Current Path Properties of the Transport Anisotropy at Filling Factor 9/2

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Abstract

To establish the presence and orientation of the proposed striped phase in ultra-high mobility 2D electron systems at \( \nu = 9/2 \), current path transport properties are determined by varying the separation and alignment of current and voltage contacts. Contacts aligned orthogonal to the proposed intrinsic striped phase produce voltages consistent with current spreading along the stripes; current driven along the proposed stripe direction results in voltages consistent with channeling along the stripes. Direct comparison is made to current spreading/channeling properties of artificially induced 1D charge modulation systems, which indicates the 9/2 stripe direction.

Since the demonstration of anisotropic transport at 9/2 filling factor \(^{[1,2]}\), considerable effort has been made to understand the underlying physical mechanism. The fundamental finding of these measurements is a peak in the longitudinal magnetoresistance at 9/2 for current driven along the [1 \( \bar{1} \) 0] direction, but a minimum there for current driven and voltage measured across this direction. The total anisotropy can be dramatic, with peak to minimum ratios at 9/2 large at low temperatures. Similar results are observed at higher filling factors 11/2, 13/2, and 15/2. These results were found only in high mobility systems \( \mu > 10^7 \text{cm}^2/\text{V-sec} \), and at low temperatures \( \leq 100 \text{mK} \), suggesting electron correlations as the origin of the effect. These experimental results are supplemented by findings at 9/2 that include non-linear I-V \(^{[3]}\) and induction of a peak in resistance for large in-plane magnetic field \(^{[3]}\).

The theoretical picture of this phenomenon has focused on the formation of charged stripes \(^{[5]}\), and has as its basis Hartree-Fock theory. It is proposed that in the middle of the high Landau levels, energetics favor separation of the otherwise homogeneous 2D system into stripes of different filling factors: at 9/2 the 2D gas separates into a unidirectional charge density wave comprised of stripes of alternating filling factors 4 and 5. These stripes are presumed to orient along the [1 1 0] direction \(^{[5]}\), resulting in a resistance peak for current driven and voltage measured across this direction, and a resistance minimum at 9/2 for current and voltage along this direction. Away from 9/2 it has been further proposed that the stripes may break in a bubble phase, with one integral filling forming a bubble within a background of the next near integral filling factor. This Hartree-Fock picture has gained substantial support in numerical studies \(^{[7]}\) that extract distinct peaks in both the static density susceptibility and the density-density correlation in the ground state, strongly
suggesting charge density wave ordering.

To date, no measurements have specifically demonstrated charge stripe formation. Re-entrant Hall resistance has been shown to occur around 9/2 filling [4], supporting the picture of two phases coexisting. The most specific experimental indication of the picture of stripe phase formation is a measurement of the reorientation of anisotropy in a square quantum well sample [8]. In this work, a theoretical calculation based upon unidirectional charge density waves predicts the values of in-plane B-field needed to induce and then re-orient anisotropy in magnetoresistance of a multiple electronic sub-band system. The ability of this model to accurately describe such a complex experimental process, in addition to the previous numerical work [7], indirectly indicates the stripe phase formation.

At present there exists some question as to which direction the proposed striped phase is aligned. At 9/2, certain models predict that the stripes of filling factor 4 and 5 are aligned along the [1 1 0] direction [5,6]. This orientation implies that the high resistance state is due to transport across the lines of alternating integral filling factor, and the low resistance state is for current along the lines. Other theories [9], based upon Chern-Simon constructions, predict an orientation of the stripes consistent with this. Also, a natural band anisotropy exists in AlGaAs/GaAs heterostructures [10], and it is proposed that the orientation of the phase separation is determined by this intrinsic feature. Given these purely theoretical descriptions, the orientation of these phases is an open experimental concern.

In this letter, we present new transport results on exceedingly high mobility 2D systems demonstrating magnetoresistance which is consistent with current spreading and channeling as heuristically expected in a picture of stripe phase formation. In addition, these results at high Landau levels are shown to be similar to the current path properties measured in magnetotransport in artificial 1D charge modulated systems: by comparison of these two experimental systems the direction of the stripe formation is inferred. These results provide a direct experimental connection between the proposed striped phase ground state and the magnetotransport properties of a charge striped system.

A series of four samples from two different wafers were used in this study. Mobility ranges from $23 \times 10^6$ cm$^2$/V-sec to $28 \times 10^6$ cm$^2$/V-sec, in excess of sample mobilities used in previous measurements addressing 9/2 transport [3,4]. Contacts to the 2D electron system were either diffused indium or lithographically defined and diffused nickel/gold/germanium. All contacts are less than 300 µm at their widest dimension, with lithographically defined contacts less than 50 µm. Standard lock-in measurement at low frequencies was used, and the samples were cooled in a dilution or He3 refrigerator.

Figures 1(a) and 1(b) demonstrate the transport anisotropy found in these samples of high quality. In 1(a) the inset describes current and voltage contact configurations, with the sample square about 5mm on each side and the contacts separated on the edges by more than 1 mm. For constant current driven along the [1 1 0] direction in the two different voltage tap configurations a peak is observed at half-integral filling for the high Landau levels ($\nu > 4$): this is as has been observed in previous transport studies. In Figure 1(b) the transport anisotropy is recognized in the black trace, where the current is driven across [1 1 0] through contacts near the center of the sample sides. As observed previously, for transport across [1 1 0] a distinct minimum is seen at half-integral filling of the high Landau levels. Using the same voltage contacts but now moving the current source and drain to the same edge of the sample produces a peak at 9/2 that is qualitatively similar to that
observed for transport in the orthogonal direction. Note that the anisotropy is therefore not apparent if transport is examined only along the sample edges. This is as expected for this contact topology along the single edge of the sample; the measured resistance should consist of a mixture of the microscopic resistivities in the form of $\sqrt{\rho_{xx}\rho_{yy}}$, where in this model small contacts are located on an infinite edge \[\square\]. Tests of the 9/2 anisotropy in this study involve systematically examining the magnetoresistance, or voltage distribution, from a constant drive current for different current/voltage separations of the same topology as the black traces in Figure 1.

By varying the relative positions of the current and voltage taps, the current distribution can be coarsely deduced. This is particularly elucidating in a simple anisotropic conductor. In assuming an ohmic yet anisotropic conductor, the voltage measured at any contact pair is proportional to the current that reaches that contact set, which is dependent upon the current distribution as established by both the current source/drain positions and the intrinsic anisotropic resistivity of the conductor. In the set of transport traces shown in Figure 2 voltage is measured between contacts alligned along either the [1 1 0] direction (a), or along the [1 1 0] direction (b), with current contacts used for each trace systematically further away from the voltage leads as shown in the inset. Again, the sample used here is about 5mm long on each side. The data taken in the two orthogonal directions show what can be interpreted as current spreading for transport in one direction but relative current channeling in the orthogonal direction. Figure 2a shows little variation in the peak at 9/2 for measurement configurations where the current and voltage leads are progressively separated by more than a factor of three in distance. An interpretation of these results is that current driven in the [1 1 0] direction spreads orthogonally (along [1 1 0]) specifically for filling factor 9/2 such that the voltage drop along [1 1 0] is relatively independent of the proximity of the current source. This implies as well that at 9/2 current driven along [1 1 0] should be channeled along that direction with a substantial reduction in measured voltage for increasing spatial separation between current and voltage contacts. This is consistent with the results in Figure 2b. The peaks adjacent to 9/2 demonstrate large changes as the separation of current and voltage contacts increases. However, specifically at 9/2 the voltage detected appears to be small (or zero) for all transport configurations.

To more closely examine the properties of this transport orthogonal to [1 1 0] a configuration with closely spaced contacts was employed. The schematic of Figure 3 shows a sample with four contacts spaced 0.5mm center to center on opposite sides of a high mobility structure with width of 5mm and crystallographic orientation as shown. Variation in voltage detected for different current to voltage contact distances is dramatic. For current driven orthogonal to [1 1 0] but with only a 0.5mm separation between I and V contacts a large peak is observed at 9/2, similar to that seen in magnetoresistance in the orthogonal direction. However, as the separation of current and voltage leads is increased the voltage measured decreases substantially: at 1.0 mm separation a remnant peak is observed at 9/2. At 1.5mm separation no significant voltage is measured at 9/2, as observed in the data of Figure 2. For this sample orthogonal transport (current driven along [1 1 0]) showed results similar to Figure 2a. These findings demonstrate a striking dependence of the voltage measured upon the proximity to current source/drain for transport along [1 1 0], but show that the voltage detected in the [1 1 0] direction for current in that direction is roughly independent of the proximity to the current contacts.
These results are consistent with the 9/2 state inducing substantial current spreading along [1 1 0] for current driven along [1 1 0], and also inducing the complementary case of current channeling along [1 1 0] for current driven along that direction. This current pattern is as expected for a simple anisotropy in magnetoconduction at 9/2 where a relatively high resistance path is observed along [1 1 0] and a less resistive path occurs along [1 1 0]. If a charge separation into a striped phase is at the root of these findings, then examining the current pattern of an artificially induced striped system should reveal similar current path properties. Magnetotransport for an artificially striped 2D system is shown in Figure 4. This sample is a high mobility 2D heterostructure with a 1D charge modulation induced by a shallow etch of the sample surface in the pattern of parallel lines with a 1.2 $\mu$m period. For current driven along the artificial lines (Fig. 4a) a large change is observed in measured voltage as current and voltage contacts are separated. This is true throughout the magnetic field spectrum, for both the fractional and integral quantum Hall regimes as shown in the insets. By comparison, for current driven orthogonal to the artificial lines, a substantially smaller change is observed in the measured voltage as the current and voltage contact separation is increased (Fig. 4b). In progressing from the smallest to largest current/voltage contact separations the ratio of measured voltage at filling factors 3/4 and 9/2 is about 10 for current driven along the artificial lines; for current across the lines this ratio is about 2. This contrast between transport along or across the artificial lines is amplified at lower temperatures. The data of Figure 4 clearly demonstrate that charge lines, artificially induced here, produce lateral current spreading if the current is driven orthogonal to the lines, and produce current channeling if current is driven along the lines. This same current distribution pattern is the essential finding in the higher Landau levels as shown in Figures 1-3, and by direct comparison to the transport in the artificial system it is inferred that the intrinsic lines of the 9/2 striped phase form parallel to the [1 1 0] direction.

While the direction of the intrinsic striped phase lines can be derived from this comparison to the fabricated 1D charge modulation, it remains unclear what sets the preferred direction of the intrinsic stripes along [1 1 0].

To summarize, current paths have been measured using varied current and voltage lead spatial separations on high mobility 2D systems in the high Landau levels where transport anisotropies have been observed, and these results are compared to magnetotransport in an artificially striped 2DES. Specifically at the high Landau level half-filling, current spreading is observed when current is driven along the [1 1 0] direction, indicating that a barrier to current propagation exists along the [1 1 0] direction as may be attributable to the intrinsic stripe phase. When current is driven along the [1 1 0] direction, current channeling is observed, wherein only small voltages are measured away from the current contacts. These current path properties are shown to be similar to an artificially induced charge striped system at high magnetic fields, allowing deduction of the stripe phase direction for the intrinsic, high Landau level states.

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FIGURE CAPTIONS

Figure 1. Transport along the edges of a high mobility \(23 \times 10^6 \text{cm}^2/\text{V-sec}\) 2D heterostructure (sample A) with contact configurations as shown in the inset to a). The sample dimension is 5mm on each side. Temperature is 65mK.

Figure 2. Transport in sample B \((\mu = 23 \times 10^6 \text{cm}^2/\text{V-sec})\) with systematically larger separation of voltage and current contacts for the two orthogonal directions as shown in the inset. Note that voltage measurements with current driven across [110] show almost no variation, in contrast to current driven orthogonally. The sample is again 5mm X 5mm. Temperature is 65mK.

Figure 3. Transport in higher mobility 2DES \((28 \times 10^6 \text{cm}^2/\text{V-sec},\ \text{sample C})\) with current driven along [110] and progressively larger separation of current and voltage contacts. The separation of nearest contacts is 0.5mm center to center, and the sample width is 5mm. Temperature is 65mK.

Figure 4. Effect of changing separation of current and voltage contacts in a 2DES with a 1.2 \(\mu\)m period density modulation along the lines as shown in the inset. Shown in the insets are respective transport at low B-fields in these modulated samples. Current channeling for current driven along the imposed lines is apparent by the precipitous change in measured voltage throughout the magnetic field spectrum in the traces shown in a. Labeled voltage scales are consistent between a and b. Temperature is 290mK.
Figure 1
Figure 2
Figure 3
Figure 4