# Current Flow in the Bubble and Stripe Phases

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The spontaneous ordering of spins and charges in geometric patterns is currently under scrutiny in a number of different material systems. A topic of particular interest is the interaction of such ordered phases with itinerant electrons driven by an externally imposed current. It not only provides important information on the charge ordering itself but potentially also allows manipulating the shape and symmetry of the underlying pattern if current flow is strong enough. Unfortunately, conventional transport methods probing the macroscopic resistance suffer from the fact that the voltage drop along the sample edges provides only indirect information on the bulk properties because a complex current distribution is elicited by the inhomogeneous ground state. Here, we promote the use of surface acoustic waves to study these broken-symmetry phases and specifically address the bubble and stripe phases emerging in high-quality two-dimensional electron systems in GaAs/AlGaAs heterostructures as prototypical examples. When driving a unidirectional current, we find a surprising discrepancy between the sound propagation probing the bulk of the sample and the voltage drop along the sample edges. Our results prove that the current-induced modifications observed in resistive transport measurements are in fact a local phenomenon only, leaving the majority of the sample unaltered. More generally, our findings shed new light on the extent to which these ordered electron phases are impacted by an external current and underline the intrinsic advantages of acoustic measurements for the study of such inhomogeneous phases.

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The interplay of competing interactions prevailing on different length scales often results in inherent instabilities towards the formation of domain patterns. Well known from ferromagnetic systems where domains form as a result of opposing Coulomb and exchange interactions, domain structures also appear in other realizations. In certain high-temperature superconductors, for instance, the electron system is believed to break up in stripelike domains of alternating spin and charge density [1–4]. Similar density-modulated phases also exist when a high-quality two-dimensional electron system enters the quantum Hall regime by applying a large, quantizing magnetic field. In this instance, charge ordering occurs in two flavors, depending on the partial filling factor of the highest occupied Landau level [Fig. 1(a)]. At half filling, electrons tend to cluster in elongated, stripelike patterns [5–8]. As a result of thermal and quantum fluctuations these stripe phases are believed to follow electron liquid crystal behavior [9]. Moving away from half filling, a circular modulation of the filling factor ordered on a triangular lattice is energetically favored [5–8]. Current flow through such inhomogeneous phases develops a complex pattern defined by details of the microscopic structure of the charge ordering. Hence, standard transport measurements probing the voltage drop along the edges of the sample need to be interpreted with caution when attempting to draw conclusions about the bulk properties of the system. Even if so, for many years resistive measurements have been the method of choice to study these broken-symmetry phases in 2D electron systems due to its simplicity and the long-standing experience with transport measurements. In many cases this is justified since microscopic current channeling or spreading leads to pronounced signatures for the existence or formation of the bubble and stripe phases: The bubble crystal is pinned by disorder. As a result the excess charge accommodated in the topmost Landau level is localized. The system behaves in transport as if it is in the nearby integer quantum Hall state and exhibits the integer quantum Hall effect outside of the main series of quantum Hall plateaus, so-called reentrant quantum Hall behavior. The pinning of the stripe phase does not cause reentrant behavior as extended states supporting current flow separate stripes of adjacent integer filling. However, the orientation of these extended states induces a strong resistance anisotropy [Fig. 1(c)] due to current spreading or channeling depending on whether the measurement current is injected perpendicular or parallel to the stripe orientation [10–13]. The orientation and nature of the stripe phases has been studied in a number of experiments in the recent years [14–31]. The pinning itself can be verified by detecting a pinning resonance in the high-frequency response of the sample using a co-planar waveguide pattern atop the

 

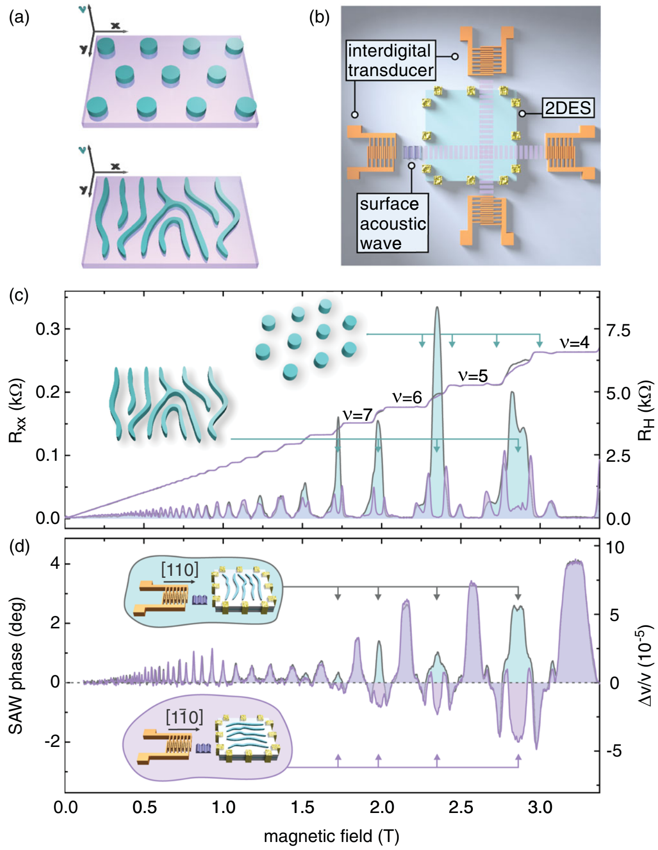


FIG. 1. (a) Filling factor variation in the topmost Landau level in the bubble (top) and stripe phases (bottom). (b) Schematic of the experimental setup. The two-dimensional electron system is confined to a square-shaped mesa surrounded by four interdigital transducers. A network analyzer is used to excite surface acoustic waves as well as to detect their phase shift after traversing the mesa. (c) Longitudinal and Hall resistance along the [110] and [1$\bar{1}$0] crystal directions as a function of the magnetic field. Bubble and stripe phases are identified by the reentrance of the integer quantum Hall effect and a strongly anisotropic transport behavior, respectively. The electron temperature is about 20 mK. (d) SAW propagation data in the same magnetic field range. The phase shift is plotted relative to the value at low magnetic fields. The change of the sound velocity follows directly from the phase shift by geometrical arguments. A negative phase shift is observed for the bubble and stripe phases [37].

sample [32–36] or indirectly by recording the time-averaged charge distribution [23].

When sending a current through the sample, a force is exerted on these localized phases, which, if strong enough, might lead to depinning [38]. Even at moderate values, the force brought about by the current may considerably affect the charge ordering and even alter the underlying symmetry of the bubble and stripe phases as the current-induced Hall field may serve as a symmetry-breaking field. Nonlinear signatures in the measurement of the differential resistance were taken as indications for such a behavior [39]. Nevertheless, the microscopic impact of current flow on the charge ordering remains unclear and controversy exists about the interpretation of the differential resistance measurements [40,41]. Here, we prove that the current-induced manipulation of the bubble and stripe phases is in fact a local phenomenon that propagates within narrow constraints across the sample, leaving the bulk of the sample largely unaffected. Our experimental technique is based on the propagation of surface acoustic waves (SAWs) [42–44], which is affected as the conductivity or reactive response of the electronic system changes. This approach offers true directionality. Contrary to conventional transport measurements, this method allows us to probe the bulk of the sample independent of the nature of the ground state and the current distribution across the sample. It is therefore ideally suited to study inhomogeneous phases emerging in high-quality GaAs/AlGaAs heterostructures.

The sample under study was fabricated from a GaAs/AlGaAs heterostructure hosting a two-dimensional electron system in a 30 nm-wide quantum well through modulation doping from superlattice structures inserted symmetrically around the well [45]. The electron density equals $3.1 \times 10^{11}$ cm$^{-2}$ and the low-temperature mobility reaches approximately $20 \times 10^6$ cm$^2$/V s. The sample was patterned into a square-shaped mesa of width 1.1 mm. Three electrical contacts were arranged on either side of the mesa as shown in Fig. 1(b). Four interdigital transducers with a finger period of 8.6 $\mu$m were deposited from aluminum on the etched region surrounding the mesa. When resonantly excited at a frequency of about 340 MHz, the transducer launches a SAW. The interaction with the two-dimensional electron system during propagation across the mesa affects the velocity of the acoustic wave and can be detected as a phase shift with the help of a network analyzer after the sound wave has been converted back to an electrical signal on the opposite side of the mesa [42–44]. The interaction originates from the electric field that accompanies the sound wave in piezoelectric materials such as GaAs/AlGaAs. The detected phase shift reflects the local screening response of the electrons to the electric field, which varies depending on the ground state of the two-dimensional electron system as well as its conductivity. The main crystal directions [110] and [1$\bar{1}$0] were probed independently by choosing different SAW traveling times along either axis (between 600 ns and 1.3 $\mu$s) and using the time-gating functionality of the network analyzer (Agilent E5071B). The temporal evolution of the SAW transmission was measured by continuously scanning a finite frequency window of 20 MHz width and performing an inverse Fourier transformation. A low input power level of −10 dBm ensured little impact on the charge order by the SAW. Further details on the measurement technique can be found in Ref. [37].

To set the stage for discussing the impact of an imposed dc current on the bubble and stripe phases, we first summarize previously reported observations [37] for the SAW phase shift in this regime in the absence of an extra dc current. Figure 1(d) provides an overview of the magnetotransport and SAW behavior across the rich phase diagram, which evolves for 2D electrons when tuning the applied perpendicular magnetic field. At small fields, the electrons are highly mobile and the piezoelectric field is screened effectively. This case of near perfect screening is conventionally chosen as the reference to define a zero phase shift. Upon entering the quantum Hall regime, a positive SAW velocity or phase shift appears at each quantum Hall state. The incompressible nature of the ground state hinders the screening of the piezoelectric field, which acts as an additional restoring force stiffening the crystal lattice and enhancing the sound wave velocity. The positive shift increases as the electronic system enters deeper into the incompressible regime. This general behavior has been described successfully in a purely dissipative model [42–44], which only considers the influence of the magnetic field dependent conductivity on the time scale for screening while ignoring any reactive, frequency-dependent response of the electrons. With the chosen reference for high conductivity, this model only allows for zero or positive velocity shifts. This is in accordance with experiment, except when stripe or bubble phases emerge. There a negative phase shift develops. For the stripe phase, the observation of a negative shift is limited to SAW propagation along the direction of the stripes. This apparent crystal softening in the bubble and stripe phases has been attributed to a local negative compressibility caused by the attractive exchange correlation upon spontaneous symmetry breaking of the 2D electron system and its effect on the low-frequency collective mode of the electronic state [37]. The dissipative relaxation model fails to capture this phenomenon, since it results solely from the dynamical reactive response of the electrons.

These distinct features for the bubble and stripe phases in conjunction with the unaffected propagation direction upon changing ground states of the electronic system, make SAWs particularly suitable to probe the influence of a dc current flow on these symmetry-broken phases. The same bulk area of the sample is inquired independent of the imposed currents, and a modification to the ground state in the bulk can be identified. Figures 2(a) and 2(b) depict the differential longitudinal resistance if a dc current of variable strength is sent either along the [110] or [$1\bar{1}0$] crystal directions. The ac current to probe the resistivity was intentionally kept small at 10 nA to avoid any interference with the charge ordering. It is injected with the same orientation as the dc current and its sole purpose is to monitor changes of the differential resistance with increasing dc current. The latter is increased in steps of 10 nA up to a maximum current of 300 nA. For the bubble phase, a strong increase of the differential resistance is observed in the direction of the dc drive. For the stripe phase, the differential resistance is reduced when driving the system along the hard axis. If the dc current is sent along the easy axis, the anisotropy persists up to large current values. Even a further reduction of the anyway small resistance value occurs, as evident by the line cut in Fig. 2(c). Our observations are consistent with the behavior reported by Göres *et al.* [39]. The current-induced anisotropy in the bubble phase has been interpreted as a depinning as well as the formation and macroscopic alignment of liquid crystal stripes by the dc Hall field. In contrast, the behavior at half filling suggests a stabilization of the stripe phase, if the dc drive is sent along the easy axis. In either case, the dc Hall field takes the role of a symmetry-breaking field. These interpretations implicitly assume a macroscopic reordering of (local) stripe crystals across the whole sample. This can, however, be questioned, since the current distribution across the sample is highly inhomogeneous and ground state specific. SAW measurements concurrent to the measurements of the differential resistance, however, enable verification of this assumption.

Figures 2(d) and 2(e) plot the velocity shift when SAWs are launched in the same direction as the dc current for the two main crystal orientations. The key observation is that an imposed dc current leaves the SAW propagation largely unaffected. All signatures of the bubble and stripe phases in the sound velocity present in the absence of the dc current remain well pronounced up to the highest dc current value [Fig. 2(f)]. This contradicts the behavior of the differential resistance, which is strongly altered [Fig. 2(c)]. The apparent discrepancy between standard transport and SAW measurements can be reconciled, as shown below, when considering that the propagating SAWs probe the electronic properties in the whole area of the SAW traveling path whereas the resistance is detected along the edges of the sample. Our observations shed light on the microscopic nature of current transport in these inhomogeneous phases, which formulates differently for the bubble and stripe phases.

For the bubble phase, the measurement of the differential resistance suggests a current-induced transition to an anisotropic phase oriented along the dc Hall field. The SAW data, however, identify the bulk of the sample to remain unaltered by the dc drive, leaving the bubble phase intact. Combining these two observations suggests the coexistence of two different phases within the sample: a pinned bubble crystal in the bulk and a compressible phase spreading out along the edges of the sample. This compressible phase may either consist of a sliding bubble crystal unpinned from the disorder potential by the strength of the local Hall field or a homogeneous electron phase comprised of a melted bubble crystal. The exact nature of the solid-to-liquid transition in the bubble phases is currently under debate [46]. In either case, the current-induced phase separation is initiated at the source and drain contacts, since here current density is largest and the merger of incompressible regions of different electrostatic potential dissipates additional heat. With increasing dc current, the

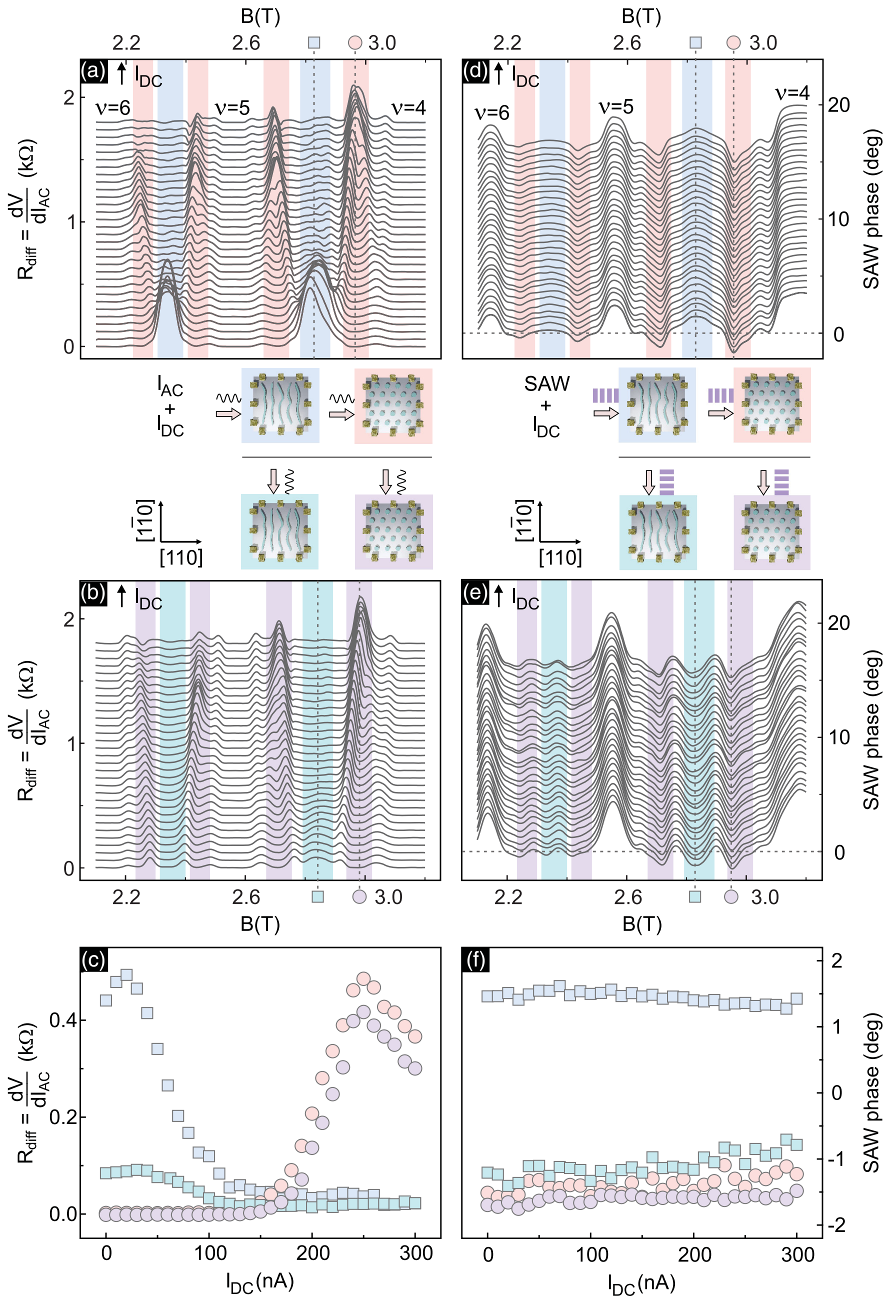


FIG. 2. (a),(b) Measurements of the differential longitudinal resistance if both ac and dc current are sent along the crystal directions [110] (a) and [1$\bar{1}$0] (b) between filling factor 4 and 6. The dc current was increased in steps of 10 nA up to a maximum current of 300 nA. Measurements are offset for clarity. (c) Evolution of differential resistance at fixed magnetic field values as indicated by colored symbols in (a) and (b). (d),(e) Measurements of the SAW phase shift between filling factor 4 and 6 if both dc current and SAWs are sent along the crystal directions [110] (d) and [1$\bar{1}$0] (e). All data were recorded simultaneously to the measurements in (a) and (b), respectively. The dc current was increased in steps of 10 nA up to a maximum current of 300 nA. Measurements are offset for clarity. (f) Evolution of SAW phase shift at fixed magnetic field values as indicated by colored symbols in (d) and (e).

excited phase expands chirally along the edge as shown by the cartoon in Fig. 3(a). The sense of chirality is determined by the orientation of the magnetic field and the electronlike or holelike character of the quasiparticles [41]. Once the phase boundary moves between the two contacts used to measure longitudinal resistance, a voltage drop occurs. This scenario explains both the disappearance of the hallmarks of a bubble phase in the resistance and the absence of such signatures in the sound propagation in the bulk of the sample. This interpretation is also in line with conclusions drawn by Rhossokhaty *et al.* after analyzing the transport behavior in the bubble regime at different contacts along the sample boundary [41].

For the stripe phase, the anisotropy in Fig. 2 is strongly suppressed when sending the dc current perpendicular to the stripes and strengthened in the orthogonal configuration. While this may be interpreted as a rotation of the stripe order induced by the unidirectional current, probing charge order by sound waves reveals the stripe orientation to remain completely unaltered along the SAW propagation path. To explain both measurements—electrical and acoustic—we propose the following scenario. When injected perpendicular to the stripes, a strong directional current melts or deforms the charge order locally such that a fissure is created in the stripe order, allowing current to flow on a straight path connecting the source and drain [Fig. 3(b)]. This way,

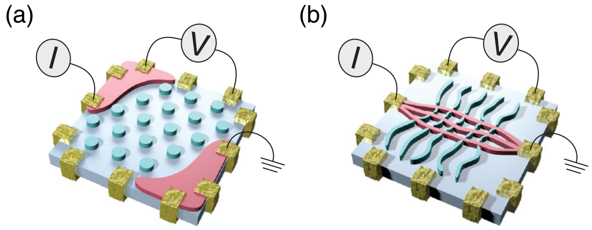


FIG. 3. Spatial filling factor modulation in the topmost Landau level for the bubble phase [(a), based on Ref. [41]] and the stripe phase (b) under the influence of a strong unidirectional current. Indicated in red is the dissipative phase which forms as a result of the dc current.

current flow is no longer spread out along the stripes and deflected towards the sample edges. As a result, the longitudinal voltage drop along the 2DES perimeter is considerably reduced. Such a scenario is compatible with the abrupt quenching of the differential resistance when reaching a critical current threshold. If sent along the stripes, current flow is anyway guided by the stripe orientation due to the extended states at the boundary between adjacent incompressible states. Hence, little force is exerted on the stripes, and the stripe order remains intact with increasing current.

We conclude that the SAW technique can serve as a powerful, complementary tool to explore inhomogeneous, broken-symmetry phases. Its directional nature ensures that we access the same bulk area of the sample irrespective of the ground state of the electronic system. This avoids complications that traditional transport measurements suffer from as these are sensitive to the spatial current distribution which may vary dramatically depending on the ground state as well as external parameters. The example addressed here is the influence of a dc current on the stripe and bubble phases. For the bubble phase, our data suggest a current-induced phase separation between the pinned electron crystal in the bulk of the sample and a dissipative phase straddling the sample perimeter. In the case of the stripe phase, the acoustic measurements reveal the stripe order to remain intact in the bulk of the sample even when a strong unidirectional current is forced to flow perpendicular to the stripes. This contradicts previous interpretation of electrical measurements, which suggested a current-induced reorientation of the stripes.

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