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Anomalous nematic-to-stripe phase transition driven by in-plane magnetic fields

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Anomalous nematic states, recently discovered in ultraclean two-dimensional electron gas, emerge from quantum Hall stripe phases upon further cooling. These states are hallmarked by a local minimum (maximum) in the hard (easy) longitudinal resistance and by an incipient plateau in the Hall resistance in nearly half-filled Landau levels. Here, we demonstrate that a modest in-plane magnetic field, applied either along $\langle 110\rangle$ or $\langle 1\bar{1}0\rangle$ crystal axis of GaAs, destroys anomalous nematic states and restores quantum Hall stripe phases aligned along their native $\langle 110\rangle$ direction. These findings confirm that anomalous nematic states are distinct from other ground states and will assist future theories to identify their origin.

Two-dimensional electrons in GaAs quantum wells can support a variety of phases when subjected to quantizing magnetic fields and low temperatures. At half-integer filling factors ($\nu = i/2, i = \text{odd}$), these states include composite fermion metals ($i = 1,3$) [1], quantum Hall insulators ($i = 5,7$) [2, 3], and quantum Hall stripe (QHS) phases ($i = 9, 11, ...$) [4–8]. The QHS phases can be viewed as unidirectional charge density waves composed of strips with alternating integer filling factors, $\nu = (i \pm 1)/2$. Being characterized by large resistance anisotropies ($R_{xx} \gg R_{yy}$) [9, 10], the QHS phases are usually aligned along $\hat{y} \equiv \langle 110\rangle$ crystal axis of GaAs, for yet unknown reason [11–14]. Recent experiments [15] have shown that some QHS phases ($i = 13, 15, 17$), once formed at ~ 0.1 K, can evolve into anomalous nematic states (ANSs) upon further cooling.

The ANSs are distinguished from the QHS phases by *opposite* dependencies of the R_{xx} and the R_{yy} on the detuning from half-filling $|\delta\nu| \equiv |\nu - i/2|$ and on the temperature T [15, 16]. In particular, unlike the QHS phases exhibiting a maximum (minimum) in the R_{xx} (R_{yy}) at $\delta\nu \approx 0$, the ANSs are marked by a minimum (maximum) in the R_{xx} (R_{yy}) and exhibit much smaller anisotropy ratio $R_{xx}/R_{yy} > 1$. In addition, the Hall resistance R_H near $\nu = i/2$ develops a plateau-like feature with the value close to $R_H = 2R_{\rm K}/i$, where $R_{\rm K} = h/e^2$ is the von Klitzing constant. As shown in Ref. 15, a small detuning of $|\delta\nu| \approx 0.08$ transforms the ANS into the QHS phase, reflecting a tight competition between these two ground states. Such sensitivity to $\delta\nu$ is well documented in the lower spin branch of the $N = 1$ Landau level. Here, within the range of $0 \le \delta\nu \le 0.1$, one finds [17] fragile quantum Hall states at $\nu = 5/2$ [2, 3] and $\nu = 32/13$ [18], the reentrant integer quantum Hall state at $\nu \approx 2.43$ [9, 10, 19, 20], and yet another quantum Hall state at $\nu = 12/5$ [21]. The $\nu = 5/2$ state can also be altered by an in-plane magnetic field which can transform it into the QHS phase [22, 23], isotropic liquid [24], or make it nematic [25].

In this Letter we report on the response of the ANSs to in-plane components of the magnetic field $B_\parallel = B_x$ and $B_\parallel = B_y$. We find that the immediate effects of $B_\parallel$ are to transform the minimum (maximum) in the R_{xx} (R_{yy}) at half-filling into a maximum (minimum), to eliminate the plateau in R_H, and to restore the ratio R_{xx}/R_{yy} to values consistent with the QHS phases. Remarkably, the ANSs respond to $B_\parallel$ in essentially the same manner when $B_\parallel$ is applied along either $\hat{x} \equiv \langle 1\bar{1}0\rangle$ or $\hat{y} \equiv \langle 110\rangle$ direction; in both cases the revived QHS phase is aligned along its native $\langle 110\rangle$ crystal axis. This is in contrast with the effect of $B_\parallel$ on the QHS phases which respond very differently to B_x and B_y while persisting to much higher $B_\parallel$ [22, 23, 26]. These observations signal that a modest $B_\parallel \approx 0.5$ T is enough to tip a delicate balance between the ANSs and the QHS phases in favor of the latter, a finding which should be taken into account by theories aimed to explain the origin of the ANSs.

Our sample is a 30 nm-wide GaAs quantum well surrounded by $Al_{0.24}Ga_{0.76}As$ barriers. The electrons are supplied by Si doping in narrow GaAs doping wells, sandwiched between thin AlAs layers, which are positioned at a setback distance of 80 nm on both sides of the main GaAs well. After a brief illumination at $T \approx 5$ K, the electrons had a density $n_e \approx 3.0 \times 10^{11}$ cm^{-2} and a mobility $\mu \gtrsim 2 \times 10^7$ cm^{2}V^{-1}s^{-1}. Samples were 4×4 mm squares with eight indium contacts at the corners and the midsides. The longitudinal resistances, R_{xx} and R_{yy}, were measured using a four-terminal, low-frequency (a few Hz) lock-in technique. The excitation current was sent through the center of the sample, i.e., between mid-side contacts along $\hat{x}$ or $\hat{y}$ direction. The in-plane magnetic field B_x or B_y was introduced by tilting the sample about either $\hat{y}$ or $\hat{x}$ axis, in separate cooldowns.

We start with the discussion of the experiments under $B_\parallel = B_x$ (i.e., applied along $\langle 1\bar{1}0\rangle$ crystal axis) and compare its effects on the QHS phase and on the ANS. In Fig. 1 (a) [(b)] we show the longitudinal [Hall] resistance R_{xx} [R_H] as a func-

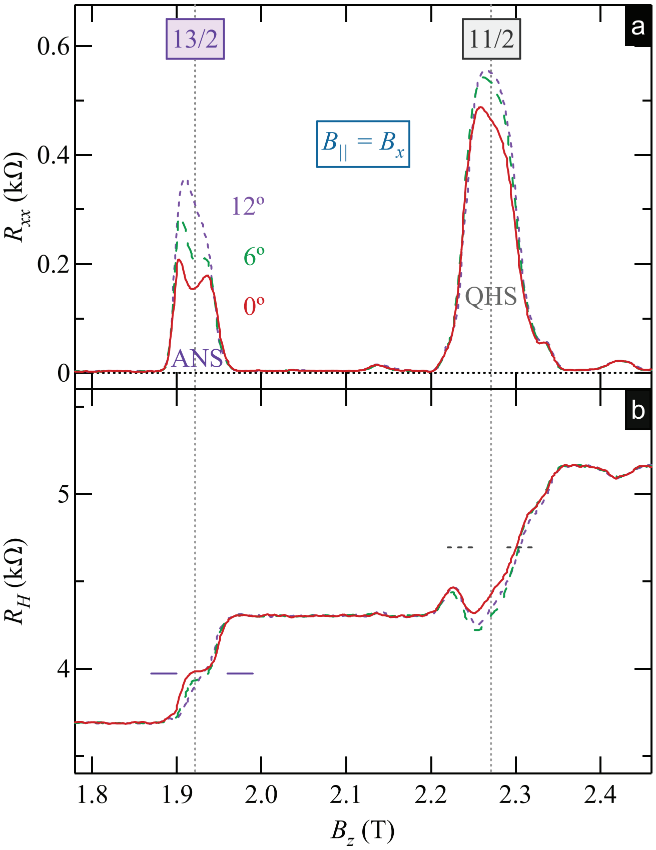

FIG. 1. (a) R_{xx} and (b) R_H as a function of B_z measured under $B_{\|} = B_y$ at $\theta = 0°$ (solid line), 6° (dashed line), and 12° (dotted line) at $T \approx 20$ mK. Horizontal solid (dashed) lines in (b) are drawn at $R_H = 2R_K/13$ ($R_H = 2R_K/11$), where $R_K = h/e^2$ is the von Klitzing constant.

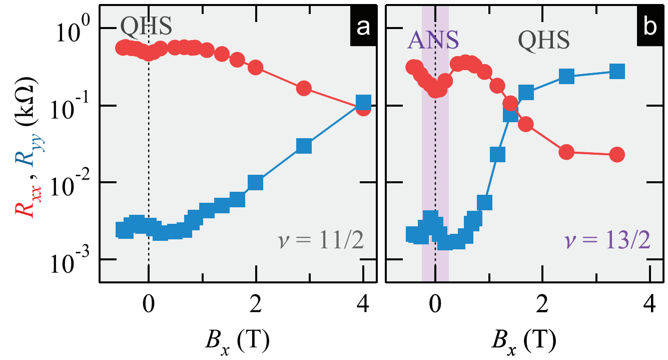

FIG. 2. (a) R_{xx} (circles), R_{yy} (squares) vs. B_x at $\nu \approx 11/2$. (b) Same as (a) but at $\nu \approx 13/2$.

tion of the perpendicular component of the magnetic field B_z at different tilt angles $\theta = 0°$ (solid lines), 6° (dashed lines), and 12° (dotted lines). Consistent with findings of Ref. 15, the data at $B_{\|} = 0$ reveal the QHS phase at $\nu = 11/2$ and the ANS at $\nu = 13/2$. The ANS at $\nu = 13/2$ is evidenced by (i) a minimum in the R_{xx}, with the resistance value much smaller than typical of a QHS phase, and by (ii) an incipient plateau in the R_H with the value close to $R_H = 2R_K/13$, as marked by horizontal solid lines. None of these features are present at $\nu = 11/2$ where the data reflect a conventional QHS phase.

Upon tilting the sample to introduce $B_{\|} = B_x$, the R_{xx} minimum at $\nu = 13/2$ becomes less pronounced at $\theta = 7°$ and disappears completely at $\theta = 12°$ [27]. The plateau in the R_H is also destroyed by B_x at this filling factor. As a result, both the R_{xx} and the R_H at $\nu = 13/2$ become akin to those at $\nu = 11/2$, hinting at a $B_{\|}$-driven transition from the ANS to the QHS phase. In contrast, the data at $\nu = 11/2$, representing the QHS phase, exhibit no qualitative changes with increasing B_x in this range of tilt angles, despite higher B_x.

To further analyze the effects of $B_{\|} = B_x$ on the QHS phase at $\nu = 11/2$ and on the ANS at $\nu = 13/2$ we construct Fig. 2 (a) and Fig. 2 (b), respectively, which show the R_{xx} (circles) and the R_{yy} (squares) as a function of B_x covering a wider range of tilt angles. The R_{xx} (R_{yy}) at $\nu = 11/2$ remains nearly unchanged up to $B_x \approx 1$ T and then gradually decays (grows) until the anisotropy disappears at $B_x \approx 4$ T, in agreement with earlier experiments [26]. In contrast, the R_{xx} at $\nu = 13/2$ shows a pronounced maximum at $B_x \approx 0.5$ T, while the R_{yy} shows a deep minimum at the same B_x. As a result, the anisotropy ratio R_{xx}/R_{yy} increases considerably and becomes consistent with the value exhibited by the QHS phase at $\nu = 11/2$. Upon further increase of B_x, both the R_{xx} and the R_{yy} at $\nu = 13/2$ evolve as expected for the QHS phase; here, the anisotropy vanishes at $B_x \approx 1.5$ T, which is lower than the corresponding B_x at $\nu = 11/2$ and the QHS phase realigns along the $\langle 1\bar{1}0\rangle$ axis at still higher B_x, as anticipated [26].

To acquire further support to the $B_{\|}$-driven ANS-to-QHS phase transition at $\nu = 13/2$ we next present the data under orthogonal orientation of $B_{\|}$ with respect to the anisotropy axis, $B_{\|} = B_y$. In Fig. 3 (a) we show the R_{xx} as a function of B_z at $T \approx 20$ mK under $B_{\|} = B_y$ (i.e., applied along $\langle 110\rangle$ crystal axis) at three tilt angles, $\theta = 0°$ (solid line), 10° (dashed line) and 21° (dotted line). The Hall resistance data are presented in Fig. 3 (b). At $\theta = 0°$, the data are similar to those obtained in another cooldown, cf., Fig. 1; both the R_{xx} and the R_H exhibit all characteristic features of the QHS phase at $\nu = 11/2$ and of the ANS at $\nu = 13/2$. It is also evident that in this cooldown the ANS is better developed, as evidenced by a deeper minimum in the R_{xx}. As discussed in Ref. 15, the strength of the ANS sensitively depends on the details of the cooldown and illumination protocols.

The evolution of the R_{xx} in the QHS phase at $\nu = 11/2$ with B_y is consistent with previous studies [26, 28]. Upon tilting to $\theta = 10°$, the R_{xx} decreases, as the QHS phase starts to reorient perpendicular to B_y [22, 23, 26, 28], and at $\theta = 21°$ the R_{xx} is reduced much more. In contrast to the R_{xx} at $\nu = 11/2$, the R_{xx} at $\nu = 13/2$ *grows* with the tilt angle and the characteristic ANS minimum quickly disappears. Indeed, at $\theta = 21°$ the R_{xx} near $\nu = 13/2$ exhibits a single maximum, as expected of a QHS phase. As shown in Fig. 3 (b) the Hall plateau with $R_H \approx 2R_K/13$ is also destroyed by B_y. We thus conclude that the effect of B_y on the ANS is essentially the same as that of B_x; in either case, the ANS yields to the

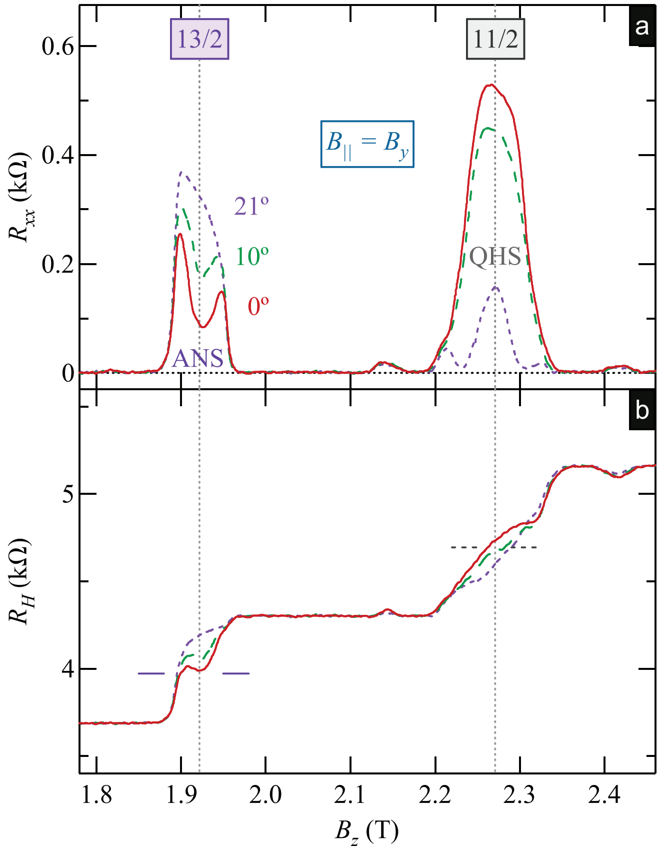

FIG. 3. (a) R_{xx} and (b) R_H as a function of B_z under $B_{||} = B_y$ at $\theta = 0°$ (solid line), $10°$ (dashed line), and $21°$ (dotted line) at $T \approx 20$ mK. Horizontal solid (dashed) lines in (b) are drawn at $R_H = 2R_{\mathrm{K}}/13$ ($R_H = 2R_{\mathrm{K}}/11$).

QHS phase once a modest $B_{||}$ is introduced.

In Fig. 4 we summarize the evolutions of both the R_{xx} (circles) and the R_{yy} (squares) near (a) $\nu = 11/2$ and (b) near $\nu = 13/2$ over the whole range of B_y studied. The data at $\nu = 11/2$ reveal two reorientations of the QHS phase; B_y first realigns the QHS phase along the $\langle 1\bar{1}0\rangle$ crystal axis (perpendicular to $B_{||}$) at $B_y \approx 1$ T and then back to along the $\langle 110\rangle$ axis (parallel to $B_{||}$) at $B_y \approx 3$ T, as previously reported [26, 29]. At $\nu = 13/2$, however, the data in Fig. 4 (b) show that the immediate effect of B_y is to dramatically *increase* (*decrease*) the R_{xx} (R_{yy}) to a value consistent with the QHS phase [30]. As a result of these changes, the resistance anisotropy ratio grows from $R_{xx}/R_{yy} \approx 10$ at $B_y = 0$ to $R_{xx}/R_{yy} \approx 300$ at $B_y \approx 1$ T. This fact further supports the B_y-driven ANS-to-QHS transition, consistent with our findings under small $B_{||} = B_x$.

Having concluded that both B_x and B_y transform the ANS to the QHS phase with native orientation, we next comment on possible mechanisms behind this transition. Let us first assume that the energetics of the ANS phase is not altered by $B_{||}$ According to the calculations of the QHS phases under $B_{||}$ [31, 32], $B_{||}$ serves ad an external symmetry breaking field which either competes with ($B_{||} = B_y$) or assists ($B_{||} = B_x$) the native field, responsible for the QHS phase

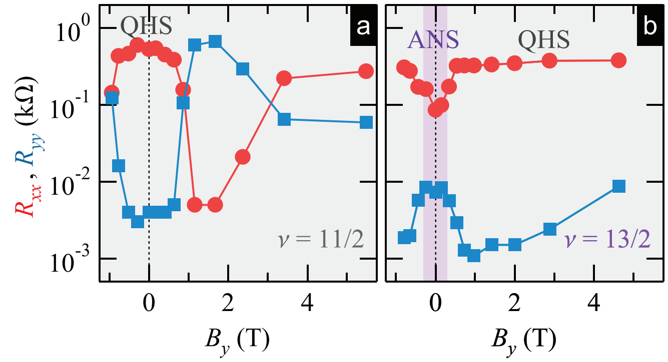

FIG. 4. (a) R_{xx} (circles), R_{yy} (squares) vs. B_y at $\nu \approx 11/2$. (b) Same as (a) but at $\nu \approx 13/2$.

alignment along $\langle 110\rangle$ direction at $B_{||} = 0$. As a result, B_x (B_y) lowers (raises) the energy of the QHS phase with native orientation with respect to its value at $B_{||} = 0$. Consistent with this picture,our QHS phase data at $\nu = 11/2$ indeed show that B_x (B_y) initially raises (lowers) the anisotropy ratio R_{xx}/R_{yy}. The situation at $\nu = 13/2$, however, is markedly different. Here, the QHS phase should win over (lose to) the competing ANS as it must become more (less) energetically favorable under modest B_x (B_y). While this prediction is consistent with our data under B_x, it clearly contradicts our observation of the ANS-to-QHS phase transition under B_y. Furthermore, even though the theory [31, 32] dictates that B_x lowers the energy of the QHS phase with its native orientation, all previous transport studies [23, 26] have shown that the anisotropy ratio R_{xx}/R_{yy} at $\nu = 13/2$ is in fact *reduced* by B_x. Our data at $\nu = 13/2$, on the other hand, clearly show significant increase of the R_{xx}/R_{yy} once B_x is turned on. Based on the above arguments, we can conclude that $B_{||}$, regardless of its orientation, raises the energy of the ANS above its value at $B_{||} = 0$, making it less favorable than the QHS phase at modest $B_{||}$.

Distinct effects of B_y on the ANS and on the QHS phase are further highlighted by opposite dependencies on the detuning $|\delta\nu|$ from half-filling. Indeed, near $\nu = 13/2$, the response of the ANS to B_y is obviously the strongest at $\delta\nu = 0$ resulting in the disappearance of the R_{xx} minimum and the restoration of a single maximum. This is in contrast to the QHS phase near $\nu = 11/2$, at which two deep R_{xx} minima emerge *away* from half-filling at $\theta = 21°$. These minima appear because lower B_y is required to reorient the QHS phase perpendicular to $B_{||}$ away from half-filling than at $\delta\nu = 0$ [28].

It is interesting to note that the local minimum in the hard resistance and the maximum in the easy resistance, as found in the ANS at $\delta\nu = 0$ without in-plane magnetic field, can also be realized under $B_{||} = B_y$ when the QHS phase is about to complete its reorientation perpendicular to $B_{||}$, see, e.g., Fig. 1(e) in Ref. 28. Such dependencies on $\delta\nu$ can be attributed to a possible decrease of the native symmetry breaking field as one moves away from half-filling [28]. However, if one were to treat the ANS as the QHS phase, the opposite conclusion emerges. Indeed, both the reduced anisotropy at $B_{\|} = 0$ and the stronger effects of $B_{\|}$at $\delta\nu = 0$ would suggest that the native field is the weakest at half-filling. It seems unlikely that the $\delta\nu$ dependencies of the native field be so drastically different at $\nu = 13/2$ and at $\nu = 11/2$ [33].

In summary, we have observed a transition from the anomalous nematic state to the quantum Hall stripe phase upon application of the a modest in-plane magnetic field, highlighting tight competition between these two ground states. The transition occurs both when $B_{\|}$ is aligned along $\langle 110\rangle$ and along $\langle 1\bar{1}0\rangle$ crystal axis of GaAs and the resultant quantum Hall stripe phase is aligned along native $\langle 110\rangle$ direction. Our analysis suggests that $B_{\|}$ likely raises the energy of the ANS compared to its value at $B_{\|} = 0$. These findings further distinguish anomalous nematic states from other ground states in half-filled Landau levels.

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