

Highly anisotropic transport in the integer quantum Hall effect

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At very large tilt of the magnetic (B) field with respect to the plane of a two-dimensional electron system the transport in the integer quantum Hall regime at $\nu=4, 6,$ and 8 becomes strongly anisotropic when two electrical subbands are occupied. At these filling factors the usual *deep minima* in the magnetoresistance occur for the current flowing *perpendicular* to the in-plane B field direction but develop into *strong maxima* for the current flowing *parallel* to the in-plane B field. The origin of this anisotropy is unknown but resembles the recently observed anisotropy at half-filled Landau levels.

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Strongly correlated electronic systems often exhibit stripe phases.¹ In two-dimensional electron systems (2DES) such a stripe phase is believed to be at the origin of the recently observed electronic transport anisotropy at half-fillings of high Landau levels.^{2–8} In a purely perpendicular magnetic field (B) the direction of this anisotropy is pinned to the crystal lattice,^{3,4} but reorients itself when an in-plane B field (B_{ip}) is added by tilting the sample. At large B_{ip} the easy axis of anisotropy in the plane of the sample (the direction of minimum resistance) is *always* perpendicular to B_{ip} .^{5,6} Although the nature of this anisotropy remains uncertain, experimental data^{2–8} and theoretical models^{9–22} point to the formation of a unidirectional charge-density wave, often referred to as the “stripe phase,” or to a state akin to a liquid-crystal phase.¹¹

In this paper, we present data that show strong electronic transport anisotropies at *fully filled* Landau levels. The sample is an $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ quantum well with two occupied electrical subbands. The anisotropies are created by very strong in-plane B fields at very large tilt in the regime of the integer quantum Hall effect (IQHE) at $\nu=4, 6,$ and 8 . An earlier observation by Zeitler *et al.*²³ detected anisotropies in the Si/GeSi system, having a complex band structure as compared to our quantum well. The origin of all these anisotropies is unknown, although, phenomenologically, they resemble the anisotropies at half-filled Landau levels. A striped spin-density wave phase may be at the origin of our observations.

Our sample consists of a 350-Å wide GaAs quantum well embedded into $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ and δ -doped from both sides at a distance of 490 Å. The specimen has a size of 5 mm \times 5 mm and is contacted via eight indium contacts placed symmetrically around the perimeter. The electron density is

established after illuminating the sample with a red light-emitting diode at ~ 4.2 K and, within limits, the density can be tuned by exposure time. At an electron density of $n=4.2 \times 10^{11} \text{ cm}^{-2}$ two electrical subbands are populated having densities $n_0 \sim 3.1 \times 10^{11} \text{ cm}^{-2}$ and $n_1 \sim 1.1 \times 10^{11} \text{ cm}^{-2}$ as determined by the Fourier analysis of the low-field Shubnikov–de Haas oscillations. All angular-dependent measurements are carried out in a dilution refrigerator equipped with an *in situ* rotator placed inside a 33-T resistive magnet. We define the axis of rotation as the y axis. Consequently, the in-plane field B_{ip} extends along the x axis when the sample is rotated.

We have measured R_{xx} and R_{yy} , which differ only in the in-plane current direction, at more than 10 tilt angles (θ) between 0° and 90° . R_{xx} represents the direction for which, under tilt, the current runs along B_{ip} . Figure 1 shows data at five selected angles, from $\theta=81.1^\circ$ to 84.4° . At $\theta=0^\circ$ (not shown) both R_{xx} and R_{yy} vanish at $\nu=6$ as expected for an isotropic quantum Hall state. As θ is increased towards 81.1° , both R_{xx} and R_{yy} remain vanishingly small at $\nu=6$, although the widths of the resistance minima and of the Hall plateau shrink with increasing θ . Very generally, such an angular dependence is readily understood for the spin-unpolarized $\nu=6$ state. While the $\nu=6$ state always occurs at the same perpendicular magnetic field B_{perp} , the total magnetic field at tilt angle, θ , increases as $B_{tot}=B_{perp}/\cos(\theta)$. Since the electron spin experiences B_{tot} , the Zeeman splitting of all Landau levels increases with increasing θ . This leads to a reduction of the energy gap at $\nu=6$ and a shrinking width and depth (not visible on the linear scale of Fig. 1) of the R_{xx} and R_{yy} minima. Eventually, this leads to a collapse and disappearance of the $\nu=6$ IQHE state. Indeed, at $\theta=83.3^\circ$, R_{xx} has turned from a deep minimum into a

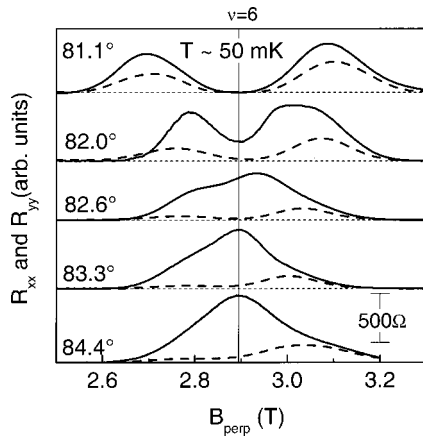


FIG. 1. R_{xx} (solid lines) and R_{yy} (dashed lines) around $\nu=6$ at $T \sim 50$ mK, $I = 10$ nA and for five tilt angles, from $\theta = 81.1^\circ$ to $\theta = 84.4^\circ$. For R_{xx} the current runs along the in-plane magnetic field. $n = 4.2 \times 10^{11} \text{ cm}^{-2}$.

strong peak and the usual Hall plateau has vanished. Therefore, the disappearance of R_{xx} can be rationalized as the closing of the $\nu=6$ energy gap. However, very surprisingly, the electrical transport turns out to be *strongly anisotropic*. In contrast to R_{xx} , which shows a strong *maximum* at this angle and filling factor, R_{yy} continues to show a strong *minimum* at $\nu=6$. Just as in the case of half-fillings^{5,6} the easy axis of this anisotropy at full-filling factors is perpendicular to B_{ip} . The direction of anisotropy is not dependent on the orientation of the crystallographic axis with respect to the in-plane field, as we determined by performing the same experiments on the same specimen mounted in a configuration rotated by 90° about the sample normal. Furthermore, none of the resistance measurements showed any hysteresis as a function of the sweep direction of the B field. Finally, in the anisotropic regime, the generally strong Hall plateau at $\nu=6$ disappears for both directions of current.

This is the first time, to the best of our knowledge, that such an anisotropy has been observed in a state as robust as an IQHE state. To learn more about this anisotropic state we perform T -dependent studies of R_{xx} and R_{yy} . For comparisons, we choose $\theta = 81.1^\circ$, where the electronic transport is isotropic, and $\theta = 83.3^\circ$, where transport is strongly anisotropic. In Figs. 2(a) and 2(b) we show three representative traces of R_{xx} and R_{yy} . At $\theta = 81.1^\circ$, R_{xx} and R_{yy} exhibit the usual activated behavior: the value of both resistances increases with increasing T . On the other hand, at $\theta = 83.3^\circ$, R_{xx} and R_{yy} behave oppositely: R_{xx} decreases whereas R_{yy} increases with increasing T . The T dependencies are quantified in Figs. 2(c) and 2(b), where R_{xx} and R_{yy} are shown on Arrhenius plots. At $\theta = 81.1^\circ$, R_{xx} and R_{yy} show well-behaved activated behavior yielding a single energy gap of $\Delta \sim 1$ K for both current directions.²⁴ On the other hand, the data for R_{xx} and R_{yy} at $\theta = 83.3^\circ$ show no longer activated behavior. R_{xx} and R_{yy} appear to start from similar values at high temperature but then diverge from each other roughly exponentially with exponents of similar magnitude but *opposite sign*. At the lowest temperatures both resistances assume an approximately T -independent behavior. This dependence

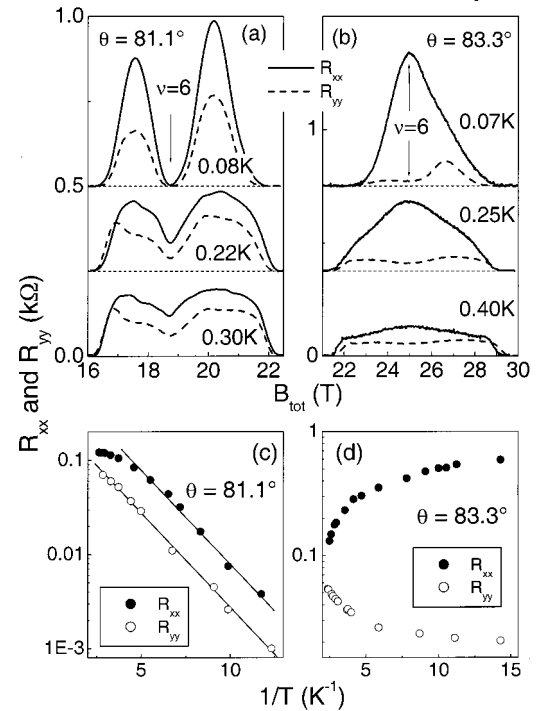


FIG. 2. Panels (a) and (b): Temperature dependence of R_{xx} (solid lines) and R_{yy} (dashed lines) at tilt angles $\theta = 81.1^\circ$ (a) and 83.3° (b) and three different temperatures each. Traces are shifted vertically for clarity. The position of the $\nu=6$ filling factor is indicated. Panels (c) and (d): corresponding Arrhenius plots for R_{xx} and R_{yy} at $\nu=6$ at the tilt angles of the panels above. The straight lines in panel (c) are a linear fit to the data (Ref. 24). The energy gap is ~ 1 K for R_{xx} and R_{yy} .

is qualitatively the same as the T dependence of the anisotropic state at $\nu=9/2$.^{4,17}

The remarkable anisotropy found in the IQHE is not limited to the $\nu=6$ state. Similar anisotropies are observed at filling factors $\nu=4$ and 8 . Figure 3 shows the $\nu=8$ and 4 anisotropy in the same sample at slightly different densities, tuned by applying different doses of light. We have not performed a systematic study of these states.

The cause of the anisotropy at integral quantum Hall states is unknown. Before speculating about the origin of this new phenomenon it is instructive to consider in more detail the single particle states in this two-electric subband specimen. Figure 4(a) shows the usual Landau fan diagram for a density of $4.2 \times 10^{11} \text{ cm}^{-2}$. The Zeeman splitting is enhanced by a factor of 10 to be visible. The position of the Fermi level, E_F , is indicated by a heavy line. Clearly, in the vicinity of $\nu=4, 6$, and 8 , Landau levels from both electric subbands contribute and E_F jumps between levels of different origin. Using such a simple single-particle picture and a 2DES of zero thickness with densities appropriate for the data of Figs. 1 and 3, one would expect the gaps at $\nu=4, 6$, and 8 to close at $\theta = 83.4^\circ, 88.4^\circ$, and 88.3° , respectively. These values differ from experiment, especially in the case of the $\nu=6$ and $\nu=8$ states.

The discrepancy is largely the result of the neglect of exchange and of the thickness of the wave function. In the

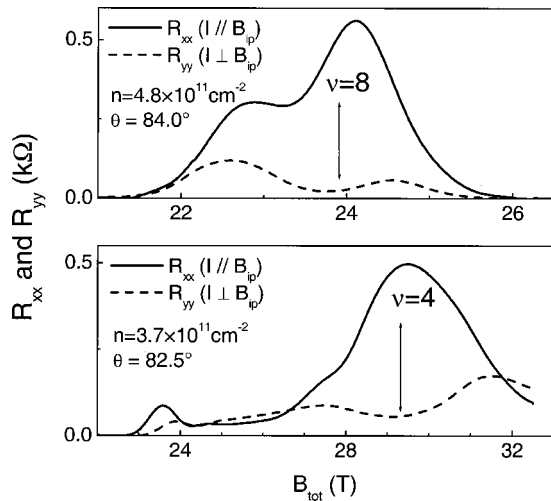


FIG. 3. (a) Anisotropic transport around $\nu=8$ at $\theta=84.0^\circ$. (b) Anisotropic transport around $\nu=4$ at $\theta=82.5^\circ$. The sample densities are slightly different from Fig. 1 and have been adjusted by different light exposure. For R_{xx} the current runs along the in-plane magnetic field.

remainder we focus on the state at $\nu=6$, which we studied most extensively and which shows the strongest anisotropy in experiment. We expect similar arguments to hold for $\nu=4$ and 8. Figure 4(b) shows the result of a self-consistent local-density-approximation calculation²⁵ performed for a density $n=4.2 \times 10^{11} \text{ cm}^{-2}$ at the filling factor $\nu=6$ as a function of B_{ip} . The gap at $\nu=6$ (shaded region) undergoes strong variations, comes almost to a close at $B_{ip} \sim 2.5 \text{ T}$ (not shown), and vanishes at $B_{ip} \sim 18.5 \text{ T}$ due to level crossing. The experimental value of B_{ip} for the strong anisotropy is $\sim 25 \text{ T}$. However, we consider the theoretical result of $\sim 18.5 \text{ T}$ to be sufficiently close to $\sim 25 \text{ T}$ to attribute the disappearance of the energy gap at $\nu=6$ in Fig. 1 to the crossing of spin-split Landau levels originating from different electrical subbands ($i=1,2$). This provides a rationale for the appearance of features in the data at this filling factor and angle. However, none of such level crossing considerations can explain the observed *anisotropy*, which represents the remarkable finding in our data. The origin of this phenomenon must be the result of correlated electron behavior.

Previously, large electrical anisotropies have only been observed at half-filled Landau levels.²⁻⁸ It is believed that there the electron system spontaneously breaks into striped domains of alternating filling factors such as $\nu=4$ and 5 around $\nu=9/2$.⁹⁻²¹ Given the similarity of the observed properties of the anisotropic phases around $\nu=9/2$ and 6 one might speculate on a similar underlying striped geometry. The driving force behind the phase separation in the $\nu=9/2$ case is exchange. The energetic gain from breaking into domains of $\nu=4$ and 5 is counteracted by a strong electrostatic cost for creating an inhomogeneous charge distribution. This is the reason for the formation of very narrow stripes of $\nu=4$ and 5 states, which are only a few magnetic lengths wide. A phase, consisting of stripes around $\nu=6$, would carry a much smaller, electrostatic burden.

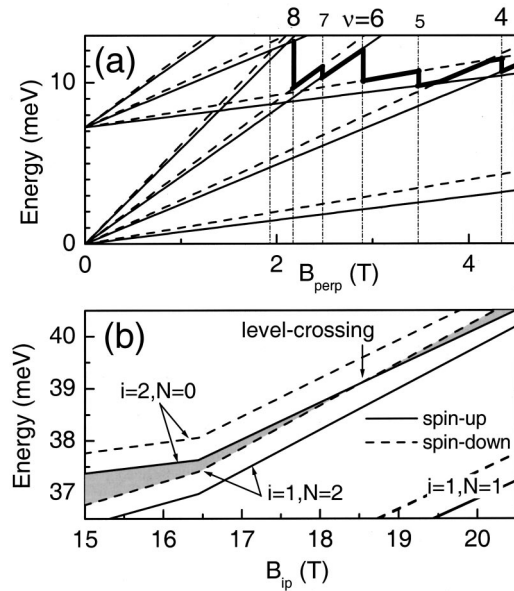


FIG. 4. Panel (a): Simple Landau fan diagram for the two-electric subband sample of density $n=4.2 \times 10^{11} \text{ cm}^{-2}$. The Zeeman splitting is enhanced by a factor of 10 to be visible. The position of the Fermi level is indicated by heavy line. Panel (b): Result of self-consistent local-density-approximation calculation (Ref. 25) at $\nu=6$ and as a function of in-plane magnetic field, B_{ip} , at the same density as panel (a). The electric subband index i and the Landau level index N are indicated. The shaded area represents the gap at $\nu=6$.

At the point of collapse of the $\nu=6$ energy gap in Fig. 4(b) two electronic configurations are degenerate. At B_{ip} smaller than the level crossing in Fig. 4(b) the electrons occupy three spin-unpolarized levels emanating from the lowest three Landau levels ($N=0, 1$, and 2) of the lower electronic subband, $i=1$.²⁶ (Note, an earlier anticrossing at $B_{ip} \sim 2.5 \text{ T}$ exchanges states $i=1, N=2$ and $i=2, N=0$.) The total system is spin unpolarized (3 spin-up, 3 spin-down). At B_{ip} larger than the level crossing in Fig. 4(b) the electrons occupy only two spin-unpolarized levels emanating from the lowest two Landau levels ($N=0,1$) of the lower electronic subband ($i=1$). In addition, they occupy the spin-up states (solid lines) of two levels emanating from the $i=1, N=2$ and the $i=2, N=0$ states. There, the total system is *partially spin polarized* (4 spin-up, 2 spin-down). In the vicinity of the level crossing in Fig. 4(b), a phase separation of the electronic system²⁷⁻²⁹ into spin-unpolarized and partially spin-polarized domains may occur driven by exchange. A very small gain in exchange energy may suffice, since the charge density in both configurations is identical and, to first order, there is no associated electrostatic cost.

Such a pattern resembles the pattern of a spin-density wave. The existence of an in-plane magnetic field and the so-induced coupling of spin and orbital motion will energetically favor a given orientation of the stripes with respect to B_{ip} . The resulting stripe phase of alternating IQHE configurations is bound to have one-dimensional edge states along its interface between neighboring domains, which carry the

electric current in a highly anisotropic fashion. This transport pattern would be analogous to the pattern invoked in the stripe phases that are believed to form at half-fillings of Landau levels, such as $\nu=9/2$ and $13/2$ and believed to be responsible for the anisotropic electronic behavior. However, without the application of other experimental techniques and without a detailed theoretical investigation this picture remains speculative.

In summary, we have observed strongly anisotropic transport under high in-plane magnetic field in the regime of the IQHE in a quantum-well sample with two occupied electrical subbands. Phenomenologically, the data have much in common with the previously discovered anisotropy at half-fillings of high Landau levels. From a simple level crossing

picture we conjecture that a striped spin-density wave may be at the origin of this phenomenon.

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