Magnetization of modulation doped Si/SiGe quantum wells in high magnetic fields

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Abstract. We have fabricated highly sensitive micromechanical cantilever magnetometers and, by this means, investigated the de Haas-van Alphen effect of a two-dimensional electron system in a modulation-doped Si/SiGe heterostructure. As a function of perpendicular magnetic field component $B_\perp$ we observe at low temperature sawtooth-like oscillations of the magnetization M. These are found at even integer filling factors $\nu = n_s/(eB_\perp/h) = 4(N+1)$ with $N = 0,1,2...$, when the chemical potential is in the Landau energy gap, and at $\nu = (4N+2)$ where the spin splitting of the Landau levels occurs. In particular, we also observe oscillations at odd ν where the valley degeneracy is lifted. This signal increases significantly with $B_\perp$. We discuss our findings in the framework of electron-electron interaction in the presence of disorder.

In Si/SiGe heterostructures the mobility of a two-dimensional electron system (2DES) is about an order of magnitude larger than in bulk Si devices. This gives the unique possibility to study the effects of the spin- and valley-splitting of Landau levels (LLs) in a magnetic field B in detail. The latter is particularly interesting since it is not fully understood since more than 25 years and interactions are found to play a dominant role [1]. Using a highly sensitive cantilever magnetometer, we have succeeded to observe both the spin and the valley splitting in the de Haas-van Alphen (dHvA) effect, i.e., in the magnetization M of a 2DES in Si/SiGe. Since M is a thermodynamic quantity, the observed sawtooth-like oscillations are directly related to jumps in the chemical potential originating from energy gaps ΔE in the density of states (DOS). These ΔE are complementary if compared to the mobility gaps deduced from magnetotransport [2] and provide further insight into the role of electron-electron interaction and disorder in the electronic spectrum.

We have measured the magnetization in a modulation-doped Si/SiGe quantum well where the 2DES resided in a strained Si channel embedded between two $Si_{0.7}Ge_{0.3}$ barriers. The 22 nm Sb doping layer in the top barrier is separated from the 25 nm wide Si channel by a 12 nm spacer. This sample design leads to a triangular potential well formed at the heterojunction between the Si and the SiGe top barrier in which a high mobility 2DES is formed.[3] The electron concentration is $n_s = 7.5 \times 10^{15}$ m^{-2} with a mobility $\mu = 20$ m^2/Vs at 1 K. After thinning the Si substrate to $d \approx 10$ μm the sample was glued onto a calibrated GaAs micromechanical cantilever magnetometer.[4, 5] This allows us to quasi-statically detect the torque $\vec{\tau} = \vec{M} \times \vec{B}$ acting on the magnetic moment $\vec{M}$ of the 2DES. We applied the external magnetic field $\vec{B}$ under a tilt angle $\theta = 15^\circ$ measured with respect to the 2DES normal. Experimental data are shown in the inset of Fig. 1 where we depict the oscillatory part of $|\vec{M}|$. Strikingly, we observe a sawtooth-like dHvA effect. The oscillations at even integer filling factors $\nu = n_s/(eB_\perp/h) = 4,8,12,16,20,24,28$ correspond to the chemical potential jumping across the energy gap between adjacent LLs. Oscillations at $\nu = 6,10,14,18$ arise from the spin splitting. Additional oscillations occur at odd filling factors $3,5,7,9$. These are in particular interesting since they result from the lifting of the valley degeneracy in Si.

In our discussion we first focus on the dHvA oscillations at LL filling factors, i.e., $\nu = 4,8,12,\dots$. These oscillations become visible below $B_\perp = 1$ T and increase monotonously with perpendicular magnetic field $B_\perp$. The jump ΔM in the magnetization is directly related to the jump in the chemical potential ΔE [6]

$$\Delta E = \Delta M B_\perp/(n_s A), \tag{1}$$

where A is the area of the 2DES. If we compare Si

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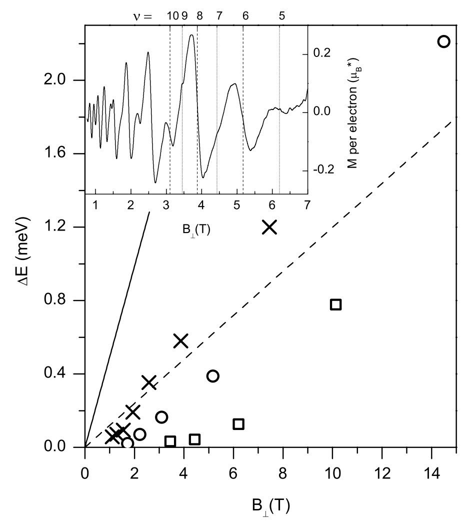

FIGURE 1. Thermodynamic energy gaps ΔE versus perpendicular magnetic field $B_\perp$. ($\times$) Landau-, ($\circ$) spin- and ($\square$) valley-filling factors. Broken line: bare Zeeman energy $\Delta E_Z = 2\mu_B B$. Solid line: cyclotron energy $\hbar\omega_c$ minus E_Z. Inset: Experimental magnetization curve as a function of $B_\perp$ at $T = 0.3$ K.

with GaAs then, due to the larger value of $|g| = 2$ and the larger effective mass $m^* = 0.19m_e$, the Zeeman energy $\Delta E_Z = |g|\mu_B B$ remarkably reduces the energy gap thus that $\Delta E/B_\perp = (\hbar\omega_c - \Delta E_Z)/B_\perp \approx 1.6\mu_B^*$. Experimentally we observe $\Delta M_{\nu=4} = 0.6\mu_B^*$. In Fig. 1 we summarize the effective energy gaps ΔE extracted from the experimental data. The LL energy gap (crosses) increases with $B_\perp$ but stays always below the $1.6\mu_B^*$ line (solid). Most likely, residual disorder in the high-mobility 2DES leads to a broadening of the levels which reduces the energy gap. Based on our model of the dHvA effect in 2DESs described in [5] we derive here from the data a field-dependent broadening parameter $\Gamma = 0.15\ \text{meV}\times\sqrt{B_\perp[T]}$ and an additional energy- and field-independent background DOS of 30 % of the zero-field DOS. By these assumptions, ΔM for the LL energy gaps can be quantitatively modeled.

Oscillations at filling factors corresponding to the spin splitting are observed up to $\nu = 18$. The peak-to-peak amplitudes ΔM at $\nu = (4N+2)$, $N = 0,1,2...$, are evaluated after subtracting a linear function accounting for the steady increase in the magnetization between the LL filling factors $\nu = 4N$ and $\nu = 4(N+1)$. The corresponding energy gaps derived via Eq. 1 increase rapidly with increasing B. Including the spin splitting $g^*\mu_B B$ in our DOS model and using $\Gamma = 0.15\ \text{meV}\times\sqrt{B_\perp[T]}$ as evaluated from the LL filling factors, we find that $g^* = 5$ models the experimentally observed ΔM at $\nu = 2$. This demonstrates that the Coulomb-exchange interaction [7] is effective in the high-mobility 2DES in the Si/SiGe heterostructure.

The oscillations at odd ν are due to the lifting of the valley degeneracy and can be observed for $\nu \leq 9$ in our experiment. The corresponding energy gaps ΔE are the smallest in Fig. 1. However, they also increase strongly with magnetic field for $B_\perp > 6$ T. At $\nu = 3$ we find $\Delta E_V = 0.78$ meV which is far larger than the splitting of ≈ 0.1 meV predicted in the noninteracting electron picture.[8] Our value is comparable to the valley energy gap in Si-metal-oxide-semiconductor (Si-MOS) inversion layers investigated in Ref. [1] by means of magnetocapacitance. Our observation of the relatively large, exchange-enhanced valley splitting is in striking contrast to the conclusion drawn in Ref. [9] where it was argued that the different shape of the confining potential in the Si/SiGe system should lead to a significantly smaller valley splitting than in the Si-MOS structures.

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