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Phonon emission and absorption in the fractional quantum Hall effect

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Abstract

We investigate the time dependent thermal relaxation of a two-dimensional electron system (2DES) in the fractional quantum Hall regime, where ballistic phonons are used to heat up the system to a non-equilibrium temperature. The thermal relaxation of a 2DES at $\nu = 1/2$ can be described in terms of a broad band emission of phonons, with a temperature dependence proportional to T^4. In contrast, the relaxation at fractional filling $\nu = 2/3$ is characterized by phonon emission around a single energy, the magneto-roton gap. This leads to a strongly reduced energy relaxation rate compared to $\nu = 1/2$ with only a weak temperature dependence for temperatures $150\,\mathrm{mK} < T < 400\,\mathrm{mK}$.

Keywords: Fractional quantum Hall effect; Phonons; Energy relaxation, Magneto-roton gap

It has been shown recently that phonon absorption experiments are an efficient tool for the investigation of the thermodynamic and spectroscopic properties of highly correlated two-dimensional electron systems (2DESs) in the fractional quantum Hall (FQH) regime [1]. In this work we will present first results on the phonon emission of a 2DES. We use ballistic phonons to heat up the 2DES to a non-equilibrium temperature and study the thermal relaxation back to equilibrium. At filling factor $\nu = 1/2$ we find a fast energy relaxation rate proportional to $T_{\mathrm{ne}}^4 - T_0^4$, where T_{ne} is the non-equilibrium temperature of the 2DES and T_0 is the equilibrium temperature of the substrate. For fractional filling $\nu = 2/3$, the energy relaxation rate is much less temperature dependent indicating the dominance of magneto-roton relaxations in the thermal relaxation process.

Our samples were grown by molecular beam epitaxy (MBE) on a 0.53 mm thick GaAs wafer. Both sides were polished to an optical finish ready for epitaxy before the growth. We have performed phonon experiments on the 2DES of two different samples. Sample 1 has a electron concentration $n = 1.1 \times 10^{11}\,\mathrm{cm}^{-2}$, and a mobility $\mu = 6 \times 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$, for sample 2 we have $n = 1.3 \times 10^{11}\,\mathrm{cm}^{-2}$ and $\mu = 6 \times 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$. The 2DESs are patterned in form of a meander on a $1 \times 1\text{-mm}^2$ square. To increase sensitivity to changes in the resistivity ρ_{xx}, the meander has a large length-to-width ratio, $L/w = 2000$ for sample 1 and $L/w = 360$ for sample 2.

The samples were mounted in vacuum on the tail of a dilution refrigerator. They are thermally

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connected to the mixing chamber by a rod made of Cu wires. The two contacts of the 2DES meander are connected to a 50-Ω coaxial line. To avoid heat leaks through the center conductors of the coaxial lines they are thermally anchored to an impedance-matched strip-line on the mixing chamber before connecting it to the sample. One contact of the sample is biased with a DC voltage of a few mV. The other contact is connected via a 5-MΩ resistor close to the sample to ground. Additionally, it is AC coupled to a 50-Ω current amplifier at the room temperature end of the coaxial line. Under DC conditions a constant current of typically 50 nA passes through the sample and the 5-MΩ bias resistor. The current is small enough to minimize Joule heating of the 2DES but still large enough to get a reasonable phonon signal (see below).

On the rear face of the GaAs substrate a constantan heater was evaporated. The heater is impedance matched to a 50-Ω coaxial line which connects it to the pulse generator. Again the line is thermally anchored to an impedance-matched strip-line before connecting it to the heater.

Non-equilibrium phonons are created by passing an electric pulse through the constantan heater. They traverse the substrate ballistically and hit the 2DES. A small part of the phonons are absorbed which leads to an increase of the 2DES temperature. As a consequence, its resistance changes and a time dependent transient current is created. This current is detected by the AC-coupled current amplifier with a 10 MHz bandwidth limiting the time resolution of our setup to about 40 ns.

The resistance change as a function of time is recorded with a digital storage oscilloscope connected to the output of the current amplifier. To increase the signal to noise ratio the curves are averaged over typically 10^4 traces with a pulse repetition period of 10–100 ms. The repetition period has to be that low to allow the whole sample holder to relax to the base temperature of the mixing chamber before a further phonon pulse is applied and to minimize the average heating effects on the sample holder.

A typical phonon signal for sample 1 is shown in Fig. 1. The measurements were performed at a base temperature of the mixing chamber $T_{mc} = 50$ mK.

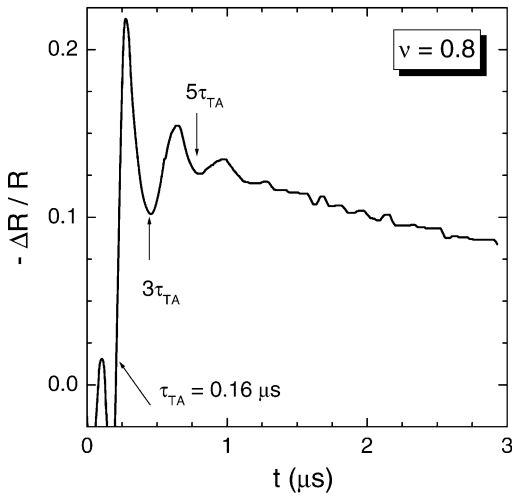

Fig. 1. Relative change of the 2DES resistance as a function of time at $\nu = 0.8$ after emission of a 50-ns phonon pulse on the rear face at $t = 0$. The arrows mark the expected transient times of ballistic TA-phonons through the 0.53-mm thick substrate. Note that the relative resistance changes are negative.

At the chosen filling factor $\nu = 0.8$, the 2DES resistance is extremely sensitive on temperature. As a consequence small changes in T show up as large changes in the resistance as shown in Fig. 1. A 50-ns phonon pulse is emitted at $t = 0$. The observed signal at small times is an artifact originating from electromagnetic pick-up of the heater pulse by the detection system (2DES and contacting wires). This effects of pick-up are already minimized by alternating the pulse amplitude and the direction of the bias current. However, due to the thinner substrate compared to previous work [1,2] they still can lead to a significant unwanted contribution to the phonon signal. Therefore, at filling factors where the 2DES is less sensitive to phonons, the pick-up can even mask the ballistic contribution originating from the clean phonon signal.

After $\tau_{TA} \approx 0.16$ μs transverse acoustic phonons have traversed the substrate and hit the 2DES. Longitudinal acoustic phonons only play a minor role in the phonon-absorption process. As a consequence of the phonon absorption the 2DES resistance R decreases drastically and starts to relax back to its original value as soon as no more

ballistic phonons are incident on the 2DES. Further decreases of R occur when the ballistic phonons which were reflected on the front and rear side of the sample hit the 2DES again after $3\tau_{TA}$ and $5\tau_{TA}$. For longer times ($t > 1$ μs), most of the ballistic phonons have thermalized and the ballistically heated 2DES relaxes back to the substrate temperature. At long time scales ($t \approx 10$ μs), the energy dissipated in the heater is equally distributed in the whole GaAs substrate leading to a higher substrate temperature compared to its value before the phonons were emitted. It takes a few 100 μs for the equilibrium phonons responsible for this background heating to leave the GaAs substrate.

The effects of the ballistic heating of the 2DES have already been described in previous work [1,2]. In this paper we concentrate on the relaxation of the ballistically heated 2DES. In this respect the precise phonon absorption mechanism does not play an important role for the understanding of our results. The phonons are simply used to create a hot 2DES on very fast time scales of a few ns with a comparably negligible heating of the substrate. By this we can directly study the time dependent thermal relaxation of a rapidly heated 2DES back to the substrate temperatures.

Such a relaxation experiment is shown in Fig. 2 for the fractional filling factor $\nu = 2/3$ (sample 2) for two different heater temperatures T_h. The 2DES is initially at a temperature $T_0 = 100$ mK. At $t = 0$, a 50-ns phonon pulse characterized by a non-equilibrium temperature T_h is emitted from the heater at the back face of the substrate. After hitting the 2DES, the electron system is heated up rapidly by the ballistic phonons and then slowly relaxes back. The non-equilibrium temperature T_{ne} of the electron system is calculated from a calibration of the sample resistance $R(T)$ under equilibrium conditions. As can been seen more clearly in Fig. 1 it is secure to assume that the time dependence of T_{ne} is mainly determined by phonon emission, i.e. absorption processes due to multiple reflections have sufficiently decayed.

After a few microseconds the 2DES has relaxed to the substrate temperature T_b defined by the total specific heat of the GaAs substrate and the heater temperature T_h (see Ref. [1] for more details).

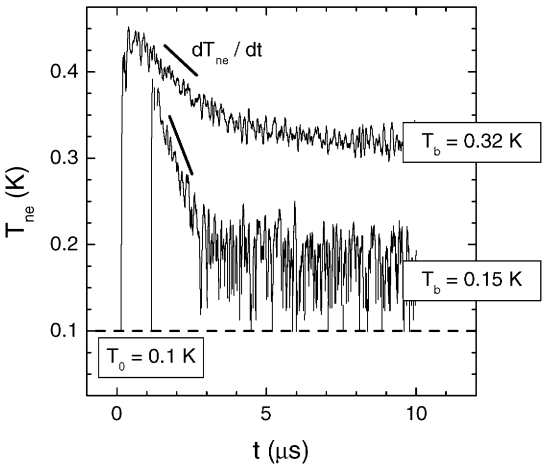

Fig. 2. Time dependent relaxation of the non-equilibrium 2DES temperature at $\nu = 2/3$ after heating the system by a ballistic phonon pulse characterized by a non-equilibrium phonon temperature $T_h = 2$ K (top trace) and $T_h = 0.9$ K (bottom trace). For clarity the bottom trace is shifted to the right by 1 μs. Artifacts originating from electromagnetic pick-up have been removed. After the time of flight for TA phonons, the 2DES rapidly warms up and relaxes slowly to the substrate temperature T_b.

To get more information about the relaxation process we have evaluated the change of the non-equilibrium temperature as a function of time, dT_{ne}/dt, at $t = 1.5$ μs where the 2DES is at a temperature T_1. At this time all possible artifacts in the phonon-signal caused by electromagnetic pick-up have sufficiently decayed. The results for filling factors $\nu = 1/2$ and $2/3$ are shown in Fig. 3, where dT_{ne}/dt measured at $t = 1.5$ μs is plotted as a function of T_1.

At filling factor $\nu = 1/2$, the relaxation rate increases drastically with increasing T_1 as indicated with the dashed line in Fig. 3a. The data available roughly follow a T^3 dependence.

For a more quantitative analysis it is more convenient to regard the energy relaxation rate, dE/dt, rather than the change dT_{ne}/dt. The energy change dE is related to dT_{ne} as $dE = C(T)dT_{ne}$. For $\nu = 1/2$ it is reasonable to assume that the specific heat is linear in T, and, as a consequence dE/dt is

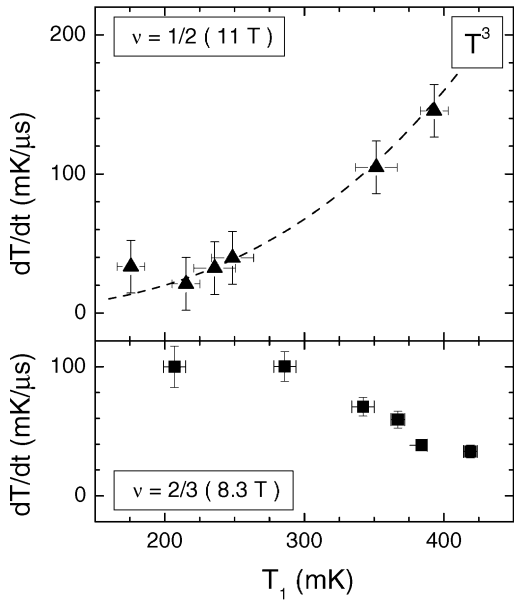

Fig. 3. Thermal relaxation of a 2DES at filling factor $\nu = 1/2$ (top panel) and $\nu = 2/3$ (bottom panel) as described in the text.

roughly proportional to T_{ne}^4.[1] This is the expected behavior for the energy relaxation of a simple metallic film emitting a black-body spectrum of phonons. The experimental accuracy at present does not allow to determine the exponent in the power law accurately enough and to compare it to the temperature dependence of phonon interaction with electrons in the fractional quantum Hall regime as deduced for transport experiments [3], thermopower [4,5] and phonon emission [6].

In contrast to $\nu = 1/2$, the relaxation rate dT_{ne}/dt at $\nu = 2/3$ *decreases* with increasing T. In other words the hotter the 2DES gets the slower it relaxes.[2] To explain the origin of this peculiar behavior we propose two possible mechanisms for the effect observed.

First, the energy relaxation rate might follow a much weaker power law than T^4. E.g. an energy relaxation rate proportional to T with an electronic specific heat $C_V \propto T$ would yield a dT_{ne}/dt which is independent of temperature. Therefore, any temperature dependence of dE/dT weaker than linear causes a dT_{ne}/dt which is decreasing with increasing T.

Second, the specific heat $C(T)$ of a 2DES at fractional filling factors is only linear in T for very low temperatures. In Ref. [1] strong deviation from a linear behavior were found for $T > T^* \approx 0.4$ K at $\nu = 1/3$. The temperature T^* is related to the width of the $\nu = 1/3$ minimum in the density of states. For our case where we investigate the $\nu = 2/3$ minimum (at a lower magnetic field in a sample with a smaller mobility) a lower T^* than 400 mK is expected. The strong decrease of dT_{ne}/dt as a function of T is therefore an indication for a strongly increasing $C(T)$.

The weak temperature dependence of dE/dT points to the fact that the emission process at fractional filling is distinct from the weakly interacting composite-fermion system at $\nu = 1/2$. It is indeed to expect that the emission process is dominated by phonon emission at a single energy, namely the magneto-roton gap.

In conclusion we have investigated the phonon emission of a hot 2DES in the FQH regime using time-resolved resistance measurements. We find first indications that the emission process is governed by the radiation of a black-body spectrum at $\nu = 1/2$, whereas at $\nu = 2/3$ an emission of phonons around a single energy is suggested by our experiments.

[1] Strictly speaking the relaxation rate is of course given by $dE/dT \propto (T_{ne}^4 - T_b^4)$. However, within our accuracy this modification does not change our qualitative arguments.

[2] Again the energy relaxation rate is strictly spoken proportional to $T_{ne}^\alpha - T_b^\alpha$ with a unknown exponent α. For high T_b and low α the second term can no more be neglected. However, it should be mentioned that we only use qualitative arguments to describe the effects observed. Including the above modification complicates the situation but does not give additional information.

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