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Enhanced finite-wave-vector conductivity at multiple even-denominator filling factors in two-dimensional electron systems

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High-frequency surface acoustic waves (>2 GHz, $\lambda<2$ μm) have been propagated on high mobility $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructures, allowing measurement of the finite-wave-vector conductivity $\sigma_{xx}(q,\omega)$. We find enhanced $\sigma_{xx}(q,\omega)$ at *multiple* even-denominator filling factors $\nu=\frac{1}{2}$, $\frac{3}{2}$, $\frac{1}{4}$, and $\frac{3}{4}$ with $\sigma_{xx}(q,\omega)$ increasing linearly in q. The enhanced $\sigma_{xx}(q,\omega)$ at $\nu=\frac{1}{2}$ persists to high temperatures (>4 K), above the temperatures at which the fractional quantum Hall effect is observed. Empirically, the effects represent a *series* of robust states in two-dimensional electron systems that support gapless excitations. These data are strikingly consistent with a recent theory describing Fermi-surface formation at even denominator ν.

Electron correlation effects dominate the small filling factor range of high mobility two-dimensional electron systems (2DES). Such a correlation, the fractional quantum Hall effect[1] (FQHE), is characterized by (dc) longitudinal conductivity minima at a series[2,3] of odd-denominator filling factors $\nu=p/q$, q odd, extending throughout the lowest Landau level. Between these states of liquidlike electron correlation, that is at *even*-denominator filling factors, the nature of the 2DES is not known. Clearly, electron interactions must be significant. Suggestions have been made that the 2D system may experience phase separation,[3] with regions condensing to different density FQHE states to minimize energy. Another approach describes electron pairing[4] at even-denominator ν, possibly allowing quantized Hall states to form, but experiments have yet to demonstrate any quantization in the Hall resistance at $\frac{1}{2}$.[5] Recently an elegant and extensive theory[6] of the half-filled Landau level has been developed, in which a Fermi surface occurs at even-denominator ν. Consequences of this Fermi surface include magnetotransport oscillations as seen in the FQHE and gapless excitations at even-denominator filling factors.

To the end of understanding the even-denominator filling factors, we have expanded[7] the use of surface acoustic waves (SAW's) to high frequencies to extract large wave-vector-dependent sheet conductivity $\sigma_{xx}(q,\omega)$ in high-quality 2D electron systems. Past results[7,8] at lower frequencies have shown that the SAW technique is good for measuring FQHE and integral quantum Hall effect (IQHE) sheet conductivity in a contactless method with the $\sigma_{xx}(q,\omega)\approx\sigma_{xx}(\mathrm{dc})$ for FQHE and IQHE states. Early results[8] also demonstrated some anomalous sound propagation at $\nu=\frac{1}{2}$. Results from transport measurements[5] likewise indicated peculiar behavior at $\frac{1}{2}$, but other small-q techniques averaging over large sample areas, such as luminescence[9] and compressibility studies,[10] revealed nothing in particular at $\frac{1}{2}$.

By propagating a $\lambda<2$-μm SAW on high mobility heterostructures, we have measured the finite-wave-vector conductivity $\sigma_{xx}(q,\omega)$ for a large range of q values over the FQHE regime. Surprisingly we found markedly enhanced $\sigma_{xx}(q,\omega)$ at a *series* of even-denominator $\nu=\frac{1}{2}$, $\frac{1}{3}$, $\frac{3}{2}$, and $\frac{3}{4}$ for large q. This enhanced $\sigma_{xx}(q,\omega)$ persists to high temperatures (>4 K), above the temperature at which even the most robust FQHE state ($\nu=\frac{1}{3}$) exists in these samples. We show that the enhanced conductivity increases linearly over a large range in q. The robustness and multiple even-denominator occurrence of these $\sigma_{xx}(q)$ peaks suggest the presence of a *series* of states, complementary to the series of FQHE states in the requisite conditions for existence, but able to support gapless excitations. These results are remarkably consistent with the recent theory describing Fermi-surface formation at even-denominator ν.

In order to study correlation effects, we employed high mobility single interface $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructures. Six samples of densities $n\sim6\times10^{10}$ cm^{-2} and mobilities around 4×10^6 $\mathrm{cm}^2/\mathrm{V\,s}$ had standard indium contacts diffused into the periphery. The 2DES was etched from the ends of the sample, leaving a mesa containing the 2DES of about 2 mm in width. On the sample ends without the 2DES, interdigitating transducers were evaporated. From one transducer a SAW could be launched across the piezoelectric GaAs sample and detected by the other transducer using standard homodyne techniques.[11] The interdigit spacing of the transducer establishes the SAW wavelength λ and the frequency f such that at $f\lambda=v$, where v is the sound velocity, a traveling wave traverses the 2DES and is detected at a later time determined by the path length and the sound velocity. The lower-frequency SAW's were achieved using the fundamental and several higher harmonics of the same transducer. The highest frequencies (>1.5 GHz) were obtained by using the fundamental frequency of transducers with submicrometer interdigit spacing. The SAW penetrates to the level of the 2DES ($\sim10^3$ Å) and both its amplitude and velocity are effected by the conductivity of the electron system.

The wave-vector and frequency-dependent conductivity $\sigma_{xx}(q,\omega)$ can be extracted from the measured SAW transmitted amplitude A and the velocity shift $\Delta v/v$ using

$$\Gamma=\left[\frac{\alpha^2}{2}\right]\frac{q\sigma_{xx}(q)/\sigma_m}{1+[\sigma_{xx}(q)/\sigma_m]^2}\ ,$$

$$\frac{\Delta v}{v}=\left[\frac{\alpha^2}{2}\right]\frac{1}{1+[\sigma_{xx}(q)/\sigma_m]^2}\ ,$$

where $A=\exp(-\Gamma x)$, x=path length, the piezoelectric coupling constant $(\alpha^2/2)=320\times10^{-6}$ for GaAs, and $\sigma_m=\sigma_m(q)\approx v(\varepsilon+\varepsilon_0)$.[13] This utilizes a simple model[12] of electronic relaxation with the sheet conductivity $\sigma_{xx}(q,\omega)$ parametrizing the relaxation time. These expressions allow inference of the wave-vector and frequency-dependent sheet conductivity $\sigma_{xx}(q,\omega)$ at the $q=2\pi/\lambda$ of the SAW. Comparison can then be made to the dc conductivity $\sigma_{xx}(q=0,\omega=0)$, which is also measured in the sample.

Figure 1 shows the low-temperature transmitted SAW amplitude and sound velocity shift for a typical sample at 3.4 GHz as a function of magnetic field. The relaxation model was used to calculate the expected SAW amplitude from the dc transport $\sigma_{xx}(q=0,\omega=0)$ (dotted lines in the figure). Direct comparison can be made between the traces to look for discrepancies, with these differences demonstrating that $\sigma_{xx}(q=0,\omega-0)\neq\sigma_{xx}(q_{\mathrm{SAW}},\omega_{\mathrm{SAW}})$. Little to no discrepancy is seen between the dc conductivity and the σ_{xx} at large q for FQHE states.

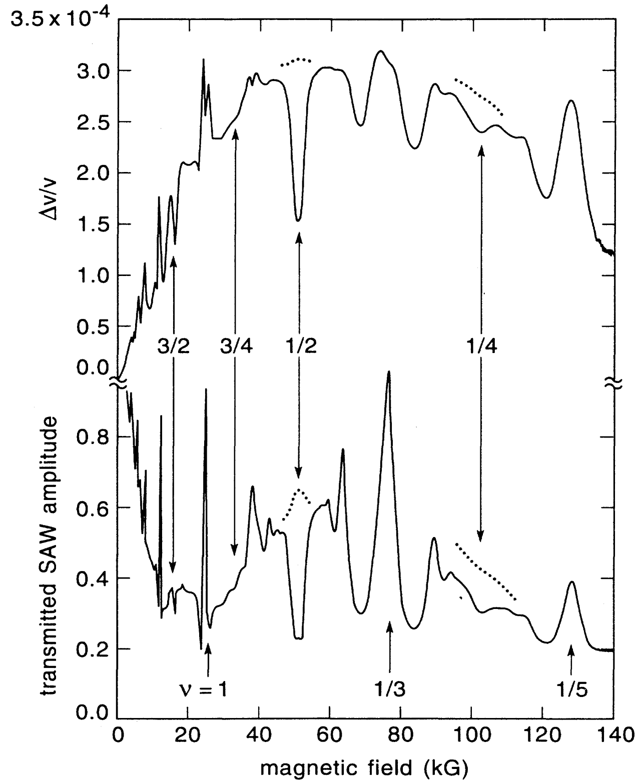

FIG. 1. The SAW velocity shift and transmitted amplitude for 3.4-GHz SAW at 120 mK vs magnetic field. The dotted lines represent the $\Delta v/v$ and amplitude calculated from the dc conductivity (offset for clarity).

For our highest SAW frequency of 3.4 GHz, a remarkably large difference between $\sigma_{xx}(q=0)$ and $\sigma_{xx}(q\neq0)$ occurs at $\nu=\frac{1}{2}$, with a marked minimum in both amplitude and $\Delta v/v$ (the relaxation model indicates that a broad shallow *maximum* should be observed at $\nu=\frac{1}{2}$ in A and $\Delta v/v$). This feature at $\frac{1}{2}$ represents *additional* or *enhanced* conductivity $\sigma_{xx}(q,\omega)$ at $q=2/\pi 0.9\ \mu\text{m}$ and $\omega=2\pi$ (3.4 GHz). The sheet conductivity $\sigma_{xx}(q,\omega)$ is well parametrized by a single σ_{xx} rather than by invoking a complex conductivity. This is apparent in a phase plot of Γ versus $\Delta v/v$—not shown. As such, the sheet conductivity $\sigma_{xx}(q,\omega)$ derived from the SAW data is the same for the amplitude and velocity measurements.

The most significant result is also displayed in Fig. 1; a distinct minimum at $\nu=\frac{1}{2}$ is demonstrated in both A and $\Delta v/v$. This effect was not observed at the small-q SAW. The finding at $\frac{1}{4}$ is corroborated by a smaller but distinct effect at $\nu=\frac{3}{4}$ in A and $\Delta v/v$. At $\nu=\frac{3}{2}$, a deep minimum similar to the $\frac{1}{2}$ result is present. The pair $\frac{1}{2}$ and $\frac{3}{2}$, occurring at the center of the spin-split Landau level, are stronger than the effects at $\frac{1}{4}$ and $\frac{3}{4}$; the magnitude of the effects does not simply increase with increasing B field. This suggests that the denominator values are important in determining the ordering of the states, similar to the ordering of the strength of the FQHE states. No discrepancy between dc conductivity and SAW results is apparent at $\nu=\frac{5}{2}$.

The wave-vector dependence of the SAW response is examined in Fig. 2. The effect at $\frac{1}{2}$ clearly becomes larger with increasing q; that is, the minimum becomes deeper. Also, the B-field width of the effect increases at larger q; for the 3.4-GHz SAW, the effect extends from about $\nu=\frac{7}{15}$ to $\frac{8}{15}$. Using the sound velocity shift $\Delta v/v$, $\sigma_{xx}(q,\omega)$ at $\nu=\frac{1}{2}$ and $\nu=\frac{1}{4}$ can be extracted for various applied q's using the same sample. Over two orders of magnitude in SAW q have been examined. Figure 2 shows that for $q>1\ \mu\text{m}^{-1}$, the $\sigma_{xx}(q,\omega)$ appears to grow linearly with q for both $\nu=\frac{1}{2}$ and $\frac{1}{4}$. Likewise, the width $(\Delta B/B)$ of the feature at $\frac{1}{2}$ increases linearly in q.

The large-q SAW measurements demonstrate a remarkable temperature dependence. In Fig. 3, the transmitted amplitude as a function of B is shown for temperatures ranging up to 4 K. It is surprising that the effect at $\nu=\frac{1}{2}$ persists even up to and beyond 4 K: the effect was found to be barely discernible at 4.5 K. This finding is remarkable in that the FQHE is gone at 3.0 K, and at 4.0 K the IQHE is only weakly apparent. Similarly, at $\nu=\frac{1}{4}$ the transmitted SAW amplitude also shows a robust effect even at 1.2 K, where the only FQHE state present is the principal fraction at $\nu=\frac{1}{3}$. The temperature dependence of the $\nu=\frac{1}{2}$ and $\frac{1}{4}$ SAW-determined conductivity is summarized in the lower panel of Fig. 3. The background of $\Delta v/v$ around $\frac{1}{2}$ (near $\frac{8}{15}$ and $\frac{7}{15}$) is relatively temperature independent.

Any theory addressing the nature of the 2DES at even denominators must explain three principal findings: (1) multiple states at $\nu=\frac{1}{2}, \frac{3}{2}, \frac{1}{4}$, and $\frac{3}{4}$ with this ordering in strength; (2) the linear wave-vector dependence of the $\sigma_{xx}(q,\omega)$; and (3) the specific temperature dependence of the states and their surprising robustness. These findings are discussed in detail below.

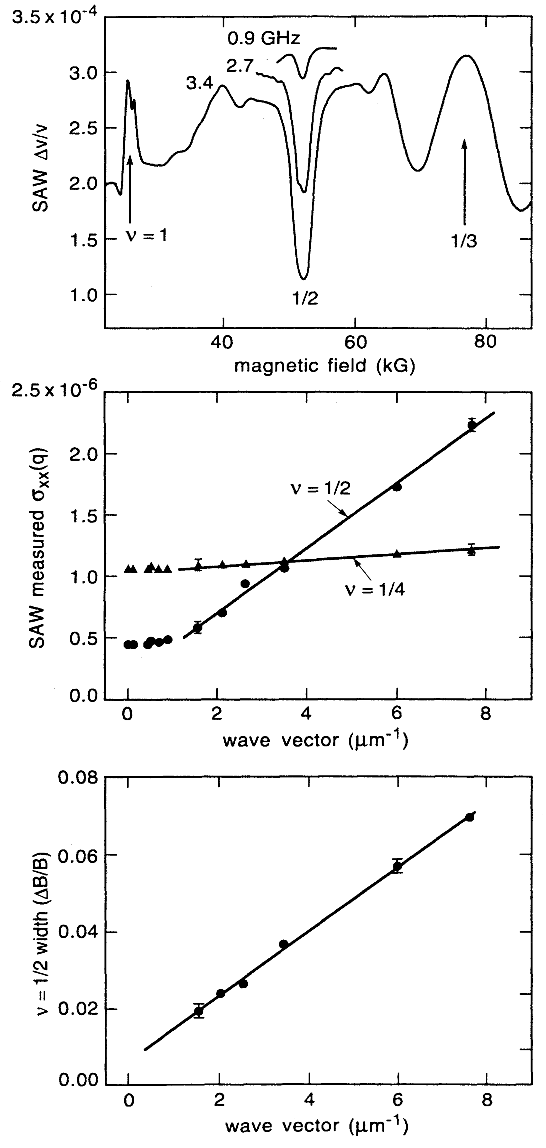

FIG. 2. Upper panel: the SAW velocity shift for three frequencies at 50 mK. The traces are offset for clarity. Middle panel: the wave-vector-dependent conductivity at 50 mK as derived from the SAW velocity shift. The $\frac{1}{2}$ data are taken from two samples cut adjacently from the same wafer, while the $\frac{1}{4}$ data are from a single sample. The lines are guides to the eye. Lower panel: $\nu=\frac{1}{2}$ width ($\Delta B/B$) vs the SAW wave vector at 50 mK. The width is defined as the full B field extent at the half maximum.

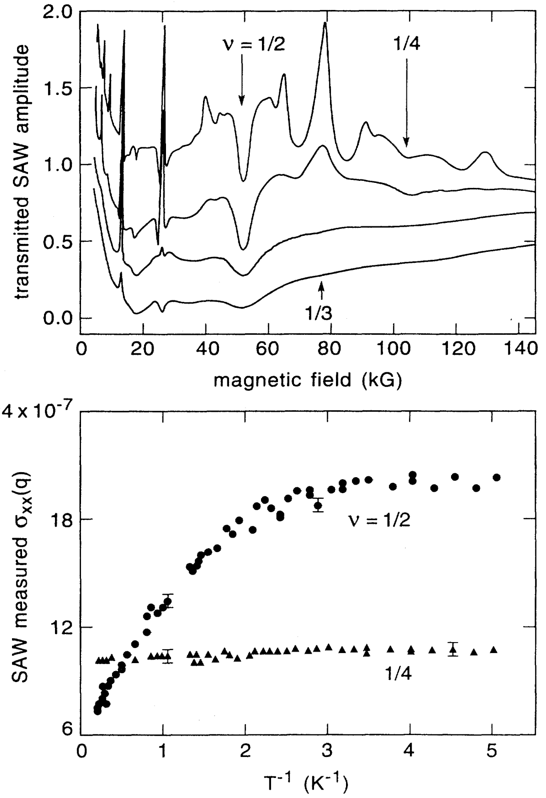

FIG. 3. The temperature dependence of the $\frac{1}{2}$ and $\frac{1}{4}$ features. The upper panel shows four transmitted SAW amplitude magnetic-field traces at temperatures of 0.45, 1.25, 3.0, and 4.0 K from top to bottom at the 3.4-GHz SAW. The lower panel shows the SAW-derived conductivity at 3.4 GHz.

The enhanced $\sigma_{xx}(q,\omega)$ at $\nu=\frac{1}{4}$ and its particle-hole symmetric point at $\nu=\frac{3}{4}$ is a strong counterargument to any suggestion that the additional conductivity represents a simple electron localization effect, since these ν have no particular importance with respect to the position of the localized states in the Landau level. Both the presence at multiple filling factors and the ordering of the magnitudes or strength of the effect is reminiscent of the FQHE and the ordering of the principal fractions. This suggests that "higher-order" even-denominator states should be explored; that is the even-denominator states between the hierarchical chain of the FQHE at $\nu=\frac{3}{8}, \frac{5}{12}$, etc. The observed ordering or decrease in strength from $\frac{1}{2}$ to $\frac{1}{4}$ indicates that the next level, such as $\frac{3}{8}$, will be substantially weaker.

At even denominators, $\sigma_{xx}(q,\omega)$ increases linearly with increasing q for sufficiently large q. This linear q dependence is distinctly different from the q independence of the rest of the extreme quantum limit 2DES and characterizes the nature of the underlying states' excitation spectrum. The filling factor extent of the enhanced conductivity also increases with q (Fig. 2). The question remains whether by increasing q this broadening will continue or be terminated when strong high-order fractions are approached.

The temperature dependence of the transmitted amplitude and $\Delta v/v$ at even denominator ν suggests the important parameter in the SAW probe is the wavelength, not the frequency. The effect persists to several K, well beyond the energy of the probe (3.4 GHz$\rightarrow\hbar\omega\approx150$ mK). One might expect a marked degradation of the effect at these high temperatures if the probe frequency was the single significant parameter. At 3.4 GHz, the SAW wavelength is less than 1 μm. This is substantially larger than the interelectron separation (~500 Å) or the magnetic length l_0(~100 Å) at 5 T. This is, however, the first time a probe of this length scale has been applied to high-quality 2D electron systems. Previous work[14] using $q=0$ but high ω radiation has not revealed the effects reported here. As such, the wave-vector dependence appears to be crucial, but its relationship to the pertinent length scales of the system (l_0, $n^{-1/2}$) must be explored and considered in any model.

The specific temperature dependence of $\sigma_{xx}(q)$ shown here is distinctly inconsistent with an excitation gap and rather is suggestive of a gapless excitation. It is intriguing that the effect is observable at temperatures beyond those able to support the FQHE. While the temperature range of the effect is comparable to the IQHE, it is difficult to invoke similarly a single-electron explanation because of the *multiple states* within the Landau level.

The possibility of phase separation[3,8] occurring between odd-denominator fractions resulting in multiple additional $\sigma_{xx}(q,\omega)$ peaks is not consistent with the data presented here for $\nu=\frac{1}{2}$. In the picture of phase separation, maxima occur at even ν in the energy versus filling factor curve with downward cusps at the FQHE states. The slopes of this curve about the pertinent ν determine the energy scale of the effects. Since experimentally we observe a stronger effect at $\nu=\frac{1}{2}$ than at $\nu=\frac{1}{3}$, it is suggested that the maximum at $\frac{1}{2}$ is as or more pronounced than the downward cusp at $\frac{1}{3}$. This is unlikely as the dc transport shows nothing pronounced in the vicinity of $\frac{1}{2}$. Phase separation is also questionable for its lack of further experimental support; luminescence studies[9] have not shown marked frequency shifts at $\nu=\frac{1}{2}$ as one would expect with charge separation occurring in phase separation. Compressibility studies[10] have likewise not displayed any distinctive behavior near $\frac{1}{2}$, as might be expected in a negatively compressible phase separated state. These negative results are not a definitive contradiction of the phase separation model, but this picture requires further experimental evidence to secure any validity.

A new description[6] of the 2DES in the extreme quantum limit has been proposed and preliminarily demonstrates many properties that are appealingly consistent with the SAW data. In this model by Halperin, Lee, and Read, a Chern-Simons gauge field construction is employed whereby the resultant quasiparticles at $\nu=\frac{1}{2}$ behave like interacting fermions in $B=0$. From this, Fermi-surface phenomena are expected. When the magnetic field is varied away from $\frac{1}{2}$, magnetotransport oscillations corresponding to the principle series of the FQHE are predicted. For sufficiently large q, a wave-vector-dependent conductivity is anticipated at $\frac{1}{2}$, specifically with a linear dependence in q. This type of construction can be carried out at other even-denominator filling factors, again with the expectation that at each a Fermi surface exists. Our principal findings of multiple wave-vector-dependent conductivities match the experimental expectations of this theory. The small-q independence then large-q linear dependence of this conductivity are as we see experimentally, although the overall magnitude of the measured $\sigma_{xx}(q)$ is not in close agreement. This construction also describes linearly increasing width ($\Delta B/B$) with q at $\frac{1}{2}$, as we observe. This theory and the experimental results together qualitatively demonstrate an important new general perspective on the interacting 2DES.

To summarize, we have used large wave-vector SAW's to examine the FQHE regime at even-denominator ν. We find additional large-q conductivity at *multiple* even-denominator ν, presenting a set of $\sigma_{xx}(q,\omega)$ peaks at $\frac{1}{2},\frac{3}{2}$ and $\frac{1}{4},\frac{3}{4}$, with the larger-denominator states weaker in similarity to the FQHE. The $\sigma_{xx}(q,\omega)$ at $\nu=\frac{1}{2}$ and $\frac{1}{4}$ increases linearly with increasing q. The effect at $\frac{1}{2}$ is extremely robust, persisting to temperatures >4 K, but with a temperature dependence consistent with a gapless excitation. Empirically, these effects represent a new series of states in the 2DES. The findings here agree extensively with a general new theory of the 2DES which is presently being developed.

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