Landau level spectrum in a two-dimensional hole gas in C-doped (100) $GaAs/Al_{0.4}Ga_{0.6}As$ square quantum well

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We study the Landau level spectrum of a two-dimensional hole gas in carbon δ-doped (100) $GaAs/Al_{0.4}Ga_{0.6}As$ square quantum well (width of 15 nm) by means of microwave cyclotron resonance (CR) and tilted field magnetotransport. Only one type of hole, with an effective mass of $0.4m_e$, was detected in CR. By analyzing the spin-splitting level coincident conditions at $B\sim 1$ T, we find that the effective g-factor is large enough to cause Landau level crossing even in zero tilt, and the product of gm^* increases with total magnetic field. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3077147]

The two-dimensional hole gas (2DHG) in modulation doped GaAs/AlGaAs has attracted much attention in recent years because of its unique charge and spin properties derived from valence band structure. Extensive experiments have been reported on exploring properties of 2DHG formed in different structures.[1–18] Until recently, the 2DHG materials have been provided by Be or Cr-doped (100) or Si-doped (311)*A* GaAs structures. Wieck and Reuter,[14] Manfra *et al.*,[16] and Gerl *et al.*[17] reported a carbon (C)-doped (100) GaAs/AlGaAs molecular beam epitaxial technique, which has led to a steady improvement in low temperature carrier mobility. Due to its unprecedented cleanliness, the C-doped GaAs/AlGaAs quantum structures become an increasingly important system for studies of strongly correlated carriers in which Coulomb interaction, disorder, and spin-orbital coupling parameters can be controlled. In this letter, we report our characterization of a high-mobility 2DHG in C-doped (100) $GaAs/Al_xGa_{1-x}As$ square quantum well (QW), including effective mass measurement with microwave (MW) cyclotron resonance (CR) and effective g-factor investigation with tilted magnetic field.

Two different samples used in our experiments were cleaved from the same wafer, which consists of a 15 nm wide $GaAs/Al_{0.4}Ga_{0.6}As$ square QW doped from a C delta-layer situated 50 nm above the well. The one for effective mass measurement is 1×1 mm^2 square without any contacts, and the other one for g-factor investigation is a 100 μm Hall bar with 20 squares lithographically defined on a 3×5 mm^2 piece. The samples have a hole density of $p\approx 2.2\times 10^{11}$ cm^{-2} and a mobility of $\mu\approx 0.7\times 10^6$ cm^2/V s at 300 mK. The effective mass experiment was performed at 4.2 K in a liquid helium Dewar equipped with a 9 T superconducting magnet; the tilted magnetic field experiment was performed in a top-loading dilution refrigerator equipped with an *in situ* rotator placed inside an 18 T superconducting magnet. With the rotator, the magnetic field could make a titled angle θ ranging from 0° to 90° with respect to the normal to the 2DHG plane.

We measured the effective mass in MW CR using a technique described in Ref. 13. Briefly, the sample was irradiated with MW with a fixed frequency ω_{MW}, and the temperature of the sample was measured as a function of magnetic field B. In linear response regime, the line shape of the CR signal can be described by the Drude formula

$$\frac{\mathrm{Re}\{\sigma_{xx}\}}{\sigma_0}=\frac{[1+(\omega_{\mathrm{MW}}\tau_{\mathrm{CR}})^2+(\omega_C\tau_{\mathrm{CR}})^2]}{[1+(\omega_{\mathrm{MW}}\tau_{\mathrm{CR}})^2-(\omega_C\tau_{\mathrm{CR}})^2]^2+4(\omega_{\mathrm{MW}}\tau_{\mathrm{CR}})^2},$$

where σ_0 is the static conductivity, τ_{CR} is the CR relaxation time, and $\omega_c=eB/m^*m_e$ is the cyclotron frequency with m^* the effective mass in unit of the electron mass m_e.

In our measurements, CR in the range between MW frequency $f=25$ and 55 GHz was detected. Three selected CR signals of $f=25.5$, 39.2, and 50.1 GHz are shown in Fig. 1. A simple fit with equation $\omega_c=eB/m^*m_e$ gives $m^*\cong 0.42$, shown in the inset of Fig. 1. The result that only one effective mass was detected implies that, roughly speaking, spin splitting is smaller than the Landau level broadening of Landau levels in this QW.

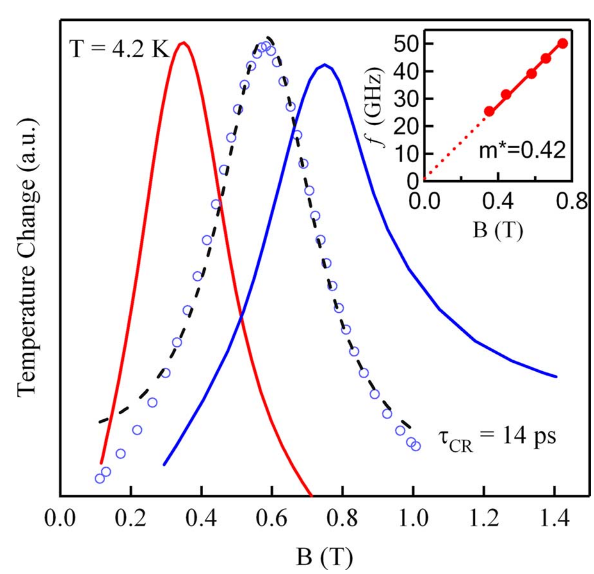

FIG. 1. (Color online) CR signals, solid line and open circle, at MW frequency of $f=25.5$, 39.2, and 50.1 GHz, respectively. Fitting in inset gives $m^*=0.42$. Dash line is Drude model fitting curve for $f=39.2$ GHz, which gave $m^*=0.41$ and CR relaxation time of $\tau_{\mathrm{CR}}=14$ ps.

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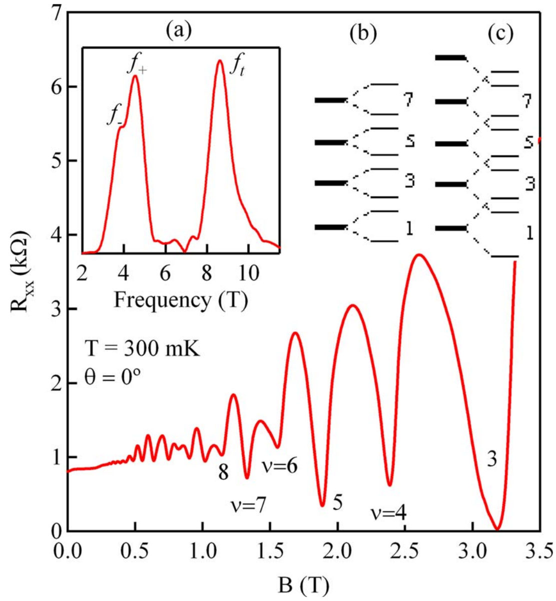

FIG. 2. (Color online) Magnetoresistance of 2DHG in C-doped GaAs/AlGaAs QW. Clear even-odd reversion of minima of $\nu=3$, 4, 5, 6, 7 is shown. Inset (a) is FT spectrum, and (b) and (c) are possible diagrams of Landau level configurations causing the reversion.

By fitting the CR signal of $f=39.2$ GHz with the Drude formula, we determine simultaneously $m^* \cong 0.41$ and $\tau_{CR} \cong 14$ ps. On the other hand, from $\mu = e\tau_{tr}/m^*$ and with $m^* \cong 0.4$, we arrive at a transport scattering time $\tau_{tr} \cong 160$ ps. The ratio $\tau_{tr}/\tau_{CR} > 10$ indicates that in our modulation C-doped (100) GaAs/AlGaAs QW, long range scattering from ionized impurities in the C-doping layer is dominant.[19] It is interesting to note that the value $\tau_{tr} \cong 160$ ps is corresponding to a mobility of 4×10^6 cm^2/V s in a GaAs 2D electron gas (2DEG), taking into account the electron effective mass 0.067. We conclude that the 2DHG measured here exhibits a high quality compatible with high-mobility 2DEGs.

Magnetoresistance of 2DHG was measured in the Hall bar sample. A typical Shubnikov–de Haas (SdH) trace is shown in Fig. 2 in which two main features should be emphasized. First, in the low field regime $B_\perp \le 1$ T, clear beating pattern indicates the existence of two SdH periods in $1/B$. The spectrum of Fourier transform (FT) of R_{xx} versus $1/B$ in the range of 0.2–3 T [inset (a) in Fig. 2] shows three frequencies f_-, f_+, and f_T with $f_T = f_- + f_+$ corresponding to total hole density. As in previous work reported for (100) GaAs/AlGaAs square QW, we relied on the relation $p_\pm = (e/h) f_\pm$ to estimate hole populations,[20] with $p_{-(+)}$ the density of lower (higher) populated subband: $p_- \cong 0.94 \times 10^{11}$ cm^{-2} and $p_+ \cong 1.09 \times 10^{11}$ cm^{-2}. A population difference of $\Delta p = 2(p_+ - p_-)/(p_+ + p_-) \sim 15\%$ indicates the existence of a finite zero-field spin splitting due to spin-orbital interaction in the 2DHG. Such value is considerably smaller than that being reported for 2DHG in a (100) single-interface heterostructure,[15] where $\Delta p \sim 67\%$ presumably due to large Rashba effect presented in the triangular potential quantum confinement.

Second, in the high field regime $B_\perp \ge 1$ T, SdH oscillations show a reversion of even-odd minima pattern from filling factor $\nu=3$ to 9. In contrast to the standard transport in GaAs/AlGaAs 2DEG, here odd minima are deeper than their adjacent even ones. A simple model based on spin-splitting Landau level diagram would suggest that the Zeeman energy is comparable to cyclotron energy, as depicted in either (b) or (c) in Fig. 2. To understand this reversion phenomenon, we measured the magnetoresistance under tilted magnetic field with θ ranging from 0° to 86°. SdH traces of selected tilted angles and the evolutions of minima of $\nu=4$, 5, 6, and 7 with tilted angle are shown in Figs. 3(a) and 3(b), respectively. From Fig. 3(b), we observe that for $\theta > 80°$, the even minima of $\nu=4,6$ become, respectively, deeper than the minima of $\nu=5,7$. In particular, from Fig. 3(a), the minimum of $\nu=9$ disappears at $\theta=85°$, indicating a coincidence of levels. The fact that such coincidence pattern occurs at $\nu=9$ requires, for $B_\perp \sim 1$ T, a level diagram as the one shown in Fig. 2(c) in which the Zeeman splitting is large enough to cause Landau level crossing even at zero tilt. This Landau level crossing requires $\frac{3}{2}\hbar\omega_c > g\mu_B B > \hbar\omega_c$, where $\mu_B = e\hbar/2m_e$ is Bohr magneton. Simple calculation gives $3 > gm^* > 2$. With $m^* \cong 0.4$, we constrain $7.2 > g > 5$, which is close to g-factor of bulk holes ($g=7.2$),[21] while it is much larger than previous results,[21,22] in which $g \sim 2$ for a 15 nm QW.

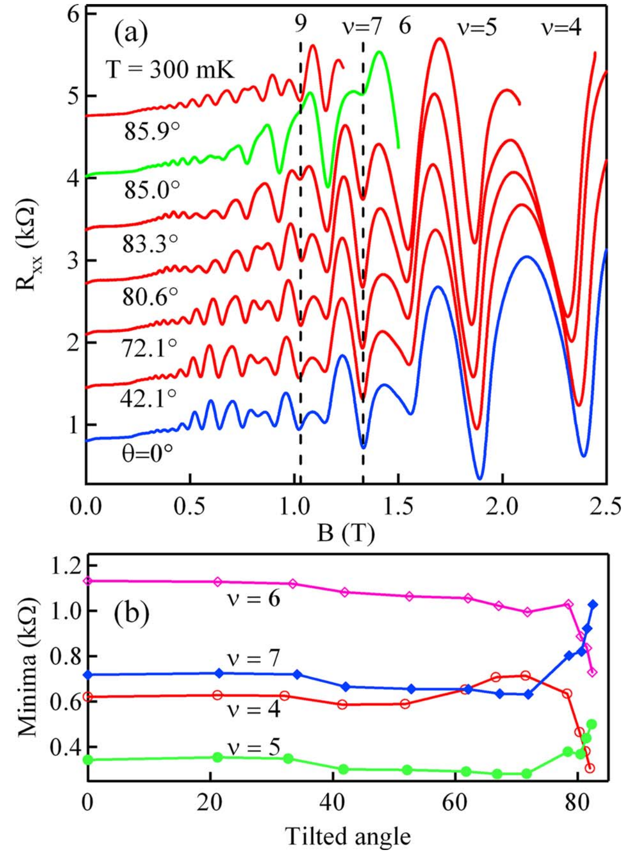

FIG. 3. (Color online) (a) Magnetoresistance traces of selected tilted angles. Traces were shifted up vertically for clarity. Coincidences for minimum of $\nu=9$ occur at tilted angle $\theta=85°$. (b) Evolution of minima of R_{xx} of $\nu=4$, 5, 6, and 7 with increasing tilted angle in which even minima become deeper than the odd ones at $\theta > 80°$.

It is known that the Landau level of 2DHG is highly nonlinear with $B_\perp$ mainly due to the magnetic field dependence of the effective mass of 2DHG.[23] Moreover under tilted magnetic field, the presence of in-plane magnetic field $B_\parallel$ is likely to increase the effective mass.[24–26] Despite these complications in 2DHG, for specific magnetic field at which coincidence occurs at $\nu=9$, we still have coincident conditions: $2\hbar\omega_c = g\mu_B B$ according to Landau level diagram Fig. 2(c). It was reported that the g-factor of 2DHG in GaAs/AlGaAs structure is strongly anisotropic,[10,11] and its in-plane component is close to zero,[11] i.e., $g = g_\perp$ so that $B_\parallel$ has no contribution to Zeeman splitting. Therefore the coincident condition becomes $2\hbar\omega_c = g\mu_B B_\perp$. Simple calculations give $gm^* = 4$, which is larger than the initial value without $B_\parallel$. Previous measurements[21,22] showed that $g_\perp$ is nearly independent of magnetic field. Assuming a constant $g_\perp$ in this QW, we can get the range of m^* under high tilted magnetic field, $0.53 < m^* < 0.8$, which is larger than its initial value of $m^* \cong 0.4$. This increase in m^* verifies the enhancement effect of in-plane magnetic field on the effective mass of 2DHG.

In conclusion, we have measured the effective mass of 2DHG in C-doped (100) $GaAs/Al_{0.4}Ga_{0.6}As$ square QW with MW CR technique. Only one effective mass, $m^* \cong 0.4$, was detected due to small zero-field spin splitting, which was confirmed in the FT spectrum of the beating pattern in SdH oscillations. Values of τ_{tr} and τ_{CR} prove the cleanness of this 2DHG QW from modulation doping. Magnetoresistance measurements under tilted magnetic field indicate that at $B \sim 1$ T, the g-factor of 2DHG is large enough to cause Landau level crossing, and with increasing total magnetic field product gm^* increases, which mainly results from an increase in m^*.

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