Zero-field spin splitting in an inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure: Band nonparabolicity influence and the subband dependence

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A gated inverted $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well is studied via magnetotransport. By analyzing the gate-voltage-dependent beating pattern observed in the Shubnikov–de Haas oscillation, we determine the gate voltage (or electron concentration) dependence of the spin-orbit coupling parameter α. Our experimental data and its analysis show that the band nonparabolicity effect cannot be neglected. For electron concentrations above $2\times10^{12}\,cm^{-2}$, it causes a reduction of α up to 25%. We report the α value for the second subband. [S0163-1829(99)09335-2]

Study of the spin-orbit coupling in semiconductor and its influence on transport phenomena is currently of growing interest. Spin-orbit coupling in heterostructures with structure inversion asymmetry is known to lift the electron subband spin degeneracy at finite values of the wave vector parallel to the interface, leading to a finite spin splitting at the Fermi level in the absence of external magnetic field (Bychkov-Rashba spin splitting).[1] It causes both macroscopic effects like a beating pattern in the Shubnikov–de Haas (SdH) oscillation[2,3] and mesoscopic effects such as antilocalization[4] and spin-orbit Berry phase.[5,6] Recently it was found that a surface gate could control the spin-orbit coupling parameter α.[7–9] This is a first step to realizing a spin-transistor proposed by Datta and Das.[10]

However, the understanding of this subject is still controversial. For example, a contribution of the average electric field to the spin splitting is estimated very differently in different theoretical models.[8,11–13] Experiments on $In_xGa_{1-x}As/In_xAl_{1-x}As$ (Ref. 7 and 8) and InAs/AlSb (Ref. 14) quantum wells, respectively, found rather different behavior of the gate voltage (or electron concentration) dependence of α. Comparing the theories with experiment requires accurate determination of the electric field distribution along the growth direction. However, it was usually done by fitting the measured total electron density based on self-consistent subband structure calculations. It is not clear to what extent one can rely on the field distribution obtained in this way. Indeed, in gated structures it is often found that the applied gate voltage differs from the value required to fit the total density, indicating that good fitting of the total density does not reflect a correct determination of the detailed field distribution. More precise and comprehensive experimental data are required. In addition, except for a general discussion given by Das *et al.*,[3] the band nonparabolicity effect was often neglected both in the evaluation of the spin splitting from SdH data and in the self-consistent band-structure calculation. While earlier work on Bychkov-Rashba spin splitting focused on mostly $GaAs/Al_xGa_{1-x}As$ heterostructures,[1,11] recently there is growing interest of using $In_xGa_{1-x}As$ or InAs quantum wells[2–8,14] where the band nonparabolicity effect is not negligible due to their smaller energy gap.

In this paper, we report on an investigation of the gate voltage V_g dependent SdH oscillations in an inverted $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well. Fourier analyzing the SdH oscillations as functions of $1/B$ confirms the existence of the zero-field spin splitting of the second electron subband. The gate voltage dependence of the spin-orbit coupling parameter α of both the first and second subband is determined. We find that taking into account the correction from band nonparabolicity leads to a reduction of α up to 25% at high concentrations. To our knowledge, this effect was not reported in previous studies.

Our sample is an inverted modulation-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum-well structure grown by molecular-beam epitaxy on a Fe-doped semi-insulating (100) InP substrate. The two-dimensional (2D) electron gas channel is formed in the undoped $In_{0.53}Ga_{0.47}As$ channel layer of 20 nm thickness. Underneath the quantum well, a 7-nm-thick $In_{0.52}Al_{0.48}As$ carrier supply layer with the doping density of $4\times10^{18}\,cm^{-3}$ is separated from the channel layer by an undoped 6-nm-thick $In_{0.52}Al_{0.48}As$ spacer layer. Standard Hall bar was fabricated, above which a gate electrode was made on the top of a 100-nm-thick SiO_2 insulating layer. The sample without a SiO_2 insulating layer and gate electrode was initially characterized by SdH measurement and its temperature dependence. The carrier concentration n_s was estimated to be $2\times10^{12}\,cm^{-2}$ with an electron mobility of 36 500 $cm^2/V\,s$. From the temperature dependence of the SdH oscillation amplitude, the effective mass m^* of the electron at the Fermi level was deduced to be $0.05m_e$, where m_e is the free electron mass.

The SdH measurement of the gated sample is performed in lock-in technique with an excitation current of 73 nA at a

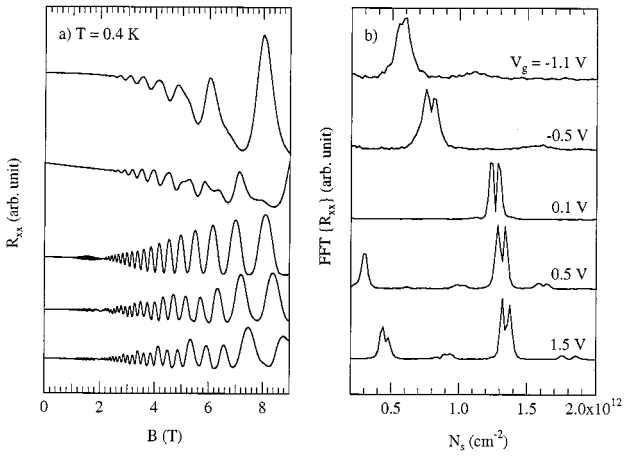

FIG. 1. (a) Shubnikov–de Haas oscillations measured at $T=0.4$ K with different gate voltage applied. (b) The corresponding Fourier power spectra of traces in (a). The horizontal axis is normalized to give the unit in the spin-dependent carrier concentration. Traces are shifted vertically for clarity.

temperature of 0.4 K. Figure 1(a) shows the typical results obtained under different gate voltage bias. Beating patterns are observed at the low magnetic-field region, in accordance with a previous study on a different sample from the same wafer.[7] The origin of the beating pattern is known to be the zero-field spin splitting, which results in two closely spaced SdH oscillation frequency components with similar amplitudes. At positive gate voltage, a different low SdH oscillation frequency component appears that becomes clearly visible for $V_g > 0.5$ V. It indicates the occupation of the second subband with small carrier density.

It is well known that the SdH oscillation for an ideal 2D system is periodic in the inverse field, whose period, with spin degeneracy 2, is given by $\Delta(1/B)=(e/\hbar\pi)/n_s$, where n_s is the carrier concentration. In a system where several spin-split subbands are occupied with electrons, a fast Fourier transform (FFT) performed on the SdH oscillations as functions of $1/B$ gives a direct measurement of spin-dependent carrier concentrations of each subband. The correspondent FFT results of the SdH oscillations displayed in Fig. 1(a) are shown in Fig. 1(b). The (horizontal) frequency axis is normalized to give the unit in the spin-dependent carrier concentration. With increasing gate voltage, carrier concentrations of both subbands are found to linearly increase till reaching saturation values. While the total saturation density is determined by the doping and layer structure, the relative concentrations of the two subbands reflect the intersubband energy. It is interesting to notice that the gate voltages at which the carrier concentrations saturate are slightly different for the two subbands. This implies that the intersubband energy could not be simply determined from the confinement potential, but it changes with the gate voltage, depending on the detail of the carrier and field distribution, which must be solved in a self-consistent way. The clearly resolved double-peak structures allow us to determine the concentration of carriers on the same subband but of different spin orientations. The presence of two types of carriers on the first subband with slightly different concentrations causes the beat observed in the SdH oscillation. Of particular interest is the double structure feature of the second subband observed for high positive gate voltage. Although it is difficult to identify beating patterns related with the second subband, the FFT analysis shows that the second subband also splits into two spin-resolved sublevels.

Recently, based on the consideration of the spin-dependent density of state, a simple formalism was developed,[8] where the spin-orbit coupling parameter α_i of the ith subband could be determined from the total (n_i) and the difference (Δn_i) of the concentrations of the spin-resolved sublevels by the form

$$\alpha_i=\frac{\Delta n_i \hbar^2}{m^*}\sqrt{\pi/2(n_i-\Delta n_i)}. \tag{1}$$

Here m^* is the electron effective mass at the Fermi level. This expression is, however, worth checking for $In_xGa_{1-x}As/In_xAl_{1-x}As$ heterostructures since it is based on the parabolic energy dispersion of the form[1]

$$E(k)=E_i+\frac{\hbar^2k^2}{2m^*}\pm\alpha_i|k|, \tag{2}$$

where E_i is the ith subband energy, k is the electron wave vector parallel to the interface, and $\pm\alpha_i k$ describes the spin-orbit coupling energy. In the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum-well structure studied here with a typical total electron concentration of about $2\times10^{12}\,cm^{-2}$, the nonparabolicity induced energy correction at the Fermi level can be estimated to be $E_F^2/E_g\approx10$ meV. Here E_F is the Fermi energy measured from the subband edge and $E_g=0.81$ eV is the energy gap of $In_{0.53}Ga_{0.47}As$. As found in this work this energy correction is larger than the Bychkov-Rashba spin splitting energy at the Fermi level (of about 5 meV). Therefore one has to take into account the modification of the density of states by the band nonparabolicity to get the correct value of α from the measured electron concentrations. The simplest way of including the band nonparabolicity effect (neglecting any anisotropy) is to start from an energy dispersion of the form

$$E(k)=E_i+\frac{\hbar^2k^2}{2m_0^*}-\frac{\left(\frac{\hbar^2k^2}{2m_0^*}\right)^2}{E_g}\pm\alpha_i|k|. \tag{3}$$

This equation is based on the two-band model for narrow-gap semiconductors and comes from an expansion of the square-root dispersion relation. Using the band-edge effective mass $m_0^*\approx0.042m_e$ for $In_{0.53}Ga_{0.47}As$, the energy dependence of the electron effective mass deduced from Eq. (3) is found to be in agreement with the previous experimental result.[15] Using this energy dispersion, α_i of the ith subband is found to be of the analytical form

$$\alpha_i=\sqrt{\pi/2}\,\frac{\hbar^2}{m_0^*}(\sqrt{n_i+\Delta n_i}-\sqrt{n_i-\Delta n_i})(1-\xi_i), \tag{4}$$

where $\xi_i=(2\pi\hbar^2/m_0^*E_g)n_i$ is the normalized modification factor arising from the band nonparabolicity. For large E_g or small n_i where $\xi_i\approx0$, and by assuming $m_0^*=m^*$, α_i deduced from Eq. (4) is approximately equal to that from Eq. (1).[16]

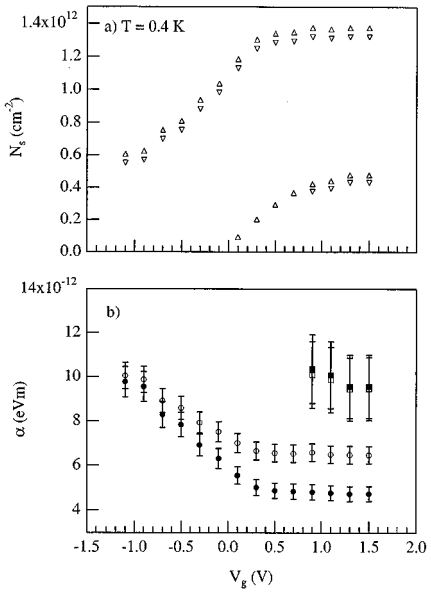

FIG. 2. (a) Up (△) and down (▽) spin electron concentrations obtained from experiment shown in Fig. 1 as a function of the gate voltage. (b) Spin-orbit coupling parameter α of the first (circle) and second (square) subband obtained including (solid) and not including (open) band nonparabolicity correction as a function of the gate voltage.

In Figs. 2(a) and 2(b) we plot the carrier concentration of the spin-resolved subbands and the spin-orbit coupling parameter α as a function of the gate voltage, respectively. In Fig. 2(a), up and down triangles represent the concentration of electrons on different spin-resolved sublevels. For the gate voltage below 1 V, the spin-splitting for the second subband was not resolved. In Fig. 2(b) we comparatively plot the value of α determined with (solid marks) and without (open marks) band nonparabolicity correction by using Eqs. (4) and (1), respectively. Circles and squares represent the spin-orbit coupling constant of the first and second subband, respectively. Clearly, the band nonparabolicity effect is not negligible when the subband is highly populated. With the saturation density of about $2.8\times10^{12}\,\mathrm{cm}^{-2}$ for the first subband, the modification of α_1 due to the band nonparabolicity effect reaches about 25%. We therefore confirm that in our structure α_1 of the first subband could be modulated from a value of $10\times10^{-12}\,\mathrm{eV\,m}$ at -1 V to about $5\times10^{-12}\,\mathrm{eV\,m}$ at $+1.5$ V. Such a 100% changing of the value of α could be applied to modulate the spin precession angle from π to 2π, which is required to get the maximum current modulation in the field effect spin transistor.[10]

Another commonly used method to determine α is to fit the measured beating pattern in SdH oscillations with the use of Landau fan chat.[2,7,8,14] Instead of using the slight difference of the density of states of the two spin-resolved sublevels, this method relies on the slight difference in the spin-dependent modification of the otherwise equally spaced Landau levels. Similar to the above discussion, if the modification of the electron kinetic energy due to the band nonparabolicity is comparable or larger than that due to the spin-orbit coupling, both effects have to be treated on the same level to get the correct value of α. This is also numerically confirmed by fitting our SdH data with the use of the Landau fan chat, where the obtained value of α (taking into account only the correction of the spin-orbit coupling), is close to the open marks in Fig. 2(b). We emphasize that the correction to α due to the band nonparabolicity depends on both the band-gap energy and the electron concentration. The recent study of a gated InAs/AlSb quantum well,[14] where the spin-orbit coupling constant was found to be gate voltage independent, need probably be revised since InAs has a small band-gap energy. Indeed, cyclotron resonance experiment on similar InAs/AlSb structures confirmed that both the effective mass and the g factor are strongly energy dependent due to the band nonparabolicity.[17]

Finally, we would like to discuss the different value of α found for the first and second subband, respectively. de Andrada e Silva, La Rocca, and Bassani[12] showed that in a square quantum well α should be determined by the penetration of the wave function into the barriers and its asymmetry at both interfaces. Since the wave function for the second (higher) subband penetrates more into the barriers than that of the first subband, they predict $\alpha_2>\alpha_1$, if the asymmetry of both wave functions is similar. That is what we observe. An estimation based on the recent theory[13] found that α_1 can be either smaller or larger than α_2, depending on the detail of the potential shape of the quantum well. A quantitative evolution of both α values would require a detailed knowledge of electric field distribution in the well, which is at present unknown.

In conclusion, the Bychkov-Rashba spin-orbit coupling parameter of the conduction-band electrons in an inverted $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterostructure with different surface gate voltage bias was investigated. The concentration dependence of the spin-orbit coupling parameter α is determined for two subbands. The band nonparabolicity effect is quantitatively analyzed and it is found to be important at high densities or/and in heterostructures with small energy gap.

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