



Beating patterns in the Shubnikov-de Haas oscillations originated from spin splitting in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ heterostructures: Experiment and calculation

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HIGHLIGHTS

- The origin of beating patterns of the SdH oscillations is due to interplay of Rashba, Zeeman and Landau splitting.
- The zero-magnetic field spin splitting energy above 3 meV was obtained due to strong Rashba spin–orbit coupling.

ARTICLE INFO

Article history:

Received 23 September 2015

Received in revised form

20 April 2016

Accepted 26 April 2016

Available online 27 April 2016

Keywords:

Semiconductor heterostructures

Quantum well

Spin–orbit coupling (SOC)

Two-dimensional electron gas (2DEG)

ABSTRACT

Shubnikov-de Haas (SdH) oscillation measurements at 1.5 K were carried out for $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ heterostructures with different Si delta-doping concentration and spacer thickness. The dominant zero-magnetic field spin splitting mechanism is attributed to the contribution by the Rashba term due to the structure inversion asymmetry (SIA) in the $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum well. The origin of the beating pattern in the SdH oscillations is investigated through the calculation of the transverse magnetoresistance versus magnetic field B by considering the Zeeman splitting and zero-magnetic field spin splitting in Si delta-doped $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum wells. The good agreement between the theoretical and experimental curves suggest that the origin of beating patterns of the SdH oscillations is due to interplay of Rashba spin splitting, Zeeman splitting and Landau splitting.

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1. Introduction

In recent years, the study of two-dimensional electron gas (2DEG) systems with the zero-magnetic field spin–orbit coupling (SOC) has become an important field of research in semiconductor electronics, especially since the spin-polarized field-effect transistors (SPFETs) are proposed by Datta and Das [1]. Devices based on strongly Spin–orbit coupled 2DEG have potential applications in spin manipulation and quantum information processing, because spin properties such as spin-polarization can be electrically controlled. While the existence of the zero-magnetic field spin splitting between spin-up and spin-down electrons is known, it quickens an enormous interest since manipulation of the electron spin instead of its charge has been considered as a candidate for the future electronics – spintronics. Lifting of the spin degeneracy of conduction band electrons in zero-magnetic field for

nonmagnetic III–V semiconductors can have two different physical theories [2–4]. One of this zero-magnetic field spin splitting is caused by the structure inversion asymmetry (SIA), the so-called Rashba term [5]. The other is due to the bulk inversion asymmetry (BIA) of the zinc-blende lattice for III–V host semiconductors, the so-called k^3 term [6]. The k^3 term dominates in large gap materials such as $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$, while the Rashba term does in small gap materials such as InSb , $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_x\text{Al}_{1-x}\text{As}$, $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$ and InAs/GaSb [9–11]. Magneto-transport at low magnetic fields is a powerful tool for measuring the strength of the SOC in these low-dimensional systems. The zero-magnetic field spin splitting is often experimentally confirmed by observing characteristic beating patterns in the Shubnikov-de Haas SdH oscillations [7–11]. However whether the zero-magnetic field spin splitting exists in the sample through SdH oscillation measurements is still controversial. For example, the origin of the beating patterns is assumed to be a result of the magneto-intersubband scattering (MIS) effect [12,13] or an inhomogeneous carrier distribution induced by the illumination [14]. We have concluded that the physical

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mechanisms of the beating patterns in the SdH oscillations are uniformly based on the Rashba SOC by a series of experiments such as spin photocurrent, current-induced spin polarization, Kerr rotation and SdH oscillations [15]. In this paper the transverse magnetoresistance versus magnetic field B is calculated by considering the Zeeman splitting and zero-magnetic field spin splitting in Si delta-doped $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum wells. We present a detailed comparison between calculated and measured transverse magnetoresistance of 2DEG systems in Si delta-doped asymmetric $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum wells. The calculated transverse magnetoresistance is in very good agreement with the measured SdH oscillation spectrum. It shows that the beating patterns are due to interplay of zero-magnetic field spin splitting, Zeeman splitting and Landau splitting. Meanwhile, the dominant zero-magnetic field spin splitting mechanism is attributed to the contribution by the Rashba SOC due to the strong SIA in the $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum wells.

2. Experiment

Two samples (named D097 and D099) were grown on semi-insulating InP (001) substrates using EPI GEN-II solid-source MBE system. The growth structures and parameters for samples D097 and D099 are given in Table 1. The SIA was achieved by Si delta-doping of only one side of the barrier layer. SdH oscillation measurements were performed over the magnetic field range of 0–1.1 T at 1.5 K. The direction of the magnetic field was perpendicular to the sample surface. The samples were in van der Pauw geometry with indium ohmic contacts at four sample corners. Hall measurements at 1.5 K showed that the carrier concentration was $2.33 \times 10^{12} \text{ cm}^{-2}$ and $1.94 \times 10^{12} \text{ cm}^{-2}$, and the corresponding carrier mobility was $6.79 \times 10^4 \text{ cm}^2/\text{Vs}$ and $6.22 \times 10^4 \text{ cm}^2/\text{Vs}$ for samples D097 and D099, respectively. In order to show clearer beating patterns and eliminate the parallel conduction effect from the Si δ -doping layer, the first differentials of the SdH oscillations for samples D097 and D099 were shown in Fig. 1. Four nodes in the striking beating pattern in the SdH oscillations for a magnetic field in the range of 0–1.1 T have been observed for each sample.

3. Results and discussion

The most popular way to detect and measure zero-magnetic field spin splitting energy is by analyzing the beating pattern in the SdH oscillations. The Landau levels of each spin population give rise to magnetoresistance oscillations described by the function $\cos[2\pi(E_f \pm \delta/2)/\hbar\omega_c]$, where E_f is the Fermi energy, δ is the total spin splitting energy of the Landau levels, $\hbar$ is the reduced Planck constant, and ω_c is the angular cyclotron frequency. The sum of the two spin components is proportional to $\cos(\pi\delta/\hbar\omega_c)$. Nodes in the beating pattern in the SdH oscillations will occur at $\delta/\hbar\omega_c = \nu = 0.5, 1.5, 2.5, 3.5$, etc. where the SdH amplitude is zero [16,17]. The last (highest-magnetic-field) null corresponds to

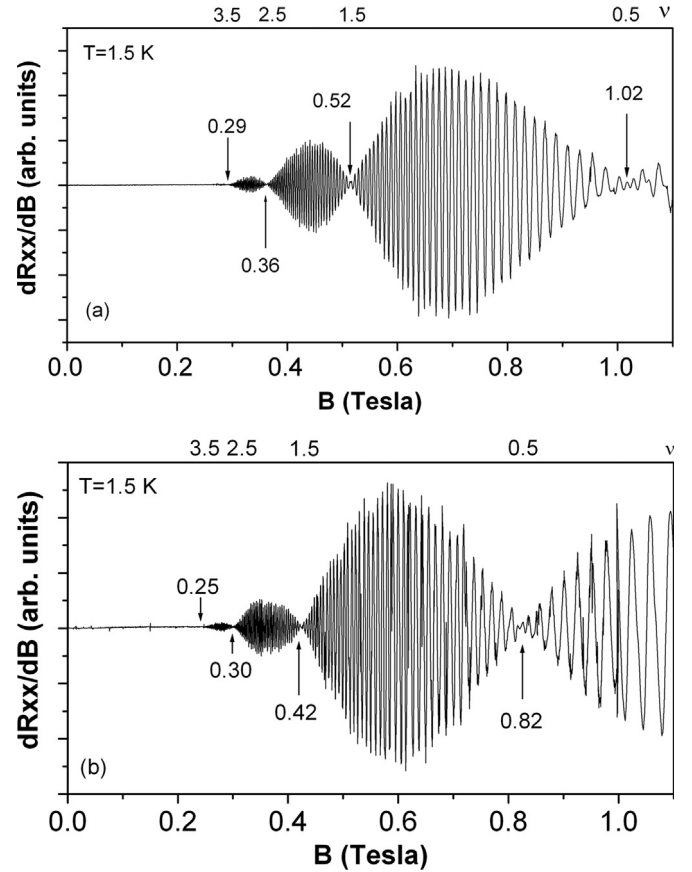


Fig. 1. The first differentials of the SdH oscillations for (a) samples D097 and (b) D099 at $T=1.5$ K. Nodes in the beating pattern in the SdH oscillations are marked by arrows and will occur at $\delta/\hbar\omega_c = \nu = 0.5, 1.5, 2.5, 3.5$, etc.

$\nu=0.5$, and that successively lower nulls occur at $\nu=1.5, 2.5, 3.5$, etc. Then the total spin splitting δ and the corresponding magnetic field B for samples D097 and D099 are shown as solid squares in Fig. 2(a) and (b), respectively.

The total spin splitting energy, including zero-magnetic field spin splitting energy, Landau splitting and Zeeman term, is given by [3]

$$\delta = E_+ - E_- = [(E_L - E_Z)^2 + \delta_0^2]^{1/2} - E_L, \quad (1)$$

where δ_0 is the zero-magnetic field spin splitting energy, Landau splitting $E_L = \hbar\omega_c$ and Zeeman splitting $E_Z = g^*\mu_B B$, where g^* is the effective g factor and μ_B is the Bohr magneton. We have used Eq. (1) to fit the experimental data with δ_0 and g^* as the fitting parameters, and g^* is treated as a constant in such a small magnetic field ($B < 1.1$ T). The results of the theoretical fit for samples D097 and D099 are shown as solid lines in Fig. 2(a) and (b), respectively. The zero-magnetic field spin splitting energy $\delta_0 = 3.7572$ meV and 3.1713 meV were obtained for samples D097 and D099, respectively. Meanwhile, Zeeman and Landau splitting are also showed as a function of magnetic field for each sample in Fig. 2(a) and (b), respectively. It is very clear that δ_0 magnitudes are greater than that of Zeeman splitting for magnetic fields up to 1.1 T.

The zero-magnetic field spin splitting energy δ_0 for sample D097 is higher 18.48% than that for sample D099. To further analyze the numerical result, we need to calculate the expectation value of electric field $\langle E \rangle$ in the $\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum well. The potential profiles of the two samples are calculated by solving the Kohn–Sham Schrödinger equation in conjunction with the Poisson equation self-consistently. Fig. 3 shows the calculated conduction

Table 1

The growth structures and parameters for samples D097 and D099.

Sample	D097	D099
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ Cap Layer (Å)	150	150
$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ (Å)	250	250
Si delta-doping ($\times 10^{12}\text{cm}^{-2}$)	4.5	4
$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ Spacer (Å)	120	150
$\text{In}_{0.65}\text{Ga}_{0.35}\text{As}$ quantum well (Å)	150	150
$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ (Å)	3500	3500
Semi-insulating InP (001) substrate		

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