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Anomalous coincidences between valley split Landau levels in a Si/SiGe heterostructure

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Abstract

We have performed magneto-transport experiments on a high mobility 2DEG in a Si/SiGe heterojunction in tilted magnetic fields up to 26 T at temperatures down to 450 mK. When tilting the sample in the magnetic field the value of the spin splitting increases with respect to the Landau level splitting leading to an overlap of spin-split sub-levels of different Landau levels, the so-called coincidences. Coincidences between up to five neighbouring Landau levels are found. From their positions we deduce a Landé factor $g^* \approx 3.4$. Coincidences between the lowest Landau levels with fully resolved individual valley states show extremely high SdH peaks compared to the individual SdH maxima outside the coincidence suggesting strong exchange enhancement effects in the occurrence of the coincidence.

Keywords: Silicon–germanium; Magneto-transport; Valley splitting; Coincidence measurements

Magnetotransport measurements in tilted magnetic fields, also known as 'coincidence measurements', are a well established way of determining the spin splitting of a two-dimensional electron gas (2DEG) [1]. In a magnetic field tilted with respect to the normal of the 2DEG the size of the Landau splitting ΔE_L only depends on the field component normal to the 2DEG, B_n, whereas the spin splitting ΔE_S is determined by the total magnetic field B: $\Delta E_L = \hbar\omega_c = \hbar e B_n/m^*$ and $\Delta E_S = g^* \mu_B B$, where $\omega_c = eB_n/m^*$ is the cyclotron frequency, m^* the electron's effective mass, g^* the effective Landé factor and $\mu_B = e\hbar/2m_e$ the Bohr magneton. Tilting the sample in the magnetic field, and therefore increasing the ratio B/B_n, leads to an increase of the spin splitting ΔE_S with respect to the Landau splitting ΔE_L. As a consequence, sub-levels of different Landau levels can overlap whenever the spin splitting is an integer multiple of the Landau level splitting, $\Delta E_S = n_c \Delta E_L$ (n_c we call the order of the coincidence). In this case, the periodicity of the Shubnikov–de Haas (SdH) oscillations changes. In Si/SiGe heterostructures the 2DEG shows an additional splitting of the spin split Landau states, the valley splitting. The field dependence of the valley splitting ΔE_V is not yet fully understood but is assumed to be mainly governed by the normal field B_n [2,3].

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In the absence of a magnetic field the effective Landé factor g^* of the Si/SiGe 2DEG has a free electron like value of 2. In a magnetic field the g^* factor is enhanced by exchange interaction effects, depending on the spin polarisation of the electron system and therefore the filling factor [4]. This enhanced effective g^* factor can be deduced from coincidence experiments whenever the value of the valley splitting is negligible. In a coincidence between two Landau states with quantum numbers N_1, N_2 given by $N_2 = N_1 + n_c$ the effective Landé factor has a value of

$$g^* = n_c \frac{\hbar\omega_c}{\mu_B B} = n_c \frac{2m_e}{m^*}\frac{B_n}{B}.$$

An effective $g^*(n_c, \nu)$ can be deduced from the ratio B/B_n at the occurrence of the coincidence in taking the effective mass ratio $m^*/m = 0.19$ for Si. When the valley splitting is also resolved in magnetotransport the former two state coincidence becomes more complicated. Then, only a mean $g^*(n_c, \nu)$ can be derived.

Our experiments were performed on a high mobility ($\mu = 19.6$ m^2/Vs, $n = 6.9 \times 10^{15}$ m^{-2}) 2DEG in a Si/SiGe heterojunction [3] in a Hall bar geometry ($l = 0.5$ mm, $w = 0.1$ mm). The structure was grown by MBE as described elsewhere [5,6].

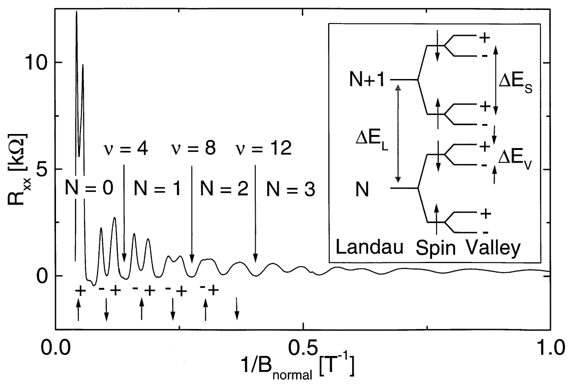

Fig. 1. Longitudinal magnetoresistance R_{xx} at $\Theta = 0°$ plotted versus the reciprocal magnetic field B^{-1} at $T = 450$ mK. Quantum numbers $(N, \uparrow\downarrow, \pm)$ of the first sublevels and filling factors belonging to the first completely filled Landau levels are marked correspondingly to the level diagram in the inset. At this temperature, valley and spin splitting is resolved up to filling factors of $\nu = 10$ and $\nu = 24$, respectively.

In Fig. 1 the measured longitudinal resistance R_{xx} is shown versus the inverse magnetic field at $\Theta = 0°$ and for $T = 450$ mK. For the lowest levels the Landau, spin and valley quantum numbers ($N, \uparrow\downarrow$ and $\pm$, respectively) are marked accordingly to the level diagram in the inset. The $1/B$ periodicity of the SdH oscillations can be easily found in the equidistantly distributed filling factors $\nu = 4i$ (i is an integer) belonging to completely filled Landau levels. The four sublevels of the Landau states can be individually resolved up to a filling factor of $\nu = 10$. Spin split Landau states are seen up to $\nu = 24$. Note the additional splitting of the $(N = 0, \uparrow, +)$ peak due to the fractional filling factor $\nu = 4/3$.

In Fig. 2 a grey scale plot compiled from an interpolation of 261 reciprocal SdH measurements at various tilting angles between $\theta = 0°$ and $\theta = 86.3°$ is shown as a function of $B/B_n = 1\cos\theta$ (x-axis) and the inverse normal field $1/B_n$ (y-axis). Values of $R_{xx} > 2.6$ kΩ are coloured white. Cuts parallel to the y-axis ($B/B_n = $ const.) represent a grey scale plot of $R_{xx}(B_n^{-1})$ as already shown in Fig. 1 for $B/B_n = 1$ ($\Theta = 0°$). Some peaks in R_{xx}, (lighter regions), are marked with their quantum numbers (left) and filling factors (horizontal lines) by analogy with Fig. 1. The cut-off lining up from the lower left to the middle right of the plot represents the maximum total field of 26.2 T.

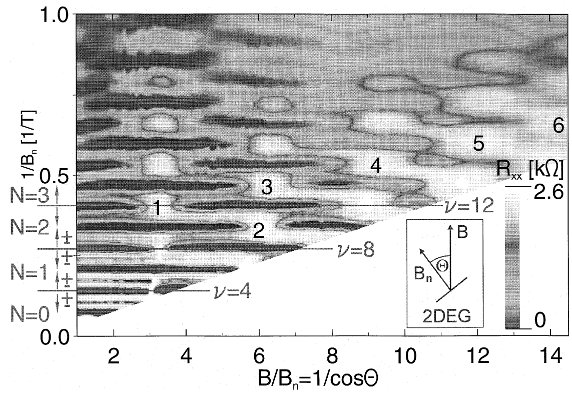

Fig. 2. Reciprocal coincidence plot: Grey scale encoded longitudinal magnetoresistance R_{xx} as a function of B/B_n (x-axis) and $1/B_n$ (y-axis), $T = 450$ mK. $R_{xx} > 2.6$ kΩ is coloured white, $R_{xx} = 0$ kΩ black.

Let us first focus on two peaks with opposite spin orientation such as $(N=2,\downarrow)$, below the $\nu=12$ ($B_n^{-1}\approx 0.4\,T^{-1}$) line and $(N=3,\uparrow)$ above it. Following the peaks from the left to the right the two peaks keep their $1/B_n$ position up to $B/B_n\approx 2.5$. Then the lower peak representing the $(\downarrow)$ spin polarisation runs upwards whereas the peak belonging to the $(\uparrow)$ spin direction moves downwards corresponding to a growing spin splitting with growing total magnetic field. At about $B/B_n=3.5$ the two peaks merge into one, forming a coincidence peak (1). For $B/B_n>3.5$, the two peaks have changed places around the $\nu=12$ line. While the $(N=3,\uparrow)$ peak continues its motion downwards coinciding at about $B/B_n=6.3$ ($\nu=10$) with the $(N=1,\downarrow)$ peak (2), the $(N=2,\downarrow)$ peak persistently moves upwards showing four higher order coincidences with $(\uparrow)$ peaks belonging to higher Landau quantum numbers ((3)–(6)). Generally speaking, at values of $B/B_n\approx 3.5, 6.5, 9.5,\ldots$ coincidences of the order $n_c=1,2,3,\ldots$ occur and peaks of neighbouring Landau levels with opposite spin quantum numbers cross. The effective g-factor $g^*(n_c,\nu)$, derived from B/B_n at the positions where the coincidences occur, lies between $g^*=3.16$ and $g^*=3.62$, depending on the relative filling of the Landau levels and the order of the coincidence in accordance with results of Koester et al. [7]. The Landé factor decreases with increasing filling factor (e.g. $g^*_{n_c=1,\nu=4}=3.4\pm 0.08$, $g^*_{n_c=1,\nu=24}=3.19\pm 0.25$) which can be easily attributed to the decrease of the g^* factor enhancement with weaker spin polarisation. A seemingly increase of g^* with increasing order of coincidence (e.g. $g^*_{n_c=1,\nu=20}=3.19\pm 0.12$, $g^*_{n_c=3,\nu=20}=3.37\pm 0.10$) is possibly due to a decrease of m^* arising from the high parallel field component. Another interesting feature is the spin dependence of the height of the SdH maxima which can be illustrated at the previously discussed $(N=3,\uparrow)$ state between $B/B_n=4$ and 5 ($B_n^{-1}\approx 0.4\,T^{-1}$). The maximum is not only higher than the neighbouring lower field peak above the $\nu=12$ line but also higher than the peak underneath. In general the $(\uparrow)$ maxima seem to be enhanced compared to the surrounding $(\downarrow)$ peaks. Here, the question arises, whether a spin depending scattering process plays a role.

Now let us take a look at coincidences between two completely spin and valley split states. The inset in Fig. 3 from (a)–(c) shows a naive picture of the occurrence of a valley split coincidence. Fig. 3(a) depicts the situation expected at the starting point of the coincidence, when the two neighbouring sublevels $(\uparrow,-)$, $(\downarrow,+)$ start to overlap. Rising spin split energy leads to mixing of all four sublevels as shown in Fig. 3(b). Finally the spin splitting energy has exceeded the Landau splitting (Fig. 3(c)) and the two neighbouring valley peaks start to diverge into separate maxima. Fig. 3 shows the $(n_c=1,\nu=4)$ coincidence as measured experimentally. Plots of R_{xx} versus B_n of the $\nu=4$ coincidence are presented in the order of ascending Θ (bottom to top). First, all four sublevels are well separated ($R_{xx}^{max}<2,6\,k\Omega$). Then, the two valley maxima on the right merge into one (1). With rising tilting angle the merged peak moves to the left and coincides with the $(N=1,\downarrow,-)$ maximum, forming an extremely high double peak (2) of about 40 kΩ. The double peak splits up again and the low field component combines with the $(N=1,\downarrow,+)$ peak, while the high field part moves out of the coincidence towards higher fields (3). Finally the merged peak disappears and resolves into the two valley peaks. Other than some higher filling factor coincidences, the occurrence of

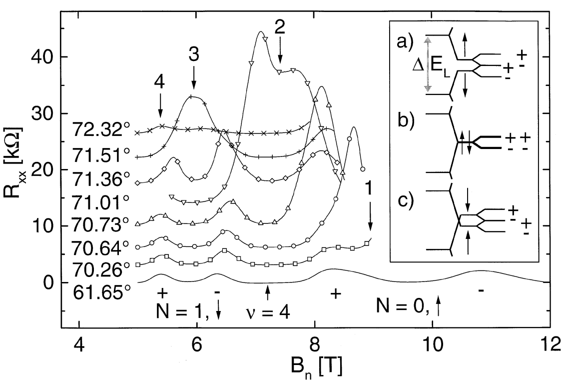

Fig. 3. Occurrence of the coincidence at $\nu=4$, $n_c=1$ between the $(N=0,\uparrow,\pm)$ and the $(N=1,\downarrow,\pm)$ Landau states. R_{xx} is shown versus B_n for various tilting angles. The plots are offset for clarity. Tilting angles, rising from bottom to top, are indicated left of the plots. The inset shows a naive picture of the occurrence of a coincidence between fully spin and valley split Landau states from (a)–(c).

this coincidence at $\nu = 4$ does not at all correspond to the naive picture sketched in the inset. A possible mechanism for the starting part of the coincidence might be a level repulsion of the two spin polarisations due to exchange interaction, leading to a quenching of the two $(N = 0, \uparrow, \pm)$ states and the overlapping of the two valley peaks. The complete shifting and intermixing of the levels in the progress of the coincidence is nevertheless unclear. The reason for the extreme height of the evolving coincidence peak compared to its components before and after the coincidence is another point of interest. It may be attributed to the existence of a strongly correlated state inside the coincidence with extremely enhanced scattering compared to its individual components.

In conclusion we have performed magnetotransport experiments in tilted magnetic fields up to 26 T on high quality Si/SiGe heterostructures. From coincidence measurements g^*-factors in the range of $g^* = 3.16$–3.62 depending on the order and filling factor of the coincidence were derived. Spin depending transport in between the coincidences was observed. The $(n_c = 0, \nu = 4)$ coincidence with fully resolved individual valley states shows extremely high SdH peaks compared to the individual SdH maxima outside the coincidence which we attribute to strong exchange enhancement effects in the occurrence of the coincidence.

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