Current-Induced Anisotropy and Reordering of the Electron Liquid-Crystal Phases in a Two-Dimensional Electron System

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The correlated phases in a two-dimensional electron system with a high index partially filled Landau level are studied in transport under nonequilibrium conditions by imposing a dc-current drive. At filling $1/4$ and $3/4$ of these Landau levels, where the charge density wave picture predicts an isotropic bubble phase, the dc drive induces anisotropic transport behavior consistent with stripe order. The easy axis of the emerging anisotropic phase is perpendicular to the drive. At half filling the anisotropic stripe phase is stabilized by the dc drive provided drive and easy-axis directions coincide.

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The spontaneous development of periodic spatial inhomogeneities is a generic feature of systems in which repulsive and attractive forces acting on different length scales compete [1]. In a 2D electron system with a large index partially filled Landau level, it is the competition between the long range repulsive and the short range attractive part of the Coulomb interaction that brings about charge textures. According to Hartree Fock theory, the system prefers to break up into patterns composed of a mixture of the adjacent integer fillings [2,3] rather than to condense in a fractional quantum Hall fluid or a compressible Fermi-liquid-like state as observed for low index partially filled levels [4]. Near half filling of the Landau level, a two-component unidirectional charge density wave (CDW) consisting of stripes of alternating integer filling forms. Near $1/4$ ($3/4$) filling, a bubble phase develops, which is made up of multiple-electron (hole) bubbles that arrange into a "super" Wigner crystal and that are immersed in a sea of the nearest integer filling. The salient experimental signature of the stripe phase is a large transport anisotropy [5,6]. The resistance is low if the current is directed along the stripes and large if injected perpendicular. The easy direction is aligned to the [110] direction of the GaAs host for densities below $3 \times 10^{11}/\mathrm{cm}^2$ [5–7]. The origin of this symmetry breaking remains enigmatic as no correlation with native surface properties was found [8–10]. The bubble phase is susceptible to pinning. Hence, its macroscopic transport properties are dominated by the incompressible sea of integer filling. They are isotropic and identical to those of the nearest integer quantum Hall state [5,6].

Even though theoretical approaches based on CDWs qualitatively capture these key features in experiment, they generally suffer from overestimating the temperature at which these features emerge: several Kelvin [2] as opposed to <150 mK in experiment [5,6]. In an attempt to alleviate this discrepancy, thermal and quantum fluctuations were considered. It has led to the electron liquid-crystal (ELC) picture [11–15]. Within this model, the onset of anisotropy at half filling does not reflect the sudden appearance of a charge density modulation with stripe order. Instead, it heralds the transition from an isotropic liquid crystal to a uniform nematic liquid that exhibits spontaneous anisotropy due to orientational ordering of domains with preexistent small-scale stripe order [11]. Despite its uniform charge density, the broken rotational symmetry of the nematic phase is sufficient to account for the transport anisotropy. This transition is predicted at temperatures close to those in experiment [14,16]. Near $1/4$ and $3/4$ filling, a pinned crystalline state composed of stripe segments with phase locked shape fluctuations between neighboring stripes is expected to form. Unlike the CDW bubble phase, this ELC stripe or rectangular crystal is anisotropic at a microscopic level and differs also from the bubble phase in the number of electrons accommodated per unit cell. The difference in the degree of isotropy has been difficult to address in macroscopic transport studies due to the insulating nature of both phases.

Here, these correlated phases in high index Landau levels are investigated in transport under nonequilibrium conditions by imposing an external dc drive. These studies were motivated by a number of questions: Can evidence be found in favor of the anisotropic ELC stripe crystal or a rectangular crystal rather than the isotropic CDW bubble phase to describe the system near fillings $1/4$ and $3/4$ of the partially filled level? Can dynamical reordering, as it has been discussed, for instance, in the context of driven vortex lattices [17–19] or other ordered media in the presence of quenched disorder, be observed? Is it possible to induce a different order upon driving the system?

The experiments were performed on square van der Pauw geometries with side lengths of 90 to 500 μm and three contacts on each side (insets in

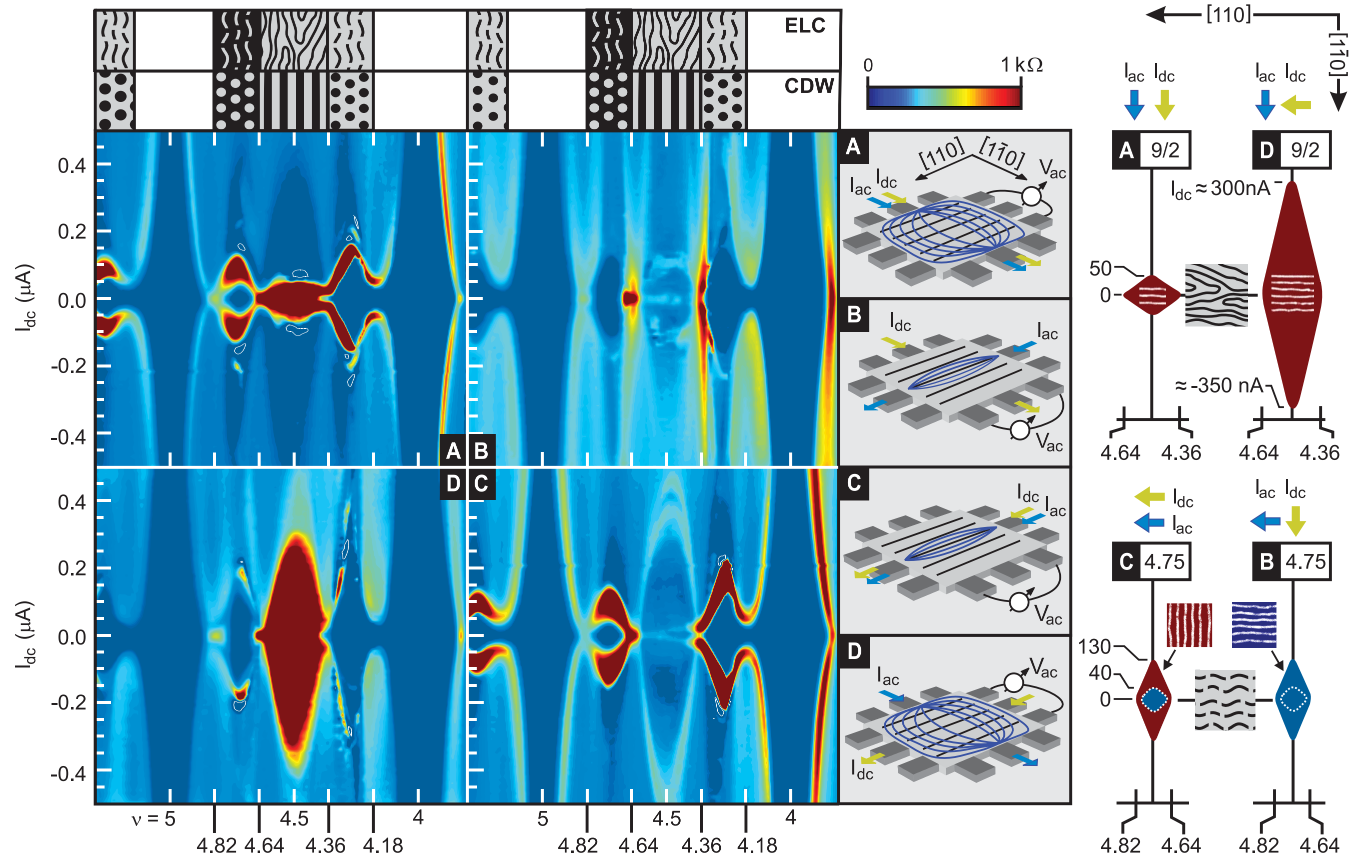

FIG. 1 (color). R as a function of ν and I_{dc} for the four (I_{dc}, I_{ac}) configurations. These current configurations are drawn schematically to the right of the data panels. Black lines mark the orientation of the CDW stripe phase at zero dc current, and blue lines illustrate the current channeling and spreading for the injected ac current. In the data panels, white contours enclose regions of negative R. Cartoons of the equilibrium phases in the CDW and ELC models are drawn in the relevant filling regions at the top. The top right inset helps to identify the important features in data of (a) and (d), which provide evidence for the stabilizing influence of a dc current when aligned along the easy direction at filling 9/2. The easy axis is marked by a set of parallel white lines. The bottom right inset highlights those features in (c) and (b), which represent evidence for anisotropic transport at $I_{dc} > 40$ nA and filling 4.75. The easy axis is aligned perpendicular to the dc-current drive direction.

Fig. 1). They were prepared from GaAs/AlGaAs heterostructures with electron mobilities ranging from 11 to 18 $\times 10^6$ cm^2/V s and a density of approximately 2.5×10^{11}/cm^2. The square geometry is preferred over a Hall bar configuration for these studies, because any resistance anisotropy is exponentially enhanced due to current channeling and spreading if current is imposed in the easy and the hard direction, respectively [20,21]. A variable dc current I_{dc} was imposed in a floating configuration along either the [110] or the [1$\bar{1}$0] crystal directions, i.e., the easy or the hard direction of the CDW stripe or ELC nematic phase (both the CDW and ELC languages will be used to refer to the equilibrium phases near half filling and fillings 1/4 and 3/4 of the partially filled level). To probe for any dc-current-induced anisotropies or modifications to the order or orientation of these phases, the resistances along and perpendicular to I_{dc} were compared. To measure these resistances, an additional small sinusoidal current I_{ac} with a frequency of 13 Hz and an amplitude of 10 nA or less was applied in either direction. The drain contact for the ac current was connected to ground. The ac voltage V_{ac} that developed across two terminals along the ac-current path was detected with a lock-in amplifier.

Figure 1 depicts color renditions of the differential resistance $R = V_{ac}/I_{ac}$ between fillings 4 and 5 for the four possible (I_{dc}, I_{ac}) configurations in a 300 μm square sample. For each color panel the corresponding measurement configuration is schematically drawn on the right. In these schematic drawings the orientation of the CDW stripe phase in equilibrium—i.e., in the absence of dc current—is indicated with black lines. Current channeling or spreading is illustrated for the injected ac current with blue lines. At zero I_{dc}, anisotropic transport in the CDW stripe phase near $\nu = 9/2$ manifests itself as a large color difference: red when I_{ac} flows in the hard [1$\bar{1}$0] direction perpendicular to the stripes [1(a) and 1(d)] and light blue when I_{ac} is injected in the easy [110] direction along the stripes [1(b) and 1(c)]. For the incompressible bubble phases near $\nu = 4.25$ and 4.75 vanishing resistance is obtained irrespective of the I_{ac} orientation (dark blue), and these phases appear the same way as the adjacent integer quantum Hall states do. Introducing I_{dc} as a parameter brings out clearly the phase boundaries. The CDW stripe phase covers fillings [4.36, 4.64]. The adjacent bubble phases extend over filling zones [4.18, 4.36] and [4.64, 4.82].

We first focus on how I_{dc} affects the anisotropic phase with stripe order in the interval [4.36, 4.64] around half filling. The bottom panels show data when I_{dc} flows along the stripe direction. A diamond shaped region of low resistance demarcated by a whitish halo and extending up to $I_{dc} > +300$ nA and < -350 nA is observed when monitoring R along the stripes [1(c)]. When probing perpendicular to the stripes, high resistance (red) persists in a nearly identical diamond [1(d)]. The top inset on the right of Fig. 1 highlights the important feature to look for in data of 1(d). If, however, I_{dc} is imposed perpendicular to the stripes (top panels), the resistance measured along the hard direction [1(a)] collapses much earlier near $I_{dc} \approx$ 50–60 nA (see schematic drawing on the right) and subsequently remains low. The drop in resistance is accompanied by a small area of negative differential resistance. Such regions are marked by white contours (The color scale has been clipped at 0 Ω.) Even though less clear, Fig. 1(b) for the resistance along the easy direction imparts similar information: some transition takes place at small I_{dc}. Taken all together, the data lend strong support for the following scenario: Imposing I_{dc} along the easy direction stabilizes the original anisotropic phase, and it survives up to a large critical $|I_{dc}| > 300$ nA where it melts. Conversely, dc-current flow perpendicular to the easy direction destabilizes the anisotropic phase already at small dc current.

When driving the system along the hard direction [1(a)], no hysteresis is observed at $\nu = 9/2$ between traces of R recorded during up and down sweeps of the drive current. An example obtained on a 90 μm sample of a different heterostructure is shown in Fig. 2 (top panel on the right). Since a CDW stripe or ELC smectic phase is not uniform and breaks translation invariance, strongly nonlinear or pinning associated behavior such as hysteresis is anticipated. The absence of hysteresis suggests that the less anisotropic and uniform ELC nematic phase better describes the system in this regime. It is then tempting to link the stabilizing influence of I_{dc} in the easy direction in Figs. 1(c) and 1(d) to a suppression of the transverse shape fluctuations in the ELC picture; i.e., the dc drive would render the original undriven nematic phase more orderly as addressed theoretically in, for instance, Ref. [22].

We now turn to the filling factor regions [4.18, 4.36] and [4.64, 4.82] where at zero dc current the incompressible pinned CDW bubble or ELC stripe crystal phases form. At small I_{dc} the resistance initially remains isotropic, i.e., independent of the ac-current direction, and essentially zero (dark blue) for all four configurations. As I_{dc} reaches approximately 40 nA (near $\nu = 4.75$) or 110 nA (near $\nu = 4.25$) a very pronounced resistance anisotropy develops

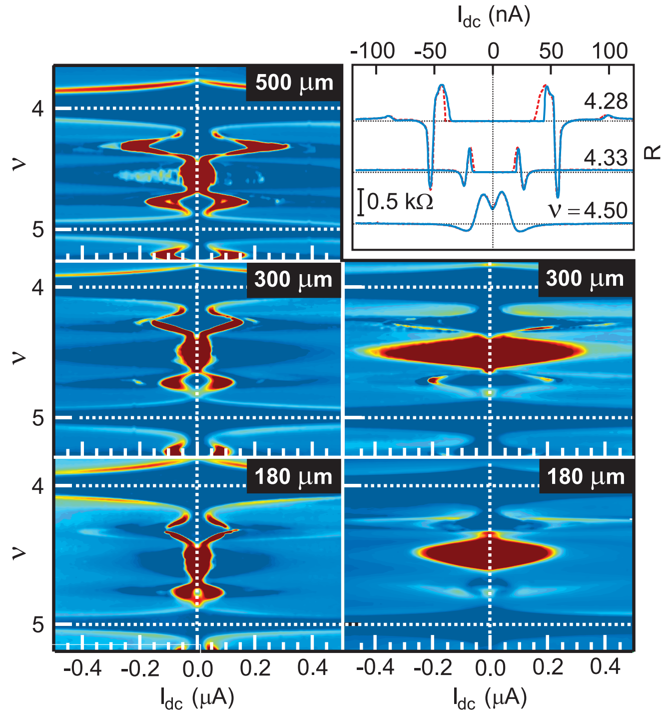

FIG. 2 (color). Color renditions of R for the current configurations of Figs. 1(a) (left panels) and 1(d) (right panels) and samples of different sizes. The rhombs with red borders at fillings $\nu = 4.25$ and 4.75 in the left panels scale with the side length, whereas the red area centered around 9/2 does not. The top right panel illustrates line traces of the differential resistance R when sweeping I_{dc} up or down (solid and dashed lines) for a 90 μm sample (different heterostructure as the other panels) at some fillings. Hysteresis is observed around $\nu = 4.25$.

reminiscent of the anisotropy near $\nu = 9/2$. The resistance rises to a large value (red) in a narrow region bordering a rhomb when I_{ac} flows parallel to I_{dc} [1(a) and 1(c)] and remains small when imposing I_{ac} perpendicular to I_{dc} [1(b) and 1(d)]. Hence, the hard direction of this emerging anisotropic phase coincides with the direction of the dc-current flow. The relevant features in the data of 1(b) and 1(c), which provide evidence for the emergence of anisotropic transport with the easy axis perpendicular to the dc current, have been highlighted schematically in the bottom inset on the right of Fig. 1. In the dark blue areas demarcated by white dotted lines, the insulating nature of the pinned and incompressible equilibrium phase makes transport appear isotropic. Beyond the white dotted line strong anisotropy develops in transport. The pictograms with white lines indicate the orientation of the easy direction (perpendicular to the dc current).

In a macroscopic transport experiment the CDW bubble and the ELC rectangular or stripe crystal phases appear isotropic, because they are insulating. At the microscopic level, only the ELC stripe crystal is anisotropic with the stripe sections extending in a particular direction. It turns this phase into the more natural starting point for constructing an explanation for the observed anisotropy. The data strongly suggest the following. When imposing a dc drive, the stripe sections of the ELC stripe crystal phase become oriented along the dc-Hall field. This reminds one of the orientation of conventional liquid crystals in an external applied electric field. Depinning by this Hall field combined with the existing stripe order would be in line with the appearance of anisotropic transport. In fact, the nearly identical resistance values of this dc-current-induced anisotropic phase and the anisotropic phase near $\nu = 9/2$ as well as the smooth transition between the high resistance areas associated with both phases in 1(a) (coalescing to the frog-shaped red colored area) are indications for an intimate connection between the two. They do differ in that at zero drive the easy axis of the nematic phase at 9/2 is prescribed by the underlying crystal axis orientation, whereas at filling factors 4.25 and 4.75 the dc-Hall field serves as the symmetry breaking field. Up and down sweeps of I_{dc} at fixed filling reveal a pronounced hysteresis near fillings 4.25 and 4.75 in this regime. An example is shown in the top graph on the right of Fig. 2. This hysteretic behavior is also consistent with depinning of a nonuniform state such as the ELC stripe crystal and further supports our interpretation that the anisotropic transport originates from a depinned ELC stripe crystal phase with some stripe order. This hysteresis and the sharp threshold to conduction appear identical to the previously reported hysteresis in the dc experiments of Ref. [23], since the critical current values are comparable when they are normalized to the sample width. The sample size dependence is plotted in Fig. 2. It indeed shows that the critical I_{dc}, where anisotropic transport at fillings 1/4 and 3/4 emerges, scales roughly linearly with the sample side length. For filling factor 4.75, the ratio I_{dc}/L equals approximately 0.12, 0.14, and 0.11 nA/μm for the 500, 300, and 180 μm devices in Fig. 2. We note that microwave studies in the absence of a dc current disclosed a resonance near 1/4 and 3/4 filling, which was attributed to a pinning mode [24]. The strength of this mode was comparable for polarization along the [110] and $[1\bar{1}0]$ crystal directions. This polarization independence is, however, not necessarily inconsistent with the anisotropic behavior observed here, since it is the large dc-Hall field that determines the easy axis orientation.

In conclusion, we demonstrated that a dc-current drive plays the role of an external symmetry breaking field. The data are consistent with the existence of a uniform, but anisotropic state like the ELC nematic near the center of a high index Landau level. The dc drive has a stabilizing influence on the orientation of the anisotropic phase if the dc drive and easy direction coincide. Our independent choice of ac- and dc-current directions unveiled striking anisotropic transport near 1/4 and 3/4 filling. Depinning of the nonuniform ELC stripe crystal due to the dc-Hall field provides a natural interpretation for the appearance of this anisotropy and accompanied hysteresis. The easy axis is determined by the direction of the dc-Hall field. Data suggest that this field orients the stripe sections of the stripe crystal phase similar to the behavior of a conventional liquid crystal.

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