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Time-resolved phonon absorption in the fractional quantum Hall regime

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Abstract

We report time-resolved measurements of phonon absorption in the fractional quantum Hall regime. Experiments have been conducted on an n-type heterojunction grown on a 1.8 mm GaAs wafer. The start of the absorption signal is consistent with the ballistic phonon time-of-flight. The initial rise time is consistent with the time constant of our device and external circuits. This is followed by unusually slow rise and decay times.

Keywords: Electrical transport measurement; Fractional quantum Hall effect; Heterojunction; Phonons

1. Introduction

The fractional quantum Hall effect which occurs in high mobility two-dimensional carrier systems, such as two dimensional electron (2DES) and hole (2DHS) systems, subject to a strong perpendicular magnetic field is ascribed to the existence of an incompressible quantum liquid at certain rational filling factors. It is believed that the low-lying excited states of the liquid are collective modes that are never gapless (except at the sample boundaries). Girvin, MacDonald and Platzman (GMP) [1] have developed a theory for these collective modes at the primary filling factors $\nu = 2\pi l^2_{c} n_s = 1/m$ (n_s is the electron sheet density, l_c is the cyclotron length, and m is an odd integer); they find that the dispersion of the collective mode has a deep minimum for wavelengths comparable to the mean interparticle spacing. This "magneto-roton" minimum occurs, as in liquid helium, because of the peak in the static structure factor. What has been lacking experimentally is a means of measuring the gap close to the magneto-roton minimum. We report here a study of these excitations using phonon absorption.

Activated magneto-transport studies have provided a measure of the energy gap that is found to depend on the mobility of the sample [2]. Theoretically it is also expected that this measurement probes the dispersion at high wavevectors rather than close to the magneto-roton minimum. Pinczuk et al. [3] have observed a feature in the inelastic light scattering spectrum that is attributed to the low wavevector excitations of the FQHE in a quantum well. More recently measurements have been reported at finite wavevector in the integer quantum Hall effect regime [4].

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Ballistic acoustic phonons have proved to be a unique probe of low-dimensional systems [5]. The typical energies and wavevectors are well matched to those of the 2DES and 2DHS and, since in the FQHE state the magneto-rotons are the only low energy modes which can couple to the ground state through the electron density, they should provide the principal channel for the absorption of acoustic phonons. This makes phonon absorption a promising method to investigate the energy gap of the FQHE in this region.

2. Phonon absorption experiments

To measure the phonon absorption signal, a CuNi heater was evaporated onto the polished rear face of the GaAs wafer. A heterojunction had previously been grown on the front face by molecular beam epitaxy, and a Hall bar fabricated opposite the heater position. The carrier system was supplied with a constant bias current. The phonon absorption was measured from the change in longitudinal resistance produced by a burst of non-equilibrium ballistic phonons generated by a 100 ns voltage pulse applied to the heater. The transient voltage was measured using a gated amplifier with an 8 μs gate length. The apparatus and methodology of these time-averaged studies is described in more detail elsewhere [6].

3. Theoretical model

The spectral distribution of the non-equilibrium phonon pulse is assumed to approximate to that of a black body at a temperature, T_h, which is calculated from the total power dissipated in the heater by acoustic mismatch theory and confirmed by measuring the energy gaps at $\nu=12$ and $\nu=14$ on a high mobility 2DES under the same conditions as the fractional energy gaps were obtained.

The rate of energy transfer from the non-equilibrium phonon pulse to the carrier system depends on the dynamic structure factor of the latter. At long wavelengths this is believed to be well described by the single-mode approximation given in Ref. [1]. This predicts that the dominant energy transfer process is the absorption of a phonon with energy and wavevector which match those of a magneto-roton at the minimum of the dispersion curve allowing the creation of such an excitation. The absorption of lower energy phonons is forbidden by energy conservation while the absorption matrix elements for higher energy phonons are exponentially smaller.

4. Previous results

Two 2DES samples with approximately the same carrier density but with zero field mobilities of 1×10^6 cm^2 V^{-1} s^{-1} and 8×10^6 cm^2 V^{-1} s^{-1} have been studied previously [6]. We find that the energy gaps at $\nu=2/3$ for the lower and higher mobility samples measured by the temperature dependence of the longitudinal magnetoresistance are 2.7 ± 0.2 K and 5.5 ± 0.5 K respectively, whereas the gaps determined by phonon absorption at 6.2 ± 0.2 K and 6.9 ± 0.4 K are very similar to each other. This leads us to believe that the phonon absorption technique is largely independent of the effects of disorder. The experimental values obtained are in good agreement with the theory of GMP, corrected for the effects of the finite thickness of the carriers and Landau level mixing. The experimental values of the energy gap expressed in units of $(e^2/4\pi\epsilon\epsilon_0 l_c)$ are 0.041 ± 0.002 and 0.045 ± 0.003 respectively, compared to a predicted gap of around 0.04. The measured energy gaps are independent of the substrate temperature. These results are discussed in more detail in Ref. [6]. The nature of the absorption and the time development of the longitudinal voltage, although of great importance to the understanding of phonon absorption in the FQHE, could not be determined from these studies.

5. Time-resolved measurements

All results reported previously have been made using a gated amplifier with a minimum gate length of 8 μs. This was chosen because performing time-resolved measurements at these low (micro-volt) signal levels was not possible with the equipment available. We now describe preliminary time-resolved measurements in the FQH regime.

The sample used in these experiments was a 1.8 mm (100) GaAs wafer with a 2DES at the front surface. The sheet density of electrons at the heterojunction was 1.1×10^{11} cm^{-2}; the zero-field mobility at 100 mK was 1.5×10^{6} cm^2 V^{-1} s^{-1}. On the front surface, two Hall bars, 1.4 mm long and 0.35 mm wide, were defined by wet-etching. The rear face was polished to an optical finish and two 60 μm × 600μm constantan heaters were fabricated as before. The heaters were aligned with the Hall bars so that angle-resolved measurements could be performed; for example, the non-equilibrium phonons could be selected to travel normal to the 2DES or at 45° to it. All results reported here are for the heater directly under the Hall bar, i.e. most of the phonons that interact with the 2DES will have travelled along the 100 crystal direction. The sample was mounted in vacuo on the tail of a dilution refrigerator.

A dc current was passed along the sample Hall bar by a floating constant current source. Two longitudinal voltage probes along the bar were connected to a high impedance ac-coupled differential amplifier with a bandwidth greater than 30 MHz. The output of this amplifier was itself amplified before recording the signal with an EG&G 9825-200 signal averaging board in a computer. This board had a 5 ns time resolution and can average over a thousand complete signal traces per second. Voltage pulses were applied to the heater on the rear face of the sample. The resulting non-equilibrium phonons traversed the 1.8 mm wafer in about 0.4 μs. The response of the sample to the heater pulse was measured using the differential amplifier. To reduce the noise inherent in this wide-bandwidth signal to an acceptable level long averaging times were required. Great care was taken to prevent noise from the computer and averaging board from reaching the sample and affecting the measurement. The cryostat and analogue amplifiers were all housed in a screened room, whilst the computer was outside this room.

As expected there was a small electrostatic breakthrough signal when the voltage pulse was applied to the heater. This signal reversed sign when the polarity of the heater pulse was reversed. The signal which we ascribe to the interaction of the phonons with the 2DES, was unchanged with the polarity of the voltage pulse. Measurements were taken in both forward and reversed direction of current flow along the Hall bar. These were then subtracted from each other to eliminate any thermoelectric effects which might arise from the non-equilibrium phonons. Thermoelectric effects were small as the zero-current trace hardly showed anything above the noise level (see Fig. 1). This observation along with the use of a differential amplifier helped to ensure that we measured the true response of the carriers rather than a thermoelectric effect in the contacts. A typical trace is shown in Fig. 2.

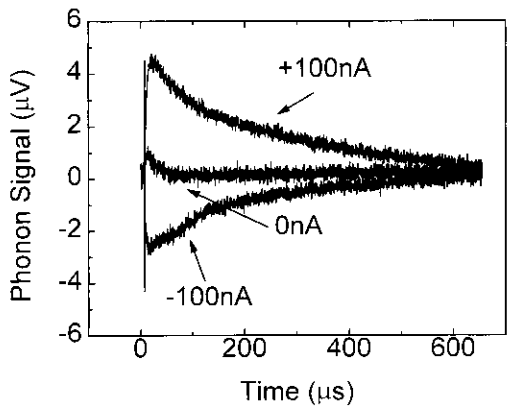

Fig. 1. Phonon signal vs time at $\nu = 2/3$ for different current biases.

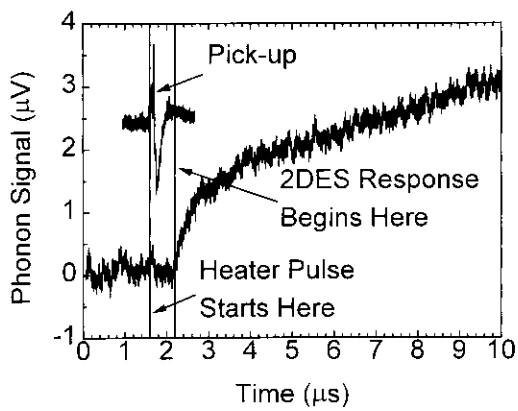

Fig. 2. Initial rise of the phonon signal at $\nu = 2/3$, showing the time-of-flight.

After a transit time consistent with the time-of-flight of transverse acoustic (TA) phonons across the wafer, the initial rise time of the voltage is consistent with the measured 1 μs time constant of the device and measurement electronics. However, the most unusual feature of this trace is the very slow time response of the system after the first few microseconds. In work reported in higher carrier density, higher temperature experiments it was possible to measure a ballistic response [7]. A particularly puzzling feature is why the signal continues to rise after the driving pulse has ended. A possible explanation is that the non-equilibrium distribution of phonons injected into the GaAs will take hundreds of microseconds to equilibrate. At the temperatures used in these experiments (≈100 mK) the mean free path of low frequency phonons such as those used in this experiment ($T_h < 4$ K) is much longer than the 1.8 mm thickness of the sample. Decay times much longer than those measured here have been observed in semiconductor samples used for dark matter detection [8]. However, when we repeated the heat pulse measurements under the same conditions but using a bolometer in place of the 2DES, much shorter decay times were seen (≈3 μs). An alternative explanation is that the phonon-created excitations in the 2DES have lifetimes of the order of hundreds of microseconds. To determine which effect is causing the long decay times is a matter for further investigation. From time-averaged measurements we know that the variation in the size of the integrated phonon-absorption signal with heater temperature suggests that one energy gap is dominating the response rather than a more usual bolometric response. To simulate the gated amplifier, the time-resolved signals, measured at different heater temperatures, were integrated on a computer. Using this technique, time-averaged and time-resolved methods gave the same value for the energy gap within experimental error.

6. Conclusion

Time-averaged measurements suggest that phonon absorption experiments provide a means of measuring energy gaps in the FQHE which is independent of the sample mobility and lattice temperature. The measured energy gap at a given filling factor depends only on the heater temperature. The results on 2DES samples are in good agreement with the predictions of GMP. Time-resolved experiments demonstrate that the system responds to the ballistic TA phonons incident on the 2DES. After the initial rise the signal continues to rise and then decay over a few hundred microseconds. The cause of these long time constants is a matter for further investigation.

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