Imaging Nonequilibrium Phonon-Induced Backscattering in the Quantum Hall Regime

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Nonequilibrium phonon pulses, generated by laser heating a metal film, have been used to probe small areas of an extended two-dimensional electron gas (2DEG) in a GaAs-AlGaAs heterojunction, at low temperature and in a quantizing magnetic field. The electron-phonon interaction was studied via the change in the two-terminal resistance of the 2D electron system. By scanning the phonon beam over the entire area of the 2DEG, images of the effects were made. We show that our images are in qualitative agreement with theoretical descriptions of the quantum Hall effect which include electron states confined near the edges of the 2DEG.

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To fully explain some of the experimental details of the integer quantized Hall effect in 2D electron systems it has become necessary to consider the behavior of electrons at the edges of the device [1–4]: Because the wave function of an electron must vanish at the sample edges, the quantum energy levels of electrons within a few cyclotron radii of the edge are shifted relative to those of bulk electrons in the same Landau subband [2]. Classically, one can visualize the edge electrons as describing "skipping orbits" along the boundaries of the device, Fig. 1(a). The electrons on opposite edges have opposite velocities and give rise to the diamagnetic current around the periphery of the device. These so-called edge states interact directly with the voltage probe contacts in a standard Hall bar geometry and give rise to a number of the observed phenomena. It turns out that in narrow samples and in high magnetic fields, such that the Hall voltage V_H is much less than $\hbar\omega_c/e$, these edge states are the only effective current-carrying states, the bulk states at the Fermi energy E_F being localized [3]. Subject to the absence of any interaction between the two sets of states at opposite edges of the two-dimensional electron gas (2DEG) the integer quantum Hall effect is observed; the longitudinal resistance R_{xx} falls to zero, the Hall resistance R_{xy} exhibits a plateau, and the net current is just the difference between the currents at each edge. In this picture, processes that bring about the scattering of electrons from one set of edge states to those at the other edge (backscattering) can lead to the breakdown of the quantized Hall state ($R_{xx}>0$). Rigorous theoretical descriptions of the quantum Hall effect also take account of the details of the coupling between the current and voltage contacts and the edge states [3,4]. The experimental situation is frequently rather different from this with $\hbar\omega_c/e$ comparable to, or even less than, V_H. Then, for a full description of the observed properties, it becomes necessary to consider currents flowing in the bulk of the 2D electron system as well as those at the edges [5]. Even in this description, however, deviations from exact quantization and eventual breakdown of the quantum Hall effect can still be associated with the backscattering of electrons via the edge states of opposite electron velocity to that associated with the net current flow.

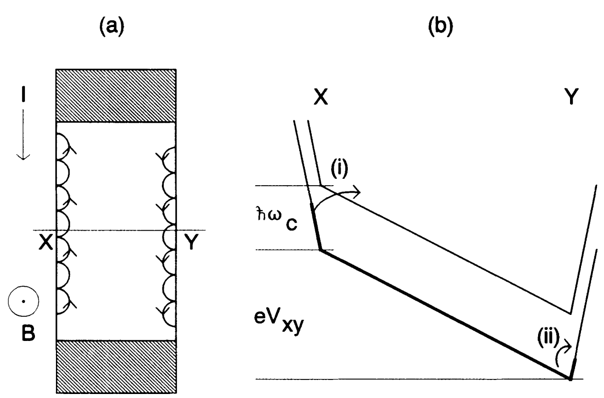

FIG. 1. (a) Skipping orbits of electrons at edges of 2DEG in a strong magnetic field. (b) Schematic diagram of electronic energy levels on a line X-Y through the center of the device assuming a uniform distribution of Hall field across the sample width.

In the experiments reported here, we have used an intense beam of nonequilibrium phonons to stimulate the backscattering of electrons in just a small part of the 2DEG. By moving the phonon beam over the active area of the 2DEG, we are able to identify which states are most readily backscattered in this way. The sample, shown in Fig. 2, was based on a (001) GaAs-AlGaAs heterojunction grown on a 380-μm-thick GaAs wafer. The 2DEG concentration was 7.8×10^{15} m^{-2} and the 4.2-K mobility was 70 m^{2}V^{-1}s^{-1}. A 5×1-mm^2 mesa was defined by etching and 1×1-mm^2 AuGe contact pads formed at the ends leaving a 3×1-mm^2 active area. The back face of the wafer was polished to remove any indium contamination and a 100-nm film of Constantan deposited by vacuum evaporation. The sample was mounted in a cryomagnetic system with optical access and maintained at a temperature of 2 K in a flow of helium gas. The focused beam from a Q-switched Nd-YAG laser (pulse length ≈100 ns and frequency ≈2 kHz) was thermal-

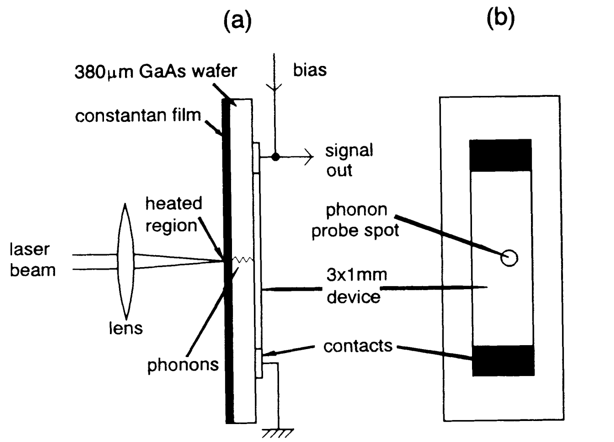

FIG. 2. Sample geometry: (a) Side view, the laser beam is positioned on the Constantan film using a pair of galvanometer driven x-y mirrors under computer control. (b) Top view (sample face), the light-shaded area indicates the approximate size of the phonon probe beam.

ized in a spot, approximately 50 μm across, on the Constantan film. We estimate that the fluence of the laser in this spot was 7×10^6 W m^{-2}, 25% of this was reflected and of the remainder, 99.995% was absorbed in the Constantan giving a hot spot temperature of about 10 K. Hence a burst of nonequilibrium acoustic phonons was generated having an approximate blackbody frequency distribution peaked at $3kT/h \approx 600$ GHz. In GaAs at 2 K, such phonons can travel ballistically, at the speed of sound, distances of up to a few millimeters. After traversing the GaAs wafer the phonons fell upon the 2DEG and their interaction with the 2DEG was monitored by passing a constant bias current of up to 100 μA through the device and looking at the change in the two-terminal resistance coincident with the phonon pulse. Typically, the signal was rather weak, of order microvolts, and so a boxcar integrator was used to average it over a thousand or more laser pulses thereby improving the signal-to-noise ratio. Transverse acoustic (TA) phonons are strongly focused close to the [001] in GaAs, therefore, the phonon flux falling on the 2DEG is much greater in an area about 100 μm across directly opposite the point of generation than it is anywhere else and consists predominantly of TA modes. The boxcar gate timing (delay after start of laser pulse, 130 ns; width, 20 ns) was set to exclude the rather weak signal due to direct photoexcitation of the 2DEG and any signals from TA phonons that had not traveled the most direct paths to reach the 2DEG. Taking into account the finite width of the gate we estimate that the detected signal very largely corresponds to interaction of phonons with a region of the 2DEG which is about 250 μm across (about 2% of the entire active area of the 2DEG). A spatial map of the sensitivity of the two-terminal resistance to the phonon pulse was made by scanning the laser beam over the area of Constantan opposite the device, by means of a pair of galvanometer driven mirrors.

Figure 3 shows a set of images taken at a magnetic field of 1.5 T, which puts E_F about three quarters of the way up the gap between the tenth (filled) and the eleventh (empty) Landau levels. The images correspond to the four permutations of magnetic field and current direction. The resistance of the 2DEG shows a transient increase (dark regions) or decrease (bright regions) depending on where on the device the phonons were incident. When the phonon beam strikes a contact the resistance decreases by approximately 0.1 Ω. This effect has also been observed using metal-oxide-semiconductor field-effect transistors [6] and can be attributed to thermally activated conduction within the n^+ contact. In the present experiments contact resistance was rather high so the two-terminal resistance was always greater than R_H. The contact through which the current enters the device shows the strongest decrease which suggests that, at low temperatures, the contacts may be behaving like lossy diodes. The more interesting though rather weaker effect is the increase in resistance when the phonons interact with the 2DEG well away from the contacts. Notice that it is strongest when the phonons are incident near the edges of the device and, at this value of the magnetic field, is stronger at one edge. This edge changes sides with reversal of the magnetic field or current direction as might be expected if the signal were in some way due to the phonons interacting with edge

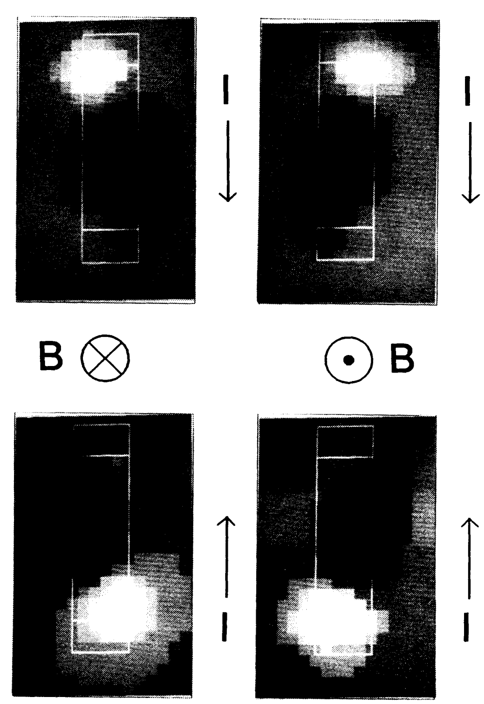

FIG. 3. Photoconductivity images of the two-terminal resistance corresponding to the four possible permutations of magnetic field and current direction. The dark areas correspond to an *increase* in the resistance.

states.

We interpret this effect qualitatively as follows: upon absorption of a phonon, an electron gains energy $\hbar\omega_p$ and is scattered to a new state. If, as a result of this, the electron is transferred into one of the empty edge states of opposite velocity, i.e., it is backscattered, an increase in the two-terminal resistance is expected. Figure 1(b) shows (according to [5]) the energy levels on a line, X-Y, through the center of the device as indicated in Fig. 1(a). We have assumed that the Hall field is distributed uniformly across the width of the device, however, the precise form of the distribution is unimportant in this interpretation. The bold line indicates the levels that are filled with electrons. There are two processes by which electrons can get into the empty states at the right-hand edge, Y. Either (i) they can tunnel into the unfilled Landau level above, whereupon they can readily move across the device to Y, or (ii) the electrons may tunnel from the bulk states within the filled level directly into the empty edge states at Y; this also increases the two-terminal resistivity since at such large Hall fields bulk states also contribute to the current. Momentum conservation considerations lead us to conclude that in the case of phonons that are normally incident upon the 2DEG, the electron-phonon coupling cuts off for phonon wave vectors greater than about $1/a_0$, where a_0 is the "thickness" of the 2D gas [7]. In a GaAs heterojunction this corresponds to a maximum phonon frequency of about 200 GHz, considerably less than the cyclotron frequency (600 GHz) in this case. Therefore process (i) is not possible except for electrons in the left-hand edge states at X when E_{FX} is just below (within 200 GHz of) the bottom of the empty Landau level. The image shown in Fig. 4(a) corresponds to this situation; the strongest signal is seen when the phonons are incident near the left-hand edge. The second process, (ii), is not possible for electrons that are many magnetic lengths away from Y because there is insufficient overlap of the electronic states. However, it does become possible for electrons near Y provided that the empty edge states are not far removed, in energy ($\Delta E/h < 200$ GHz), from the nearby bulk states. This is the case when E_{FY} is just above the filled level and the corresponding image is shown in Fig. 4(c); note that the strongest signal is seen when the phonons are incident near the right-hand edge. When E_F is approximately midway between two levels both processes are equally probable but somewhat reduced in strength. The corresponding image is shown in Fig. 4(b); both edges contribute to the signal which merges at the center. The maximum signal is about a half of the maximum in Figs. 4(a) and 4(c). (Note that the images have been normalized to make the most of the available grey-scale range.)

We have demonstrated that an intense beam of nonequilibrium phonons stimulates the backscattering of electrons in a 2DEG in the quantum Hall regime. Our spatially resolved measurements show that the region of the device which is initially responsible for the breakdown

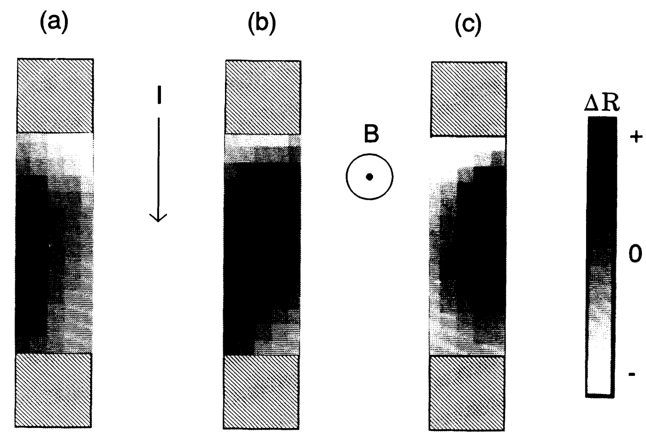

FIG. 4. Images of the change in two-terminal resistance at three different filling factors. (a) E_F just below an empty Landau level, (b) E_F midway between two levels, and (c) E_F just above a filled level.

of the integer quantum Hall effect is dependent on the position of the Fermi level in the gap between Landau subbands. The symmetry of the images with respect to the current and magnetic field direction confirm that this is an intrinsic effect and not due to inhomogeneities in the 2DEG concentration. These results are consistent with electrical transport measurements of the temperature dependence of the width of the longitudinal resistivity, R_{XX}, minimum. Its width depends on the range over which E_F can be varied without either of the backscattering processes (i) or (ii), discussed above, cutting in. As the temperature is increased, the equilibrium phonon energy increases and so the minima narrow. At a fixed temperature, one might also expect to see R_{XX} breaking away from zero at a different value of filling factor depending on which side of the Hall device it is measured. Unfortunately, attempts to observe the latter have suffered from problems associated with 2DEG inhomogeneities.

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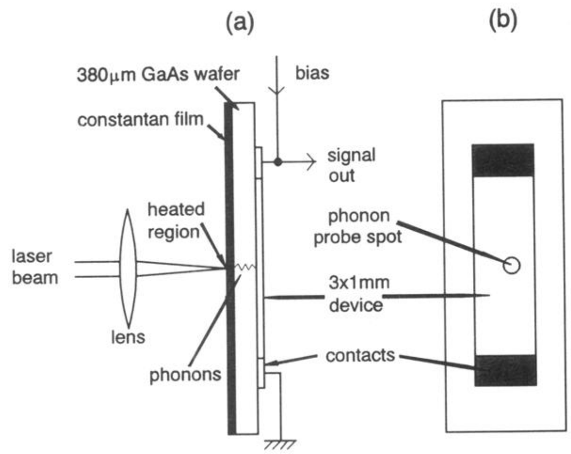
[1] R. B. Laughlin, Phys. Rev. B **23**, 5632 (1981).
[2] B. I. Halperin, Phys. Rev. B **25**, 2185 (1982).
[3] P. Streda, J. Kucera, and A. H. MacDonald, Phys. Rev. Lett. **59**, 1973 (1987).
[4] M. Büttiker, Phys. Rev. B **38**, 9375 (1988).
[5] P. C. van Son and T. M. Klapwijk, Europhys. Lett. **12**, 429 (1990).
[6] A. J. Kent, Physica (Amsterdam) **169B**, 356 (1991).
[7] L. J. Challis, A.J. Kent, and V. W. Rampton, Semicond. Sci. Technol. **5**, 1179 (1990).



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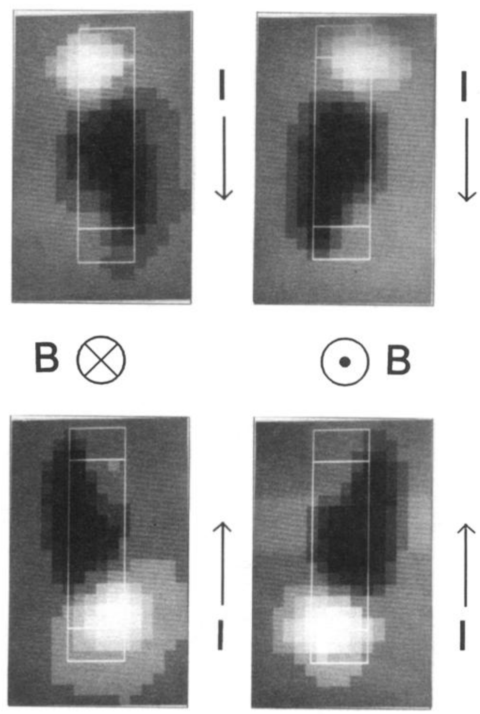

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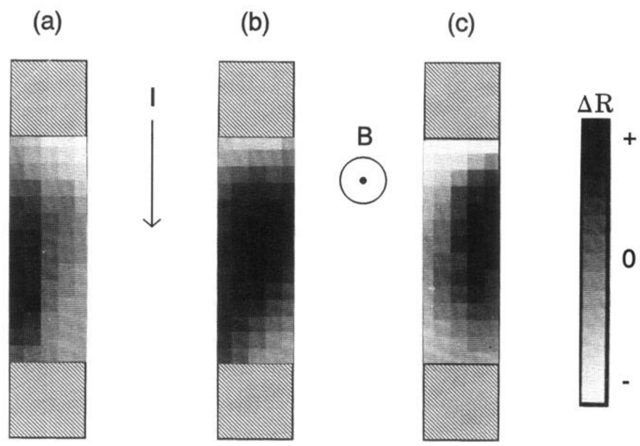

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