High Mobility Si/SiGe Heterostructures for Spintronics Applications

D. Gruber [1], H. Malissa [1], G. Chen [1], D. Pachinger [1], H. Lichtenberger [1], T. Fromherz [1], F. Schäffler [1], G. Bauer [1], W. Jantsch [1], A. M. Tyryshkin [2], and S. A. Lyon [2]

[1] Institute of Semiconductor and Solid State Physics Johannes Kepler University Linz, A-4040 Linz

[2] Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA

We investigate techniques for using Silicon-Germanium as material for solid-state quantum computing. Two topics are presented: First, the use of quantum well structures with different Ge content which can be used to shift the g-factor of conduction band electrons via voltages applied to gates above and below the structure. The change in g-factor allows then to put the electrons in and out of resonance in an Electron Spin Resonance experiment. Second, measurement of spin relaxation times of electrons confined in the strain field above Ge dots in a SiGe heterostructure. Photoluminescence (PL) shows indirect transitions from the VB of the Ge dots to the confined Si CB states. A single line is seen in ESR with g ≈ 2.0000 during illumination.

Introduction

The Silicon Germanium (SiGe) material system is a promising candidate for solid-state spintronics applications due to its very long spin relaxation times and its compatibility to standard Si process technology. There are proposals (*e.g.* [1]) for spin transistors in the SiGe material system which could be used for Quantum Computing. For this application very long spin coherence times and the ability to control and to read spin orientation is necessary. We address the topic with two different experiments: One is to demonstrate the ability to control the g-factor of electron spins in SiGe Quantum well structures by applying electrical fields, which can be used for selective spin manipulation. The second is the measurement of spin relaxation times of electrons confined in the strain fields above Ge dots in a SiGe matrix.

g-Factor Tuning in SiGe Quantum Wells

Our samples are grown in a Molecular Beam Epitaxy (MBE) system with electron beam evaporators for Si and Ge. The channels are n-type modulation-doped with Sb. High mobilities of up to μ_e = 250,000 cm^2/Vs have been reached in pure Si channels without back gate. The spin lifetimes are extremely long as well: Spin-echo measurements give T_1 = 2.3 μs and T_2= 3 μs for a magnetic field perpendicular to the 2DEG plane [2]. The high quality of our samples was also shown in recent magneto-transport experiments, where the ν = 1/3, 4/7 and 4/9 composite fermion states in the fractional quantum Hall effect were seen for the first time in the SiGe material system [3].The samples are either pure Si wells or double quantum well (QW) structures with a pure Si well and one with 5% Ge, which are separated by a barrier with 15% Ge content. The second structure is designed in a way that by applying electrical fields relative to the quantum wells one can completely shift the electronic wave function from one well to the other as depicted in a self-consistent band structure simulation in Fig. 1. Hand in hand with the change in the surrounding material goes a change in g-factor of the electrons [4] and hence a change in resonance frequency in an Electron Spin Resonance (ESR) experiment. Spin manipulation via pulsed ESR techniques is then possible on the spins which have been shifted into resonance.

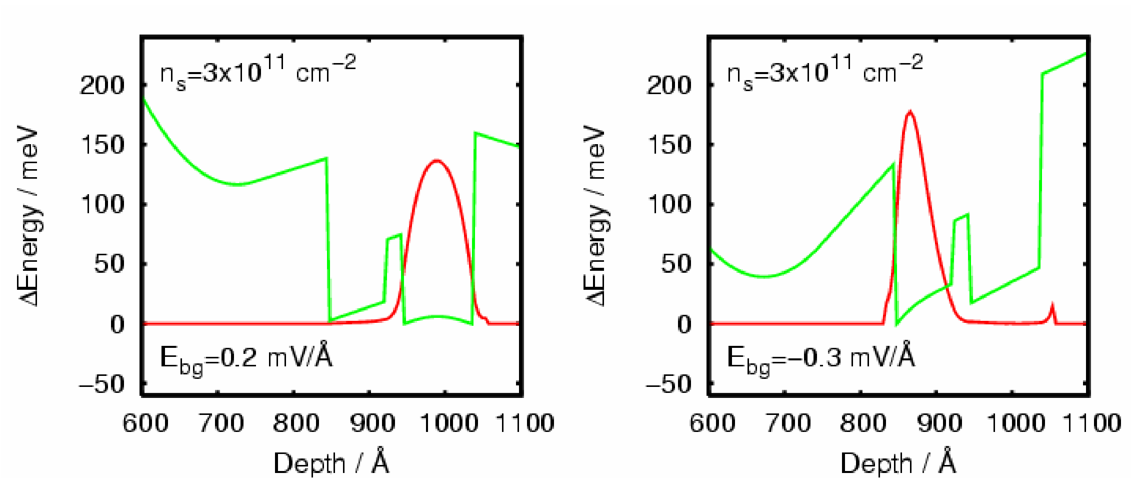


Fig. 1: Self-consistent band structure calculation of the double quantum well structure (as shown above and right) with different applied backgate fields: A front gate was used to keep the carrier concentration at a constant density of n_s = $3x10^{11}$ cm^{-2}. The calculated change in g-factor can be estimated as Δg = $2.5x10^{-4}$, which is enough to separate the resonances and allow spin manipulation.

The required electrical fields are created by applying voltages to a Schottky-type topgate and either a grown-in n-type backgate or an evaporated Al backgate on the backside of the sample. Figure 2 shows how the carrier density and the mobility can be changed in a pure Si channel with Schottky topgate and evaporated Al backgate. Our next goal is the combination of front- and backgate and the double QW structure.

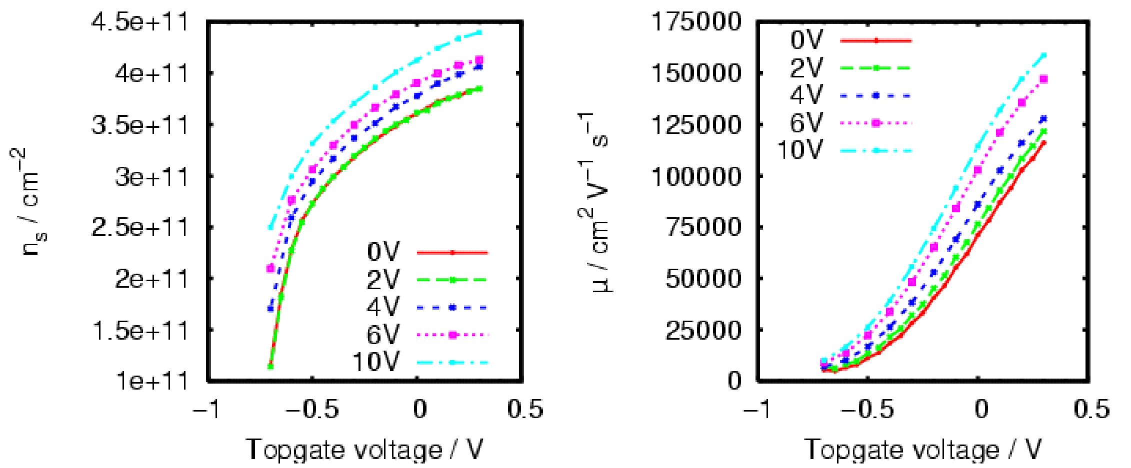


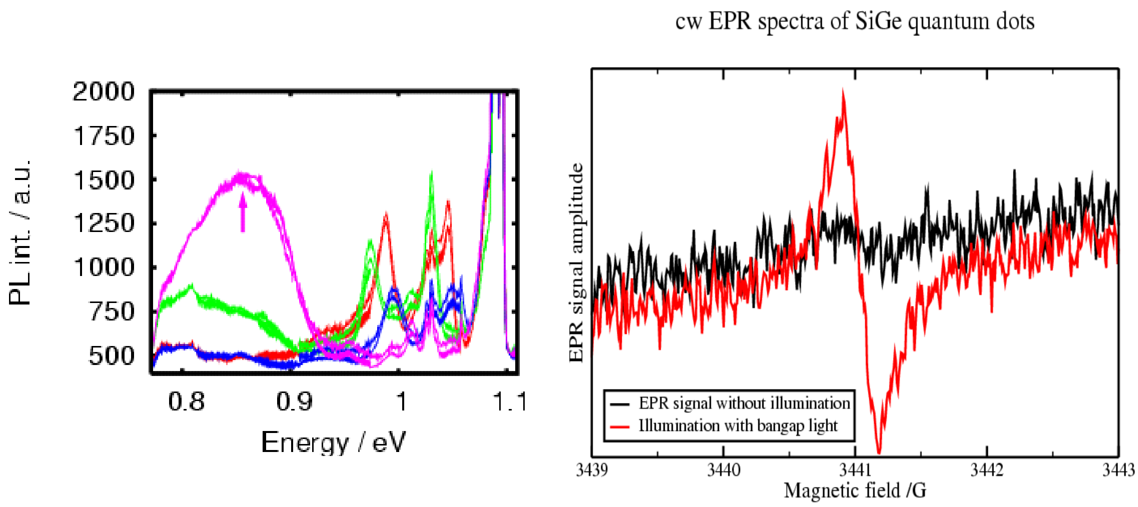
Fig. 2: Carrier density and mobility of a sample with pure Si channel with a Pd Schottky gate on top and an evaporated Al backgate on the back side plotted as a function of the topgate voltage for different backgate voltages. Both mobility and carrier density can be influenced by shifting the wave function away from the interface (higher backgate voltages).

In summary, we report about a SiGe double QW structure designed for tuning the electronic g-factor of electrons. Simulations show that it is possible to completely shift the electronic wave function between two wells with different Ge content and hence the g-factor which is a requirement for quantum computing in SiGe. The process for top- and backgate electrodes is established, and demonstrated on a single Si well sample. The next step will be the combination of double QW structure and front- and backgate.

Spin Relaxation Times in SiGe Islands

In III-V compounds it was shown that the confinement in low dimensional structures such as dots leads to a significant increase of spin lifetimes [5]. In order to achieve confinement in the SiGe material system, we grow Ge islands on Si(100) substrates (i) in a self-organized Stranski-Krastanov growth mode, which leads to an inhomogeneous distribution of island sizes and locations, and (ii) by prepatterning the substrate by either electron beam or holographic lithography. In the first type of samples (i) the density of dots is about 5 times higher than in the prestructured samples (ii), which we estimate from AFM measurements. The Ge dots were overgrown with Si which is locally strained due to the buried Ge dots. The strain causes an attractive potential for electrons. Repeating this procedure, Ge dots grow exactly on top of the strained Si areas. Up to 12 periods of dots were grown in that way which yielded a total of $>10^{10}$ dots.

In photoluminescence experiments a wide band appears around 0.8 eV which corresponds to transitions from the valence band of the Ge dots to conduction band states in the strained silicon (Fig. 3 (a)). This feature is much stronger in the samples with inhomogeneous size distribution (i), which can be attributed to the higher dot density. In EPR experiments a sharp line at g = 1.998 with a line-width of 0.25 G appears under illumination with sub-bandgap light (Fig. 3 (b)). The amplitude of this signal scales with the estimated total number of spins in the sample and also with the PL signal, and is very weak in the structured samples.



(a) (b)

Fig. 3: (a) photoluminescence data from structured and unstructured (marked) samples; (b) EPR line at g = 1.998 with and without illumination with bandgap light.

The spin relaxation times were measured in time-resolved EPR experiments. In such experiments, the sample is not continuously irradiated by microwaves (MW). Instead, short high power MW pulses are applied. At resonance, these pulses cause the spins to rotate out of their thermal equilibrium orientation parallel to the direction of the static external magnetic field H_0 by an angle that is proportional to the pulse duration around the direction of H_1, where H_1 the value of magnetic component of the MW field. Applying a π/2 pulse causes the spins to rotate into the plane perpendicular to the H_0, and a π pulse rotates the spins by 180°, thus inverting the spin orientation. Interaction with the surrounding lattice (longitudinal relaxation) and with other spins (transverse relaxation) causes the spins to dephase and to return to their thermal equilibrium value.

Specific pulse sequences are applied in order to observe longitudinal (T_1) and transverse (T_2) relaxation [6]. A π/2 pulse puts the overall magnetization in a plane perpendicular to H_0 where it decays due to spin-spin interaction (transverse relaxation) which is observed as free induction decay (FID). Some time τ after the first pulse a π pulse is applied to rotate the spins by 180°. As a consequence, a second FID appears after a time τ, 2τ after the initial π/2 pulse (Hahn echo). By varying τ, T_2 results from:

$$M = M_0 e^{-2t/T_2},$$

where M is the echo amplitude at time τ and M_0 at τ = 0.

When a π pulse is applied, the magnetization is rotated opposite to its thermal equilibrium orientation. Due to interaction with the environment the spins will relax back to their initial orientation parallel to H_0 (longitudinal spin relaxation). After a time T, a π/2 pulse is applied to put the magnetization into the plane perpendicular to H_0, and a π pulse is used to observe the Hahn echo as described above. T_1 results from:

$$M = M_0 \left(1 - 2e^{-T/T_1}\right).$$

Only the sample containing self-organized dots could be measured with time resolved EPR. We obtain a value of 0.8 μs for T_2 which is isotropic, whereas T_1 depends on sample orientation: in the case where H_0 is perpendicular to the sample plane, T_1 is 0.7 μs; in the case where H_0 is oriented in-plane, T_1 is 1.2 μs which is roughly what one expects for spin orbit coupling. Expressed in terms of line width, the homogeneous transverse line width is 0.082 G (isotropic) and the longitudinal line width is 0.070 G for perpendicular H_0 and 0.022 G for in-plane H_0. For comparison, the inhomogeneously broadened line width from cw EPR is 0.220 G for perpendicular and 0.350 G for in-plane H_0, which is considerably larger than the homogeneous contributions. The large inhomogeneous line width is attributed (i) to a fluctuation of the g-factor for different dot sizes and (ii) the hyperfine interaction with ^{29}Si.

References

[1] R. Vrijen, E. Yablonovitch, K. Wang, H.W. Jiang et al.: "Electron-spin-resonance transistors for quantum computing in silicon-germanium heterostructures", Phys.Rev.A, Vol. 62, 2000, pp. 012306

[2] A. M. Tyryshkin, S. A. Lyon, W. Jantsch, and F. Schäffler: "Spin Manipulation of Free Two-Dimensional Electrons in Si/SiGe", Phys. Rev. Lett. 94, 2005, 12802

[3] K. Lai, W. Pan, D.C.Tsui, S. Lyon, et al.: "Two-Flux Composite Fermion Series of the Fractional Quantum Hall States in Strained Si", Phys. Rev. Lett. 93,2004,156805

[4] H. Malissa, W. Jantsch, M. Mühlberger, F. Schäffler, Z. Wilamowski, M. Draxler, and "Anisotropy of g-factor and electron spin resonance linewidth in modulation doped SiGe quantum wells", Apl. Phys. Lett. 85, 2004, 1739

[5] M. Kroutvar, Y. Ducommun, D. Heiss, M. Bichler, et al.: "Optically programmable electron spin memory using semiconductor quantum dots", Nature 432, 2004, 81

[6] A. Schweiger and G. Jeschke: "Principles of Pulse Electron Paramagnetic Resonance" (Oxford University Press, Oxford, 2001)