Experimental Analysis of Shubnikov-de Haas Oscillation for slightly asymmetric InGaAs/InAlAs Double Quantum Wells

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Abstract

We report the observation of beatings of the Shubnikov-de Haas (SdH) oscillations in InGaAs/InAlAs double quantum wells (QW), where the two QWs are only weakly coupled each other and their potential profiles are slightly asymmetric \((N_{S1} \neq N_{S2})\) even after the maximum gate adjustment. We were able to identify the origins of all the beating nodes observed, i.e., whether they originate from the subband or spin (Rashba) energy splitting, clearly. We in addition studied the Fermi circle matching by the in-plane magnetic field \(B_{||}\) between QW1 and QW2 and observed a peak in the electric resistance \(R_{xx}\) measured as a function of \(B_{||}\).

1. Introduction

The spin-orbit interaction has been studied extensively over the decades since the proposal of Datta-Das spin transistor in 1990 [1]. InGaAs/InAlAs Double Quantum Well (DQW) with the interband Rashba effect is considered as an important building block for a spin-filtering device in the future [2].

In this paper, we present the electron transport properties of slightly asymmetric InGaAs/InAlAs DQW with the magnetic field perpendicular \((B_{\perp})\) or parallel \((B_{||})\) to the plane of QWs.

2. Experimental

The samples used in the present study were grown by the Metal-Organic Chemical Vapor Deposition on (001) InP substrate [Fig. 1(a)]. The QW located in the substrate side and that in the surface side are denoted as QW1 and QW2, respectively. Four epi-wafers of such are named as KH3-3, KH3-4, KH3-5, and KH3-6 in this study, where the thicknesses of the barrier layer \((d_{B})\) between QW1 and QW2 are 1.5, 2.0, 3.0 and 5.0 nm, respectively [Fig. 1(a)]. The thicknesses of QW1 and QW2 \((d_{NW})\) are always 10 nm. Our DQW forms a two-subband system (no occupation in the third subband), whose carrier densities, denoted as \(N_{S1}\) and \(N_{S2}\), are associated with QW1 and QW2, respectively. We could not make \(N_{S1}\) and \(N_{S2}\) completely equal to each other even with the maximum control by gate [Fig. 1(b)]. The n-doped carrier supplying layers were placed both below and above the DQW layers with the thickness \(d_{doping} = 6\) nm, where the doping densities are \(n_{1} = 4.0 \times 10^{18} \text{cm}^{-3}\) and \(n_{2} = 4.5 \times 10^{18} \text{cm}^{-3}\) [see Fig. 1(a)].

The measurements of electric resistance \(R_{xx}\) were carried out in a \(^{4}\text{He}\) cryostat using the standard ac lock-in technique at 1.4 K. The magnetic field \(B_{||}\) was applied either perpendicularly or parallelly to the plane of the samples using a 7 T superconductor solenoid.

![Fig. 1](image_url)

(a) Schematic layer structure of the DQW samples used in the present experiment. The thickness of the middle barrier layer \((d_{B})\) are 1.5 nm, 2.0 nm, 3.0 nm and 5.0 nm, for KH3-3, KH3-4, KH3-5 and KH3-6, respectively. (b) Gate voltage \(V_{g}\) dependence of \(N_{S1}\) and \(N_{S2}\) for KH3-5 deduced from the SdH analysis [3].

3. Results

Shown in Fig. 2(a) is the plot of the electric resistance \(R_{xx}\) as a function of \(B_{||}\) for KH3-5 with the gate voltage \(V_{g} = 0.4\text{V}\), which exhibits the SdH oscillation with clear beatings. Such beatings in the SdH oscillation evidence the existence of multiple subbands with different carrier densities. We therefore analyzed the \(V_{g}\) dependences of the SdH oscillations and extracted the values of \(N_{S1}\) and \(N_{S2}\) as in Fig. 1(b) [3].

In Fig. 2(a), multiple beating nodes are observed for \(B_{||} > 1.5\) T (indicated by arrows with symbols). We attribute them to the subband splitting \(\Delta_{ab}\), ignoring spins, which is related to the site potential energy \(\pm \hbar E_{c} < z >\) or equivalently the carrier density difference \(N_{S1}-N_{S2}\).

\[
\Delta_{ab} = 2eE_{c} < z > \frac{\hbar}{m} (N_{S1} - N_{S2}),
\]

where \(\hbar, e, m^{*}, E_{c}\) and \(< z >\) are Planck’s constant divided by \(2\pi\), elementary charge, the effective mass, the gate electric field within the DQW and \(<QW2|eE_{c}|QW2>\), respectively, \(|QW2>\) being the spinless eigenfunction of QW2 along \(z\) for an isolated QW2 \((z = 0)\) at the middle of the barrier layer between QW1 and QW2. The positions of these nodes \((B_{\text{nodes}})\) are found to follow the rule shown below.
experimental data are plotted as a function of $N_{\text{tot}}^{\text{het}}$, which was controlled by $V_g$. These nodes can be classified into three groups. The first is those caused by the subband splitting ($\Delta_{\text{sub}}$) in DQW [Fig. 2(a)]. The second and third are those caused by the Rashba splitting ($\delta_{i}$) for QW1 and QW2, respectively. In all cases, $B_{\text{node}}$s are indexed with integers (0, 1, 2, ...) and agree perfectly with the predictions by Eqs. (2) and (3).

Plotted in the right inset of Fig. 3 are the measured $R_{xx}$ as a function of the magnetic field $B_{||}$ parallelly applied to the sample (KH3-3), where the peaks features are clearly observed. The peak positions $B_{\text{peak}}$ are extracted by taking the second derivative of $R_{xx}$ with respect to $B_{||}$ for all $V_g$s (colored square symbols). Theoretically, such peaks may result from the matching of the Fermi circle edges between QW1 and QW2 by the effect of $B_{||}$ as sketched in the top inset of Fig. 3. The condition for this to happen is written as [2]

$$B_{\text{peak}} = \frac{h}{2e} \frac{2\pi}{(z)} \left( \sqrt{N_{S1}} - \sqrt{N_{S2}} \right). \tag{5}$$

Here, $(z)$ is calculated to be 6.92 nm for KH3-3. A good agreement between the experimental and theoretical values of $B_{\text{peak}}$s is found in the main panel of Fig. 3.

Fig. 3 (main panel) The experimentally extracted values of $B_{\text{peak}}$ (colored $\bigcirc$), extracted from the $R_{xx}$ vs $B_{||}$ measurements as in the right inset (each traces are shifted vertically for better presentation), together with the theoretically predicted curve by Eq. (5) (solid curve). The sketch of the Fermi circle matching by $B_{||}$ between QW1 and QW2 is shown in the upper inset.

4. Conclusions

We succeed in identifying nodes that arise from both the subband and Rashba splittings. We then observed a peak in the experimental $R_{xx}$ as a function of $B_{||}$. The position of this peak ($B_{\text{peak}}$) shifted to the higher field with decreasing $V_g$, which is in quantitative agreement with the theoretical prediction based on the matching of the Fermi circle edges between the constituent QWs.

References