Spectroscopy of Phonon Emission in the Quantum Hall Effect Regime

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(Received 21 October 1997)

Phonon emission from two-dimensional electron gases in the quantum Hall effect (QHE) state of a Si MOSFET was measured using the phonon-induced conductivity of the substrate. The inherent phonon energy detection threshold of this system was used to analyze the frequency spectra of the phonons in strong magnetic fields. It was found that phonons with cyclotron energy are emitted in the QHE state. The emission takes place in the corners of the Hall bar sample where the current enters and exits. This observation probably indicates that, in the QHE state, the temperature of the electrons in the corners rises sufficiently to allow inter-Landau-level transitions. [S0031-9007(98)05967-5]

PACS numbers: 73.40.Hm, 66.70.+f

In the quantum Hall effect (QHE) [1], all dissipative processes are concentrated in "hot" spots in two diagonally opposite corners of a two-dimensional electron gas (2DEG) leading to the near vanishing of the longitudinal resistance R_{xx}. The existence of hot spots was suggested in 1978 [2] and was experimentally verified both by measuring the local temperature [3] and by fountain-pressure imaging [4]. Little is known, however, about the nature of the dissipative processes on a microscopic scale, the size of the hot spots, or the value of the electric field inside them. Indeed, it is not even known whether the hot spots are located mainly inside the 2DEG or the contacts.

Power is dissipated in a 2DEG at low temperatures either as photons (far infrared radiation) or as acoustic phonons. The far infrared comprises less than 10^{-4} (GaAs heterostructures) or 10^{-6} [Si MOSFETs (metal-oxide-semiconductor field-effect transistors)] of the total emission [5–7] and has been observed only at source-drain currents I_{SD}, which exceed the breakdown currents for the QHE. The study of the acoustic phonon emission is an alternative and more desirable approach because it directly reflects the majority of the dissipation.

Spectroscopic study of the phonons emitted from 2DEG systems, both in zero and in large magnetic fields, had been tackled previously but encountered experimental difficulties due to limitations in the available techniques. In zero magnetic field, the detection threshold of superconducting tunnel junctions was used to show there is a $2k_F$ cutoff in the spectrum of the emitted phonons [8]. Only very indirect techniques were available in high magnetic fields, and the sensitivity limited the experiments again to currents greatly exceeding the breakdown threshold of the QHE. Using these techniques Kent *et al.* [9] observed that the phonons were strongly scattered by impurities in the substrate and so concluded that phonons emitted had predominantly high, i.e., cyclotron, energy. Cooper *et al.* heated the 2DEG to electron temperatures near 100 K and observed a small ($<1\%$) oscillation of the angular distribution of the emission [10] consistent with the theoretical prediction for cyclotron phonon emission.

In this Letter, we report experiments which use the intrinsic B^+ doped substrate of a Si-MOSFET structure as a phonon detector with a well-defined energy threshold: the first use of this system as a spectroscopic detector in high magnetic fields. Its sensitivity allows measurements to be made for currents well below the breakdown current of the QHE. We find that the hot corners emit phonons with a significant component at the cyclotron energy only if the Hall bar sample is in the QHE state. From this information we estimate the temperature of the electrons in the hot spots and their approximate diameters. The sizes should differ depending if the sample is in the QHE regime or not.

In our experiment, positively charged B^+ centers are produced from the neutral boron dopant atoms; an extra hole is captured on optical excitation. This extra hole has a binding energy of only 1.8 meV, and acoustic phonons with energies exceeding this value can ionize the hole, and so increase the substrate conductivity. The properties of this process were originally studied in zero magnetic field [11]. The dependence of the binding energy on magnetic field was measured using metallic tunnel junctions as quasimonochromatic phonon sources [12]. It was found that the binding energy increases linearly with magnetic field according to the relation $E(B) = E_0 + (\hbar e/2m_h^*)B$, where $E_0 = 1.8$ meV is the binding energy in zero magnetic field and m_h^* is the effective mass of the heavy holes in Si.

We use the minimum phonon energy needed to ionize the substrate conductivity to analyze the emission. Figure 1 shows the binding energy $E(B)$ as a function of magnetic field together with the cyclotron resonance energies of the electrons in the 2DEG. The two lines intersect at 3.6 T, so, if the 2DEG emits phonons at $\hbar\omega_c$, the conductivity of the substrate should increase at this field. If

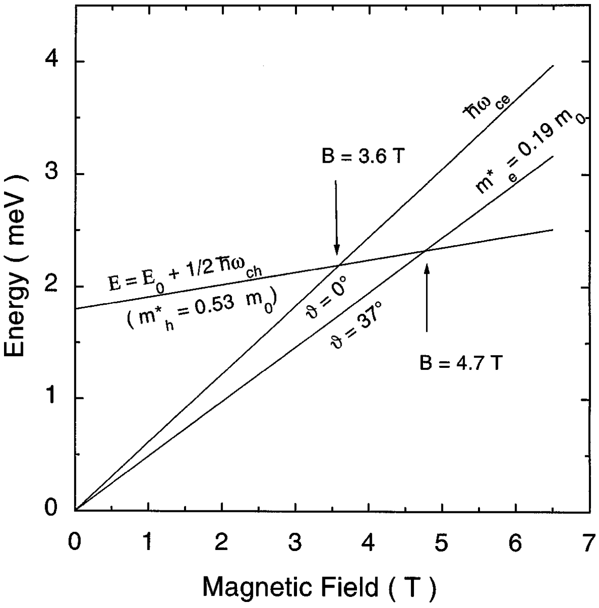

FIG. 1. The cyclotron energies of electrons in Si-MOSFET structures in a magnetic field applied in two different angles to the normal to the 2DEG. These energies exceed the binding energy of the extra hole of a B^+ center in the substrate. At magnetic fields exceeding these threshold fields an increase in substrate photo conductivity should occur, if phonons with cyclotron energy are emitted.

the magnetic field is tilted, the detection threshold shifts to higher magnetic fields, for example, to 4.7 T for a tilt angle of 37° (the directional dependence of the heavy hole mass is negligible).

The Si-MOSFET structures used were from the same batch as those of Refs. [9,10]. The substrates were 400 μm thick and had a boron concentration of 10^{13} cm^{-3}. The oxide layer of the MOSFET structure was 100 nm thick. The 2DEG had a peak mobility of about 10^4 cm^2/V sec and was shaped as a Hall bar measuring 1500 μm × 500 μm with three voltage probes on each side. The conductivity of the substrate was measured using two evaporated Al pads opposite the source-drain contacts on the other side of the substrate. The separation of the Al pads was 1500 μm so that the volume over which the conductivity was measured coincided approximately with that covered by the Hall bar. The sample was immersed in liquid helium at 1.1 K.

The B^+ centers were produced by illumination from a light bulb through a window in the bottom of the cryostat. The substrate conductivity was measured by applying 1.5 V across a 10 kΩ resistor in series with the substrate contacts and monitoring the voltage across the resistor with a lock-in amplifier. A source-drain current was switched on and off with a frequency between 17 Hz and 3 kHz, and the resulting conductivity changes were monitored. No frequency dependence was observed. In Fig. 2, the phonon-induced currents are plotted as a function of magnetic field. The two panels correspond to different angles of the sample with respect to the external magnetic field. The density of the electrons was the same, 1.1×10^{12} cm^{-2}, in both sets of experiments. Several source-drain current amplitudes were used in the experiment as indicated in the figure. Also shown are the Shubnikov–de Haas oscillations in R_{xx}, the longitudinal resistance in perpendicular magnetic field.

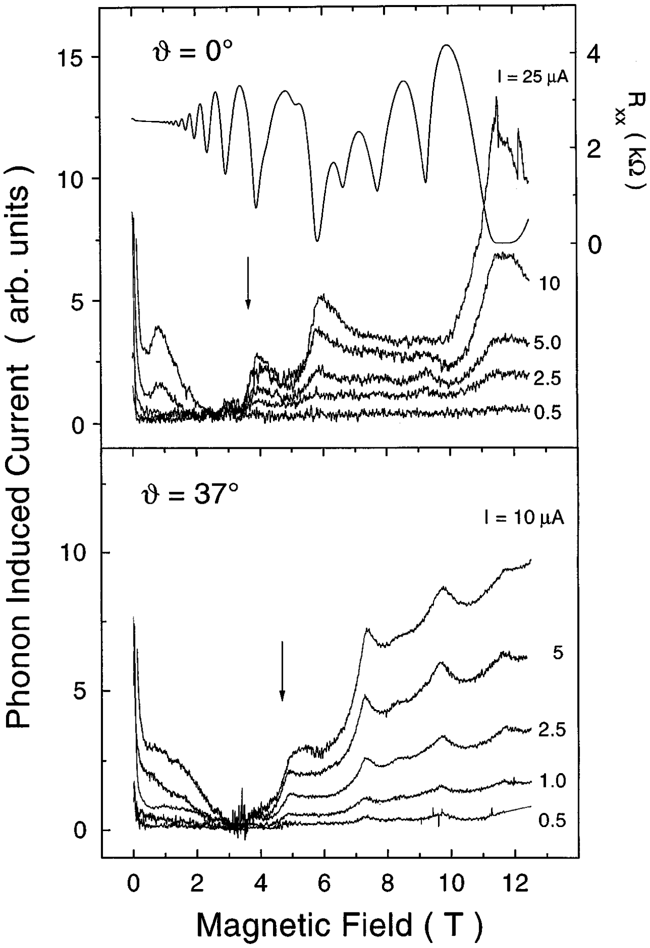

FIG. 2. Phonon-induced conductivity of the Si substrate as a function of magnetic field. The two panels correspond to different angles of the magnetic field with respect to the normal to the 2DEG with a carrier density of 1.1×10^{12} cm^{-2}. The different traces were taken with different currents (in μA). The signal onsets (arrows) take place at fields at which the cyclotron energy crosses the phonon detection threshold. The top panel also shows the longitudinal resistance of the 2DEG. The phonon signal is maximal when the longitudinal resistance vanishes. The spin and valley splitting was more pronounced at oblique angles leading to clearer maxima.

The phonon signals show several features. Most important, however, are the clear signal onsets at 3.6 T and at 4.7 T for angles of 0° and 37°, respectively. These fields (arrowed) correspond closely to the intersection of the cyclotron energy with the threshold energy of the B^+ centers expected from Fig. 1. This shows very clearly that acoustic phonons with energies equal to the cyclotron energy are emitted by the 2DEG. The signal onset is observed at currents as small as 1 μA corresponding to 2 nW dissipated power at the threshold field. All measurements were made at currents less than breakdown: $\sim$55 μA at filling factor 4 ($B = 11.7$ T).

At larger magnetic fields, the signal oscillates in opposite phase to R_{xx}. Strikingly then, the cyclotron phonon emission is maximal in the dissipationless QHE state of the bulk of the 2DEG, when the only emission is from the corners. So this is a clear demonstration that this emission contains a significant component at the cyclotron energy. Outside the QHE state the longitudinal resistance is nonzero. So the total source-drain resistance and hence dissipation increases. However, this is accompanied by a drop in the intensity of the cyclotron phonon emission, and this must indicate a shift in the phonon spectrum emitted from the corners to lower frequencies below our detection threshold. At larger current amplitudes, an additional feature becomes visible at small magnetic fields where the Landau levels overlap. We attribute this to electron transitions across the Fermi surface, the dominant process at $B = 0$ [8]. This is known to produce a significant fraction of phonons with energies of several meV, i.e., above the present threshold energy.

The general behavior of the phonon signal is independent of sheet density n_s. This can be seen in Fig. 3 which shows the effect of varying the gate voltage. As expected, the peak in the phonon signal shifts in field linearly with n_s, in line with the shift in the minima in R_{xx}, while the onset remains at $\sim$3.6 T.

We summarize the results as follows: The onsets at 3.6 and 4.7 T occur when the cyclotron energies of the phonons emitted by the 2DEG exceed the detection threshold of the B^+ centers. The similarity of the peaks for various values of B and n_s strongly suggests they are due to cyclotron energy phonons even at larger magnetic fields where we do not have direct spectroscopic evidence. It is also of note that no features are visible at magnetic fields at which phonons at $\hbar\omega_c/2$ [13] should become detectable. From Fig. 1, this should be at 9.2 T for 0° and 13.4 T for 37° (not reached).

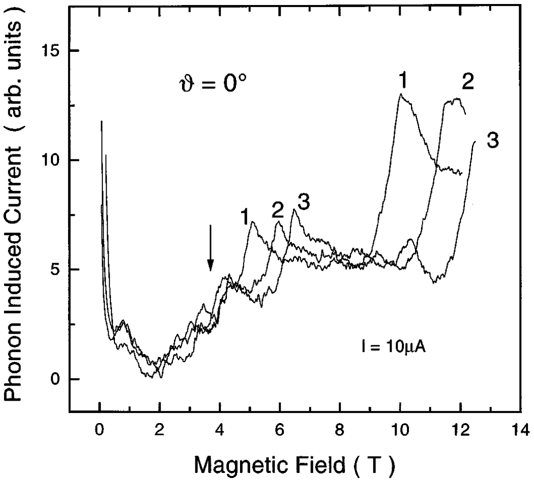

FIG. 3. Phonon-induced conductivity curves at different carrier concentrations (1: 0.9×10^{12} cm^{-2}, 2: 1.1×10^{12} cm^{-2}, and 3: 1.3×10^{12} cm^{-2}). The maxima positions in the signal increase linearly with field in line with the shift in the minima in R_{xx}. There is, however, no detectable shift in the detection threshold (arrow).

In conclusion, we have introduced a new experimental technique which allows spectroscopic investigation of the phonons emitted by a Hall bar at currents smaller than the QHE breakdown current. In interpreting the results obtained, we note first that, since the two-point resistance measurements show almost perfect Hall quantization, there is no measurable contact resistance. So the total dissipated power and hence total phonon emission in the device is lowest in the QHE states. On the other hand, our phonoconductivity signal shows maxima in the QHE state with intensities which are up to 4 times higher than in the adjacent non-QHE state. These large maxima indicate that, in the QHE state, the spectrum of the dissipated phonons contain a significant fraction at $\hbar\omega_c$. It is possible, of course, that there is still some emission at low energies which we do not detect. The magnitude of this emission is not, however, important for the following analysis.

For a phonon emission with energies at $\hbar\omega_c$ to occur a significant population of the upper Landau level must be created in the hot spots, where all dissipation takes place in the QHE state. The most probable way to achieve this is by heating the electrons to a sufficient high electron temperature, T_e. This would require $T_e \sim 10$ to 20 K [14,15], because, in Si-MOSFETs, the Landau level separation is about 2 to 4 meV at the magnetic fields investigated here. The power density p needed to heat to these temperatures evidently determines the size of the hot spot. This argument is related to the local temperature model developed for the breakdown of the QHE [16,17]. We cannot deduce the electron temperature precisely from our data nor has the dependence of T_e on p been measured in high magnetic fields. However, an estimate of the spot size is possible if we assume that $T_e \sim 10$ K and use the measured values of $T_e(p)$ at zero field. The assumption that $T_e(p)$ is not heavily dependent on B is reasonable because at $T_e \sim 10$ K the thermal smearing is comparable with the Landau-level splitting in this case. With $p = 500$ W/m^2 at $T_e \sim 10$ K [6] this suggests a hot spot size of $\sim$25 μm at 10 μA and filling factor 4. The choice of T_e is not very critical, e.g., using 20 K instead of 10 K only halves the size of the hot spot. This range of spot sizes is reasonable if one compares the size of $\sim$140 μm expected at 55 μA, the breakdown current, with the sample width, 500 μm. For completeness we note that this analysis suggests the average electric field in the hot spots is about 5400 V/m.

Outside the QHE state, this model suggests that, for a given power input, the cyclotron phonon emission should be weaker because now the Fermi energy is within a Landau level and intra-Landau-level transitions become possible. This leads to $p \propto T_e$ [15] so that T_e does not rise sufficiently for significant emission from inter-Landau-level transitions. So the maxima in Figs. 2 and 3 also correspond to maxima in T_e. Hot spots still exist, of course, outside the QHE state because the Hall angle remains large. However, in order to achieve a balance between the electrical power dissipation and the phonon emission, the electron temperature of hot spots may be lower, and therefore the hot spots may be less contracted. Consequently, if one sweeps the magnetic field, there should be oscillations in the size of the hot spots as well as in their temperature.

In summary, we have used the phonon-induced conductivity of the boron doped Si substrate to obtain significantly better spectroscopic information on the phonons emitted from 2DEGs in strong magnetic fields than was previously available. We have observed cyclotron phonon emission at power levels as low as a few nW in the QHE regime where the dissipation is restricted to small hot spots at the current entry and exit corners. We interpret the results by a local heating model and conclude that the electron temperature in the hot spots oscillates with magnetic field and, in the QHE state, it is high enough for inter-Landau-level transitions to occur.

It would be of great interest to extend these measurements to GaAs heterostructures, where the role of the form factors controlling the phonon emission would be more important and other dissipative processes like two phonon emission may dominate. Investigation of possible acceptors in the GaAs substrate for such an experiment is under way.

We gratefully acknowledge discussions with K. v.Klitzing, K. Lassmann, and G. Nachtwei. We thank C. M. K. Starbuck and colleagues of the Department of Electronics and Electrical Engineering of Southampton University for the Si-MOSFET structures. This work was partially supported by the European Union.

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