the barrier layer(s), only a fraction of the electrons transfer from the δ-doped layer(s) to the well. This results in the presence of parallel conduction in modulation-doped heterostructures [see Figs. 2(C)–2(E)]. Similar parallel conduction has been attributed to the electrons resident in the Si δ-doped layers.[12,14] Furthermore, there is no significant difference in the well electron density between Si δ doping in the cap or

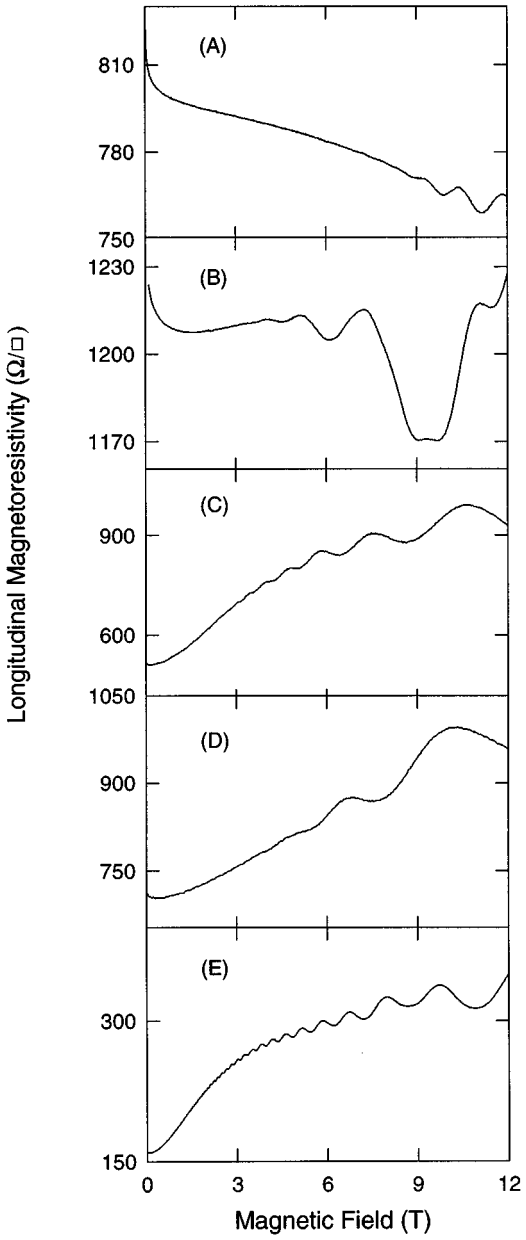

FIG. 2. The longitudinal resistivity as a function of magnetic fields in the dark at 1.7 K. (A)–(E) correspond to different δ-doping configurations:

buffer barrier. Compared to the structure in which only one barrier is modulation doped, Si δ doping in both of the barriers leads to an increase of the electron density by almost a factor of 2. The parallel conduction becomes even more significant. This further demonstrates that the deep V-shaped potential well formed in the Si δ-doped layer prevents the electrons from completely transferring from the δ-doped layer to the InGaAs quantum well. The well-doped structures appear to be more efficient in terms of having more free electrons in the channel, even though more electrons could be transferred into the InGaAs well by reducing the spacer layer thickness between the Si δ-doped layer and the well–barrier interface.

Skuras *et al.* reported that the quantum mobility of subband electrons can be estimated using the half-width at half-height of a FFT power spectrum.[15] Table I shows that the shift of a Si δ-doped layer from the well center to the well–

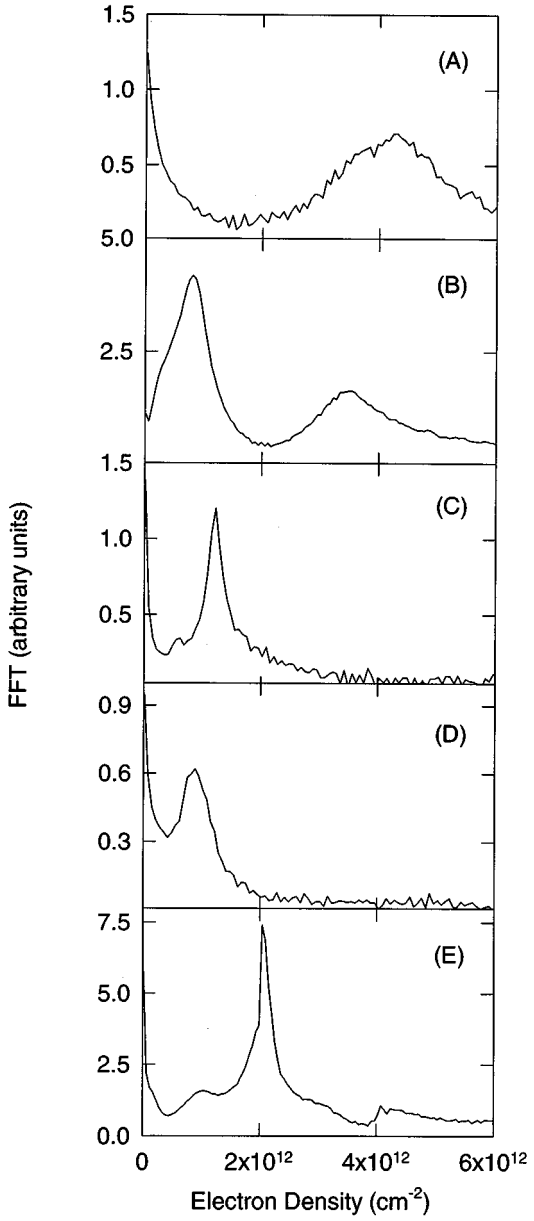

FIG. 3. The fast Fourier transform spectra of the traces shown in Fig. 2.

barrier interface does not significantly enhance the quantum mobility of electrons in the ground subband ($n=0$). This implies that the wave function of the ground-state electrons always strongly overlaps with the ionized Si donors regardless of the position of a Si δ-doped layer in such a narrow quantum well. However, the band structure of the quantum well seems to be sensitive to the position of a Si δ-doped layer. This results in only one subband occupied in the well-center-doped structure but two subbands occupied in the well–barrier-interface-doped one. The electron wave function can be spatially separated from the ionized Si donors by using modulation-doping configurations. Quantum mobilities of the modulation-doped structures are always much greater than those of the well-doped structures. Due to the presence of parallel conduction in the modulation-doped heterostructures and the two subband occupancy in the well–barrier-interface-doped heterostructure, the transport mobility of the subband electrons cannot be easily obtained to make a meaningful comparison with the quantum mobility.

TABLE I. The subband electron densities of Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures. n_0 and n_1 are subband electron densities deduced using the FFT spectra in Fig. 3, μ_0 and μ_1 are quantum mobilities deduced using the equation presented in Ref. 16. The electron densities are in the unit of 10^{12} cm^{-2} and the mobility in the unit of $cm^2\,s^{-1}\,V^{-1}$.

Sample	n_0	n_1	μ_0	μ_1
A	4.0	⋯	750	⋯
B	3.4	0.8	465	920
C	1.2	⋯	2200	⋯
D	0.9	⋯	2140	⋯
E	2.1	⋯	2700	⋯

In conclusion, the subband electronic structure of Si δ-doped $In_{0.2}Ga_{0.8}As/GaAs$ heterostructures grown in MOVPE have been studied using magnetotransport measurements. The shift of a Si δ-doped layer from the well center to the well–barrier interface has little effect on the quantum mobility of the ground-state electrons and the total electron density in the well. Two subbands are occupied in the well–barrier-interface-doped structure but only one in the well-center-doped heterostructure. Compared to Si δ doping in the well, Si δ-modulation-doped heterostructures have much lower electron densities in the well, but much higher quantum mobility due to spatial separation of the wave function from the ionized Si donors. The low electron densities arise from incomplete transfer of the electrons from the δ-doped layer(s) into the well. The electrons resident in the δ-doped layer(s) lead to the parallel conduction in Si δ-modulation-doped structures.

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