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Exchange interaction effects in the crossing of spin-polarized Landau levels in a silicon-germanium heterostructure: transition into a ferromagnetic state

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Abstract

The crossing of spin-split Landau levels in a Si/SiGe heterostructure is investigated by means of magneto-transport experiments in tilted magnetic fields. We observe a transition from a paramagnetic into a fully spin polarized state. During the transition strongly enhanced maxima in the transverse resistivity ρ_{xx} appear when the parallel field component is oriented along the Hall bar. We assign this effect to an energy level structure strongly modified by exchange interaction effects between different Landau levels. Surprisingly the maximum in ρ_{xx} totally disappears when the parallel field component is perpendicular to the Hall bar. © 2000 Elsevier Science B.V. All rights reserved.

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The interplay of Landau quantization and Zeeman splitting in the level structure of a two-dimensional electron system (2DES) can be accessed by means of magneto-transport experiments in tilted magnetic fields [1]. Such coincidence measurements are used to investigate the spin splitting in various 2DESs in heterostructures based on GaAs/GaAlAs [2], Si/SiGe [3–7] and InAs/AlSb [8].

The density of states (DOS) of a 2DES in a magnetic field with a component perpendicular to the 2DES, $B_\perp$, is quantized into discrete Landau levels N. Each Landau level (LL) splits into two spin-levels $s = \pm\frac{1}{2}$. The LL splitting, $\Delta E_\mathrm{L} = \hbar\omega_\mathrm{c}$, is governed by $B_\perp$. Here $\omega_\mathrm{c} = eB_\perp/m^*$ denotes the cyclotron frequency of electrons with effective mass $m^* = 0.19m_\mathrm{e}$ for Si. In contrast, the spin splitting,

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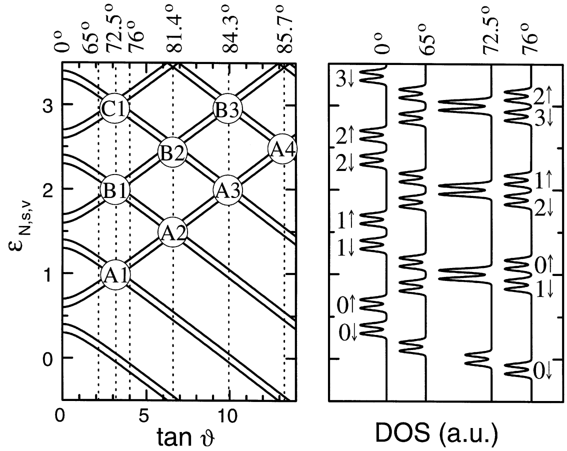

Fig. 1. (a) Energy levels $\varepsilon_{N,s}$ of a 2DES in a Si (in units of $\hbar\omega_c$) as a function of the tilt angle. The circles mark positions of coincidences where ΔE_Z equals an integer multiple m of $\hbar\omega_c$; (b) schematic DOS of the Landau levels for different tilt angles.

$\Delta E_Z = g^*\mu_B B_{tot}$ ($g^* \approx 3.15$ [7] is the effective Landé factor of the electrons), depends on the *total* magnetic field, B_{tot}. In Si/SiGe heterostructures an additional splitting into two valley states is present in the level structure with a valley splitting, $\Delta E_V = \varphi\hbar\omega_c$. Here we assume ΔE_V to be governed by $B_\perp$ [3,5,6].

The principle of coincidence experiments is based on the fact that the ratio $\Delta E_Z/\Delta E_L$ can be increased drastically by tilting the magnetic field. The general quantization energies in a magnetic field tilted by an angle ϑ away from the direction normal to the 2DES can be written as

$$E_{N,s} = \hbar\omega_c\left(N + \frac{1}{2}\right) + sg^*\mu_B B_{tot} \pm \frac{1}{2}\Delta E_V$$

$$= \hbar\omega_c\left[N + \frac{1}{2} + s\frac{g^*m^*}{2m_e}\sqrt{1+\tan^2\vartheta} \pm \frac{\varphi}{2}\right].$$

In the following, we will always consider energy levels in units of the LL splitting, i.e. we define their relative energies $\varepsilon_{N,s} = E_{N,s}/\hbar\omega_c$.

The evolution of the lowest LLs as a function of $\tan\vartheta$ is illustrated in Fig. 1 for $g^* = 3.15$ [7] and $\varphi = 0.1$. On the left panel, the relative energy $\varepsilon_{N,s}(\vartheta)$ is shown, the right panel sketches the DOS for three exemplary tilt angles. In a perpendicular field ($\vartheta = 0^\circ$) ΔE_Z is about $0.3\hbar\omega_c$, each spin-level contains two valley states. When increasing the tilt angle, the ↑-levels move to a higher relative energy whereas the ↓-levels move downwards. ΔE_Z reaches about $0.7\,\hbar\omega_c$ at $\vartheta = 65^\circ$ and as a consequence the splitting between the states $(N,\downarrow)$ and $(N,\uparrow)$ of one given Landau level is more than two times larger than the splitting between two neighboring Landau levels with opposite spin. At $\vartheta = 72.5^\circ$ the spin splitting equals the LL splitting, $\varepsilon_{N,\uparrow}$ coincides with $\varepsilon_{N+1,\downarrow}$, see positions (A1), (B1), and (C1) in Fig. 1. Increasing ϑ further, the $(N,\uparrow)$-level moves further upwards. The $(N+1,\downarrow)$-level keeps moving downwards. Finally, $\varepsilon_{N+1,\downarrow}$ is situated below $\varepsilon_{N,\uparrow}$, see $\vartheta = 76^\circ$. Increasing the tilt angle further leads to higher-order coincidences when the Zeeman splitting equals an integer multiple m of the LL splitting, see positions (Am) and (Bm) in Fig. 1. This simple picture is modified by the fact that due to exchange interaction effects g^* also depends on ϑ and the LL filling [7]. The positions of the coincidences are shifted, however, the global picture remains similar.

To access the level structure experimentally we have performed magneto-transport experiments in the 2DES defined in a Si channel of a Si/SiGe heterostructure (sheet density $n = 7.2\times10^{15}$ m^{-2}, electron mobility $\mu = 20$ m^2/Vs, patterned into a 100-μm wide Hall bar) in tilted magnetic fields up to 30 T at temperatures down to 400 mK. The experimental consequences of the first coincidence is displayed in Fig. 2 where the magneto-resistivity ρ_{xx} and the Hall resistivity ρ_{xy} at $T = 0.4$ K are shown as a function of $B_\perp$ for three different tilt angles ϑ. In a perpendicular magnetic field ρ_{xx} displays Shubnikov–de Haas oscillations and quantized Hall plateaus show up in ρ_{xy}. The strongest minima (broad plateaus) occur at filling factors $v = 4N$ corresponding to the situation when the Fermi energy lies between two LLs, $N-1$ and N. Additional minima occur at $v = 4N-2$ where the Fermi energy is situated between the two spin-levels of the same Landau level. Even the valley splitting can be resolved for the lower Landau levels, $v = 5, 7, 9$ [9,10].

For $\vartheta = 68.7^\circ$ the situation is essentially similar. However, the strengths of the $v = 4N$ minima have decreased. The dominant minima are now related to the spin-splitting [3]. This corresponds to the above illustrated situation ($\vartheta = 65^\circ$) where the splitting between the two spin-states $(N,\downarrow)$ and $(N,\uparrow)$ exceeds the splitting between the $(N,\uparrow)$-level and the next higher Landau level with opposite spin.

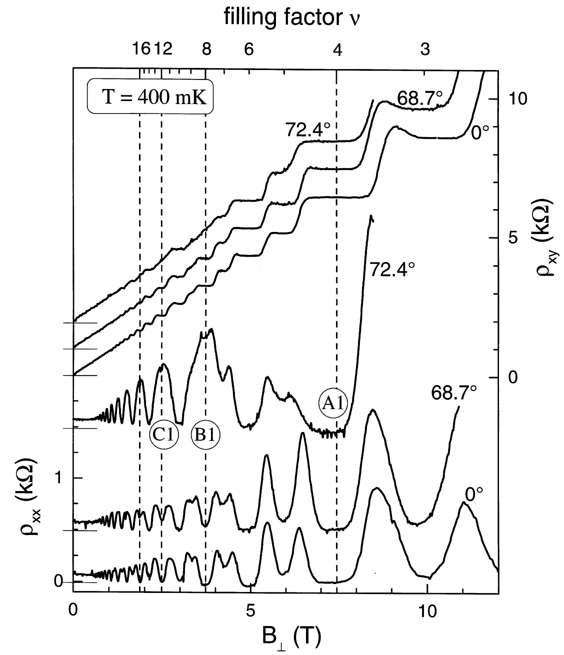

Fig. 2. Transverse resistivity ρ_{xx} and Hall resistivity ρ_{xy} as a function of the magnetic field perpendicular to the 2DES for different tilt angles. The traces are offset for clarity, the zero values for each trace are labeled on the left axis.

In the first series of coincidence ($\vartheta = 72.4^\circ$) the minima for $\nu = 8, 12, 16, \ldots$ are lifted. Now the Fermi energy lies in the middle of two degenerate levels with opposite spin, namely $(N, \downarrow)$ and $(N+1, \uparrow)$. Due to the presence of valley splitting the maximum around $\nu = 8$ displays an additional structure, for higher filling factors the valley splitting is no more resolved. The expected maximum for $\nu = 4$ (position (A1) in Figs. 1 and 2) only occurs in a very narrow range of tilt angles $\vartheta = 69$–70°, see below. The behaviour of this coincidence peak strongly deviates from that expected from the naive level structure as sketched above.

In the following we will concentrate on the coincidences (A1), (A2), and (A3). Their particular interest lies in the fact that these coincidences transform the 2DES into a ferromagnetic state. Evidences for such a phase transition were already reported using coincidence experiments at $\nu = 2$ in the 2DES of a GaInAs/InP heterostructure [11] and in p-doped SiGe structures [12,13].

In Si this transition happens at $\nu = 4$ when crossing the (A1) coincidence. Initially $(0, \downarrow)$ and $(0, \uparrow)$ are situated below the Fermi energy. Leaving ν constant and increasing the tilt angle ϑ redistributes electrons from the $(0, \uparrow)$-state into the $(1, \downarrow)$-level when moving through coincidence (A1). Finally, the $(0, \uparrow)$-level is totally depopulated and the $(1, \downarrow)$-level has moved below the Fermi energy, see illustration for $\vartheta = 75^\circ$ in Fig. 1. The electrons are now totally spin polarized. For higher tilt angles a totally spin polarized state can also be obtained for $\nu = 6$ when only the spin-down polarizations of the three lowest Landau levels remain occupied after having crossed coincidence (A2). Finally, crossing (A3) at $\nu = 8$ leaves the 2DES with four spin-down polarized Landau levels occupied.

The development of ρ_{xx} during the crossing of the (A1) coincidence is shown in Fig. 3. Strongly enhanced maxima occur in ρ_{xx} when the parallel field component is oriented along the current direction. They are more than an order larger than the SdH-peaks in the untilted case. We assign this effect to a modified energy level structure in the system due to exchange interaction which becomes important when the energy levels start coinciding. Temperature-dependent experiments give another insight into the nature of this new correlated state. From 0.4 to 0.8 K the height of ρ_{xx} in the maximum of the coincidence remains unaffected by temperature. This indicates that we still deal with a metallic systems where the ρ_{xx}-enhancement originates from correlation effects. It breaks down drastically between 1 and 1.3 K. Here it recovers a value comparable to the SdH-peaks outside the coincidence. The energy related to this level correlation can be estimated to $\Delta E_C \approx 1$ K.

Also for $\nu = 6$ and 8 (sketched (A2) and (A3) in Fig. 1) we observed similar extremely enhanced peaks in ρ_{xx}, again more than an order of magnitude larger than SdH-peaks outside the coincidences. This observation supports the above model that the enhancement of ρ_{xx} can be in fact related to a correlated state formed during the transition into the ferromagnetic 2DES. The anomalous enhancement of ρ_{xx} is absent for all other coincidences which do not result into a spin-polarized state.

Very surprisingly the ρ_{xx}-enhancement as a signature of the spin-correlated state is also absent when the parallel field component is turned by 90° with respect to the orientation of the Hall bar, see right

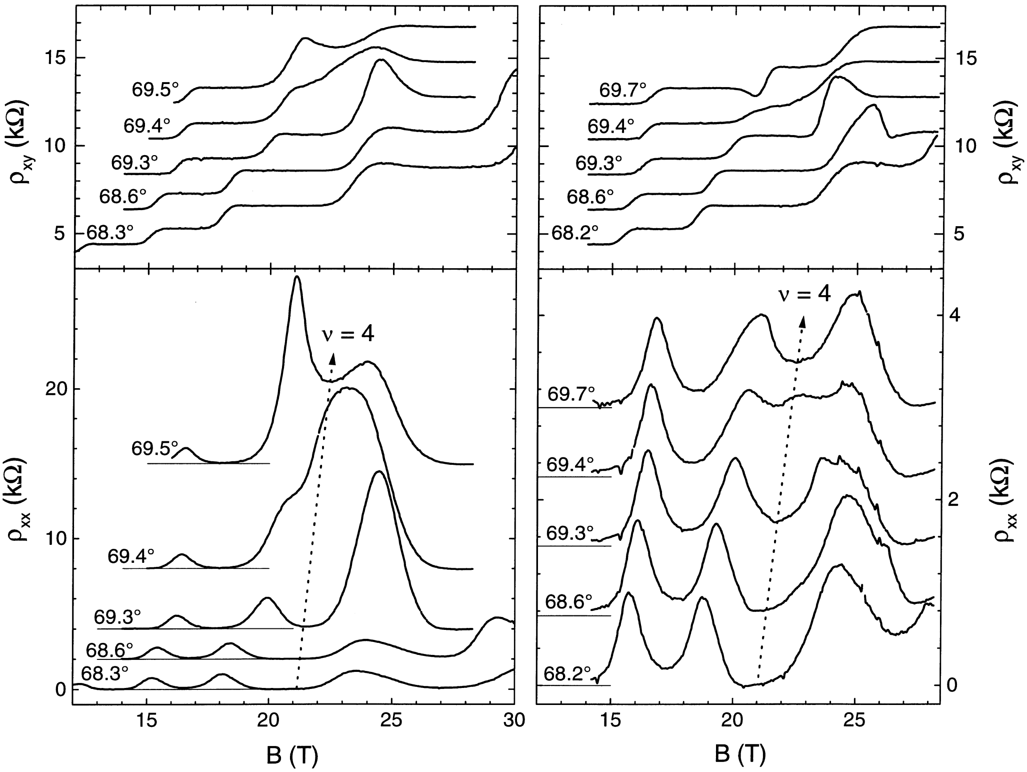

Fig. 3. ρ_{xx} and ρ_{xy} at 400 mK around the (A1) coincidence. On the left panel the parallel field component $B_{||}$ is oriented along the direction of the Hall bar, on the right $B_{||}$ is perpendicular to the Hall bar. Note the different scales for ρ_{xx}. The zero values of the ρ_{xx}-traces are marked by the horizontal lines assigned to them. For clarity also the traces of ρ_{xy} are offset by 2 kΩ for each curve.

panel of Fig. 3. This may be due to a domain structure introduced by an anisotropic 2DES. An alternative explanation might lie in the fact that for this field orientation an additional Hall voltage is induced perpendicular to the 2DES which might quench the correlation effects.

Another hint for a level redistribution can be gained from Hall-effect measurements. For a tilt angle $\vartheta = 69.4^\circ$, slightly below the angle where the broad maximum in ρ_{xx} occurs, the $\nu = 4$ plateau is still present. When changing the filling factor by increasing the magnetic field ρ_{xy} strongly overshoots the value for $\nu = 3$ nearly approaching its expected value for $\nu = 2$, see Fig. 3. This means that a level with a two-fold degeneracy is depopulated simultaneously. Only when the magnetic field is increased further the naive level structure is recovered. Now one valley state of the $(0, \uparrow)$ level and the far below situated two valley states of $(0, \downarrow)$ are occupied.

In conclusion, we have measured extremely enhanced coincidence peaks in the SdH oscillations of 2DES in a Si/SiGe heterostucture which we assign to the formation of a new correlated state formed during the transition into a fully spin-polarized 2DES.

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References

[1] F. Fang, P.J. Stiles, Phys. Rev. 174 (1968) 823.
[2] R. Nicholas et al., Phys. Rev. B 37 (1988) 1294.
[3] R.B. Dunford et al., Solid State Commun. 96 (1995) 57.
[4] S.J. Koester, K. Ismail, J.O. Cho, Semicond. Sci. Technol. 12 (1996) 348.

[5] P. Weitz et al., Surf. Sci. 361/362 (1996) 542, to be published.
[6] F.F. Fang et al., in: D. Heimann (Ed.), High Magnetic Fields in the Physics of Semiconductors, World Scientific, Singapore, 1995, pp. 620–623.
[7] H.W. Schumacher et al., Physica B 256–258 (1998) 260.
[8] S. Brosig et al., Physica B 256–258 (1998) 239.
[9] S.F. Nelson et al., Appl. Phys. Lett. 61 (1992) 64.
[10] D. Többen et al., Phys. Rev. B 46 (1992) 4344.
[11] S. Koch et al., Phys. Rev. B 47 (1993) 4048.
[12] R.B. Dunford et al., J. Phys.: Condens. Matter 9 (1997) 1565.
[13] P.T. Coleridge et al., Solid State Commun. 102 (1997) 755.