Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 550-552

Increased Electron Concentration in InAs/AlGaSb Heterostructures Using a Si Planar Doped Ultrathin InAs Quantum Well

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We demonstrate that the two-dimensional electron gas concentration in an InAs/AlGaSb heterostructure can be greatly increased by introducing a Si planar doped ultrathin InAs quantum well sandwiched by AlSb barriers as an additional electron supplying layer in a well controlled fashion. With the Si planar doped quantum well formed 8 nm below the channel layer, the sheet electron concentration increased up to 4.5 x 10^{12} cm^{-2} with the electron mobility of 4 x 10^4 cm^2/Vs at 77K. Shubnikov-de Haas measurements revealed that only two subbands are occupied even for heavily doped samples. The energy separation between the first and the second subbands is as large as 200 meV indicating the strong electron confinement in the selectively doped InAs/AlGaSb heterostructures.

1. Introduction

Major limitations of InAs/Al(Ga)Sb heterostructures for device applications arise from difficulties in the formation of selectively doped heterostructures. Higher two-dimensional electron gas (2DEG) concentration is advantageous for increasing the current drive capability of high electron mobility transistors (HEMTs)[1] and for the realization of superconducting transistors[2, 3]. In order to increase the 2DEG concentration, n-type doping is reported using Te as the donor in AlSb[4]. Use of Te may cause long term memory effects for molecular beam epitaxy (MBE). An alternative approach using Si as the n-type dopant is recently reported by Malik et al. using a Si doped InAs quantum well sandwiched by GaSb layers as an additional electron supplying layer[5]. Strong electron confinement is essential for the design of the quantum well electron supplying layer. Contrary to InAs, due to the heavier electron effective mass of GaAs, the limit lies at a fairly low concentration for planar doped GaAs/AlAs heterostructures even for the large bandgap of AlAs barriers[6, 7]. For InAs based heterostructures, the barrier height of the confinement layer is crucial for achieving the strong electron confinement since the effective mass of InAs is much smaller than that of GaAs. We thus employ AlSb barrier layers for achieving strong confinement effect in order to form an effective electron supplying layer.

2. Experimental

The cross sectional structure of our nominally undoped InAs/AlGaSb single quantum well heterostructure is shown in Fig. 1. The buffer layer consists of a 300-nm-thick GaAs, a 300-nm-thick GaSb, a 1.5-μm-thick AlSb, an AlSb/GaSb superlattice, and a 200-nm-thick AlGaSb barrier layer. The GaAs layer is grown at a substrate temperature of 600°C, the succeeding layers, 500°C. On top of the AlGaSb barrier layer, a 15-nm-thick InAs channel layer, a 15-nm-thick AlGaSb layer, and a 10-nm-thick GaSb layer are grown at 450°C. The sample is grown on a (100) semi-insulating GaAs substrate. Typical 2DEG mobility and concentration are 2 x 10^5 cm^2/Vs and 1 x 10^{12} cm^{-2} at 77K, respectively.

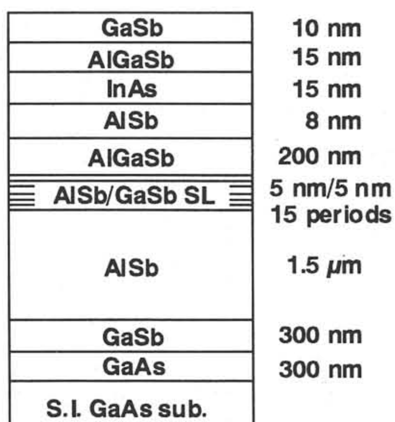

Fig. 1 Cross sectional structure of the undoped InAs/AlGaSb heterostructure.

We designed the Si planar doped ultrathin quantum well electron supplying layer based on the undoped structure. Since the 2DEG concentration is strongly affected by the surface structure[8], we kept the surface structure down to the InAs channel layer identical to that of the undoped structure. Figure 2 is the energy band diagram of the selectively doped structure formed with the Si planar doped ultrathin InAs quantum well electron supplying layer. The additional ultrathin quantum well is composed of a 6-monolayer-thick InAs layer. The Si planar doped plain is located at the center of the ultrathin InAs quantum well. The Si planar doping is made by impinging Si and As fluxes onto the growth interrupted surface after the 3-monolayer-thick InAs growth at a substrate temperature of 450°C. By increasing the Si flux while maintaining the growth interruption duration constant, we varied the Si sheet doping concentration, N_{ds}, from 1.4×10^{12} cm^{-2} to 6.5×10^{12} cm^{-2}. The corresponding Si cell temperature was increased from 947°C to 1030°C. This ultrathin quantum well is sandwiched between a 8-nm-thick AlSb on the surface side and a 4-nm-thick AlSb on the substrate side. Therefore, the planar doped electron supplying layer is 9 nm below the InAs channel layer where the 2DEG is formed. Undoped sample with the undoped thin InAs quantum well was also grown as a reference to study if the structure itself has an influence on the electronic properties of the 2DEG in the channel layer.

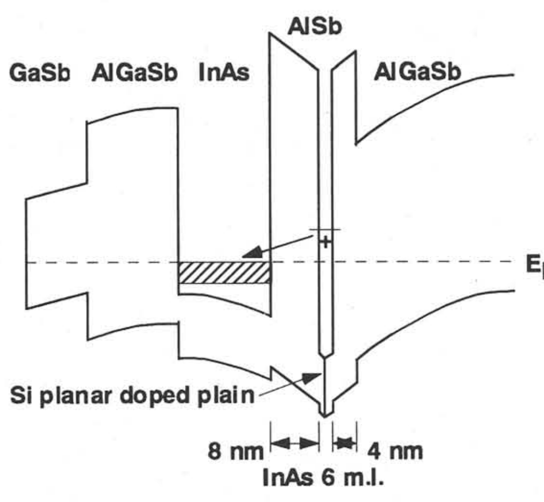

Fig. 2 Energy band diagram of the InAs/AlGaSb structure with a Si planar doped ultrathin InAs electron supplying layer. Most of electrons transfer from the elevated donor states in the ultrathin InAs quantum well into the thick InAs channel layer.

Van-der Pauw measurements were made to study the temperature dependence of the 2DEG mobility and the concentration for various N_{ds} at a temperature between 15 - 300K. In order to estimate the accurate 2DEG concentration in each electronic subband and the energy separation between the first and the second subbands, Shubnikov-de Haas (SdH) oscillations were observed for magnetic fields up to 8T at 4.2K.

3. Results and discussion

The 2DEG concentration, N_s, measured by van-der Pauw method at 77K is shown in Fig. 3. For $N_{ds} = 0$, both the undoped structure show in Fig. 1 and the reference structure with the undoped ultrathin InAs well showed almost identical 2DEG mobilities of $1.5\text{-}2 \times 10^5$ cm^2/Vs and concentrations of $8\text{-}9 \times 10^{11}$ cm^{-2}. Thus, the InAs electron supplying layer does not affect to the electronic properties of the 2DEG in the channel layer. The N_s value increases as the N_{ds} increases for $N_{ds} < 4 \times 10^{12}$ cm^{-2}, and then saturates. The increase in the 2DEG concentration corresponds to the increase of the N_{ds} indicating that all the Si donors doped in the thin InAs quantum well are ionized and contribute to the increase in the 2DEG concentration in the InAs channel layer. Since Si is a well controlled dopant for InAs, the 2DEG concentration can be varied in a well controlled fachion. For $N_{ds} > 4 \times 10^{12}$ cm^{-2}, the extra Si atoms, however, remain neutral and no longer contribute to the increase in Ns. The saturated value of N_s is as high as 4.5×10^{12} cm^{-2} which proves the achievement of the strong electron confinement due to the AlSb barrier layers.

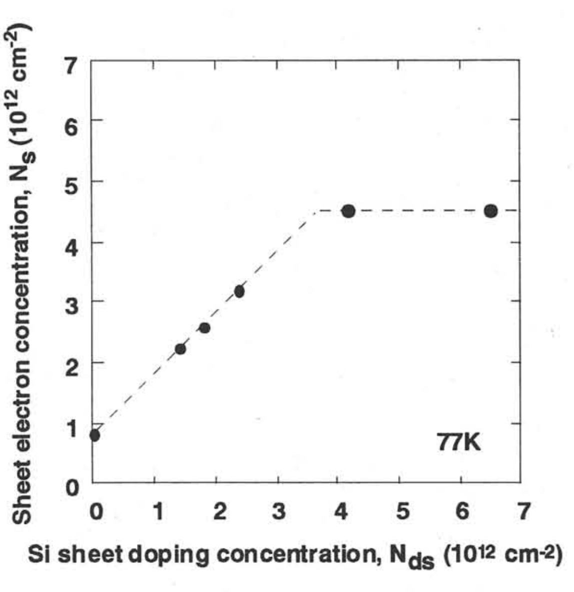

Fig. 3 Two-dimensional electron gas concentration, N_s, as a function of Si sheet doping concentration, N_{ds}, measured by van-der Pauw method at 77K.

The low temperature 2DEG mobility for $N_s > 2 \times 10^{12}$ cm^{-2} decreased as N_{ds} increased. It is explained by the onset of intersubband scattering as is evidenced by Shubnikov-de Haas measurements. We cannot, however, exclude increased ionized impurity scattering due to the possible diffusion of Si atoms toward the InAs channel layer since the 2DEG mobility continues to decreased as the N_{ds} increases. Therefore, further optimization of the growth condition for the formation of the planar doped quantum well would improve the 2DEG moblity.

The observed SdH oscillations were analyzed by taking fast Fourier transforms in order to estimate the 2DEG concentration for each occupied state and the subband energy spacing. Figure 4 shows the SdH oscillations for N_{ds} = 4 x 10^{12} cm^{-2}. Two oscillation components corresponding to N_s values of 3.1 x 10^{12} cm^{-2} and 1.1 x 10^{12} cm^{-2} can be seen in the figure. The subband spacing between the first and second lowest states is about 200 meV indicating the strong electron confinement in our InAs/AlGaSb heterostructure. This large subband spacing is especially useful for applications to quantum effect devices operating at higher temperatures.

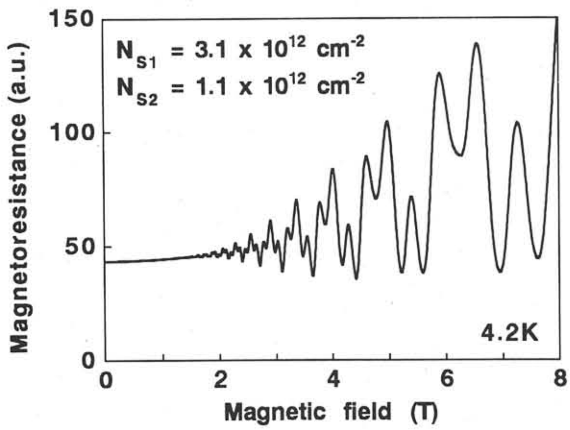

Fig. 4 Shubnikov-de Haas oscillations for N_{ds} = 4.1 x 10^{12} cm^{-2}. Two oscillation components correspond to the 2DEG concentrations of 3.1 x 10^{12} cm^{-2} and 1.1 x 10^{12} cm^{-2}.

4. Conclusions

We have demonstrated that the 2DEG concentration in InAs/AlGaSb heterostructures can be increased utilizing a Si planar doped ultrathin InAs quantum well. The use of AlSb barriers are crucial for the strong electron confinement for the formation of the electron supplying layer. The resulted 2DEG concentration was well controled by the Si sheet doping concentration and reached as high as 4.5 x 10^{12} cm^{-2}.

Acknowledments

The authors wish to thank C. Dono and K. Koike for their technical assistance in MBE growth. This work was partly supported by Grant-in-Aid for Scientific Research on Priority Area "Quantum Coherent Electronics, Physics and Technology."

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