Cyclotron resonance of two dimensional Rashba systems in InGaAs

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Abstract. We observed an anti-crossing behavior for the magnetic field dependence of the cyclotron resonance in a InGaAs/InAlAs two-dimensional Rashba system. Two resonances can be observed at a narrow millimeter frequency region, and this is due to the resonant coupling between different two spin levels because of the large zero-field spin splitting by the Rashba effect. The electron effective mass is obtained as \( m^* = 0.04m_0 \), which is in good agreement with the previous result at a terahertz region.

1. Introduction

Large zero-field spin splitting has been studied intensively in various semiconductors for realizing novel spintronic applications such as the spin FET. Among narrow gap semiconductors, the InGaAs system, which has a larger spin-orbit interaction, is one of good candidates for studying the structure induced spin splitting, namely, the Rashba effect. The zero-field spin splitting energy for the Rashba system is estimated through the beat pattern analysis or the FFT analysis in the Shubnikov-de Haas (SdH) oscillation [1]-[4]. Cyclotron resonance (CR) is also a powerful tool for the direct observation of the spin splitting energy, recently [5]. Since the Zeeman energy becomes dominant rather than the Rashba spin splitting energy at high magnetic fields, the CR measurement at low magnetic fields is quite essential to determine the Rashba spin-orbit parameter quantitatively. In this study, hence, we measured the magnetic field dependence of the CR in a high In-content InGaAs/InAlAs inverted heterostructure at a millimeter wave range.

2. Experiment and Sample

A In\(_{0.75}\)Ga\(_{0.25}\)As/In\(_{0.75}\)Al\(_{0.25}\)As inverted heterostructure sample for the present experiment was grown on a semi-insulating GaAs substrate by the molecular beam epitaxy method. Magneto-transport experiments were performed with the van der Pauw method at high magnetic fields up to \( B = 27T \) under \( T = 1.5K \). Ohmic contacts were fabricated with pure Indium soldering. The high magnetic field is generated by the water-cooled magnet in the Tsukuba Magnet Laboratory of National Institute for Materials Science. The sweeping rate of the magnetic field was done in the range of 0.01T/s.

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Figure 1. Magnetic field dependence of $R_{xx}$ and $R_{xy}$ at high magnetic fields up to 27T. The carrier concentration of the sample is obtained as $n=1.5\times10^{12}$ cm$^{-2}$.

Figure 2. Typical cyclotron resonance spectra with using the MVNA : magneto-transmission ($r$) and phase ($\theta$) data at $f=306$GHz.

field is 1.25T/min. The SdH oscillation and the quantum Hall plateau are observed clearly at the integer filling factor in figure 1. The mobility and the carrier concentration of the sample were obtained as $\mu \sim 20$m$^2$/V·s and $n \sim 1.5\times10^{12}$ cm$^{-2}$, respectively.

CR spectra were measured with a millimeter-wave vector network analyzer (MVNA) in the range between $f=150$GHz and 340GHz. The magnetic field is applied perpendicular to the two-dimensional electron layer with a superconducting magnet up to $B=15$T. The typical dimension of the sample is $5\times5\times0.5$mm$^3$, and the backside of the sample is wedged to avoid interference effects. More details of the MVNA is described in Ref.[6].

3. Results and Discussion

Figure 2 shows the typical CR spectra at $f=306$GHz. The CR measurement was performed at $T=1.7$K. Single Lorentzian absorption is observed around $B=0.45$T with the large variation of its phase. The electron effective mass is obtained as $m^* = 0.04m_0$ from the resonant magnetic field. This value is in good agreement with the previous result of the terahertz cyclotron resonance [5]. However, in case of the frequency below $f=200$GHz, additional resonant peaks appear in some CR spectra. Further frequency dependence of the CR spectra below $f=184$GHz is shown in figure 3. Single CR peak is observed around $f=172$GHz, and evident additional peak appears at the higher magnetic field side in some CR data (indicated by arrows in figure 3). The magnetic field dependence of the additional peak is different from the one of the main CR peak around $B=0.25$T.

In order to confirm the additional resonance, a $r$-$\theta$ plot for the CR data of $f=169$GHz and 178GHz is shown in figure 4. The advantage for the $r$-$\theta$ plot analysis with both transmission data and phase data is known well to determine the resonant field correctly even for weak and broad resonances in the MVNA measurement [6]. In figure 4, the dashed data at $f=178$GHz shows a single circle. On the other hand, the solid data at $f=169$GHz consists of two circles, indicating that the CR data at $f=169$GHz include two resonances.
Figure 3. CR spectra between $f=168\text{GHz}$ and $184\text{GHz}$. Arrows indicate the resonant position of the additional peak.

Figure 4. $r$-$\theta$ plot for the data of $f=169\text{GHz}$ and $178\text{GHz}$. The dashed data at $f=178\text{GHz}$ shows a single circle. On the other hand, the solid data at $f=169\text{GHz}$ consist of two circles. This indicates that the CR data at $f=169\text{GHz}$ consist of two resonances.

Figure 5 shows the magnetic field dependence of the CR at the frequency between $f=150\text{GHz}$ and $340\text{GHz}$. The CR energy is proportional to the applied magnetic field except around $f=170\text{GHz}$. The solid line shows a calculated CR energy with $m^*=0.04m_0$, and the calculation is in good agreement with the main CR data at the wide frequency region.

The dashed curve shows the calculated result of the transition energy between different spin levels, $N=14^+$ and $14^-$ from the formula:

$$E_{N\pm} = \hbar \omega_c \left( N \pm \frac{1}{2} \sqrt{(1 - \frac{gm^*}{2m_0})^2 + N \frac{\Delta R^2}{E_F \hbar \omega_c}} \right),$$  

\[\Delta R^2 = \frac{8\alpha^2m^*E_F}{\hbar^2}, \tag{2}\]

where $\omega_c$ is the cyclotron energy, which is given by $\omega_c = eB/m^*$, and $g$ is the effective g-factor. $\Delta_R$ and $E_F$ are the zero-field spin splitting energy and the Fermi energy, respectively. $\alpha$ is the Rashba spin-orbit coupling parameter.

The dashed curve, calculated with $\alpha=9\times10^{-12}\text{eV}\text{m}$ and $|g|=7$, explained the anomalous magnetic field dependence of the resonance around $f=170\text{GHz}$ qualitatively well. This Rashba spin-orbit coupling parameter, $\alpha$, is in fair agreement with the value estimated from the transport measurements ($\alpha=12\sim15\times10^{-12}\text{eV}\text{m}$) in the same sample. Hence, we assign that the origin of the additional peak is due to the spin-flip (SF) transition between different spin levels. The SF resonance was proposed theoretically by Fal’ko in the coupling of the Landau levels through the spin-orbit interaction, and an anti-crossing behavior was observed experimentally in a modulation-doped CdMnTe/CdMgTe single quantum well [8]. In the present sample, other anti-crossing points between different spin levels should appear at lower magnetic fields below $B=1\text{T}$, and two resonances were observed even at other frequency regions (not shown here). However, the carrier concentration of the present sample is too high, and the anomalous magnetic field dependence of the additional resonance has not been understood quantitatively well yet.
Further experimental confirmation and theoretical support are needed to clarify the CR spectra at the wide range of the frequency in the InGaAs/InAlAs two-dimensional Rashba systems.

Figure 5. Magnetic field dependence of the CR between $f=150\,\text{GHz}$ and $340\,\text{GHz}$ at $T=1.7\,\text{K}$. The solid line shows the calculated result of the cyclotron energy with $m^*=0.04m_0$. The dashed curve indicates a theoretical curve of the spin-flip transition between $(14, \downarrow)$ and $(14, \uparrow)$ with the Rashba spin-orbit coupling constant, $\alpha=9\times10^{-12}\,\text{eVm}$ and $|g|=7$.

4. Summary

We studied the CR in the InGaAs/InAlAs inverted heterostructure at the millimeter wave region. Single CR is observed at higher frequency region, and the effective mass is obtained as $m^*=0.04m_0$ from the magnetic field dependence of the CR. The additional resonance appears below $f=184\,\text{GHz}$ at the high magnetic field side of the CR. This resonance is probably due to the spin-flip transition between different spin levels. The resonant coupling of Landau levels through the large spin-orbit interaction is essential to explain the anomalous magnetic field dependence of the CR in the two-dimensional Rashba system.

5. References

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