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Limitations in the Tunability of the Spin Resonance of 2D Electrons in Si by an Electric Current

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We analyse the recently observed effect of an in-plane electric current through a Si quantum well on the conduction electron spin resonance. We find that the ratio of resonance shift and current density is independent of temperature and dissipation processes, but the channel current is reduced due to a parallel electric channel in heavily modulation doped samples. The inhomogeneous current distribution results in some broadening of the ESR line width. In high mobility Si/SiGe layers the current induced increase in the electron temperature is considerably larger than the increase in the lattice temperature. The signal amplitude scales with the square of electron mobility.

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1. Introduction – current induced spin–orbit field

The efficient manipulation of spins is one of the prerequisites for any spintronic device [1]. Recently we have found a possibility to tune the resonance field in electron spin resonance (ESR) of conduction electrons in Si quantum wells by sending a dc current in the quantum well plane and we demonstrated that a moderate current is already sufficient to shift the resonance field by more than the

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line width [2]. This effect is caused by the Bychkov–Rashba (BR) field [3], $\boldsymbol{B}_{\mathrm{BR}}$, which appears in our one-sided modulation doped SiGe quantum well structures due to the structure inversion asymmetry [4]. We also argued that a high frequency current can be utilized to introduce spin transitions in a most effective way as compared with the traditional way of exciting ESR by a microwave magnetic field and we found evidence for that from the line shape in standard ESR experiments [2]. In this contribution we investigate limitations of the tuning effect of a dc current. We show that one of the limitations is the occurrence of a bypass channel for the electric current in our modulation doped samples.

The condition for ESR is

$$h\nu = g\mu_{\mathrm{B}}|\boldsymbol{B}_0 + \boldsymbol{B}_{\mathrm{BR}}|, \tag{1}$$

where ν is the microwave frequency, g — the g-factor, μ_{B} — Bohr's magneton and B_0 — the externally applied magnetic field. The current induced BR field is proportional to the mean value of the electron momenta and thus (assuming ohmic transport) to the current density and therefore a linear shift of the resonance field B_0 is expected with current density. The slope of B_{BR} vs. current was obtained as [2]:

$$B_{\mathrm{BR}}/j_x = \beta_{\mathrm{BR}}/en_{\mathrm{s}}, \tag{2}$$

where $\beta_{\mathrm{BR}} = \alpha_{\mathrm{BR}} m^*/g\mu_{\mathrm{B}}\hbar$ contains the sample- and spin–orbit dependent Bychkov–Rashba coefficient α_{BR} and n_{s} stands for the sheet carrier density. Within this simple model, this slope should thus be constant and the question arises to the validity limits of the model.

2. Experimental results

Our first experiments were done on rather moderately doped samples at temperatures of 2–4 K and we observed a linear shift of the ESR. Nevertheless, only a limited current can be experimentally applied, since an increase in electron temperature will affect eventually the experimental results. Actually we observed some broadening of the ESR line and a decrease in its amplitude for the highest current density of $j_x = 3$ mA/cm^2 for a sample with $n_{\mathrm{s}} = 2.7 \times 10^{11}$ cm^{-2}. Here we investigate the influence of current and temperature on $\boldsymbol{B}_{\mathrm{BR}}$ and on the ESR amplitude for samples with a higher doping concentration yielding at He temperatures a carrier density of $n_{\mathrm{s}} = 5.1 \times 10^{11}$ cm^{-2}. For this sample, the ESR amplitude decreases slightly up to a current density of 3.6 mA/cm^2 and then it drops to zero when j_x is increased to 5.1 mA/cm^2. The line width increases in the whole range quadratically with j_x.

In order to distinguish effects caused by sample- and electron heating we investigated also the temperature dependence of the ESR. The data measured for a sample with $n_{\mathrm{s}} = 5 \times 10^{11}$ cm^{-2} are shown in Fig. 1.

As can be seen in Fig. 1a, the ESR amplitude decreases by more than a factor 10 between 2 and 23 K. The dependence can be described by a phenomenological dependence with the characteristic temperature $T_0 = 10$ K. The applied current

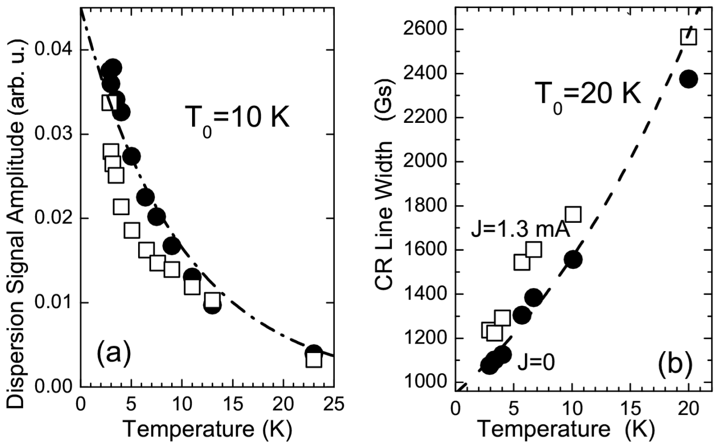

Fig. 1. (a) Temperature dependence of the dispersive component of the ESR signal for a Si/SiGe layer with $n_\mathrm{s} = 5 \times 10^{11}$ cm^{-2}. Solid dots stand for $j_x = 0$ and open squares for $j_x = 4$ mA/cm^2. The dash-dot line gives a phenomenological dependence $\propto \exp(T/T_0)$ with $T_0 = 10$ K. (b) Cyclotron line width and amplitude with and without current as a function of temperature. The line width can be described by the exponential dependence (see above) with $T_0 = 20$ K.

causes an additional decrease in the ESR amplitude for this sample. The ESR line width changes in the investigated temperature range by about 10% only. The ESR line width becomes minimal at about 8 K and then it weakly increases for higher temperatures.

The ratio of the resonance shift to current, B_BR/j_x, is temperature independent up to 7 K, but decreases for higher temperatures. This temperature is a few times smaller than the Fermi temperature, which for this sample is about $T_\mathrm{F} \approx 35$ K. According to Eq. (2) this finding suggests an increase in n_s with increasing temperature.

In our experiment, the cyclotron resonance (CR) of the electrons in the quantum well is also observed [4, 5]. From the CR signal the carrier concentration and the electron mobility can be estimated. The data for the sample with $n_\mathrm{s} = 5 \times 10^{11}$ cm^{-2} are shown in Fig. 1b. The increase in line width simply reflects the decrease in the electron mobility with increasing temperature — a well-known effect (for a detailed discussion of 2D mobility see Ref. [5]). The data in Fig. 1b imply that the mobility decreases by a factor 2.3 in the range of 2.7–20 K. The mobility can be described by a phenomenological dependence $\propto \exp(T/T_0)$ with $T_0 = 20$ K. We do not attribute any meaning to this dependence, but it allows us to conclude that the ESR amplitude scales with the square of the electron mobility. For this metallic sample, i.e., for $T \ll T_\mathrm{F}$, the increase in the CR amplitude can be attributed to an increase in the carrier concentration.

3. Discussion

This increase in carrier concentration implies that in strongly doped Si/SiGe layers only a fraction of donors is ionized at low temperature. With increasing temperature, additional donors are activated. A fraction of the donated electrons are transferred to the 2D channel and the other part is excited to the conduction band in the doping layer. An increase in temperature by 19 K results in an increase in n_{s} in the 2D channel by 50%. On the other hand, B_{BR}/j_x decreases by an order of magnitude within a similar temperature range. We conclude thus that this decrease is due to the activation of the conductivity in the doping layer. At $T = 23$ K, most of the applied current runs already through the doping channel in which the mobility and thus also the electron momentum and the BR field are much smaller. This effect naturally is much weaker for moderately doped layers.

In the low temperature range the ESR line width increases with electric current but it decreases with increasing temperature. Therefore, the dependence of the line width on current cannot be interpreted as resulting from the layer heating. A decrease in the line width with increasing temperature is expected for Dyakonov–Perel spin relaxation. The increase in a single electron momentum scattering, including e–e scattering, is expected to lead to more effective line narrowing [6]. Therefore, we associate the increase in the resonance line width under current, which occurs also at low temperature, with an inhomogeneous distribution of the current in the sample layer: the non-uniform current density causes different line shifts in different sample areas, leading to broadening of the resonance.

The increase in the line width at higher temperature can be related to the increasing carrier density, which results in an increase in the Fermi k-vector, and consequently the BR field and thus the Dyakonov–Perel line width $\sim B_{\mathrm{BR}}^2\tau$ (where τ is the single electron momentum scattering time).

An increase in the temperature under current is well visible in all experimental data. A current of 4 $\mathrm{mA/cm^2}$ results in an increase in the electron temperature, monitored by the electron mobility, by a few K, while the increase in the lattice temperature, as monitored by the donor excitation, is hardly visible. It does not exceed 1 K.

4. Conclusions

In conclusion, we have shown that in heavily doped samples the tuneability of the spin resonance of electrons in a quantum well is impaired by a parallel channel at the doping layer. We also observed the decrease in ESR line width expected for the Dyakonov–Perel relaxation. The increase at higher temperatures ($T > 7$ K) can be consistently explained in terms of the increase in carrier concentration in the 2D channel.

The main conclusion of this paper is, however, that the ESR signal scales with the square of the electron mobility. Consequently, the increase in the carrier temperature under current leads to a decrease in the signal amplitude.

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