

Tuning of spin resonance by an electric current in a Si quantum well

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Electron spin resonance of a two-dimensional electron gas in an asymmetric silicon quantum well has been investigated. Applying a small dc current, we observe a shift in the resonance field due to the additional, current induced Bychkov–Rashba type of spin orbit field. We also show that a high frequency current may induce electric dipole spin resonance very efficiently.

Key words: *spin orbit field; spintronics; electron spin resonance*

1. Introduction

Present concepts for spintronic devices invoke the manipulation of spins by electric voltages or currents. This task is conceptually accomplished making use of spin-orbit (SO) coupling which is a mechanism involving both electronic and spin properties: SO interaction is seen by the spin of an electron as an additional energy splitting of the two allowed spin states, or, equivalently, an effective magnetic field which depends on the electron velocity. Here we investigate this Zeeman splitting, performing electron spin resonance (ESR) experiments on two-dimensional electrons in an asymmetric silicon quantum well.

ESR studies allow one to evaluate the magnitude of the SO field [1–3]. This additional magnetic field causes a shift of the spin resonance field, in principle, of individual electrons. The momentum scattering time is, however, about $\tau_k \approx 10^{-11}$ – 10^{-12} s, and thus by orders of magnitude shorter than the characteristic time of the measurement, which is essentially limited by the transverse relaxation time $T_2 \approx 10^{-6}$ s. Consequently, ESR monitors a mean value of the SO field only. At thermal equilibrium, the

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mean value of electron velocity vanishes, and consequently, the mean SO field vanishes as well. Therefore, the analysis of the g -factor and linewidth anisotropy allows one to determine the mean value of the square of the SO field only. The magnitude of the SO field in the investigated Si/SiGe 2D structures has been found to be of the order of 10 mT.

In this paper, we investigate the effect of electric current on ESR. This is a continuation of our earlier investigations [4]. When a current is applied then a finite mean value of the SO field appears, proportional to the drift velocity. This current induced SO field can be measured as a shift of ESR. This finding, together with its characteristic geometry dependence, demonstrates SO coupling in the most straight-forward way: the drift velocity of the carriers imposes a magnetic field in the presence of a transverse electric field. The induced field is proportional to the vector product of the drift velocity and an electric field built in the 2D structure.

2. Bychkov–Rashba spin-orbit field

In asymmetric 2D structures, the lowest order – bilinear – SO term for the energy of an electron contains the vector product of the electron velocity (or, equivalently, its momentum, $\hbar\mathbf{k}$) and the spin, σ . Such a linear term may exist only for lower than mirror symmetry, caused e.g., by the existence of an electric field, \mathbf{E}_0 , as discussed by Bychkov and Rashba [5, 6]. This type of SO coupling is described by a one electron Hamiltonian term $\alpha_{BR}(\mathbf{k} \times \mathbf{n}) \cdot \vec{\sigma}$ which implies spin splitting already without an externally applied magnetic field. Here α_{BR} is the Bychkov–Rashba (BR) coefficient which depends on the strength of SO interaction and the asymmetry of the system, $\vec{\sigma}$ stands for the Pauli matrices describing the spin state, and \mathbf{n} is a unit vector pointing in the direction in which the inversion symmetry is broken (parallel to \mathbf{E}_0 , and perpendicular to the 2D sample layer).

The SO induced spin splitting can be described also in terms of an effective magnetic Bychkov–Rashba (BR) field

$$\mathbf{B}_{BR} = \frac{2\alpha_{BR}}{g\mu_B} (\mathbf{k} \times \mathbf{n}) \quad (1)$$

seen by each electron. Here g is the g factor and μ_B the Bohr magneton. The BR field is thus perpendicular to both the momentum of the electron, and the direction \mathbf{n} .

3. ESR measurements

We investigate ESR of the 2d electron gas (2DEG) in a Si layer confined by Si/SiGe barriers. The asymmetry of the layer originates from an asymmetric, one sided

modulation doping. In such structures, free carriers are introduced to the quantum well by accommodating donors at a distance of some 10 nm from the quantum well in the barrier material. Consequently, electrons are weakly scattered by ionised donors and they are affected by the electric field \mathbf{E}_0 originating from ionised donors in the δ layer.

ESR measurements were done in a standard ESR spectrometer working at a frequency of 9.4 GHz. The sample was placed at the centre of a TE_{102} microwave cavity, at the node of the electric microwave field. Additional thin Au wires attached to the end faces of the sample allow us to apply a dc electric current passing through the quantum well of the sample. The direction of the current density, j , is perpendicular to the applied dc field, B_{0z} , (z axis) and parallel to the rotation axis and to the direction of microwave magnetic field (y axis). The layered sample can be rotated in the cryostat. The normal to the layer, n , rotates in the (xz) plane. The angle θ stands for the angle between the normal n and the z axis.

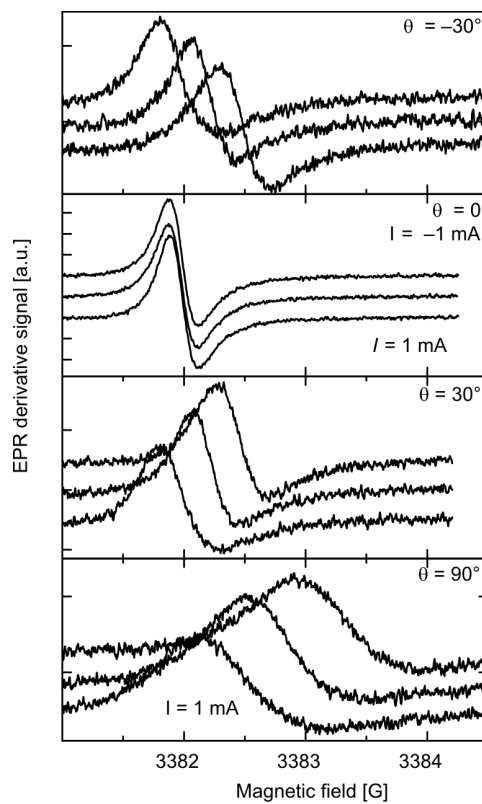


Fig. 1. ESR spectra for various orientations of the Si/SiGe sample with $n_S = 5 \times 10^{11} \text{ cm}^{-2}$. The central line stands for ESR without any electric current. The line is shifted up- or downwards for $J = \pm 1 \text{ mA}$, respectively, passing through a 3 mm wide Si/SiGe quantum well

Examples for the ESR spectra are shown in Fig. 1. The spectra are characterized by an asymmetric line shape. The line shape analysis is shown in Fig. 2. Rotation of the sample in the applied field results in a change of the resonance line width and the resonance field. The line width becomes maximum for in-plane orientation of the magnetic field. The angular dependence of the resonance field is shown in Fig. 3. The

dc current passing by 2D electron gas causes a shift of the resonance field, B_0 . The observed shift is considerably bigger than the line width for a current of the order of 1 mA passing through the sample of 3 mm width.

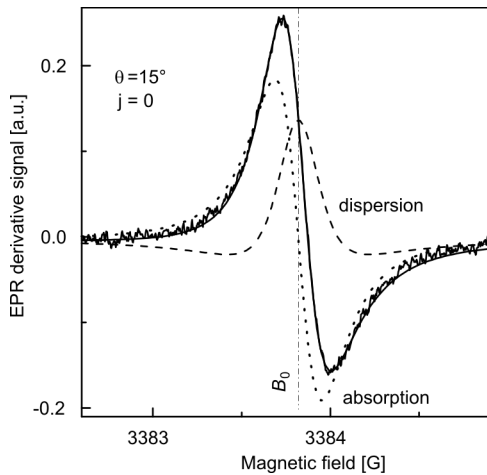


Fig. 2. Analysis of the ESR line shape. The solid line represents the sum of an absorption like, $\chi''(\omega)$ (dotted), and a dispersion like, $\chi'(\omega)$ (dashed). The vertical dot-dashed line indicates the centre of the ESR line, B_0

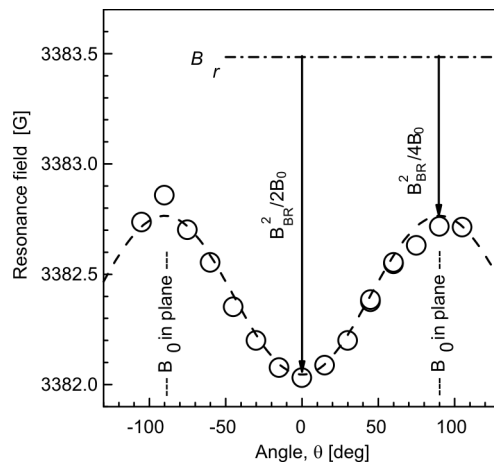


Fig. 3. Angular dependence of the resonance field, measured for a sample with $n_S = 3.3 \times 10^{11} \text{ cm}^{-2}$, without any applied current. The arrows show a shift of the resonance field due to the BR field. The dashed line is described by the equation: $B_0 = B_r - B_{BR}^2 (1 - 0.5 \sin^2 \theta) / 2B_r$.

The fitted value $B_{BR}^2 = (98 \text{ G})^2$ corresponds to $2\alpha_{BR} = 1.45 \times 10^{-33} \text{ J}\cdot\text{m}$

The shift caused by the electric current, J , is proportional to J and changes its sign when the sign of the current is changed. The dependence of the resonance position on current density is shown in Fig. 4. For the same current the magnitude of the resonance shift depends on the sample orientation. The angular dependence of the slope, dB_0/dJ is shown in Fig. 5. One has to underline that a rotation of the sample by an angle $\pm\theta$ from its symmetric orientation, (where the external field is perpendicular to the layer, *i.e.*, parallel to the normal vector \mathbf{n}) results in a slope of different sign, depending on the direction of rotation. This dependence clearly shows that the current causes a symmetry breaking. The angles $\pm\theta$ are not equivalent anymore, in spite of the fact that these two orientations are crystallographically equivalent.

All geometrical dependences observed reflect a specific geometry of the SO field: the mean BR field is proportional the vector product of the mean velocity, i.e., the drift velocity of carrier and a built-in electric field, parallel to the symmetry axis, n .

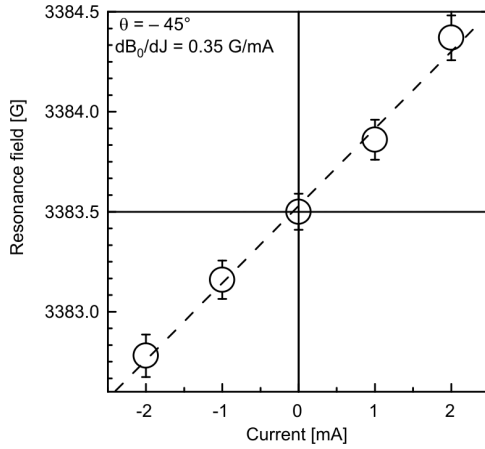


Fig. 4. Dependence of the resonance field on the dc current

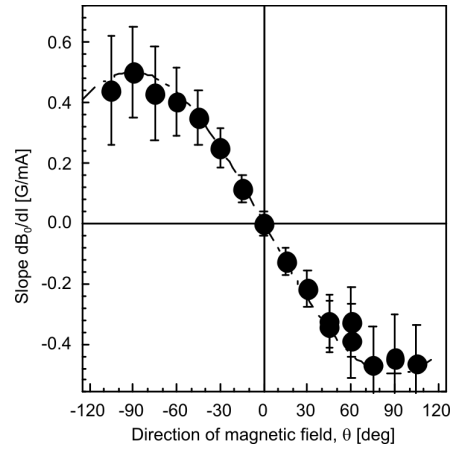


Fig. 5. Angular dependence of the slope of resonance field on current

In our experiment, we use magnetic field modulation, a microwave bridge with reference arm, and an automatic frequency control. Such systems yield the derivative of the absorbed power. All observed spectra exhibit the so-called Dysonian line shape, which, as is shown in Fig. 2, can be composed as a sum of absorption and dispersion Lorentzian line shape functions. The deconvolution allows a precise evaluation of the resonance field. The origin of the Dysonian line shape in a 2DEG is a complex problem. The classical Dyson approach predicts a pure absorption-like shape for 2D samples. We relate the occurrence of the dispersion component in this case to the SO field. Details will be published elsewhere.

4. Magnitude of BR field

The angular dependence of the resonance field can be explained taking into consideration the distribution of B_{BR} , caused by the distribution of the k -vectors [1]. For $\theta=0$, all electrons at the Fermi circle are affected by the same BR field. As a consequence, the resonance occurs for an applied field, B_0 , slightly smaller than the real resonance field, B_r . Because B_0 is perpendicular to B_{BR} , the lengths of these vectors are related by $B_r^2 = B_0^2 + B_{BR}^2$. For a small SO field, when $B_{BR} \ll B_r$, B_0 the shift of the resonance field, $-B_{BR}^2/2B_0$, is indicated in Fig. 3. The shift for in-plane orientation of the applied field is smaller by the factor 2. This way the anisotropy of the resonance field allows an evaluation of the absolute value of the BR field. In Si/SiGe structures, B_{BR} is of the order of 100 G.

5. Current induced shift of the resonance field

The current induced shift of the resonance field is proportional to the applied current. An example of such a dependence is shown in Fig. 4. In the whole investigated range of applied currents, the shift varies linearly with the current changing its sign for the inverse current direction. When a bigger current is applied, the amplitude of the signal decreases, but the linear dependence is still observed.

The observed shift results from a non-zero drift velocity, v_d . When the Fermi sphere (disc) is shifted in k -space by $\delta k_y = -m^* j_y / e \hbar n_s$, then the mean value of the BR field experienced by all electrons is not zero any more. The mean value of the BR field is given by:

$$\delta B_{BR} = 2v_d \alpha_{BR} \frac{m^*}{g\mu_B \hbar} \quad (2)$$

where m^* is the effective mass, n_s the sheet electron concentration. The ratio of the shift to the current density is given by:

$$\frac{\delta B_{BR}}{j} = \frac{\alpha_{BR} m^*}{g\mu_B \hbar e n_s} \quad (3)$$

This ratio is thus ruled by material parameters, in particular by the electron concentration, but it is expected to be independent of temperature and of spin- and momentum relaxation rates. The experimental results in Fig. 4 well confirm these predictions. The shift-to-current ratio is constant in the whole range of the applied currents, in spite of the fact that the electron temperature is considerably enhanced, as seen by the observed decrease of the signal amplitude. It is well known that an increase in temperature is accompanied by a decrease of electron mobility and a change in the spin relaxation rate.

The resonance occurs when the external field, \mathbf{B}_{ex} , fulfils the resonance condition

$$|\mathbf{B}_{ex} + \delta \mathbf{B}_{BR}| = B_0 \quad (4)$$

The direction of $\delta \mathbf{B}_{BR}$ is ruled by the vector product of Eq. (1) where the single electron k -vector is replaced by the current induced mean value, $\delta \mathbf{k}$. In our experimental geometry the current and $\delta \mathbf{k}$ are parallel to the y -axis while n is in the (xz) plane, tilted by the angle θ from the z axis. Consequently, the model predicts that \mathbf{B}_0 is modified by the projection of $\delta \mathbf{B}_{BR}$ on \mathbf{B}_0 as described by the dependence

$$B_{ex} = B_0 - \delta B_{BR} \sin \theta \quad (5)$$

This function is plotted in Fig. 5 as a dash-dotted line. The current-induced shift, as measured by the value of B_{ex} , attains its extreme values when \mathbf{B}_{ex} is parallel or anti-

parallel to \mathbf{B}_{BR} . For $\theta=0$, the mean BR field, $\delta\mathbf{B}_{BR}$, is perpendicular to \mathbf{B}_{ex} and, practically, no shift is observed.

6. Conclusions

The occurrence of the current induced SO field has been theoretically predicted by Kalevich and Korenev [7]. They found also an influence of the electric current on the Hanle effect. Application of the concept of a current- (velocity-) induced field has been proposed in the Datta–Das transistor. Recently Kato et al. [8] found an effect of current on the precession of magnetization by ultra fast Faraday spectroscopy. Our results obtained by resonance measurements, however, are the most direct evaluation of the current induced SO field.

The fact that an electric current allows for tuning of the spin resonance has also practical aspects. First of all, controlling a current is technically much easier than applying a magnetic field. Moreover, the current can be well applied to a local micro-element of a large electronic structure.

Finally, the fact that a dc current allows to generate a dc magnetic field allows one to predict that an ac current can lead to an ac SO field. The model estimations show that resonance excitation by an ac current can be by orders of magnitude more effective for a high mobility electron gas than the classical resonance excitation by an ac magnetic field.

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