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Huge Photoresponse in the Non-Local Transport Regime.

E. DIEßEL (*), G. MÜLLER (*), D. WEISS (*), K. VON KLITZING (*), K. PLOOG (**)
H. NICKEL (***), W. SCHLAPP (***) and R. LÖSCH (***)

(*) *Max-Planck-Institut für Festkörperforschung*
Heisenbergstraße 1, D-70569 Stuttgart 80, Germany
(**) *Paul-Drude-Institut - Hausvogteiplatz 5-7, D-1086 Berlin, Germany*
(***) *Forschungsinstitut der Deutschen Bundespost - D-6100 Darmstadt, Germany*

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Abstract. – We present experiments showing a significantly increased FIR photosensitivity of a high-mobility two-dimensional electron gas when transport in the quantum Hall regime is non-local, *i.e.* when scattering between adjacent edge channels is suppressed on macroscopic length scales. The resonant absorption under cyclotron resonance conditions enhances interedge channel scattering processes leading to a huge resistance maximum in the longitudinal resistance and to the suppression of the non-local resistance.

The discrete energy spectrum of a two-dimensional electron gas (2DEG) in strong magnetic fields seems to be an interesting tunable photodetector since the electrical conductivity σ_{xx} vanishes (as in an intrinsic semiconductor) if the Fermi energy lies in an energy gap. A maximum change of transmission is observed when the cyclotron energy $\hbar\omega_c = \hbar eB/m^*$ matches the energy $h\nu$ of the incident FIR radiation. In principle photoconductivity measurements are more sensitive in comparison to transmission experiments since the electron gas itself acts as a detector. In this type of experiment the change of the resistance of the sample in the presence of radiation is analysed. This has been demonstrated in spin resonance experiments in a 2DEG [1], where conventional microwave transmission or reflection techniques are not sensitive enough. In previous FIR photoconductivity experiments in GaAs-AlGaAs heterojunctions the obtained resonances were small (a change in the resistivity of 0.5% for a FIR intensity of $10^{-4}\,\mathrm{W/cm^2}$ has been reported [2]) and difficult to interpret. The very short lifetime of excited electrons leads to a very small variation in the occupation of the different Landau levels. Therefore the electrical resistance does not change drastically. This is true as long as the experiments are performed under experimental conditions where the transport is *local*, which means that the resistances can be described by the resistivity tensor components ρ_{xx} (longitudinal resistance) and ρ_{xy}

(Hall resistance). However, in the non-local regime where the measured electrical signals are dominated by an *electric-current–induced* non-equilibrium [3] in the occupation between Landau levels, the cyclotron resonance process can lead to a drastic change of the non-equilibrium situation and therefore to a strong photosignal.

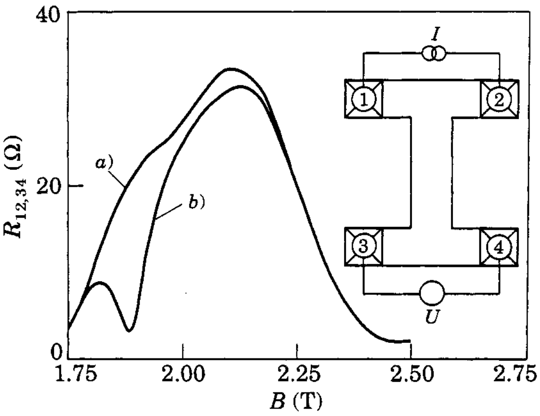
In this letter we demonstrate that the resistance increases by 700% under resonant (low intensity) FIR irradiation if the experiments are performed in the *non-local* transport regime.

Non-local transport phenomena cause magnetotransport anomalies at low temperatures and excitation currents of typically less than 1 μA. In this regime, Shubnikov-de Haas (SdH) oscillations of a high-mobility 2DEG show features like an asymmetric lineshape [4], a strong current dependence [5] and a non-monotonic increase of the SdH amplitudes with increasing magnetic field. The longitudinal resistance R_{xx} does not scale with the aspect ratio l/w of the Hall bar, with l being the voltage probe separation and w the width of the Hall bar [6-8]. Therefore the diagonal element of the resistivity tensor ρ_{xx} is not an appropriate quantity to describe the resistance. The assumption of a local relationship between the current density and the electric field breaks down; one has to use global resistances or conductances. An appropriate picture to describe the observed phenomena is the edge channel model [9, 10]. Within this model the current flow and the electrochemical potentials of the contacts are connected by transmission and reflection probabilities of states at the Fermi energy. These states correspond classically to skipping orbits moving along the boundary of the sample. The number of edge channels is equal to the number of occupied Landau levels.

An important property of edge channel transport is the suppression of interedge channel scattering [11-14] which is caused by a flat lateral confining potential. Due to this suppression, a selective population of the edge channels can be maintained over macroscopic distances. This is the origin of the above-mentioned transport anomalies investigated in a variety of experiments [15-18]. Transport in this regime is usually denoted as adiabatic if the Fermi level is between two bulk Landau levels, and non-local otherwise. In contrast, in the equilibrated transport regime, all edge channels (on one side of the device) have the same electrochemical potential and therefore carry the same amount of current. Recent experiments demonstrated that adiabatic transport behaviour is also observed when spin-flip scattering [19] or scattering between fractional edge channels is suppressed [20].

The samples investigated here are high-mobility, modulation-doped AlGaAs/GaAs heterostructures with carrier densities ranging between $1.8 \cdot 10^{11}\ \mathrm{cm}^{-2}$ and $2.3 \cdot 10^{11}\ \mathrm{cm}^{-2}$ and mobilities between $720\,000\ \mathrm{cm}^2/\mathrm{Vs}$ and $1.6 \cdot 10^6\ \mathrm{cm}^2/\mathrm{Vs}$ at 4.2 K. Hall-bar mesas (see inset of fig. 1 and 2) were patterned using optical lithography and wet chemical etching. We used alloyed AuGe/Ni layers to contact the 2DEG. In a typical experiment the four-point resistance $R_{ab,\,cd}$ is measured at $T = 1.3$ K. We apply a low-exitation a.c. current (≈ 17 Hz, $I \leqslant 100$ nA) between contact a and b and measure the voltage drop between the probes c and d using conventional lock-in techniques. The magnetic field is always perpendicular to the 2DEG. The sample, mounted in the centre of a superconducting magnet, is positioned at the end of a light pipe in order to illuminate the sample with c.w. FIR (70–871 μm) radiation. We used a molecular-gas laser pumped by a CO_2 laser. The FIR intensity at the sample position is below $10\ \mu\mathrm{W/cm}^2$. A polyethylene filter mounted above the sample blocks room temperature radiation.

In order to study the photoconductivity in the non-local transport regime we measured the *non-local resistance* $R_{12,\,34}$ (fig. 1) with FIR radiation ($\lambda = 392$ μm) switched off (trace a)) and on (trace b)). The currend applied between contacts 1 and 2 (fig. 1, inset) is separated by 190 μm from the potential probes 3, 4 and «classically» one expects a vanishing signal between the voltage probes. Here «classically» denotes a situation involving strong interedge channel scattering. The data of fig. 1 (trace a)), however, display a pronounced



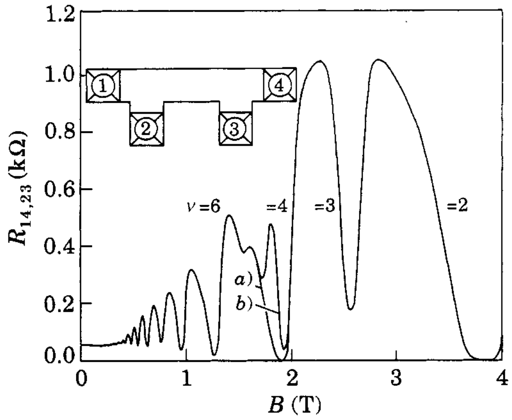


Fig. 1. Fig. 2.

Fig. 1. – Non-local four-point resistance $R_{12,34}$ as a function of the magnetic field. The inset shows schematically the sample layout ($l/w = 1.9$). The investigated 2DEG has a carrier density N_s of $2.3 \cdot 10^{11}\ \mathrm{cm}^{-2}$ with a mobility μ of $720\,000\ \mathrm{cm}^2/\mathrm{Vs}$ at $T = 4.2$ K. Non-local resistance before (trace a)), and during (trace b)) illumination with a FIR laser with $\lambda = 392\ \mu\mathrm{m}$; $T = 1.3$ K, $I = 100$ nA.

Fig. 2. – Longitudinal resistance $R_{14,23}$ *vs.* magnetic field. Trace a) is measured before and trace b) during FIR illumination ($\lambda = 392\ \mu\mathrm{m}$, $T = 1.3$ K, $I = 100$ nA). The inset sketches the layout of the device. ($N_s = 1.8 \cdot 10^{11}\ \mathrm{cm}^{-2}$, $\mu = 1.6 \cdot 10^6\ \mathrm{cm}^2/\mathrm{Vs}$).

resistance peak in the magnetic-field range between filling factor 6 (three Landau levels occupied) and filling factor 4 (two Landau levels occupied). This behaviour is a well-known manifestation of non-local phenomena [21]. A non-equilibrium population of the edge channels in the presence of backscattering is the origin of the detected voltage $V_{3,4}$, decaying with a characteristic equilibration length. The equilibration length is the mean distance between two interedge channel scattering events. Equilibration lengths of up to 1 mm [19, 22, 23] have been obtained experimentally. Under FIR radiation we find a minimum in $R_{12,34}$ (trace b)) at the cyclotron resonance condition $eB/m^* = 2\pi c/\lambda$ indicating that the non-local resistance is drastically reduced. Here, $\lambda = 392\ \mu\mathrm{m}$ is the wavelength of the FIR laser and c is the velocity of light.

The increased FIR sensitivity in the non-local regime can also be seen in the longitudinal magnetoresistance. Figure 2 demonstrates the striking performance of this simple kind of FIR detector. Here, the longitudinal resistance $R_{14,23}$ (see insert) is shown, measured with a current of 100 nA at a temperature of 1.3 K (trace a)). Illumination of the sample with the 392 μm FIR line results in trace b). Over a wide magnetic-field range the resistances measured with and without FIR illumination are identical. Striking deviations occur around ~ 1.8 T, where an additional peak in the longitudinal resistance emerges at the cyclotron resonance position $B = 1.82$ T. Comparison of photoconductivity data with corresponding cyclotron resonance transmission experiments on a variety of samples show no significant shift in the resonance position.

To observe such a huge photosignal, it is essential to be in the non-local transport regime. This is not the case at 4.2 K due to the temperature-induced strong interchannel scattering. Illumination of the sample with visible light from a light-emitting diode (LED) also destroys the photosensitivity. This is in accordance with previous transport experiments [23]. A brief

LED illumination steepens the lateral confining potential, the interedge channel scattering increases and causes a crossover from non-local to local transport.

We have done similar experiments using 10 FIR laser lines in the wavelength range between 70 μm and 871 μm to obtain information about the underlying mechanism. The resonant peak in fig. 2 could in principle be attributed to a resonant heating effect of the whole system (electrons in equilibrium with the lattice) since the SdH maximum at filling factor ~ 4.5 increases with increasing temperature (heating of the sample). Using the 232 μm FIR laser line, cyclotron resonance absorption takes place at $B = 3.14$ T for the sample of fig. 2. Again we find an increased resistance at the cyclotron resonance. Here, in contrast, the resistance *decreases* with *increasing* temperature. This demonstrates that the resistance change is not simply due to an increased sample temperature. The analysis of the photosignal using the 287 μm line at $B = 2.55$ T points in the same direction. Here, the temperature dependence of the resistance at the resonance field is at least three times larger than that of the resonance shown in fig. 2. Nevertheless, the photoresponse is considerably smaller. For filling factors smaller than one, non-local effects become unimportant at 1.3 K, since non-local behaviour requires decoupled fractional edge channels. The fact that we have not observed a pronounced photosignal for 70 μm is consistent with this.

By increasing the applied current, non-local effects are drastically reduced because the interedge channel scattering rate increases with increasing difference in the electrochemical potentials [24-26]. Therefore an investigation of the current dependence of the photoconductivity provides additional information whether the huge photosensitivity is due to non-local transport or not. In fig. 3 the current dependence of the resonance of fig. 2 is shown for magnetic fields ranging from 1.5 T to 2.1 T. For currents smaller than 250 nA, no current dependence can be seen. A further increase in the current, however, results in an increase of the SdH peak height and a reduction of the FIR signal at $B \approx 1.8$ T. From other experiments it is well known that the corresponding non-local four-point resistance and therefore the decoupling of the innermost edge channel are simultaneously reduced [23]. For currents larger than 5 μA, we no longer observe a pronounced additional resistance maximum at the

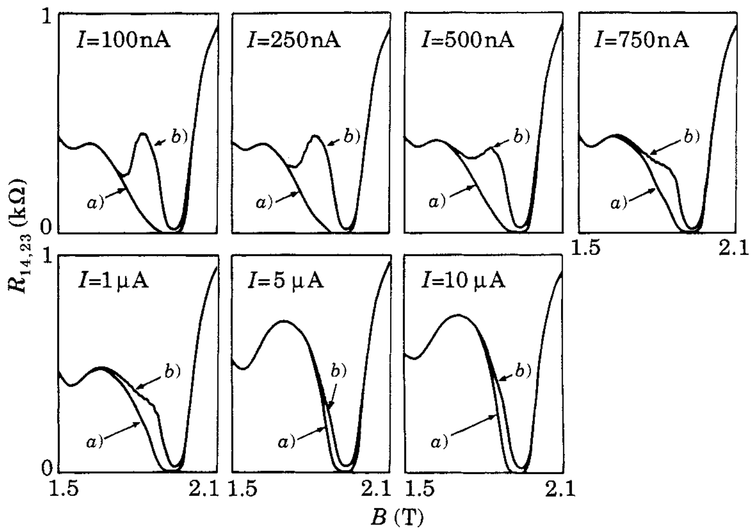


Fig. 3. – $R_{14,23}$ *vs.* magnetic field taken from the sample of fig. 2 ($T = 1.3$ K, $\lambda = 392$ μm) for different probe currents. The resonant resistance peak vanishes with increasing current.

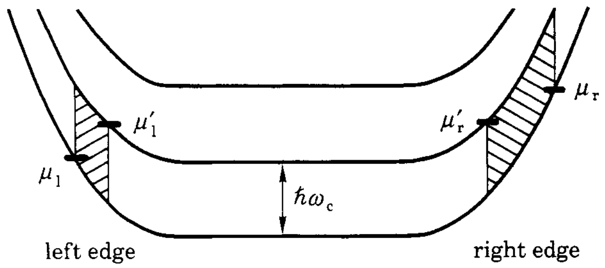


Fig. 4. – Sketch of the positions of the chemical potentials μ on the right (index r) and left (index l) side of a Hall bar for perfect adiabatic transport. Under such conditions the edge states of the upper Landau level (index ′) are completely decoupled from the edge states of the lower one ($\mu'_r = \mu'_l$). Hence no current is carried by the states of the upper Landau level. The optical pumping of electrons into the higher edge channels is more effective on the right side of the sample (see hatched areas), hence raising μ'_r. Now a net current is carried by the upper Landau level pushing the system towards equilibrated transport.

resonance magnetic field. The small change in the resistance is a consequence of the relatively weak temperature dependence under equilibrated transport conditions. This seems to be the origin of why the photoconductivity data reported previously display no pronounced resonances. All these experiments were carried out in the equilibrated transport regime. Under non-local transport conditions the resistance change at the cyclotron resonance magnetic field is significantly larger.

We have demonstrated that cyclotron resonance photons can suppress non-local transport effects which lead to drastic changes in the measured resistances. We have checked that an increased interedge channel scattering rate due to an increased temperature [26-28], or higher currents [24-26] or by tuning the edge potential [23] strongly reduces the photosensitivity.

A possible explanation based on the simplified one-electron picture close to the edges is connected with a «vertical» optical transition between edge channels followed by strong intrachannel scattering. Whereas interedge channel scattering is suppressed in high magnetic fields, intrachannel scattering is not [11]. The excited carriers relax through intrachannel scattering processes, which are accompanied by the excitation of edge magnetoplasmons and the emission of acoustic phonons. Such vertical transitions are expected to push the system closer towards equilibrium since now the upper Landau level also carries some net current (see fig. 4). A recent experiment where the photoresponse was measured spatially resolved [29] is consistent with our simple picture. It is obvious that this picture cannot be correct for a quantitative interpretation as long as the more realistic description of the edge channels as a series of compressible and incompressible stripes is ignored [30] and collective excitations are not discussed. However, it seems to be clear that the huge photoresponse presented in this paper originates from a strongly reduced non-equilibrated transport due to cyclotron resonance.

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