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Transport anisotropies in a Si/SiGe heterostructure induced by an in-plane magnetic field

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Abstract

We have observed strong transport anisotropies in magneto-transport experiments in the two-dimensional electron system of a SiGe heterostructure. These effects occur in tilted magnetic fields where two neighboring Landau levels with opposite spin are close to half filling. We propose that the observed anisotropies may be due to the formation of a unidirectional stripe phase formed by two energetically coinciding Landau levels. © 2001 Elsevier Science B.V. All rights reserved.

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Recently tremendous anisotropies were observed in magneto-transport experiments in very high mobility two-dimensional electron systems (2DESs) in GaAs/AlGaAs heterostructures [1,2]. They occur at very low temperatures ($T < 100\,\mathrm{mK}$) when a higher Landau level is half filled. These observations are possibly related to the formation of a unidirectional stripe phase consisting of stripes with an entirely full or a totally empty Landau level [3–5]. In the experiments the orientation of the stripes was found to be along the natural cleavage direction [1 1 0] in GaAs [1,2]. Using an additional in-plane field B_{ip} it is possible to tune the stripe orientation into the direction perpendicular to B_{ip} [6–8].

In this paper we report on experimental evidence for a possible stripe formation in the 2DES of a Si/SiGe heterostructure [9]. We use an in-plane field B_{ip} to tune two neighboring Landau levels with opposite spin to energetic coincidence [10]. By this the spin-up sub-level of a Landau level can be tuned from entire filling via half filling to totally empty. Simultaneously the spin-down level of the next Landau level is tuned from totally empty via half filling to entirely full. In the situation when the two Landau levels involved in the coincidence are both half filled huge maxima appear in the resistivity ρ_{xx} when B_{ip} points along the current direction. Surprisingly these maxima do not show up, if B_{ip} is oriented perpendicular to I. We will propose that these anisotropies may be caused by the formation of a unidirectional stripe phase oriented perpendicular to the in-plane field.

Our sample is a 2DES formed in the Si channel of a Si/SiGe heterostructure grown on a [0 0 1] Si substrate [11–13]. We patterned a standard Hall bar in the [1 1 0] direction and performed transport experiments in tilted magnetic fields up to 30 T at temperatures down to below 0.5 K.

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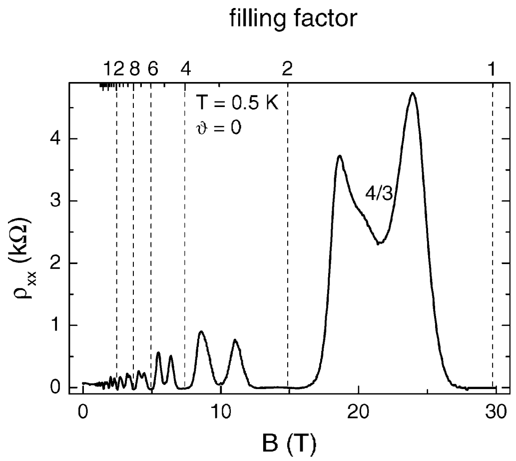

Fig. 1. Resistivity ρ_{xx} in a perpendicular magnetic field.

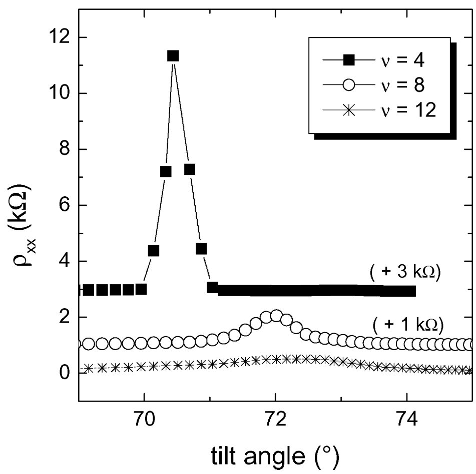

Fig. 2. ρ_{xx} at filling factors $\nu = 4N = 4, 8, 12$ as a function of the tilt angle ϑ. The maxima occur when two neighboring Landau levels with opposite spin are energetically coinciding. The curves are shifted for clarity.

As shown in Fig. 1 the sample displays Shubnikov–de-Haas (SdH) oscillations in a magnetic field applied perpendicular to the 2DES. From the SdH period and the zero-field resistance we deduce an electron concentration $n = 7.2 \times 10^{11}$ cm^{-2} and a mobility $\mu = 2 \times 10^5$ cm^2/V s. The pronounced minima at Landau level fillings $\nu = 4, 8, 12$, etc. occur when the Fermi level is positioned between two Landau levels. Additional minima are observed at $\nu = 2,6,10$, etc. where the Fermi level lies in between two spin-split levels of the same Landau level. For the lowest two Landau levels also the valley-splitting is visible as distinct SdH minima at $\nu = 1, 3, 5, 7$, and 9 [14–16].

When the field is tilted away from the perpendicular direction the spin-splitting inside a Landau level, ΔE_Z, is increased with respect to the Landau splitting, ΔE_{L}. At the tilt angle where ΔE_Z equals ΔE_{L} two spin-levels with opposite spin originating from two neighboring Landau levels are energetically coinciding. As a consequence the pronounced SdH minima observed at $\nu = 4, 8, 12$, etc. develop into maxima. Higher-order coincidences occur when ΔE_Z equals an entire multiple of ΔE_{L}.

The situation in the first-order coincidence is displayed in Fig. 2 where the resistivity ρ_{xx} at constant Landau level filling $\nu = 4, 8$, and 12 is plotted as a function of the tilt angle ϑ. The in-plane field is oriented along the current direction. Before and after the coincidence $\rho_{xx} = 0$. The energetic coincidence of two neighboring Landau levels with opposite spin shows up as a maximum in ρ_{xx}. The maxima occur at slightly different tilt angles for the different filling factors. We attribute this to an exchange-like enhancement of the g-factor which is particularly pronounced for lower Landau levels [12].

A striking observation is the fact that the coincidence at $\nu = 4$ is extremely pronounced and is only present in a very narrow angle range [12,13]. The SdH maximum at $\nu = 4$ reaches values of more than 10 kΩ, one order of magnitude larger than the SdH maxima around $\nu = 4$ outside the coincidence, see Fig. 1.

Even more astonishing is the fact that this ρ_{xx} enhancement is not present if the in-plane field is applied perpendicular to the Hall bar as shown in Fig. 3. In contrast, the SdH maximum even seems to be suppressed around $\nu = 4$ when $B_{\mathrm{ip}} \perp I$. This observation is visualized more clearly in Fig. 4a. The magnitude of the dominant SdH peak at $\nu = 4$ increases to more than 10 kΩ when $B_{\mathrm{ip}} \| I$ whereas it is clearly suppressed for $B_{\mathrm{ip}} \perp I$.

Finally, the observed transport anisotropies in the first-order coincidence at $\nu = 4$ disappears drastically for temperatures above 1 K. This effect is shown in Fig. 4b where we have plotted $\rho_{xx}^{\max}$ as

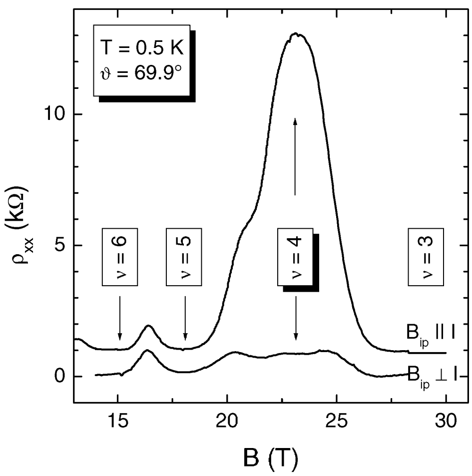

Fig. 3. Resistivity ρ_{xx} in the centre of the first-order coincidence around $\nu = 4$ as a function of the *total* magnetic field. The two traces (shifted for clarity) correspond to two orientations of the in-plane field component.

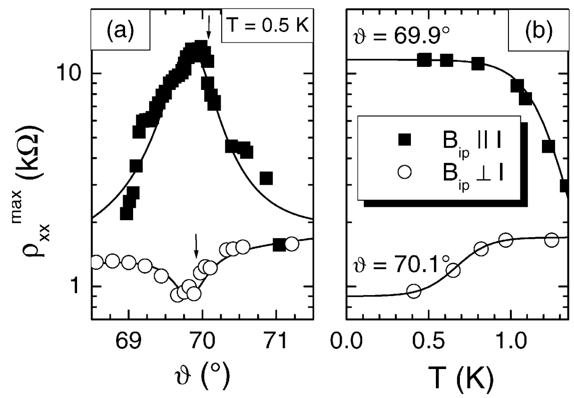

Fig. 4. (a) Development of the dominant SdH maximum $\rho_{xx}^{\max}$ at $T = 0.5$ K when tilting the sample through the first-order coincidence around $\nu = 4$ for the two field orientations. (b) Temperature dependence of $\rho_{xx}^{\max}$ close to the center of the coincidence.

a function of temperature for both field orientations. The temperature dependent measurements were performed at two slightly different angular positions as marked by the arrows in Fig. 4a.

We observed similar huge transport maxima for $B_{ip}||I$ together with a pronounced anisotropy as a function of the orientation of B_{ip} at higher order coincidences where the spin-down level of the lowest Landau level is coinciding with the spin-up level of a higher Landau level [9].

In order to explain our experimental findings we propose that the anisotropies observed are caused by the formation of a unidirectional stripe phase formed by electrons from two coinciding Landau levels. The stripes are oriented perpendicular to B_{ip}. The huge coincidence maxima observed for $B_{ip}||I$ are then due to the fact that transport across the stripes is strongly obstructed. The suppression of $\rho_{xx}^{\max}$ for $B_{ip}\perp I$ is explained by a facilitated transport along the stripes.

The stripe phase seems to disappear for temperatures above 1 K which allows us to estimate the energy gain of the stripe phase compared to a homogeneous situation to be about 0.1 meV.

Until present experimental evidence for striped electron phases have mainly been found in the 2DES of very high quality GaAs/AlGaAs heterostructures with mobilities $\mu \approx 10^7\ \mathrm{cm^2/V\,s}$ [1,2]. The stripe formation was found at very low temperatures below 100 mK proposing a typical correlation energy of the stripe phase of less than 0.01 meV.

In this respect it is rather astonishing that such a stripe phase occurs in SiGe with correlation energies which are an order of magnitude higher. Even when taking into account the higher effective mass ($m^* = 0.19m_0$ in Si as compared to $m^* = 0.067m_0$ in GaAs) the energy relaxation time in Si is still one order of magnitude lower as compared to GaAs.

However, the additional valley splitting present in Si may be a key point for the possible stabilization of a stripe phase with respect to disorder. It is interesting to remark that the typical valley splitting of 0.1 meV is comparable to the above mentioned formation energy of the stripe phase. In this respect it may be possible that a redistribution of electrons in k-space may be sufficient to stabilize a possible spatially ordered unidirectional stripe-phase with respect to disorder.

Certainly the precise nature of any possible phase still has to be clarified which involves a detailed theoretical consideration of the complex energy-level structure of the 2DES in a Si/SiGe heterostructure.

It should be mentioned that morphology of the Si channel in a SiGe structure may be slightly modulated. This effect is essentially caused by misfit dislocations formed during growth in the graded SiGe buffer far below the active region of the Si channel [17]. As a consequence a cross-hatched surface morphology is formed leading to a spatial variation of the angle between the 2DES and a tilted magnetic field.

In this respect it may be possible that stripe like domains with different Landau level filling form along the in-plane field. However, we point out that the period of these stripes of the order of μm (as deduced from atomic force microscopy) would be far too large to explain the temperature dependence and the magnitude of the SdH maxima in a simple sequential tunneling model. Therefore, the most promising explanation for our experimental findings seems to remain the formation of a new phase of two coinciding Landau levels with opposite spin.

In conclusion, we regard the observed anisotropies in the magneto-transport properties of coinciding Landau levels in the 2DES of a Si/SiGe heterostructure as an experimental evidence for the formation of a unidirectional stripe phase. This phase most probably consists of a rather complex valley-spin-structure and detailed theoretical considerations are required to prove any existence of the proposed phase.

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