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Ballistic phonon absorption in the fractional and non-quantised Hall effects

U. Zeitler*, A.M. Devitt, J.E. Digby, C.J. Mellor,
A.J. Kent, K.A. Benedict, T. Cheng

Department of Physics, University of Nottingham, Nottingham, NG7 2RD, UK

Abstract

We have measured the direct absorption of ballistic phonons by a two-dimensional electron system (2DES) in the fractional quantum Hall regime. We show experimentally that the electron–phonon interaction in our heterojunction sample is dominated by coupling to TA phonons. At odd integer denominator fractional filling factors a strong non-equilibrium heating of the 2DES is observed which can be attributed to excitations across the magneto-roton gap. Away from fractional minima, in particular at a filling factor, $\nu = \frac{1}{2}$, a much smaller temperature increase is found. © 1998 Elsevier Science B.V. All rights reserved.

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The interaction of phonons with a two-dimensional electron system (2DES) in the fractional quantum Hall (FQH) regime has attracted a substantial interest in recent years as phonons are able to couple to electron states with finite in-plane wave vector [1–4]. The coupling of phonons to fractional quantum Hall states at odd denominator fractional filling factor has been studied using time-averaged phonon absorption in electrical transport [1] as well as in phonon emission experiments [4]. The coupling of phonons to composite fermions (CFs) at filling factor $\frac{1}{2}$ [5] has also been investigated and compared to zero-magnetic-field properties of electrons using the temperature dependence of the resistivity [2] and thermopower experiments [3]. In the present experiments we observe, for the first time, the direct absorption of ballistic phonons by a 2DES in the FQH regime.

The device we have investigated was based on a high mobility 2DES ($\mu = 150\,\mathrm{m^2\,V^{-1}\,s^{-1}}$, $n = 1.16 \times 10^{15}\,\mathrm{m^{-2}}$) grown on a 2 mm semi-insulating GaAs substrate. In order to maximize the sensitivity of resistivity measurements the 2DES was patterned into a 270 μm wide meander line on a $5 \times 5\,\mathrm{mm}^2$ surface with an aspect ratio $l/w \approx 300$. On the rear surface, facing the centre of the meander line, a thin-film constantan heater was evaporated. The sample was mounted, in vacuo, on the

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* Correspondence author. Institut für Festkörperphysik, Universität Hannover, Appelstraße 2, 30167 Hannover, Germany Tel.: + 49 0511 768 2904; fax: + 49 0511 768 2903; e-mail: zeitler@nano.uni-hannover.de.

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tail of a dilution refrigerator. The 2DES meander line was electrically connected to a room temperature preamplifier with a low-capacitance coaxial cable.

Applying a short voltage pulse on the heater creates hot phonons at the interface between the heater and the GaAs substrate. The non-equilibrium temperature, T_h, of phonons entering the cold substrate can be calculated from the power, P_h, dissipated in the heater using acoustic mismatch theory [6] as $P_h = \sigma A_h(T_h^4 - T_0^4)$ ($\sigma = 524\ \mathrm{Wm^{-2}\,K^{-4}}$, A_h is the surface area of the heater, T_0 is the substrate temperature).

At low enough temperatures the phonons travel ballistically through the GaAs and are incident on the 2DES. A small proportion of the incident phonon flux is absorbed by the 2DES leading to an increase of its temperature. The increase in the electron temperature was deduced from the change of 2DES resistance which had been calibrated against temperature under equilibrium conditions.

When passing a DC current through the 2DES the phonon response was measured by recording the voltage across the meander as a function of time and averaging over typically 10^3–10^6 traces. The repetition rate was kept low enough to minimize effects of substrate heating. The electric time response of the system is limited by its RC-time constant of 0.15 μs, $C \approx 30$ pF is the cable capacitance between sample and amplifier, $R \approx 5\ \mathrm{k\Omega}$ is defined by the (variable) input impedance of the preamplifier in parallel with the two-point resistance of the meander.

In Fig. 1, the typical responses of the 2DES at filling factors of $\frac{1}{3}$ and $\frac{1}{2}$ to a pulse of ballistic phonons are shown. The ballistic effects are much more pronounced at fractional filling factors. In the following discussion we will first concentrate on $\nu = \frac{1}{3}$, the behaviour at $\nu = \frac{1}{2}$ will be analysed later.

Initially the 2DES is at an equilibrium temperature $T_0 = 130$ mK. The heater is pulsed with a $\tau = 100$ ns voltage pulse at $t = 0$ when hot phonons ($T_h = 1.95$ K) are emitted into the GaAs. After 0.4 μs, LA phonons have traversed the 2-mm-thick GaAs substrate and hit the 2DES. This leads to a small increase in its temperature $T_{2\mathrm{DES}}$. Subsequently, after $\tau_{\mathrm{TA}} = 0.6$ μs, TA phonons which have directly traversed the substrate couple to the 2DES. $T_{2\mathrm{DES}}$ strongly increases until $t = 1.2$ μs, the time when TA phonons travelling along the [111] direction hit the corner of the meander structure. Subsequently, with no hot ballistic phonons present in the vicinity of the 2DEG, the system starts to cool. The ballistic phonons are reflected by the top surface and the rear surface of the wafer and are again incident on the 2DES after $3\tau_{\mathrm{TA}} = 1.8$ μs. A second increase in $T_{2\mathrm{DEG}}$ is observed around this time along with a third ballistic phonon peak after $5\tau_{\mathrm{TA}} = 3$ μs. After several μs all the hot phonons have thermalized inside the substrate leading to an increase in its temperature from T_0 to T_b which can be calculated from the total energy $E_{\mathrm{ph}} = \sigma A_h(T_h^4 - T_0^4)\tau$ dissipated in the heater and the specific heat of the substrate. The electrons reach thermal equilibrium with T_b after relaxation of the initial excitations. The substrate heating was determined by measuring $T_{2\mathrm{DES}}$ at long times and is shown in Fig. 2 where it is compared to the expected behaviour.

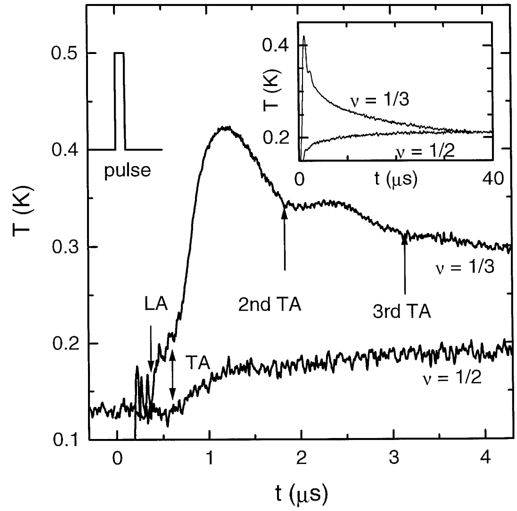

Fig. 1. Phonon response showing the variation of the 2DEG-temperature at $\nu = 1/3$ and $\nu = 1/2$ after a 100 ns pulse of 1.95 K phonons has been emitted by the heater at $t = 0$.

Finally, the substrate slowly cools to its initial base temperature $T_0 = 130$ mK before the next ballistic phonon pulse is generated. Both the value of T_b (see Fig. 2) and the time scale of the cooling

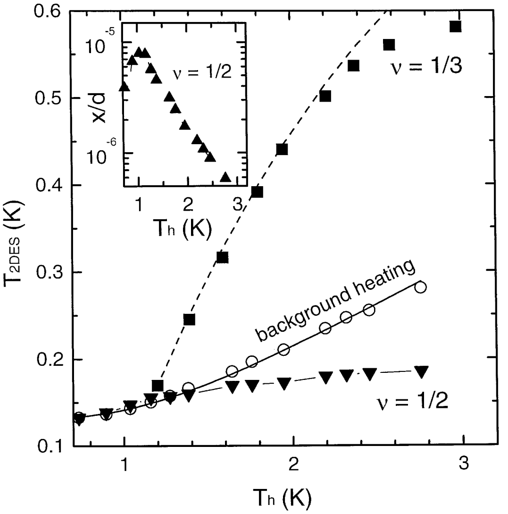

Fig. 2. Dependence of the heating of the 2DES on the heater temperature (100 ns pulses): ballistic heating at $\nu = 1/2$ and $\nu = 1/3$ and background heating of the lattice. The dashed line shows the expected heating of the substrate, the solid line models the ballistic response at $\nu = 1/3$ by excitation across a gap $\Delta = 5$ K. The inset shows the relative proportion of enegy absorbed at $\nu = 1/2$ as a function of T_h.

are consistent with a heating of the GaAs via thermalization of the hot ballistic phonons within the substrate and a slow cooling via thermal conduction to the heatsink.

We can understand the general behaviour in terms of a simple model: When the phonon pulse reaches the 2DES a small proportion, x, of the incident phonon energy, E_{ph}, is absorbed and the electron temperature will increase from its equilibrium value T_0 to a non-equilibrium temperature T_1 given by

$$\int_{T_0}^{T_1} AC(T)\,\mathrm{d}T = xE_{\mathrm{ph}}, \tag{1}$$

$C(T)$ is the specific heat of the 2DES with a total surface area A. Kim and Lee [8] have shown that at $\nu = \frac{1}{2}$ the specific heat for quasiparticles with a Coulomb interaction varies almost linearly with temperature with only a weak logarithmic divergence. For this reason we assume a simple form for the specific heat,

$$C(T) = \frac{\pi^2 k_{\mathrm{B}}^2}{3} T\tilde{D}(E_{\mathrm{F}}). \tag{2}$$

At $T = 0$, $\tilde{D}(E_{\mathrm{F}})$ is the *integral* (i.e. localized and extended) CF density of states (DOS) at the Fermi-level E_{F}. Substituting Eq. (2) into Eq. (1) and neglecting thermal broadening, the change in temperature of the 2DEG due to the absorption of ballistic phonons can then be calculated as

$$T_1^2 = T_0^2 + \frac{6xE_{\mathrm{ph}}}{\pi^2 k_{\mathrm{B}}^2 \tilde{D}(E_{\mathrm{F}})A} = T_0^2 + \alpha\tau T_{\mathrm{h}}^4 \frac{x}{d}. \tag{3}$$

Here $\alpha = 5.13 \times 10^9\ \mathrm{K}^{-2}\,\mathrm{s}^{-1}$ is a constant, τ is the pulse length, and $d = \tilde{D}(E_{\mathrm{F}})/D_0$ is the relative DOS at the Fermi level with respect to the DOS for free, spin polarized electrons $D_0 = m_0/2\pi\hbar^2$. For $\nu = \frac{1}{2}$ the CF effective mass is of the order of the free electron mass, i.e. d is of the order of unity.

At $\nu = \frac{1}{2}$ the increase of T_{2DEG} due to an absorption of ballistic phonons is much weaker than at $\nu = \frac{1}{3}$ (see Fig. 1). Moreover, it is only weakly dependent on the heater temperature, see Fig. 2. The relative amount of energy absorbed by the 2DES peaks around a heater temperature $T_{\mathrm{h}} \approx 1.1$ K. There are two possible reasons for this behaviour. This temperature corresponds to the maximum in the DOS of ballistic phonons coinciding with the diameter of the Fermi surface $2k_{\mathrm{F}}$ of the CFs at $\nu = \frac{1}{2}$. For higher T_{h} only low-energy phonons with $q_{\parallel} < 2k_{\mathrm{F}}$ ($q_{\parallel}$ is the phonon wave vector parallel to the 2DES) can couple to the 2DES leading to a drastic decrease in the relative amount of phonon energy absorbed. The finite thickness of the 2DES also provides a momentum restriction which is estimated to occur for phonons with an energy greater than approximately 1.4 K for this wafer. So far it has not proved possible to differentiate between these two effects.

The phonon-induced ballistic heating of the 2DES at $\nu = \frac{1}{3}$ is a consequence of excitations in the 2DES across the magneto-roton gap [1,9]. In contrast to $\nu = \frac{1}{2}$ no severe cut-off is observed due to momentum restriction. This clearly shows that the dominant coupling of the phonons to the 2DES mainly happens at a single energy, namely the magnetoroton minimum. The geometric cut-off for this fixed energy is constant for all heater temperatures. The energy absorbed increases exponentially when the heater temperature is increased, $xE_{\mathrm{ph}} \propto 1/(\exp(-\Delta/k_{\mathrm{B}}T) - 1)$ in the simplest model [1]. It is probable that the DOS in the energy gap is finite due to spin excitations, sample inhomogeneity and edge states. These states contribute to the specific heat. Over the temperature range of interest this DOS may also be taken as constant implying that the specific heat is again linear in temperature. Using Eq. (3) we compare the experimentally measured variation of the ballistic heating T_1 with the theoretically expected behaviour for an excitation across a gap $\Delta = 5$ K in Fig. 2. This rather crude analysis which neither takes into account any temperature dependence of the excitations nor the fact that excitations are possible in a rather broad energy window around the gap gives only an approximate value for the gap.

Moving slightly away from $\nu = \frac{1}{3}$ the change of the 2DES resistance due to absorption of ballistic phonons increases. This is consistent with the increased temperature dependence of the equilibrium resistance. Away from the resistance minima a much weaker change in T_{2DES} is observed. Using Eq. (3) this observation can be explained straightforwardly by a decrease of the CF-DOS in the FQH minima.

The direct absorption of ballistic phonons by a two-dimensional electron system in the fractional and non-quantized Hall effect has been measured for the first time. The absorption is dominated by TA phonons. At a filling factor of $\frac{1}{2}$ the coupling of the phonons to the quasiparticles weakens above a heater temperature of 1.1 K. This cutoff could be due to the CF $2k_{\mathrm{F}}$ cutoff or the finite thickness of the 2DES. At $\nu = \frac{1}{3}$ a crude analysis finds an energy gap that is in approximate agreement with the expected value. However, more detailed calculations and further experiments are needed to provide a more exact value. The magnetic field dependence of the heating suggests that the specific heat is greatly reduced at $\nu = \frac{1}{3}$ compared to $\nu = \frac{1}{2}$.

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