Quantum Hall stripes in high-density GaAs/AlGaAs quantum wells

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We report on quantum Hall stripes (QHSs) formed in higher Landau levels of GaAs/AlGaAs quantum wells with high carrier density ($n_e > 4 \times 10^{11}$ cm^{-2}) which is expected to favor QHS orientation along the unconventional $\langle 1\bar{1}0\rangle$ crystal axis and along the in-plane magnetic field $B_\parallel$. Surprisingly, we find that at $B_\parallel = 0$ QHSs in our samples are aligned along the $\langle 110\rangle$ direction and can be reoriented only perpendicular to $B_\parallel$. These findings suggest that high density alone is not a decisive factor for either abnormal native QHS orientation or alignment with respect to $B_\parallel$, while quantum confinement of the 2DEG likely plays an important role.

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Electron nematic (or stripe) phases are known to form in a variety of condensed matter systems [1–7], including a two-dimensional electron gas (2DEG) in GaAs/AlGaAs quantum wells which offered the first realization of such broken symmetry states [8–13]. Arising from an interplay between exchange and direct Coulomb interactions [8,9], quantum Hall stripes (QHSs) in a 2DEG are manifested by the resistivity minima (maxima) in the easy (hard) transport direction near half-integer filling factors, $\nu = 9/2, 11/2, 13/2, \ldots$. In a purely perpendicular magnetic field, QHSs in GaAs are nearly [14,15] always aligned along the $\langle 110\rangle$ crystal direction, but the origin of such native symmetry-breaking potential remains a mystery [15–17]. Two experiments [14,18], however, have suggested that QHSs along the $\langle 1\bar{1}0\rangle$ direction are favored at higher carrier densities ($n_e \gtrsim 3 \times 10^{11}$ cm^{-2}), a regime which has not yet been systematically explored.

Shortly after the discovery of QHSs, it was realized that an in-plane magnetic field $B_\parallel$ can easily reorient stripes [19–21] perpendicular to it. This finding was well explained by theories considering the finite thickness of the 2DEG [22,23]. Subsequent experiments, however, revealed evidence for another mechanism which favors *parallel* QHS alignment with respect to $B_\parallel$ [14,24–26]. While the nature of this mechanism is not yet understood, experiments established that is it highly sensitive to both Landau and spin quantum numbers [25] and that it becomes increasingly important at higher electron densities [26]. In particular, it was found that $B_\parallel$, applied parallel to native QHSs at $\nu = 9/2$, could not alter their native orientation at all when $n_e > 3.5 \times 10^{11}$ cm^{-2} [26]. Unfortunately, densities above $n_e \approx 3.6 \times 10^{11}$ cm^{-2} were not accessible because of the population of the second electrical subband.

Exploring QHSs in the regime of high carrier densities is interesting for several reasons. First, will native QHSs be oriented along $\langle 110\rangle$ or unconventional $\langle 1\bar{1}0\rangle$ crystal axis as suggested by earlier studies [14,18]? If oriented along $\langle 1\bar{1}0\rangle$, what would be the effect of $B_\parallel$, e.g., will $B_\parallel$ be able to alter orientation of such QHSs? In light of recent evidence that the mechanism favoring parallel-to-$B_\parallel$ QHS alignment is itself anisotropic [25], i.e., it appears sensitive to the direction of $B_\parallel$ with respect to the crystal axes, answering this question may provide an insight not only on this mechanism but also on the native symmetry-breaking potential.

In this paper we investigate QHSs in high density ($n_e > 4 \times 10^{11}$ cm^{-2}) GaAs/AlGaAs quantum wells to determine (i) if QHSs are aligned along the $\langle 110\rangle$ or $\langle 1\bar{1}0\rangle$ crystal axis and (ii) if QHSs can be reoriented by $B_\parallel$ regardless of their initial alignment. Our experiments reveal that our high-density samples exhibit well developed native QHSs with the orientation along the conventional $\langle 110\rangle$ direction. In addition, we find that $B_\parallel$ applied along native stripes produces a *single* reorientation whereas $B_\parallel$ applied perpendicular to QHSs does not alter their orientation. We thus conclude that high n_e alone is not a decisive factor for either abnormal native orientation of QHSs or their ultimate alignment with respect to $B_\parallel$. We suggest that quantum confinement is playing a crucial role in suppressing a symmetry-breaking mechanism which favors QHSs alignment along the in-plane magnetic field.

The 2DEG in sample A (B) resides in a GaAs quantum well of width 24 nm (25 nm) surrounded by $Al_{0.28}Ga_{0.72}As$ barriers. Sample A (B) utilized Si doping in narrow GaAs doping wells surrounded by thin $Al_{0.8}Ga_{0.2}As$ layers and positioned at a setback distance of 73 nm (80 nm) on both sides of the GaAs well hosting the 2DEG. After a brief low-temperature illumination, sample A (B) had the density $n_e \approx 4.1 \times 10^{11}$ cm^{-2} ($n_e \approx 4.3 \times 10^{11}$ cm^{-2}). Low-temperature mobility was estimated to be $\mu \approx 1.2 \times 10^7$ cm^2 V^{-1} s^{-1} in sample A and $\mu \approx 0.9 \times 10^7$ cm^2 V^{-1} s^{-1} in sample B. Both samples were 4×4 mm squares with eight indium contacts fabricated at the corners and the midsides. The longitudinal resistances, R_{xx} and R_{yy}, were measured at $T \approx 20$ mK using four-terminal, low-frequency lock-in technique. An in-plane magnetic field (up to $B_\parallel = 16.7$ T) was introduced by tilting the sample about the $\hat{x} \equiv \langle 1\bar{1}0\rangle$ or $\hat{y} \equiv \langle 110\rangle$ axis, in two separate cooldowns.

In Figs. 1(a) and 1(b) we present R_{xx} (solid line) and R_{yy} (dotted line) measured in perpendicular magnetic field

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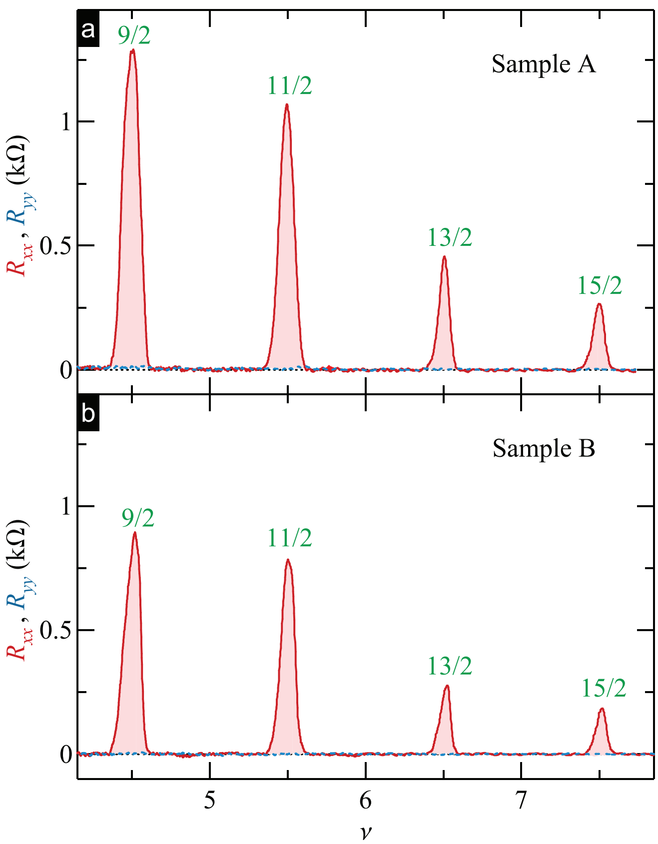

FIG. 1. R_{xx} (solid line) and R_{yy} (dotted line) versus filling factor ν measured in (a) sample A and (b) in sample B at $B_\parallel = 0$.

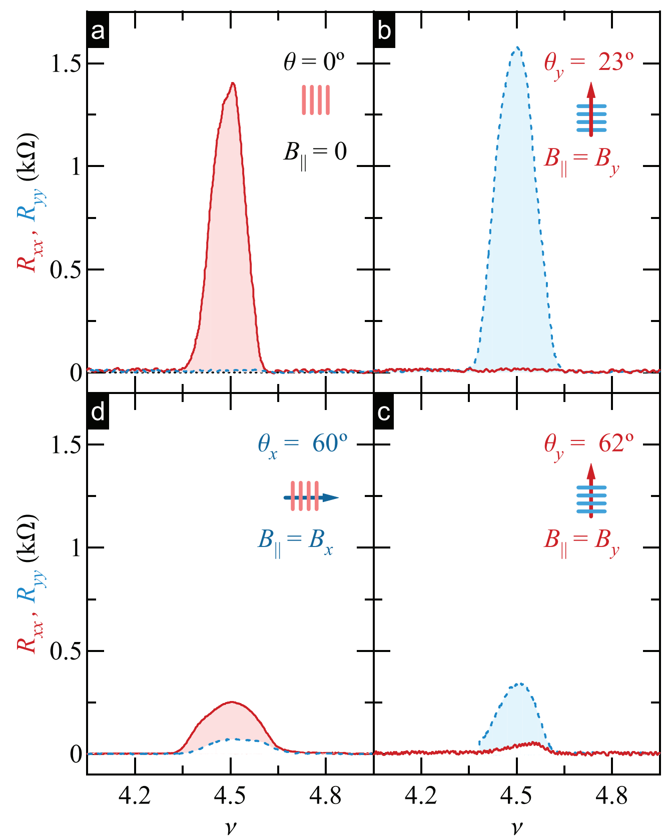

FIG. 2. R_{xx} (solid line) and R_{yy} (dotted line) versus ν in sample A at (a) $\theta = 0^\circ$, (b) $B_\parallel = B_y, \theta_y = 23^\circ$, (c) $B_\parallel = B_y, \theta_y = 62^\circ$, and (d) $B_\parallel = B_x, \theta_x = 60^\circ$.

($B_\parallel = 0$) in sample A and B, respectively, as a function of the filling factor ν covering $N = 2$ and $N = 3$ Landau levels. Both data sets reveal formation of well-developed QHSs, as evidenced by sharp maxima in R_{xx} near $\nu = 9/2, 11/2, 13/2$, and $15/2$ and vanishing R_{yy}. Since $R_{xx} \gg R_{yy}$, we conclude that native QHSs are oriented along the conventional $\hat{y} = \langle 110 \rangle$ crystal axis. Observation of conventional orientation in our samples with $n_e > 4 \times 10^{11}$ cm^{-2} is somewhat surprising in light of previous experiments [14,18] which indicated a transition from $\langle 110 \rangle$ to $\langle 1\bar{1}0 \rangle$ native stripe orientation for densities above 3×10^{11} cm^{-2}. We thus conclude that high density alone is not a decisive factor for native QHS alignment along the $\langle 1\bar{1}0 \rangle$ crystal axis.

Having established native QHS orientation, we now turn to the effect of the in-plane magnetic field. In Fig. 2 we present the results obtained in sample A near $\nu = 9/2$ with $B_\parallel$ applied along either the $\hat{y}$ or $\hat{x}$ direction. Figure 2(a) shows the data at $B_\parallel = 0$ revealing the native QHSs along the $\hat{y} \equiv \langle 110 \rangle$ direction ($R_{xx} \gg R_{yy}$). As shown in Fig. 2(b), when $B_\parallel$ is applied parallel to the native stripes ($B_\parallel = B_y$, $\theta_y = 23^\circ$), R_{xx} and R_{yy} switch places and we find $R_{xx} \ll R_{yy}$ indicating that stripes have been reoriented along the $\hat{x} = \langle 1\bar{1}0 \rangle$ direction (perpendicular to $B_\parallel$). This reorientation is known since the discovery of the QHSs and has been observed in nearly every experiment examining the effect of $B_\parallel = B_y$ [15,19–21,24,25,27]. However, observation of this reorientation in our high-density sample could not be readily anticipated since, as mentioned in the introduction, a recent study in a tunable-density 2DEG has found that the native QHS orientation remained unaffected by $B_\parallel = B_y$, provided that the density is higher than 3.5×10^{11} cm^{-2} [26].

Upon further increase of $B_\parallel = B_y$, stripes preserve their orientation along the $\hat{x} = \langle 1\bar{1}0 \rangle$ direction remaining perpendicular to $B_\parallel$ up to the highest field accessible in our experiment. However, the resistance along the hard (easy) axis eventually decreases (increases) as illustrated in Fig. 2(c) showing the data at $\theta_y = 62^\circ$. On the other hand, when $B_\parallel$ is applied perpendicular to the native stripes ($B_\parallel = B_x$), we observe no QHS reorientation up to the highest tilt angle. As illustrated in Fig. 2(d), at $\theta_x = 60^\circ$, R_{xx} remains larger than R_{yy} although the anisotropy ratio is greatly reduced, similar to what is observed in Fig. 2(c) for $\theta_y = 62^\circ$.

To better illustrate the effect of $B_\parallel$ observed in sample A at $\nu = 9/2$ we construct Fig. 3 which shows the resistance anisotropy $A_R \equiv (R_{xx} - R_{yy})/(R_{xx} + R_{yy})$ as a function of (a) $B_\parallel = B_x$ and (b) $B_\parallel = B_y$. With increasing B_y, A_R stays close to unity up to $B_y \approx 0.5$ T, vanishes at $B_y = B_\parallel^c \approx 0.8$ T, and reaches $A_R \approx -1$ at $B_y \approx 1.1$ T. The anisotropy then remains close to -1 up to $B_y \approx 4.9$ T after which $|A_R|$ starts to decrease reaching $A_R \approx -0.3$ at the highest $B_y \approx 16.7$ T [see Fig. 3(b)]. As a function of $B_\parallel = B_x$, A_R shows a decay and virtually vanishes at $B_x \approx 16.7$ T [see Fig. 3(a)] [28].

As we show next, at other half-integer filling factors in $N = 2$ and $N = 3$ Landau levels the response to $B_\parallel = B_y$ is qualitatively the same, although there is some sensitivity

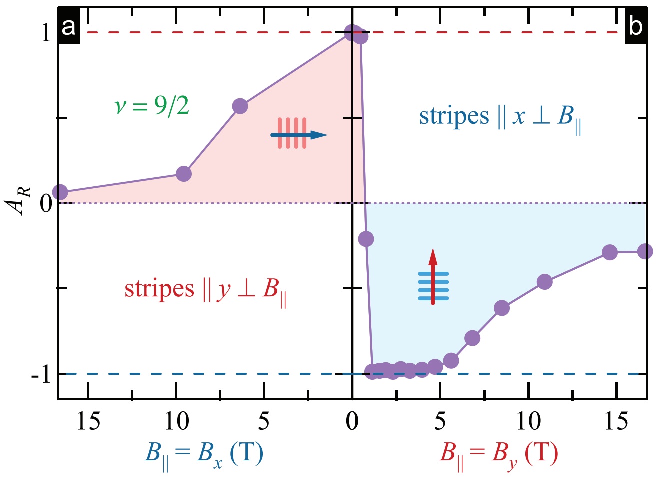

FIG. 3. Resistance anisotropy $A_R \equiv (R_{xx} - R_{yy})/(R_{xx} + R_{yy})$ as a function of (a) $B_\parallel = B_x$ and (b) $B_\parallel = B_y$ at $\nu = 9/2$.

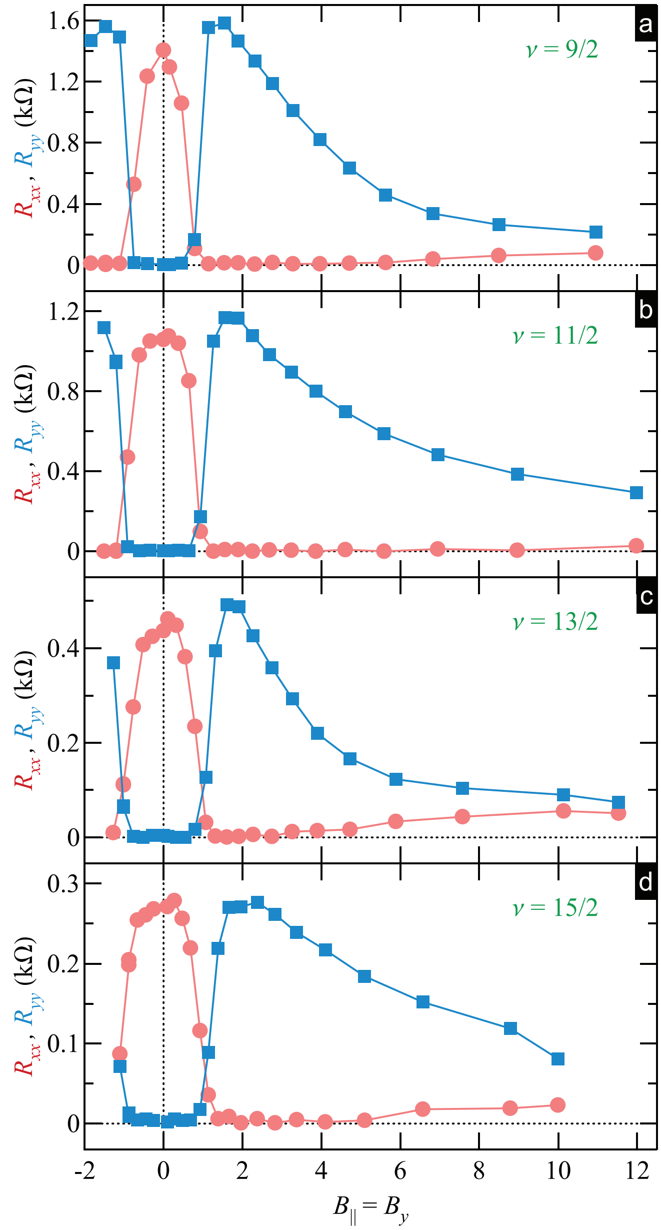

FIG. 4. R_{xx} (circles) and R_{yy} (squares) versus $B_\parallel = B_y$ at (a) $\nu = 9/2$, (b) 11/2, (c) 13/2, and (d) 15/2 measured in sample A.

to the spin index. In Fig. 4 we present R_{xx} (circles) and R_{yy} (squares) versus $B_\parallel = B_y$ at (a) $\nu = 9/2$, (b) 11/2, (c) 13/2, and (d) 15/2 measured in sample A. All data sets reveal one QHS reorientation occurring at $B_\parallel = B_\parallel^c$ which, consistent with the previous study [25], monotonically increases with ν from $B_\parallel^c \approx 0.8$ T at $\nu = 9/2$ to $B_\parallel^c \approx 1.1$ T at $\nu = 15/2$. It is also now clear that even though $A \approx -1$ at 1.1 T $< B_y <$ 4.9 T [see Fig. 3(b)], the hard resistance R_{yy} decreases by a factor of about three within this range at $\nu = 9/2$. As R_{yy} continues to drop with B_y, the decay of $|A_R|$ observed at $B_y >$ 4.9 T in Fig. 3(b) occurs primarily due to the increase of R_{xx} (which remained close to zero at 1.1 T $< B_y <$ 4.9 T).

Even though the data are qualitatively the same at all filling factors, closer examination reveals that the anisotropy ratio at lower spin branches ($\nu = 9/2$ and 13/2) decays noticeably faster with $B_\parallel$ than at upper spin branches ($\nu = 11/2$ and 15/2). While not well understood, sensitivity of the response to $B_\parallel$ to the spin index has been noticed in previous experiments [7,19,25,26]. Since the results obtained from sample B are essentially the same, the observed response of QHSs to $B_\parallel$ in both of our high-density samples is similar to that reported by previous studies employing considerably lower density samples [19–21,26].

At the same time, the evolution of QHSs under applied $B_\parallel$ observed in our high-density samples is qualitatively distinct from that seen in a tunable-density 30-nm quantum well in the higher density regime ($n_e \gtrsim 2.7 \times 10^{11}$ cm^{-2}) [26]. The higher-density 2DEGs in our samples, however, have to reside in narrower quantum wells (24–25 nm) to avoid population of the second electrical subband. It is therefore plausible that quantum confinement plays a crucial role in deciding the reorientation behavior.

Since the reorientation under $B_\parallel$ is believed to be due to finite thickness of the 2DEG, the effect of $B_\parallel$ should become weaker in thinner 2DEGs. In other words, everything else being equal, larger characteristic fields $B_y = B_\parallel^c$ should be needed to reorient stripes in narrower quantum wells. While $B_\parallel^c$ can be affected by other factors, the obvious one being the native anisotropy energy, the observed values of $B_\parallel^c$ in our experiment are in fact two to three times higher than those typically found in symmetric 30 nm quantum wells [25,26]. This finding is in agreement with Ref. [15] which experimentally established strong sensitivity of $B_\parallel^c$ to the separation between electrical subbands.

What is puzzling, however, is that a rather modest decrease of the quantum well width from 30 nm to 25 nm seems to a have a dramatic influence on the reorientation behavior; despite higher n_e and much higher values of $B_\parallel$ reached in our experiment, we find no range of $B_\parallel$ which favors stripes parallel to $B_\parallel$, in contrast to Ref. [26]. This finding indicates that quantum confinement suppresses the mechanism responsible for parallel stripe alignment with respect to $B_\parallel$ much more strongly than the one favoring perpendicular stripes. This suppression seems to fully overwhelm any enhancement anticipated due to higher density [26].

One should note that in the experiment which established that parallel-to-$B_\parallel$ stripes are more likely to occur at higher carrier densities at a given ν, the width of the 2DEG was increasing with n_e as the quantum well became more symmetric under positive voltage applied to the backgate [29]. While complementary measurements of QHS orientations at $\nu = 9/2$ and $11/2$ performed at fixed B_z and $B_\parallel = B_y$ seem to rule out the change of confinement as a primary driver of the transition to a parallel-to-$B_\parallel$ QHS alignment, comparison of spin-up and spin-down branches might not be straightforward even when they belong to the same Landau level [7,25].

In summary, our experiments establish that electron density, while likely relevant, is not a decisive factor for either abnormal native orientation of QHSs or their ultimate alignment with respect to in-plane field. Instead, quantum confinement plays a crucial role in determining QHSs alignment with respect to $B_\parallel$. In particular, we found that the recently identified mechanism which favors QHSs along $B_\parallel$ is strongly suppressed in narrower 2DEGs, despite their considerably higher carrier density. These finding should be useful for future theories aiming to explain what causes a particular QHSs alignment with respect to the in-plane magnetic field. Understanding of the role of the in-plane field might also help to unveil the origin of the native QHS orientation, which remains a long-standing mystery despite continuing efforts.

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[28] At higher filling factors exhibiting QHSs ($\nu = 11/2$, $13/2$ and $15/2$), A_R remains close to unity up to higher $B_\parallel = B_x$ but eventually decreases as well.
[29] On a qualitative level, this observation is in agreement with theoretical considerations [23] predicting QHSs alignment along $B_\parallel$ when 2DEG thickness exceeds a certain value ($\sim$6 nm).