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X. Fu, Q. Shi, M. A. Zudov, G. C. Gardner, J. D. Watson, M. J. Manfra, K. W. Baldwin, L. N. Pfeiffer, and K. W. West

1School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA
2Microsoft Quantum Lab, Purdue, West Lafayette, Indiana 47907, USA
3Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA
4Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA
5School of Electrical and Computer Engineering and School of Materials Engineering, Purdue University, West Lafayette, Indiana 47907, USA
6Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

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It is well established that the ground states of a two-dimensional electron gas with half-filled high (N ≥ 2) Landau levels are compressible charge-ordered states, known as quantum Hall stripe (QHS) phases. The generic features of QHSs are a maximum (minimum) in a longitudinal resistance (R) of QHSs in a 2DEG confined to GaAs quantum wells as quantum Hall stripes (QHSs) [7]. With few exceptions [8, 9], QHSs in a 2DEG confined to GaAs quantum wells align along (110) crystal axis of GaAs. This symmetry breaking field remains enigmatic, despite many efforts to identify its origin [9–12].

The ground state of a two-dimensional electron gas (2DEG) at half-integer filling factors ν = i/2, i = 1, 3, 5, ..., can depend sensitively on the Landau level (LL) index N. At N = 0 (ν = 1/2, 3/2) it is a compressible composite fermion metal [1], whereas at N = 1 (ν = 5/2, 7/2) it is an incompressible fractional quantum Hall insulator formed by paired composite fermions [2, 3]. At N = 2 and several higher LLs (ν = i/2, i = 9, 11, ...), the competition between long-range repulsive and short-range attractive components of Coulomb interaction leads to compressible charge-ordered phases [4–6]. These phases can be viewed as unidirectional charge-density waves consisting of stripes with alternating integer ν (e.g., ν = 4 and ν = 5) and are commonly known as quantum Hall stripes (QHSs) [7]. With few exceptions [8, 9], QHSs in a 2DEG confined to GaAs quantum wells align along (110) crystal axis of GaAs. This symmetry breaking field remains enigmatic, despite many efforts to identify its origin [9–12].

The generic QHS features are a maximum (minimum) in a longitudinal resistance Rxx (Ryy), which develop at temperatures T ≲ 0.1 K, and a non-quantized Hall resistance RH [13, 14]. More precisely, QHSs form when partial filling factor ν∗ = ν − [ν], where [ν] is an integral part of ν, falls in the range of 0.4 ≤ ν∗ ≤ 0.6. The resistance anisotropy ratio αR ≡ Rxx/Ryy normally achieves a single maximal value αR ≈ 1 at δν ≡ ν∗ − 0.5 ≈ 0 and quickly drops to αR ≈ 1 at δν ≈ ±0.1. This drop occurs due to a monotonic decrease (increase) of the Rxx (Ryy) with |δν|.

In this Letter, we report on anomalous nematic states which are distinguished from QHS by minima (maxima) in Rxx (Ryy) and plateau-like features in RH in half-filled N ≥ 3 Landau levels. The global maxima (minima) in the Rxx (Ryy) occur away from half-filling, at δν ≈ ±0.08, where the resistance anisotropy ratio attains its maximal value. Remarkably, all these features emerge at temperatures considerably lower than the onset temperature of QHSs, which indicates possible transition to a new phase.

The 2DEG in sample A (B) resides in a GaAs quantum well of width 29 nm (30 nm) surrounded by Al0.25Ga0.75As barriers. After a brief low-temperature illumination, samples nominally had the electron density n ≈ 3.0 × 10^{11} cm^{-2} and the mobility μ ≈ 2 × 10^7 cm^2V^{-1}s^{-1}. Samples were 4 × 4 mm squares [15] with indium contacts fabricated at the corners and the middles. Rxx (Ryy) was measured using a four-terminal, low-frequency lock-in technique, with the current sent between mid-side contacts along x ≡ (110) (y ≡ (110)) direction.

In Fig. 1(a) we present Rxx and Ryy versus magnetic field B measured in sample A at T ≈ 25 mK. Near ν = 11/2, 15/2, and ν = 17/2, Rxx (Ryy) exhibits maxima (minima), with Rxx ≪ Ryy, as expected of the usual QHS phases. Remarkably, the behavior in the vicinity of ν = 13/2 is qualitatively different; even though Rxx ≫ Ryy (like at other ν = i/2), Rxx exhibits a pronounced minimum whereas Ryy shows a maximum near half-filling. The global maxima (minima) in Rxx (Ryy) occur away from half-filling, namely at ν = 13/2 ± 0.08, as illustrated by vertical dashed lines. As a result, αR becomes a non-monotonic function of |δν|, it is relatively small at δν = 0 and exhibits maxima at δν ≈ ±0.08. The variation of αR with ν∗ is quite significant, it drops from αR > 600 at ν = ν∗ ≈ 6.58 to αR < 10 near half-filling.

In Fig. 1(b) we show the Hall resistance RH as a function of B. Concurrent with the unexpected extrema in Rxx and Ryy at ν = 13/2, the Hall resistance shows a plateau-like feature, marked by solid horizontal lines drawn at 2RK/13, where RK ≡ h/e^2 is the von Klitz-
Quantization at was also established that in AlAs quantum wells, Hall recently observed in the signatures of even-denominator quantum Hall states were in these cases $R_{xx}$ quantized values (cf. dashed horizontal line segments drawn at $2R_K/11$ and $2R_K/15$ ($\nu = 15/2$), where $R_K \equiv h/e^2 = 25812.80745 \Omega$ is the von Klitzing constant.

FIG. 1. (Color online) (a) $R_{xx}$ and $R_{yy}$ versus $B$ measured in sample A at $T \approx 25$ mK. Half-integer $\nu$ are marked by $15/2$, $13/2$, and $11/2$. The $R_{xx}$ minimum and the $R_{yy}$ maximum at $\nu \approx 13/2$ are marked by $\dagger$ and $\ddagger$, respectively. Dashed vertical lines are drawn at $\nu_+ = 6.5 \pm 0.08$. (b) Hall resistance $R_H$ versus $B$. Solid horizontal lines, drawn at $2R_K/13$, mark a plateau-like feature near $\nu = 13/2$, while dashed horizontal lines are drawn at $2R_K/11$ ($\nu = 11/2$) and $2R_K/15$ ($\nu = 15/2$), where $R_K \equiv h/e^2 = 25812.80745 \Omega$ is the von Klitzing constant.

FIG. 2. (Color online) $R_{yy}$ versus $B$ measured in the sample A at $T \approx 25$ mK (light line) and at $T \approx 70$ mK (dark line). Half-integer $\nu$ are marked by $13/2$, and $11/2$.

and be accompanied by a maximum in easy resistance [17]. Finally, fractional quantum Hall nematic states have been reported at $\nu = 7/3$ [18] and $\nu = 5/2$ [19] in tilted magnetic fields.

The anomalous nematic state near $\nu = 13/2$ depicted in Fig. 1 is best observed at low temperatures. As a glimpse at the temperature dependence, we present in Fig. 2 the easy resistance $R_{yy}$ as a function of $B$ measured in sample A at two different temperatures. Remarkably, as the temperature is raised from $T \approx 25$ mK to $T \approx 70$ mK, the two $R_{yy}$ minima near $\nu = 13/2 \pm 0.08$ and the maximum near $\nu = 13/2$ are replaced by single minimum, centered at $\nu = 13/2$ with $R_{yy} \approx 0$. Such a broad minimum is a characteristic feature of the well-developed QHS phase. In contrast, the broad minimum near $\nu = 11/2$ observed at $T \approx 25$ mK becomes narrower at $T \approx 70$ mK, consistent with previous studies of QHSs. These data demonstrate that unexpected extrema near $\nu = 13/2$ emerge at temperatures lower than the onset temperature of QHSs.

Remarkably, some of our samples revealed the unexpected $R_{xx}$ minima not only near $\nu = 13/2$, as in Fig. 1, but also near other half-integer $\nu$ [20]. In Fig. 3 we show the data obtained from sample B which exhibit pronounced $R_{xx}$ minima at $\nu = 13/2, 15/2$, and $17/2$. All of these minima are accompanied by plateau-like features in $R_H$, see right axis, which assumes the values close to $2R_K/i$, with $i = 13, 15, 17$, as indicated by horizontal line segments in Fig. 3. Moreover, the $R_{xx}$ maxima occur nearly precisely at the same $\nu^*$ as in Fig. 1, i.e., at $\nu^* = 1/2 \pm 0.08$, as illustrated by vertical dashed lines. Whether or not the value of $|\delta\nu| = 0.08$ is universal remains an open question.

We now turn to the temperature dependence in sample B which is illustrated in Fig. 4(a) showing $R_{xx}$ (dark line) and $R_{yy}$ (light line) as a function of $B$ measured at different $T$, as marked. The Hall resistances $R_H$ measured at $T \approx 135$ mK (light line) and $T \approx 30$ mK (dark line) are shown in Fig. 4(b). At $T \approx 135$ mK, $R_{xx}$ and $R_{yy}$ near $\nu = 11/2$ and $\nu = 15/2$ are featureless and $R_H$ is classical. Near $\nu \approx 13/2$, however, the
anisotropy is already developed ($\alpha_R \approx 6$) and $R_H$ shows a clear signature of a re-entrant integer quantum Hall state near $\nu \approx 6.72$ (as marked by $\uparrow$ in the figure), indicative of a bubble phase. As anticipated, $R_{xx}$ ($R_{yy}$) exhibits a single maximum (minimum) at $\nu \approx 13/2$, i.e., the strongest anisotropy occurs close to half-filling, consistent with nearly all previous experiments [21]. The fact that transport anisotropies in the lower-spin branches of a LL develop at higher temperatures (e.g., $\nu \approx 9/2, 13/2$) than in the upper-spin branches ($\nu \approx 11/2, 15/2$) is well documented (see, e.g., Ref. 13).

Upon cooling to $T \approx 100$ mK, transport anisotropy with a maximum in $R_{xx}$ and a minimum in $R_{yy}$ also emerges at both $\nu \approx 11/2$ ($\alpha_R \approx 20$) and at $\nu \approx 15/2$ ($\alpha_R \approx 30$). Near $\nu \approx 13/2$, however, even though the anisotropy becomes an order of magnitude stronger ($\alpha_R \approx 60$), $R_{xx}$ now exhibits a pronounced minimum near half-filling indicating an onset of the anomalous nematic state. When the sample is cooled to $T \approx 60$ mK, the resistance anisotropy at $\nu \approx 11/2$ increases dramatically ($\alpha_R > 300$), in agreement with previous studies. Concurrently, we observe that the $R_{xx}$ minimum at $\nu \approx 13/2$ deepens and that the resistance anisotropy is reduced by about a factor of three compared to its value at $T \approx 100$ mK. Remarkably, the $R_{xx}$ near $\nu \approx 15/2$ also develops a minimum at this temperature. At $T \approx 30$ mK, the magnetotransport near $\nu = 11/2$ remains qualitatively unchanged, although the anisotropy ratio becomes even higher ($\alpha_R \approx 400$). Near $\nu \approx 13/2$, however, further development of the $R_{xx}$ minimum and the appearance of the $R_{yy}$ maximum reduce the anisotropy to $\alpha_R \approx 10$. While we do not observe a maximum in the $R_{yy}$ near $\nu = 15/2$, the $R_{xx}$ minimum becomes more pronounced and the anisotropy reduces to $\alpha_R < 20$. As previously noted, the $R_{xx}$ minima near $\nu = 13/2$ and $\nu = 15/2$ are accompanied by plateau-like features in the $R_H$, see Fig. 4(b).

It is evident that the temperature dependencies near $\nu = 13/2$ and $\nu = 15/2$ are qualitatively similar. At temperatures immediately below the onset temperature at which the QHS anisotropy sets in, the data at both filling factors exhibit normal behavior, i.e., a broad single maximum (minimum) in the $R_{xx}$ ($R_{yy}$). Upon cooling down further, both filling factors demonstrate the gradual development of the “splitting” in the $R_{xx}$, around half-filling, marked by a reduction of the anisotropy ratio and by the emergence of plateau-like features in the

![Figure 3](image-url) FIG. 3. (Color online) $R_{xx}$, $R_{yy}$ (left axis), and $R_H$ (right axis) versus $B$ measured in sample B at $T \approx 30$ mK. Half-integer $\nu$ are marked by $17/2, 15/2, 13/2, 11/2$. The $R_{xx}$ minima at $\nu = 13/2, 15/2, 17/2$ and the $R_{yy}$ maximum near $\nu = 13/2$ are marked by $\uparrow$ and $\downarrow$, respectively. Dashed vertical lines are drawn at $\nu \pm = i/2 \pm 0.08$, $i = 13, 15, 17$. Near $\nu = i/2$ ($i = 13, 15, 17$), $R_H$ shows plateau-like features with $R_H \approx 2R_{K}/i$, marked by solid horizontal lines.

![Figure 4](image-url) FIG. 4. (Color online) (a) $R_{xx}$ (dark line), $R_{yy}$ (light line) versus $B$ measured in sample B at $T \approx 135$ mK (bottom), $T \approx 100$ mK (offset by 0.1 k$\Omega$), $T \approx 60$ mK (offset by 0.3 k$\Omega$), and $T \approx 30$ mK (offset by 0.6 k$\Omega$). Vertical dashed lines mark $\nu^{*} = 0.58$. (b) $R_H$ versus $B$ at $T \approx 30$ mK (dark line) and at $T \approx 135$ mK (light line). Solid horizontal lines next to the $R_H$ mark concurrent plateau-like features at $2R_{K}/13$ and $2R_{K}/15$, while dashed horizontal lines are drawn at $2R_{K}/11$. 


We can thus conclude that, while definitely more robust in the lower spin branch of the $N = 3$ LL, the anomalous nematic state is also supported by the upper spin branch.

The contrasting behavior between temperature dependencies of the $R_{xx}$ (circles) and of the $R_{yy}$ (squares) near $\nu = 13/2, 15/2$ and those near $\nu = 11/2$ is summarized in Fig. 5. While $R_{xx}$ ($R_{yy}$) at $\nu \approx 11/2$ monotonically increases (decreases) as the temperature is lowered, $R_{xx}$ ($R_{yy}$) at both $\nu = 13/2$ and $\nu = 15/2$ shows a clear maximum (minimum) at some intermediate “turnover” temperatures, $T_{13/2} \approx 100$ mK and $T_{15/2} \approx 70$ mK, respectively [22]. For comparison, we also include in Fig. 5 the $R_{xx}$ data at $\nu = i/2 + 0.08$ ($i = 11, 13, 15$), represented by triangles. As can be seen in Fig. 5(a), the $R_{xx}$ at $\nu = 5.58$ is always smaller than that at $\nu = 11/2$ at all temperatures studied. In contrast, at $\nu = 6.58$ ($\nu = 7.58$) $R_{xx}$ is larger than at $\nu = 13/2$ ($\nu = 15/2$) only at $T > T^*_{13/2}$ ($T < T^*_{15/2}$) and the opposite is true when $T < T^*_{13/2}$ ($T > T^*_{15/2}$). This observation further confirms that filling factors $\nu = i/2$ ($i = 13, 15$) are governed by the same physics which sets in at $T \approx T^*_{i/2}$ and is considerably more effective at reducing the transport anisotropy at $\nu = i/2$ than away from half-filling. Indeed, the temperature dependencies of the $R_{xx}$ at $\nu = 6.58, 7.58$ are rather similar to that at $\nu = 5.58$.

According to the transport theory of QHS state, which treats it as a pinned smectic [23], the decrease (increase) of the $R_{xx}$ ($R_{yy}$) upon cooling can be attributed to the increased electron scattering between stripe edges. This model, however, predicts weaker anisotropy away from half-filling than at $\nu = i/2$, in contrast to our observations. In addition, Ref. 23 predicts considerably stronger $T$-dependence of $R_{xx}$ and $R_{yy}$ at $\nu = i/2$ [24] than away from half-filling and our data do not reflect that. Therefore, the observed dependencies on $\nu$ and $T$ are inconsistent with QHS or a nematic-to-smectic phase transition [25]. Instead, the observed low-temperature emergence of unexpected extrema in $R_{xx}$ and $R_{yy}$ along with the plateau-like features in the $R_{yy}$ likely reflects the formation of another competing ground state.

In addition to the temperature dependence, it is interesting to investigate the effects of the carrier density and of the in-plane magnetic field. Our measurements on a state-of-the-art tunable-density Van der Pauw device with in-situ back gate have not revealed these anomalous states at any density from $2.2$ to $3.6 \times 10^{11}$ cm$^{-2}$ [26], as neither have those using high density [$n_e = (4.1-4.3) \times 10^{11}$ cm$^{-2}$] heterostructures [27]. However, the carrier mobility in the above experiments was below $1.2 \times 10^7$ cm$^2$V$^{-1}$s$^{-1}$ and, since the anomalous nematic states form at considerably lower temperatures than QHSs, it is reasonable to expect that they are more easily destroyed by disorder. The absence of anomalous nematic states in these more-disordered samples yields further support to the importance of electron-electron correlations. Measurements in tilted magnetic fields are currently under way and will be a subject of future publication. We note, however, that the effect of in-plane magnetic field remains poorly understood even for conventional QHSs [26, 28, 29] which might complicate the interpretation of the data.

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$^1$X.F. and Q.S. contributed equally to this work.

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* Present address: Department of Physics, Columbia University, New York, NY, USA

† Corresponding author: zuhov001@umn.edu

‡ Present address: Microsoft Station-Q at Delft University of Technology, 2600 GA Delft, The Netherlands


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FIG. 5. (Color online) $R_{xx}$ (circles), $R_{yy}$ (squares) versus $T$ at (a) $\nu = 11/2$, (b) $\nu = 13/2$, and (c) $\nu = 15/2$. For comparison, $R_{xx}$ at $\nu^* = 0.58$, cf. dotted vertical lines in Fig. 4(a), versus $T$ is shown by triangles.


[7] With further consideration of thermal and quantum fluctuations, several electron liquid crystal-like phases have also been proposed [30].

[8] J. Zhu, W. Pan, H. L. Stormer, L. N. Pfeiffer, and K. W. West, 


[10] D. V. Fil, 


[12] I. Sodemann and A. H. MacDonald, 

[13] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, 


[15] Signatures of anomalous nematic states have also been observed in Hall bar geometry.

[16] Y. Kim, A. C. Balram, T. Taniguchi, K. Watanabe, J. K. Jain, and J. H. Smet, 


[18] J. Xia, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, 

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[20] Anomalous nematic states are very fragile and the $R_{yy}$ maxima near $ν = 1/2$ are more elusive than the $R_{xx}$ minima. As for other fragile states in quantum Hall systems forming below $0.1$ K, the uniformity of the carrier density is obviously an important factor. Another requirement is a good sample “state” which, we believe, is determined by the disorder landscape. The latter, in turn, sensitively depends on the details of both cooldown and illumination procedures, which are known produce charge redistribution between the quantum well, the doping layers, and the sample surface [31–33], thereby leading to different degrees of screening of the disorder potential [34]. Nevertheless, after multiple cooldowns of different samples we are confident that the phenomenon is generic.

[21] We are aware of only two experiments which observed maximum resistance anisotropy at $ν^* > 0.5$ [25, 35].

[22] A turnover in the temperature dependence has been observed previously [25, 36], but no local resistance extrema away from $ν^* = 0.5$ have been reported to date.


[24] At $ν^* = 1/2$, Ref. 23 predicts $ρ_{xx} \propto T^{−α}$ and $ρ_{yy} \propto T^α$ with $α \approx 0.5$.


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[34] M. Sammon, M. A. Zudov, and B. I. Shklovskii, 

[35] Q. Shi, M. A. Zudov, B. Friess, J. Smet, J. D. Watson, G. C. Gardner, and M. J. Manfra, 

[36] K. Cooper, 