Collective Modes and the Periodicity of Quantum Hall Stripes

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We investigate the quantum Hall stripe phase at filling factor 9/2 at the microscopic level by probing the dispersion of its collective modes with the help of surface acoustic waves with wavelengths down to 60 nm. The dispersion is strongly anisotropic. It is highly dispersive and exhibits a roton minimum for wave vectors aligned along the easy transport direction. In the perpendicular direction, however, the dispersion is featureless, although not flat as predicted by theory. Oscillatory behavior in the absorption intensity of the collective mode with a wave vector perpendicular to the stripes is attributed to a commensurability effect. It allows us to extract the periodicity of the quantum Hall stripes.

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In state-of-the-art two-dimensional electron systems, the fractional quantum Hall effect is ubiquitous when the first and second Landau levels are partially filled [1]. In higher index levels, however, the fractional quantum Hall effect is conspicuously absent, and the physics at temperatures below 150 mK is dominated by spontaneous symmetry breaking instead. For a review we refer to Ref. [2]. At half filling of these higher lying levels, Hartree-Fock theory has predicted that the system develops a charge density wave referred to as a quantum Hall stripe phase [3–5]. It is composed of alternating regions of the nearby integer filling quantum Hall states. Indeed, this stripe phase manifests itself in dc-transport experiments through a strong anisotropy in the diagonal resistivity measured along and perpendicular to the stripes [6,7]. The resistivity is low if the current is directed along the stripes (easy direction) and large (hard direction) if imposed perpendicular. For densities below $3 \times 10^{11}/\mathrm{cm}^2$, the easy direction in experiment is aligned to the [110] direction of the host GaAs crystal [6–9]. The theory of the quantum Hall stripe states was later refined to include thermal and quantum fluctuations and revealed a powerful analogy between liquid crystals and quantum Hall stripes [2,10–12]. At temperatures accessible in experiment, an impressive agreement was found between the measured resistance and a finite temperature model based on the nematic liquid crystal phase [13,14]. For the sake of completeness, we note that such anisotropic transport was also discovered at filling factor 5/2 when the sample was exposed to sufficiently large in-plane magnetic fields. The initially isotropic and gapped $\nu = 5/2$ state, which has been of strong interest due to the possible non-Abelian nature of its excitations [15], apparently gives way in an in-plane magnetic field to an anisotropic quantum Hall stripe state [16–18]. In 2D hole systems, the $\nu = 5/2$ state is already anisotropic even without an in-plane field [19].

Even though transport studies have served as a useful probe for the existence of the stripe phase, they only yield a macroscopic picture and do not provide microscopic insight. Scanning probe measurements would be highly desirable but are challenging in view of the required temperature (below 100 mK) and most of all the spatial resolution. Theoretical calculations have estimated the characteristic width or period of the stripe phase to be $2.7R_c$. Here, $R_c = k_F l_B^2$ is the cyclotron radius at the Fermi level [3], with k_F the Fermi wave number and $l_B = \sqrt{\hbar/eB}$ the magnetic length. The cyclotron radius is less than 60 nm for typical sample densities and far smaller than the depth of state-of-the-art heterostructures, which inherently sets a limit on the spatial resolution that scanning methods can achieve. Here we take a different route to access the stripe phase near filling factor $\nu = 9/2$ at the microscopic scale based on a combination of surface acoustic waves, microwave excitation, and optical detection. The key ingredient is a surface acoustic wave that can be launched across our sample along either the easy or the hard direction. The wavelength of the surface acoustic wave (SAW) introduces an additional length scale, which allows us simultaneously to probe the dispersion of the collective modes of the quantum Hall stripe phase at wave numbers equal to the inverse of the SAW wavelength and to search for commensurability effects, when the SAW wavelength matches the stripe periodicity or a multiple thereof.

The experiments were performed on modulation-doped GaAs/AlGaAs heterostructures containing a 30 nm wide quantum well. The density was tuned with the optodepletion effect in the range from 2×10^{11} up to $3 \times 10^{11}/\mathrm{cm}^2$. The electron mobility varied from 10×10^6 to $14 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,s}$. Cross-shaped mesas as depicted in Fig. 1(a) were fabricated. The center part of the cross serves as the active device region and has a size of $100 \times 100\ \mu\mathrm{m}^2$. Each leg of the cross terminates in a wider section, where identical interdigital transducers to generate SAWs were patterned with electron beam lithography and

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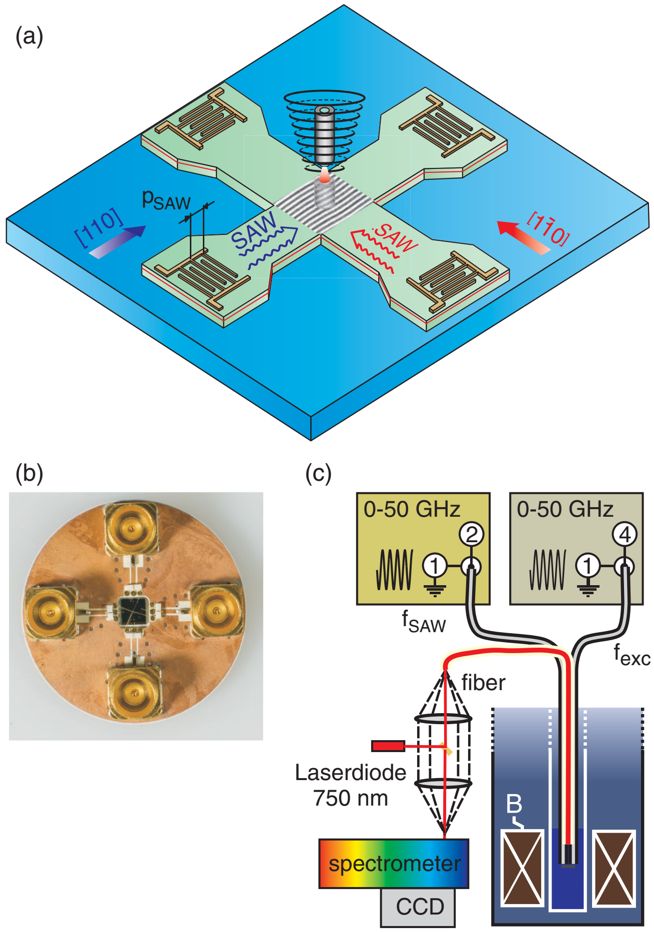

FIG. 1 (color). (a) The device geometry consisting of a cross-shaped mesa with legs oriented along the main crystal directions. SAW transducers are located at the end of each leg. (b) Chip carrier containing high frequency coaxial connectors and terminated coplanar waveguides. The chip with cross-shaped mesa is mounted in the central cavity. (c) Experimental setup highlighting the three electromagnetic waves incident on the sample.

metal evaporation. The transducers consist of 100 fingers. The periodicity p_{SAW} was changed from 360 to 120 nm on a set of samples from the same heterostructure [20,21].

To measure the energy dispersion of neutral excitations, which involve the simultaneous generation of a quasihole and quasielectron by a microwave photon, at filling factor 9/2 three electromagnetic waves are simultaneously incident on the sample, each serving a different purpose: (i) A high frequency signal in resonance with the transducer at frequency f_{SAW} generates surface acoustic waves and determines the nonzero wave vector $k_{SAW} = 2\pi/p_{SAW}$ at which the neutral excitations are probed. This wave vector can be oriented along the [110] or [1$\bar{1}$0] crystal direction by choosing the appropriate transducer on the legs of the cross. The high frequency signal is inserted into the cryostat with a coaxial line, which is connected to an impedance-matched coplanar waveguide. The waveguide is terminated to avoid reflections, and its inner and outer conductor are wire bonded to the two electrodes of the transducer [Fig. 1(b)].

When driven at their fundamental frequencies, wave numbers up to 5.2×10^7/m are accessible for the fabricated set of transducers. They can also be operated at the second harmonic by using a contactless excitation scheme as described in Refs. [20,21]. This extends the accessible wave vector size to 1.04×10^8/m. (ii) Quasimonochromatic microwave radiation with frequency f_{exc} irradiates the central part of the cross and triggers the neutral excitations when the microwave photon energy matches the energy of the excitation at the nonzero wave vector defined by the SAW transducer. The microwaves propagate along a second coaxial line and an impedance-matched and terminated coplanar waveguide. The central conductor of the waveguide is wire bonded to an electrode of an unused transducer. The ground planes of the waveguide are short-circuited to the ground electrode of the transducer producing SAWs on the opposite side of the cross. These connected electrodes act as a dipole antenna, and the central part of the mesa is exposed to radiation. (iii) Finally, the active device region is also excited by 10 μW of cw light from a stabilized semiconductor laser operating at a wavelength of 750 nm. The light reaches the sample with the help of a multimode fiber. The luminescence signal from the sample is collected by the same fiber and spectrally resolved with a double grating spectrometer with a resolution of 0.03 meV and a CCD camera. When the microwave radiation is in resonance with the neutral excitation of the system, the resonant absorption heats up the electron system. The luminescence spectrum reflects the thermal redistribution of the electrons as a result of the increased temperature. Hence, the differential spectrum, obtained by subtracting the luminescence spectra recorded in the presence and absence of microwave radiation, will reveal resonant absorption. It is convenient to capture the influence of the microwave radiation in a single quantity, which will hereafter be referred to as the absorption strength. It is defined as the integral of the absolute value of the differential luminescence across the recorded spectral range. The experiments are carried out in a top-loading-into-mixture dilution refrigerator at a mixture temperature of approximately 30 mK in the presence of radiation.

Figures 2(a) and 2(b) plot the microwave absorption strength measured at filling 9/2 ($B = 2.41$ T) for $k_{SAW} = 1.98 \times 10^7$ and 3.97×10^7/m oriented along the [110] and [1$\bar{1}$0] crystal directions, respectively. These data manifest a strong anisotropy. For instance, at $k_{SAW} = 3.97 \times 10^7$/m the incident microwave radiation triggers collective excitations at a frequency of 25.3 GHz when the wave vector is aligned along the [110] direction. When the wave vector is parallel to the [1$\bar{1}$0] crystal direction, the resonance frequency drops more than a factor of 3 down to 7.4 GHz. These resonances were recorded for different values of k_{SAW} and both crystal orientations. The resulting

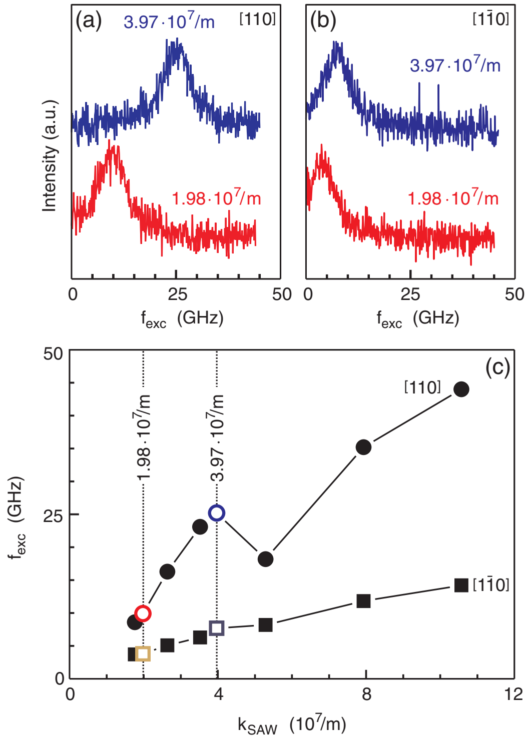

FIG. 2 (color). (a)–(b) Absorption strength versus excitation frequency recorded at filling factor 9/2 for an electron density of $2.63 \times 10^{11}/\mathrm{cm}^2$ and $k_{\mathrm{SAW}} = 3.97 \times 10^7$ (top curve) or $1.98 \times 10^7/\mathrm{m}$ (bottom curve). In (a) the SAW propagates along the [110] direction, while in (b) along the $[1\bar{1}0]$ direction. (c) Resonance frequency as a function of k_{SAW} for both propagation directions. The data points were recorded at the same density on samples with different SAW transducers.

dispersions are displayed in Fig. 2(c). For k_{SAW} along the [110] direction, the dispersion possesses a minimum for a wave number k_{SAW} close to $5 \times 10^7/\mathrm{m}$ or $0.8 l_B$ in good agreement with theoretical predictions of the dispersion [22]. According to theory there should be no dispersion in the perpendicular direction. Even though a roton minimum is indeed absent for the $[1\bar{1}0]$ direction, the resonance frequency is not constant with k_{SAW}. It grows with increasing k_{SAW}, albeit at a much lower rate in comparison with the data for the [110] direction.

Figures 3(a) and 3(b) plot the filling factor and temperature dependence of the resonance frequency for k_{SAW} along both main crystal directions. The anisotropy vanishes if the filling factor deviates by more than 0.08 from 9/2 or the temperature is raised above 120 mK. Both of these observations conform with the previously reported anisotropy in transport studies. They corroborate that the same charge density wave or liquid crystal physics is under investigation, despite the discrepancy between theory and experiment for the dispersion along the $[1\bar{1}0]$ direction.

The characteristic length scale or periodicity of the stripe phase is an important issue but has not been disclosed so far in experiment. According to theory, the

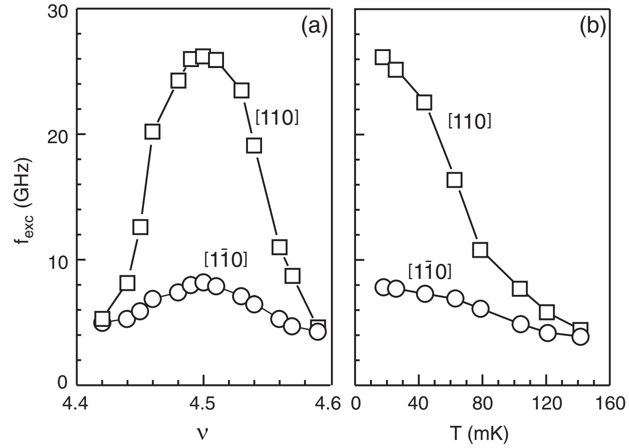

FIG. 3. (a) Filling factor dependence of the frequency of the collective excitations of the quantum Hall stripe phase at filling $\nu = 9/2$ at an electron density of $2.63 \times 10^{11}/\mathrm{cm}^2$ for $k_{\mathrm{SAW}} = 3.97 \times 10^7/\mathrm{m}$ along either the [110] or $[1\bar{1}0]$ propagation direction. (b) Temperature dependence of the resonance frequency at $\nu = 9/2$ for the same values of the density and k_{SAW}.

periodicity p_{stripe} should be equal to $2.7R_c$, where R_c is the cyclotron radius [3]. The cyclotron radius can be expressed as $R_c = \sqrt{\nu} l_B$. At the densities addressed here, p_{stripe} is less than 60 nm. In view of the depth of the two-dimensional electron systems, scanning probe methods probing the local electrostatic potential are bound to fail in detecting the striped phase. Here, the surface acoustic waves introduce an additional length scale which is comparable in size to p_{stripe}. For a given sample, it is possible to vary p_{stripe} by tuning the electron density with the help of the optodepletion effect [23] from 2×10^{11} up to $3 \times 10^{11}/\mathrm{cm}^2$. One might anticipate a commensurability effect of the periodicity of the SAW with p_{stripe} when SAWs are launched perpendicular to the striped phase. Figure 4(a) indeed illustrates a drastic variation of approximately 200% in the intensity of the resonant microwave absorption when the surface acoustic waves are launched along the $[1\bar{1}0]$ direction ($I_{[1\bar{1}0]}$) upon changing the density while keeping the filling factor $\nu = 9/2$ and k_{SAW} fixed. Along the [110] direction, this effect is absent. Figure 4(c) plots the intensity ratio $I_{[1\bar{1}0]}/I_{[110]}$ with p_{SAW}/R_c as dimensionless abscissa. The data points were collected by varying the density on four samples with different SAW transducers operating in their fundamental and second-order mode. The intensity ratio exhibits oscillations when p_{SAW} is equal to $3.6R_c$ or an integer multiple j thereof. We speculate that, under commensurate conditions, the surface acoustic waves propagating along the $[1\bar{1}0]$ direction impose long range order which is absent without SAWs. As a result the stripe phase is stabilized, which is reflected in an increased absorption intensity. As the index j increases and the period of the surface acoustic wave spans multiple periods of the stripe phase, the intensity enhancement drops.

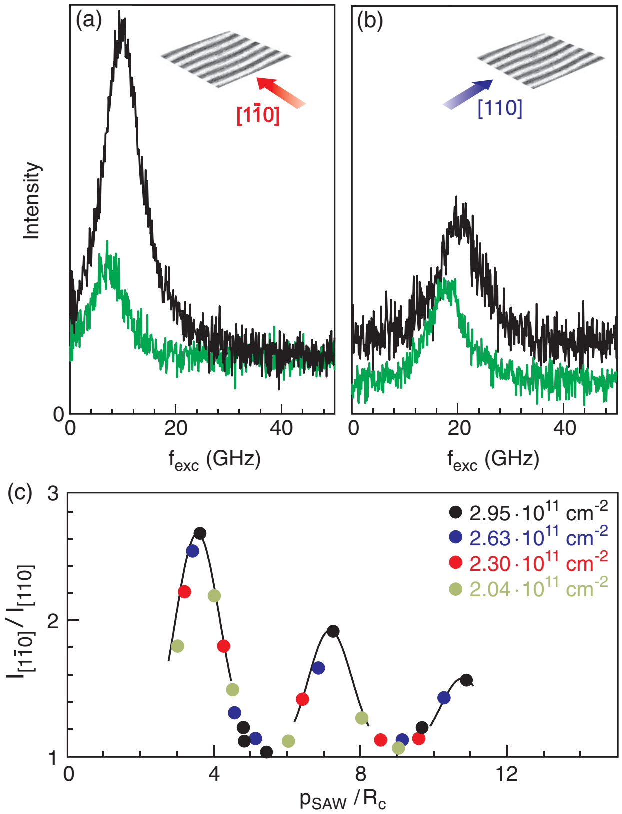

FIG. 4 (color). (a) Microwave absorption strength at filling $\nu = 9/2$ for density 2.04×10^{11} (bottom green curve) and $2.95 \times 10^{11}/\text{cm}^2$ when the SAW with $k_{\text{SAW}} = 5.29 \times 10^7/\text{m}$ propagates along the $[1\bar{1}0]$ direction. (b) The same as in (a) except that the SAW is launched along the [110] direction. (c) Ratio of the absorption intensity of the resonances for surface acoustic waves propagating along the $[1\bar{1}0]$ and [110] directions as a function of p_{SAW}/R_c. This ratio oscillates and exhibits maxima when p_{SAW} equals a multiple of $3.6R_c$.

In conclusion, we have investigated the neutral excitations at filling factor 9/2, where transport is highly anisotropic. The dispersion of these excitations also displays strong anisotropy. Along the hard direction, the dispersion is weak, although not absent as theory predicts. Along the easy direction, the dispersion is 3 times stronger and accompanied by a roton minimum as predicted in theory. The absorption intensity displays commensurability oscillations. They reveal the long-sought-for periodicity of the stripe phase: $3.6R_c$. This is larger than what theory has predicted ($2.7R_c$). An extension of these experiments with in-plane magnetic fields may be very fruitful. In-plane fields can rotate the quantum Hall stripe phase [16–18]. Such studies may also deepen our understanding of the enigmatic $\nu = 5/2$ quantum Hall state, which can be converted to a quantum Hall stripe state in the presence of an in-plane magnetic field [16,17]. Substantial technical advances are, however, required to combine the present experimental arrangement with tilted magnetic fields.

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