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Phonon excitation of a two-dimensional electron system around $\nu = 1$

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Abstract

We have measured the absorption of ballistic non-equilibrium phonons by a two-dimensional electron system in the quantum Hall effect around filling factor $\nu = 1$. Directly at $\nu = 1$, the system is insensitive to phonons. However, moving slightly away from the resistance minimum, a strong ballistic phonon absorption starts to show up. We assign this to a drastic decrease of the excitation gap which in turn increases the absorption probability for ballistic phonons. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Phonons are an efficient tool to probe the collective excitations of a two-dimensional electron system (2DES), particularly, in the quantum Hall effect [1]. In this regime, the relevant energy scales and wave vectors of the 2DES excitations are comparable to typical acoustic-phonon energies of a few Kelvin with the corresponding in-plane wave vectors. In this work, we use ballistic non-equilibrium phonons to excite a 2DES around filling factor $\nu = 1$. We find indications for a strong decrease of the excitation energy when moving away from $\nu = 1$ which may be related to skyrmion excitations existing in this regime.

2. Experimental

The sample used in the experiments consists of a 2DES (electron concentration $n = 1.07 \times 10^{15}\ \text{m}^{-2}$, mobility $\mu \approx 70\ \text{m}^2/\text{V s}$) grown on a 2-mm GaAs substrate and patterned into a $3 \times 3\ \text{mm}^2$ meander with a large aspect ratio $L/w \approx 500$. A schematic setup is shown in Fig. 1a. The 2DES is DC-biased symmetrically with a constant voltage U_b via two series resistors $R = 10\ \text{k}\Omega$ yielding a bias current $I = U_\text{b}/(2R + R_{2pt})$, where R_{2pt} denotes the two-terminal resistance of the 2DES meander. Phonon pulses with length τ, typically $\tau = 10$–400 ns, are created in a $1 \times 1\ \text{mm}^2$ constantan heater evaporated on the rear of the GaAs substrate (for a more detailed description of the technique, see, e.g. Ref. [2]).

The phonons are characterized by a non-equilibrium temperature $T_\text{h} = (P_\text{h}/\sigma A + T_0^4)^{1/4}$ [3], determined from the power P_h dissipated in the heater, the surface area

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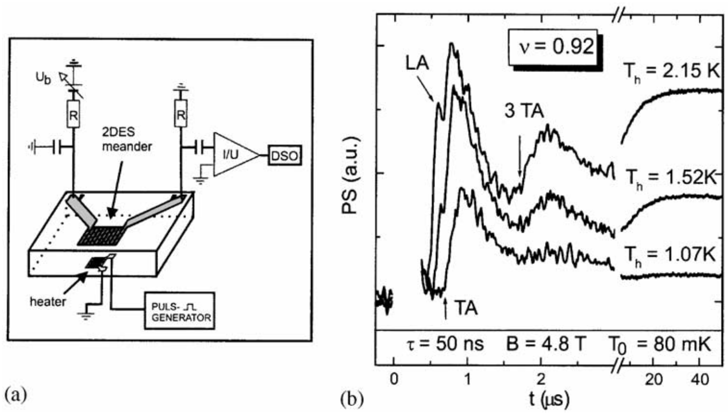

(a) (b)

Fig. 1. (a) Schematic experimental setup. (b) Phonon signal at $B = 4.8$ T for different T_h. The arrows indicate the arrival times of LA and TA phonons on the 2DES. The second peak is due to multiply-reflected TA phonons arriving on the 2DES after 3 τ_{TA}. At long times ($t > 40$ μs), the signal is purely determined by substrate heating. The data were recorded in 1 ns intervals and averaged over 10 ns before the break and 0.5 μs after the break.

A of the heater–GaAs interface, and the acoustic mismatch constant, $\sigma = 524$ W/m^2 K^4 [2]. These phonons travel ballistically through the substrate and start hitting the 2DES after a time of flight $\tau_{LA} = 0.42$ μs for longitudinal acoustic (LA) phonons and $\tau_{TA} = 0.6$ μs for transverse acoustic phonons, respectively. Phonon absorption leads to an increase of the 2DES temperature and thus to a change of its temperature-dependent resistance R_{2pt}. As a consequence, a transient current ΔI is generated in the sample and detected with an AC-coupled 10-MHz current amplifier. The output is then averaged in a digital sampling oscilloscope (DSO) over typically 10^4 individual traces.

In Fig. 1b, we have plotted an example of such a phonon signal (PS) for different heater powers, i.e. different non-equilibrium temperatures T_h. The traces were recorded at a base temperature $T_0 = 80$ mK in a magnetic field $B=4.8$ T after a 50 ns phonon pulse was emitted at $t=0$. The signal for small times ($t < 0.3$ μs) is dominated by electromagnetic pickup and was removed for clarity. Subsequently, the absorption of ballistic phonons by the 2DES shows up. For low phonon temperatures, $T_h = 1.07$ K, only absorption of TA phonons is observed, whereas for higher temperatures T_h, even LA phonons appear, while the heating effects of TA and LA phonons become comparable for $T_h = 2.15$ K. This observation clearly indicates the stronger energy dependence of LA phonon absorption compared to the absorption of TA phonons.

On longer time scales ($t > 40$ μs), the signal is purely determined by substrate heating, see Ref. [1] for more details. Here, the substrate and 2DES are in thermal equilibrium with a T_b given by $T_b^4 = 4P_h\tau/\gamma V + T_0^4$. Here $\gamma = 3.4$ J/K^4 m^3 is defined by the specific heat of the GaAs substrate, $c_{GaAs} = \gamma T^3$, and $V = 2 \times 10^{-7}$ m^3 is the total volume of the substrate. We used this background heating for the determination of the 2DES temperature from the measured phonon signal which is essentially constant for $40 < t < 50$ μs. Measuring this long time signal for varying total dissipated energy $P_h\tau$, we derive a calibration curve T(PS) from the calculated $T = T_b(P_h)$. This calibration was then used to calculate the 2DES temperature $T(t)$ from the phonon signal PS(t).

3. Results and discussion

Particularly interesting effects occur when the filling factor in the 2DES is tuned to $\nu = 1$, corresponding to $B = 4.4$ T for our sample as shown in Fig. 2, where we plot the evolution of the 2DES temperature after emission of 100 ns phonon pulses with $T_h = 2.15$ K. Essentially, no heating of the 2DES due to the absorption of ballistic phonons is observed directly at $\nu = 1$. This shows that the relevant excitation gap at $\nu = 1$ is far too large to permit excitations with phonons of a few Kelvin in energy. Of course, this behavior is no

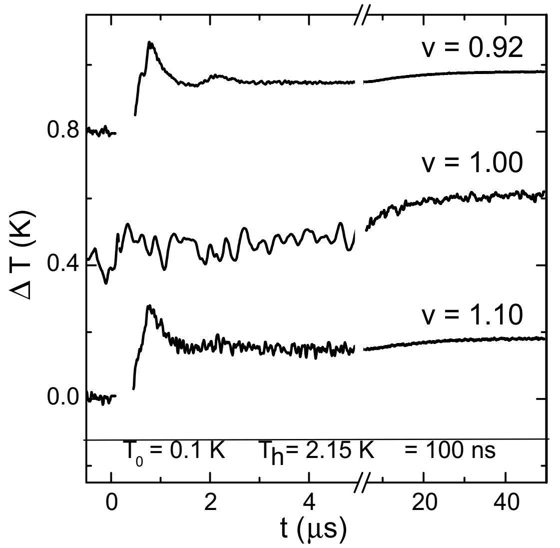

Fig. 2. Change of the 2DES temperature around $\nu = 1$ due to a 100 ns phonon pulse with $T_h = 2.15$ K. The traces are shifted by 0.4 K and the pickup is removed for clarity. The same data smoothing as in Fig. 1 are used.

particular surprise. However, when moving away from $\nu = 1$, a clear absorption of ballistic phonons starts to show up, see top and bottom trace in Fig. 2. Therefore, the relevant excitation gap is now reduced to the available phonon energies. In this context, it is important to state that we cannot make a definite statement about the precise nature of the finite-wave vector excitations generated by ballistic phonons. However, the drastic decrease of the gap when moving away from $\nu = 1$ points to effects beyond a single particle picture. This observation may then be related to the existence of skyrmion excitations around $\nu = 1$ as observed in nuclear magnetic resonance [4] and transport experiments [5].

The particularity of $\nu = 1$ as described above can be underlined when analyzing the phonon signal at other filling factors. Examples for $\nu = \frac{1}{2}$ and $\frac{1}{3}$ are shown in Fig. 3.

Around $\nu = \frac{1}{2}$, the ballistic response is, within experimental certitude, not dependent on the filling factor. This is in accordance with a gapless excitation spectrum of composite fermions existing around $\nu = \frac{1}{2}$ [6].

Also at $\nu = \frac{1}{3}$, a strong ballistic response is observed indicating phonon excitation across the magneto-roton gap [1], see Fig. 3. The energy of the magneto-roton

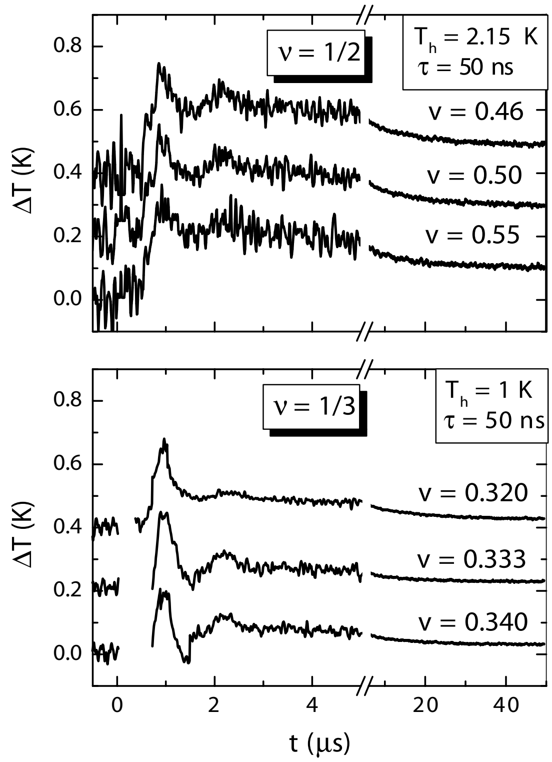

Fig. 3. (a) Change of the 2DES temperature around $\nu = \frac{1}{2}$ due to a 50 ns phonon pulse with $T_h = 2.15$ K. The traces are shifted by 0.2 K each for clarity and smoothened as in Fig. 1. (b) Ballistic 2DES heating around $\nu = \frac{1}{3}$ with a 50 ns phonon pulse, $T_h = 1$ K. The traces are shifted by 0.2 K and smoothened as above.

gap, $\delta \approx 7$ K, is indeed well accessible by the available phonons, a more detailed discussion can be found in Ref. [1]. In contrast to $\nu = 1$, the excitation energy does not depend drastically on the filling factor when moving away from $\nu = \frac{1}{3}$ again emphasizing a specific behavior of the excitation spectrum around $\nu = 1$.

4. Conclusions

In conclusion, we have measured the phonon excitation of a 2DES at filling factor $\nu = 1$. Compared to other filling factors, e.g. $\nu = \frac{1}{3}$ and $\frac{1}{2}$, no ballistic phonon absorption is observable. This can be assigned to the large excitation gap inaccessible to phonons. Moving away from $\nu = 1$, a strong ballistic phonon absorption was shown to appear which may be related to low-energy skyrmion excitations of a 2DES.

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