Spin resonance of electrons confined by SiGe nanostructures

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Abstract. We performed electron spin resonance measurements at 9.56 GHz on SiGe nanostructures to study coherence and relaxation times of electron spins in Si confined by SiGe quantum dots. Multilayers of self-assembled SiGe quantum dots were grown by molecular beam epitaxy. With illumination below the Si bandgap the intensity of the ESR signal increases strongly. We discuss the relationship between structural parameters of the layers and resulting spin coherence and relaxation times of the confined spins as measured by ESR.

1. Introduction
The technique electron spin resonance (ESR) offers the possibility to study statics and dynamics of spin ensembles. It was used extensively already in the 1960/70s to investigate donors and acceptors in bulk materials like Si and Ge [1, 2, 3]. With the development of semiconductor heterostructures, two-dimensional electron gases in Si$_{1-x}$Ge$_x$ [4] and SiGe [5] were studied with ESR. ESR studies on self assembled Si$_{1-x}$Ge$_x$ quantum dots are still limited to references [6, 7]. Si$_{1-x}$Ge$_x$ quantum dots in a Si matrix are characterized by a type II band alignment. Due to band offset between the dot and the surrounding silicon matrix, holes are localized inside the quantum dot, whereas the conduction band discontinuity weakly confines electrons in the strained silicon region close to the Si$_{1-x}$Ge$_x$ quantum dots. The lowest energy state is formed by the $\Delta_2$ state at the apex of the dot [8].

A continuous-wave ESR measurement provides information about the $g$-factor - which is sensitive to spin-orbit coupling - and the dephasing time of a spin ensemble, given by the linewidth of the resonance. The $g$-factor of electrons localized on donors (phosphorus) in unstrained bulk silicon is isotropic with $g = 1.99875$ [1]. Under uniaxial strain it becomes anisotropic with an axial symmetry and $\Delta g = 1.04 \cdot 10^{-3}$ [9]. For conduction band electrons in bulk Si the $g$-factor is found to be $g = 1.9995$ [10]. The recent results on quantum dots report an isotropic $g$-factor of $g = 1.998$ [6] and an anisotropic $g$-factor with $g|| = 1.9995$ and $g\perp = 1.9984$ [7]. This difference makes further studies necessary to understand the behavior of electrons on Si$_{1-x}$Ge$_x$ nanostructures. In addition, the quoted results make clear that a high experimental precision is needed and great care has to be taken to differentiate between the different effects in SiGe structures.
Figure 1. (a) AFM image of the top layer; (b) aspect ratio (defined as height to base ratio) as a function of island volume; (c) Histogram of the island heights

2. Results
ESR experiments were performed in a commercial X-band spectrometer around a frequency of 9.56 GHz. To enable an accurate determination of the \( g \)-factor, the spectrometer was equipped with an external frequency counter and a high precision Teslameter. Measurements were done at 4 K because of high signal to noise ratio and temperature stability.

The sample investigated here was grown by molecular beam epitaxy (MBE). The growth proceeds via the Stranski-Krastanow growth mode: The first few monolayers of deposited material grow pseudomorphically on Si forming a 2D flat wetting layer. Further deposition of Ge leads to the formation of three-dimensional islands. The evolution of Si\(_{1-x}\)Ge\(_x\) islands with coverage has been studied extensively, and details can be found for instance in [11]. The sample consists of a five-fold stack of 6.5 monolayer of Ge deposited at 600°C, each layer separated by a 70 nm thick Si spacer. This multilayer structure provides a large number of dots to increase the signal to noise ratio for the ESR measurement. Atomic force microscopy (AFM) images (see, e.g. Figure 1(a)) of the topmost layer show a very narrow monomodal size distribution of dots (see Figures 1(b), (c)). Because of the relatively large Si spacer thickness it is expected that islands in subsequent layers are not vertically aligned [12], so that the strain induced in the Si by the individual dots is similar and with that the confining potentials for the electrons.

Two reference structures were grown: Si buffer on the Si substrate and a sample in which 2.7 monolayer of germanium were deposited on silicon in the same way as for the quantum dots. Because of the smaller Ge thickness no formation of islands occurs.

Since the spin-orbit coupling for electrons in Si is small, the \( g \)-factor as a measure for spin-orbit coupling is expected to be close to the free electron value. For the magnetic field in growth direction an inhomogenously broadened ESR peak is found around a \( g \)-factor \( g = 1.9992 \) (see Figure 2(a)). Under illumination with light of smaller energy than the bandgap in Si the signal intensity increases strongly, which is attributed to an increase in the electron concentration. No
Figure 2. (a) ESR spectra of sample under illumination with sub-bandgap light $\lambda = 1310$ nm and in the dark with magnetic field in growth direction; (b) ESR spectra of illuminated sample with magnetic field in the [001] growth direction and in the plane of the quantum dots

signal is identified in any reference structure.

When the magnetic field is turned towards the in-plane direction of the quantum dots the resonance field of the signal is shifted to higher values (Figure 2(b)), meaning that the $g$-factor becomes smaller. As shown in Figure 3 it can be described by an axial symmetry with $g_{||} = 1.99915$ and $g_{\perp} = 1.99902$. This very small anisotropy in the $g$-factor goes along with an anisotropic broadening of the line from $\Delta H_{pp||} \approx 0.30$ Oe to $\Delta H_{pp\perp} \approx 0.47$ Oe. The linewidth in a continuous wave ESR experiment is directly related to the dephasing time $T_2^*$. The coherence time $T_2$ is usually much longer, therefore $T_2^*$ can be seen as a minimum for $T_2$. The measured linewidth corresponds to $T_{2||} \approx 220$ ns and $T_{2\perp} \approx 140$ ns.

An anisotropy in $g$-factor and linewidth indicates a difference in the spin-orbit coupling for the two crystallographic directions investigated. The anisotropy observed in the investigated structures is one order of magnitude smaller than the one observed on donors in silicon [9]. For donors the spatial extension of the wavefunction is given by the Bohr radius, which in Si is about 3 nm. With the dots having heights $h \leq 16$ nm and base lengths $l \approx 80$ nm the strained region and with that the region in which the conduction band is lowered and electrons confined is considerably larger. Furthermore, the confining potential should not be symmetric with respect to the magnetic field quantization axis, that can be rotated from the growth direction to the quantum dot plane, therefore causing a difference in the spin-orbit coupling. Going to smaller quantum dots [7] the situation might become closer to the donor state scenario, for which the (stronger) anisotropy is explained by a strain induced repopulation effect of the different conduction band valleys and the anisotropy of the individual valleys [9].
Figure 3. Change of linewidth and \( g \)-factor with respect to the magnetic field, \( 0^\circ \) refers to the external magnetic field \( H_0 \) parallel to the growth direction.

3. Summary & Conclusion
The ESR signal of electrons on \( \text{Si}_{1-x}\text{Ge}_x \) quantum dots was observed. It shows a very small anisotropy in \( g \)-factor suggesting a confinement of electrons in a region of several nm around a quantum dot. An estimate of their coherence times from the ESR-linewidth yields values above \( T_2 \geq 200 \text{ ns} \).

Acknowledgments
Support of the DFG through FOR 912 is gratefully acknowledged.

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