g-Factor Tuning and Manipulation of Spins by an Electric Current

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We investigate the Zeeman splitting of the two-dimensional electron gas in an asymmetric silicon quantum well, performing electron-spin-resonance (ESR) experiments. 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. We identify different contributions to this type of ESR signal.

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One of the key requirements for spintronics is the possibility to control the spin state of electrons via an externally applied electric field. In principle, SO interaction provides a mechanism for that. In solids, SO interaction results from the relative motion of an electron with respect to the other charges [1,2]. Here contributions to the SO field of odd power in the electron momentum, $\hbar\mathbf{k}$, are of particular interest. They lead to spin splitting which can be described in terms of an effective magnetic SO field. Such terms require lack of inversion symmetry which is found, e.g., in zinc blend semiconductors [bulk inversion asymmetry (BIA)] [1,3,4] or in heterostructures and asymmetric quantum wells even in crystals with inversion symmetry [structure inversion asymmetry (SIA)] [5].

In the presence of k-linear terms, as pointed out by Datta and Das, the spin of conduction electrons will precess around the SO field of moving carriers and this can be used to modulate an electric current in the presence of spin-selective contacts [6]. At about the same time, Kalevich and Korenev obtained experimental evidence for the SO magnetic field produced by a current via its effect on the Hanle depolarization [7]. They also predicted that a dc current should cause a shift in the electron spin resonance (ESR) and an ac current will induce spin transitions. Spin precession induced by a dc current was recently observed by Kato *et al.* [8] in strained GaAs by time and spatially resolved ultrafast Faraday spectroscopy. They also demonstrated the excitation of Rabi spin oscillations by high frequency (hf) currents. In this Letter, we demonstrate the original prediction of Kalevich and Korenev [7]—namely the shift of the ESR by a dc current and its excitation by ac currents in asymmetric Si quantum wells. For the dc case we evaluate the SO field and we find quantitative agreement with results independently obtained from the g-factor anisotropy without current. We show that high frequency currents cause a particular kind of electric dipole spin resonance (EDSR) [4,9–11], and we provide further insight into its mechanisms. The EDSR amplitude exceeds that of the magnetic dipole transitions substantially and thus it can be utilized for a most efficient spin manipulation.

We investigate these effects in Si quantum wells which exhibit the simplest kind of SO term discussed first by Bychkov and Rashba (BR) [4,5]: it is proportional to the electron velocity (or equivalently its momentum, $\hbar\mathbf{k}$) and the spin: $\hbar\omega_{\mathrm{BR}} = \alpha_{\mathrm{BR}}[\mathbf{k}\times\hat{\mathbf{n}}]$. The required SIA results from the one-sided modulation doping of our samples. α_{BR} is the Bychkov-Rashba coefficient which depends on the strength of SO interaction and the asymmetry of the system. $\hat{\mathbf{n}}$ is a unit vector pointing in the direction in which the symmetry is broken. Formally, the SO term can be described also by an effective magnetic BR field, $\mathbf{B}_{\mathrm{BR}} = \alpha_{\mathrm{BR}}(\mathbf{k}\times\hat{\mathbf{n}})/g\mu_B$, seen by each electron. The BR field thus is perpendicular to both $\hbar\mathbf{k}$ and the direction $\hat{\mathbf{n}}$, and thus it is oriented in-plane. An earlier systematic study showed that the Dresselhaus type of SO coupling [1] is not detectable in these samples [12].

Various effects of the BR field have been demonstrated already. In a two-dimensional electron gas (2DEG), the BR field causes anisotropy of both the ESR linewidth and the line position [12,13]. The BR field has been shown also to cause additional longitudinal spin relaxation of the Dyakonov-Perel type [12,14]. In the presence of a current, the BR field also causes steady state spin polarization [15–17]. The so-called spin galvanic effects also connect spins and the electric current [18]. In the latter effect, spin dependent relaxation of photoinduced carriers leads to an electric current. In the inverse spin galvanic effect the asymmetry of spin relaxation rates for electrons in the two spin subbands, split by SO coupling, leads to a spin polarization induced by an applied electric current [18].

Here we consider the effect of a macroscopic current (of density j_x) within a 2DEG (x-y plane, Fig. 1): the non-vanishing mean carrier velocity leads to a finite first-order mean value of the BR field, $\delta B_{\mathrm{BR},y}$, which causes additional spin splitting and thus a shift in the electron spin resonance. We investigate the ESR of the conduction electrons in a Si quantum well defined by $Si_{0.75}Ge_{0.25}$ barriers

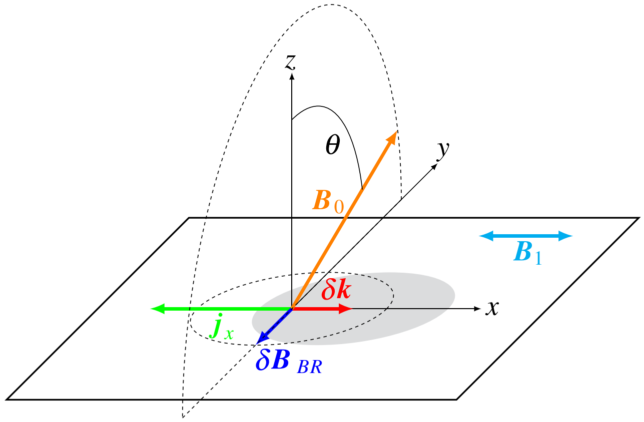

FIG. 1 (color online). A current j_x passes through a 2DEG (x-y plane). The Fermi circle (momentum distribution, dashed for $j_x = 0$, gray for $j_x \neq 0$), shifts by an amount $\hbar\delta\mathbf{k}$. Within this approximation, each electron experiences a Bychkov-Rashba field $\delta B_{\mathrm{BR},y}$ in addition to that resulting from its momentum $\hbar\mathbf{k}$. The static field B_0 (not drawn to scale) is applied in the y-z plane to enable ESR measurements.

grown by molecular beam epitaxy (MBE). The layer structure and the basic ESR properties have been described elsewhere [12,19]. Here we added electric contacts to the 2DEG. The sample was then glued to a quartz holder and inserted into a TE_{102} rectangular microwave cavity equipped with an intracavity cryostat, which allows cooling to 2.5 K. ESR measurements were done with a standard X-band Bruker ElexSys E500 system.

Spectra are given in Fig. 2 for different dc currents applied during the measurement. Because of the use of field modulation and lock-in detection (standard in ESR instruments), we obtain the first derivative of the microwave absorption with respect to B_0 which here was tilted by $\theta = 45°$ with respect to the sample surface normal $\hat{\mathbf{n}}$. The line shape is asymmetrical (see below). It is clearly seen that (i) a current shifts the resonance, (ii) the shift occurs in the opposite sense when the current direction is inverted, and (iii) the signal broadens with increasing current. Figure 3 shows the shift of the resonance field for in-plane orientation of $\mathbf{B}_0$ (along the y axis) as a function of the current density for different densities of the 2DEG.

In thermal equilibrium ($j_x = 0$), the anisotropy of the ESR position can be fully described by treating $\mathbf{B}_{\mathrm{BR}}$ like a real field and by adding it to the external field [12,13]. In spite of the isotropic distribution of the Fermi momenta and the resulting isotropic distribution of the BR fields in the 2DEG plane, their superposition with the external field B_0 results in the angular dependence shown by the open squares in Fig. 4. This anisotropy of the resonance field [20] allows the evaluation of the mean value [21] of $\langle B_{\mathrm{BR}}^2 \rangle$ at the Fermi circle and thus of α_{BR}. The dashed line corresponds to a fit using $B_{\mathrm{BR}} = 10$ mT. For this sample with an electron concentration of $n_S = 5 \times 10^{15}\ \mathrm{m}^{-2}$ this value yields a BR coefficient of $\alpha_{\mathrm{BR}} = 0.85 \times 10^{-12}$ eV cm $= 1.4 \times 10^{-33}$ J m, which compares well to earlier published values [13].

A current causes an antisymmetric shift of the ESR position (see Fig. 4). For in-plane field ($\theta = 90°$) the current-induced shift is maximal. There $\delta B_{\mathrm{BR},y}$ is oriented along the y axis, parallel to B_0 (see Fig. 1) and thus the field required for resonance is reduced by $\delta\mathbf{B}_{\mathrm{BR}}$. For $\theta = -90°$, $\delta\mathbf{B}_{\mathrm{BR}}$ is antiparallel to the applied field and therefore the resonance field is increased by the same amount. For the data presented, the maximum shift is 50 μT and this shift directly corresponds to $\delta B_{\mathrm{BR},y}$. For $\theta = 0°$, $\delta\mathbf{B}_{\mathrm{BR}}$ is perpendicular to the applied field and its effect on the reso-

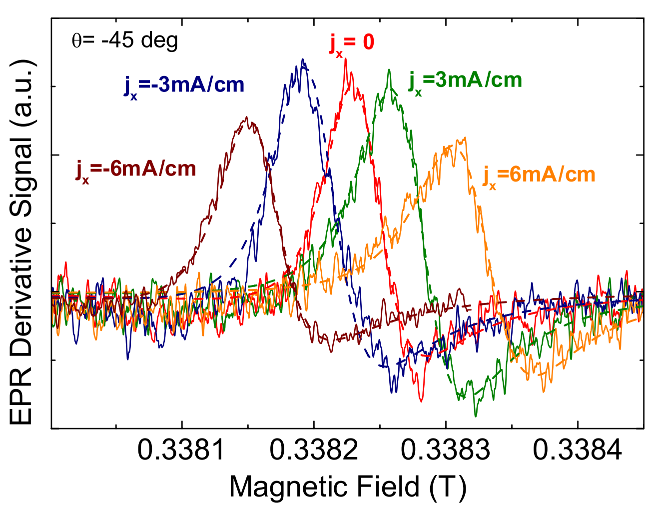

FIG. 2 (color online). ESR spectra of a 2DEG in a Si quantum well for various values of an electric current density passing a 3 mm wide sample. Measurements were performed with B_0 tilted by $\theta = -45°$ from the direction perpendicular to the sample plane at a microwave frequency of 9.4421 GHz.

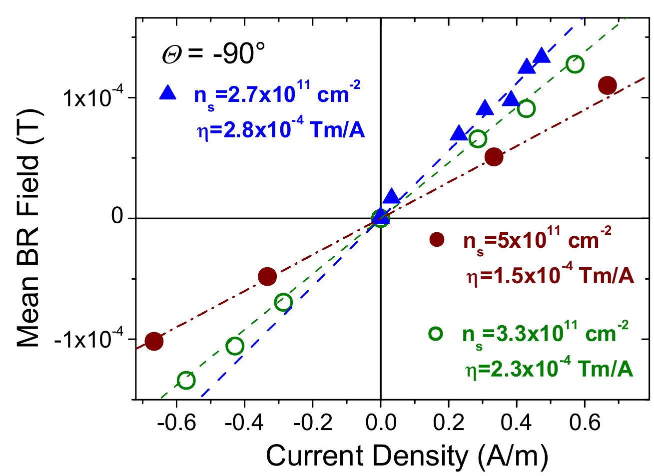

FIG. 3 (color online). Dependence of the resonance shift for in-plane orientation of the dc electric current density for three samples of different sheet carrier concentration n_S.

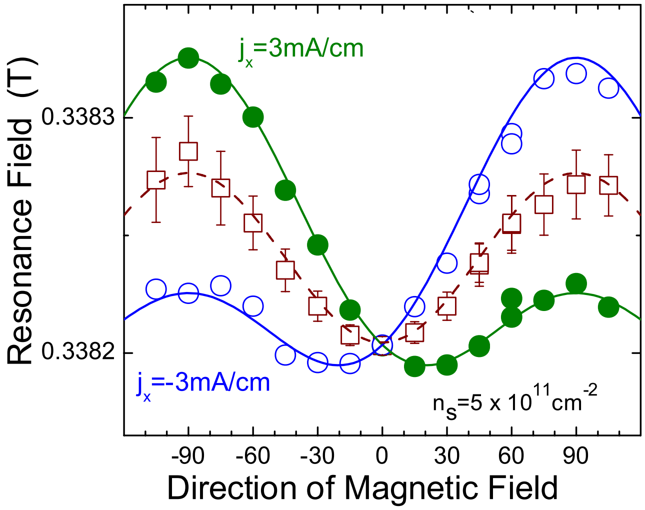

FIG. 4 (color online). Angular dependence of the ESR field for a current density $j = 0$ (squares) and ± 3 mA/cm (open and solid circles, respectively). The electron concentration is $n_S = 5 \times 10^{15}$ m^{-2} and the sample width 3 mm. Error bars correspond to 20% of the resonance linewidth.

nance field is negligible. Altogether, the geometrical dependencies seen reflect the vector product of electron velocity and the built-in electric field which characterizes SO coupling.

For moderate electric fields, j_x corresponds to a drift shift of the Fermi circle by $\delta k_x = -m^* j_x/e\hbar n_S$ (see Fig. 1). Consequently, since $B_{\rm BR}$ increases with increasing k vector, each electron experiences an additional BR field $\delta B_{{\rm BR},y}$ (see Fig. 1), which is proportional to the shift of the Fermi circle, yielding $\delta B_{{\rm BR},y} = \beta_{\rm BR} v_d$, where $\beta_{\rm BR} = \alpha_{\rm BR} m^*/g\mu_B\hbar$ is a material parameter and v_d stands for the drift velocity.

The current-induced resonance shift is expected to change linearly with current, where the slope $\eta = \delta B_{{\rm BR},y}/j_x = \beta_{\rm BR}/en_S$ is proportional to $\alpha_{\rm BR}$ and inversely proportional to n_S. Our experiments confirm this, as can be seen in Fig. 3: the slope η is larger for smaller n_S. The experimental value of η allows for an independent evaluation of the BR parameter $\alpha_{\rm BR}$. Within the experimental error of about 20%, the resulting values for different samples are equal to those obtained from the anisotropy of the resonance field for $j_x = 0$.

From the observed effect of a dc current we may also infer that high frequency effective fields can be generated by a hf current. The latter is limited in frequency only by the momentum scattering rate and therefore microwave magnetic fields can be generated this way. High frequency fields are of particular interest as they can be used to excite spin precession [8], ESR, and Rabi oscillations [22].

In a classical ESR experiment, the absorption signal originates from (i) magnetic dipole transitions. The magnetic energy is absorbed and in a steady state experiment the spin energy is dissipated due to spin relaxation. Therefore the sample is placed in the node of the electric field within an ESR microwave cavity. Nevertheless, in our experiment a microwave electric field within the high mobility 2DEG is evident from the appearance of cyclotron resonance [12].

The microwave electric field may induce also (ii) EDSR [4,9–11]. Currents, produced by a microwave field E_1, cause a hf BR field leading to additional spin precession. As a result, electric dipole absorption is observed. At high frequency (if the frequency is higher than the momentum relaxation rate $\omega\tau_k \gg 1$), only a displacement current occurs and this is the classical absorption caused by oscillating electric dipoles. At lower frequency, the drift current, and consequently the hf BR field, become momentum relaxation dependent [9,10]. In both frequency ranges the energy at EDSR is dissipated in spin relaxation processes.

One can distinguish two additional types of ESR signals: a "polarization" signal (iii) and current-induced spin resonance (CISR) (iv). In contrast to classical ESR (i) and EDSR (ii), here the energy is dissipated by Joule heating. The polarization signal (iii) results from the dependence of electric conductivity on spin polarization which varies in the vicinity of the ESR condition [12] while CISR (iv) originates from the interference of eddy currents induced by the external microwave electric field with that induced by the precessing magnetization. A similar effect has been discussed by Dyson for bulk metals [23]. There the phase shift of the current induced by magnetization is caused by spin diffusion beyond the skin depth. For 2D electrons the interference occurs due to the phase shift between electric field and current, $\tan\phi_{Ej} = -\omega\tau$, and by the phase shift between the hf BR field and the precessing magnetization, $\tan\phi_{\rm BM} = -(\omega_0 - \omega)T_2$. Here T_2 is the transverse spin relaxation time which rules the resonance width and ω_0 the Larmor frequency. According to this expression, $\phi_{\rm BM}$ changes its sign at the ESR. The electrical power absorption of CISR (iv) is described as the sum of two components weighted by frequency- and mobility-dependent coefficients:

$$P(\omega) = \frac{\sigma_0 E_1 \epsilon}{(1 + \omega^2\tau^2)^{3/2}}[f_d(\omega) + \omega\tau f_a(\omega)],$$

where the σ_0 is the low frequency conductivity. The shape function $f_d(\omega)$ is the Lorentzian dispersive function and $f_a(\omega)$ its absorption counterpart. The parameter ϵ scales with sample magnetization and spin-orbit coupling $\alpha_{\rm BR}$. It describes the effective electric field induced by the precessing magnetization, averaged over the whole sample area. It depends in a complex way on the sample shape and size, and on sample position and orientation within the microwave cavity. Therefore the amplitude of CISR is strongly dependent on the experimental geometry.

We find that among mechanisms (i)–(iv), only the CISR has a dispersive component for 2D layers [24]. All other components of the signal [(i)–(iii)] are characterized by symmetric, absorptionlike signals. The Dyson model, which considers solely magnetic dipole excitations, predicts a pure absorptionlike signal when extrapolated to very thin samples. Therefore, for the 2D case, the experimental observation of an antisymmetric component (symmetric in Fig. 2 due to differential recording) of the absorption line shape shows that CISR (iv) contributes to the ESR signal which is excited by the SO field.

Our CISR model explains the relative magnitude of dispersive and absorption signals as a function of microwave power and geometry [24]. The latter is modified by rotating the 2DEG relative to $\mathbf{B}_0$ and the microwave magnetic field $\mathbf{B}_1$. Turning the sample within the cavity, we find the expected behavior. The highest signal is obtained if the 2DEG is perpendicular to $\mathbf{B}_1$ (by 10^2 bigger as compared to the case when it is perpendicular to $\mathbf{B}_0$). In that case, $\mathbf{B}_1$ very efficiently induces eddy currents within the 2DEG, which in turn cause the additional hf BR field. The latter can be much stronger than the original microwave magnetic field. It causes electric dipole-induced (ii) and current-induced (iv) spin resonance. The expected ''gain'' in the resulting Rabi frequency (in comparison to excitation by B_1) is proportional to the electron mobility in the 2DEG and for state-of-the-art mobilities in Si quantum wells we estimate gain values of 10^3 and more.

In summary, the presented experimental data demonstrate the occurrence of a current-induced first-order spin-orbit field. A dc current allows one to tune the ESR frequency while a high frequency current occurs to be a very effective tool for spin excitation. These methods of spin manipulation can be applied locally, e.g., to a nanowire without heating the rest of a sample in contrast to methods employing a resonator.

Both the Rabi frequency and the spin relaxation rate increase with increasing SO coupling. SO coupling in III-V compounds is by up to 3 orders of magnitude stronger than in Si. The Rabi frequency and η scale linearly with SO interaction and the linewidth with the square of it. Therefore, materials like Si are much better suited if a big shift-to-linewidth ratio of the ESR is needed. On the other hand, we expect an even higher efficiency for the current-induced spin manipulation for III-V compounds.

The current-induced shift of the spin resonance described in this Letter is probably the most direct and conceptually simplest effect of SO interaction in solids. Moreover, the ratio of the g shift and current density η is ruled by the BR parameter and the carrier density only, but it is independent of temperature, electron mobility, or details of spin relaxation.

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