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Collective response in the microwave photoconductivity of Hall bar structures

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We have investigated the microwave photoconductivity of 100-μm- and 50-μm-wide Hall bars fabricated from $GaAs/Al_xGa_{1-x}As$ heterostructures. We found resonant responses at frequencies f_{res} with $f^2_{\mathrm{res}}(B)=f^2_{\mathrm{res}}(B=0)+f^2_c$, where f_c is the cyclotron frequency of the two-dimensional electron gas in the perpendicularly applied magnetic field B. This shows that the photoresponse is dominated by collective plasmon excitations confined within the width of the Hall structure.

For research on mesoscopic systems with microwave or far-infrared radiation (FIR), where sample sizes are too small for transmission or absorption spectroscopy, photoconductivity experiments offer a highly sensitive alternative. In this work we have studied the photoconductivity of high-mobility two-dimensional electron systems (2DES's) in Hall bar geometries fabricated from modulation-doped $GaAs/Al_xGa_{1-x}As$ heterojunctions. Former reports of photoconductivity experiments on 2DES in $GaAs/Al_xGa_{1-x}As$ heterostructures describe distinct resonances, which were achieved by FIR excitation using wavelengths between 96 and 186 μm and magnetic fields of up to 20 T.[1,2] A comparison between FIR transmission experiments and photoconductivity experiments[3] shows that the peak positions of the resonances are the same within an error of 1%. Usually, these resonances were described as cyclotron resonances (CR's) and were observed in photoconductivity experiments in the integer quantum-Hall regime, near the maxima of ρ_{xx}, but not directly at $\rho_{xx}=0$ or in the Hall plateaus. Recently, a significantly increased FIR photosignal reflected the CR in the nonlocal transport regime.[4] A successful example of a photoconductivity experiment with microwaves was the detection of electron spin resonance in a 2DES.[5,6]

Resonant photoresponse was previously explained in terms of electron transitions between either Landau levels or subbands.[7] The main effect described there is resonant heating of electrons, which is also called a bolometric behavior of the 2DES. The resonant absorption of radiation power leads to a temperature change ΔT of the electron gas, which causes a change in the conductivity $\partial\sigma$ and, therefore, produces a photosignal which depends on $(\partial\sigma/\partial T)\Delta T$. In the edge channel experiments[4] the microscopic origin of the photoresponse was ascribed to an enhanced transition rate of electrons between edge channels,[8,9] thus pointing towards the important role of the sample's boundaries.

In our experiments we found what initially appeared to be an unusual frequency response in the magnetic field, which was shifted with respect to the CR frequency. We show that this response is dominated by a collective confined plasmon excitation with the confinement length determined by the width of the Hall bar.

Two-dimensional plasmons[10,11] have been studied previously using grating couplers in FIR experiments.[12–14] The grating coupler provides a periodic modulation of the incident electric field in the (xy) plane of the 2DES. This allows the FIR radiation to couple with plasmons of a wave vector $k_x^n=n2\pi/a$, where a is the grating period and $n=1,2,\ldots$ an integer number. In a magnetic field applied perpendicularly to the 2DES, the plasmons evolve to magnetoplasmons,[11] which have been experimentally observed.[13] Our experiments presented here are quite different from previous ones since we do not use any grating coupler. In this paper we can show that the boundaries of the Hall bar themselves provide the coupling and determine the frequency of the confined plasmons.

Our experiments were performed on conventional Hall bar geometries, some with six contacts, others with eight contacts, as shown in Fig. 1. This structure has been designed with two different Hall bar widths w, namely, 100 and 50 μm, in order to study the microwave response of two different widths on one sample. The distance l between the contact pairs (2,3) and (3,4) was 900 μm. The Hall bar samples were fabricated from a high-mobility, modulation-doped $GaAs/Al_xGa_{1-x}As$ heterostructure. Most of the results are shown for a sample with an electron density N_s of 2.3×10^{11} cm^{-2}, as determined from the periodicity of the Shubnikov–de Haas oscillations, and with a mobility $\mu=1.2\times10^6$ cm^2/V s at $T=1.3$ K in

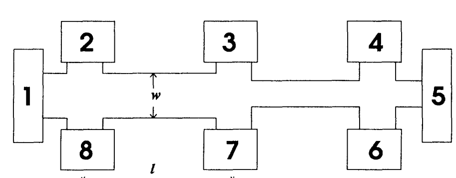

FIG. 1. Sketch of the Hall bar geometry used in the microwave photoconductivity experiments. The Hall bar width w is 100 μm on the left (between the contacts 2 and 3) and 50 μm on the right (between the contacts 3 and 4). The length l between the contacts (2,3) and (3,4) is 900 μm.

the dark. The Hall bars were produced using optical mask lithography and wet chemical etching of the mesa structures. The contacts to the 2DES are alloyed AuGe/Ni contacts with a CrAu layer on top to which bonding wires were attached.

For the measurements we have used a double-modulation technique. A sinusoidally modulated current I with an amplitude between 10 and 20 μA, driven through either the contact pairs (2,3) or (3,4), was modulated with the frequency $f_{\mathrm{ac}} = 14.5$ Hz. The microwave radiation was chopped with the frequency $f_{\mathrm{mw}} = 1.3$ kHz. This technique has the advantage that the difference in the voltage drop with and without microwaves can be measured directly. The in-phase voltage induced by the microwave was measured at the contact pairs (8,7) or (7,6) (see Fig. 1). To measure the induced photovoltage we used two lock-in amplifiers in series (see also Ref. 15): The first lock-in amplifier locks to the higher frequency $f_{\mathrm{mw}} = 1.3$ kHz, while the second one probes the output channel of the first lock-in at a reference frequency f_{ac} of 14.5 Hz. The microwaves were provided by several tunable backward wave oscillators covering the frequency range from 70 up to 170 GHz. The microwaves were guided in oversized waveguides into the center of a cryostat, containing a superconducting magnet, in which the Hall bar sample was mounted. The magnetic field was applied perpendicularly to the 2DES. The experiments were carried out at a temperature of 1.3 K.

In Fig. 2, we have plotted the magnetoresistance ρ_{xx} without microwave radiation and the change of the resistance $\Delta R_{xx}(B)$ with an incident microwave of frequency $f = 90.7$ GHz. A significant resonance peak is observed in ΔR_{xx} at $B = 0.15$ T. The onset of the Shubnikov–de Haas oscillations for $B = 0.2$ T shows that for all our measurements the relation $\omega_c \tau \approx 1$ holds, where ω_c is the cyclotron frequency and τ the electron-scattering time.

The experimental dependencies of the photoresponse versus magnetic field taken from the 50- and 100-μm-wide Hall bars are shown in Fig. 3 for several fixed microwave frequencies. We observe well-pronounced resonances which shift with increasing frequency to higher magnetic field. From experiments on samples with different lengths l between the voltage contacts of the Hall bar, we find that the amplitude of the photosignal is proportional to l. This suggests that the signal does not originate from any material imperfections or from the Ohmic contact region where scattering due to the transition from the three-dimensional to the two-dimensional electron system occurs. In Figs. 3(a) and 3(b), it can be seen that the photoconductivity signals are clearly pronounced over a large magnetic-field range and the corresponding frequency range. Furthermore, we find that the induced voltage does not change if the current is applied to the contact pair (1,5).

If we plot these resonances f vs B_{res}, as shown in Fig. 4, we find that the resonance position does not coincide with the CR of electrons in an infinitely large 2DES, i.e., $f_c = eB/2\pi m^*$, where $m^* \approx 0.07 m_e$ is the effective mass

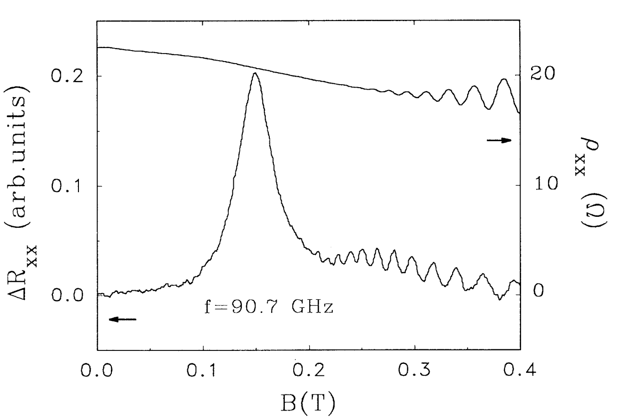

FIG. 2. Photoconductivity response ΔR_{xx} (lower curve, left scale) for a fixed microwave frequency $f = 90.7$ GHz and magnetoresistance ρ_{xx} without microwave radiation (upper curve, right scale) vs B for the 100-μm-wide Hall bar. The temperature was 1.3 K.

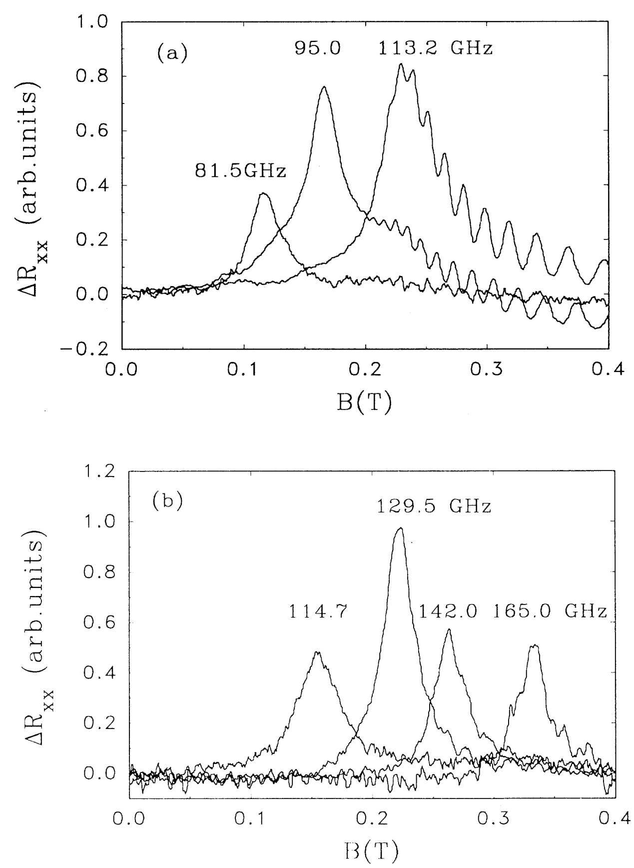

FIG. 3. Graph of measured photoconductivity signals of the two Hall bars with (a) $w = 100$ μm and (b) $w = 50$ μm vs B for several fixed frequencies. The peak position shifts to higher B with increasing frequency f. The signal for different frequencies is not normalized since in our experimental setup it was not possible to achieve exactly the same microwave field strength in the plane of the sample.

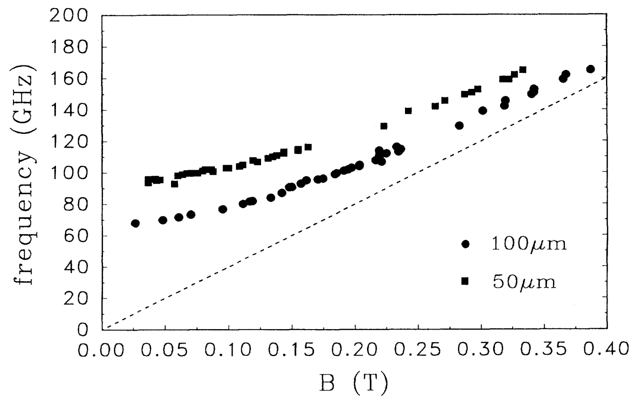

FIG. 4. Dispersion of the incident microwave frequency f vs the magnetic field position B_{res} of the photoconductivity signal. The square and circle symbols mark the experimentally determined resonance frequencies f_{res} at B_{res} of the 50- and 100-μm-wide Hall bar, respectively. The dashed line displays the cyclotron frequency $f_c = eB/2\pi m^*$ with $m^* = 0.07m_e$, which would be expected in an infinitely large 2DES, but is not observed in our experiment.

in units of the free electron mass m_e. The resonance frequency is definitely higher than the CR and increases with decreasing width of the Hall bar. In Fig. 5, the experimental resonance positions are plotted on quadratic scales f_{res}^2 vs B^2. From this we find that the resonance positions follow the relation $f_{res}^2 = f_{res}^2(w, B=0) + f_c^2$, where w is the different widths of 50 and 100 μm, respectively. The extrapolation of the data to $B=0$ gives the resonance frequencies $f_{res}(w=50\ \mu\text{m}) = 95.4$ GHz and $f_{res}(w=100\ \mu\text{m}) = 67.6$ GHz. We can also obtain then the ratio $f_{res}(w=50\ \mu\text{m})/f_{res}(w=100\ \mu\text{m}) = \sqrt{2}$. From the slope $\Delta(f_{res}^2)/\Delta(B^2) = (e/2\pi m^*)^2$ in this figure we extract an $m^* = 0.070m_e$, which is the effective mass of GaAs.

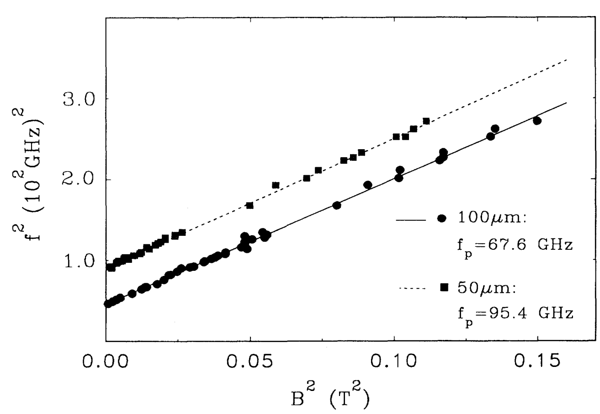

FIG. 5. Data from Fig. 4 plotted on quadratic scales, i.e., f_{res}^2 vs B_{res}^2. The plasmon frequencies $f_{res} = 95.4$ and 67.6 GHz for the 50- and the 100-μm-wide Hall bars, respectively, are obtained from extrapolation of the data to $B=0$. From the slope one can determine an effective mass $m^* = 0.070m_e$.

This quadratic behavior and the frequency ratio of $\sqrt{2}$ indicate that the photoresponse is determined by collective effects. The frequency $\omega_p = 2\pi f_p$ of plasmon oscillations in an infinitely large 2DES is given by[10]

$$\omega_p^2 = \frac{N_s e^2}{2\varepsilon_{\text{eff}}\varepsilon_0 m^*} k \ , \tag{1}$$

where k is the plasmon wave vector, N_s the 2D electron density, and ε_{eff} the effective dielectric constant. If the thickness of the $Al_xGa_{1-x}As$ and the GaAs cap layer is small compared to $1/k$, which is the case in our experiments, ε_{eff} is well approximated by $\varepsilon_{\text{eff}} = \frac{1}{2}(\varepsilon_{\text{GaAs}} + \varepsilon_{\text{vac}})$, where $\varepsilon_{\text{vac}} = 1$ and $\varepsilon_{\text{GaAs}} = 12.8$. In the presence of a perpendicular magnetic field the magnetoplasmon frequency ω_{mp} is[11,13,14]

$$\omega_{\text{mp}}^2(B) = \omega_p^2(B=0) + \omega_c^2 \ , \tag{2}$$

where $\omega_c = eB/m^*$ is the CR frequency and $\omega_p^2(B=0)$ is defined in Eq. (1). However, in our Hall bars we do not have freely propagating plasmons; our experiments rather suggest that we observe plasmons confined by the width of the Hall bar. For a quantitative explanation we use a very simple model and assume that just one-half of the plasmon wavelength fits into this width w, such that $k = \pi/w$. With this assumption we calculated for $w = 50$ μm an $f_p(B=0) = 109.1$ GHz and for $w = 100$ μm an $f_p(B=0) = 77.2$ GHz using $N_s = 2.3 \times 10^{11}$ cm^{-2} and $\varepsilon_{\text{eff}} = 6.9$. These values are in good (about 10%) agreement with the experimental results of 95.4 and 67.6 GHz for $w = 50$ and 100 μm, respectively, which tends to support our explanation. We note that the ratio of the plasmon frequencies $\omega_p(w=50\ \mu\text{m})/\omega_p(w=100\ \mu\text{m})$ derived from Eq. (1) is equal to $\sqrt{2}$ as observed in the experiments. We have also measured additional Hall bars and found a similar good agreement between the experiments and the simple confined plasmon model. For example, from a Hall bar with $w = 100$ μm, $N_s = 3.3 \times 10^{11}$ cm^{-2}, and $\mu = 6.5 \times 10^5$ cm^2/V s, we obtained an experimental value $f_{res}(B=0) = 81.2$ GHz and a calculated value $f_p(B=0) = 90.5$ GHz.

We would like to make some additional remarks: (i) The plasmons we observed here have a wavelength λ of 200 μm. To our knowledge these wavelengths are much longer than in previous experiments, e.g., in Ref. 16. (ii) The agreement between the experimental plasmon frequency and the value calculated within our simple confined plasmon model is good, however not perfect. We find consistently that the calculated value is higher than the experimental one. Here, our model certainly needs improvement, i.e., one has to calculate more accurately the correct electromagnetic fields in the region surrounding a bar of finite width. These fields are of course modified as compared to the infinite plane of the 2D plasmons being considered in Eq. (1). Note that the experimental frequency ratio $f_{res}(w=50\ \mu\text{m})/f_{res}(w=100\ \mu\text{m})$ is exactly $\sqrt{2}$, thus, it seems that these corrections scale in proportion to $1/w$. (iii) In principle, one expects for a finite size sample at least two resonances: for instance, for a rectangularly shaped "dot" with lengths l

and widths w the frequencies $f_l(k=\pi/l)$ and $f_w(k=\pi/w)$ in our simple model. The lower frequency decreases with increasing magnetic field and becomes an edge magnetoplasmon with a frequency determined by the circumference of the dot.[16] Our experiments suggest that the dominant response is determined by the oscillation of charge perpendicularly to the length of the Hall bar. This shows that for our sample geometries the frequencies f_l are small compared to f_w. (iv) In a comparable microwave photoconductivity experiment in a 2DES with periodic antidot potential,[15] the resonance frequencies at the corresponding weak magnetic fields are quantitatively smaller than the CR frequency. This would correspond to an augmented effective mass $m^* \approx 0.09 m_e$. In contrast, we find in our experiments increased resonance frequencies compared to the CR originating from the excitation of magnetoplasmons confined within the width of the Hall bar.

In conclusion, we have performed photoconductivity experiments using microwaves to demonstrate that the resonant response of a 2DES in a standard Hall bar geometry has the character of a collective plasmon excitation with a plasmon localization length governed by the width of the Hall bar.

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