Magnetoresistance Anisotropy in Si/SiGe in Tilted Magnetic Fields: Experimental Evidence for a Stripe-Phase Formation

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We observe pronounced transport anisotropies in magnetotransport experiments performed in the two-dimensional electron system of a Si/SiGe heterostructure. They occur when an in-plane field is used to tune two Landau levels with opposite spin to energetic coincidence. The observed anisotropies disappear drastically for temperatures above 1 K. We propose that our experimental findings may be caused by the formation of a unidirectional stripe phase oriented perpendicular to the in-plane field.

Two-dimensional electron systems (2DESs) in high magnetic fields show many interesting fundamental effects. Widely known is the quantization of the energy spectrum into discrete Landau levels (LLs). For high magnetic fields the electron-electron interaction becomes important and novel states emerge. One of the most prominent of such features is the fractional quantum Hall effect (FQHE) [1] where new collective quasiparticles for electrons in the lowest two LLs appear.

For higher LLs it has been proposed that an ordered charge-density wave forms an energetically lower lying state compared to the FQHE states [2,3]. In the situation when a higher LL is half filled the electrons arrange in stripes where the LL considered is either totally full or totally empty. Experimental evidence for the existence of such a stripe phase at half LL filling was found recently by several groups in 2DESs of very high mobility GaAs/AlGaAs heterostructures [4–7]. With an additional magnetic field B_{ip} parallel to the 2DES the orientation of the stripes can be tuned to the direction perpendicular to B_{ip} [6–8].

In this Letter we report on magnetotransport experiments in the 2DES of a Si/SiGe heterostructure. Adding an in-plane field B_{ip}, with the normal field component left constant, two neighboring LLs with opposite spin can be tuned to half filling simultaneously. We will show that huge maxima in the Shubnikov–de Haas (SdH) oscillations appear if the current direction I is oriented along B_{ip}. Such an enhancement of the SdH maxima is not observed when I is oriented perpendicular to B_{ip}. We will propose the formation of a unidirectional "stripe phase" to explain the huge transport anisotropies and possible physical origins of the stripe formation will be discussed.

Our sample is a Si/SiGe heterostructure with a 25-nm-thick strained Si channel embedded between two $Si_{0.7}Ge_{0.3}$ barriers [9]. The electrons are provided by doping the top barrier with Sb starting 12 nm away from the Si channel. The resulting band structure leads to a high mobility 2DES formed in a triangular potential at the heterojunction between the Si channel and the top SiGe barrier (electron concentration $n = 7.2 \times 10^{15}$ m^{-2}; mobility $\mu = 20$ m^2/V s). In order to perform transport experiments a 100-μm-wide Hall bar was patterned on the sample along the [100] direction.

In a magnetic field the energy level structure of the 2DES consists of discrete LLs at energies $E_N = (N + 1/2)(\hbar e B_n/m^*)$, where $N = 0, 1, 2, \ldots$ is the LL index, B_n is the field component perpendicular to the 2DES, and $m^* = 0.19 m_e$ is the effective electron mass in Si. Each LL is split into two spin levels, $E_{N,s} = E_N \pm \frac{1}{2} g^* \mu_B B$. Here $s = \uparrow/\downarrow$ denotes the spin orientation, g^* is the effective Landé factor, and B is the *total* magnetic field. Additionally, each spin level consists of two distinct valleys [10] resolved as individual levels in transport experiments in Si/SiGe heterostructures [11,12].

With a magnetic field oriented perpendicular to the 2DES the longitudinal resistance ρ_{xx} displays SdH oscillations, see Fig. 1a, bottom trace, where ρ_{xx} is plotted as a function of the LL filling factor $\nu = hn/eB_n$, where B_n is the normal field component with respect to the orientation of the 2DES. The SdH oscillations are characterized by pronounced minima at filling factors $\nu = 4(N + 1) = 4, 8, 12, 16$, etc. Here the Fermi level E_F is situated inside the gap between two neighboring LLs N and $N + 1$. Additional minima occur at $\nu = 2 + 4N = 2, 6, 10, 14, 18$, etc. when E_F is positioned between the two spin-split sublevels inside a LL N. For the two lowest LLs $N = 0$ and $N = 1$ also the valley splitting is resolved visible as minima at $\nu = 3, 5, 7,$ and 9.

Before analyzing the results further we will shortly introduce the coincidence technique [13] used in our experiments; more details are given in [14]. Its main idea is based on the possibility of modifying the LL structure of a 2DES in a perpendicular magnetic field B_n by adding an additional in-plane field B_{ip}. For simplicity we will first not consider valley splitting in the following description.

In our Si/SiGe structure the spin splitting with $B_{ip} = 0$ is about one-third of the LL splitting. Adding B_{ip} with B_n
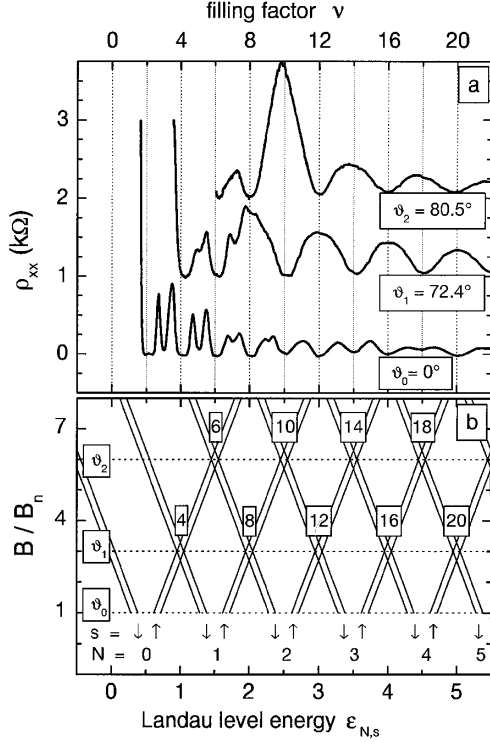
FIG. 1. (a) Resistivity ρ_{xx} as a function of the filling factor ν for tilt angles $\vartheta_0 = 0°$, $\vartheta_1 = 72.4°$ (first-order coincidence), and $\vartheta = 80.5°$ (second-order coincidence). (b) Landau-level structure at constant normal field B_n as a function of the total magnetic field B (in units of B_n). The numbers indicate the even integer filling factors where coincidences occur. At the horizontal line marked ϑ_0 the magnetic field is oriented perpendicular to the 2DES; the lines marked ϑ_1 and ϑ_2 sketch the angle positions where the first- and second-order coincidences are found.

constant increases the spin splitting $\Delta E_Z = g^* \mu_B B$ between two levels $(N, \uparrow)$ and $(N, \downarrow)$, which depends on the total magnetic field $B = (B_n^2 + B_{\mathrm{ip}}^2)^{1/2}$, while leaving the LL splitting constant. The resulting energy level structure is illustrated in Fig. 1b, where the LL energies $\epsilon_{N,s}$ (in units of $\hbar e B_n / m^*$, bottom axis) are plotted as a function of the total field B (normalized to B_n, left axis). The valley splitting of each level is marked as two parallel lines. Here we suppose a constant effective g-factor $g^* = 3.5$. In fact, g^* in Si/SiGe heterostructures is also dependent on the LL filling as well as on the strength of the in-plane field. For illustration purposes we do not take into account this complication; see [11,12,14].

As sketched in the figure, increasing B while leaving B_n constant leads to a relative increase of the spin splitting ΔE_Z compared to the LL splitting $\hbar \omega_c$. As soon as ΔE_Z equals $\hbar \omega_c$ two neighboring LLs with opposite spin, $(N + 1, \downarrow)$ and $(N, \uparrow)$, are situated at the same energy, they coincide. As a consequence, the Fermi energy at filling factors $\nu = 4(N + 1) = 4, 8, 12, 16, 20$, etc. is no more situated in a gap but inside these degenerate levels. The pronounced minima in ρ_{xx} at filling factors $\nu = 4(N + 1)$ change into maxima. This coincidence is found experimentally at a tilt angle $\vartheta = 72.4°$, see Fig. 1a, where SdH

maxima are found at filling factors $\nu = 8, 12, 16,$ and 20. No coincidence maximum is visible at $\nu = 4$. In fact, a very pronounced SdH maximum appears only in a very narrow angle range around $\vartheta_1^* = 70°$. This observation will be analyzed in more detail below.

Higher-order coincidences occur when the spin splitting equals an integer multiple of the LL splitting. In particular, the second-order coincidence is found experimentally at $\vartheta = 80.5°$ when $\Delta E_Z = 2\hbar \omega_c$. Now the $(N + 2, \downarrow)$ and the $(N, \uparrow)$ levels coincide at filling factors $\nu = 2 + 4(N + 1)$ etc. and maxima appear at $\nu = 10, 14, 16,$ and 22 in Fig. 1a. Again the expected coincidence at $\nu = 6$ is not visible in the data presented; see below.

As already stated above, the first-order coincidence at $\nu = 4$ was not observed in the traces in Fig. 1a. Therefore, we will analyze this range in more detail in the following. In Figs. 2a and 2b a color contour plot of ρ_{xx} is shown when moving through the coincidence, with some selected traces in Figs. 2c and 2d.

The most striking feature is the appearance of a strongly pronounced transport anisotropy as a function of the orientation of the in-plane field measured in the *same* Hall bar. The two orientations of the in-plane field, $B_{\mathrm{ip}} \parallel I$ and $B_{\mathrm{ip}} \perp I$ are sketched in the top part of Fig. 2. The anisotropy has been reproduced experimentally in several cooldown cycles of the sample and on different voltage contacts of the Hall bar.

Before the coincidence ($\vartheta = 68.5°$) the SdH oscillations of ρ_{xx} look similar for both orientations of B_{ip} with respect to the current direction; see bottom traces in Figs. 2c and 2d. The slight differences are most probably due to slightly different 2DES properties originating from different cooldown cycles. When moving towards the coincidence by increasing ϑ drastic differences start to appear. For $B_{\mathrm{ip}} \parallel I$ a huge maximum in ρ_{xx} develops reaching peak values of more than 13 kΩ at $\vartheta = 69.98°$.

Also for $B_{\mathrm{ip}} \perp I$ the coincidence shows its presence by the disappearance of the $\nu = 4$ minimum, but no unusual enhancement of ρ_{xx} is observed. In contrast, the magnitude of the SdH maximum inside the coincidence is with less than 1 kΩ even lower than the typical peak values of ρ_{xx} outside the coincidence.

Similar huge transport anisotropies with a strong enhancement of ρ_{xx} are observed when the spin-up level of the lowest LL is coinciding with a higher LL with opposite spin. Experimentally we find this behavior for the second-order coincidence at $\nu = 6$, where the $N = 0$ and the $N = 2$ LLs are coinciding, and indications for it for the third-order coincidence at $\nu = 8$ [15]. At all these positions huge in-plane fields $B_{\mathrm{ip}} > 20$ T are present.

As already shown in Fig. 1 no spectacular effects occur when only higher LLs are involved in the coincidence where the parallel field component is comparably lower. This statement also remains true for third- and higher-order coincidences not shown in the figure.

In order to investigate further the properties of the electron system for the first-order coincidence at $\nu = 4$ we
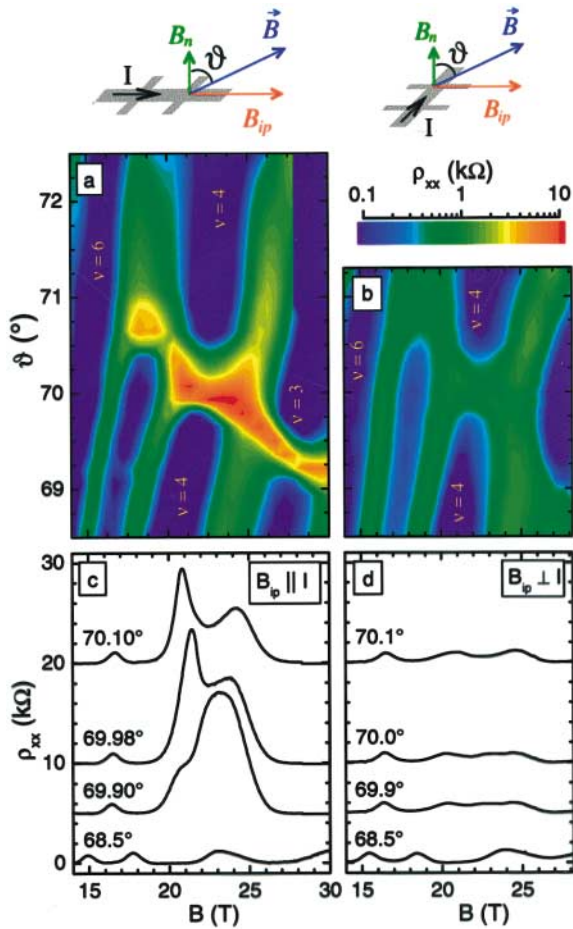
FIG. 2 (color).   Top: Orientation of the Hall bar in a tilted magnetic field for $B_{ip} \parallel I$ (left) and for $B_{ip} \perp I$ (right). Middle: Color contour plot of ρ_{xx} in the first-order coincidence around $\nu = 4$ on a logarithmic scale from $100 \, \Omega$ (blue) via $1 \, k\Omega$ (green) to $10 \, k\Omega$ (red). Values lower than $100 \, \Omega$ and missing values are violet; values higher than $100 \, k\Omega$ are dark red. In (a) the in-plane field B_{ip} is oriented along the current; in (b) B_{ip} is perpendicular to the current. Bottom: Selected traces of ρ_{xx} in the coincidence for the two orientations of the in-plane field. The curves are shifted for clarity.

FIG. 3.   Temperature dependence of ρ_{xx} in the first-order coincidence at $\nu = 4$. In (a) the in-plane field is parallel to the current; in (b) B_{ip} is perpendicular to I. The insets show the temperature dependence of the dominant SdH for both field orientations.

LL $(N, \uparrow)$ with the simultaneous filling of the initially empty LL $(N + 1, \downarrow)$. In the center of the coincidence two charge-degenerate LLs are half filled. The particularity of this half filling points to possible similarities with recent experiments concerning a *single half-filled* higher LL in very high mobility GaAs/GaAlAs structures [4–7].

Considering that the mobility of these GaAs-based 2DESs is nearly 2 orders of magnitude higher than in our Si/SiGe structures it is at first sight rather astonishing that we observe any stripe phases at all. However, the additional valley splitting in Si/SiGe structures leads to a much more complex phase diagram as compared to GaAs. In this respect it is interesting to state that the typical size of the valley splitting is comparable to the disorder broadening of an individual valley- and spin-split LL. Therefore, the presence of two valleys may well stabilize a possibly existing stripe phase with respect to disorder.

In the most simple picture the proposed stripe phase would consist of stripes with alternating spin orientation. However, without considering valley splitting in detail, such a charge-homogeneous spin-density phase was shown to be unstable with respect to a first-order phase transition into a ferromagnetic state [16,17]. Evidence for such a transition was indeed found experimentally in a GaInAs/InP heterostructure [18]. We stress that this prediction does not exclude a stable charge-inhomogeneous state. Since the spin and orbital degrees of freedom are rigidly coupled to each other, both charge-density wave and spin-density wave order parameters are finite in this type of ground state. Preliminary theoretical considerations suggest that the charge-inhomogeneous Hartree-Fock state in a half-filled higher LL may survive the addition of electrons from the half-filled LL below [19].

From the temperature dependence shown in Fig. 3 we can estimate the typical correlation energy for our proposed stripe phase to be on the order of 0.1 meV. In this respect a stripe phase would be energetically favorable if the energy separation of the two Landau levels involved in the coincidence is smaller than the correlation energy. At low temperatures where the stripes are formed transport

have performed temperature dependent experiments for the two orientations of the in-plane fields shown in Fig. 3. In the insets the temperature dependence of the dominant SdH peak in the center of the coincidence is displayed. The strongly enhanced maxima in ρ_{xx} for the first-order coincidence at $\nu = 4$ with $B_{ip} \parallel I$ disappears for temperatures larger than 1 K. With $B_{ip} \perp I$ the suppression of ρ_{xx} weakens in the same temperature range. Now ρ_{xx} approximately doubles its value when the temperature is increased from 0.45 K to above 1 K; see Fig. 3b.

In order to explain our experimental findings we propose that during the coincidence, where the huge anisotropy appears, a unidirectional stripe phase oriented perpendicular to the in-plane field is formed. In such a picture transport along the stripes would be facilitated and transport across the stripes would be obstructed.

We suggest that the effects observed are caused by the successive depopulation of an initially totally filled
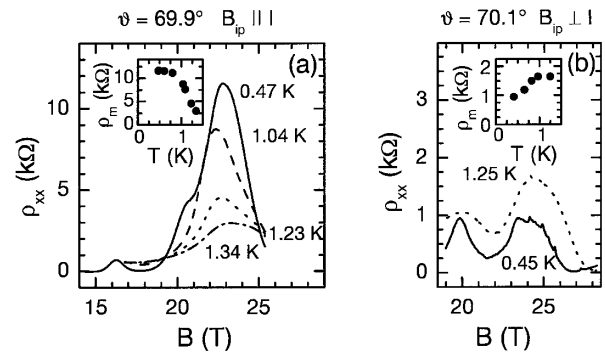
across the stripes is obstructed and as a consequence the resistance increases drastically with decreasing temperature as soon as the stripe phase starts to form. Transport along the stripes would be facilitated compared to a homogeneous electron distribution; the resistance decreases with decreasing temperature.

The correlation energy for a stripe formation can be deduced independently from the narrow angle range where the coincidence between the two levels $(0, \uparrow)$ and $(1, \downarrow)$ appears, approximately $\pm 0.3°$ around $\vartheta_1^* = 70°$. At a constant filling factor $\nu = 4$ (corresponding to a normal field $B_n = 7.5$ T) the energy separation of the two levels, $\Delta E = E_{0,\uparrow} - E_{1,\downarrow}$, changes from -0.07 to $+0.07$ meV in a single particle picture. Here $\Delta E = g^* \mu_B B_n (1/\cos\vartheta - 1/\cos\vartheta_1^*)$ is defined by the relative change of the Zeeman energy of the two levels. $g^* = 2(m/m^*)\cos\vartheta_1^* = 3.6$ is the effective g-factor at $\nu = 4$ deduced from the position of the first-order coincidence at $\vartheta_1^* = 70°$. In other words, correlations between the levels become important as soon as their energetic separation gets below the correlation energy.

Since the energy gain for forming our proposed stripe phase is of the order of the typical valley splitting [11,12] it is worthwhile speculating that the stripes are due to a redistribution of electrons between different pockets in k space (i.e., different valleys) and the interaction between these valleys during the coincidence. Without any doubt a detailed theoretical consideration of the complex energy-level structure including valley splitting is necessary to indicate more clearly the existence of stripe phases in Si/SiGe heterostructures.

The proposed stripe formation might be supported by a geometrical modulation of the Si quantum well and the adjacent SiGe barriers. The linearly graded relaxed buffer is known to relax by long misfit dislocations distributed over the whole thickness of the graded buffer part [20]. Each dislocation creates a double atomic height step on the surface; dislocation multiplication can lead to a pileup of these surface steps. This is the origin of the crosshatch surface morphology, which is oriented along the [110] direction, as are the misfit dislocations. Preferential growth on surface steps smears out the surface steps, which leads to a smoothly varying modulation of ± 2 nm with an average period of 1.3 μm for the crosshatch (measured with an atomic-force microscope on the surface of the heterostructure).

This surface morphology can be viewed as a slight modulation of the orientation of the 2DES. A strong in-plane field will then lead to a modulated tilting angle along B_{ip}. As a consequence stripes perpendicular to B_{ip} will form where the energetically lower lying LL is either the $(N, \uparrow)$ level or the $(N + 1, \downarrow)$ level. However, we point out that the period of these stripes of more than 1 μm would be far too large to explain the temperature dependence and the magnitude of the SdH maxima in a simple sequential tunneling model. Therefore, it seems very improbable that the crosshatched surface morphology is the major cause for the experimentally observed transport anisotropies.

In conclusion, we have observed strong anisotropies induced by an in-plane field in the magnetotransport properties of coinciding Landau levels in the 2DES of a Si/SiGe heterostructure. We propose that they are caused by the formation of a unidirectional stripe phase formed by electrons from two Landau levels with opposite spin. From temperature dependent experiments we deduced a typical correlation energy on the order of 0.1 meV for the formation of the stripe phase.

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