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Suppression of the Landau-level coincidence: A phase transition in tilted magnetic fields

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Magnetotransport studies of $Ga_xIn_{1-x}As/InP$ heterostructures in strong parallel magnetic fields at mK temperatures reveal a suppression of the coincidence of two Landau levels with opposite spin at filling factor 2. This phenomenon is explained by the occurrence of a phase transition from a spin-unpolarized state (at small tilt angles) to a spin-polarized state (at large tilt angles).

Landau levels and Zeeman splitting fundamentally govern the behavior of a two-dimensional electron gas (2D EG) in a magnetic field. If the magnetic field is oriented perpendicularly to the plane of the 2D EG, in common heterostructure systems the Zeeman splitting is much smaller than the Landau splitting. This situation is changed if the sample is tilted with respect to this orientation, so that the magnetic field and the normal to the plane of the 2D EG enclose an angle Θ. Under these conditions Landau and Zeeman splitting can be of comparable magnitude (as is schematically depicted in Fig. 1), because the Zeeman splitting increases with increasing total magnetic field B_{tot}, while the Landau splitting, to a first approximation, only depends upon the perpendicular component $B_\perp = B_{\text{tot}} \cos\Theta$. This fact has been used in previous work[1-3] to determine the effective g^* factor. In these "coincidence experiments" a maximum in the longitudinal resistivity ρ_{xx} is found at even integer filling factors if the extended states of two spin levels of different Landau levels (LL's) $(N+1)\uparrow$ and $N\downarrow$ overlap or "coincide." It was generally found that the g^* factor can be significantly enhanced if the Fermi energy E_F is situated between the two spin levels of a particular LL, when compared to the bare, nonenhanced g^* factor. This enhancement was explained by exchange interactions of the electrons in the 2D EG.[4]

However, up to now such experiments were limited to LL's with comparatively large LL index N. This was due to limitations of the available magnetic fields, a small bare g^* factor (in $Ga_{1-x}Al_xAs/GaAs$ systems), or a carrier concentration n_e which was too high to obtain small filling factors $\nu = n_e/n_L$ (n_L: LL degeneracy) at large tilt angles. In particular, to the best of our knowledge no experimental studies of the coincidence of the LL's $N=0\downarrow$ and $N=1\uparrow$ have been published.

On the other hand, extremely interesting effects are expected for this coincidence. In particular, Giuliani and Quinn[5] predicted a first-order *phase transition* from a spin-unpolarized (or "paramagnetic") state to a spin-polarized (or "ferromagnetic") state at filling factor $\nu = 2$. The system undergoes a transition from the spin-unpolarized situation, where the LL's $0\downarrow$ and $0\uparrow$ are below the Fermi energy E_F [Fig. 1(a)], to the spin-polarized case where LL's $1\uparrow$ and $0\uparrow$ are below E_F [Fig. 1(b)]. It was argued that this magnetization change does not take place in a continuous manner, but as a sudden jump, which was attributed to the electron-electron interactions. While in the work of Giuliani and Quinn the disorder-broadening of the LL's was ignored, in a recent paper by Yarlagadda[6] a finite LL width Γ was included, as well as screening effects. He found that the LL broadening must be sufficiently small in order to observe the magnetization jump, with experimentally accessible values of the corresponding electronic mobility.

In the present work, we have performed magnetotransport studies of the coincidence of the LL's $N=0\downarrow$ and $N=1\uparrow$ at mK temperatures in strong tilted magnetic fields. At tilt angles of the order of $\Theta = 80°$, this coincidence is accessible in samples with low carrier concentration ($n_e = 1\times 10^{15}$ m^{-2} and less). We demonstrate that in samples of sufficiently high mobility ($\mu > 10$ m^2/V s) the coincidence of these two LL's *vanishes.* This is strong evidence that the phase transition for the magnetization predicted in Ref. 5 in fact takes place. The mobility

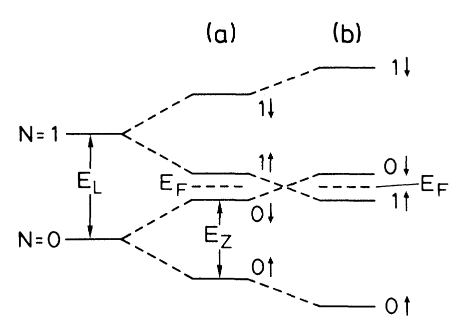

FIG. 1. Schematic of the Landau splitting E_L and Zeeman splitting E_Z in tilted magnetic fields for the spin-split Landau levels ($N=0\uparrow, N=0\downarrow$) and ($N=1\uparrow, N=1\downarrow$). (a) Small tilt angle, (b) large tilt angle.

threshold expected from Ref. 6 is explicitly verified and found to be in good agreement with the theory.

The samples used in the present work are $Ga_{0.47}In_{0.53}As/InP$ heterostructures. We have selected this system because here the bare $\tilde{g}$ factor of $|\tilde{g}| = 4.1$ (Ref. 7) is much larger than in, e.g., $Ga_{1-x}Al_xAs/GaAs$ heterostructures, where $|\tilde{g}| = 0.44$ (Ref. 8) is found. The structures are grown by metal-organic chemical vapor deposition. On an iron-doped InP substrate a 50-nm InP layer is grown. This is followed by a 450-nm (sample 1) or 600-nm (samples 2 and 3) $Ga_{1-x}In_xAs$ layer and a 30-nm InP cap layer. The carrier concentration n_e and mobility μ_e of the three samples at low temperature (T) are $n_e = 0.25 \times 10^{15}$ m^{-2}, $\mu = 6.8$ m^2/V s (sample 1), $n_e = 0.69 \times 10^{15}$ m^{-2}, $\mu = 9.8$ m^2/V s (sample 2), and $n_e = 1.03 \times 10^{15}$ m^{-2}, $\mu = 11.4$ m^2/V s (sample 3). The samples show an inhomogeneity of n_e of a few percent, which, however, does not substantially influence our experiment. The samples are mounted on a rotation platform in the glass tail of a top loading dilution refrigerator which allows for *in situ* tilting of the sample. On the back side of the platform a second sample is mounted, which is used for the simultaneous and accurate determination of the tilt angle. The samples are studied in the T range from 35 mK to 1.1 K and in magnetic fields up to 15 T. A certain tilt angle Θ is selected and then the resistivities ρ_{xx} and ρ_{xy} are determined as a function of the total magnetic field B_{tot}.

In Fig. 2 we show the longitudinal resistivity ρ_{xx} as a function of B_{tot} for various tilt angles around the angle where the coincidence is expected. Figure 2(a) displays the results for the sample 1 ($\mu = 6.8$ m^2/V s). Here the regular coincidence behavior is found. At small angles ($\Theta = 80.26$) a minimum at filling factor $\nu = 2$ appears, corresponding to the situation in Fig. 1(a). Such a minimum is also found at large angles ($\Theta = 85.03$), corresponding to Fig. 1(b). At $\Theta = 82.57$, the extended states of the LL's $N = 0 \downarrow$ and $N = 1 \uparrow$ overlap, and a maximum is found close to $\nu = 2$.

A strikingly different situation is found in sample 3 ($\mu = 11.4$ m^2/V s). As shown in Fig. 2(b), at no angle in the relevant range a maximum in ρ_{xx} is observed at $\nu = 2$. (The relevant range is shifted in magnetic field and tilt angle due to a different carrier concentration and g^* factor, as will be discussed below.) Instead, at any angle a broad field region appears around $\nu = 2$ where ρ_{xx} is zero. This means that an overlap of the extended states of the LL's $N = 0 \downarrow$ and $N = 1 \uparrow$ does not occur in this sample. The system can *only* be in either one of the situations represented in Figs. 1(a) and 1(b); the intermediate situation (where the extended states of the levels overlap) is not realized. A completely analogous situation is also found in the Hall effect: at any angle ρ_{xy} is quantized to $\rho_{xy} = \frac{1}{2}\frac{h}{e^2}$, with a plateau width of always more than 1.5 T. The situation is different for the coincidence at filling factor $\nu = 4$: here the overlap of the LL's $N = 1 \downarrow$ and $N = 2 \uparrow$ does take place, a ρ_{xx} maximum occurs around $\nu = 4$, and the plateau at $\rho_{xy} = \frac{1}{4}\frac{h}{e^2}$ disappears.

The T dependence of the vanishing of the coincidence at $\nu = 2$ is exemplarily shown in Fig. 3 at a particular angle. While at low T the minimum at $\nu = 2$ is found as already discussed, at higher T it vanishes and roughly approaches the form expected for a regular coincidence [as shown, e.g., in Fig. 2(a), $\Theta = 82.57$], but shows some additional structure. Due to different g-factor enhancement the coincidence condition for filling factor $\nu = 4$ is reached at a tilt angle of $\Theta = 78.77$. The inset of Fig. 4 shows that for the filling factor of $\nu = 4$ even at the lowest temperatures studied a minimum is not observed for the coincidence condition, i.e., the coincidence does not vanish. Instead, the maximum in ρ_{xx} between filling factors $\nu = 5$ and $\nu = 3$ has the asymmetric form as known for high-mobility two-dimensional systems with no sign of a minimum at a filling factor of $\nu = 4$.

An important and experimentally nontrivial point is the determination of the parallel magnetic field where the coincidence is expected. In sample 3, where the coincidence at $T = 35$ mK has disappeared, measurements at considerably higher T make this determination possi-

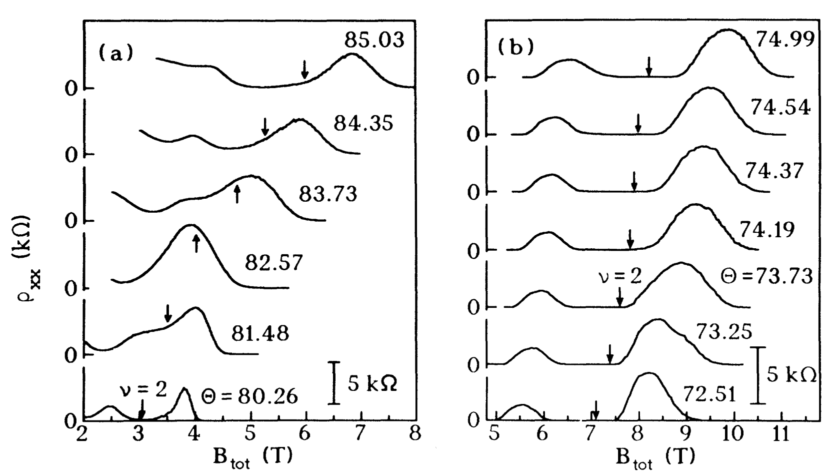

FIG. 2. Longitudinal resistivity ρ_{xx} as a function of the total field B_{tot} for several tilt angles Θ at $T = 35$ mK. The field B_{tot} where $\nu = 2$ is indicated by an arrow. (a) Sample 1 (low mobility), (b) sample 3 (high mobility). The curves are offset for clarity.

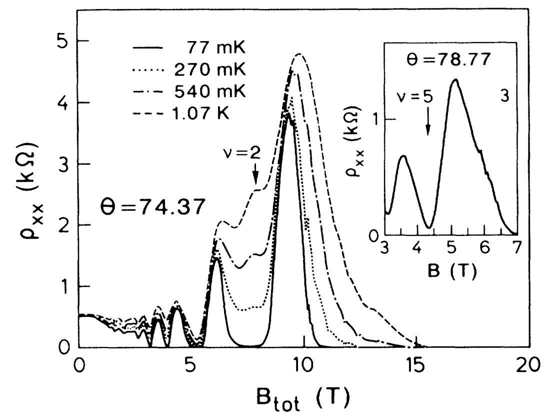

FIG. 3. Temperature dependence of $\rho_{xx}(B_{\text{tot}})$ for sample 3 at a tilt angle of $\Theta = 74.37$ corresponding to the coincidence condition at a filling factor of $\nu = 2$. The inset gives ρ_{xx} at a temperature of $T = 50$ mK and a tilt angle of $\Theta = 78.77$ corresponding to the coincidence condition at a filling factor of $\nu = 4$.

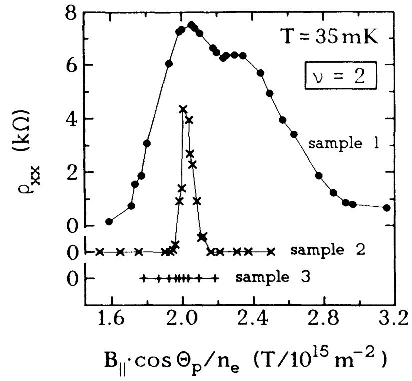

FIG. 5. ρ_{xx} at $\nu = 2$ as a function of the normalized $B_{\parallel}$ (see text) for the three samples. The thin lines are guides for the eye. The curves are offset for clarity.

ble. This is shown in Fig. 4, where the value of ρ_{xx} at $\nu = 2$ is given as a function of the parallel magnetic field $B_{\parallel}$. At $T = 500$ mK we clearly identify the coincidence condition which appears at a parallel magnetic field of $B_{\parallel} = 7.6$ T corresponding to a tilt angle of $\Theta = 74.3$. At $T = 200$ mK the maximum value of ρ_{xx} at $\nu = 2$ drops significantly, corresponding to the T dependence shown in Fig. 3. At $T = 35$ mK we find $\rho_{xx} = 0$ at all angles. In Fig. 4 the corresponding data for sample 2 are also given. We note the strong qualitative difference between the T-dependent behavior shown for sample 3 and the data for sample 2. Whereas for sample 3 a strong decrease of the maximum value of ρ_{xx} is observed, in the case of sample 2 the maximum value of $\rho_{xx}(B_{\parallel})$ is practically T independent in the range from 1.5 K down to 35 mK, even though the width of the peak shrinks by a factor of more than 6. In this case the coincidence does not vanish even at the lowest temperatures.

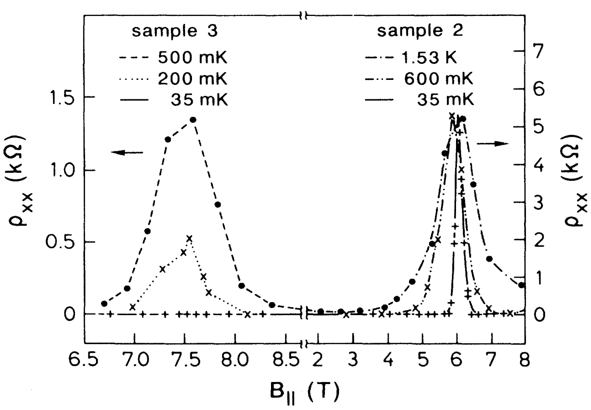

FIG. 4. ρ_{xx} at $\nu = 2$ as a function of the parallel field $B_{\parallel}$ in sample 3 and in sample 2 at three different temperatures. The lines are guides for the eye.

In Fig. 5 we compare the low T $\rho_{xx}(B_{\parallel})$ dependence of the three samples. For such a comparison it is necessary to rescale the $B_{\parallel}$ axis, taking into account the different carrier concentrations n_e and the different angles Θ_p where the respective $\rho_{xx}(B_{\parallel})$ curve attains its peak value. The necessity of the latter rescaling is caused by the different effective g^* factors in the three samples. By comparing the first and second sample, we notice a dramatic narrowing of the half-width of the curve, by a factor of more than 10. It has to be noted here that the mobilities of the two samples differ by less than 50%. If we furthermore compare samples 2 and 3, we notice that a mobility increase of less than 20% leads to the complete vanishing of the peak. This convincingly demonstrates the existence of a mobility threshold for the occurrence of the phase transition at around $\mu = 10$ $m^2/V\,s$, in qualitative agreement with the theoretical work of Ref. 6.

The suppression of the coincidence at filling factor $\nu = 2$ shows that the extended states of the LL $N = 0\downarrow$ and those of the LL $N = 1\uparrow$ at low T never overlap, because the appearance of extended states at the Fermi energy would lead to a nonvanishing ρ_{xx}. We argue that during the sweep of the total magnetic field the magnetization jump occurs at filling factor $\nu = 2$. Since the jump takes place between two situations where localized states are at the Fermi energy (so that $\rho_{xx} = 0$ before and after the jump), it is not directly observed in the magnetoresistance. At higher T, a larger fraction of states is effectively extended, and a thermal excitation of carriers across the mobility gap becomes possible. As a result, ρ_{xx} at filling factor $\nu = 2$ becomes larger than zero (see Fig. 3). However, it is not possible to attribute the T-dependent data to a single activation energy.

We want to stress here that the phase transition from a spin-unpolarized state to a spin-polarized state cannot be explained within the single-particle picture, which we have used for simplifying the discussion. Instead, electron-electron *interactions* are an absolute prerequisite for the occurrence of the phase transition, as was already stated by Giuliani and Quinn in their original work.[5] In comparison to the quantitative results of Yarlagadda[6] we note that the actual mobility threshold that we find is somewhat higher than calculated in Ref. 6. This may be due to either some of the simplifications in that work, or simply by the particular way in which the LL broadening Γ is calculated from the mobility. In Ref. 6 it is somewhat arbitrarily assumed that Γ is half the broadening Γ_{SCBA} obtained in the self-consistent Born approximation from the mobility: $\Gamma = \frac{1}{2}\Gamma_{SCBA}$. If this prefactor is not $\frac{1}{2}$ but, e.g., 1, it is clear that higher mobilities are necessary to obtain a certain LL broadening. In agreement with the results of Ref. 6 we find that while the vanishing of the coincidence of the LL's $N = 0 \downarrow$ and $N = 1 \uparrow$ is observed, at $\nu = 4$ a regular behavior is found. This is not astonishing in a system which is just above the threshold at $\nu = 2$.

From our results it is also possible to determine the effective g^* factors for $\nu = 2$, which correspond to a partially enhanced $g(\frac{1}{2})$ factor (see Ref. 3 for the notation). For the three samples 1, 2, and 3 we find an increase of $g(\frac{1}{2})$ from 5.6 via 9.9 to 11.5. We note that both the mobility and the carrier concentration increase from sample 1 to sample 3. Ando and Uemura[9] found in their calculations of the enhanced g^* factor that for smaller LL broadening a larger g^* factor is expected, which corresponds to our results.

In conclusion, we have observed a phase transition of a two-dimensional electron gas in a strong parallel magnetic field. Magnetotransport measurements in $Ga_{1-x}In_xAs/InP$ heterostructures exhibit the vanishing of the Landau-level coincidence at filling factor $\nu = 2$ at low temperature. This shows that the system undergoes a transition from a spin-unpolarized state (at small tilt angles) to a spin-polarized state (at large tilt angles), in agreement with theoretical predictions. We have reported the existence of a mobility threshold of $\mu \approx 10$ $m^2/V\,s$ for the observation of the effect.

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