Density Induced Interchange of Anisotropy Axes at Half-Filled High Landau Levels

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We observe density induced 90° rotations of the anisotropy axes in transport measurements at half-filled high Landau levels in the two-dimensional electron system, where stripe states are proposed (ν=9/2, 11/2, etc). Using a field effect transistor, we find the transition density to be 2.9×10^{11} cm^{-2} at ν=9/2. Hysteresis is observed in the vicinity of the transition. We construct a phase boundary in the filling factor-magnetic field plane in the regime 4.4<ν<4.6. An in-plane magnetic field applied along either anisotropy axis always stabilizes the low density orientation of the stripes.

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The physics of electrons in higher Landau levels has recently drawn much attention due to the discovery of large transport anisotropies at half fillings (ν=9/2, 11/2 etc) in high quality two dimensional electron gases (2DEG) in GaAs. At these filling factors, longitudinal magneto resistances R_{xx} of samples grown on (001)-oriented GaAs show strong maxima in the ⟨110⟩ direction and deep minima in the ⟨110⟩ direction. The ratio of the resistance values can exceed 1000:1 in high quality samples. This large anisotropy is viewed as strong evidence for the formation of a unidirectional Charge Density Wave or so called “stripe state” around these filling factors. Calculations based on the Hartree-Fock approximation show the stripes to form as the result of the competition between the short-range attractive exchange interaction and the long-range Coulomb repulsion. Recently there appeared calculations beyond the Hartree-Fock approximation. Some of them propose the existence of liquid crystalline states with stripe ordering and broken rotational symmetry. Employing an edge state transport mechanism, the “easy” (low resistance) axis is along the stripes whereas the “hard” (high resistance) axis is perpendicular to the stripes. This identification is supported by experiments.

In spite of the strong evidence supporting the formation of a stripe state, the origin of its preferred orientation remains poorly understood. Theory does not a priori provide a preferred direction for the stripes. However, all previous experiments have identified the (110) direction as the “easy” axis. It is often assumed that anisotropic imperfections at GaAs/AlGaAs interface act as the native symmetry breaking potential. Anisotropic roughness has been observed in GaAs layers grown by Molecular Beam Epitaxy. Two groups have investigated the correlation between the surface roughness and the orientation of the stripes which form a few thousand A below the surface. Atomic Force Microscope images reveal the presence of roughness elongated along both the ⟨110⟩ and the ⟨110⟩ directions. However, its correlation with the orientation of the stripes remains controversial. Theoretical studies on the influence of a simple periodic modulation on the orientation of the stripes suggest that they prefer to align perpendicular to a weak potential. However, a parallel alignment may occur in the strong potential limit.

Previous experiments that identified the ⟨110⟩ direction as the “easy” axis were limited to fixed densities in the range of 1.5 – 3.0×10^{11} cm^{-2}. Furthermore, the correlation between the orientation of the stripes and the native symmetry breaking potential is difficult to deduce since the latter is likely to vary from specimen to specimen. Employing a tunable density Heterostructure Insulated Gate Field Effect Transistor (HIGFET) in our experiments, we have the unique opportunity to access a wide density regime and to change the 2DEG density in situ without affecting other parameters. Our data show that as the density of the 2DEG is raised above 2.9×10^{11} cm^{-2}, the “easy” axis rotates from the ⟨110⟩ direction to the ⟨110⟩ direction. This result demonstrates that the pinning direction of the stripes is not unique.

Our HIGFET consists of a 600µm square mesa with edges along the ⟨110⟩ and the ⟨110⟩ directions. The structure of the specimen consists of a (001) GaAs substrate, overgrown by MBE with 0.5µm of GaAs. A 50Å layer of AlAs is deposited, followed by a 4000Å layer of Al_{0.33}Ga_{0.67}As and capped by a heavily doped GaAs n+ layer, serving as a top gate. The AlAs layer at the interface with GaAs is intended to improve mobility. Sixteen Ni-Ge-Au contact pads are placed evenly along the edges of the mesa using standard optical lithography. One corner pad provides the contact to the top gate (see inset to Fig.1). Biasing the gate, we are able to continuously change the 2DEG density from 5×10^{9} cm^{-2} to 4.9×10^{11} cm^{-2}. The peak mobility is 1.1×10^{6} cm^{2}/Vsec at 2.3×10^{11} cm^{-2}. The 2DEG density has a reproducible
linear dependence on gate voltage. Only the lowest electronic subband is occupied for the whole density range. Fragile fractional quantum Hall states such as the 5/2 state and those around 3/2 are well developed for a wide range of densities, attesting to the high quality of the sample. The anisotropies at 9/2 and 11/2 are large, enabling us to identify the anisotropy axes unambiguously.

The electrical measurements are carried out in a dilution refrigerator with a base temperature of 20mK using standard low frequency (13-21Hz) lock-in techniques. An excitation current of 10nA is used to avoid electron heating. R_{xx} traces are taken at fixed perpendicular magnetic field while sweeping gate voltage to change density. The left and right panels of Fig. 1 show traces taken at 2.1 Tesla and 3.1 Tesla, respectively. At 2.1T, the 9/2 state occurs at 2.3 \times 10^{11} \text{cm}^{-2}. At 3.1T, it occurs at 3.4 \times 10^{11} \text{cm}^{-2}. The two central insets in Fig. 1 show the two orthogonal contact configurations used to measure the anisotropy [2]. They are labelled \langle110\rangle and \langle110\rangle according to the direction of the current flow. The \langle110\rangle configuration is always represented by a solid line and the \langle110\rangle configuration by a dash-dotted line. In the left panel, at 2.1T, the “easy” axis is along the (110) direction, in agreement with all previous experiments. In the right panel, at 3.1T, the “easy” axis is rotated 90° and points now along the (110) direction. We conclude that the underlying stripe state has also rotated 90° and is now aligned along the (110) direction. This demonstrates that the pinning direction of the stripes is not unique. This observation is the most striking result of our experiments.

Our results indicate that the pinning mechanism of the stripes is more complex than previously assumed. A few conclusions can be drawn. First, contrary to earlier results, a (110) orientation of the stripes does exist in a perpendicular magnetic field. Second, assuming that the stripes are pinned by a unidirectional periodic potential, these stripes can be aligned either parallel or perpendicular to it. Although we do not know the mechanism responsible for the reorientation, we identify several consequences of changing density and discuss their effects. With increasing density, the electron wave function is squeezed and pressed harder against the interface. Therefore, the electrons experience the interface potential more strongly. On the other hand, with increasing density, screening also increases, effectively weakening the interface potential. In addition, the period of the stripes, calculated to be a few magnetic lengths at \nu = 9/2 [3], decreases with increasing density. Any of these factors could lead to the observed reorientation of the stripes [20]. Furthermore, we can not rule out the possibility of the coexistence of two orthogonal periodic potentials in our sample. Changing the period of the stripes could shift the relative effectiveness of these two potentials and may cause a reorientation.

To find the transition density for the reorientation of the stripes, we take density sweeps at fixed magnetic fields from 2.0T to 3.3T in steps of 0.1T and identify the corresponding density \nu = 2.9 \times 10^{11} \text{cm}^{-2} as the transition point at \nu = 9/2. From 2.2T to 3.0T, we observe hysteresis between density up-sweeps and down-
sweeps in a narrow range of filling factors ($\Delta \nu \sim 0.2$) around $9/2$. As an example, Fig. 2a and b show the hysteresis at 2.6T and 40mK in both contact configurations. Sweep directions are indicated by arrows and the hysteretic area is hatched. The hysteresis decreases with increasing temperature and disappears altogether at 90mK while the anisotropy remains although it is weaker. These 90mK data unambiguously identify the orientation of the stripes in close vicinity to $\nu = 9/2$. Fig. 2c shows the area of the hysteresis loop in the $\langle 1\bar{1}0 \rangle$ configuration at 40mK as a function of magnetic field. It peaks near 2.5T and vanishes at 2.1T and 3.0T. In Fig. 2d, we plot the range of the hysteretic behavior in the $\nu$-B plane. This hysteresis “ellipse” is bounded by $\nu = 4.4$ and $\nu = 4.6$, which coincides with the filling factor range in which the stripe state is expected to exist theoretically.

In general, the presence of hysteresis indicates a first order phase transition. As the system crosses the transition point, the initial phase continues to survive due to some pinning mechanism. In our sample, the phase transition corresponds to the reorientation of the stripes while impurities act as the pinning mechanism. In the $\nu$-B plane, the stripe state exists in a horizontal band between $\nu=4.4$ and $\nu=4.6$. The hysteresis “ellipse” is embedded within this band, indicating the transition region. To the left of the “ellipse”, the stripes have the $\langle 1\bar{1}0 \rangle$ orientation. To the right of the “ellipse”, the stripes have the $\langle 1\bar{1}0 \rangle$ orientation. Therefore, the boundary separating the two phases must stretch through the whole bubble from the left side to the right side. We know from the 90mK data that the boundary intercepts the $\nu = 4.5$ line at 2.7T. Furthermore, the orientation of the stripes along the border of the hysteresis “ellipse” can be deduced from data such as Fig. 2a and b since hysteresis always prolongs the initial phase. For example, at 2.6T, on density up-sweeps, the stripes are along the $\langle 1\bar{1}0 \rangle$ direction, as seen from the minimum in the $\langle 1\bar{1}0 \rangle$ configuration and the maximum in the $\langle 1\bar{1}0 \rangle$ configuration. This indicates that the stripes near $\nu = 4.4$ have the $\langle 1\bar{1}0 \rangle$ orientation. Conversely, density down-sweeps indicate the stripes near $\nu = 4.6$ have the $\langle 1\bar{1}0 \rangle$ orientation. Similar identifications can be made for most other points along the border of the hysteresis “ellipse”. From these inputs, we conclude that the phase boundary must run from the lower left to the upper right of the “ellipse”, intercepting the $\nu = 4.5$ line at 2.7T. Although the exact position of the phase boundary can not be derived from our data, a straight line as shown in Fig. 2a indicates its general position. Within the $4.4 < \nu < 4.6$ band, the stripes align along the $\langle 1\bar{1}0 \rangle$ direction to the left of the boundary. To the right of the boundary, the stripes align along the $\langle 1\bar{1}0 \rangle$ direction. This analysis provides a phase diagram for the stripes around $\nu = 9/2$. Hystereses with much smaller areas are also observed around $\nu = 11/2$.

It remains unclear why in previous studies samples with densities inside the transition region of Fig. 2d neither show the $\langle 1\bar{1}0 \rangle$ orientation nor the hysteresis. It suggests the importance of the individual sample details. Along this line, the thin AlAs layer at the interface may play a role in establishing the specific transition density.

The application of an in-plane magnetic field has become a useful tool in investigating the native symmetry breaking potential since it gives us additional control over the orientation of the stripes. In previous fixed density samples, the stripes always aligned perpendicular to a sufficiently strong ($>0.5T$) in-plane field $B^p$. This means that an in-plane field parallel to the $B^p=0$ orientation of the stripes reorients the stripes to the perpendicular alignment.

We apply an in-plane magnetic field $B^p$ to the 2DEG by rotating the HIGFET in situ in our dilution refrigerator. Two cooldowns are required to align $B^p$ along the $\langle 1\bar{1}0 \rangle$ or the $\langle 10 \rangle$ direction respectively. The rotor assembly is able to reach a base temperature of 70mK. Tilting angles were determined from a calibration of the rotator and from positions of well defined QHE and FQHE minima. The accuracy is better than 1°. By sweeping density at a fixed angle, i.e. fixed perpendicular magnetic field, $B^p_{\perp}$, and fixed $B^p$, we determine the orientation of the stripes at $\nu = 9/2$. Fig. 3 shows the phase diagram in the $B^p_{\perp}$-$B^p$ plane constructed from such data. The left panel represents data taken with $B^p$ along the $\langle 1\bar{1}0 \rangle$ direction. The right panel represents data taken with $B^p$ along the $\langle 10 \rangle$ direction. A $\langle 1\bar{1}0 \rangle$ orientation of the stripes is represented by a hollow triangle and a $\langle 10 \rangle$ orientation by a solid square.
In order to assess the properties of the phase diagram, we first focus on the $B_{\text{ip}}=0$ axis which simply reflects the reorientation of the stripes discussed earlier: below $B_{\text{ip}}=2.7T$ (equivalent to $n=2.9 \times 10^{11}\text{cm}^{-2}$, right axis), the stripes have the $\langle 110 \rangle$ orientation whereas above 2.7T, the $\langle 110 \rangle$ orientation prevails. As we increase $B_{\text{ip}}$ along either the $\langle 110 \rangle$ or the $\langle 110 \rangle$ direction, the $\langle 110 \rangle$ to $\langle 110 \rangle$ transition moves to higher densities. The density shift indicates a $B_{\text{ip}}$ induced energy gain of the $\langle 110 \rangle$ phase. It can be viewed as a sum of two terms: an isotropic term and an anisotropic term. The isotropic term is independent of the direction of $B_{\text{ip}}$. The anisotropic term reflects the difference in energy gain between a $B_{\text{ip}}$ parallel to the stripes and a $B_{\text{ip}}$ perpendicular to the stripes. Two conclusions can be drawn from the phase diagram. First, the roughly symmetric shape of the phase boundary indicates that in our sample, the dominant in-plane magnetic field effect is an isotropic energy gain of the $\langle 110 \rangle$ phase. The anisotropic term only becomes significant for $|B_{\text{ip}}| > 0.4T$. Second, in the high $B_{\text{ip}}$ regime, in the right panel, the transition to the $\langle 110 \rangle$ phase occurs at lower densities than in the left panel. From this, we conclude that stripes oriented parallel to $B_{\text{ip}}$ are energetically favored as compared to stripes oriented perpendicular to $B_{\text{ip}}$. Both conclusions are in contrast to previous fixed density samples where the anisotropic term, which favors a perpendicular alignment of the stripes with respect to $B_{\text{ip}}$, dominates. Together with previous results, we must conclude that the reaction of the stripes to an in-plane magnetic field is non-universal and sensitively depends on the details of individual samples. The unique density tunability of a HIGFET is essential to such a systematic study. In fact, diverse behaviors are seen even within one specimen. As an inset to Fig. 2, we show the phase diagram of the 11/2 state, constructed during the same cooldowns as the 9/2 state using the same method. The $B_{\text{ip}}=0$ transition also occurs at ~2.7T. We can clearly see that the isotropic behavior observed at $\nu=9/2$ is missing. The differences between the behaviors of the 9/2 state and the 11/2 state strongly attest to the subtlety of the interactions involved. Examining other half-fillings, we note that the isotropic states of $\nu=5/2$ and $\nu=7/2$ become anisotropic in an in-plane field and the “hard” axis is always along the in-plane field direction. This is consistent with previous experimental findings and theoretical calculations.

In summary, we have observed a density induced reorientation of the stripe state at $\nu=9/2$. As the density of the 2DEG is raised above $2.9 \times 10^{11}\text{cm}^{-2}$, the stripes rotate from the $\langle 110 \rangle$ orientation to the $\langle 110 \rangle$ orientation. Our results demonstrate that the pinning direction of the stripes is not unique.

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