ANISOTROPY OF SPIN-RESONANCE POSITION IN *p*-TYPE InSb INVERSION LAYER

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The dependence of the position of spin resonance on the tilt angle between the surface normal and the magnetic field direction observed in *p*-type InSb inversion layer can be explained quantitatively by the spin-orbit or Rashba term. From the analysis the sign and magnitude of the spin-orbit coupling constant are determined. We also demonstrate that the linear extrapolation of the spin resonance energy to zero magnetic field cannot be used to obtain zero-field splitting energy.

THE SPIN splitting of conduction-band states in semiconductor heterostructures and quantum wells has been extensively studied both experimentally and theoretically. This splitting results from the anti-symmetry of macroscopic or microscopic crystal potential which splits the twofold energy degeneracy when there is a spin-orbit interaction. Effects of this splitting have been observed in spin-polarized photo-emission in GaAs surface [1], infrared spin resonance in GaAs–Al_xGa_{1–x}As heterostructures [2] and in *p*-type InSb inversion surface layer [3], and Shubnikov-de-Haas oscillations in In_xGa_{1–x}As–In_xAl_{1–x}As heterostructures [4]. Infrared spin resonance is known to be able to provide a very accurate information of the energy band structure in semiconductors. For example, at low temperature (< 5 K) the spin resonance line appearing in the spectrum is extremely sharp (the line is less than 100 G wide at 40 kG), allowing a very precise determination of the energy separation between the two spin states. A very interesting behaviour of spin resonance has been observed in GaAs–Al_xGa_{1–x}As heterostructures [2] and in *p*-type InSb inversion layer [3]. It is found that the magnetic field of the spin resonance depends on the tilt angle between the surface normal and the magnetic field direction. In other words, the spin-resonance position in semiconductor heterostructures is anisotropic. To our knowledge, there has been no attempt to interpret this behaviour so far. In this paper we show that this anisotropy is due to the spin-orbit or Rashba term [5]. From the analysis, the sign and magnitude of the coefficient associated with the spin-orbit term are determined. We will analyze the data of spin resonance in *p*-type InSb inversion layer [3] since it is the only data available for us.

For zinc-blende bulk semiconductors, the spin resonance induced by electric dipole transition can

arise from three possible sources: the lack of inversion asymmetry [6, 7], wave-function mixing through $\mathbf{k} \cdot \mathbf{p}$ interaction [8] (nonparabolicity), and/or warping [7]. As shown by our early work [9], we know from experimental data that electric-dipole-spin-resonance in InSb is dominated by inversion asymmetry. To include the term contributed by inversion asymmetry, the effective-mass Hamiltonian of a conduction electron in an applied d.c. magnetic field is given by [10]

$$H = \frac{\hbar^2 k^2}{2m^*} + \delta_0 \boldsymbol{\sigma} \cdot \boldsymbol{\kappa}, \quad (1)$$

where $\boldsymbol{\sigma}$ are the Pauli matrices, m^* is the effective mass, $\hbar \mathbf{k}$ is the kinematic momentum associated with the vector potential $\mathbf{A}$ of the d.c. magnetic field,

$$\hbar \mathbf{k} = -i\hbar \nabla + \frac{e}{c} \mathbf{A}, \quad (2)$$

δ_0 is a parameter which is associated with spin-orbit interaction and the microscopic inversion asymmetry of the zinc-blende lattice, and $\boldsymbol{\kappa}$ is a vector given by

$$\kappa_x = k_y k_x k_y - k_z k_x k_z, \quad (3)$$

κ_y and κ_z are obtained from κ_x by cyclical permutation of the indices. From our early studies [11], we found that the maximum fractional anisotropy of the magnetic field position of the spin resonance in bulk InSb is 0.85%. The magnetic field position of the transmission minimum shifts from 41.29 to 41.66 kG when the direction of magnetic field is changed from [1 0 0] to [1 1 1]. This shift is much smaller than the result observed in *p*-type InSb inversion layer. Thus, we conclude that the dominant mechanism of spin resonance in *p*-type InSb inversion layer is not the inversion-asymmetry-induced bulk κ^3 term, but rather the asymmetry of macroscopic potential in the surface layer.

It has been pointed out by Bychkov and Rasha [5] that in a semiconductor heterostructure there is an additional term in the Hamiltonian of the spin-orbit interaction of an electron due to asymmetry of macroscopic potential. This Hamiltonian is given by

$$H_{so} = \alpha \hat{\mathbf{z}} \cdot (\boldsymbol{\sigma} \times \mathbf{k}), \quad (4)$$

where $\hat{\mathbf{z}}$ is a unit vector perpendicular to the surface, α is the spin-orbit coupling constant. This term shows the admixture of orbital and spin states of electrons in a magnetic field caused by the spin-orbit interaction. It thus can give rise to spin-flip transitions within the electric dipole approximation. We believe that this is the mechanism responsible for the spin resonance in *p*-type InSb inversion layer as suggested by Lommer *et al.* [12]. To further investigate the role of H_{so} playing in the anisotropy of spin resonance, we rewrite equation (4) as follows

$$H_{so} = \alpha \boldsymbol{\sigma} \cdot (\mathbf{k} \times \hat{\mathbf{z}}) \\ = g\beta \boldsymbol{\sigma} \cdot \mathbf{B}_{\text{eff}}, \quad (5)$$

where g is the effective g factor for conduction electrons, $\beta = e\hbar/2m_0c$ is the Bohr magneton, and

$$\mathbf{B}_{\text{eff}} = \frac{\alpha}{g\beta} \mathbf{k} \times \hat{\mathbf{z}}. \quad (6)$$

Note that $\mathbf{B}_{\text{eff}}$ is in the surface plane.

From equation (5) we can see that the spin-orbit interaction H_{so} is equivalent to the existence of an effective magnetic field $\mathbf{B}_{\text{eff}}$ experienced by the magnetic moment of the electron. When there is an applied magnetic field $\mathbf{B}$, the spin splitting is not only caused by $\mathbf{B}$ but also by $\mathbf{B}_{\text{eff}}$, thus the magnetic moment of the electron experiences a total magnetic field $\mathbf{B}_t$ given by

$$\mathbf{B}_t = \mathbf{B} + \mathbf{B}_{\text{eff}}. \quad (7)$$

Because the wave vector of the cyclotron motion in the surface plane only depends on the component of $\mathbf{B}$ that is parallel to the unit vector $\hat{\mathbf{z}}$, the magnitude of the wave vector will be changed when $\mathbf{B}$ is tilted an angle ϕ away from the surface normal direction. The dependence of the wave vector on the angle ϕ can be written as

$$k(\phi) = k(0) \sqrt{\cos \phi}, \quad (8)$$

where $k(0)$ is the magnitude of the wave vector when $\mathbf{B} \parallel \hat{\mathbf{z}}$. Equation (8) is obtained by the fact that the square of the magnitude of wave vector is proportional to the component of $\mathbf{B}$ in the surface normal direction. Thus, the effective magnetic field $\mathbf{B}_{\text{eff}}$ will depend on the direction of the magnetic field $\mathbf{B}$ by the expression

$$\mathbf{B}_{\text{eff}} = \mathbf{B}_{\text{eff}}^0 \sqrt{\cos \phi}, \quad (9)$$

where $\mathbf{B}_{\text{eff}}^0$ is the effective magnetic field when $\mathbf{B} \parallel \hat{\mathbf{z}}$. In

the far-infrared magnetotransmission measurements at a fixed wavelength, equations (7) and (9) lead to the fact that the spin resonances for different directions of $\mathbf{B}$ locate at different magnitudes of $\mathbf{B}$ since the spin flip transitions occur when

$$\hbar\omega = g\beta |\mathbf{B} + \mathbf{B}_{\text{eff}}^0|, \quad (10a)$$

for $\mathbf{B}$ along the surface normal direction, or

$$\hbar\omega = g\beta |\mathbf{B} + \mathbf{B}_{\text{eff}}^0 \sqrt{\cos \phi}|, \quad (10b)$$

for $\mathbf{B}$ tilted by an angle ϕ , where ω is the angular frequency of FIR radiation. Thus, from the study of the dependence of the spin-resonance position at different directions of the magnetic field, we are able to determine the $\mathbf{B}_{\text{eff}}^0$, and hence the spin-orbit coupling constant α .

Here, we will apply the above description to the measurements of spin resonance in an inversion layer on *p*-type InSb [3]. The dependence of the spin-resonance magnetic field on the angles ϕ ($\phi = 0^\circ, 30^\circ$ and 45°) obtained by Därr *et al.* [3] can be well described by equation (10) if we let $B_{\text{eff}}^0 = 3.0$ kG. For comparison, in Table 1 we list the values of the theoretical calculation and experimental measurement of the spin-resonance positions at different angles ϕ . According equation (6), the corresponding spin-orbit coupling constant α is $9.8 \times 10^{-10} \text{ eV cm}^{-1}$, where we have used the value of g factor to be 41.4 taken from [3]. Because the spin-resonance magnetic field is shifted to higher magnitude by increasing the tilt angle ϕ , the sign of the spin-orbit coupling constant has to be negative which can easily be seen from equation (10). At present, it is difficult for us to compare the value of α obtained here with that of the theoretical calculation by Lommer *et al.* [12] because we do not know the expectation value of the surface electric field. However, we believe a detailed analysis of the data may allow us to understand the more information about semiconductor heterostructures.

The spin-orbit coupling constant in a GaAs/

Table 1. Values of theoretical calculation and experimental measurement of spin-resonance positions (B) at different angles ϕ , where ϕ is the tilt angle between the surface normal and the magnetic field direction. The theoretical values are calculated by equation (10). The experimental results are taken from [3]

ϕ	B	Theory (Tesla)	Experiment (Tesla)
0°		4.36	4.37
30°		4.50	4.45
45°		4.55	4.60

Fig. 1. The resonance magnetic field B at different photon energies for n -type InSb. Data are from [11] (squares), [16] (circles), [17] (triangles).

AlGaAs heterostructure has been determined by Bychkov and Rashba [5] using the zero-field splitting energy obtained in [2]. The zero-field splitting energy was determined from the linear extrapolation of spin resonance energy to $B = 0$ T. However, it was pointed out by Lommer *et al.* [13] that the zero-field splitting reported in [2] turns out to be an artifact of the linear extrapolation from experimental data because of the nonparabolicity of the band structure. Here, we also give an example to show that the linear extrapolation of spin resonance energy to $B = 0$ T cannot be used to determine zero-field splitting energy. Figure 1 shows resonances in bulk InSb at different photon energies, the data was taken from several authors [11, 14–17]. These results fall on a straight line not drawn through the origin. Thus, the observed spin resonances obey a law

$$\hbar\omega = \hbar\omega_0 + \gamma B. \quad (11)$$

According to Stein *et al.* [2], $\hbar\omega_0$ is the zero-field splitting energy, and γ is a constant proportional to the g factor. Although equation (11) can describe the experimental data obtained from different groups, it is unphysical for the following reasons. First, the zero-field splitting energy is too large to be believed. If the zero-field splitting energy has the magnitude as indicated in Fig. 1, the effect should be observed in Shubnikov–de-Haas measurements as shown in HgSe [18]. However, a number of studies [19, 20] of InSb have shown no indication of the zero-field splitting.

Second, in the bulk the splitting is described by the Hamiltonian $\delta_0 \sigma \cdot \kappa$ as shown in equation (1). This conduction-band splitting is equivalent to the existence of an effective magnetic field parallel to κ experienced by the magnetic moment of the electron. The changes of electron momentum in the bulk result in a random variation of magnitude and orientation of this effective magnetic field. Thus, from the measurement of spin resonance in bulk sample we should not see the effect. In fact, the dependence of the magnetic field on the photon energy of spin resonance has been described very well by the modified Pidgeon–Brown model [21]. The model shows that the g factor varies with applied magnetic field. This has been verified experimentally by several authors [22, 23]. We thus demonstrate that the linear extrapolation of spin resonance energy to zero magnetic field can lead to erroneous estimates of zero-field spin splitting energy. Hence, it cannot be used to determine the spin-orbit coupling constant.

In summary, we have shown that the dependence of the magnitude of the spin-resonance magnetic field in p -type InSb inversion layer on the tilt angle ϕ between the surface normal and the magnetic field direction can be explained by the spin-orbit or Rashba term. The sign and magnitude of the spin-orbit coupling constant can be determined from the study of this anisotropic behaviour. Here we have only analyzed the results of an inversion layer on InSb. Extending these considerations to other semiconductor heterostructures should lead to similar results. In view of the same behaviour of spin resonance in GaAs/AlGaAs heterostructures, such analysis would be useful and timely. In addition, we have also demonstrated that the linear extrapolation of the spin resonance energy to zero magnetic field can no be used to determine the zero-field splitting energy.

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