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Photoinduced electron coupling in δ-doped GaAs/In$_{0.18}$Ga$_{0.82}$As quantum wells

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We have measured the Shubnikov–de Haas (SdH) effect on δ-doped GaAs/In$_{0.18}$Ga$_{0.82}$As quantum wells for the magnetic field up to 12 T at the temperature of 1.2 K. We found two SdH oscillations due to the lowest two subbands in the In$_{0.18}$Ga$_{0.82}$As well with the electron densities of 14.12 and 11.02×10^{11} cm^{-2} and the parallel conduction due to the electrons of about 4.86×10^{11} cm^{-2} in the V-shaped potential well. After the illumination of the sample for different time periods, the electron densities of the two subbands oscillate, and the amplitude of SdH oscillation for E_0 increases but that for E_1 decreases. We believe that the reduction of SdH oscillation for E_1 is due to the electron coupling with E_δ when the V-shaped potential well is lowered by the illumination. In addition, the intersubband scattering between E_0 and E_1 becomes less important than screening effect for E_0 when E_δ coupled with E_1. [S0163-1829(96)00731-X]

The δ-doping technique has been recently applied to semiconductor quantum structures for the improvement of device performance.[1–3] In a δ-doped bulk semiconductor, the dopant atoms are introduced to a single atomic layer while the growth process is interrupted, resulting in a sheet of impurities. When the impurities are ionized, the charged donors create a V-shaped potential well at the δ-doped layer. If the V-shaped potential well is deep enough to confine the free electrons, the electron motion in the V-shaped potential well is quantized into a two-dimensional subband E_δ. The two-dimensional electron gas (2DEG) in the V-shaped potential well has been observed on a pulse-doped GaAs structure by Nakajima *et al.*[4] and on δ-doped GaAs layers by Egues *et al.*[5] Nakajima *et al.* found that the temperature dependence of electron mobility and concentration for pulse-doped GaAs are similar to those for δ-doped GaAs. The observation of 2DEG in the V-shaped potential well revealed some interesting and important questions; for example, what kind of impurity the δ-doping procedure creates and how it affects the electronic property of the sample. Because the ionized impurity does not capture a free electron at the low temperature when they coexist at the δ-doped layer, this impurity level may have some kinds of characters that prevent the recombination with electron, like the *DX* center. However, the *DX* center prefers to be formed in Al$_x$Ga$_{1-x}$As for $x>0.2$ rather than GaAs; thus the impurity level formed at the δ-doped GaAs layer is probably not a *DX* center. Because of the strong impurity scattering at the δ-doped layer, the 2DEG in the V-shaped potential well is difficult to be detected so that the questions still remain unsolved up to date. In the quantum well (QW) with a δ-doped barrier, there are two potential wells: one is the V-shaped potential well formed at the δ-doped layer and the other is the regular QW. The free electrons may reside in E_δ of the V-shaped potential well or in the subbands ($E_0,E_1,\dots$) of the regular well. The properties of E_0 and E_1 in such a δ-doped QW will be affected by the scattering mechanisms including (i) intersubband scattering between E_0 and E_1, (ii) ionized impurity scattering, and (iii) electron-electron coupling with E_δ. In order to investigate these 2DEG's, van der Burgt *et al.* studied a δ-doped Al$_{0.25}$Ga$_{0.75}$As/In$_{0.2}$Ga$_{0.8}$As/GaAs QW and found that the presence of electrons at the V-shaped potential well results in drastic changes in the transport data.[6] They also observed the magnetic freeze-out of carriers in the δ-doped layer at high magnetic fields (>30 T). Moreover, by illuminating the sample at low temperature, they found that the photoexcited electrons from deep donor level increase the carrier concentration and that an oscillatory electron density occurs in the different channels due to the electron flow between these layers. The effect that the electron density increases by low-temperature illumination is known as a persistent photoconductivity effect. It needs to be mentioned that the *DX* center is not the only defect to produce the persistent photoconductivity effect.[7] The illumination can significantly influence the V-shaped potential well of the δ-doped QW. van der Burgt *et al.* proposed that in the Al$_{0.25}$Ga$_{0.75}$As/In$_{0.2}$Ga$_{0.8}$As/GaAs QW sample, only the lowest subband (E_0) in the regular QW is populated before illuminated. When the sample is illuminated, the second subband (E_1) in the regular QW begins to be populated. Further illumination brings the electronic level (E_δ) at the δ-doped layer down below the Fermi level (E_F) and the electrons transfer back to E_δ, and hence E_1 depopulates. At last, the two subbands in the regular QW and E_δ at the δ-doped layer are occupied after long time illumination.[6] However, van der Burgt *et al.* ignored the contribution of the second subband to the conduction in transport experiments due to a lack of precise information about the second subband and the subband structure at the δ-doped layer.

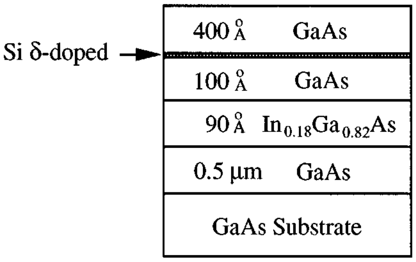


FIG. 1. The sample structure.

Recently the persistent photoconductivity effect in a δ-doped $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ QW has been studied by Lo *et al.*[8] We found that the electron density of the lowest two subbands in the regular QW increased by 7%, and the deep donor level is not affected by the preannealed substrate in the growth procedure. From the Shubnikov–de Haas (SdH) measurement, the properties of the lowest two subbands in the triangular $Ga_{0.47}In_{0.53}As$ well were studied as well. It was found that the electron quantum lifetime (the average time that an electron stays in a quantum state before being scattered) of the second subband is greater than that of the first subband and the separation between the two subbands ΔE_{01} $(=E_1-E_0)$ is equal to 54 meV. The greater electron quantum lifetime for the second subband is due to the triangular potential well in which the electron wave function of the first subband is, on average, closer to the heterojunction so that the electron scattering by the interface roughness and ionized impurities for the first subband is stronger than that for the second subband. Thus the contribution to the conduction from the second subband cannot be ignored. Because the conduction-band offset ΔE_c is about 0.6 eV for the $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ QW,[9] the Fermi level is not high enough to reach the V-shaped potential well at the δ-doped $Al_{0.48}In_{0.52}As$ barrier. Therefore there is no free electron in the V-shaped potential well. The absence of the electron at the δ-doped layer was confirmed by the SdH data which did not show any parallel conduction channel other than E_0 and E_1. The information about the electronic level E_δ at δ-doped layer is still void. In order to study the electronic properties of E_δ at the δ-doped layer, we specially designed a simple silicon δ-doped $GaAs/In_{0.18}Ga_{0.82}As$ QW which has the conduction-band offset ΔE_c about 0.2 eV. Because of the small ΔE_c, the Fermi level easily reaches the V-shaped potential well. In this paper, we show the properties of electronic level E_δ in the V-shaped potential well and the photoinduced electron coupling between E_δ and the second subband E_1 in the $In_{0.18}Ga_{0.82}As$ QW.

The sample structure designed for this study consists of a 400-Å GaAs cap layer, a silicon δ-doped layer, 100-Å GaAs spacer, 90-Å $In_{0.18}Ga_{0.82}As$ carrier channel, and 0.5-μm GaAs buffer layer which were grown on a GaAs substrate by low-pressure metalorganic chemical-vapor deposition (see Fig. 1). The conduction-band offset evaluated from the band gaps of the two components, 1.512 eV for GaAs and 1.249 eV for $In_{0.18}Ga_{0.82}As$ [which is obtained by using $x=0.18$ in Eq. (1) of Ref. 10], is about 0.2 eV. The subband levels $(E_0, E_1, \ldots)$ of the 2DEG in the $In_{0.18}Ga_{0.82}As$ layer are determined by the quantum confinement of the potential well. In order to create double quantum wells (one is the δ-doped V-shaped potential well and the other is the regular quantum well), we chose here a small conduction-band offset (0.2 eV) and thin $In_{0.18}Ga_{0.82}As$ layer (90 Å) so that the Fermi level can be easily moved up to the electronic level E_δ in the V-shaped potential well and the electrons will populate the E_δ level. The thick spacer (100 Å GaAs) was used to reduce the ionized impurity scattering for the 2DEG in the $In_{0.18}Ga_{0.82}As$ well, but it is thin enough to allow the free electrons to transfer forward and backward between the V-shaped potential well and the $In_{0.18}Ga_{0.82}As$ well. The concentration of silicon in the δ-doped layer is about 3–5 $\times 10^{12}$ cm^{-2}. The SdH measurements have been performed on the designed δ-doped $GaAs/In_{0.18}Ga_{0.82}As$ QW for the magnetic field from 0.25 to 12 T at the temperature of about 1.2 K. The SdH measurement can determine the individual electron density of a multiple carrier system such as a two-subband-populated 2DEG. The magnetoresistance of the sample oscillates with the reciprocal magnetic field $(1/B)$ and the frequency of the oscillation is determined by the carrier concentration; $f_i=hn_i/2e$, where h is Planck constant, f_i the SdH frequency, n_i the electron density of the ith subband. The SdH data were taken in equal spacing of reciprocal magnetic field for the purpose of fast Fourier transformation (FFT) analysis. The number of data points for the field range was 2048, which gave the resolution of FFT spectrum about 0.128 T, equivalent to the electron density of 0.06×10^{11} cm^{-2}.

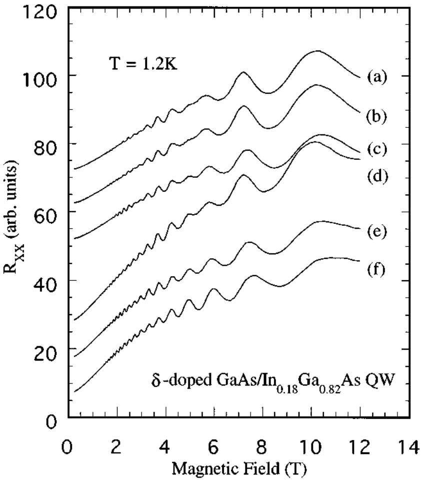


FIG. 2. The results of Shubnikov–de Haas measurements for the different illumination conditions.

Figure 2 showed some results of the SdH measurements for the illumination of different time periods. For example, (a) is for the SdH experiment performed without any illumination at the beginning, and then repeated the measurements after 3 sec, 10 sec (b), 1 min, and 30 min (c) illuminations. In order to check the effect of thermal cycling on the electron density, we also warmed the sample up to room temperature for five days and then repeated the SdH measurements (d), and then with the illuminations of 1 sec, 3 sec, 10 sec, 2 min (e), and 10 min (f), in addition. The SdH data showed two oscillations beating each other. The frequencies of these two oscillations obtained from the fast Fourier transformation give the electron densities of 14.12 and 11.02×10^{11} cm^{-2}. Figure 3 showed the FFT results of the SdH data in Fig. 2.

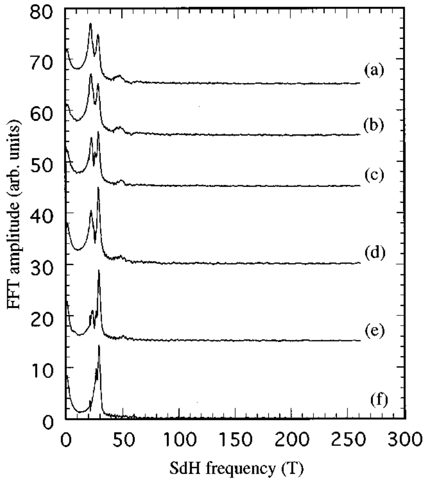
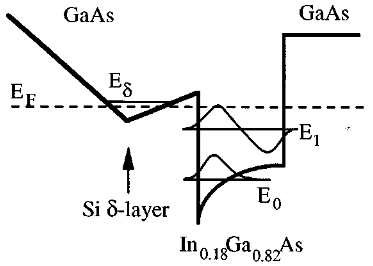
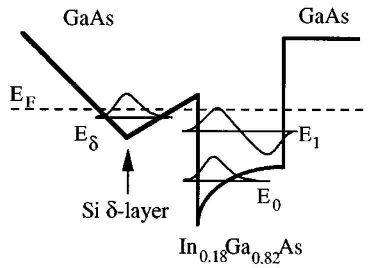


FIG. 3. The spectra of fast Fourier transformation for the SdH data in Fig. 2.

(a) Single Quantum Well



(b) Uncoupled Double Quantum Wells



(c) Coupled Double Quantum Wells

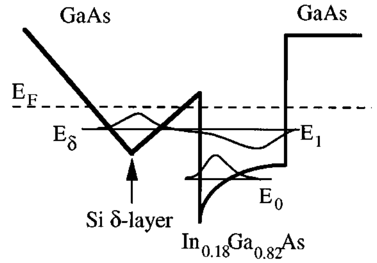


FIG. 4. The schematic diagram of δ-doped GaAs/$In_{0.18}Ga_{0.82}As$ quantum well. (a) No electron populates the δ-doped layer and it looks like a single quantum well. (b) E_δ is slightly populated but the electron wave function of E_δ is unable to penetrate through the central barrier. The structure looks like uncoupled double quantum wells. (c) When E_δ is kept moving down, it will couple with E_1 and becomes a coupled quantum well.

The zeros of the y axis for the data sets of (a)–(e) in both Figs. 2 and 3 have been offset by different units. Because the sample structure is so simple, the possible layers at which the free electrons may reside are the V-shaped potential well and the $In_{0.18}Ga_{0.82}As$ well. However, because of the strong impurity scattering at the silicon δ-doped layer, the SdH signal for the free electron in the V-shaped potential well is difficult to detect. Thus the two peaks in Fig. 3(a) are due to the oscillations of the lowest two subbands in the $In_{0.18}Ga_{0.82}As$ well. This is confirmed by the comparison with the SdH measurement on the δ-doped $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ QW.[8] In Fig. 2 of Ref. 8, there are two peaks corresponding to the oscillations from the first (n_0) and second (n_1) subbands, and the FFT amplitude of the second subband is higher than that of the first subband. Because the amplitude of the oscillatory magnetoresistance[11] consists of the predominated factor, $\exp(-\pi/\omega\tau)$, the higher FFT amplitude implies the greater quantum lifetime, where τ is the quantum lifetime and $\omega = eB/m^*$. In the QW with a δ-doped barrier, the square quantum well turns into a triangular well due to band bending. As we mentioned before, the electrons in the first subband are closer to the interface and ionized impurities so that they are scattered more strongly than those in the second subband, resulting in a smaller quantum lifetime. After illuminating the sample of $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$, the electron densities and FFT amplitudes of the two subbands increase due to the persistent photoconductivity effect. Because of the big conduction-band offset ($\Delta E_c \approx 0.6$ eV), the illumination is not able to bring E_δ down to the Fermi level. Therefore all of the photoexcited electrons transfer from the defect level of the δ-doped layer to the $In_{0.53}Ga_{0.47}As$ well. The extra electrons increase the screening effect for E_0 and E_1, and hence both FFT amplitudes increase after illumination. However, the conduction-band offset of $GaAs/In_{0.18}Ga_{0.82}As$ QW ($\Delta E_c \approx 0.2$ eV) is relatively small. The electronic level E_δ at the V-shaped potential well was low; see the schematic diagram in Fig. 4(a). If the concentration of the positively charged impurities at the δ-doped layer increases (for example, by illumination), the V-shaped potential well becomes deeper and then the electronic level E_δ moves down below the Fermi level, resulting in the electron population in the V-shaped potential well [see Fig. 4(b)]. If the electron wave function of E_δ is not able to penetrate through the central barrier, the sample looks like uncoupled double quantum wells. The slightly populated δ-doped layer plays a role of scattering source for the electron-electron interaction on the electrons in $In_{0.18}Ga_{0.82}As$ well. If the electron level E_δ keeps moving down (for example, by further illumination), the electron wave function of E_δ starts to couple with that of the second subband E_1 [see Fig. 4(c)]. Jogai calculated the band structure of δ-doped $Al_xGa_{1-x}As/In_xGa_{1-x}As$ QW ($\Delta E_c \approx 0.4$ eV), and obtained the electron distribution at both the V-shaped potential well and the $In_xGa_{1-x}As$ well.[12] Therefore if the electronic level E_δ is moved down slowly, we should be able to see the effect of the V-shaped potential well coupled with the second subband in the $In_{0.18}Ga_{0.82}As$ well. To do so, we illuminated the sample by a red-lightemitted diode at the temperature of 4.2 K for different time periods.

From the two peaks of the FFT spectrum in Fig. 3(a), the electron densities of the first and second subbands are 14.12 and 11.02×10^{11} cm^{-2}, respectively. The total electron density obtained from the conventional Hall measurement is about 3×10^{12} cm^{-2}. Therefore the density of the free electron in the V-shaped potential well is about 4.86×10^{11} cm^{-2}. In Fig. 2(a), the SdH data showed a parallel conduction channel, in addition to the beating oscillations. The parallel conduction contributes to the background of magnetoresistance which increases with magnetic field. Because the sample structure used here is so simple, we believe that the parallel conduction is due to the free electron in the V-shaped potential well. This is one of the reasons why the relative difference of FFT amplitudes between the two peaks in GaAs/$\mathrm{In}_{0.18}\mathrm{Ga}_{0.82}\mathrm{As}$, Fig. 3(a), is not as large as that in $\mathrm{Al}_{0.48}\mathrm{In}_{0.52}\mathrm{As}/\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$, which has no electron populating E_δ; see Fig. 2 in Ref. 8. Therefore, in the GaAs/$\mathrm{In}_{0.18}\mathrm{Ga}_{0.82}\mathrm{As}$ QW, E_δ is lower than the Fermi level and it is populated before illumination. The illumination increases the positively charged impurities at the δ-doped layer and makes the V-shaped potential well deeper. Some of the free electrons may transfer back to the V-shaped potential well and increase the electron-electron interaction between E_δ and E_1. Because the electron wave vectors along the interface for E_δ and E_1 are comparable, the electron-electron interaction between E_δ and E_1 is stronger than that between E_δ and E_0. Figures 2(b)–2(f) show the SdH measurements under different illumination conditions. Their FFT spectra are shown in Figs. 3(b)–3(f). The FFT amplitude of E_1 is greater than that of E_0 before illumination but it is gradually reduced by the illumination and finally disappears. The reduction of FFT amplitude for E_1 arises from the electron-electron interaction with E_δ. It disappears after the strong coupling of E_δ and E_1. Figure 4(c) shows the schematic diagram of the overlapped wave function for the coupled electronic level. In Fig. 3, the FFT amplitude of E_0 increases instead of decreasing after the illuminations. This is because, as mentioned before, the electron-electron interaction between E_δ and E_1 is stronger than that between E_δ and E_0, and the persistent photoconductivity effect increases the screening effect for E_0.

In order to investigate the E_δ and its effect on E_0 and E_1, we calculated these electronic levels from the electron densities determined from the SdH measurements. For a two-dimensional electron gas, the energy difference between the Fermi level and the minimum of ith subband is $\Delta E_{iF}=E_F-E_i=\pi\hbar^2 n_i/m^*$. Using the electron densities of the first and second subbands, 14.12 and 11.02×10^{11} cm^{-2}, respectively, and the electron effective mass $m^*=0.059m_0$ [which was calculated from the linear approximation of $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ with $m^*(\mathrm{GaAs})=0.067m_0$, $m^*(\mathrm{InAs})=0.023m_0$, and $x=0.18$], we obtained $E_1=44.71$ meV and $E_0=57.28$ meV below the Fermi energy before any illumination. Assuming that the density of the free electron in the V-shaped potential well is about 4.86×10^{11} cm^{-2} and $m^*=0.067m_0$, we have $E_\delta=17.36$ meV below the Fermi energy. Therefore the electronic level E_δ is located between the Fermi level and E_1, as the case of Fig. 4(b). This is consistent with the results observed in the sample we studied here. Figure 5 shows the electron densities of E_0 and E_1, and the data of the second subband for the eleventh experiment was not able to be determined from the FFT spectrum in Fig. 3(f). The electron densities of E_0 and E_1 fluctuated after the different illuminations. It implied that the electrons transferred forward and backward between the V-shaped potential well and the $\mathrm{In}_{0.18}\mathrm{Ga}_{0.82}\mathrm{As}$ well. The oscillatory electron density is consistent with the result observed on the $\mathrm{Al}_{0.25}\mathrm{Ga}_{0.75}\mathrm{As}/\mathrm{In}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As}$/GaAs QW by van der Burgt *et al.*[6] and the calculation on the $\mathrm{Al}_x\mathrm{In}_{1-x}\mathrm{As}/\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ QW by Jogai.[12] The FFT amplitudes of the SdH oscillations for E_0 and E_1 are also shown in Fig. 6 for the 11 experiments. It is very obvious that the SdH amplitude of E_1 decreases and that of E_0 increases after the illuminations. It means that the electron coupling occurs between E_δ and E_1 and it has a minor effect on E_0. The intersubband scattering between E_0 and E_1 is another source that affects the quantum lifetime[13] and hence the amplitude of the SdH oscillation. In Fig. 6, we found that, for E_0, the electron screening effect becomes more important than intersubband scattering when E_δ and E_1 coupled together. It is noted that the changing of the SdH amplitude by illumination may be caused by the scattering from the residual impurities in the $\mathrm{In}_{0.18}\mathrm{Ga}_{0.82}\mathrm{As}$ well, by the surface state scattering, by the interface roughness scattering,[14] or by the scattering from

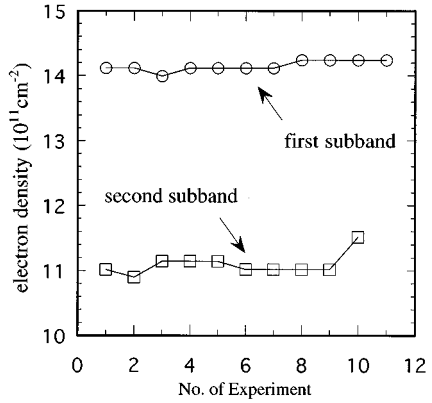


FIG. 5. The electron densities of the first and second subbands for the 11 SdH measurements.

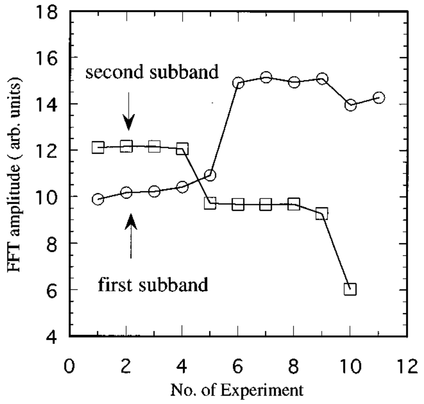


FIG. 6. The FFT amplitudes of the first and second subbands for the 11 SdH measurements.

nonuniform distribution of indium in $In_xGa_{1-x}As$.[15] However, these scatterings will reduce the SdH amplitudes for both E_0 and E_1; this is not the case observed here. Moreover, Mani and Anderson investigated the persistent photoconductivity effect and the influence of thermal cycling on quantum lifetime and found that the small-angle scattering in the semiconductor quantum structures is caused by charged centers associated with deep defects responsible for the persistent photoconductivity effect.[16] By comparing the δ-doped QW of $Al_{0.48}In_{0.52}As/In_{0.52}Ga_{0.47}As$ (Ref. 8) and that of $GaAs/In_{0.18}Ga_{0.82}As$ (this study), the low-temperature illumination increases the SdH amplitudes for the lowest two subbands of the former but it decreases that of E_1 for the latter. The major difference between these two QW's is the population of the electron in the V-shaped potential well. The reduction of the SdH amplitude for E_1 in $GaAs/In_{0.18}Ga_{0.82}As$ is due to the electron coupling with E_δ. Although the character of the impurity defect at the δ-doped layer remains unknown, we believe that the illumination of the δ-doped QW sample will produce the electron coupling between E_δ and E_1, due to the lowering of the V-shaped potential well. Under this circumstance, we found that the intersubband scattering between E_0 and E_1 becomes less important comparing with the screening effect for E_0.

The results are supported by the Coulomb scattering mechanism. In most cases, the dominant scatterers at low temperatures are charged impurities or defects. The detailed evaluation of the scattering rate for 2DEG in an inversion layer or heterojunction has been done by many authors.[17,18] Moreover, Stern formulated the cross section $\sigma(\theta)$ for scattering with wave vector transfer $\mathbf{q}$ by[19]

$$\sigma(\theta)=\frac{\pi^2 m e^4}{\varepsilon^2 h^3 \mathbf{v}}\,\frac{\exp(-2\mathbf{q}d)}{(\mathbf{q}+\mathbf{q}_s)^2},$$

where $\mathbf{q}_s$ is the screening parameter, $\mathbf{v}=\hbar\mathbf{k}/m$ is the carrier velocity, and the scattering angle is given by $q=2k\sin(\theta/2)$. Here he assumes that the electrons lie in a plane with zero thickness (the extreme two-dimensional limit), that the surrounding material has permittivity ε, and that the scatterers are randomly distributed on a plane (like the δ-doped layer) with a distance d from the electron plane. Taking the charge transfer conditions into account, Stern showed that the highest mobility for a given channel electron density is achieved by maximizing the doping in the barrier layer and by keeping the residual density of ionized impurities in the electron channel as low as possible. After illumination, the carrier density in the heterostructures usually increases, and an effect attributes to lattice relaxation around donors in the barrier when they are ionized, resulting in an energy barrier that impedes electron recombination with the ionized donors at low temperatures. The mobility usually increases after illumination, and the screening by mobile carriers will contribute to the mobility as well. Thus we believe that the increase of the SdH amplitude for the first subband is due to the scattering mechanism by the remote ionized impurity, and the disappearance of the SdH oscillation for the second subband arises from the electron coupling with E_δ.

In conclusion, we have measured the Shubnikov–de Haas effect on a δ-doped $GaAs/In_{0.18}Ga_{0.82}As$ QW for the magnetic field up to 12 T at the temperature of 1.2 K. We found two SdH oscillations beating together with a parallel conduction. From the FFT spectrum, we obtained the electron densities of the lowest two subbands in the $In_{0.18}Ga_{0.82}As$ well to be 14.12 and 11.02×10^{11} cm^{-2}, and about 4.86×10^{11} cm^{-2} electrons in the V-shaped potential well. After illuminating the sample for different time periods, the electron densities of the two subbands oscillate, and the SdH amplitude of E_0 increases but that of E_1 decreases. We believe that the reduction of the SdH amplitude for E_1 is due to the electron coupling between E_δ and E_1 whose wave vectors along the interface are comparable and that the increase of the SdH amplitude of E_0 is due to the screening of remote ionized impurity scattering. In addition, the intersubband scattering between E_0 and E_1 becomes less important for E_0 as E_δ coupled with E_1.

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