Magnetotransport study on the defect levels of delta-doped In$_{0.22}$Ga$_{0.78}$As/GaAs quantum wells

Ikai Lo, a J. R. Lian, H. Y. Wang, M. H. Gau, J. K. Tsai, and Jih-Chen Chiang
Department of Physics and Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan, Republic of China

Y. J. Li and W. C. Hsu
Institute of Microelectronics, National Cheng Kung University, Tainan 70101, Taiwan, Republic of China

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We have studied the electronic properties of delta-doped In$_{0.22}$Ga$_{0.78}$As/GaAs quantum wells (QWs) by van der Pauw Hall measurements and Shubnikov–de Haas measurements. From the temperature-dependent van der Pauw Hall measurements, we observed two kinds of donors, which have binding energies of 104±7 and 9.6±0.1 meV. After inserting In$_{0.1}$Ga$_{0.9}$As layers between the In$_{0.22}$Ga$_{0.78}$As and GaAs layers, a single donor with binding energy of 50±2 meV was observed. The carrier concentration determined by SdH measurements did not change after the QWs were illuminated at low temperature, which indicates that these deep donors could not produce a persistent photoconductivity in delta-doped In$_{0.22}$Ga$_{0.78}$As/GaAs QWs. © 2006 American Institute of Physics. [DOI: 10.1063/1.2337857]

I. INTRODUCTION

InGaAs-based quantum wells (QWs) have recently attracted great interest due to a wide range of electronic properties induced by the fundamental built-in strain and variety of constituent materials in the applications of electronic and optoelectronic devices. For instance, one can select appropriate alloy compositions and barrier materials for QWs to match the lattice constant of the substrate, e.g., In$_{0.52}$Al$_{0.48}$As/In$_{0.55}$Ga$_{0.47}$As QW grown on InP substrate, or choose the more mature GaAs as a substrate to grow a strain-layered QW, e.g., In$_{0.1}$Ga$_{0.9}$As/GaAs QW. 3–6 Because the lattice constant of InAs (6.0583 Å) is much greater than that of GaAs (5.653 25 Å), a strain is built in the In$_{1-x}$Ga$_x$As/GaAs system when the lattice-mismatched QW is grown. To attain the optimum strain properties in the lattice-mismatched QW, one has to overcome two obstacles: (i) keeping the layer thickness under the critical strained-layer condition and (ii) reducing the defects caused by the lattice mismatch. The lattice-mismatched In$_{1-x}$Ga$_x$As/GaAs system becomes an important example to study the mechanism of strain relaxation and the critical strained-layer condition. 7 It can be either a pseudomorphic structure, in which the lattice mismatch is accommodated only by coherent elastic strain, or a relaxed structure, in which the mismatch is accommodated by both elastic strain and the formation of misfit dislocations. The critical strained-layer thickness for the In$_{1-x}$Ga$_x$As/GaAs system grown by molecular beam epitaxy (MBE) showed an approximate inverse-square-law dependence on the indium composition $x$, the so-called Dodson-Tsao model. 7,8 In Fig. 1, we drew the critical thickness curve for In$_{1-x}$Ga$_x$As layer based on Dodson-Tsao’s model (referred to curve b in Fig. 1 of Ref. 8). In the relaxed structure, the dislocations always induce deep-level electron traps, which affect the electronic properties and deteriorate the performance of devices made of the QWs. In previous studies, persistent photoconductivity (PPC) effect was used as a tool to investigate the effect of the deep-level donors on the two-dimensional electron gas (2DEG). In Fig. 1, we plotted the layer thickness ($w$) versus indium composition ($x$) for $\delta$-doped pseudomorphic In$_{1-x}$Ga$_x$As/GaAs QWs, in which a PPC effect has been reported (point A is obtained from Ref. 3, point B from Ref. 4, point C from Ref. 5, and point D from Ref. 6). These QWs have an indium composition ($x$) from 0.15 to 0.2 and an In$_{1-x}$Ga$_x$As well thickness ($w$) between 9 and 15 nm. Based on Dodson-Tsao’s model, these In$_{1-x}$Ga$_x$As layers are strained and the $\delta$-doped QWs are pseudomorphic structures.

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1Electronic mail: ikailo@mail.phys.nsysu.edu.tw

FIG. 1. The Dodson-Tsao critical layer thickness vs indium composition for InGaAs/GaAs layer at 550 °C growth temperature. Points A, B, D, and D are the sample structure of the pseudomorphic InGaAs/GaAs quantum wells shown in Refs. 3–6 respectively, where a persistent photoconductivity was reported. The band profile of sample 1 is shown in the inset.
Because DX centers are not favored to form in a δ-doped layer, an interesting question has arisen: what is the origin and physical mechanics of the PPC effect on these δ-doped pseudomorphic QWs? Particularly, when the δ-doped layer was placed close to the InGaAs well, the problem became more complicated due to the presence of two possible channels (InGaAs well and the V-shaped potential well at δ-doping layer) where electrons can transfer from one channel to the other. The characteristics of the deep-level donors, which produce PPC effect in the δ-doped pseudomorphic QWs, are still unclear. The binding energy of the donors, which produce PPC effect in the channel to the other. The characteristics of the deep-level donors, which produce PPC effect in the channel to the other. The characteristics of the deep-level donors, which produce PPC effect in the channel to the other.

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obtained the donor level of Ed and Lo et al. /H20849 while concentration exponentially increases with temperature. The exponential increment becomes even faster in the high temperature region (i.e., >175 K). From Fig. 3, it is obvious that the slopes of the exponential curve in the middle and high temperature regions are quite different. Because the exponential increase of carrier concentration is mainly due to the ionization of donor levels, two different kinds of donor levels exist, and each dominates the different temperature regions. We fitted the curve to the equation \( n_H \sim \exp(-E_d/2kT) \) and obtained the donor level of \( E_d1 = 104 \pm 7 \) meV, which was dominant in the high temperature region, and another level of \( E_d2 = 9.6 \pm 0.1 \) meV, which was dominant in the middle temperature region. The carrier mobility \( \mu \) is almost constant in the low temperature region when the phonons are frozen and then decreases with increasing temperature. This is a typical characteristic of two-dimensional electron gas in QW.\(^{12}\)

The van der Pauw Hall measurement was performed on sample 2 in the same way. The carrier concentration of sample 2 was plotted in logarithmic scale versus 1000/T in Fig. 4 and its mobility against T in the inset. At the low temperatures, the carrier concentration is equal to 3.895 \( \times 10^{12} \) cm\(^{-2} \), and exponentially increases in a monominal manner up to 4.509 \( \times 10^{12} \) cm\(^{-2} \) at 300 K. A single donor level of \( E_d2 = 50 \pm 2 \) meV was derived from the equation \( n_H \sim \exp(-E_d/2kT) \). The carrier mobility \( \mu \) showed the characteristic of 2DEG as well. From Figs. 3 and 4 we found that after the insertion of In\(_{0.1}Ga_{0.9}\)As layers, the carrier concentration increased (e.g., at 4.2 K, \( n_H = 3.127 \times 10^{12} \) cm\(^{-2} \) for sample 1 and \( 3.895 \times 10^{12} \) cm\(^{-2} \) for sample 2), and the mobility was enhanced (\( \mu = 13.9 \times 10^{3} \) cm\(^2\)/V s for sample 1 and \( \mu = 17.0 \times 10^{3} \) cm\(^2\)/V s for sample 2 at 4.2 K). After the insertion of In\(_{0.1}Ga_{0.9}\)As layers, the further separation of 2DEG from the doping barriers is one of the sources that the mobility is enhanced. In addition, the removal of the electron-dislocation scattering may enhance the electron mobility at low temperatures, when the sample structure turns from a relaxed QW to a pseudomorphic one. The donor level evaluated from above equation, \( n_H \sim \exp(-E_d/2kT) \), is sometimes underestimated due to the contribution of shallow donors. Schubert and Ploog studied the shallow and deep donors in bulk n-type Al\(_{0.22}Ga_{0.78}\)As including the contribution of shallow-donor concentration \( N_{SD} \), and derived an equation \( (n_H - n_PN_{SD})^{1/2} = \exp(-E_d/2kT) \) to fit the plot of carrier concentration versus 1000/T.\(^{13}\) They found that the donor level increased to 135 meV, which was 78 meV if calculated by the equation \( n_H \sim \exp(-E_d/2kT) \). However, if we recalculated the donor levels using Schubert and Ploog’s equation \( (n_H - n_PN_{SD})^{1/2} = \exp(-E_d/2kT) \), we obtained \( E_d1 = 70 \pm 7 \) meV with \( N_{SD} = 3.127 \times 10^{12} \) cm\(^{-2} \) for sample 1 (\( E_d2 \) could not be calculated due to the negative value inside the square root) and \( E_d2 = 32 \pm 2 \) meV with \( N_{SD} = 3.895 \times 10^{12} \) cm\(^{-2} \) for sample 2. It suggested that Schubert and Ploog’s equation could not be applied to our case. In our case, most of the shallow donors that reside at the Si-doped n-type Al\(_{0.22}Ga_{0.78}\)As barriers are much higher than the Fermi level. The electron transfer occurs from the shallow donors into the In\(_{0.22}Ga_{0.78}\)As well at the whole temperature range (4.2 K < T < 300 K). They do not contribute to the Boltzmann thermal statistics. Therefore, Schubert and Ploog’s equation is appropriate to the case of bulk semiconductors (e.g., in Ref. 13) or the heterostructure whose barrier height is about the same order as the thermal energy (kT). For a deep quantum well sample (e.g., our case), the donor level is more appropriately calculated by the equation \( n_H \sim \exp(-E_d/2kT) \).

Shubnikov–de Haas measurement was applied to two Hall-bar samples cut from the same wafers as van der Pauw samples, for the magnetic field from 0.25 up to 12 T at the temperature of 0.38 K. The magnetoresistance \( R_{XX} \) of 2DEG was taken in equal spacing of reciprocal field (1/B) for the Fourier analysis purposes. The data points (total number = 2048) were taken by an ac lock-in technique with the modulation frequency of 80 Hz and a current of about 1 \( \mu \)A. The resolution of SdH frequency in the FFT spectrum is equal to 0.255 T. Figure 5(a) shows the \( R_{XX} \) versus magnetic field for sample 1 before and after illuminating the sample by a blue light-emitting diode (LED) at 0.38 K for more than 1 h. The SdH oscillations appeared at the magnetic field...
The effective mass was checked with the result obtained by [1]. In 0.22Ga0.78As well. The carrier concentration of 2DEG EF was derived from the frequency of SdH oscillations, n2D =0.023×1012 cm−2. The higher than 3 T before the illumination, but the noise level was almost in the same order of amplitude as the signal. The Shubnikov–de Haas (SdH) frequency (fSdH) was obtained from the fast Fourier transformation (FFT) of the data. The SdH oscillations were attributed by the 2DEG in In0.22Ga0.78As well. The carrier concentration of 2DEG (n2D) was derived from the frequency of SdH oscillations, fSdH =hn2D/2e, where h is the Planck constant and e is the electron charge. From the fast Fourier transformation of the SdH oscillations, we obtained fSdH=39.319 T for sample 1, and the corresponding carrier concentration is n2D =1.907×1012 cm−2. The carrier concentration n2D is much smaller than that obtained from the van der Pauw Hall measurement at 4.2 K (nH=3.127×1012 cm−2). This indicates that free electrons might populate more than one subband in In0.22Ga0.78As well and in the V-shaped potential well. We can check this by comparing Fermi level of the 2DEG with the energy separation between the lowest two subbands (≈75 meV measured by photoluminescence). For a 2DEG, the energy difference between the Fermi level (EF) and the minimum of the ith subband (Ei) is equal to EF−Ei=rh2n2D/m∗, where m∗ is the effective mass and h is the reduced Planck constant (h/2π). From the carrier concentration (n2D=1.907×1012 cm−2) and the effective mass m∗=0.057m0 [which was calculated from the linear approximation of InxGa1−xAs with m∗(GaAs)=0.067m0, m∗(InAs) =0.023m0, and x=0.22], we obtained EF−Ei=80.1 meV. The effective mass was checked with the result obtained by van der Burgt et al.,4 who measured the effective mass of In0.2Ga0.8As/GaAs QW by temperature-dependent SdH oscillation, m∗=0.058m0 for x=0.2. Therefore, the Fermi level is high enough that the carriers will populate more than one subband of 2DEG in the well. However, after the illumination, the SdH frequency determined from the FFT analysis did not change. The zero of y axis for the illuminated data has been offset for easy comparison. It implies that the carrier concentration of 2DEG in the In0.22Ga0.78As well did not change and the donor levels (Ei1 and Ei2) would not produce a PPC in this relaxed QW.

How does the PPC effect work when the relaxed QW turns to a pseudomorphic QW? We repeated the SdH measurement on sample 2 under the same conditions. Figure 5(b) shows the RXX versus magnetic field before and after illumination. The SdH oscillations are very clear and can be detected even at the magnetic field lower than 1 T. The SdH frequency determined from the FFT analysis is fSdH =36.621 T, and the carrier concentration obtained is n2D =(1.776±0.006)×1012 cm−2. The carrier concentration n2D is much smaller than that obtained from the van der Pauw Hall measurement at 4.2 K (nH=3.895×1012 cm−2). If we used the same calculated effective mass m∗=0.057m0, the energy difference between the Fermi level and the minimum of the ith subband is (EF−Ei)=75 meV. This indicates that the subband levels in the In0.22Ga0.78As QW were shifted up (related to the Fermi level). This upshift of energy is generated by the strain built in the pseudomorphic In0.22Ga0.78As layer and the reduction of the layer thickness from 12.5 nm to 9 nm. The multiple-subband population results in the parallel conduction and the deformation of SdH oscillations at high magnetic fields. We also checked the PPC effect for sample 2 to evaluate the role of the deep donor. After illumination, the frequency of SdH oscillations did not change. The zero of y axis for the illuminated data has been offset as well. Because the In0.22Ga0.78As well is relaxed in sample 1 but strained in sample 2, it is expected that the binding energy Ed of the donor in sample 2 is different from that in sample 1. After the low temperature illumination on both samples, we only observed the fluctuation of RXX background, but the frequencies of SdH oscillations were not changed. It indicated that the PPC effect did not occur in these two samples.

IV. CONCLUSIONS

The magnetotransport properties of δ-doped In0.22Ga0.78As/GaAs quantum wells were studied by van der Pauw and Shubnikov–de Haas measurements. From the temperature-dependent van der Pauw Hall measurement, we obtained two donor levels with binding energies of 104 and 9.6 meV in the δ-doped In0.22Ga0.78As/GaAs quantum wells. After inserting In0.1Ga0.9As layers between the In0.22Ga0.78As and GaAs layers, a single donor with binding energy of 50 meV was observed. The carrier concentration determined by SdH measurement did not change after the QWs were illuminated at low temperature, which indicates that these deep donors could not produce a persistent photoconductivity in δ-doped In0.22Ga0.78As/GaAs QWs.
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