JOURNAL OF APPLIED PHYSICS VOLUME 96, NUMBER 11 1 DECEMBER 2004

Magnetotransport properties of two-dimensional electron gas in AlSb/InAs quantum well structures designed for device applications

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(Received 9 March 2004; accepted 23 July 2004)

The mobility and the sheet electron density of two-dimensional electron gas in AlSb/InAs quantum well structures optimized for device applications were measured in the temperature range $4.2\ \mathrm{K} < T < 90\ \mathrm{K}$. A maximum electron mobility $\mu = 3.24 \times 10^5$ was found at 4.2 K at a sheet electron density $n_{2D} = 1.1 \times 10^{12}\ \mathrm{cm}^{-2}$. Measurements of the integral quantum Hall and Shubnikov-de Haas oscillations in the temperature range 0.07–9 K were also carried out to obtain additional information on the characteristics of the two-dimensional electron gas. The electron effective mass m^* and the effective electron g-factor g^* were determined from these measurements and found to be, respectively, 0.032 m_0 and 14.6. The latter is in good agreement with the recent experimental data obtained from cyclotron resonance and titled magnetic-field experiments. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1792385]

I. INTRODUCTION

The large conduction-band offset and the high mobility of the two-dimensional electron gas (2DEG) in the well have made the AlSb/InAs quantum well (QW) structures a highly interesting material for use in the development of high-speed electron devices.[1–3] Because of its large spin-orbit interaction. InAs QWs are current the focus of considerable interest for developing spin field-effect transistors (FETs) based on the Rashba spin precession.[4–7] Such devices hold considerable promise as multifunction devices. Despite the strong spin-orbit interaction, the spin coherence length in InAs fairly large, on the order of a few microns at 4.2 K.[8] This is what makes InAs QWs a promising material for the development of spin devices. A major problem facing the development of such spin devices is the injection of polarized spins into a semiconductor channel and the subsequent detection of it. A simple way of obtaining 100% spin-polarized electrons and detecting them in a one-dimensional (1D) electron system is to spin split the 1D electron energy level and place the Fermi level between the split levels. The larger the spin splitting, the higher will be the chances for getting highly polarized electrons at a given temperature. The spin splitting depends directly on the effective electron g-factor g^*. It is therefore of considerable interest to have information on the g^* value of 1D electrons in an InAs channel. The g^* of 1D electrons is expected to be larger than that of 2D electrons.[9,10] A knowledge of g^* of 2D electrons in InAs QW structures will help design devices to experimentally verify Rashba spin precession in 1D channels. This, in turn, may lead to the future development of 1D spin FFTs. Unfortunately, large discrepancy exist between the experimentally measured value of g^* obtained by different groups. The measured values cover the range from 6 to 60.[11–14] For 1D spin devices, the electron effective mass m^* is also of considerable importance. The 1D energy-level separation is inversely proportional to m^*, and the larger this separation, the higher will be the operating temperature of the device. Measurements of g^* and m^*, especially the former, have been the prime motivation for this work.

Recently, we have reported [15] an optimized procedure for the molecular-beam epitaxy (MBE) growth of AlSb/InAs QW structures designed to yield high sheet electron density n_{2D} and mobility μ of the 2DEG in the well and the results of electrical characterization of a number of such structures. In this work, we present the results of the comprehensive magnetotransport measurements on the 2DEG of a few optimized InAs QW structures especially designed to determine g^* and m^*. A technique was used to determine g^*.

II. EXPERIMENT

The AlSb/InAs QW structures with a 2DEG in the well were grown by MBE on a semi-insulating GaAs(001) using the optimized procedure described elsewhere.[15] The width of the unintentionally doped InAs QW was 15 nm. The samples at 4.2 K had a sheet electron density n_{2D} of about $10^{12}\ \mathrm{cm}^{-2}$ and a mobility μ of about $3.2 \times 10^5\ \mathrm{cm}^2/\mathrm{Vs}$.

The magnetotransport experiments were carried out in a liquid ^{4}He cryostat equipped with either a ^{3}He-^{4}He dilution or a variable-temperature insert. Measurements were made in the temperature range 0.06–100 K. A magnetic field up to 8 T, perpendicular to the plane of the sample, was generated by a superconducting solenoid. We have carried out the classical and quantum Hall measurements on square samples with the Van der Pauw geometry with four indium contacts at the corners. A standard lock-in technique was used at $f = 33$ Hz with a constant ac, small enough to prevent electron heating.

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0021-8979/2004/96(11)/6353/4/$22.00

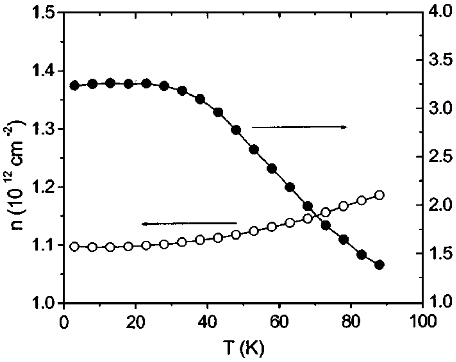

FIG. 1. Temperature dependence of the sheet electron density n_{2D} and mobility μ of InAs QW sample m0238.

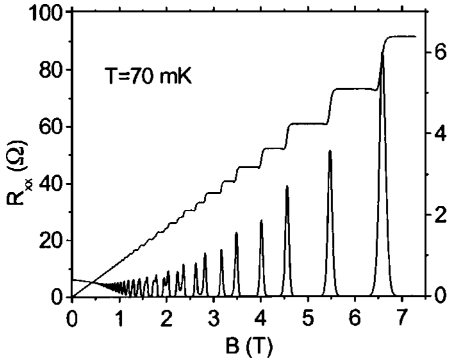

FIG. 2. Shubnikov-de Haas oscillations and quantum Hall effect measured on InAs QW sample m0234 at $T=70$ mK.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the sheet electron density n_{2D} and the mobility μ of the 2DEG measured on a sample. The results shown are representative of the InAs QW structures studied. Both n_{2D} and μ are found to be temperature independent at $T < 30$ K. At a higher T, when phonon scattering becomes important, the mobility decreases, and at $T \approx 80$ K becomes about twice smaller than the low-temperature value. In the same temperature range, n_{2D} shows a small increase (5%–7%). The measured values of Hall mobility μ and sheet electron density n_{2D} at 77 and 4.2 K are shown in Table I for several samples with high mobility. The corresponding values of the electron mean free path $l[=\mu h/e(2\pi n)^{1/2}]$ are also given. It is worth noting that at $T=77$ K, for all of the samples, the electron mean free path l_{77} is about 3μm, indicating that it is possible to have a ballistic electron transport in nanoscale-size devices [3] even at a liquid-nitrogen temperature. The electron mobility reported in Table I is very similar to those reported by many other.[16,17] However, it is much smaller than the highest mobility of 6.0×10^5 cm^2/Vs reported about a decade ago.[18]

In Fig. 2 are shown the Shubnikov-de Haas (SdH) oscillations measured on sample m0234 at $T=70$ mK. Deep minima in R_{xx} and good R_{xy} plateaus, characteristic of quantum Hall regime in a 2D electron system, are observed. The sheet electron densities obtained from the Hall effect and SdH oscillation measurement are practically the same. This, together with the presence of only one main frequency in the Fourier spectrum of the SdH oscillations, indicates that only the lowest electron 2D sub-band is occupied. Our results parctically reproduce those reported earlier.[19] From the temperature and magnetic-field dependencies of the SdH oscillation amplitude, the electron effective mass m^* and quantum relaxation time τ_0 were determined [Figs. 3(a) and 3(b)]. The measured values of τ_0, presented in Table I, are considerably smaller than the transport relaxation time calculated from the mobility, $\tau_{tr} = m^* \mu / e \approx 5.5$ ps. This indicates that τ_0 is primarily determined by the small-angle scattering. Effective electron mass was found to be equal to $m^* = 0.032\ m_0$, in good agreement with the values reported in the literature.[20,21]

To obtain the value of g^*, we used two different methods. The first method uses the Landau level width Γ as a reference energy. It is assumed that the first SdH oscillation appears when the Landau level separation $\hbar\omega_c (=\hbar eB/m^*)$ just exceeds Γ. Similarly, the first spin splitting of a SdH oscillation is observed when the Zeeman spin splitting $\Delta E_z (=\mu_B g^* B)$ just exceeds Γ. If B_1 is the field at which the first SdH oscillation occurs and B_2 is the field when the first spin splitting shows up, we then have $\hbar e B_1 / m^* = \mu_B g^* B_2$, where μ_B is the Bohr magneton. This leads to a simple analytical expression for g^*,

$$g^* = 2(B_1 m_0 / B_2 m^*).$$

One can determine g^* from the experimentally measured values of B_1 and B_2. The cited method is valid if the level broadening Γ does not change in the field range $(B_1 - B_2)$. In a different published work, the Landau level broadening is reported [22,23] to be either constant or proportional to $B^{1/2}$. We believe that in our samples, Γ is not field dependent, and this is supported by the experimentally observed linear dependence of the function $Y = \ln(2\pi^2 k_B T m^* / e\hbar B)$ on $1/B$ ("Dingle plot"), as shown in Fig. 3(b). This plot demonstrates that the quantum relaxation time τ_0, which determines the level broadening, $\Gamma = \hbar / \tau_0$ does not depend on the mag-

TABLE I. Hall mobility μ and sheet electron density n_{2D} at 77 and 4.2 K for the high-mobility AlSb/InAs QW structures studied.

Sample	μ_{77} (cm^2/Vs)	n_{77} (10^{12} cm^{-2})	$l\eta$ (μm)	$\mu_{4.2}$ (cm^2/Vs)	$n_{4.2}$ (Hall)(10^{12} cm^{-2})	$n_{4.2}$ (ShdH)(10^{12} cm^{-2})	$l_{4.2}$ (μm)	τ_0 (ps)
m0234	183000	0.83	2.8	260000	0.78	0.75	3.8	0.13
m0238	168600	1.15	2.9	324800	1.10	1.07	5.7	0.12
m0243	169000	1.26	3.2	295000	1.18	1.15	5.1	0.12
m0253	177000	0.88	2.8	291000	0.83	0.84	4.3	0.15

[a] Electron mean free path l was calculated from the μ and n_{2D} values. Last column presents the quantum relaxation time τ_0.

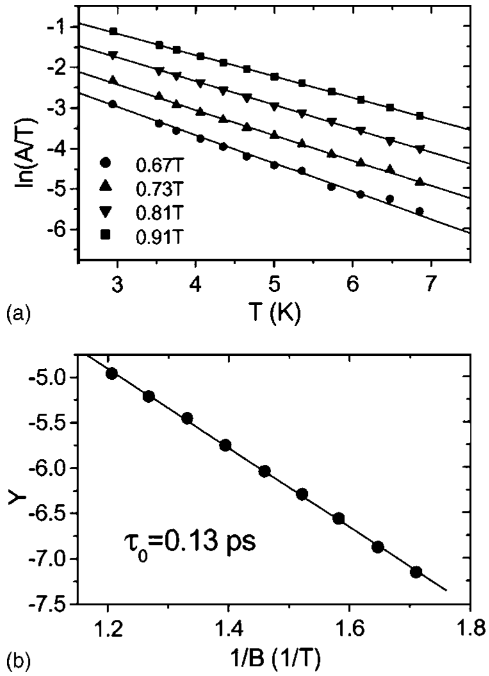

FIG. 3. (a) Temperature dependence of SdH oscillation amplitude A. (b) Dingle plot showing magnetic-field dependence. Data of Fig. 2 were used.

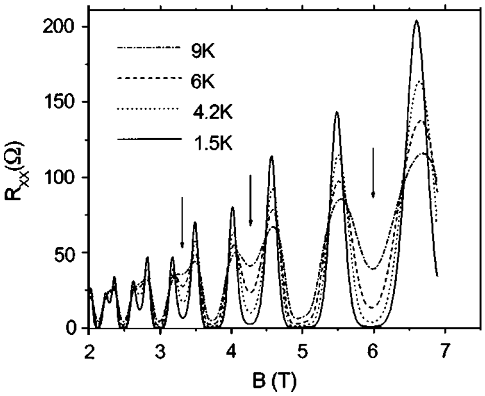

FIG. 5. Influence of temperature on the SdH oscillations for sample m0234. Arrows indicate the spin-split minima R_{xx} used to determine thermal activation energy ΔE.

netic field, at least for the small values of the field. Figure 4 shows the dependence of g^* on n_{2D} obtained for a set of samples with different n_{2D} values. The experimental data follow reasonably well the linear dependence $g^*=g^*(0)(1-\alpha n_{2D})$, where $g^*(0)=17.9$ and $\alpha=0.2\times10^{-12}$ cm^2. We realize that the proposed method is not very accurate because the fields B_1 and B_2 cannot be determined with precision. Nevertheless, the data presented in Fig. 4 are in good agreement with the g^* values obtained from the cyclotron resonance [13] and recent tilted magnetic-field [20] experiments. The negative slope of $g^*(n)$ dependence is probably due to the nonparabolicity effects.[24]

The second method to determine the g-factor is based on the measurements of the temperature dependence of the spin-split minima of R_{xx} in the SdH oscillations[25] when the Fermi level lies in the gap between the spin-split levels. If the Landau levels are assumed to be discrete energy levels and the spin-split energy gap ΔE satisfies $\Delta E \gg k_BT$, then R_{xx} minimum is proportional to $\exp(-\Delta E/2k_BT)$ due to the thermal activation of electrons across the gap ΔE. The condition $\Delta E \gg k_BT$ is likely to be satisfied at high magnetic fields. Then, assuming ΔE is equal to the spin-splitting energy $\Delta E_z=\mu_B g^* B$, one can determine g^* from the experimentally determined value of the activation energy ΔE. Figure 5 shows the SdH oscillations at different temperatures and Fig. 6 presents the Arrhenius plots from which the activation energies at three different values 3.3, 4.3 and 6.0 T of the magnetic field were calculated and are found to be field dependent. The values of g^* for these three fields are found to be 4.2, 5.9, and 7.8 respectively. These values are considerably smaller than the value of 14.6 obtained for the same sample from the B_1/B_2 ratio using the first method. The reason for this discrepancy becomes clear when one takes into account the finite width Γ of the Landau levels and the existence of tails to the Landau level density of states.[23] The data of Fig. 2, based on the analysis of the first method of determining g^*, gave a value of Γ about 10 K. Figure 7 shows the dependence of ΔE on magnetic field. An estimate of Γ can be obtained by extrapolating the data to zero field and is found to be around 18 K. The Landau levels are not therefore discrete. At low temperatures, electrons are thermally excited predominatly to the tails of the upper Landau level, and so experimentally observed apparent activation energy will be lower than the spin-split energy ΔE_z by an amount of the

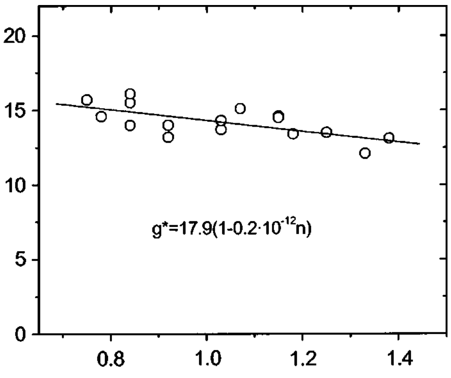

FIG. 4. Effective g-factor g^* measured on the InAs QW samples with different sheet electron density of the 2DEG.

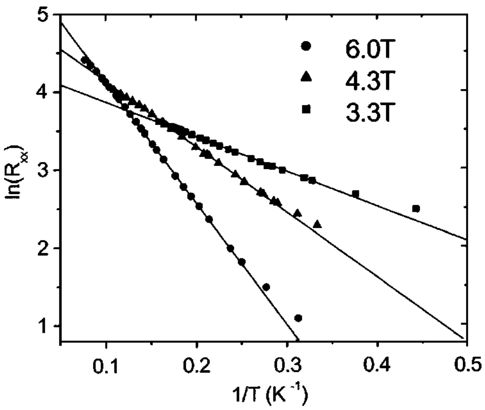

FIG. 6. Temperature dependence of spin-split minima R_{xx} of SdH oscillations for sample m0234.

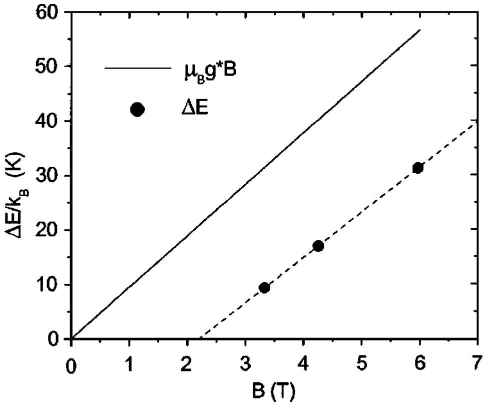

FIG. 7. Spin splitting energy ΔE_s for $g^*=14.6$ and activation energy ΔE as a function of magnetic field for sample m0234.

order of Γ. This also explains why g^*, determined from the measured value of the activation energy, increases with magnetic field. Figure 7 shows the dependence of the activation energy ΔE and the spin-splitting energy ΔE_z for $g^*=14.6$ on the magnetic field. It is interesting to note that the difference between the measured ΔE and ΔE_z is close to Γ. It is therefore conceivable that the measurements of ΔE at sufficiently high values of the field will yield a value of g^* close to 14.6. The measurements of g^* from the temperature dependence of the R_{xx} minima in the SdH oscillations were recently carried out on narrow 4-nm QW InAs/InGaAs samples.[11] As in our experiments, g^* was found to be field dependent and the $\Delta E(B)$ behavior was similar.

This work was supported by the European Union project DEW IST-1999-29012.

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