PHYSICAL REVIEW B VOLUME 55, NUMBER 20 15 MAY 1997-II

Effect of well thickness on the two-dimensional electron-hole system in $Al_xGa_{1-x}Sb/InAs$ quantum wells

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(Received 16 September 1996; revised manuscript received 23 December 1996)

We have studied the effect of well thickness on the two-dimensional electron-hole system in semimetallic $Al_xGa_{1-x}Sb/InAs$ quantum wells by Shubnikov–de Haas (SdH) measurements. The number of hole carriers in the $Al_xGa_{1-x}Sb$ barriers was changed by a negative persistent photoconductivity effect. From the amplitude of SdH oscillation for the sample with the thinnest well, we found that the interface roughness scattering dominated when the number of hole carriers is small. After the number of holes is increased by the negative persistent photoconductivity effect, the electron-hole scattering becomes more important, and results in a reduction of the electron quantum lifetime. The competition between electron-hole scattering and interface roughness scattering depends on the amount of holes in the barriers. [S0163-1829(97)06820-3]

Quantum wells (QW's) made from $Al_xGa_{1-x}Sb$ barriers and InAs wells have been studied with great interest for their unique band structure, in which the valence-band edge of $Al_xGa_{1-x}Sb$ can be tuned above the conduction-band edge on InAs by changing either the Al composition x or the InAs well thickness, and thus the QW can be shifted from a semiconducting phase to a semimetallic phase with two-dimensional (2D) electrons in the well and 2D holes in the barriers.[1] Munekata *et al.* measured the alloy-dependent carrier densities for both electrons and holes in $Al_xGa_{1-x}Sb/InAs$ QW's.[2] They found that electrons and holes coexisted when $x<0.3$ (semimetallic phase) and that the holes vanish when $x>0.3$ (semiconducting phase). This is an electron-hole QW system that has been made in which the electrons and holes are spatially separated. Many special physical phenomena have recently been discovered, such as the negative persistent photoconductivity effect,[3–5] the magnetic-field-induced semimetal-to-semiconductor transition,[6,7] and the intrinsic excitonic ground state.[8] In addition to the experimental work, some theoretical calculations have been carried out lately. For example, Naveh and Laikhtman predicted that the intrinsic ground-state excitons can exhibit a Bose-Einstein condensation phase under a particular condition.[9] Chiang *et al.* showed, from band calculation, that a conduction-valence Landau-level mixing effect may also result in the X-line transition observed in semimetallic $Al_xGa_{1-x}Sb/InAs$ QW's by far-infrared magnetotransmission spectra.[10] Besides its interesting physical properties, this QW system has been proposed for high-speed electronic devices and infrared photodetector applications.

To engineer this QW for optimum performance, the scattering due to ionized impurities, interface roughness, and electron-hole interaction needs to be taken into account. For a single-carrier quantum structure (e.g., $Al_xGa_{1-x}As/GaAs$), Mani and Anderson found that the electron quantum lifetime (τ_q) increased when the electron density was increased by a positive persistent photoconductivity effect.[11] The additional electrons enhance the screening effect on a two-dimensional electron gas (2DEG), and screen out the extra photoionized impurities, which are located in the barrier. When the remote ionized impurities in the barriers are the major scattering centers, the electron quantum lifetime will increase with increasing electron density due to the stronger screening effect. However, the remote ionized impurities are no longer the dominant scattering centers when the 2DEG is confined in a very thin well or the interface is very rough. This is because, in a very thin QW, a small amount of roughness at interface can cause a large fluctuation in the quantization energy of 2DEG in the well. The higher electron density has a higher Fermi energy, so that the deeper penetration of interface by the electron wave function results in a smaller τ_q. The screening effect, which arises from Coulomb interaction, does not affect the interface roughness scattering. Therefore, when interface roughness scattering dominates, τ_q will decrease with increasing electron density, which is the opposite of the situation where ionized impurity scattering dominates. This was supported by Noda, Tanaka, and Sakaki's calculation, which included the scattering due to both ionized impurities and interface roughness.[12] They showed that the mobility increases linearly with increasing electron density if ionized impurity scattering dominate (see the dotted line marked ''ION'' in Fig. 2 of Ref. 12), but decreases when interface roughness scattering becomes comparable to or greater than ionized impurity scattering (see the solid lines for the lateral correlation length, i.e., the roughness island size, $\Lambda<100$ Å in the same figure). The previous result in semiconducting $Al_{0.6}Ga_{0.4}Sb/InAs$ QW's showed a good example that the quantum lifetime is dominated by interface roughness scat-

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tering (see Fig. 2 of Lo *et al.* in Ref. 4) because the $Al_{0.6}Ga_{0.4}Sb$/InAs interface is rougher than $Al_xGa_{1-x}As$/GaAs interface (the Sb atom is very active when InAs is grown on the $Al_xGa_{1-x}Sb$ surface). It needs to be mentioned that the quantum lifetime τ_q, which is the average time of an electron staying in a quantum state and defined by the Landau level broadening ($\tau_q=\hbar/2\Gamma$, where $\hbar$ is the reduced Planck constant and Γ the half-width of the broadening), is not identical to the transport scattering time τ_H, which is determined by the Hall mobility ($\tau_H=m^*\mu_H/e$, where m^* is the electron effective mass and μ_H the Hall mobility). In general, τ_H is sensitive to the large-angle scattering (i.e., large momentum transfer after scattering), but τ_q is sensitive to all scattering events.[13] The ionized impurity scattering and electron-hole scattering are due to the long-range Coulomb interaction, but interface roughness scattering is limited by the short-range roughness islands. Thus τ_q is a better parameter than τ_H to evaluate the interface roughness scattering. When the QW is in a semimetallic phase, the scattering mechanism should include the electron-hole interaction as well. Lo *et al.* showed that τ_q decreased when the electron density was reduced by a negative persistent photoconductivity effect in the semimetallic $In_{0.25}Ga_{0.75}Sb$/InAs QW's (see Fig. 3 of Ref. 5). It was pointed out that electron-hole scattering should dominate remote ionized impurity scattering in the 2D electron-hole system, because the holes, which reside near the interface, are closer to the electrons in the well than the remote ionized impurities, which are localized in the barriers. However, τ_q increased with decreasing electron density in the semiconducting $Al_{0.6}Ga_{0.4}Sb$/InAs QW's,[4] but it decreased in the semimetallic $In_{0.25}Ga_{0.75}Sb$/InAs QW's.[5] The method used to reduce the electron density in both QW's was the same (the negative persistent photoconductivity effect). The interfaces of both QW's should be rough. The only difference between the two QW's is the presence of holes in the semimetallic $In_{0.25}Ga_{0.75}Sb$/InAs QW's. A comparison between interface roughness scattering and electron-hole scattering has not been made to date, to our knowledge. Both the roughness and hole are located at or near the interface, but they have different scattering mechanisms; the former arises from the fluctuation of quantization energy and the latter from Coulomb interaction. In order to evaluate the effect of interface roughness scattering on the 2D electron-hole system, we studied the effect of well thickness on semimetallic $Al_xGa_{1-x}Sb$/InAs QW's in which the number of holes can be changed by the negative persistent photoconductivity effect.

The sample structure designed for this study is shown in Fig. 1. It consists of a 150-Å GaSb cap, a 150-Å $Al_xGa_{1-x}Sb$ barrier layer, an InAs well of thickness L_Z, another $Al_xGa_{1-x}Sb$ barrier of 9000 Å thickness, and an AlSb/GaSb superlattice buffer layer, grown on a semi-insulating GaAs substrate by molecular-beam epitaxy at Wright Laboratory (Avionics Directorate). We changed the well thickness of $x=0.2$ samples by 100 Å (sample 1), 150 Å (sample 2), and 200 Å (sample 3). When the InAs well thickness is reduced, the energy level (E_0) of a 2DEG will move up, and so will the Fermi level (E_F). The electrons will flow back to the $Al_xGa_{1-x}Sb$ valence band, and thus reduce the number of hole carriers in the barriers as well as that of electron in the well. This means that sample 1 has the fewest hole carriers compared to samples 2 and 3. The Shubnikov–de Haas (SdH) measurements were performed on these QW's for magnetic fields from 0.25 to 4.5 T at a temperature of about 1.2 K. The SdH data were taken in equal spacings of reciprocal magnetic fields for fast Fourier transformation (FFT) analysis. The number of data points for this field range was 1024. The resolution of the FFT spectrum is about 0.132 T, equivalent to the electron density 0.06×10^{11} cm^{-2}. Illumination for negative persistent photoconductivity studies was provided by a red-light-emitted diode mounted above the sample.

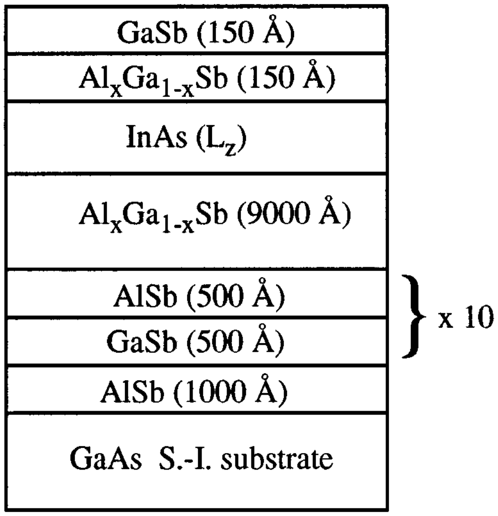

FIG. 1. The sample structure.

The Shubnikov–de Haas measurement is very effective in characterizing the individual electronic properties of a multiple-carrier system. The measured magnetoresistance consists of nonoscillatory and oscillatory parts. The oscillatory magnetoresistivity of a two-dimensional multiple carriers system can be written as[14]

$$\delta\rho_{xx}=\sum_i A_i(T,B)\cos\left(\frac{2\pi\Delta E_i}{\hbar\omega_i}+\phi_i\right), \tag{1}$$

$$A_i(T,B)=\frac{\rho_i(\omega_i\tau_i)^2}{[1+(\omega_i\tau_i)^2]^2}\exp\left(\frac{-\pi}{\omega_i\tau_i}\right)\frac{\xi_i}{\sinh(\xi_i)}, \tag{2}$$

where the sum is over the different carriers, and $\xi_i=2\pi^2k_BT/\hbar\omega_i$, $\omega_i=eB/m_i^*$ is the angular cyclotron frequency, τ_i is the quantum lifetime, ρ_i is a constant proportional to the zero-field resistivity, and ϕ_i is the phase of the individual carrier. k_B is the Boltzmann constant, and e the charge of electron. For a 2DEG, the energy difference between the Fermi level and the conduction-band edge is

$$\Delta E_i=\pi\hbar^2 n_i/m_i^*. \tag{3}$$

Therefore the individual magnetoresistivity ($\delta\rho_{xx}$) of Eq. (1) oscillates with inverse magnetic field ($1/B$), and the frequency (f_{SdH}) of the oscillation is determined by the density of that carrier (n_i), $f_{\mathrm{SdH}}=hn_i/2e$. In the case of a 2D electron-hole system (e.g., in our case), the effective mass of

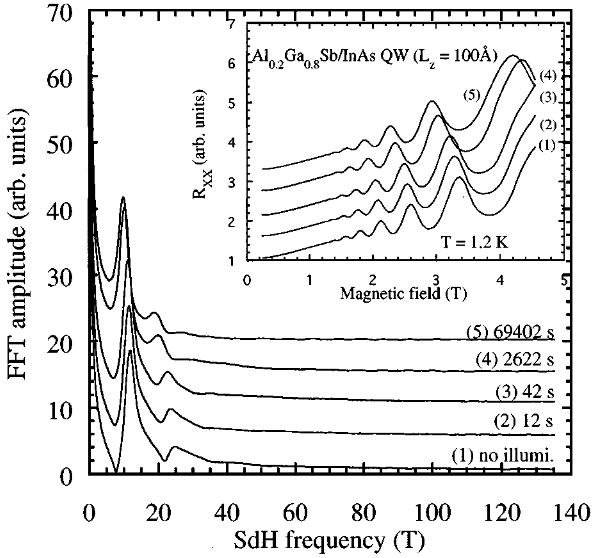

FIG. 2. The SdH measurements (inset) for sample 1 with different illumination times, and their FFT spectra.

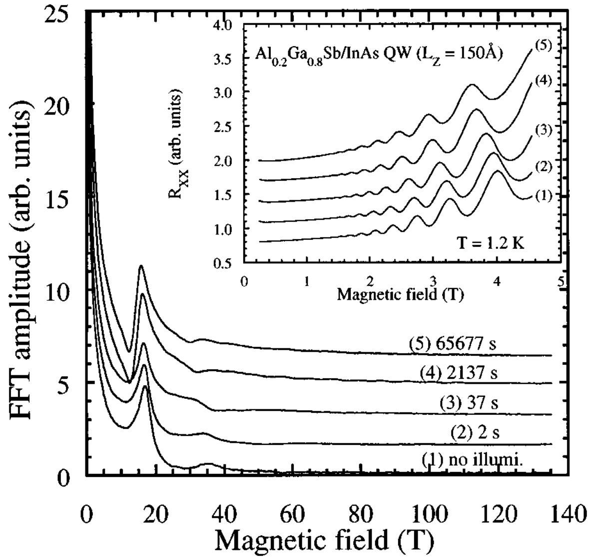

FIG. 3. The SdH measurements (inset) for sample 2 with different illumination times, and their FFT spectra.

a hole carrier is much heavier than that of an electron carrier, and therefore the SdH oscillation of the magnetoresistance for the hole carrier is very difficult to detect, resulting in an up-shift contribution to the nonoscillatory background, a so-called parallel conduction. In this study, because many sources are involved in the electron scatterings, only several periods of the SdH oscillation can be observed. Thus we are not able to derive τ_q directly from the SdH data as we did in the previous studies.[4,5] However, we still can evaluate the quantum lifetime from the Fourier transformation analysis. The FFT amplitude (in frequency space) of an oscillation indicates the average amplitude of the oscillation with that frequency component. If we perform the SdH measurement for a fixed field range (i.e., $B=0.25$–4.5 T) at a constant temperature ($T=1.2$ K), the amplitude $A_i(T,B)$ in Eq. (2) will depend on m^* and τ_q only. If we assume that m^* is about constant in the range of electron density changing by the illumination, then the amplitude $A_i(T,B)$ is proportional to τ_q. This makes the physical sense that the shorter τ_q gives a smaller $A_i(T,B)$ and so a smaller FFT amplitude component.

Figures 2–4 show the SdH measurements and their FFT spectra for different illumination time periods on these samples. It is obvious that the SdH data for all samples exhibit a parallel conduction; the 2DEG contributes to the oscillatory magnetoresistance R_{xx}, and the other carriers with lower mobility (including holes) are responsible for the background. After illuminating these samples at low temperature (1.2 K), the peak position of the SdH oscillation moved to lower magnetic fields for all samples, indicating that the electron density for all of the samples decreased. The electron densities before illumination for samples 1, 2, and 3 were determined by f_{SdH} to be 5.7, 8.2, and 8.1 $\times 10^{11}$ cm^{-2}, respectively. After extended illumination, they were reduced to 4.8, 7.7, and 7.2×10^{11} cm^{-2}, respectively. The negative persistent photoconductivity in this QW system was studied previously on a different set of samples which did not have AlSb/GaSb superlattice buffer layers.[1,4] Because of the semimetallic band structure of these QW's, the reduction of electron density in the well by the negative persistent photoconductivity effect will move the Fermi level down, and electrons will flow from the $Al_xGa_{1-x}Sb$ valence band to the InAs conduction band, resulting in an increase of hole carriers in the barriers. Therefore, the negative persistent photoconductivity effect was used as a tool to reduce the electron density and, at the same time, increase the holes in the semimetallic QW's. This is different from the situation of reducing well thickness, which will reduce both electron and hole carriers. The photoexcited electrons were trapped by the ionized deep donors in the barriers.[3–5] The electron quantum lifetime τ_q is difficult to obtain from these SdH data because many scatterings are present (e.g., ionized impurity scattering, interface roughness scattering, and electron-hole scatter-

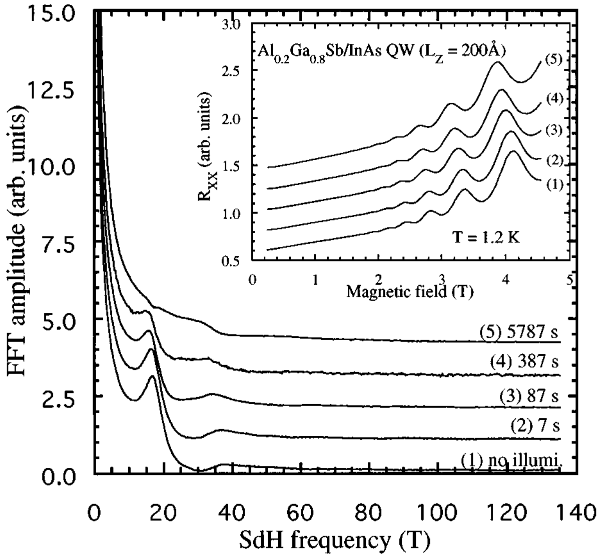

FIG. 4. The SdH measurements (inset) for sample 3 with different illumination times, and their FFT spectra.

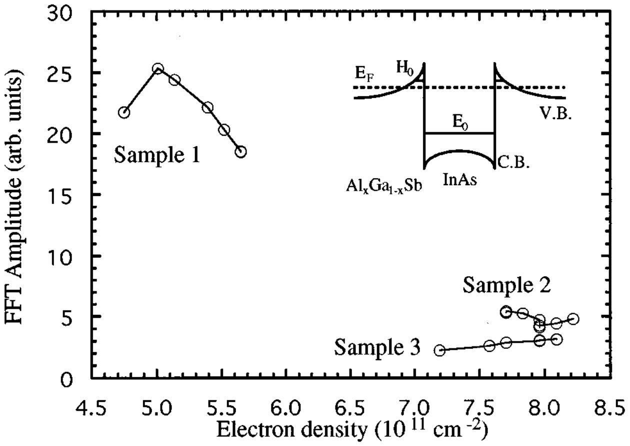

FIG. 5. The FFT amplitude as a function of electron density for the samples. The inset shows the semimetallic band alignment of these samples.

ing). However, the amplitude of the oscillatory R_{xx} includes the factor $\exp(-\pi/\omega\tau_q)$, where $\omega = eB/m^*$. A larger τ_q always gives a higher SdH amplitude.[4] The amplitude of the SdH oscillations can be a measure of the quantum lifetime for the carriers producing that oscillation. In Fig. 5, we evaluate the electron quantum lifetime by plotting the FFT amplitude for the peaks in Figs. 2–4 as a function of electron density. Some of the peaks for sample 3 were buried in the background, and do not show in the figure.

Because antimony tends to ride the surface when InAs is grown on GaSb, the interface of InAs grown on $Al_xGa_{1-x}Sb$ is less abrupt than that of $Al_xGa_{1-x}Sb$ grown on InAs.[15] The interface roughness was expected to be greater at the lower interface of the InAs well and the quadrupole mass spectrometer results on similar samples showed this to be so.[16] Therefore, the roughness for these three samples is about the same, because they were grown under the same conditions in sequence, and the InAs well, whose thickness is the only parameter changing for these samples, is grown above the rough interface. The scattering due to interface roughness should depend simply on the well thickness. Because of the deeper penetration of the electron wave function, the thinner QW should have a stronger interface roughness scattering, so that sample 1 would have the strongest interface roughness scattering. However, as we mentioned above, the thinner well thickness results in fewer hole carriers. Thus the number of hole carriers in sample 1 is the smallest, and that in sample 3 is the largest. In Fig. 5, we see that the FFT amplitude of sample 1 increases at the beginning when the electron density is reduced by the negative persistent photoconductivity effect, and that it drops after longer illumination. We believe that interface roughness dominates the scattering at the beginning, when the number of hole carriers is small. After illuminating the sample, the electron density is reduced but the hole carriers increase; therefore the electron-hole scattering becomes more significant. After overnight illumination, the hole density increased by about 0.45×10^{11} cm^{-2} (half of the reduction of electron density Δn_e if the QW is symmetric), and then the electron-hole scattering became more important, resulting in the reduction in the FFT amplitude. For the data of sample 3, which has the largest number of hole carriers and the smallest interface roughness scattering, the FFT amplitude decreases with decreasing electron density, indicating that electron-hole scattering dominates. The hole density in sample 2 is not as high as sample 3, but more than sample 1. In addition, the interface roughness scattering of sample 2 is somewhere between those of samples 3 and 1. The FFT amplitude of sample 2 showed a n_e-dependent character between those of samples 1 and 3. This means that the electron-hole scattering is comparable to the interface roughness scattering in sample 2. Therefore we conclude that the interface roughness dominated the scattering mechanism in the thin 2D electron-hole QW's. When the number of hole carriers increases, the electron-hole scattering becomes more important. The ionized impurity scattering and electron-hole scattering arise from the long-range Coulomb interaction. Because of the screening effect, the electron quantum lifetime due to these two scatterings will increase with increasing electron density. However, the screening effect cannot be

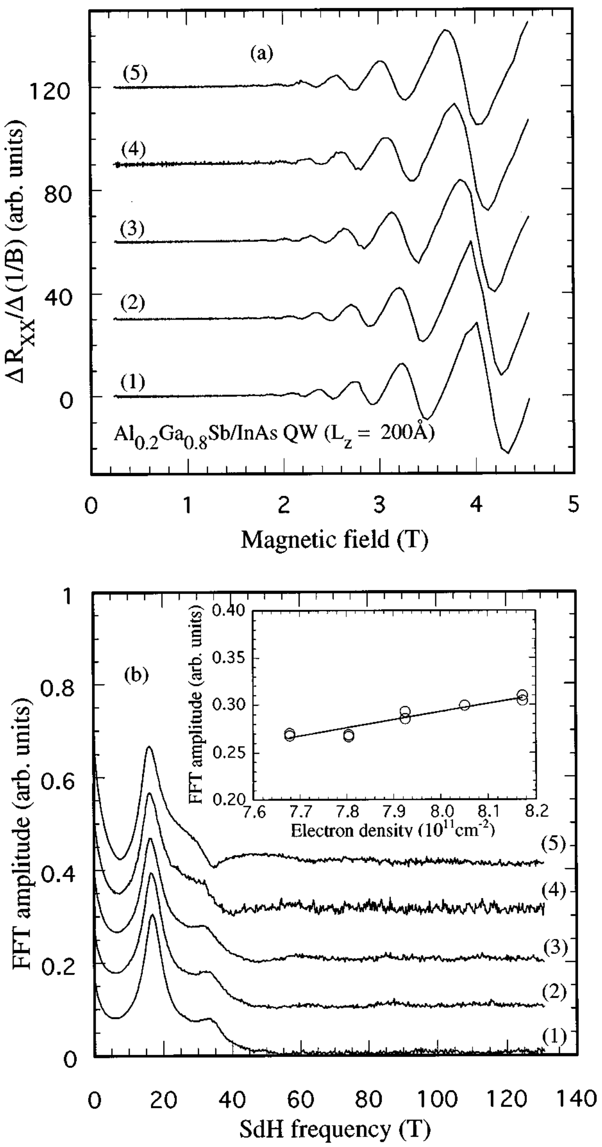

FIG. 6. (a) The plot of $\Delta R_{xx}/\Delta(1/B)$ vs the magnetic field for sample 3 using the data set of the inset in Fig. 4. (b) the FFT spectra of (a) and the inset show the FFT amplitude vs the electron density.

applied to the interface roughness scattering because the roughness is charge neutral. The electron quantum lifetime due to interface roughness scattering will decrease with increasing electron density by the deeper penetration of the electron wave function. The competition between these two scatterings depends on the amount of hole carriers. If the number of hole carriers is large enough, then the electron quantum lifetime will increase with increasing electron density. This conclusion is supported by the early results in semiconducting $Al_{0.6}Ga_{0.4}Sb/InAs$ QW's,[4] and semimetallic $In_{0.25}Ga_{0.75}Sb/InAs$ QW's.[5] There are no hole carriers in the semiconducting $Al_{0.6}Ga_{0.4}Sb/InAs$ QW's, and thus the n_e-dependent character of τ_q shows a scattering dominated by interface roughness (see Fig. 2 of Lo *et al.* in Ref. 4). In semimetallic $In_{0.25}Ga_{0.75}Sb/InAs$ QWs, the n_e-dependent character of τ_q in EL No. 760 showed an electron-hole-dominated scattering, but when the hole carriers are reduced due to the higher Fermi level (e.g., higher electron density) it showed a n_e-dependent character of τ_q with the comparable interface roughness and electron-hole scattering (EL No. 761 in Fig. 3 of Ref. 5).

The results can be confirmed by the plot of $\Delta R_{xx}/\Delta(1/B)$, where $\Delta R_{xx}(n)=R_{xx}(n)-R_{xx}(n-1)$, and $\Delta(1/B)=(1/B_1-1/B_N)/N$. In our case, the beginning and ending fields are $B_1=0.25$ T and $B_N=4.5$ T, and the number of data points $N=1024$. Because the SdH is a sinusoidal function of $(1/B)$, the derivative of the oscillatory part is also a sinusoidal function with the same frequency but a 90° phase difference. The nonoscillatory parallel conduction is then removed from the Fourier transform of the plot. It is noted that the removal of the nonoscillatory part implies that we will lose information about the hole carrier. Figure 6(a) shows the plots of $\Delta R_{xx}/\Delta(1/B)$ against a magnetic field obtained from the data set shown in the inset of Fig. 4 for sample 3, which has the highest hole density. It is very obvious that peaks shifted to the lower field after the illumination due to the negative persistent photoconductivity effect. The phase difference between R_{xx} and $\Delta R_{xx}/\Delta(1/B)$ is about 90° off, and the background is removed as well. We also performed FFT on the data set of $\Delta R_{xx}/\Delta(1/B)$, and the results are plotted in Fig. 6(b). The inset showed the FFT amplitude against the electron density obtained from the FFT spectra. We found that the FFT does decrease as the electron density is reduced by the illumination. The electron density is slightly higher than that in Fig. 4. We believe that the uncertainty in the electron density arises from the removal of background and the mathematic limit that $\Delta(1/B)$ is not approached to zero for the derivative. However, the results are consistent with those from R_{xx}, and support the conclusion.

In conclusion, we studied the effect of well thickness on the electron-hole and interface roughness scatterings in semimetallic $Al_xGa_{1-x}Sb/InAs$ QWs by Shubnikov–de Haas measurements. The negative persistent photoconductivity effect was used as a tool to reduce the electron density and increase the hole carriers in the QW's. For a QW with a certain rough interface, we found that interface roughness dominated the scattering mechanism on the thinnest QW. As the number of hole carriers is increased by the negative persistent photoconductivity effect, the electron-hole scattering becomes more significant, resulting in a reduction of the amplitude of SdH oscillation. The competition between electron-hole scattering and interface roughness scattering depends on the amount of holes in the barriers. This scattering mechanism was checked, successfully, with the previous results on the semiconducting $Al_{0.6}Ga_{0.4}Sb/InAs$ QW's and the semimetallic $In_{0.25}Ga_{0.75}Sb/InAs$ QW's.

The authors are grateful to R. E. Perrin and Dr. P. M. Hemenger for the helpful assistance and Y. C. Chang and H. M. Weng for their computer analysis. The project at NSYSU was supported in part by the National Science Council of Taiwan, the Republic of China. This work was supported by the U. S. Air Force Office of Scientific Research and Wright Laboratory, Wright-Patterson Air Force Base, via Systran Corporation.

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