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Ballistic phonon studies in the lowest Landau level

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Abstract

We report time-resolved studies of ballistic phonon absorption in the fractional quantum Hall regime at Landau level filling factors of $\nu = \frac{1}{3}, \frac{2}{5}$ and $\frac{1}{2}$. The technique used can resolve the interaction of the two-dimensional electron system with LA and TA phonons and has been used to measure the temperature variation of the heat capacity of a single layer of electrons at $\nu = \frac{1}{3}$. The energy gaps at $\nu = \frac{1}{3}$ have also been measured and found to be in good agreement with theory. The roles of compressible and incompressible regions in the phonon absorption process are discussed. Angle resolved measurements at $\nu = \frac{2}{5}$ are also in good agreement with theory. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The fractional quantum Hall effect (FQHE) occurs due to the formation of a quantum liquid when the Landau level filling factor, $\nu = r/s$, where r and s are integers and s is odd. When $\nu = 1/s$ the wave function is accurately described by Laughlin's variational wave function [1] and the low-lying collective excitations of the system, by the theory of Girvin et al. [2,3]. More generally, the collective excitation dispersion has been calculated by Kamilla et al. [4]. The most significant features of the excitations are the existence of a finite energy gap at low wave vectors, due to the incompressibility of the FQHE state, and a deep minimum in the energy, Δ^*, of the excitations known as magnetorotons, close to the wave vector where the static structure factor of the liquid is a maximum. The experiments described here probe the interaction of acoustic phonons with these excitations and use the results to determine the temperature variation of the heat capacity of the 2DES at $\nu = \frac{1}{3}$. The inter- action between longitudinal acoustic (LA) and transverse acoustic (TA) phonons and the two-dimensional electron system (2DES) have been resolved.

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2. Experimental method

The detailed description of the experimental technique has been given elsewhere [5,6]. The samples used are single GaAs/AlGaAs heterojunctions grown on a 2 mm thick substrate. The 2DES ($n_s = 1.1 \times 10^{15}\,\mathrm{m}^{-2}$, mobility $=150\,\mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$) is patterned into a meandering hall bar with a length-to-width ratio of around 260. This maximises the sensitivity to changes in longitudinal resistance. On sample A, the meander covers an area of 5 mm × 5 mm, whilst on sample B the area of the meander is 1 mm × 1 mm to decrease the solid angle of the device as seen from the other side of the wafer. On the reverse of the wafer, thin film constantan heaters have been evaporated directly opposite the meander and at 45° to it.

A voltage pulse (5–50 ns) is applied to the thin film heater causing it to emit a black body spectrum of phonons of known temperature [7]. The emitted phonons travel ballistically across the wafer and a small fraction are absorbed by the 2DES. This absorption process heats the 2DES causing a change in the longitudinal resistance of the device. This resistance change is measured with a time resolution of approximately 30 ns by a signal averaging technique. By calibrating the meander resistance against substrate temperature in the absence of ballistic phonons, the transient electron temperature during the absorption of ballistic phonons can be found. A typical trace for the case of a heater at a 45° to the meander in the [1 1 0] direction is shown in Fig. 1.

3. Ballistic phonon absorption at $\nu = \frac{1}{2}$

Previously, we have shown that at $\nu = \frac{1}{2}$, the fraction of incident phonon flux absorbed is reduced above a heater temperature of 1.4 K for the case when the heater is directly under the meander [5,6]. Along with other measurements, this suggests that the strength of the phonon interaction is limited by the finite thickness, a_0, of the 2DES which can be determined to be around 5 ± 1 nm from the phonon measurements. This is in agreement with the behaviour of two-dimensional systems at zero-magnetic field [8] and suggests a broad spectrum frequency absorption due to the creation of particle hole pairs until the perpendicular component of the phonon wave vector, $q_\perp$, exceeds $1/a_0$.

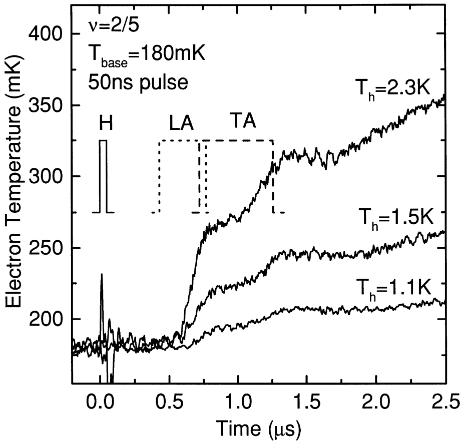

Fig. 1. 2DES response to 50 ns pulses of ballistic phonons emitted at $t = 0$ from a heater at 45° to the 2DES meander in the (1 1 0) direction. The arrival times of TA and LA phonons are shown.

4. Ballistic phonon absorption at $\nu = \frac{1}{3}$

The fraction of acoustic phonons absorbed, r_0, at the magnetoroton energy, Δ^*, will be approximately constant as long as $\exp(-\Delta^*/k_B T) \ll 1$. This means that the energy absorbed by the FQHE liquid from a pulse of non-equilibrium phonons,

$$\mathrm{d}E = C(T)\,\mathrm{d}T = r_0 P_h \tau,$$

where $P_h$is the heater power, τ, the pulse length, C the 2DES heat capacity and $\mathrm{d}T$, the temperature change of the 2DES. Keeping the heater temperature and pulse length constant, we vary the lattice temperature and as long as the temperature variation $\mathrm{d}T \ll T$, a good estimate of the temperature variation of the heat capacity can be determined. Whilst a Schottky heat capacity is predicted [9], the heat capacity is found to vary as $C(T) = AT + BT^7$ (see Fig. 2). A density of states can be constructed from the heat

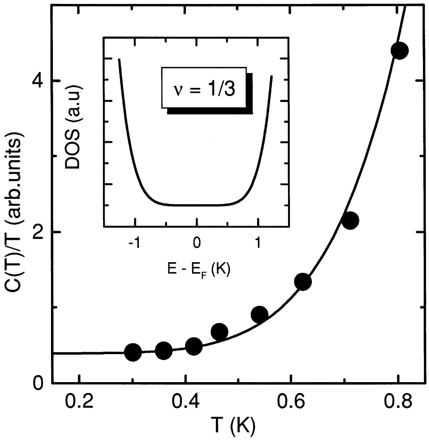

Fig. 2. Variation of the specific heat of the 2DES with temperature at $\nu = \frac{1}{3}$. The solid line shows a fit taking into account only the T and T^7 terms in the Sommerfeld expansion of the specific heat. The inset sketches the composite fermion density of states at $\nu = \frac{1}{3}$ as extracted from the specific heat data.

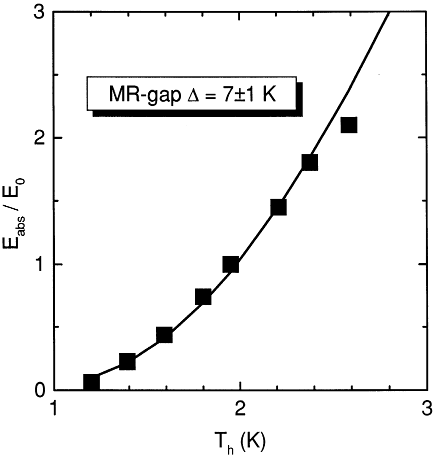

Fig. 3. Dependence of the energy absorbed by the 2DES on the heater temperature, T_h. The solid line shows the fitted behaviour for the absorption across a magnetoroton gap, $\Delta^* = 7 \pm 1$ K. The energy absorbed varies as $1/(\exp(-\Delta^*/k_B T) - 1)$.

capacity using the Sommerfeld construction (see Fig. 2). A possible explanation of the data is that the linear term in the heat capacity at low temperatures is due to compressible localised states whilst the higher power is the low-temperature tail of a Schottky-like heat capacity due to the incompressible FQHE liquid.

Initially the 2DES is at a low base temperature $T_e(0)$ whilst the phonons are characterized by an effective temperature, T_h. The 2DES is not uniform but consists of compressible islands within a percolating sea of incompressible electron liquid. Within the incompressible regions screening is very inefficient and the lowest lying excitations are the magnetorotons. In the compressible regions, the screening is metallic and relatively more efficient while the low lying density excitations (to which the phonons couple directly) are particle–hole pairs as in a normal metal. When the phonon pulse comes into contact with the 2DES particle–hole pairs are created in the compressible regions and magnetorotons in the incompressible regions. The relative efficiency of the screening in the compressible regions leads us to suppose that the coupling to the phonons will be relatively weak and that, for a sufficiently small coverage of compressible regions, the energy transfer will be dominated by magnetoroton creation in the incompressible regions. The expectation is that the excitations created by the absorption processes will then rapidly (on the timescale of the experiment) equilibrate leading to an increased electron temperature. The heat capacity of the compressible regions will be metallic ($\sim a_c T_e$) while that of the incompressible regions will be activated ($\sim a_i \exp(-\Delta^*/kT_e)$ so that the latter is negligible at a sufficiently low electron temperature. In other words, the rare high-energy phonons create magnetorotons in the incompressible fluid, these deposit their energy into the compressible regions which act as heat baths establishing a well-defined electron temperature. The longitudinal conductance is activated, $\sigma_{xx} \sim \sigma_0 \exp(-\Delta_\infty/T_e(t))$, where Δ_∞ is the energy gap for the creation of unbound Laughlin quasiparticles, so its measurement gives the electron temperature.

If the intial temperature of the lattice is maintained and the heater temperature varied for constant pulse length, the energy absorbed as a function of heater temperature can be calculated (Fig. 3). The results are consistent with phonon absorption across a well-defined energy gap. The energy gap obtained from the measurements is in good agreement with theoretical estimates of the magnetoroton gap [2,3] and is unaffected by disorder in the sample. The energy

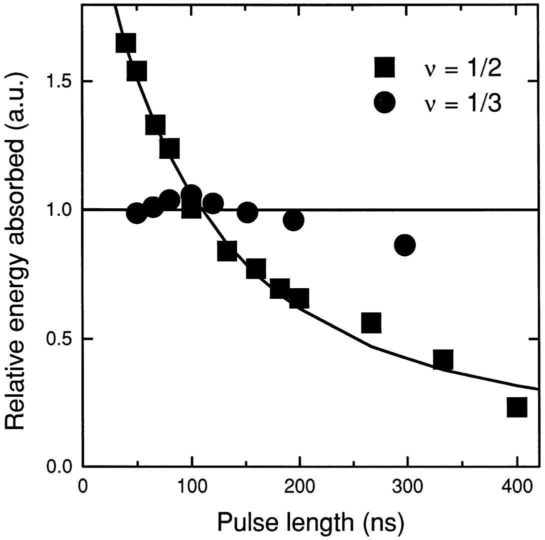

Fig. 4. Total energy absorbed at $\nu = \frac{1}{2}$ and $\frac{1}{3}$ as a function of the pulse length. The lines represent the behaviour of a system coming into a dynamic equilibrium by emitting phonons on time scales of $\tau = 70\,\mathrm{ns}$ ($\nu = \frac{1}{2}$) and $\tau = \infty$ ($\nu = \frac{1}{3}$), i.e. no equilibrium at all.

gap obtained from magnetotransport measurements is much lower than the phonon-determined gap.

It is possible to imagine a process whereby the creation of magnetorotons by the absorption of phonons from the high-energy tail of the non-equilibrium Bose distribution leads directly to the formation of unbound charged quasiparticles. However a careful analysis shows that it is not possible for magnetorotons to sizes in excess of a few times the magnetic length, l_0. Collisions between magnetorotons are therefore the most likely mechanism by which the magnetorotons decay to charged quasiparticles that can contribute to the resistance.

Experimental evidence in support of the above hypothesis can be found in the fraction of energy absorbed from the phonon pulse as the length of the pulse is varied. The results are shown in Fig. 4. At $\nu = \frac{1}{2}$, as the proportion of energy absorbed by the 2DES decreases as the pulse length is increased. All phonon energies up to the cut-off can be absorbed but also emitted by the 2DES. This leads to a saturation of the total energy absorbed as a function of the pulse length. At long times the 2DES emits as much energy in phonon emission as it absorbs. The curve in Fig. 4 is the expected saturation behaviour with a saturation time of 70 ns. At $\nu = \frac{1}{3}$, no saturation is observed even at times as high as 300 ns. This strongly suggests that the 2DES loses energy by internal processes rather than by the direct emission of acoustic phonons.

5. Angle-resolved experiments at $\nu = \frac{2}{5}$

At $\nu = \frac{2}{5}$, we have observed ballistic phonon absorption in which the in-phonon wave vectors lie in a small range close to the wave vector at which the magnetoroton minimum is predicted (Fig. 1). The geometric range of angles subtended by the heater was from 30° to 60°. Experimentally, both absorption of both LA and TA phonons are observed. To calculate the range of in-plane wave vectors the effect of phonon anisotropy needs to be taken into account in the interaction, therefore here we present the results for the LA phonons only, as LA phonons are only weakly focussed. For $\nu = \frac{2}{5}$ we find that the magnetoroton energy gap for phonons with in-plane momenta, q, in the range $0.4 < ql_0 < 0.75$ is $0.025(3)\mathrm{e}^2/4\pi\varepsilon\varepsilon_0 l_0$. This is in reasonable agreement ($0.032(3)\mathrm{e}^2/4\pi\varepsilon\varepsilon_0 l_0$) with theoretical estimates [4] corrected for finite thickness effects [10].

6. Conclusion

In summary, the use of ballistic phonons provides unique information on the excitations of the fractional quantum Hall effect. The results support the magnetoroton theory and have provided the first measurements of the temperature variation of the heat capacity of a single-layer 2DES at a fractional filling factor. At $\nu = \frac{2}{5}$, the magnetoroton gap has been probed at large, in-plane wave vectors.

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