Anomalous Sound Propagation at $\nu = \frac{1}{2}$ in a 2D Electron Gas: Observation of a Spontaneously Broken Translational Symmetry?

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Surface-acoustic-wave propagation on high-quality AlGaAs/GaAs heterostructures containing a two-dimensional electron system has been examined in the fractional quantum Hall effect (FQHE) regime. The response of the electron system to the sound wave is found to be similar in the FQHE states to that previously studied in the integral quantum Hall states. However, a striking disparity is observed at Landau-level filling $\nu = \frac{1}{2}$, where sound propagation is distinctly different from that in the neighboring filling-factor range. We propose that phase separation of the 2DEG may be responsible for the feature at $\nu = \frac{1}{2}$.

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Crucial to the understanding of a two-dimensional electron gas (2DEG) are studies of the dynamic response of the electron layer to an applied electric field. This is particularly true in the extreme quantum limit of low temperatures and high magnetic fields where collective electron effects, such as the fractional quantum Hall effect[1] (FQHE), predominate. The largest and most fruitful body of data examining this regime has come from dc electronic transport.[2] A means of probing the *dynamical* properties of the 2DEG is to exploit the strong electron-phonon interaction in the piezoelectric host material of AlGaAs/GaAs heterostructures. By propagating surface acoustic waves (SAW) on the heterostructures, a spatially and time-varying electric field is generated at the surface which penetrates to the 2DEG layer. The interaction of the SAW electric field with the 2D electrons affects the sound velocity and attenuation, providing an indirect way of measuring the dynamical conductivity $\sigma_{xx}(\mathbf{k},\omega)$ at high frequencies ω and finite wave vectors $\mathbf{k}$. This technique was employed by Wixworth, Kotthaus, and Weimann[3] in the integral quantum Hall effect (IQHE) regime, revealing quantum oscillations in both the sound attenuation and velocity corresponding to Shubnikov–de Haas oscillations of the dc conductivity. These SAW data were quantitatively explained using the dc conductivity to model the 2D electron response to the sound in a relaxation-type interaction.

In the Letter we report surface-acoustic-wave studies in high-quality 2D electron systems in the fractional quantum Hall effect regime. We have measured the sound attenuation and velocity as a function of magnetic field. We have also measured simultaneously the dc conductivity of the 2DEG and use this to calculate the expected sound velocity and attenuation. In general, we find good agreement between the measured and calculated sound properties over the entire IQHE and FQHE regime.

However, a surprising new feature occurs in the sound measurements at Landau-level filling factor $\nu = \frac{1}{2}$. We observe a decrease in the sound velocity and an increase in absorption, in stark contrast to that expected from the dc-conductivity model and contrary to the responses observed in the FQHE and IQHE states. We present the properties of the anomaly as seen in SAW studies at various frequencies, temperatures, and in several samples. Finally, we discuss the origin of this anomaly with respect to a full range of possibilities, from single-particle to collective electron effects. We will argue that this finding at $\nu = \frac{1}{2}$ may represent a manifestation of spontaneously broken translational symmetry in the 2D electron system.

We have studied a total of four high-quality, low-density ($< 1\times10^{11}$ cm^{-2}) GaAs/AlGaAs single-interface heterostructures. Samples 1–3 had high mobility $\mu \sim 4\times10^6$ cm^2/V sec while sample 4 had mobility $\sim 2\times10^6$ cm^2/V sec. Each sample was grown with typically 5000 Å between the sample surface and the 2DEG and 1000 Å between the Si dopant layers and the 2DEG. This distance was considerably less than the penetration depth of our SAW, which is about one wavelength (> 2.5 μm). Both ends of the sample surface were etched down leaving 2DEG-free zones where SAW transducers were patterned. The rectangular mesa remaining between the transducers provided a 2DEG path of ~ 4 mm. Six indium contacts were diffused into the periphery of the 2DEG mesa to allow simultaneous transport measurement using standard lock-in techniques. The interdigital SAW transducers were patterned using electron-beam lithography and evaporated directly onto the samples, with wavelengths ranging from 8 to 32 μm. Typically the fundamental, third, and fifth harmonics up to 1.2 GHz were observed in each sample. At kHz repetition rates, SAW pulses of ~ 1-μsec duration were launched across the 2DEG mesa, with amplitude and frequency measured using standard boxcar integration and homodyne detection.[4] Sample temperatures down to ~ 50 mK and magnetic fields up to 12 T were achieved in a dilution-refrigerator–superconducting-magnet system.

Typical longitudinal conductivity (σ_{xx}), SAW amplitude, and SAW velocity traces are shown in Fig. 1 as a

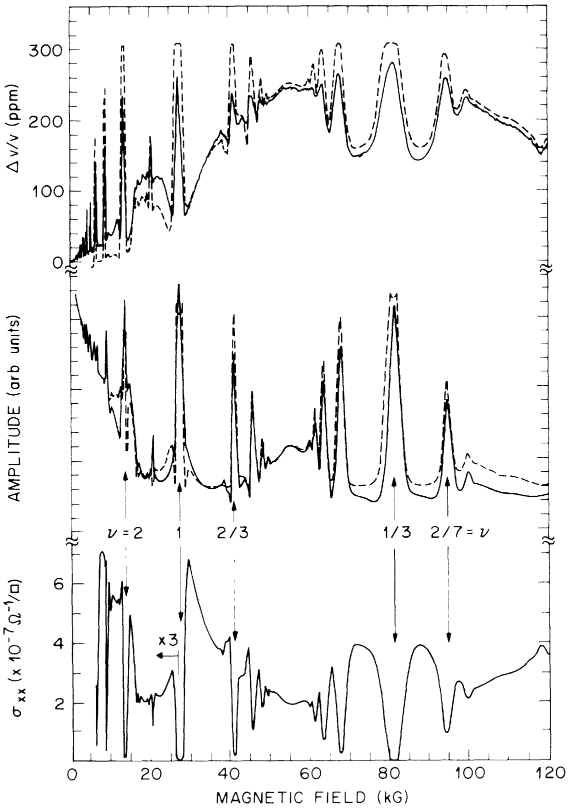

FIG. 1. Conductivity, SAW amplitude, and SAW velocity shift vs magnetic field at 160 mK and 235 MHz in sample 1. Solid lines are measured values, and dashed lines are results of the conductivity model using the measured $\sigma_{xx}(B)$ and $\sigma_m = 4 \times 10^{-7}\ \Omega^{-1}$ in Eqs. (1) and (2).

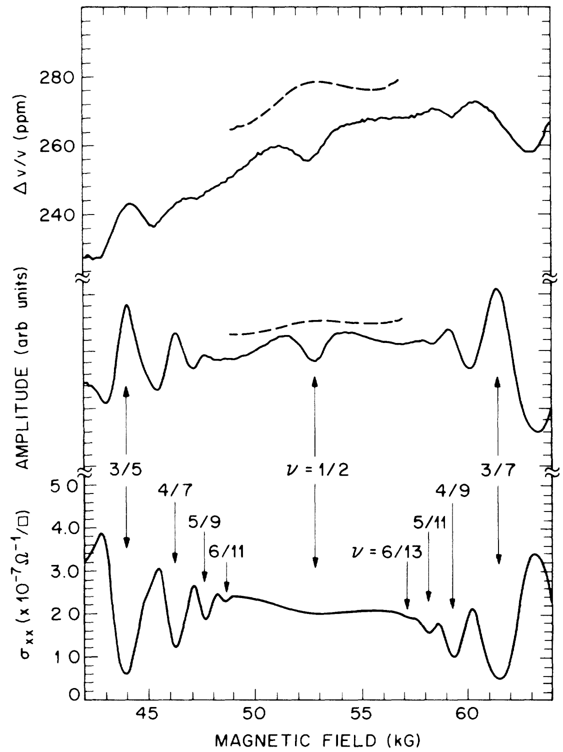

FIG. 2. Conductivity, SAW amplitude, and SAW velocity shift at 700 MHz and 50 mK for sample 1 over a magnetic-field range centered around filling factor $\nu = \frac{1}{2}$. The solid lines are measured values and the dashed segments are conductivity-model results as in Fig. 1 using $\sigma_m = 5.0 \times 10^{-7}\ \Omega^{-1}$ and slightly offset from the measured trace for clarity.

function of magnetic field. The more dominant features in the sound propagation are associated with the FQHE features, in particular with the fractional series $\frac{1}{3}$, $\frac{2}{5}$, $\frac{3}{7}$, $\frac{4}{9}$ observed in the amplitude.

As was demonstrated in previous work in the IQHE regime,[3] the SAW interaction with the 2D electron layer may be well modeled using the dc conductivity $\sigma_{xx}(\omega = 0)$. In this picture,[5,6] the piezoelectric field produced by the SAW interacts with the 2D electron layer and the electron system responds in a manner characterized by a relaxation time represented by the sheet conductivity $\sigma_{xx}(B)$. According to this model, the attenuation coefficient Γ [amplitude$\sim\exp(-\Gamma x)$] and the sound velocity v can be calculated from the conductivity using, respectively,

$$\Gamma = \frac{(\alpha^2/2)k(\sigma_{xx}/\sigma_m)}{1+(\sigma_{xx}/\sigma_m)^2} \tag{1}$$

and

$$\frac{\Delta v}{v} = \frac{v(\sigma_{xx}) - v_0}{v_0} = \frac{\alpha^2/2}{1+(\sigma_{xx}/\sigma_m)^2}, \tag{2}$$

where α is the effective piezoelectric coupling coefficient,[7] $\alpha^2/2 = 3.2 \times 10^{-4}$, $\sigma_m = v(\epsilon_0 + \epsilon_s) = 3.5 \times 10^{-7}$ $(\Omega/\Box)^{-1}$, and ϵ_0, ϵ_s are the dielectric constants of the vacuum and semiconductor. Plotted in Fig. 1 are our best fits of the above formulas to the data using the measured dc conductivity σ_{xx} and adjusting only the parameter σ_m. Good agreement between the measured sound features and the model is achieved with $\sigma_m = 4 \times 10^{-7}$ $(\Omega/\Box)^{-1}$, which is reasonably close to the theoretical estimate. This agreement holds throughout the range of frequencies and temperatures tested, from 90 MHz to 1.2 GHz and 50 mK to 4 K, with a slight increase in σ_m necessary for a good fit at higher frequencies. Overall, almost all FQHE and IQHE features seen in transport are expressed in the sound measurements.

The focus of our study is the striking feature at $\nu = \frac{1}{2}$ observed in the sound measurements. Figure 2 shows transport and ultrasound data in a magnetic-field range centered around filling factor one-half. As expected, when the conductivity drops in the FQHE states, the sound velocity and amplitude increase. Correspondingly, over the broad minimum in σ_{xx} around $\nu = \frac{1}{2}$, these sound properties generally increase. However, in the immediate vicinity of $\nu = \frac{1}{2}$, the sound velocity and ampli-

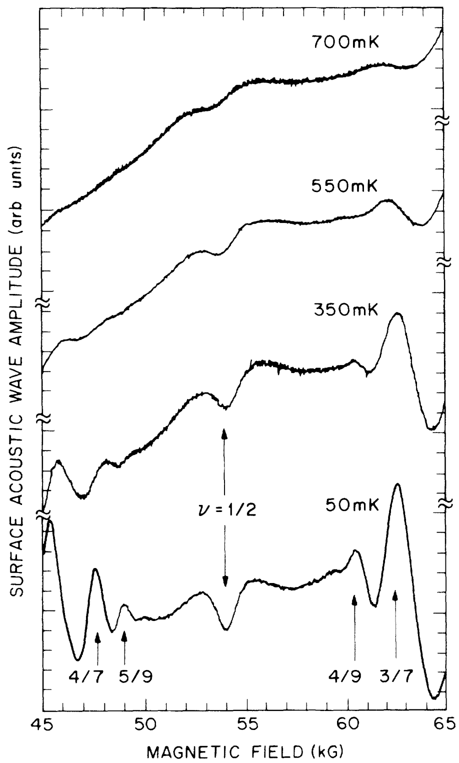

FIG. 3. SAW amplitude vs magnetic field at four different temperatures at 700 MHz in sample 1.

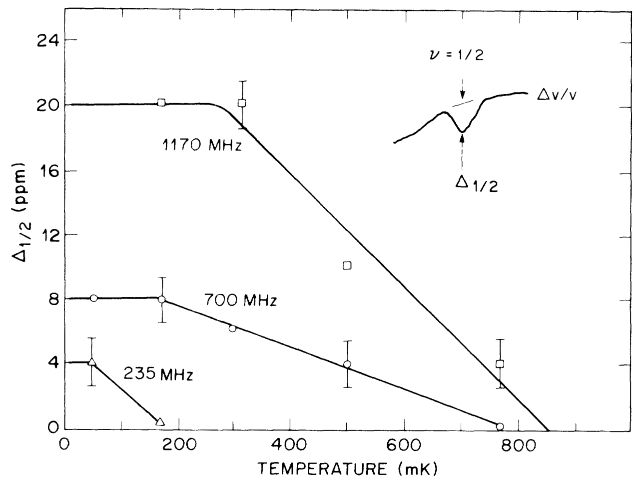

FIG. 4. Sound-velocity shift vs temperature for different frequencies in sample 1. Inset: The sound-velocity shift. The lines are a guide for the eye.

tude show a sharp minimum. This is in contrast to the broad *maximum* predicted by the dc-conductivity model, as shown by the dotted line in the figure. The magnitude of the $\nu=\frac{1}{2}$ anomaly is clearly as large as the sound response to several of the higher-order fractions ($\frac{4}{9}$, etc.) with the width of the feature about 2 kG ($\Delta\nu\sim 2\%$).

The $\nu=\frac{1}{2}$ sound anomaly at 700 MHz is displayed in Fig. 3 for several temperatures. As the temperature is increased, the magnetic-field width of the anomaly does not change appreciably. However, the magnitude of the minimum at $\nu=\frac{1}{2}$ decreases and finally the feature disappears near 750 mK. The temperature dependence of the strength of the minimum at $\nu=\frac{1}{2}$ in sound velocity, as defined in the inset, is shown in Fig. 4 for the three observable SAW harmonics in sample 1. From the figure it is seen that the higher-frequency SAW measurements reveal stronger anomalies at $\nu=\frac{1}{2}$ which then persist to higher temperatures.

All four samples tested displayed the sound anomaly at $\nu=\frac{1}{2}$. Given this unexpected observation at $\nu=\frac{1}{2}$ we examined closely the sound propagation at $\nu=\frac{9}{2}$, $\frac{7}{2}$, $\frac{5}{2}$, $\frac{3}{2}$, and $\frac{1}{4}$. No feature is discernible except at $\nu=\frac{3}{2}$, where a similar but weaker minimum was found in both the amplitude and the sound velocity.

The feature at $\nu=\frac{1}{2}$ is clearly distinct from the FQHE in that the sound response is opposite to that observed in FQHE states. In addition, no quantization is manifested in ρ_{xy} at $\nu=\frac{1}{2}$. Recent dc-transport experiments[8] observing a narrow conductivity minimum at $\nu=\frac{1}{2}$ offer no immediate explanation: A more pronounced minimum in $\sigma_{xx}(\omega=0)$ translates to a stronger sound-velocity maximum using the relaxation model and not the minimum we observe.

The cause of this anomaly at $\nu=\frac{1}{2}$ is presently not known. We shall discuss a range of possible explanations. First, we consider localization effects. Recent localization studies[9] indicate that the magnetic-field range over which the electronic states are extended near $\nu=\frac{1}{2}$ obeys $\Delta B\sim T^{\kappa}$, where $\kappa=0.42$. From Fig. 3 it is clear that the magnetic-field range of the anomaly does not increase appreciably in width over an order-of-magnitude increase in the temperature. This suggests localization effects are not responsible for the $\nu=\frac{1}{2}$ anomaly.

An inhomogeneous 2DEG could result in a SAW measurement indicating increased $\sigma(\omega)$ when compared to σ_{dc}. The SAW detects an average conductivity,[10] whereas dc transport measures a local conductivity which may be dominated by series resistance effects in very inhomogeneous samples. However, if this mechanism applies to our 2D systems, the question remains as to why the effect occurs over such a narrow range of ν around $\frac{1}{2}$.

Another possibility at $\nu=\frac{1}{2}$ is the presence of a distinct collective electron state, possessing an excitation mode to which the sound couples over our experimentally accessible ω and k range. In this possibility, the energy scale of such a condensate must be ~ 1 K as this is the temperature range over which we observe the $\frac{1}{2}$ anomaly in Fig. 4. The simplest excitations of a noncondensed 2DEG are plasma oscillations with no applied magnetic field, and cyclotron resonances with an applied magnetic field. The SAW frequencies are well below both the cyclotron frequency $\omega_c = eB/m^* \sim 10^{13}$/sec at $\nu = \frac{1}{2}$ and the short-wavelength ($\lambda \sim 1$ μm) plasma frequencies $\omega_{pl} \sim 10^{12}$/sec of the 2DEG. Therefore, any proposed condensed electron state must have both a condensation energy consistent with the 1-K scale of the data and a relatively soft excitation mode in the GHz range to explain the coupling we observe.

Such a collective electron state to be considered is a charge-density-wave (CDW) state or a Wigner lattice. In this scenario the linear sound dispersion of the SAW parallels a broadened $\omega \sim k^{3/2}/B$ dispersion of the soft shear mode in the electron lattice.[11] However, experimentally we do not observe crossing of the SAW dispersion and shear modes, which would appear as a double-minimum structure rather than a single minimum. This finding argues against Wigner-lattice formation at $\nu = \frac{1}{2}$, as do theoretical studies. Trial wave functions[12] at $\nu = \frac{2}{7}$ to $\frac{5}{11}$ show marked energy reduction in the liquid state versus the CDW state in the Hartree-Fock approximation approaching $\nu = \frac{1}{2}$; at $\nu = \frac{5}{11}$ this difference is ~ 2 K for our system. It is difficult to imagine such an increase in the energy per particle sufficient to describe the Wigner crystal as the ground state and yet not have this manifested as a gross feature in simple transport, where the conductivity is relatively calm over this ν range near $\frac{1}{2}$ (see Fig. 2).

Our favored description of the 2DEG at $\nu = \frac{1}{2}$ producing anomalous sound properties is a picture based on the quasiparticle-excitation calculations of Halperin.[13] In this energy versus ν approximation a marked upward pointing cusp at $\nu = \frac{1}{2}$ implies instability (negative compressibility), remedied by breakup of the 2DEG into small regions of larger and smaller density. This spontaneous breaking of the translational symmetry lowers the free energy of the 2DEG as the resultant electron patches of different densities are separately more stable. The energy scale of this picture is roughly correct according to our data; the temperature below which the anomaly is observed in Fig. 4 is ~ 1 K. In Halperin's calculation, to descend from the $\frac{1}{2}$ peak to near the ν extent of our $\frac{1}{2}$ feature ($\sim 2\%$), a difference in energy of ~ 1 K is traversed. This lowering of the free energy produces electron clusters or produces a 2DEG density fluctuation (CDW with λ greater than interelectron separation) and is balanced by an increase in the Coulomb energy.

The question remains within this picture of phase separation as to what specifically the SAW wave couples to in order that we see the $\nu = \frac{1}{2}$ anomaly. We propose the electron clusters should nucleate at impurity sites. Additionally, these imperfections may act as pinning sites for the electron clusters. Consequently, the center-of-mass motion of the cluster about the pinning site provides a low-frequency excitation mode to which the SAW couples.[14] Alternatively, deformations in the cluster surfaces may provide low-frequency modes.

In conclusion, we have observed anomalous SAW propagation at $\nu = \frac{1}{2}$. While FQHE and IQHE filling factors displayed sound amplitude and velocity consistent with dc-conductivity measurements of the 2DEG, at $\nu = \frac{1}{2}$ a distinctly different response to the SAW field occurs. This feature is most pronounced at low temperatures (< 200 mK) and high SAW frequencies (> 500 MHz). The cause of this effect is yet undetermined; however, it is suggested that a phase separation of the 2DEG with a spontaneously broken translational symmetry may, in fact, be responsible.

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