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Angle-resolved ballistic phonon absorption spectroscopy in the lowest Landau level

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Abstract

We report the results of a study of the absorption of non-equilibrium ballistic phonons by a two-dimensional electron system, in strong magnetic fields, by measuring its change in resistance. At the even denominator Landau level filling factor, ν, of $\frac{1}{2}$ the electron–phonon interaction is observed to be cut-off above a particular value of the component of the wavevector perpendicular to the low dimensional system. This cut-off is consistent with that due to the finite thickness of the 2DES. At the fractional quantum Hall effect minima of $\nu = \frac{2}{3}$ we observe that the cut-off occurs at a lower heater temperature. The experimental results are consistent with phonon absorption across a well-defined energy gap in a range of known wave vectors. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Fractional quantum Hall effect; Phonon spectroscopy; Magnetoroton

The interaction of phonons with a two-dimensional electron system (2DES) in strong magnetic fields has been a topic of great interest in recent years. Experimental techniques that have been used include time-averaged phonon spectroscopy [1] and thermopower experiments [2]. It is expected that different mechanisms will dominate the electron–phonon interaction depending on the value of Landau level filling factor, ν. At even denominator filling factors such as $\nu = \frac{1}{2}$ and $\frac{3}{2}$, the 2DES can be regarded as a Fermi liquid of composite fermions with a well-defined Fermi wave vector, k_F [3]. In the GaAs/AlGaAs heterojunctions studied here the electron–phonon interaction is cutoff above a particular wave vector due to the finite thickness of the 2DES. It is found that when the perpendicular wave vector is greater than $1/a_0$, where a_0 is a measure of the thickness of the 2DES, the electron–phonon interaction is greatly reduced.

At an odd denominator filling factor such as $\nu = \frac{1}{3}$ or $\frac{2}{3}$, the 2DES forms an incompressible fractional quantum Hall effect state. This incompressibility results in a finite energy gap at low wave vectors. The low-lying excited states are predicted to have a deep minimum in their dispersion relation, known as the magnetoroton minimum, at wave vectors comparable to the magnetic length [4]. In

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recent years, these excitations have been studied by resonant Raman scattering [5,10] and time-averaged phonon absorption [6,11].

In the experiments described here a GaAs/AlGaAs heterojunction with a carrier density of $1.4\times10^{15}\ \mathrm{m}^{-2}$ and mobility of $140\ \mathrm{m}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$ was grown on a 2 mm GaAs substrate. The 2DES was etched into a meandering path over a $1\times1\ \mathrm{mm}^2$ area. The length to width ratio was ~ 300. Contacts were positioned well away from the meander so that contact heating effects would not affect the experiment. On the rear surface of the wafer, two $1\times1\ \mathrm{mm}^2$ CuNi heaters were evaporated. One heater was directly under the 2DES (geometrical acceptance angle at the 2DES of 0°–35°), whilst the other was displaced in the 110 direction so that the centre-to-centre heater to meander angle was 45° (geometrical acceptance angles between 27° and 58°).

The sample was mounted, in vacuo, on the tail of a dilution refrigerator. The meandering 2DES was connected to the room temperature preamplifier (1–5 kΩ variable input resistance) via a coaxial cable with a total capacitance of ~ 30 pF. This gave a response time of 30–150 ns. A pulse of non-equilibrium phonons was created by applying a short voltage pulse (5–50 ns) to one of the heaters. The temperature, T_h, of this pulse was calculated using acoustic mismatch theory [7]. When the ballistic phonons reach the 2DES, a small proportion of the phonon energy is absorbed and the temperature of the 2DES increases. This temperature rise is monitored by observing the resistance change of the meander as a function of time. Typically 50 nA is passed along the meander. To attain acceptable signal–noise ratios, the signal is averaged 10^3–10^6 times.

Fig. 1 shows the response of the 2DES to phonon pulses from the direct and angled heaters. The 2 mm wafer allows us to resolve LA and TA phonon polarisations. In Fig. 1a the 2DES temperature rises as the TA phonons travelling directly across the wafer reach the heterojunction. The contribution of LA phonons to this heating is much smaller. After the TA phonon pulse has passed the 2DES starts to cool. Subsequent interactions between the phonons and the 2DES take place as the reflected pulse hits the 2DES. These later temperature increases demonstrate that the phonon pulse is travelling ballistically over distances greater than 4 mm, even after reflection from the top and bottom of the GaAs wafer. Fig. 1b shows the 2DES temperature rise as the LA phonons arrive from the angled heater. At later times, the arrival of TA can be seen.

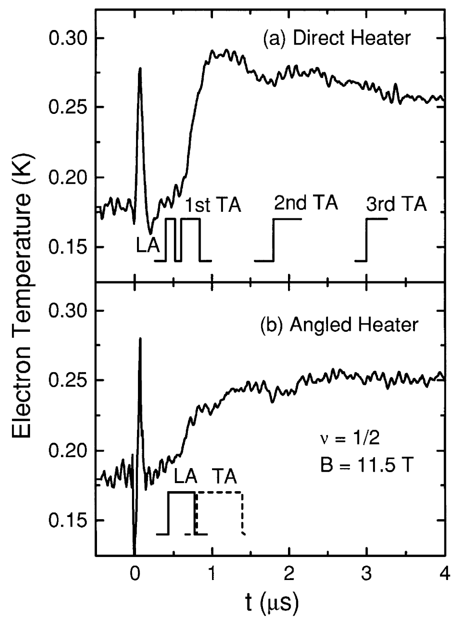

Fig. 1. Variation in electron temperature at $\nu = \frac{1}{2}$ after generation of a 5 ns pulse of 2.6 K phonons by (a) the direct heater and (b) the angled heater. Expected arrival times of LA and TA phonons are also shown.

When the phonon pulse reaches the 2DES, a small proportion of the incident phonon energy, $\mathrm{d}E_\mathrm{ph} = r(T_\mathrm{h})P_\mathrm{h}\,\mathrm{d}t$, is absorbed in a time interval $\mathrm{d}t$. Here, P_h, is the power dissipated by the heater in the form of ballistic phonons and $r(T_\mathrm{h})$ is the fraction of phonons absorbed by the 2DES when the non-equilibrium phonon spectrum has a temperature, T_h. Normally, $r(T_\mathrm{h}) \propto (T_\mathrm{h}^n - T_\mathrm{l}^n)$ where T_l is the lattice temperature [8]. Ignoring screening, the exponent $n \approx 3$ for piezoelectric coupling and 5 for deformation potential coupling. In the case described here, T_h is much greater than T_l and so the fraction of phonons absorbed will depend only on T_h. The energy absorbed by the 2DES will manifest itself as an increase in the electron temperature from its equilibrium value T_0 to a non-equilibrium temperature T_1 given by

$$\int_{T_0}^{T_1} \frac{C(T_e)}{r(T_h)}\, dT_e = P_{ph}\tau, \quad (1)$$

where $C(T_e)$ is the total specific heat of the 2DES, P_{ph} is the phonon power.

At $\nu = \frac{1}{2}$, the heat capacity of the composite fermions is predicted to be linear in temperature (except for a small logarithmic correction) [9]. We therefore approximate the heat capacity as $C = \alpha T$. Inserting this into Eq. (1), we find that

$$r(T_h) = \alpha(T_1^2 - T_0^2)/2P_{ph}\tau. \quad (2)$$

If we calculate $r(T_h)/\alpha$ from our data we find that the fraction of phonons absorbed peaks at a particular value of T_h (Fig. 2). Comparing the results from the direct and angled heaters we find that the heater temperature at which r is a maximum differs in a way that is consistent with a $1/a_0$ cutoff. The value of a_0 is found to be $\sim$5 nm. The perpendicular component of the phonon wavevector is calculated using the time of flight and considerations of phonon focussing to estimate the incident angles. Similar results have been found at $\nu = \frac{3}{2}$.

At $\nu = \frac{2}{3}$, it is observed that $C(T_e)/T_e$ is approximately constant at electron temperatures below 350 mK. Under these conditions we can use the analysis described for $\nu = \frac{1}{2}$, at $\nu = \frac{2}{3}$. The results are shown for LA phonons from the angled heater in Fig. 2. The fraction of phonons absorbed is observed to peak at a lower value of T_h than at $\nu = \frac{1}{2}$. It is expected that phonon absorption at odd-denominator fractions will be dominated by the creation of magnetorotons close to the magnetoroton minimum. For deformation potential coupling it would be expected that the curve will peak at $T_p \approx \Delta_{MR}/4k_B T_h$, where the dominant phonon energy in the black-body spectrum coincides with the magnetoroton gap. From this analysis we find that $\Delta_{MR}/k_B = 5.6 \pm 0.5$ K, i.e. $(0.037 \pm 0.003)\, e^2/4\pi\varepsilon_0\varepsilon l_B$, where l_B is the magnetic length. As the range of incident angles is known and LA phonons are not strongly focussed, it is also possible to say that the absorption took place at values of ql_B between 0.6 and 1.1 where q is the in-plane component of the phonon wave vector. This represents the first measurement of energy absorption in a known range of finite wave vectors in the fractional quantum Hall regime.

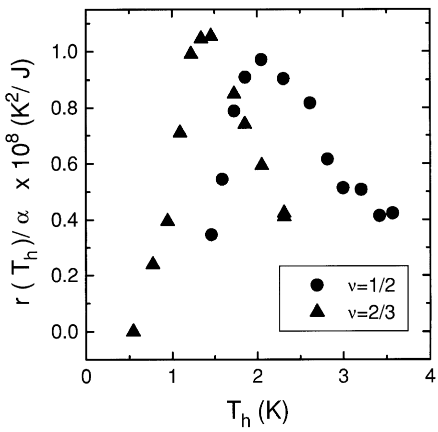

Fig. 2. Variation of $r(T_h)/\alpha$ as a function of heater temperature, at $\nu = \frac{1}{2}$ ($B = 11.5$ T) and $\nu = \frac{2}{3}$ (8.8 T) for LA phonons from the angled heater. The specific heat prefactor, α, is not expected to be the same for the two filling factors. The duration of the heat pulses were 5 and 50 ns for $\nu = \frac{1}{2}$ and $\frac{2}{3}$, respectively.

In conclusion, the results obtained at $\nu = \frac{1}{2}$ and $\frac{2}{3}$ demonstrate that ballistic phonon absorption can be used to obtain quantitative information on the electron–phonon interaction and electronic excitations in strong magnetic fields at well-defined in-plane wave numbers.

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