Novel far-infrared-photoconductor based on photon-induced interedge channel scattering

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We demonstrate experimentally that the far-infrared photoresponse of GaAs/AlGaAs heterostructures at photon energies corresponding to cyclotron resonance absorption is strongly enhanced in the adiabatic transport regime of the quantum Hall effect (QHE). Ideal adiabatic transport is characterized within the edge channel picture of the QHE by the absence of interedge channel scattering. We realize adiabatic transport by the means of a multiple gate finger structure, which is used for a selective population of the edge channels. The cyclotron resonance absorption is interpreted as an additional interchannel scattering process increasing the magnetoresistance.

High mobility two-dimensional electron gases (2DEGs) in GaAs/AlGaAs heterostructures are promising systems for the realization of far-infrared (FIR), frequency-selective photodetectors, because the photoresponse in strong magnetic fields is governed by the sharp ($\Delta E < 1$ cm^{-1}) and tunable cyclotron resonance ($\hbar\omega_c \propto B$, $\hbar$, ω_c, B are Planck's constant, the cyclotron frequency, and the magnetic field, respectively). The photoconductivity in such systems under quantum Hall conditions with a homogeneous electron density has been investigated by previous authors[1-4] and the interpretation of their data is based on the assumption that the redistribution of carriers between Landau levels (LLs) changes the resistivity tensor. In this letter we introduce a novel concept for a cyclotron resonance (CR) photoconductor based on the edge channel picture[5] of the quantum Hall effect (QHE). We show that the sensitivity of our devices composed of regions with different electron densities, can be increased by more than one order of magnitude compared to samples with homogeneous carrier density.

For small currents forced through the device (Hall voltage $\ll \hbar\omega_c/e$) the QHE can be described within the Landauer–Büttiker picture.[5,6] The current flows in one-dimensional channels (see Fig. 1) formed at the intersection of the Fermi energy and the bent-up Landau levels at the sample boundaries. The number of the edge channels is equal to the integer filling factor (fully occupied spin split LLs), given by $2\pi\hbar N_s/eB$. Here N_s is the carrier density and e the elementary charge. Ideal contacts to the 2DEG emit carriers up to their electrochemical potentials μ_j and each carrier reaching the contact is absorbed. Within this model, transport is described by balancing the outgoing and incoming carrier fluxes for each potential probe j using transmission and reflection coefficients.[7] Using negatively biased Schottky gates we can add potential barriers to the system to manipulate reflection and transmission coefficients between the contacts.[8] In Fig. 1 a situation is sketched with two spin degenerate edge channels, occupied in the ungated areas. A gate voltage V_g is applied to reduce the carrier density by a factor of 2 in the gated regions. This leads to the inner edge channel being reflected by each barrier and forming a closed loop in the region between the two barriers. If there is no interedge channel scattering (ideal adiabatic transport), the loop is totally decoupled from the transmitted edge channel. The current selectively injected into the outermost transmitted edge channel stays within this channel and the two barriers behave as a single one described by the ideal adiabatic resistance[7,8]

$$R^{\mathrm{ad}}_{14,23} = \frac{h}{e^2}\left(\frac{1}{\nu_g} - \frac{1}{\nu_b}\right). \qquad (1)$$

Here, the current is applied between contacts 1 and 4, whereas the voltage drop is measured between contacts 2 and 3. ν_g and ν_b are the integer filling factors under the gate and in the ungated region, respectively.

Recently, it has been shown[8] that one can realize adiabatic transport over macroscopic distances in such structures. Equation (1) also holds for the adiabatic resistance

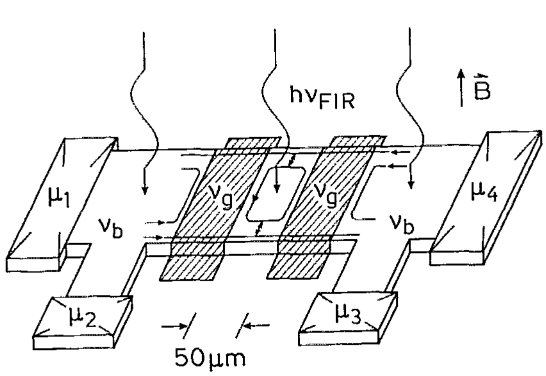

FIG. 1. Schematic layout of the photoconductor. Current contacts are denoted by the electrochemical potentials μ_1, μ_4, the potential probes by μ_2, μ_3. The hatched regions represent the Schottky gates with the filling factor $\nu_g = 2$ underneath. The filling factor in the ungated region is $\nu_b = 4$ (two spin degenerate Landau levels). The edge channels are sketched only in the vicinity of the Schottky gates. The double arrows between the edge channels symbolize the photon induced interedge channel scattering.

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across more than two barriers. However, the presence of interedge channel scattering breaks down the adiabatic transport and leads to an increase in resistance. The extreme limit is reached if the electrochemical potentials of the individual edge channels on each side of the sample are forced to be the same (equilibrated transport). This situation has been realized experimentally by adding contacts to the region inbetween the barriers.[8] The equilibrated resistance across N barriers is the series resistance across N single barriers

$$R^{eq}_{14,23}=N\cdot R^{ad}_{14,23}, \tag{2}$$

where $N=2$ for the situation sketched in Fig. 1.

The novel concept for FIR photoconductivity presented here is the photon-induced switching between adiabatic and equilibrated transport. This means that incident photons with the energy $\hbar\omega_c$ provide an effective interedge channel scattering mechanism to enlarge the longitudinal magnetoresistance. From the simple formulae above, it is evident that the photoresponse ΔR of the sample should be amplified by $(N-1)$. Equations (1) and (2) are strictly valid only for integer ν_g, ν_b, a condition which can not be generally fulfilled under resonance condition. Qualitatively, however, we expect the picture above to be valid also for noninteger filling factors.

We have used molecular beam epitaxy (MBE) grown GaAs/AlGaAs heterostructures with an electron density of $N_s=1.8$–$2.7\times10^{11}/\text{cm}^2$ and a mobility of $\mu=0.6$–$1.2\times10^6\ \text{cm}^2/\text{V s}$ at liquid-helium temperature. 100-nm-thick NiCr/Au films as Schottky gates are evaporated on top of the etched Hall bar geometry. These Schottky gates tune the electron density underneath. The sample is immersed in liquid helium and kept at a temperature of 1.3 K. The magnetic field perpendicular to the plane of the 2DEG is provided by a superconducting magnet. Parallel to the magnetic field the FIR beam of an optically pumped molecular gas laser is guided to the sample through lightpipes. For the measurements we used the $\lambda=211$, 232, 287, 311, and 392 μm laser lines. The intensities at the output of the lightpipes lie in the range from 10^{-6} W/cm^2 to 10^{-5} W/cm^2.[9] Above the samples a cold filter stops the blackbody radiation from the top of the cryostat. The photoconductivity measurements under FIR illumination are performed in ac technique. The laser is chopped with 830 Hz[10] while the ac current has a frequency of 13 Hz. This additional lock-in step eliminates photovoltaic signals, which have been discussed recently.[11]

As initial check for the FIR experiment we verified that the transport in our device is adiabatic by measuring the resistance according to Eqs. (1) and (2). For both integer and noninteger filling factors, resistances in the intermediate range between the ideal adiabatic and equilibrated values indicate adiabatic transport.

The striking performance of our photoconductor and the proof for the concept described above are demonstrated in Fig. 2. Here, photoconductivity spectra $\Delta R_{14,23}$ as a function of applied magnetic field are shown under three different gate bias conditions. The amplification by more than one order of magnitude of the photoconductivity signal is evident by comparing traces (a) and (b). In (a) a gate voltage of $V_g=-220$ mV is applied to both gates and we observe a huge positive peak in the photoresponse. The gate voltage is adjusted such that the filling factor in the gated areas is $\nu_g=1$ at the magnetic field, where the 232 μm laser line matches the CR. The filling factor in the ungated regions is $\nu_b=3.5$. These settings fulfill two experimentally verified conditions for the observation of an amplified photoresponse. First, at least two spin degenerate edge channels have to be occupied (filling factor $\nu_b>2$). Since the two lowest spin-resolved edge channels are only separated by a spin gap, no photosignal can be expected from the mechanism discussed above. Second, the filling factor under the gate ν_g has to be adjusted such that at least the innermost edge channel is reflected by the barriers.

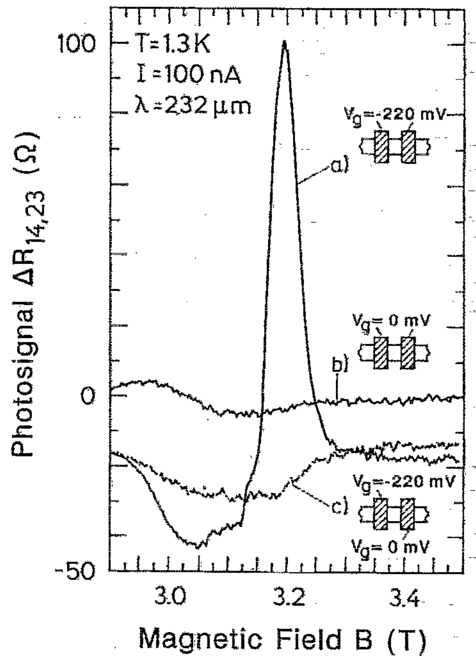

FIG. 2. Photoresponse $\Delta R_{14,23}$ of the two-gate finger configuration: (a) $V_g=-220$ mV simultaneously at gates 1 and 2, (b) no gate voltage at gates 1 and 2 (c) $V_g=-220$ mV applied to gate 1 only. The laser intensity, electron density, and the mobility are $I_{\text{FIR}}=10^{-6}\ \mu\text{W/cm}^2$, $N_s=2.7\times10^{11}/\text{cm}^2$, and $\mu=560\,000\ \text{cm}^2/\text{V s}$.

In (b) the gate voltage is removed and we observe only a weak negative signal. In this case the electron density across the device is homogeneous and we interpret the signal as resonant CR heating.[3] This is supported by the temperature dependence of the magnetoresistance measured in the same magnetic field range.

We have checked the concept of photon-induced interedge channel scattering by applying the gate voltage to only one gate. In this case decoupled innermost edge channels between the gates (closed loops) no longer exist and the measured resistance displays the equilibrated value. An amplified photoresponse is not expected, which is confirmed by trace (c), where the gate voltage is applied to gate 1 only. A similar curve is obtained for a bias applied to gate 2 only. The CR peak of (a) rises significantly from the underlying enhanced thermal underground induced by

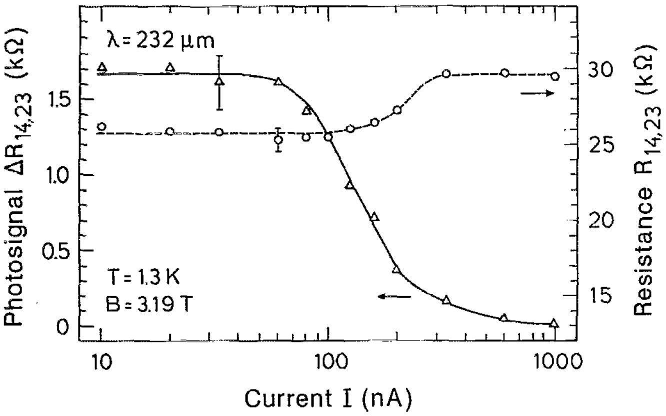

FIG. 3. Current dependence of the photoresponse $\Delta R_{14,23}$ and of the resistance $R_{14,23}$ without illumination for the same sample as in Fig. 2. The gate voltage is $V_g = -220$ mV, the filling factor in the gated and in the ungated regions are $\nu_g = 1$ and $\nu_b = 3.5$, and the laser intensity is $I_{\rm FIR} = 10^{-5}$ W/cm^2.

a single gate. We conclude that in the two-gate case, the CR photons raise the interedge channel scattering rate monitored by the huge increase of resistance. Similar amplification factors of the photoresponse have been observed for different samples and laser lines.

Further support for the concept of strongly enhanced photoconductivity in the adiabatic transport regime is evident from the current and temperature dependence of the photosignal. Both the raise in current and in temperature lead to an enhanced interedge channel scattering.[12] The possibility for photon-induced equilibration is therefore reduced and smaller photosignals are observed. To get the optimum performance at $T = 1.3$ K it is essential that the current is fixed well below 1 μA. This can be seen in Fig. 3, where it is evident that the photosignal drops when the resistance of the structure increases due to the enhanced interedge channel scattering. The accuracy of the resistance measurements is within 3%, whereas the accuracy of the photoresponse is estimated to 10%. Increasing the temperature from 1.3 to 4.2 K at a fixed current of $I = 100$ nA reduces the photosignal by a factor of 4. Both these observations are consistent with the corresponding transport measurements.[12]

To enlarge the photoresponse ΔR obtained from the two-gate configuration we have used an analogous structure to that of Fig. 1 but with four gates between the potential probes 2 and 3. Measurements on this structure show an amplification factor of about 2 compared to the two-gate system. For a laser intensity of 10^{-5} W/cm^2 and the very small active detector area between the gates we obtain responsitivities larger than 10^4 V/W[9] using the two-gate system and currents around 100 nA. Here, the increase in resistance is 7%. The resonance positions, both in the photoconductivity measurements and the corresponding transmission experiment, are within 0.2%.

Our concept of enhanced photoconductivity can also be applied to samples, where an anomalous geometrical scaling behavior of the longitudinal magnetoresistance is observed, that can be explained by adiabatic transport.[13] First experiments on these samples show an enhanced photosignal as expected.

In summary we have demonstrated that resonant photon-induced interedge channel scattering is the dominant photoconductivity contribution in the adiabatic transport regime of the presented multiple gate finger structures. This has been verified by comparing the photoresponse of the single gate structure (equilibrated transport) with the multiple gate structure (adiabatic transport). A further proof originates from the current and temperature dependence of the photosignal. We conclude that the already achieved responsitivities of more than 10^4 V/W favor the device for an application as a tunable narrow-band FIR detector.[14]

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[10] Since the time constant of the photoconductor is small in comparison to the duration of the laser pulse, we measure the first Fourier component of the change in resistance.
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