Spin Relaxation and g-Factor of 2-Dimensional Electrons in Si/SiGe Quantum Wells

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We investigate spin relaxation and the g-factor of conduction electrons in modulation doped Si/SiGe quantum wells by means of electron spin resonance. We find that both the transverse and the longitudinal relaxation times are of the order of microseconds, much longer than in III-V compounds. For high mobility, at carrier densities sufficiently far away from the metal-to-insulator transition, both quantities can be explained consistently in terms of the Bychkov-Rashba field, together with the g-factor anisotropy and its dependence on the carrier density. The properties found make Si/SiGe quantum structures interesting candidates for quantum computing.

1. Introduction

One essential prerequisite for spintronics is the ability to manipulate individual spins. Spin manipulation requires that both the longitudinal [1] (spin-lattice) relaxation time, T_1, and the transverse spin (dephasing) time [1], T_2, are longer than the time required to flip a spin, T_π. It is generally accepted that in many spin relaxation processes spin orbit interaction, SOI, enters [2]. Therefore materials with small SOI should be better suited for spintronic applications, and in some concepts for quantum computing silicon is chosen accordingly [3]. Nevertheless, most experimental [4], [5], [6] and many theoretical papers [2], [7], [8] are dealing with spin relaxation in III-V and II-VI compounds with much faster spin relaxation. Therefore spin relaxation in low-dimensional Si structures deserves attention [2]. There are of course also other requirements for spintronic devices, like the effective injection of spin-polarized electrons into the active material. Here again III-V and II-VI compounds have been investigated since they have well-known semimagnetic or even ferromagnetic variants. Now, most recently, ferromagnetism was reported also for an epitaxially grown group IV material [9], $Ge_{1-x}Mn_x$, which may be taken as indication that eventually spin injection may work also in the Si-Ge system.

In this work, we investigate spin relaxation and spin manipulation of two-dimensional (2D) electrons in Si and SiGe quantum wells. We make use of the electron spin resonance of conduction electrons, CESR, which, because of the outstandingly long relaxation times can be easily observed on single quantum wells in a conventional ESR spectrometer. We determine T_2 from the line width, and T_1 from the saturation behavior seen both in the power dependencies of the ESR amplitude and the line width. We show that

T_1 and T_2 are of the order of microseconds for conduction electrons in Si quantum wells embedded between $Si_{1-x}Ge_x$ barriers. On the other hand, for the power available in a standard pulsed-ESR spectrometer and the parameters of Si, the time required to invert the spin polarization is of the order of $T_\pi \sim 10$ ns and can be shorter for higher power.

We show also that the g-factor can be easily adjusted by either changing the Fermi energy or by shifting the electron to a SiGe layer, and the g-shift is sufficient to change the ESR resonance field to an extent that exceeds the line width. This observation demonstrates that it is possible to select individual spins, *e.g.*, by a voltage on some gate structure, and to manipulate it by a resonant microwave field on a time scale that is short in comparison to the spin life times. This possibility proves that Si is attractive candidate for quantum computing devices.

2. Experimental

CESR in modulation doped Si quantum wells has been observed in conventional microwave absorption experiments [10], [11] and also by electrically detected magnetic resonance [12], EDMR. The latter originates from the spin-dependent conductivity, $\sigma(\Pi)$, of the 2DES, where the spin polarization Π is changed at resonance. In conventional CESR experiments, this effect causes unusual signal shapes (see Fig. 1): apart from the microwave absorption signal observed in the reflectivity of a critically tuned cavity (the absorption is proportional to the imaginary part of the magnetic susceptibility, χ"), there is also a contribution of the EDMR effect – an indirect "polarization" signal that is proportional to $d\sigma/d\Pi$ and thus it may even differ in sign [13]. (Both signals are detected as derivatives with respect to the static magnetic field since the latter is modulated in order to improve the signal to noise ratio).

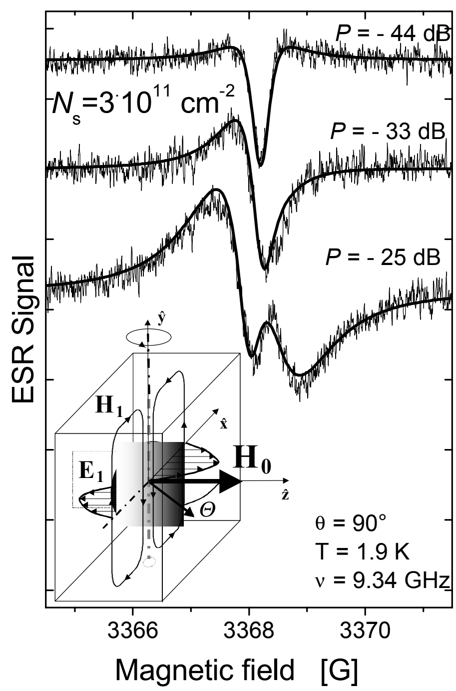

Fig. 1: ESR spectra at different microwave power. The inset schematically shows the mode used in the rectangular cavity.

Parts of the sample experience an in-plane component of microwave electrical field. Therefore we have to deconvolve the signal into its components. This is possible because of their different dependencies on the microwave power P – the polarization signal is proportional to $P^{3/2}$ in contrast to the absorption which varies like $P^{1/2}$. There is still another type of signal that appears because of the automatic frequency control of standard ESR equipment. This unit is used in ESR in order to keep the microwave frequency at the minimum reflection of the cavity and thus it eliminates contributions due to the dispersive part of the magnetic susceptibility, χ'. Here a dispersive signal appears again because of the frequency dependence of the conductivity. This dispersion signal is proportional to $d\sigma/d\omega$, it has even parity in its derivative in contrast to the absorption and polarization signals and it varies as $P^{1/2}$.

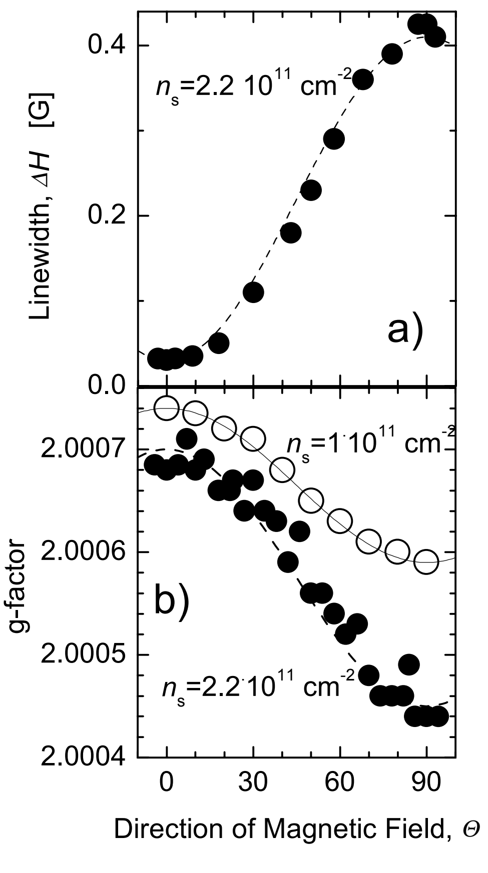

Fig. 2: (a) ESR line width and (b) g-factor as a function of the tilt angle, θ, of the sample relative to the surface normal.

The effective transverse spin relaxation rate is obtained from the CESR line width in the low power limit where the polarization signal amplitude and saturation broadening are negligible. Results are given in Fig. 2 (a) as a function of the tilt angle θ of the static magnetic field. The line width and thus T_2 show a strong anisotropy which depends also on the carrier density. Both dependencies can be explained consistently in terms of the Bychkov-Rashba field, H_{BR} [14]. For perpendicular field (θ = 0), where the longitudinal component of H_{BR} (parallel to H_0) vanishes, the line width turns out to be life time limited. From the linewidth we obtain then a T_2 value of 1..2 μs.

Another quantity that can be determined from the CESR spectra right away is the g-factor. Owing to the narrow line width of the CESR the g-factor can be determined with great accuracy. Results are given in Fig. 2 (b) as a function of θ for two different n_s values. A strong n_s-dependent anisotropy is visible, consistent again with the Rashba field [14].

The evaluation of the longitudinal relaxation rate, T_1^{-1}, is somewhat more complex. In cw CESR measurements it relies on investigations of the saturation behavior of the absorption. This is a standard procedure in the investigation of localized paramagnetic defect states in semiconductors and insulators. Usually T_1 is evaluated from the ESR amplitude measured as a function of power. Here, since the amplitude is a relatively complicated function of power already due to its different contributions, we preferred to use the power dependence of the line width which also shows saturation effects. Results for T_1 are given in Fig. 3.

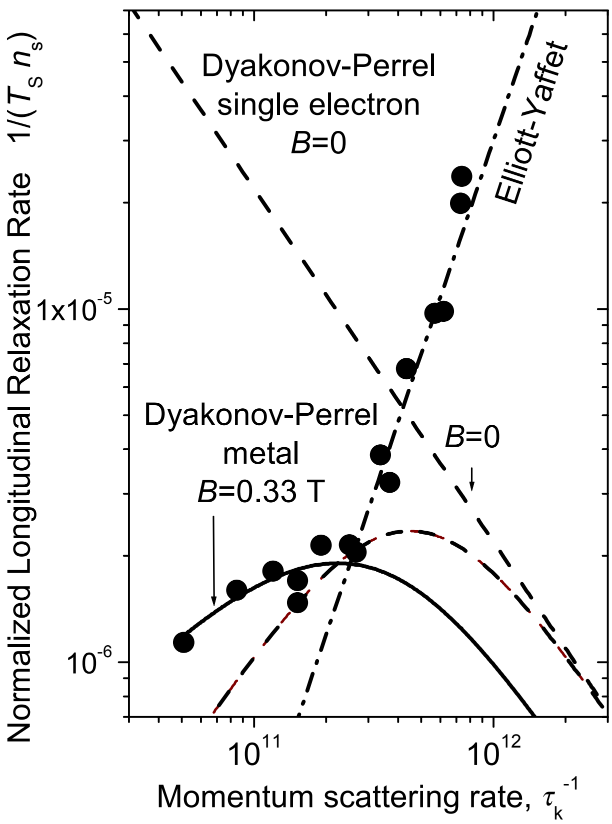

Fig. 3: Longitudinal spin relaxation rate, normalized with respect to the density of a 2D electron system in a Si quantum well at 1.9 K as a function of the electron scattering rate. The former is obtained from the power dependent line width, the latter from the cyclotron resonance width. The straight dash-dotted line is calculated for the Elliott-Yafet mechanism, the straight dashed line for the D'yakonov-Perel' mechanism for non-interacting electrons, the dash-dotted line taking Fermi statistics into account for B=0, and the full curve for B≠0.

3. Conclusion

In order to manipulate a spin in a specific quantum dot that might be defined by a gate structure, a change in the gate voltage may be used in the following way. Let us assume the whole structure (containing many quantum dots) is exposed to a cw microwave field and a static magnetic field, slightly off-resonance. A slight modification of the g-factor (we have very narrow lines) will be sufficient to bring individual electrons into resonance. This g-factor tuning can be achieved either by moving the wavefunction of the electron into a region with different g-factor due to (i) some admixture of Ge, or (ii) by changing the localization of the electron. Replacing (i) the Si well material by a $Si_{1-x}Ge_x$ alloy has been shown to change the resonance field by more than the linewidth for a Ge content of 5% already. The dependence of the g-factor on the Fermi energy in a 2DES indicates that the g-factor will be sensitive also to localization, and the latter can be also changed in a split-gate structure by the gate voltages. In both cases, a voltage pulse of appropriate duration can be used to bring a specific electron into resonance and to flip its spin.

In summary, we have shown that SiGe-based structures have a few properties that appear attractive and promising for spintronic applications: spin control and spin memory appear favorable under realistic conditions.

Acknowledgements

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