Impact of Spin-Orbit Coupling on Quantum Hall Nematic Phases

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Anisotropic charge transport is observed in a two-dimensional (2D) hole system in a perpendicular magnetic field at filling factors $\nu = 7/2$, $\nu = 11/2$, and $\nu = 13/2$ at low temperature. In stark contrast, the transport at $\nu = 9/2$ is *isotropic* for all temperatures. Isotropic hole transport at $\nu = 7/2$ is restored for sufficiently low 2D densities or an asymmetric confining potential. The density and symmetry dependences of the observed anisotropies suggest that strong spin-orbit coupling in the hole system contributes to the unusual transport behavior.

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Presently, the study of the properties of half-filled Landau levels of clean two-dimensional (2D) systems is the focus of intense research. In 2D *electron* systems (2DESs) at half filling, a surprisingly diverse set of ground states has been uncovered. In the $N = 0$ Landau level (LL), at $\nu = 1/2$ and $\nu = 3/2$, compressible composite-fermion Fermi liquid states are observed [1,2]. Here $\nu = hcn/eB$ is the filling factor, with B the magnetic field and n the carrier density. In the $N = 1$ Landau level, dc transport measurements have convincingly demonstrated the presence of incompressible quantized Hall states at $\nu = 5/2$ and $\nu = 7/2$ [3–5]. At half filling in the $2 \leq N \lesssim 5$ Landau levels, electronic transport is anisotropic [6,7] and is consistent with either a quantum smectic or a nematic phase (i.e., a "striped" phase) [8]. While it is clear that all of these phenomena derive from strong electron-electron interactions, the exact relationship between the different ground states possible in half-filled LLs and the sample parameters necessary to stabilize one phase over another remain interesting experimental questions [9–11]. Access to a greater range of sample parameters than is currently available in high mobility 2DESs may enhance our understanding of these exotic states.

Transport studies of high mobility 2D *hole* systems (2DHSs) in GaAs offer a complimentary approach to the investigation of correlation physics in 2D systems [12]. The larger effective mass of holes ($m_h \sim 0.5$ vs $m_e \sim 0.067$, in units of the free electron mass) reduces kinetic energy such that interactions play a more prominent role at a given 2D density. In addition, 2DHSs offer a ideal platform to study the impact of spin-orbit coupling on half-filled Landau levels since spin-orbit coupling can significantly alter the ground state through mixing of the light and heavy hole states [13].

In this Letter we detail the impact of strong spin-orbit coupling on quantum Hall nematic phases. We present low temperature magnetotransport measurements of a series of extremely high mobility, carbon-doped 2DHSs grown on the high symmetry (100) surface of GaAs. At $T \sim 15$ mK we observe a pronounced anisotropy in transport at filling factors $\nu = 7/2$, $\nu = 11/2$, and $\nu = 13/2$ while the transport at $\nu = 9/2$ remains *isotropic*. The resistance at $\nu = 7/2$ in the $[01\bar{1}]$ direction exceeds the resistance in the [011] direction by a factor of $\sim 10^4$ [14]. The observed transport anisotropies are extremely sensitive to temperature. Isotropic transport is restored for temperatures greater than $T \sim 130$ mK. Furthermore, isotropic transport at $\nu = 7/2$ can also be restored by reducing the density of the 2DHS in a quantum well or by changing the symmetry of the potential confining the 2DHS at a constant 2D density. Our results for a 2D hole system differ substantially from 2D electron transport where an isotropic fractional quantum Hall state is observed at $\nu = 7/2$ and the strongest anisotropy occurs at $\nu = 9/2$.

Square samples (4 mm by 4 mm) from a total of 4 separate wafers were examined in this study. All samples are grown on the (100) surface of GaAs by molecular beam epitaxy [15]. The sample parameters are detailed in Table I. Samples A, B, and C are 20 nm wide, symmetrically doped, GaAs/AlGaAs quantum wells. The samples have a fixed setback of 80 nm, and the Al mole fraction of the barrier is varied to control the density. Sample D is a single heterojunction. The mobility of sample A reaches 2×10^6 cm^2/Vs at low temperature, which combined with a large effective mass in these samples ($m_h \sim 0.54$) [16] attests to the unprecedented quality of these newly developed structures. Equally important, the zero field mobility anisotropy for these (100) structures is $\lesssim$20% [15]. This residual anisotropy is also typical in high mobility 2DESs. Transport is measured in two separate dilution refrigerators

TABLE I. Sample parameters of the 4 carbon-doped (100) 2DHSs studied in this work. p is the 2D density and μ is the mobility. QW indicates a quantum well, while SHJ indicates a single heterojunction.

Sample	p (10^{11} cm^{-2})	μ (10^6 cm^2/Vs)	Structure
A	1.2	2.0	20 nm QW
B	2.0	1.5	20 nm QW
C	2.3	1.3	20 nm QW
D	2.3	0.8	SHJ

that reach base temperatures of $T \sim 45$ mK and $T \sim 15$ mK. Standard low frequency lock-in techniques with excitation currents ≤ 10 nA are used to monitor the resistance.

Figure 1 presents an overview of transport in sample C, for filling factors $\nu \geq 2$ at $T \sim 15$ mK along the [011] and $[01\bar{1}]$ directions. We note that the resistances along [011] and $[01\bar{1}]$ have *not* been scaled to have equal amplitude at low magnetic field. Starting from the low field regime, the resistance becomes clearly anisotropic at $\nu = 13/2$ and $\nu = 11/2$, with weaker features visible at $\nu = 15/2$ and $\nu = 17/2$. In sharp contrast, the resistance is isotropic at $\nu = 9/2$. At $\nu = 7/2$ the resistance again becomes highly anisotropic. No indication of a quantized Hall state in R_{xy} is present at $\nu = 7/2$ (not shown). Moreover, the resistance ratio $R_{[01\bar{1}]}/R_{[011]}$ reaches $\sim 10^4$ at $\nu = 7/2$. This behavior is strongly reminiscent of the anisotropic transport first seen in 2D electron systems at half filling, but only at $\nu \geq 9/2$ in the $N \geq 2$ LLs. The appearance of such highly anisotropic transport has been interpreted as evidence for the formation of a unidirectional charge density wave (i.e., striped) phase or nematic liquid crystal-like phase in 2D electron systems [8]. The data of Fig. 1 suggest that similar physics may be active in our hole system at $\nu = 7/2$, $\nu = 11/2$, and $\nu = 13/2$. While we have not yet systematically studied $\nu = 5/2$, it shows no strong anisotropy in this sample. The temperature evolution of the magnetotransport for filling factor $\nu = 7/2$ for sample C is shown in Fig. 2. At $T = 130$ mK, the resistance is nearly isotropic. Upon reducing the temperature below $T = 80$ mK, the anisotropy at $\nu = 7/2$ develops rapidly in a manner similar to that seen in 2D electron systems at $\nu = 9/2$ [6,7].

To date, only one other study has been dedicated to the investigation of half-filled Landau levels in 2DHSs. Shayegan *et al.* [17] have reported intriguing anisotropic transport at half filling for 2DHSs grown on the (311)A orientation, but the exploration of anisotropic behavior in excited hole Landau levels of (311)A samples has been hindered by the presence of a significant transport anisotropy at zero magnetic field [18]. The data of Fig. 1 unambiguously demonstrate that 2DHSs grown on the (100) orientation of GaAs can display a novel sequence of isotropic or anisotropic states at half filling while maintaining isotropic behavior at zero magnetic field.

The observation of isotropic transport for 2D holes at $\nu = 9/2$ flanked by strongly anisotropic transport at $\nu = 11/2$ and $\nu = 7/2$ in sample C is the most striking feature of this study. In 2D electron systems that display anisotropic transport, the anisotropy resides only in the $N \geq 2$ LLs and also shows the largest resistance ratio at $\nu = 9/2$. Although 2D electron systems do not exhibit anisotropic transport in the $N = 1$ Landau level at $\nu = 5/2$ and $\nu = 7/2$ in a perpendicular magnetic field, Lilly *et al.* [9] and Pan *et al.* [10] have observed that the incompressible quantum Hall states at $\nu = 7/2$ and $\nu = 5/2$ are replaced by compressible anisotropic states under the application of large in-plane magnetic fields. These results suggest that the physics influencing the formation of compressible striped phases in the $N \geq 2$ LLs may be active in the $N = 1$ LL under the appropriate change of the effective interaction induced by the large in-plane field. In numerical studies, Rezayi and Haldane [11] have shown that the incompressible quantum Hall state at $\nu = 5/2$ is near a phase transition into a compressible striped phase. Similar behavior may be expected at $\nu = 7/2$. In the pseudo-

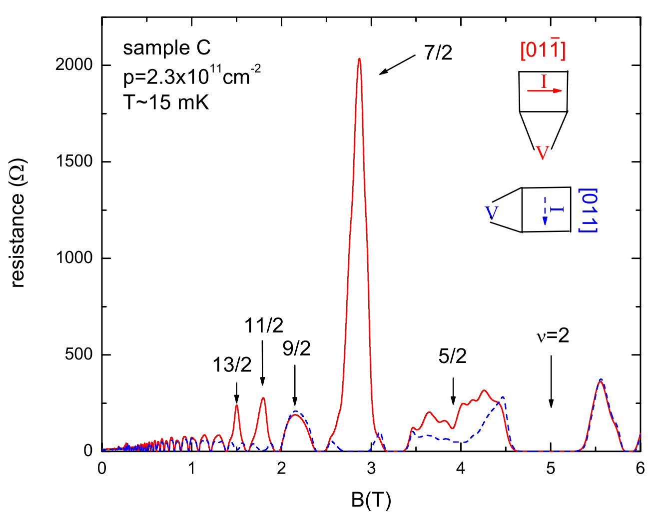

FIG. 1 (color online). Overview of magnetoresistance in sample C with $p = 2.3 \times 10^{11}$ cm^{-2} at $T \sim 15$ mK. The dashed trace is measured with current flowing in the [011] direction. The solid trace corresponds to the magnetoresistance with the current flowing in the $[01\bar{1}]$ direction. The transport is anisotropic at $\nu = 7/2$, $\nu = 11/2$, and $\nu = 13/2$ but remains isotropic at $\nu = 9/2$.

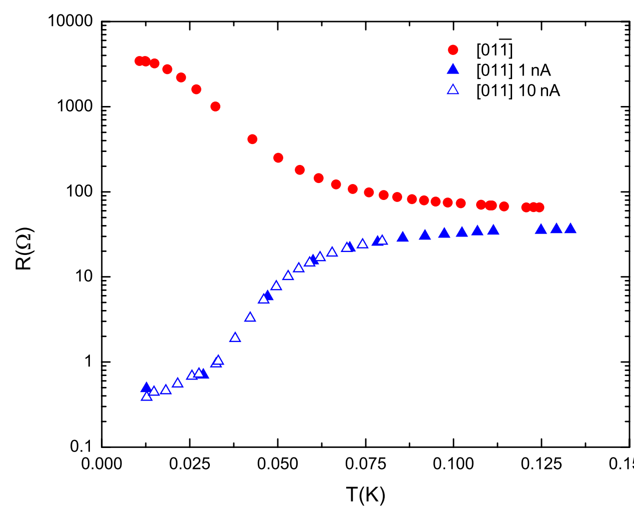

FIG. 2 (color online). Magnetoresistance along $[01\bar{1}]$ (solid circles) and [011] (open and solid triangles) directions as a function of temperature for sample C at $\nu = 7/2$. Along the $[01\bar{1}]$ direction, a 1 nA excitation is used. Along the [011] direction, the resistance is measured with 1 nA (solid triangles) and 10 nA (open triangles) excitations.

potential formulation of the fractional quantum Hall effect [19], the nature of the ground state is found to depend sensitively on the relative strengths of the pseudopotential parameters V_1 and V_3, where V_m is the energy of a pair of electrons in a state of relative angular momentum m. Rezayi and Haldane find that at $\nu = 5/2$ small variations in V_1 and V_3 can drive the phase transition and suggest that the proximity of the critical point to the Coulomb potential is the principle reason that transport becomes anisotropic in the tilting experiments.

What distinguishes our 2D hole system from the 2D electron system such that the fractional quantum Hall state at $\nu = 7/2$ is destabilized and replaced by a compressible anisotropic state and the transport at $\nu = 9/2$ remains isotropic rather than displaying the anisotropy seen in electron systems? We suggest that the strong spin-orbit coupling in the 2DHS is a critical difference. Spin-orbit coupling strongly mixes valence band states, which alters the orbital structure of hole Landau levels at $B \neq 0$ [20,21]. The nature of the single particle wave functions that comprise a given LL alters the pseudopotential parameters, significantly influencing the correlations among the holes [22,23]. Following Ref. [23], we have self-consistently calculated the Landau level structure in the Hartree approximation (while keeping axial terms as in [20]). The energy level and orbital structure of the valence LLs appropriate to our samples are, not surprisingly, quite complex, but agree at least qualitatively with many of our observations. For sample C, at $\nu = 7/2$, the valence LL is a mixture of primarily the $N = 2$, $N = 4$, and $N = 5$ orbitals, which results in a hole-hole interaction potential consistent with a striped phase. At $\nu = 9/2$, the valence LL is a mixture of $N = 1$, $N = 2$, and $N = 3$. The $N = 1$ LL contributes 30% to the wave function, while the $N = 2$ and $N = 3$ LLs contribute a total of 50%. As the data of Fig. 1 show, the inclusion of the $N = 1$ LL appears to drive $\nu = 9/2$ into an isotropic state.

In order to further understand the impact of spin-orbit coupling on anisotropic transport in hole systems we have examined a series of 20 nm symmetrically doped quantum wells with differing densities. Figure 3 summarizes the density dependence of the anisotropic transport at $\nu = 7/2$ and $T \sim 50$ mK. In sample A, the transport is isotropic. With an increase in the density to 2.0×10^{11} cm^{-2} in sample B, a nascent anisotropy is visible, but $R_{[01\bar{1}]}/R_{[011]}$ reaches only ~ 2 at $\nu = 7/2$. We note that while the amplitude of anisotropy in sample B is small, it displays temperature dependence for $50 \text{ mK} \leq T \leq 150$ mK similar to that observed in sample C (see Fig. 2). At a density of 2.3×10^{11} cm^{-2} in sample C, the anisotropy becomes more pronounced, with a resistance ratio of about 10. The data of Fig. 3 show that the ground state at $\nu = 7/2$ can undergo an isotropic-to-anisotropic transition as a function of increasing density in 20 nm quantum wells. This density driven transition can also be qualitatively understood. Our calculations indicated that as

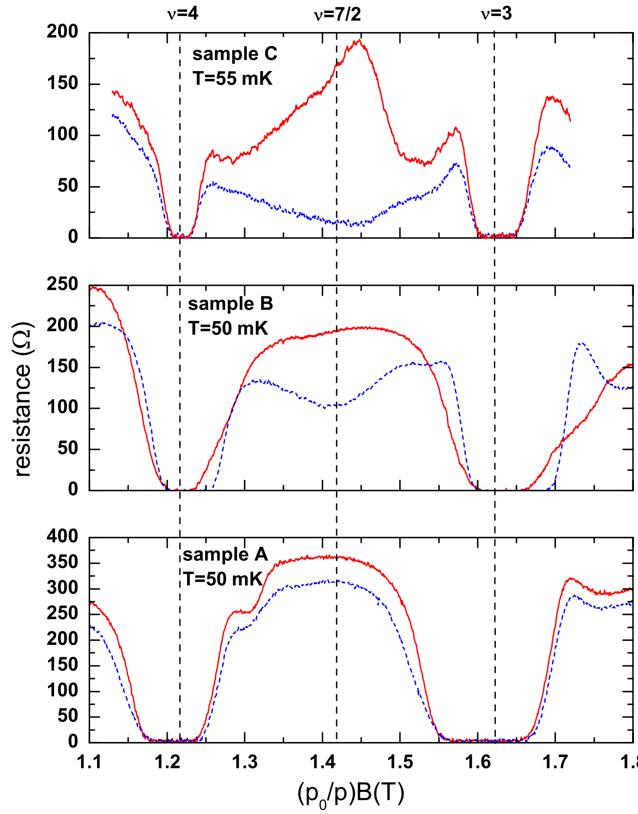

FIG. 3 (color online). Density dependence of the resistance anisotropy in the vicinity of $\nu = 7/2$ at $T \sim 50$ mK for samples A, B, and C. The magnetic field axis for each sample has been scaled by the density of sample A, $p_0 = 1.2 \times 10^{11}$ cm^{-2}, to facilitate comparison at $\nu = 7/2$. As the density is reduced from 2.3×10^{11} cm^{-2} to 2.0×10^{11} cm^{-2}, the anisotropy weakens. Sample A, at $p = 1.2 \times 10^{11}$ cm^{-2}, shows no significant anisotropy at $\nu = 7/2$.

the density is decreased there is a quantum phase transition such that the valence LL at $\nu = 7/2$ is primarily composed of the $N = 1$ orbital which will stabilize an isotropic state. While our simplistic calculation predicts that this transition occurs at a density of approximately 1.0×10^{11} cm^{-2}, exchange terms not included in our calculation will likely move this transition to higher density, possibly bringing it into better agreement with our experimental observation of isotropic transport in sample A at a density of 1.2×10^{11} cm^{-2}. We believe the isotropic behavior observed in sample A is of fundamental origin and is not simply a reflection of an insufficiently clean sample or insufficiently low measurement temperature. The mobility of sample A is 2.0×10^6 cm^2/Vs, the highest of all the samples used in this study. Furthermore, the interaction energy scale determining stripe formation is expected to scale only as $p^{1/2}$. If the ground sate of sample A were to be anisotropic at lower temperatures, we would have expected to see indications of its onset at $T = 50$ mK. While we cannot rule out the possibility that anisotropy will appear at very low temperatures, we think this scenario is unlikely. Finally, we note that the $B = 0$ conductivity (σ) of sample A is large,

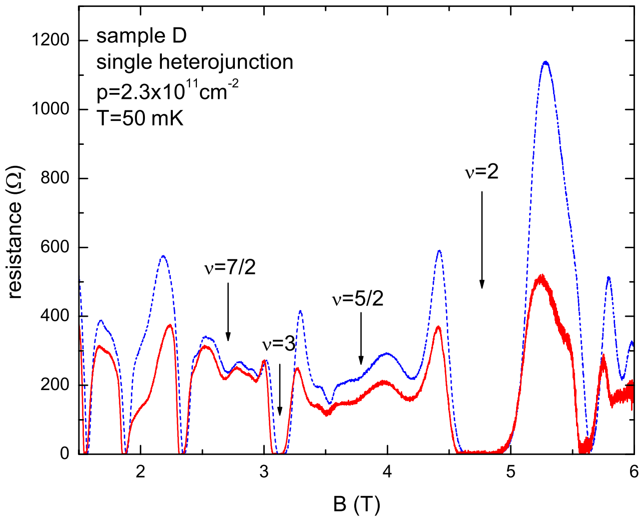

FIG. 4 (color online). Magnetoresistance for sample D at $T = 50$ mK. While the 2D density is the same as sample C, no anisotropy is seen at $\nu = 7/2$ in the single heterojunction.

$\sigma \gg e^2/h$, such that the sample is not expected to exhibit any transport anomalies associated with the metal-to-insulator transition.

We have also examined a single heterojunction (sample D) with density $p = 2.3 \times 10^{11}$ cm^{-2} to investigate if the anisotropy observed in sample C is stable against a change of the symmetry of the confining potential. As seen in Fig. 4, the change in the transport properties is striking. Even though the density is the same as sample C, the transport in sample D is largely isotropic, especially at $\nu = 7/2$. The observation of a symmetry driven anisotropic-to-isotropic transition at fixed carrier density is a strong indication that spin-orbit coupling alters the ground state at $\nu = 7/2$. It is well known that the spin-orbit interaction depends sensitively on the electric field present in quantum well, and not just the 2D density [13]. Our calculations for the single heterojunction indicate that the valence LL at $\nu = 7/2$ is comprised of several oscillator functions ($N = 0$ through $N = 5$), but more importantly it contains significant contributions from $N = 0$ (13%) and $N = 1$ (20%). While more sophisticated calculations will certainly be necessary to understand in greater detail the nature of anisotropic states in half-filled Landau levels of 2DHSs, the calculated LL structure of the single heterojunction contrasts sharply with that found in the 20 nm symmetric quantum well that does not contain significant contributions from the $N = 0$ and $N = 1$ LLs.

In conclusion, we observe anisotropic transport at filling factors $\nu = 7/2$, $\nu = 11/2$, and $\nu = 13/2$ and isotropic transport at $\nu = 9/2$ in high quality (100) oriented symmetrically doped 2DHSs. Transport experiments combined with calculations of the Landau level structure indicate that the type of correlated ground state observed at a particular filling factor depends sensitively on the nature of the single particle states available to the system.

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