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Onset of anisotropic transport of two-dimensional electrons in high Landau levels: Possible isotropic-to-nematic liquid-crystal phase transition

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The recently discovered anisotropy of the longitudinal resistance of two-dimensional electrons near half filling of high Landau levels is found to persist to much higher temperatures T when a large in-plane magnetic field $B_\parallel$ is applied. Under these conditions we find that the longitudinal resistivity scales quasilinearly with $B_\parallel/T$. These observations support the notion that the onset of anisotropy at $B_\parallel=0$ does not reflect the spontaneous development of charge density modulations but may instead signal an isotropic-to-nematic liquid-crystal phase transition.

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Transport experiments[1,2] on clean two-dimensional electron systems (2DES) at high perpendicular magnetic field have recently revealed a new class of collective phases at low temperatures. These new phases, which have been observed only when electrons occupy the excited Landau levels, are quite different from the fractional quantized Hall liquids found almost exclusively in the lowest ($N=0$) Landau level.[3] The new phases exhibit strong electrical transport anisotropies near half filling and curious re-entrant insulating behavior in the flanks of the third and higher ($N\geqslant 2$) Landau level (LL). At the phenomenological level, these properties are remarkably consistent with those expected from the "stripe" and "bubble" charge-density waves (CDW) predicted on the basis of Hartree-Fock (HF) theory.[4,5] These inhomogeneous states are stabilized by an exchange-energy-driven tendency to phase separate which is particularly effective in the excited LLs. Near half filling, the ground state is approximately a unidirectional CDW, i.e., a stripe phase. The anisotropy of the longitudinal resistance observed at this filling is presumed to result from very different electrical conductivities parallel and perpendicular to stripes whose orientation relative to the crystal axes of the host semiconductor is determined by some, as yet unknown, symmetry-breaking field.

With the filling factor ν defined as the ratio of the 2D electron density n_s to the degeneracy eB/h of a single-spin-resolved LL, the simplest HF stripe state consists of parallel strips in which the filling factor ν alternates between adjacent integers. For example, at *average* filling $\nu=9/2$, corresponding to half filling of the lower spin branch of the $N=2$ LL, the local filling factor alternates between $\nu=4$ and $\nu=5$. The period of this alternation is set by the competition between the direct and exchange Coulomb interactions and is estimated to be on the order of 100 nm in typical samples. These same interactions also determine the temperature at which the stripes form, and HF estimates are in the few Kelvin range.[4] This contrasts with the experimental observation that resistive anisotropy only sets in below about 100 mK. Although disorder in the 2D system may account for some of this discrepancy, a more interesting idea is that the onset of anisotropy does not in fact signal the initial development of charge-density modulation, but instead reflects the orientational ordering of local regions having pre-existing stripe order. This idea, suggested by Fradkin and Kivelson,[6] emerges naturally from the view that quantum and thermal fluctuations destroy the long-range translational order of the stripe phases and render them analogous to nematic liquid crystals. The onset of anisotropy is therefore viewed as an isotropic-to-nematic phase transition. Wexler and Dorsey[7] have estimated the transition temperature to be on the order of 200 mK, not far from the experimental result. In this paper, we report temperature-dependent magneto-transport studies which address this issue. Our results reveal that the sharp thermal onset of resistive anisotropy is replaced by a heavily smeared transition when a strong in-plane magnetic-field component $B_\parallel$ is added to the existing perpendicular field. This observation, which is reminiscent of the behavior of a ferromagnet in a strong symmetry-breaking field, supports the isotropic-to-nematic liquid-crystal transition idea. In addition, we report an intriguing scaling of the resistive anisotropy with $T/B_\parallel$ which may prove important in developing a quantitative understanding of the putative nematic phase.

The sample used for the present experiments is a conventional single-interface GaAs/$Al_xGa_{1-x}As$ heterojunction grown by molecular-beam epitaxy (MBE) on an [001]-oriented GaAs substrate. A thin sheet of Si impurities is positioned in the $Al_{0.24}Ga_{0.76}As$, 80 nm from the interface with the GaAs. Charge transfer from these donors results in a 2DES whose density and low-temperature mobility are $n_s=1.48\times10^{11}\ \mathrm{cm}^{-2}$ and $\mu=1.1\times10^{7}\ \mathrm{cm}^2/\mathrm{Vs}$, respectively. These parameters are obtained after brief low-temperature illumination of the sample by a red-light-emitting diode. The sample itself is a 4×4 mm square cleaved from the parent wafer. The edges of this square are parallel to the [110] and $[1\bar{1}0]$ crystallographic directions. Eight diffused In Ohmic contacts are positioned at the corners and midpoints of the sides of the sample. Longitudinal resistance measurements are performed by driving a 20 nA, 13 Hz ac current between opposing midpoint contacts and detecting the resulting voltage between corner contacts. We denote by R_{xx} and R_{yy} the resistances obtained for average current flow parallel to the

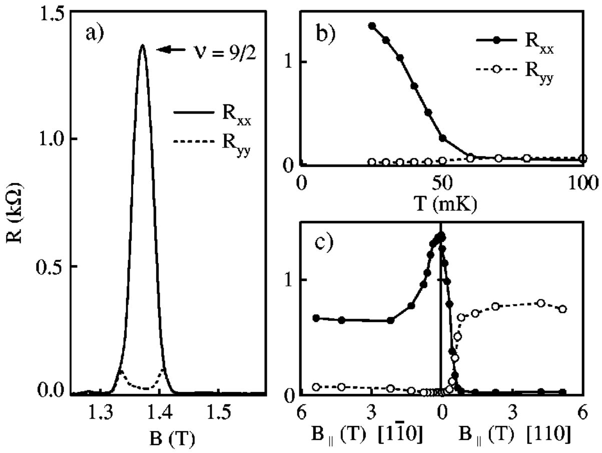

FIG. 1. (a) Longitudinal resistance anisotropy around $\nu=9/2$ at $T=25$ mK. Solid trace: R_{xx}; average current flow along $[1\bar{1}0]$ crystallographic direction. Dashed trace: R_{yy}; average current flow along $[110]$. (b) Temperature dependence of resistances at $\nu=9/2$. (c) R_{xx} and R_{yy} at $\nu=9/2$ at $T=25$ mK vs in-plane magnetic field along $[110]$ and $[1\bar{1}0]$.

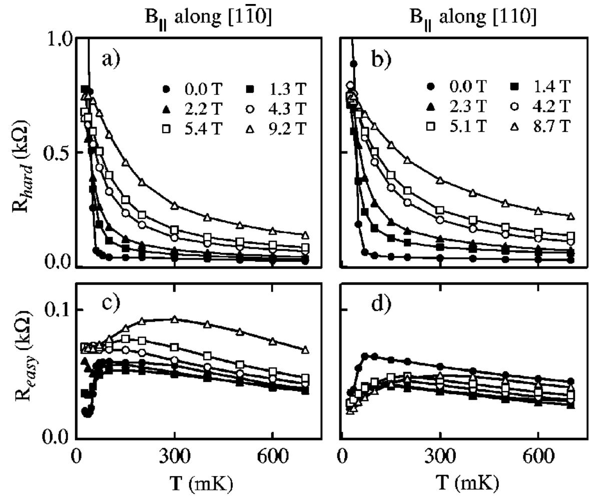

FIG. 2. Temperature dependencies of longitudinal resistance in hard and easy directions at $\nu=9/2$. (a) and (b): R_{hard} vs T for various in-plane magnetic fields $B_{\|}$ directed along $[1\bar{1}0]$ and $[110]$, respectively. (c) and (d): Analogous results for R_{easy}. Note magnified vertical scale.

$[1\bar{1}0]$ and $[110]$ directions, respectively. Adjustable in-plane and perpendicular magnetic fields are obtained by *in situ* tilting of the sample relative to the field B of a single superconducting solenoid.[8]

Figure 1(a) summarizes the resistance anisotropy effect observed around filling factor $\nu=9/2$. The solid and dashed curves represent R_{xx} and R_{yy}, respectively, at $T=25$ mK in a purely perpendicular magnetic field (i.e., $B_{\|}=0$). The anisotropy is largest at half filling, where R_{xx}/R_{yy} reaches a value of approximately 60 mk in this sample. As Fig. 1(b) shows, raising the temperature causes R_{xx} to fall rapidly and R_{yy} to rise somewhat. Above about 60 mK both resistances are saturated at values less than 60 Ω. This transport anisotropy is also present at filling factors $\nu=11/2, 13/2, 15/2$, etc., albeit with decreasing strength. As reported previously,[1,2] no anisotropy is observed in the $N=1$ first excited Landau level[11] nor in the $N=0$ lowest LL.

An in-plane magnetic field can alter the orientation of the resistive anisotropy in high Landau levels.[9,10] Figure 1(c) summarizes this effect by displaying the dependences of R_{xx} and R_{yy} at $\nu=9/2$ and $T=25$ mK on $B_{\|}$. In the right half of the panel, $B_{\|}$ is directed along the $[110]$ direction; in the left half it is along $[1\bar{1}0]$. For $B_{\|}$ along $[110]$, R_{xx} quickly falls to a small value just as R_{yy} quickly rises to a large value: The in-plane field interchanges the ''hard'' and ''easy'' transport directions. On the other hand, with $B_{\|}$ directed along $[1\bar{1}0]$, no such interchange occurs. These data demonstrate that large in-plane fields can overwhelm the native symmetry-breaking potential in the sample and force the hard resistance direction to be parallel to the in-plane field. Jungwirth *et al.*[12] have argued that this effect arises from the finite thickness of the 2DES. For samples such as the present one, their HF theory reveals an energetic advantage for the stripes to lie perpendicular to the in-plane magnetic field. By comparing the in-plane field required to interchange the anisotropy axes with this theory, an estimate of the native anisotropy energy may be obtained: Typical values are around 1 mK per electron.[13]

Figures 2(a) and 2(b) display the temperature dependencies of the longitudinal resistance in the hard and easy directions, R_{hard} and R_{easy}, at $\nu=9/2$. The data in Fig. 2(a) were taken with the in-plane magnetic field directed along $[1\bar{1}0]$. In this case, the in-plane field does not interchange the principal axes of the resistance anisotropy and thus $R_{hard}=R_{xx}$. For Fig. 2(b), however, the in-plane field is along $[110]$ and therefore *does* interchange the hard and easy directions, provided $B_{\|}>0.5$ T. With the exception of the $B_{\|}=0$ data, the traces in Fig. 2(b) correspond to R_{yy}, which is R_{hard} at the in-plane fields chosen. Figures 2(c) and 2(d) show the corresponding results for R_{easy}, the longitudinal resistance in the easy direction, on a magnified scale. Note that R_{easy} is small compared to R_{hard} for all $B_{\|}$ at low temperatures.

It is clear from Figs. 2(a) and 2(b) that a large $B_{\|}$ systematically broadens out the variation of R_{hard} at low temperatures. At $B_{\|}=0$ the bulk of the change in R_{hard} occurs in a relatively narrow window below $T\approx 60$ mK. In contrast, at $B_{\|}=9$ T, R_{hard} diminishes gradually up to temperatures above 600 mK. This qualitative broadening effect due to the in-plane magnetic field occurs for both orientations of the field relative to the crystal directions. Interestingly, the effect is not obviously present in R_{easy}, although close inspection does reveal some softening at low temperatures.

The thermal broadening of the resistive anisotropy in high Landau levels induced by strong in-plane magnetic fields is reminiscent of the behavior of a ferromagnet in the presence of an external magnetic field.[14] Very weak external fields merely break rotational symmetry and orient the magnetization of the system which otherwise develops spontaneously below the Curie temperature T_c. In the presence of a strong external field, however, the ferromagnetic transition is broadened out in temperature and substantial magnetization is

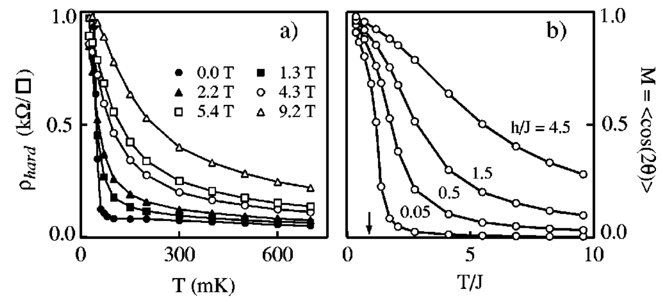

FIG. 3. (a) Temperature dependence of ρ_{hard} at $\nu=9/2$ for various $B_\parallel$ along $[1\bar{1}0]$. (b) Temperature dependence of order parameter of the 2D XY model for various symmetry-breaking fields h/J. Arrow denotes Kosterlitz-Thouless transition temperature for $h=0$.

present at temperatures $T>T_c$. For $T\gg T_c$ the magnetization is that of the free spins in the system. By analogy, our observation that the high Landau level resistive anisotropy persists to high temperatures in the presence of large $B_\parallel$ suggests that local stripe "moments" exist in the 2DES at such temperatures. Lacking a strong symmetry-breaking in-plane field, these moments are disordered at high temperature and transport is isotropic. This scenario is consistent with the nematic-to-isotropic liquid-crystal transition proposed by Fradkin and Kivelson.[6]

To pursue this idea further we have extracted, in an approximate manner, the microscopic *resistivities* of the 2DES from the measured macroscopic *resistances*. As emphasized by Simon,[15] the resistances R_{hard} and R_{easy} in square samples exaggerate the actual anisotropy of the underlying resistivities ρ_{hard} and ρ_{easy}.[16] This stems from the fact that the current distribution in an anisotropic sample is quite different from that in an isotropic one. In particular, currents flowing in the easy direction are channeled in toward the axis connecting the source and drain contacts. As a result, the voltages present at the remote contacts used to determine R_{easy} can be extremely small and therefore particularly sensitive to local inhomogeneities and other defects in the sample. Conversely, current flow in the hard direction is spread out more uniformly across the sample and the voltages used to determine R_{hard} are robust. As a consequence, we will focus our attention on ρ_{hard}.

Figure 3(a) displays the temperature dependence of ρ_{hard} at $\nu=9/2$ for several $B_\parallel$ along $[1\bar{1}0]$. These resistivities were computed from the measured resistances R_{hard} and R_{easy} under the assumption of Simon's[15] classical model of the current distribution in the sample. While this model has shortcomings, its success in reconciling the differences between the resistive anisotropy in square and Hall bar samples suggests that it provides reasonable estimates of the resistivities.[17] In any case, Fig. 3(a) reveals that ρ_{hard} exhibits the same broadening of its temperature dependence as does R_{hard} when a large in-plane magnetic field is applied.

Fradkin *et al.*[6,18] and Wexler and Dorsey[7] have argued that the stripe system undergoes a finite-temperature Kosterlitz-Thouless (KT) transition from an isotropic state possessing only local stripe order to a nematic phase whose director field possesses algebraically decaying correlations. Below the KT transition temperature, the system is singularly susceptible to external symmetry-breaking fields and is thus readily oriented by some (as yet unexplained[13]) weak symmetry breaking field in the GaAs/Al$_x$Ga$_{1-x}$As sample. Fradkin *et al.* have modeled the system as a classical 2D XY magnet, modified to accommodate a director field. The order parameter for the system is taken to be $M=\langle\cos(2\theta)\rangle$, where θ is the angle between the director and an arbitrarily weak symmetry-breaking field h. Using Monte Carlo methods, they have been able to achieve good fits to the observed temperature dependence of the resistive anisotropy at $\nu=9/2$ (in a different sample) using a sensible value of the exchange energy, J, and a weak symmetry-breaking field, $h\sim0.05J$. We have extended these calculations to larger h to simulate the effect of the large in-plane magnetic field used in the present experiments.[19] As Fig. 3(b) shows, the temperature dependence of M is systematically broadened out as h increases, and it bears a strong qualitative resemblance to the behavior of ρ_{hard} (and R_{hard}) at large $B_\parallel$.

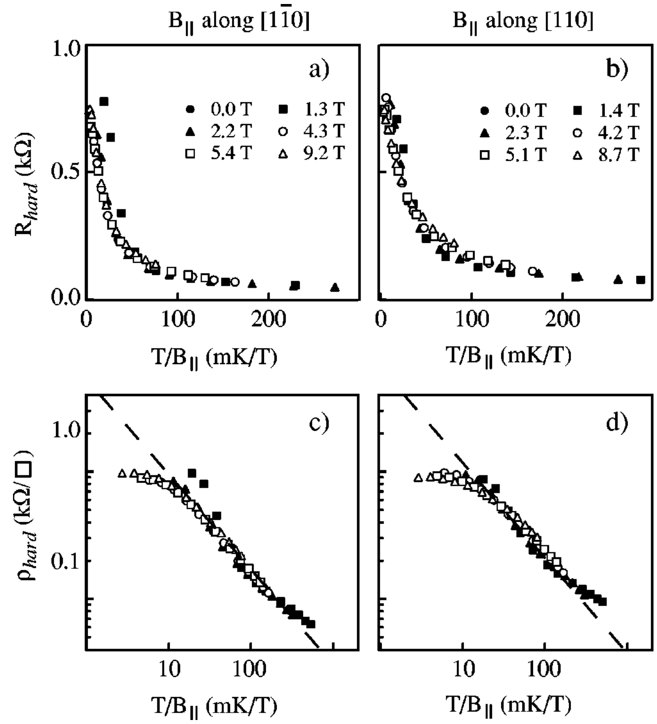

FIG. 4. (a) and (b): R_{hard} vs the scaled temperature $T/B_\parallel$ for $B_\parallel$ directed along $[1\bar{1}0]$ and $[110]$, respectively. (c) and (d): Log-log plot of the hard axis resistivity, ρ_{hard}, calculated from the measured resistances, vs $T/B_\parallel$. Dashed lines are power laws: $\rho_{hard}\propto(T/B_\parallel)^{-\alpha}$ with $\alpha=0.75$.

We turn now to an intriguing scaling property exhibited by the longitudinal resistance R_{hard}. Figures 4(a) and 4(b) display the same R_{hard} data plotted against the *scaled* temperature $T/B_\parallel$ (for nonzero $B_\parallel$). Plotted in this way, the data collapse onto a single curve with impressive precision. Figures 4(c) and 4(d) show log-log plots of the computed resistivities ρ_{hard} vs $T/B_\parallel$ and again the scaling is evident. This result demonstrates that the hard resisitivities depend on temperature and in-plane field only through the ratio $T/B_\parallel$. The log-log plots reveal that this dependence is quasilinear: The dashed lines in the figure are proportional to $(T/B_\parallel)^{-0.75}$.

However, this specific functional form should be interpreted with caution because the data of Figs. 4(a) and 4(c) cover only a limited dynamic range. We note in passing that the easy direction resistance R_{easy} does not exhibit this scaling behavior. Although the origin of this difference is not known, it may be related to the aforementioned current-channeling effects which are inherent to transport in anisotropic conductors.

The connection between the scaling behavior of R_{hard} and the nematic-to-isotropic phase transition picture is not yet understood. While at sufficiently high temperature T, solutions to the 2D XY model must eventually approach a Curie law $M \sim h/T$, this limiting behavior is not well developed in the (h,T) parameter range which seems most relevant to our experimental data. On the other hand, a quantitative comparison of the 2D XY model with our data is hindered by several factors. For example, the relation between the symmetry-breaking parameter h and the in-plane magnetic field $B_{\parallel}$ is subtle and highly sample-specific.[12] Also, $B_{\parallel}$ may affect the transport mechanism of current along and across the stripes to some degree. Even the appropriateness of the classical 2D XY model itself can be questioned, and a more relevant model may require an incorporation of quantum fluctuations.[20] We emphasize, however, that the experimental observation of scaling is robust and offers a new insight into the nature of the anisotropic phases.

In the picture outlined above, the essential role of the in-plane magnetic field is to orient pre-existing local striped regions. It is, however, also possible that $B_{\parallel}$ so alters the energetics of the electron system that it *creates* stripe order at temperatures far above where anisotropic transport appears spontaneously. If this is the case, then the nematic-to-isotropic transition interpretation of our data may be unjustified. Although we cannot completely rule out such a scenario, there are good reasons to discount it. First, the data shown above clearly indicate that the in-plane field severely broadens the onset of resistive anisotropy; it does not merely shift the sharp transition encountered at $B_{\parallel}=0$ to a higher temperature. Second, the scaling behavior we observe is sublinear in $T/B_{\parallel}$. A model in which both the stripe formation and orientation are dependent on $B_{\parallel}$ would presumably lead to a superlinear dependence on $B_{\parallel}$.

In conclusion, we have found the anisotropy characteristic of transport in half-filled high Landau levels to be heavily broadened by a strong in-plane magnetic field. Although we have concentrated here on the $\nu=9/2$ state, the same effect is observed at $\nu=11/2$ and other half-filled high Landau levels. This finding suggests that local stripe moments exist at relatively high temperatures where the transport is isotropic in the absence of the in-plane field. In addition, we have also observed a remarkable scaling of the resistive anisotropy with the ratio $T/B_{\parallel}$.

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