Probing Quantum Hall State Homogeneity with Surface Waves

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Abstract. We study single quantum wells and matched density bilayer samples. Simultaneous measurements of the Hall voltages using low frequency lock-in techniques and of the changes in the 232 MHz (12.6 µm) SAW propagation measured with a vector network-analyzer allow comparison of the complex bulk and edge conductivities. The \( \nu_{\text{total}} = 1 \) bilayer state is seen directly in the SAW measurement only when the conductivity is below \( \sim 6 \times 10^{-8} \) Siemens and is destroyed at moderate SAW powers by localized heating. The simultaneous reduction of the conductivity minima extracted from Hall data and from SAW data conclusively demonstrates that the \( \nu_{\text{total}} = 1 \) state disappears simultaneously throughout the bulk and not by the formation of competing domains or conducting filaments.

1. Introduction

Past use of SAW probes has provided insight into the composite fermion state and the domain structure in quantum hall ferromagnets. [1, 2] Flexible techniques using proximity effects of the 2-DEG on SAW travelling on adjacent LiNbO\(_3\) surfaces have allowed the extraction of the complex conductivity, whereby the ratio of imaginary to real components is a measure of the fraction of localized charge carriers. [3] SAW can also provide momenta to probe the energy dispersion of neutral excitations through microwave spectroscopy, e.g., the roton minima at filling factor 9/2. [4] The general benefit is that SAW wavelengths can be tailored to probe structure at particular length scales and provide information about bulk states without edge effects. This work presents the first SAW measurements of a bilayer quantum well system along with calibrated measurements of the complex conductivity of a single 2-DEG derived directly from SAW measurements. We find strong SAW sensitivity to the \( \nu_{\text{total}} = 1 \) state, where an excitonic condensate forms due to coupling between electrons and holes in the upper and lower layer which individually have filling factor 1/2 of the lowest Landau level.

2. Simultaneous SAW and Resistivity Measurements

In our experiments a standard 300 x 840 µm\(^2\) Hall Bar is flanked by a set of interdigital 12.6 µm (232 MHz) interdigital Al transducers (IDT). SAW pulses are generated and detected with an Agilent 5070 Network Analyzer (NA). Electrical voltages are monitored with Stanford 830 DSP Lock-in Averagers. The IDT in our single quantum well experiments has a width of 50 µm and can be aligned with the center or the edge of the Hall bar as seen if Fig. 1. For the bilayer measurements the IDT is centered on and matched in width (300 µm) to the Hall bar.
2.1. Predicting SAW Phase Change and Attenuation from Conductivity Data

In order to calibrate the SAW sensitivity to changes in the 2-DEG we first investigate the effect of a single quantum well sample on the SAW signal. Simultaneous DC resistance and SAW measurements (Fig. 1) show the clear correspondence between longitudinal resistance (and conductance) minima and peak SAW phase shifts. The SAW magnitude is minimal (maximum attenuation) at magnetic field values corresponding to the edges of Hall plateaus, where the longitudinal resistance begins to rise. A simple relaxation model relates the expected attenuation per meter, and relative phase shift to the conductivity:

\[
\Gamma = \frac{a k_{ref} \sigma_{xx} / \sigma_m}{\left(1 + \sigma_{xx}^\prime / \sigma_m\right)^2 + \left(\sigma_{xx} / \sigma_m\right)^2} \quad \Delta \phi = \frac{-\Delta \nu}{\nu_{ref}} = \frac{-a \left(1 + \frac{\sigma_{xx}^\prime}{\sigma_m}\right)}{\left(1 + \frac{\sigma_{xx}}{\sigma_m}\right)^2 + \left(\frac{\sigma_{xx}^\prime}{\sigma_m}\right)^2}
\]

where \(\nu\) is the SAW wavespeed, \(k\) the wavenumber and \(a\) is the piezoelectric coupling constant (~6.4 \(x\) 10\(^{-4}\)). \(\sigma_{xx}\) and \(\sigma_{xx}^\prime\) are the real and imaginary parts of the complex conductivity of the 2-DEG and \(\sigma_m\) is the GaAs conductivity (~3.7 \(x\) 10\(^{-7}\)). The subscript \(ref\) refers to expected values for the SAW on GaAs in the absence of the 2-DEG. For our low frequency (lock-in at 8.3 Hz) electrical measure-
ments, the conductivity is assumed to be purely real. The predicted SAW phase maximum from this mode, shown in Fig. 1, is in good agreement with the measurement. The higher than predicted values of attenuation are attributed to parallel conduction. The distance between the free surface and the buried 2-DEG (50-70 nm) is not likely to affect attenuation for these samples.

The interdigital transducers are excited with a bandwidth of 10-20 MHz. Thus, a range of excited wavelengths inversely proportional to the frequency are present in the SAW pulse. The phase shift with frequency can be used to estimate the maximum expected phase shift from Eqn. 1, \( \Delta \phi_{\text{max}} = \alpha \phi_{\text{ref}} \). For a typical measurement after transit over a surface distance of 1.9 mm including an 0.84 mm Hall bar, the phase difference measured at 231 and 232 Hz was 2.5 radians at zero field, yielding an estimated maximum phase shift in the Hall bar of:

\[
\Delta \phi_{\text{max}} = \alpha \phi_{\text{ref}} \approx \alpha \frac{\Delta \phi}{x} \approx 0.16 \text{ radians (9.4°)}
\]

where \( x \) and \( d \) represent the total surface distance and the distance in the 2-DEG traversed by the wave. The maximum measured phase shift of 6.8° and maximum predicted phase shift of 7.4° shown in Fig. 1 are both low, suggesting a lower bound to the measurable conductivity.

2.2. Predicting SAW Phase Change and Attenuation from SAW Data

The Network Analyzer measures the phase shift and attenuation of the surface acoustic wave (SAW) with outputs in the form:

\[
A_{\text{out}} (\text{in dBm}) = 10 \log \left( \frac{P_{\text{transmitted}}}{1 \text{ mW}} \right) = -10 \Gamma d + C_A
\]

\[
\varphi_{\text{out}} = \Delta \varphi + C_\varphi = d k - k_{\text{ref}} + C_\varphi
\]

The Analyzer phase output is in degrees modulo 360. The constants \( C_A \) and \( C_\varphi \) represent the accumulated attenuation and phase in the connecting wires and in the region of SAW travel unaffected by the 2-DEG. These are removed by a simple baseline subtraction from the output data.

The SAW conductivity peaks shown in Fig. 2 are more symmetric with field than the Hall conductivity peaks, because they are less affected by edge states. Similar conductivity values are derived from 1.162 GHz SAW data and from data taken with SAW positioned at the Hall Bar center. These measurements on single quantum wells prove that the accumulated phase and attenuation changes, which essentially average over a 50 \( \mu \)m wide propagation strip, are dominated by the bulk conductivity and do not show size effects at these filling factors.

**Figure 2.** The SAW data cannot be used to calculate conductivity at low B fields because of large offsets in the output of the superconducting Al transducers (which disappear when higher B fields). The SAW conductivity peaks are symmetric with field, because they are less affected by edge channels.
2.3. Bilayer SAW response

Our bilayer samples consist of two 19 nm GaAs QWs, separated by a 10 nm GaAs/AlAs superlattice barrier. Two Si-doping layers are embedded 430 nm away in an $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$ matrix. At low temperature ($T = 20 \text{ mK}$), the bilayer samples show very clear Hall plateaus at 1.3 and 2.6 Tesla, corresponding to filling factor 1 ($\nu_{\text{total}} = 1 + 1 = 2$) and filling factor $\frac{1}{2}$ ($\nu_{\text{total}} = \frac{1}{2} + \frac{1}{2} = 1$) in the individual bilayers. The bilayer SAW signals are detected at 232 MHz with a 300 µm wide transducer centered on the Hall bar. Higher frequency SAW were not detected in the bilayer experiments, possibly due to scattering from the high mesa formed in etching the Hall bar.

In comparison to the single quantum well data of Fig. 1, the field dependent SAW changes in the bilayer system shown in Fig. 3 are a factor of 3 smaller. This factor is consistent over multiple samples, and must be attributed to differences in the growth structure. The expected maximum phase shift, based upon the measured phase change with frequency at zero field (Eqn. 2) for this sample is very close to the single well value ($10^0$). The overall signal level in the bilayer sample is 10 dB higher than that measured in the single well, most likely due to decreased scattering at lower temperature. The sample does not have top or back gates, but the field dependent SAW signal could be affected by the upper Si doping layer.

The $\nu_{\text{total}} = 1$ state is sensitive to temperature. The longitudinal resistance minimum and the associated conductivity minimum is shallower at higher probe temperatures and at higher SAW power, which raises the temperature locally. Fig. 4 shows the correlated changes in the peak height and conductivity extracted from the Hall data with increasing temperature (right) and increasing SAW power (left). The reported temperatures here are those recorded with a low temperature thermistor mounted on the probe stage of the dilution refrigerator. Judging the effect of heating with SAW by the effect on peak height, it appears that $P_{\text{SAW}} = 0 \text{ dBm}$ corresponds to $T_{\text{probe}} \sim 200 \text{ mK}$. At this level, the SAW
peak at $\nu_{\text{total}} = 1$ is completely suppressed, although a shallow longitudinal minima persists. In contrast, the peak height and conductivity minimum at $\nu_{\text{total}} = 2$ remain constant up to 10 dBm.

3. Conclusions
We have studied single quantum wells along with matched density bilayer samples. Our simultaneous measurements of the SAW propagation and Hall voltages allow direct comparison of the complex bulk and real (~DC) edge conductivities. The $\nu_{\text{total}} = 1$ state is seen directly in the SAW measurement only when the conductivity is below $\sim 6 \times 10^{-7}$ Siemens and is destroyed at moderate SAW powers by localized heating. Heating does not diminish the SAW peak at $\nu_{\text{total}} = 2$, though there are small changes in the field range of this state. The strong correlation between the disappearance of the conductivity minima and the SAW signal at $\nu_{\text{total}} = 1$ demonstrates that the homogeneous excitonic state disappears across the entire sample simultaneously. In contrast, Quantum Hall Breakdown in a single quantum well shows persistent SAW signal well beyond the breakdown current (where conductivity minima are no longer measureable). [6] This conclusively demonstrates that the $\nu_{\text{total}} = 1$ excitonic state is uniformly distributed in the bulk and not restricted to small domains or filaments.

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