Effects of barrier height on electron scattering mechanisms in δ-doped InAlAs/InGaAs/InAlAs Heterostructures

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Abstract

The effects of conduction band offset on 2 dimensional electron gas (2DEG) in N-InAlAs (AlAsSb) /InGaAs/ InAlAs (AlAsSb) metamorphic heterostructures (MMHS) are studied. A combination of the Shubnikov-deHaas oscillations and the Hall measurements is used to investigate the electron transport properties of these structures. The mobility in the second subband is higher than that in the first subband in all heterostructures. This is attributed to the fact that electrons in the first subband are, on average, closer to the interface and are therefore scattered more strongly by ionized impurities. The results suggest that intersubband scattering rate is more dominant in structures with higher conduction band offset whereas alloy scattering is found to be more dominant in the higher band offset system.

Key Words : Shubnikov-de Haas (SdH) oscillation, Hall effect, Heterostructures.

1. Introduction

The growth of InAlAs/InGaAs/InAlAs epilayer on lattice-mismatched GaAs substrates has gained much attention recently. This heterojunction system has potential applications in the field of infrared detector [1-3] and integrated optoelectronic devices with highly matured GaAs technology [4]. The exceptionally large conduction band discontinuity (ΔEc) in this system leads to excellent carrier confinement and high two dimensional electron gas (2DEG) concentration in modulation doped structures. Such an InGaAs channel also offers high electron mobility at low field, high peak electron velocity, and low contact resistance. All of these attributes make the strained InAlAs/InGaAs/InAlAs a very important material system for high speed modulation doped field-effect transistors (MODFETs). They have larger conduction band offset which enhance their transconductance and performance. Because of the higher peak electron velocity in the InGaAs channel, devices with high current gain cut-off frequency and fast switching speeds have been realized fabricated. Delta doping technique has been successfully used in molecular beam epitaxy to confine dopants in layers only a few monolayers wide [5]. The high density electron gases in delta-doped heterostructures are desirable for field effect transistors because they enhance their transconductance. Furthermore, the delta-doping also results in enhanced electron mobility. However, if the 2DEG is large, population of higher subbands may occur and a new scattering channel due to intersubband transitions is introduced. This could lead to a significant reduction in the electron mobility. Thus an understanding of the effect of the population of the excited subband on the transport properties in these structures is essential.

In this paper, we reported for the barrier height and multiple subband population on the 2DEG in δ-doped InAlAs(AlAsSb)/InGaAs/InAlAs(AlAsSb) heterostructures on lattice-mismatched GaAs substrates are investigated using the temperature dependence of the Shubnikov-de Haas (SdH) oscillations and the Hall effect. Scattering processes caused by ionized impurities, alloy disorder, and intersubband transitions are tentatively deduced from the dependence of the mobility on carrier concentration using the persistent photoconduc(PPC) effect.

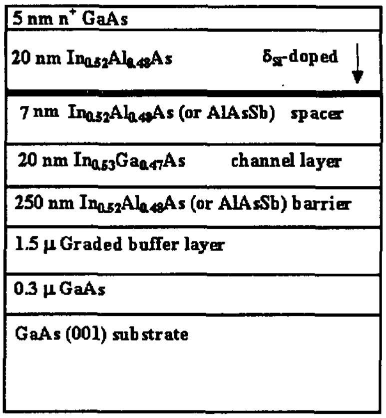

Fig.1 A vertical metamorphic structure N-In$_X$Al$_{1-X}$As/In$_V$Al$_{1-V}$As/In$_X$Al$_{1-X}$As.

2. Experimental details

N-InAlAs(AlAsSb)/InGaAs/InAlAs(AlAsSb) metamorphic heterostructures (MMHSs) were grown by solid-source molecular beam epitaxy (MBE) on semi-insulating GaAs (001) substrates. The graded buffer layer (GBL) in which composition varied from In$_{0.1}$(GaAs)$_{0.99}$As to In$_X$Al$_{1-X}$As were grown between heterostructures and substrates. We studied MMHSs with the different barrier layer of AlAs$_{0.56}$Sb$_{0.44}$ and In$_{0.52}$Al$_{0.48}$As. All layers, except the GBL, were grown at T$_{sub}$=520°C, but GBL were grown at T=420°C. In fig.1 showed a typical vertical structure of MMHS. This structure has 0.3 μm thickness undoped GaAs, 1.5 μm thickness GBL, 0.25 μm thickness undoped In$_{0.52}$Al$_{0.48}$As, 20 nm In$_{0.53}$Ga$_{0.47}$As channel layer, 7 nm undoped In$_{0.52}$Al$_{0.48}$As spacer, Si delta-doped N-In$_{0.52}$Al$_{0.48}$As donor layer with $N_{Si}^{2D}= 7\cdot10^{12}$ cm^{-2}, 20 nm undoped In$_{0.52}$Al$_{0.48}$As layer and, finally, 5 nm GaAs n$^+$ cap layer for sample A. For sample B, instead of In$_{0.52}$Al$_{0.48}$As, AlAs$_{0.56}$Sb$_{0.44}$ barrier was grown. As a result the conduction band offsets for the two structures are different. It is 0.52 eV for the sample A and 1.75 eV for the sample B. Mobility n_H and 2DEG Hall concentration n_H in MMHSs were measured by Van der Pauw method at various temperature helium. The double cross Hall bridges were fabricated by the photolithography and subsequent wet etching technique. Hall and longitudinal magneto-resistivities were measured on dc current in normal magnetic fields up to 10 T in the steady regime within the temperature range of 1.4 to 300 K.

3. Results and discussion

Much information concerning scattering mechanism in our structures is available from temperature dependent mobility measurements. Plotted in fig.2 are the electron mobility and sheet density of sample A before illumination with a red light emitting diode (LED) and after saturation which

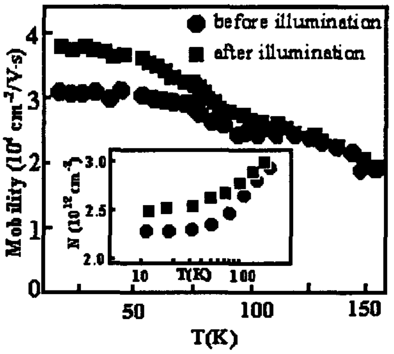

Fig.2 Temperature dependence of mobility before and after illumination in metamorphic heterostructures (MMHSs).

occurred after an extended period of illumination. The light illumination produces an enhancement in the 2DEG density and mobility at low temperatures. However, the light has no substantial effect on electron mobility above about 105 K, though an increase in the 2DEG density is clearly observed. Any increase in the concentration due to illumination is negligible when the doping level is fixed and the temperature varies. The PPC effect is also negligible, as shown in the fig.2. As a result the density of the DX center is negligible in this sample. Similar effects were obtained for sample B but with higher mobility and carrier concentration.

In Fig.3 the ρ_{xx} and ρ_{xy} spectra of sample A are displayed as a function of magnetic field at a temperature of 1.4 K. Well-defined quantum hall plateaus corresponding zeros in the magnetoresistivity are typical behavior of 2DEG systems. The SdH oscillation in fig.3 clearly shows a beating pattern which is indicative of a multiple subband population. The occupation of the second subband causes an intersubband scattering of the two subbands producing the beat. The fast Fourier transform of the magnetoresistance in inverse magnetic field(see the inset of fig.3) yields two peaks at two different frequencies. The amplitude of the peak of the fast Fourier transform for the second subband is higher than that of the first subband. This means that the quantum lifetime of the second subband is higher than that ofthe first subband [6]. Because electrons in the first subband in a heterostructure are, on average, closer to the interface and hence closer to the ionized impurities in the doped layer, they will be scattered more strongly than those in the second subband [7]. Therefore the electron mobility of the first subband is smaller than that of the second subband. The electron densities in the first and the second subbands calculated from these two SdH frequencies are 1.42 and 0.41×10^{12} cm^{-2}, respectively. Similarly, the electron densities in sample B were found to be 2.13 and 0.70×10^{12} cm^{-2}. Through the PPC effect in the InGaAs channel layer, the electron density in the samples studied can be increased by illumination with a red light emitting diode. After cooling to 4.2 K in the dark, the electron densities increased from 1.42 to 1.72×10^{12} cm^{-2} (2.13 to 2.42×10^{12} cm^{-2}) for the first subband and from 0.41 to 0.52×10^{12} cm^{-2} (0.70 to 0.86×10^{11} cm^{-2}) for the second subband in sample

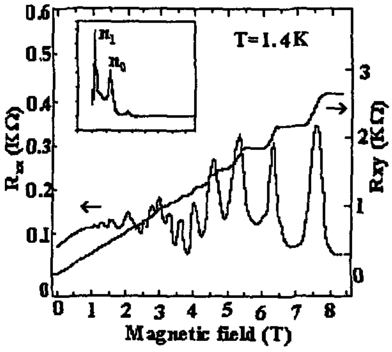

Fig.3 Magnetoresistivity and the quantum Hall resistance of sample A for an electron density of n_H= 1.61×10^{12} cm^{-2} at a temperature T=1.4 K. This n_H has been reached by illumination with red LED using the persistent photoconductivity effect. The inset shows the FFT of the magnetoresistance in inverse magnetic field.

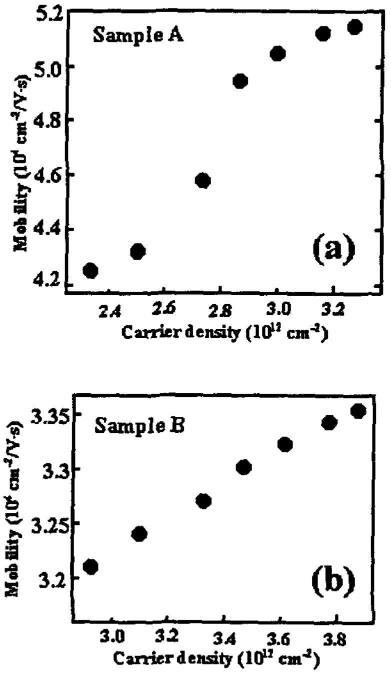

Fig.4 The Hall mobility vs. carrier concentration for sample B and for sample A in the inset.

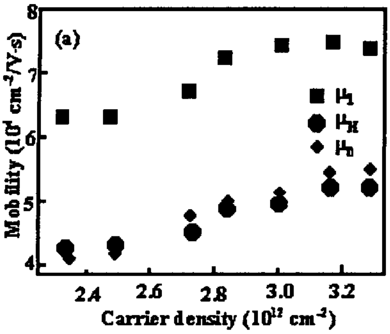

Fig.5 The mobilities of the first and second subbands and Hall mobility as a function of total carrier concentration in sample A.

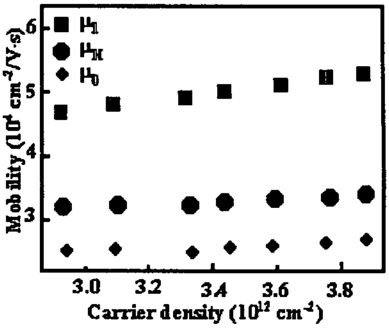

Fig.6 The mobilities of the first and second subbands and Hall mobility as a function of total carrier concentration in sample B.

A (B). The dependence of the Hall mobility on the Hall concentration is shown in fig.4 for both heterostructures. It is clear that the Hall mobility increases with increasing carrier concentration. The values of n_H and μ_H are obtained from the low field Hall measurements, while n_0 and n_1 are obtained from the frequencies of the SdH oscillations as discussed earlier. Then the mobility in the ground and excited subbands are calculated. The results together with the Hall mobility are plotted as a function of the Hall concentration in fig.5 for structure A and in fig.6 for that of B. The mobility in the second subband exceeds that of the first subband by a factor of 1.5 in both structures. This is consistent with the report of Ramvall et al. [8] where it was found that the quantum scattering time is determined by the remote ionized impurity scattering rate. The data suggests that there are two major differences between the two different heterostructures. First, the carrier concentration in the well of structure B is higher than that of A. Second, the mobility in structure B is lower than those of structure A. It is noticeable that the only difference between the two heterostructures is the conduction band offset. The conduction band offset of structure B is 1.75 eV, while that of A is only 0.52 eV. The larger conduction band offset in B results in stronger potential confinement and therefore more electrons can be accommodated in the well. Bastard et al. [9], in a study of electronic transport properties of InGaAs-based heterostructures focusing on a comparison between InP/InGaAs and InAlAs/InGaAs, determined that alloy disorder scattering in InGaAs quantum wells is important. They found that for a given well width, the quantum wells with larger conduction band offset displayed a lower mobility, in agreement with our results. The occupation of the second subband results in a new scattering channel, giving rise to intersubband scattering.

Intersubband scattering leads to about 30-50% reduction in mobility [10, 11]. In our case, the first and second subbands were populated before illumination for both structures. Therefore, we were unable to study this effect. However, one would expect that intersubband scattering would be more dominant in sample A as the energy level separation is lower. The energy difference between the minima of the first subband and the second subband are 59 and 68 meV for sample A and B, respectively. The mobility dependence on carrier concentration in figs. 5 and 6 show that the Hall mobility is equal to the mobility of the first subband in sample A but higher in sample B. It is believed that this due to a stronger intersubband scattering rate between the first and the second subband in sample A.

4.Conclusions

We have studied the electronic transport properties of δ-doped InAlAs/InGaAs/InAlAs metamorphic heterostructures (MMHSs) grown by solid-source MBE on semi-insulating GaAs (001) substrates, using the temperature dependence of the Shubnikov-de Haas oscillations and the quantum

Hall effect. We have observed two oscillations due to the population of the first two subbands in the InGaAs quantum wells in both heterostructures. Both structures showed a positive PPC response after illumination with a red LED. The electron mobility increased with increasing concentration in both heterostructures. This is attributed to the effects of electron screening by ionized impurities. This is due to the fact that the electrons in the first subband are, on average, closer to the interface and hence closer to the ionized impurities. As a result, they will scatter more strongly than electrons in the second subband. We have also found that the mobilities in the AlAsSb/InGaAs/AlAsAb (sample B) are lower than those in the InAlAs/InGaAs/InAlAs (sample A) heterostructures. We attributed this as due to the stronger alloy scattering rate as a result of higher barrier height confinement. Since the barrier height of InAlAs/InGaAs/InAlAsis lower than that of AlAsSb/InGaAs/AlAsSb, it is expected that the electrons are more confined in the latter and as a result they are affected more by alloy scattering in the InGaAs channel. The ionized impurity scattering tend to be dominant at temperatures below about 105 K. For samples with the second subband is lightly populated, the mobility can be increased due to the suppression of intersubband scattering, when the subband separation is increased by a higher barrier.

References

[1] Y. C. Tzeng, S. S. Li, Y. W. Lin, P. Ribas, and R. M. Park, Appl. Phys. Lett. 58, p.2396, 1991.

[2] W. Dobbelaere, J. De Boeck, P. Heremans, R. Mertens, G. Borghs, W. Luyten, and J. Van Landuyt, Appl. Phys. Lett. 60, p.868, 1992.

[3] W. Dobbelaere, W. De Raedt, J, De Boeck, R. Mertens, and G. Borghs, Electron. Lett. 28, p.372, 1992.

[4] D. L. Rogers, J. M. Woodall, G. D. Pettit and D. McInturff. IEEE electron device Lett. EDL-9, p.515, 1998.

[5] E. F. Schubert. J. Vac. Sci. Technol. A 8, p.2980, 1990.

[6] Ikao. Lo, W. C. Mitchel and M. Ahoujja, Appl. Phys. Lett. 66, p.754, 1995.

[7] T. P. Smith and F. F. Fang, Phys. Rev.B 37, p.4303, 1988.

[8] P. Ramvall, Appl. Phys. Lett.70, p.243, 1997.

[9] G. Bastard and R. Ferreira, Semicond. Sci, Technol, 5, p.470, 1990.

[10] H. L. Stormer, A. C. Gossard, and W. Wiegmann, Solid State Commun.41, p.707, 1982.

[11] T. Englert, Solid State Commun. 45, p.989, 1983.