Local far-infrared spectroscopy of edge states in the quantum Hall regime

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Using local spectroscopy, we study the far-infrared response of edge channels in the quantum Hall regime. Both nonresonant and resonant excitations are observed. The resonant signal is shifted with respect to the cyclotron resonance in the two-dimensional electron gas, which reflects the local curvature of the edge potential. The observation of higher-order transitions, which are forbidden in the bulk, reveals the presence of nonparabolic contributions to the edge potential.

The edge states in the quantum Hall (QH) effect can be viewed as an ideal model system for one-dimensional (1D) electron transport.[1] These channels, which are confined to within ≈ 0.5 μm from the edge of a Hall bar, lack many of the imperfections of lithographically defined 1D systems, and electronic mean-free paths of up to ≈ 100 μm have been observed in dc transport experiments.[2–4] Lithographically defined 1D systems have been extensively studied with respect to both their static and dynamic response.[5] QH edge states, on the other hand, have been investigated almost exclusively in the low-frequency regime. Only recently, the dynamic behavior of QH edge channels was studied using time- or spatially resolved techniques.[6–8] One problem in exploring the high-frequency (THz) properties of edge channels in the QH regime is to separate their signal from that of the adjacent high-mobility two-dimensional electron gas (2DEG), which covers an area typically three orders of magnitude larger than that of the edge. Two techniques can be used to overcome this problem: one is local spectroscopy with a lateral resolution well below typical Hall bar dimensions,[7,8] the other is the use of the edge channels themselves as detectors.[9] In the present study, we combine both techniques and obtain sufficient selectivity to directly investigate the far-infrared (FIR) excitations of quantum Hall edge states.

The samples are prepared from molecular-beam epitaxially grown $Al_xGa_{1-x}As$ heterostructures. The individual layers are as follows: Buffer and smoothing layers, 1 μm GaAs, a 15-nm $Al_xGa_{1-x}As$ ($x=0.3$) spacer layer, 3.9×10^{12}-cm^{-2} Si δ doping, 5-nm $Al_xGa_{1-x}As$, 36-nm AlAs (2-nm)/GaAs (2-nm) superlattice, and a 4-nm GaAs cap layer. In the unprocessed wafer the carrier density and mobility at liquid He temperatures are 4.5×10^{15} m^{-2} and 50 m^2/V s, respectively. Using standard lithographic patterning techniques, 20 to 30 Hall strips, 36 μm wide and 2.2 mm long, are defined by wet etching. All channels are connected in parallel through common Ohmic contacts at the ends. This geometry (many parallel strips) has the advantage that it increases the active area of the sample and thus allows us to probe the FIR transmission and the transport properties simultaneously. A 5-nm-thick, semitransparent NiCr layer is evaporated as a continuous gate electrode to vary the carrier density of the 2DEG. Finally, 120-nm-thick Ag stripes are deposited which blank out the FIR radiation from one edge of the Hall bars and allow excitation of only the other. For the laser wavelengths used, $\lambda=118$, 163, 170 μm, this constitutes a spatial confinement of the FIR radiation to within $\approx\lambda/5$ of the edge channel. Nevertheless, more than 90% of the exposed area consists of ''bulk'' 2DEG and therefore the transmission signal is dominated by the (bulk) cyclotron resonance excitation. We obtain the additional selectivity, necessary to probe the edge excitations, by recording the *lateral* (i.e., between the Ohmic contacts) photovoltage induced by the FIR radiation. In the present geometry (two-probe, long-channel, high magnetic fields) this voltage directly reflects the difference in chemical potential between the illuminated and the not-illuminated edge of the Hall strips.[10]

The samples are mounted in a liquid He cryostat, in the center of a superconducting solenoid, with the direction of the magnetic field perpendicular to the 2DEG. The far-infrared radiation from an optically pumped molecular laser is coupled into the cryostat using an oversized waveguide. An aperture is used to minimize interfering voltage signals from irradiation of the Ohmic contacts. The laser light is chopped with a frequency $\nu\approx30$ Hz, and the transmission and photosignals are recorded using standard lock-in detection. A schematic of the sample layout and measurement geometry is shown in Fig. 1(a).

Figure 2 displays the measured lateral photovoltage V_{phot} of sample I at magnetic fields $0\leqslant B\leqslant4$ T and at a gate voltage $V_g=0$. Pronounced oscillations are observed which are periodic in $1/B$ with the same period as the Shubnikov–de Haas oscillations of the magnetoresistance (see arrows in Fig. 2). We attribute these oscillations to FIR radiation-induced heating of the electron system.[11,12] In the following, we will label this signal ''nonresonant'' photovoltage, because it reflects a temperature gradient in the sample which can be equally well induced by external, resistive heating. A thorough discussion of the thermoelectrical properties of 2DEG's, in terms of the diffusion model, can be found, e.g., in Ref. 12. An alternate, simple explanation for the temperature-induced lateral photovoltage is given in the inset of Fig. 2 . When the filling factor N is just above an integer, a rise in temperature will lead to a decrease of the

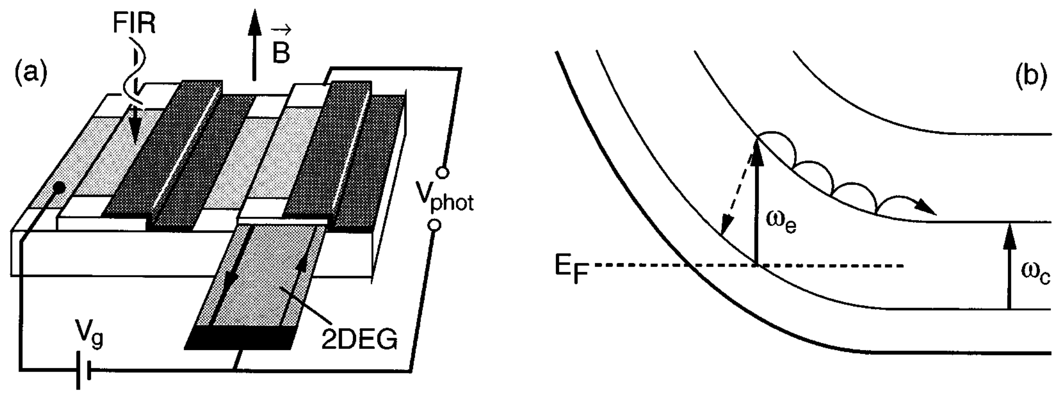

FIG. 1. (a) Schematic of the measurement setup, depicting the continuous gate (light shading) and the metallic masking strips (dark shading). Also shown is the 2DEG with the two counterpropagating edge channels. (b) Edge (ω_e) and bulk (ω_c) excitations at high magnetic fields. Possible relaxation mechanisms which can lead to different local chemical potentials at the edge and in the bulk are sketched.

Fermi level. Just below an integer filling factor, on the other hand, the Fermi level will increase. (In the present experiment we are not able to resolve spin splitting, up to a magnetic field of $B=7$ T. We therefore only consider Landau levels and not spin levels in the determination of the filling factor N.) Similar effects have been observed in the *vertical* photovoltage (between the 2DEG and the gate).[13] We can rule out, however, that the oscillations observed in Fig. 2 are caused by cross-talk between vertical and lateral V_{phot}: The dotted line shows that V_{phot} changes sign when the magnetic field is reversed. From symmetry considerations, a possible vertical photovoltage should be an even function of B.[14]

As mentioned above, Fig. 2 displays the *nonresonant* photovoltage. For the laser wavelength used, $\lambda_{\mathrm{Laser}} = 118.8$ μm, cyclotron resonance occurs at $B=6.24$ T, as inferred from the transmission signal shown in Fig. 3. In this magnetic-field regime, the lateral photovoltage signal differs drastically from that observed in Fig. 2 in several respects: It is up to two orders of magnitude larger, its amplitude is very sensitive to the applied gate voltage, and it does not change sign when the filling factor N is swept across an integer (it does, however, change sign when the magnetic field is reversed). As shown in the lower trace of Fig. 3, maximum response is observed at $V_g=-270$ mV and $B=5.9$ T, which corresponds to $N=0.8$. At the position of the cyclotron resonance, the signal is more than 50% smaller, independent of the applied gate bias, even though at this magnetic field the total absorbed power is approximately an order of magnitude larger than at 5.9 T.

We interpret the strong photoresponse shown in Fig. 3 as resonant far-infrared excitation of the QH edge channels. As discussed below, the transition energy between the edge channels, $\hbar\omega_e$, is expected to be larger than the cyclotron resonance energy $\hbar\omega_c$. Thus, at a fixed laser frequency, resonance for ω_e is expected at a lower magnetic field than for ω_c, in agreement with Fig. 3. Furthermore, independent of the filling factor, we do not observe any peaks in V_{phot} at magnetic fields *above* the cyclotron resonance, also in agreement with the fact that (at least for vertical transitions) all

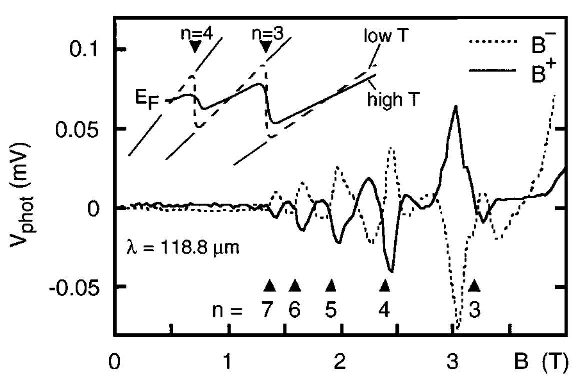

FIG. 2. Lateral photovoltage as a function of the magnetic field for positive (solid line) and negative (dotted line) field orientation. Upward arrows identify integer filling factors N. The excitation wavelength is 118.8 μm. Inset: Schematic representation of the Fermi level as a function of the magnetic field for high (dashed line) and low (solid line) temperatures. The sharp drop in the Fermi level at integer filling factors N (downward arrows) is washed out at high temperatures, resulting in a decrease (increase) of the Fermi level just above (below) integer N.

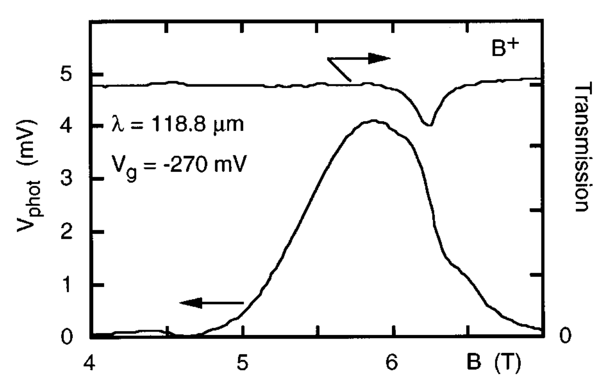

FIG. 3. Transmission and photovoltage, measured simultaneously at high magnetic fields. The shift between the maximum of the photovoltage and the minimum in the transmission reflects the energetic difference between edge and bulk excitations.

edge excitations are expected to have a larger energy than the bulk cyclotron resonance.

For a more quantitative picture, we calculate the energy shift of QH edge states by first-order perturbation theory, starting from the well-known wave functions of free electrons in high magnetic fields.[15] Another instructive picture is to view the edge as one-half of a (parabolic) quantum wire.[5] In high magnetic fields, both approaches give the same results: The transition energies are not affected by a linear term in the potential; the parabolic term causes a frequency shift of

$$\Delta\omega \approx \frac{\omega_0^2}{2\omega_c}, \tag{1}$$

with ω_0 being the characteristic frequency of the parabolic term. The relation between ω_0 and the magnetic fields at resonance is $\omega_0 = e/m\sqrt{B_{\rm bulk}^2 - B_{\rm edge}^2}$. For the values obtained from Fig. 3, this leads to $\omega_0 = 5\times10^{12}\ \mathrm{s}^{-1}$, in agreement with results for etched quantum wires,[5] which are expected to exhibit a similar edge profile. Assuming a constant curvature, this value leads to an estimate for the width of the edge channel of $\approx 0.4\ \mu$m, also in agreement with other experimental[16] and theoretical[17] estimations. Caution is advised, though, in directly relating the local curvature to the FIR response, since the latter is affected by depolarization and other electron-electron interactions. However, from comparison with FIR data of lithographically defined quantum wires, we infer that the generalized Kohn theorem,[18,19] which well describes the relation between the bare (single-particle) potential and the collective, high-frequency response in quantum wires, also applies to the present excitation of QH edge channels. We therefore conclude that the shift between the bulk and the edge excitation as seen in Fig. 3 reflects to a good approximation the *bare* curvature of the QH edge potential, rather than the self-consistent potential calculated, e.g., by Chklovskii, Shklovskii, and Glazman.[17] Other possible explanations for a shifted resonance, such as localization or plasmon effects, can be ruled out, since they would lead to much smaller shifts and would affect the transmission in a similar fashion as the photovoltage.

In order to observe the edge excitations through lateral photovoltage measurements, it is essential that the edge states equilibrate only slowly with each other and the bulk 2DEG. One would therefore expect maximum photosignal at integer filling factors. In Fig. 3 we observe the strongest response at $N=0.8$ (neglecting spin), slightly below an integer. The strongest photoresponse is observed in a narrow range of gate voltages, $-300\ \mathrm{mV} \leqslant V_g \leqslant -230$ mV. In this regime, the position of the maximum shifts from $B=5.7$ T (-300 mV) to $B=6.1$ T (-230 mV). The corresponding filling factors are $N=0.73$ (-300 mV) and $N=0.92$ (-230 mV). This means that the local curvature, as inferred from the shift between the cyclotron resonance and the maximum photoresponse, is filling factor dependent and that our experiment enables us to map out this dependence in a small range of filling factors just below $N=1$.

The concept of a local variation of the curvature implies the presence of higher-order terms in the Taylor expansion of the potential. Another strong indication for nonparabolic contributions to the edge potential comes from the observation of higher-order transitions, in particular from Landau level m to level $m+2$.

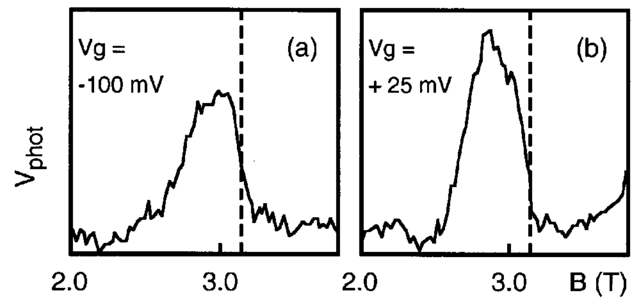

FIG. 4. Photovoltage signal of sample II around $B_{1/2}$ (dashed line) for gate voltages $V_g = -100$ mV (a) and $V_g = +25$ mV (b). The peaks slighly below $B_{1/2}$ are attributed to higher order edge excitations which are forbidden in the bulk. The excitation wavelength is 118.8 μm.

Figure 4(a) shows the photovoltage of sample II around 3 T for gate voltages $V_g = -100$ mV and $+25$ mV. The excitation wavelength is $\lambda_{\rm Laser} = 118.8\ \mu$m, and we again observe a strong photoresponse around $B=6$ T (not shown). We also observe pronounced maxima close to the magnetic field $B_{1/2}$, where $2\omega_c = \omega_{\rm las}$ [dashed line in Fig. 4(a)]. Similar to the ω_e excitation above, this signal is strongly dependent on V_g in both amplitude and position. Maximum signal is observed for $N=3.9$ ($V_g = 25$ mV) and $N=2.9$ ($V_g = -100$ mV), again, slightly below integer filling factors, as for the fundamental excitation shown in Fig. 3. Furthermore, the peaks are shifted to slightly below $B_{1/2}$ and change sign when the magnetic field is reversed. From this we conclude that the photoresponse shown in Fig. 4(a) is caused by an edge excitation between Landau levels 3 and 5 ($V_g = -100$ mV) and between levels 4 and 6 ($V_g = +25$ mV), respectively. These transitions, which are forbidden for bulk 2DEG electrons, are made possible by nonparabolic contributions to the edge potential. We do not observe any resonances in the transmission signal around $B=3$ T, which gives additional support for the assumption that the photosignal around $B_{1/2}$ is not related to bulk effects.[20]

Higher-order transitions are also observed in sample I; however, they are somewhat obscured by the strong thermoelectric signal (cf. Fig. 2), which is much weaker in sample II.

At present, we do not want to speculate how the edge excitations lead to a lateral photosignal. Among the possible schemes are the following [cf. Fig. 1(b)]: (1) Different drift velocities in the upper Landau level, caused by higher-order terms of the edge potential; (2) nonvertical transitions, involving phonon emission; and (3) multiple phonon emission and transfer of carriers into the bulk 2DEG. Mechanisms 1 and 2 will directly induce a net current; mechanisms 2 and 3 will change the local chemical potential. Since current and chemical potential are closely interrelated, more experimental investigations, including current and multiprobe voltage measurements, are necessary to identify the dominant processes.

Finally, we would like to briefly mention some unexpected and so far unexplained resonancelike features that are observed superimposed upon the broad V_{phot} signal at high magnetic fields. Their occurrence is strongly dependent on the applied gate voltage and they are observed close to the position of the 2DEG cyclotron resonance. Typically, these spikes are separated by $\Delta B = 60$ mT. Using the energy scale given by the cyclotron resonance, this corresponds to only 0.1 meV. The sharpness of the resonances, their occurrence at high magnetic fields, and the low energies involved suggest that they are related to edge magnetoplasmons.[21] However, we could not find the clear filling factor dependency commonly found for such excitations.

In conclusion, we have developed a simple, yet powerful technique for local far-infrared spectroscopy of edge states in the quantum Hall regime. Making use of the one-dimensionality of the system, we could confine the FIR excitation to within $\approx \lambda_{\mathrm{Laser}}/5$ of the edge channels without having to employ evanescent waves. Using, in addition, the edge channels as detectors, we obtain sufficient selectivity to directly probe the resonant excitations of QH edge states. The difference between the position of maximum photoresponse and the position of the 2DEG cyclotron resonance reflects the local curvature of the edge potential. The observation of higher-order transitions, which are forbidden in the bulk, reveals the presence of nonparabolic contributions to the edge potential. Unusual, presently unexplained, sharp resonances are observed, which might be related to collective excitations between or within the edge channels.

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[1] There are, however, fundamental differences between edge states and regular 1D systems. Quantum Hall edge states have, e.g., a chiral character. In the present work we repeatedly make use of this fact when we study the antisymmetric behavior of the edge photosignal as the magnetic field is reversed.

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