

# Circular Polarization Dependent Study of the Microwave Photoconductivity in a Two-Dimensional Electron System

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The polarization dependence of the low field microwave photoconductivity and absorption of a two-dimensional electron system has been investigated in a quasi-optical setup in which linear and any circular polarization can be produced in-situ. The microwave induced resistance oscillations and the zero resistance regions are notably immune to the sense of circular polarization. This observation is discrepant with a number of proposed theories. Deviations only occur near the cyclotron resonance absorption where an unprecedented large resistance response is observed.

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The recent discovery of zero resistance induced by microwaves [1, 2, 3, 4, 5, 6, 7] in ultra-clean two-dimensional electron systems (2DES) over extended regions of an applied perpendicular magnetic field  $B$  has revived the general interest in microwave photoconductivity and has triggered a remarkably large and diverse body of theoretical works. Original photoconductivity experiments on lower quality samples only revealed the intuitively expected feature due to resonant heating at the cyclotron resonance or more accurately — due to the finite size of the sample — at the combined dimensional plasmon cyclotron resonance frequency [8]. Unanticipated  $1/B$ -periodic oscillations with minima close to the harmonics of the cyclotron resonance first entered the scene [9, 10]. They later turned out precursors of the zero resistance regions. The majority of theoretical accounts subdivides the argumentation to explain the zero resistance into two main points. First some mechanism produces an oscillatory photoconductivity contribution that may turn the overall dissipative conductivity negative near the minima. Examples of proposed mechanisms include spatially indirect inter-Landau-level transitions based on impurity and phonon scattering [11, 12, 13, 14, 15, 16, 17, 18, 19], the establishment of a non-equilibrium distribution function [3, 20, 21, 22], photon assisted quantum tunneling [23] and non-parabolicity effects [24]. Second, it is argued that negative values of the dissipative conductivity render the initially homogeneous system unstable [25, 26] and an inhomogeneous domain structure develops instead [26, 27, 28, 29, 30], which results in zero resistance in experiment. Some theoretical work does not invoke an instability driven formation of domains to explain zero resistance. It relies either on radiation induced gaps in the electronic spectrum [31] or on the microwave driven semi-classical dynamics of electron orbits [32].

The sheer multitude of models and their divergence un-

derline that no consensus has been reached on the origin of this non-equilibrium phenomenon. In order to assist in isolating the proper microscopic picture, a detailed polarization dependent study was carried out. In previous work, microwaves were guided to the sample with oversized rectangular waveguides [1, 2, 3, 4, 5] or with a coaxial dipole antenna [6, 7]. These approaches do not permit control over the polarization state. Rectangular waveguides operated in their fundamental mode allow a comparison between the two orthogonal linear polarization directions, although usually not without warming up the sample. Here, we adopt a quasi-optical approach [33] to guide the microwaves onto the sample and to produce any circular or linear polarization. Circular polarization offers the perspective of activating and deactivating the cyclotron resonance absorption by reversing the rotation for a given  $B$ -field orientation. Knowledge of the influence of the polarization on the microwave induced resistance oscillations may turn out an important litmus test for theoretical models. For the non-parabolicity model for instance these oscillations do not survive when switching to circular polarization [24]. Theories based on a non-equilibrium distribution function and on phonon- or impurity assisted indirect transitions predict oscillations for both senses of circular polarization, however with substantially different amplitudes [19, 21]. Other models have assumed linear polarization and have not been analyzed for the case of circular polarization [23, 31, 32]. Here, we establish in experiment that these oscillations are entirely insensitive to the polarization state of the incident radiation.

A  $4 \times 4$ -mm<sup>2</sup> van der Pauw sample is glued on a 25  $\mu$ m thick Mylar foil, which itself has a hole of 3 mm at the location of the sample. This arrangement is mounted in the Faraday geometry in the variable temperature insert of an optical cryostat with a split coil. The insert was operated down to approximately 1.7-1.8 K during the experi-

ments. The cryostat is equipped with 100  $\mu\text{m}$  thick Mylar inner and outer windows. The outer windows are covered with black polyethylene foil to block visible light. The sample of which we show data here consists of a double-sided modulation doped 30 nm wide GaAs quantum well surrounded by  $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$  barriers. It exhibits an electron mobility in excess of  $18 \times 10^6 \text{ cm}^2/\text{Vs}$  without prior illumination for a density of  $2.6 \cdot 10^{11}/\text{cm}^2$ . Backward wave oscillators generate quasi-monochromatic radiation (bandwidth  $\Delta f/f \approx 10^{-5}$ ). Our studies focused on frequencies from 100 GHz up to 350 GHz.

Schematic drawings of the quasi-optical setup [33] are depicted in Fig. 1. The radiation passes through three dense wire grids with a periodicity of 50  $\mu\text{m}$  and a wire thickness of 20  $\mu\text{m}$  ( $P_1$ ,  $P_2$ ,  $P_3$ ) as well as a so-called polarization transformer (PT). The latter consists of the fixed wire grid  $P_4$  with the same specifications and a mobile metallic mirror placed in parallel to grid  $P_4$  at a tunable distance  $d$ . Grid  $P_4$  reflects the component of the incident radiation beam with the electric field vector aligned along the wires. The remainder of the beam with an electric field vector polarized perpendicular to the wires passes undisturbed through the grid. It is reflected by the mirror instead and hence acquires an additional phase shift  $\Delta\phi = 2\pi d\sqrt{2}/\lambda$ . Grids  $P_1$ ,  $P_2$  and  $P_3$  serve to continuously adjust the overall intensity as well as to ensure equal intensities of the radiation components with electric field vectors aligned with and perpendicular to wire grid  $P_4$ , so that proper adjustment of  $d$  (or  $\Delta\phi$ ) yields linear or any circular polarization state. The radiation intensity can also be reduced with fixed attenuator  $A_1$  or blocked with absorber  $A_2$ . The quartz lens  $L_2$  focuses the radiation onto the sample, while quartz lens  $L_3$  recollimates the beam after transmission through the cryostat. The degree of circular polarization  $\eta$  is verified at various locations along the beam by monitoring the power with a pneumatic (Golay) detector (used in conjunction with the chopper) and an additional dense wire grid  $P_5$  for two orthogonal directions ( $\parallel$  and  $\perp$ ) of the electric field vector:  $\eta = 1 - |P_\perp - P_\parallel|/(P_\perp + P_\parallel)$ . Typical values for the circular polarization purity have been included in Fig. 1. After the first quartz lens, but before entering the cryostat,  $\eta$  exceeds 98%. The warped Mylar windows and the quartz lenses deteriorate somewhat the polarization status, but the circular polarization character remains better than  $\eta > 92\%$  after transmission through the cryostat and sample holder in the absence of a sample. Preliminary experiments, not shown here, were also carried out in a setup with a circular microwave waveguide and a polarizer at room temperature mounted at the entrance of the waveguide. With this approach however the circular polarization degree was limited to 70% or less, presumably due to imperfections of the stainless steel circular waveguide with a diameter of 2.9 mm.

Fig. 1 depicts the outcome of a transmission experi-

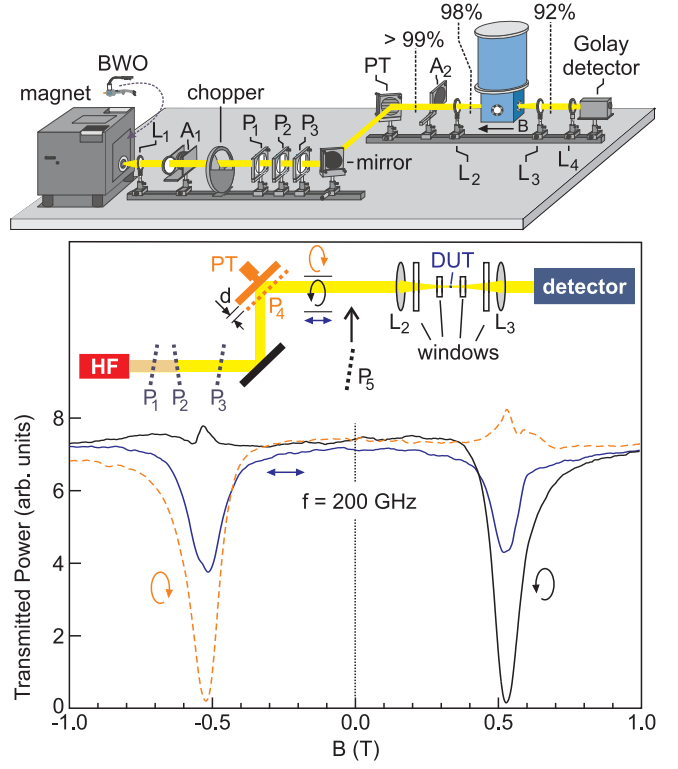


FIG. 1: Top panel: Quasi-optical setup for a polarization dependent study of the microwave photoconductivity. Bottom panel: Transmission data for a frequency of 200 GHz and linear, left or right hand circular polarized radiation. The inset highlights those optical components controlling or affecting the polarization state.

ment for both circular polarization directions and linear polarization of the incident radiation obtained with the quasi-optical setup. Transmission experiments for unpolarized radiation were reported previously in Ref. [34]. Data is shown for both positive and negative values of the magnetic field. Active cyclotron resonance absorption should only occur for the proper sense of circular polarization with respect to the magnetic field orientation. Indeed, the transmitted power drops nearly to zero for cyclotron resonance absorption in the active sense of the polarization (CRA), whereas reversing the magnetic field orientation while maintaining the circular polarization direction turns the cyclotron resonance mode inactive (CRI). For linear polarization, the transmitted power does not drop below 50% as it should. These transmission data confirm the quality of the various polarization states. We note that as in Ref. [8] the resonance should not occur at the bare cyclotron frequency, but rather at the frequency of the combined dimensional plasmon cyclotron resonance mode:  $(\omega_c^2 + \omega_{dp}^2)^{1/2}$ . Here,  $\omega_{dp}$  is the plasmon frequency at  $k = \pi/L$  with  $L$  the size of the sample. The estimated value of  $\omega_{dp}$  is 12 GHz. Hence, at a microwave frequency of 200 GHz, the combined mode is only 0.5 % larger than the bare cyclotron frequency. In

view of the large conductivity of the 2DES, the radiation is mainly reflected near the resonance for the active circular polarization sense and the linewidth is not determined by the scattering rate. It is broadened orders of magnitude and this broadening has been referred to as saturation effect [35] or radiative decay [36]. Noteworthy is also the absence of discernible absorption signals at the harmonics of the cyclotron resonance frequency. The dissipative photoresistivity is far more sensitive and exhibits microwave induced oscillations up to the 10th harmonic of the cyclotron resonance (see data below).

Fig. 2 illustrates the influence of the circular polarization sense on the microwave induced resistance oscillations for different microwave frequencies: 200, 183 and 100 GHz. The absorption signals for 200 GHz have been included at the top to allow for easy comparison of any features relative to the cyclotron resonance position. At fields below the cyclotron resonance absorption where the microwave induced oscillations occur, the magnetoresistivity traces for both senses of circular polarization are nearly indistinguishable. The same conclusion holds for linearly polarized radiation irrespective of the orientation of the electric field vector (an example is shown below in

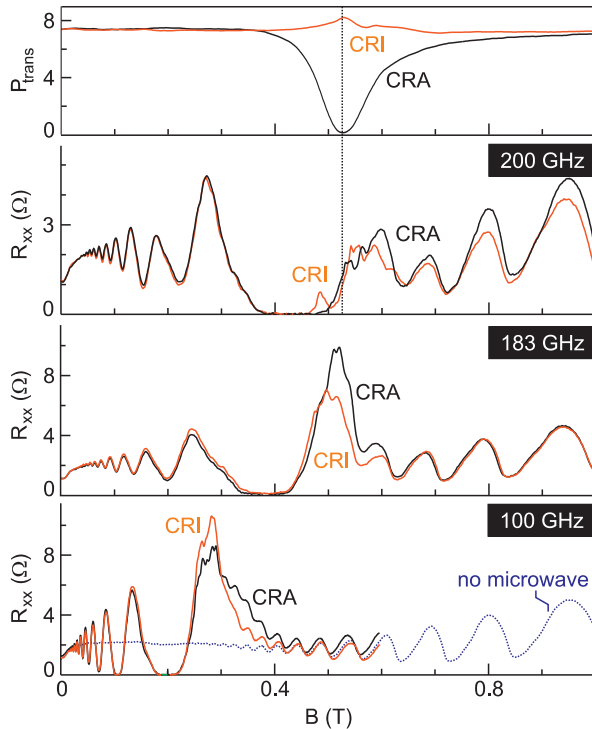


FIG. 2: Comparison of the magnetoresistivity under microwave radiation for both senses of circular polarization and three different frequencies. The transmitted power  $P_{\text{trans}}$  (arb. units) at a frequency of 200 GHz is plotted at the top for the sake of comparison with the 200 GHz transport data. The blue dotted curve in the bottom panel displays the magnetoresistivity in the absence of microwave radiation.

Fig. 3). To rule out that the microwave induced oscillatory photoresistivity has saturated, data were taken at power levels three times as high as for the traces plotted in Fig. 2. The amplitude of the second and higher order oscillations increased by as much as a factor of two. So we can safely discard the possibility that the presence of the small residual power of radiation with the undesirable polarization direction in conjunction with saturation of the microwave induced oscillations would produce this apparent polarization insensitivity. Hence, the experiments here only support theoretical mechanisms in which the polarization state of the microwaves is not relevant. Only at fields near the cyclotron resonance, where significant absorption takes place, deviations between the CRA and CRI curves do arise (see also below). The experimental observation that the higher order maxima and minima remain unaltered when reversing the sense of circular polarization may be regarded as a crucial test for theories. For instance, it contradicts the non-parabolicity model which only produces an oscillatory photoconductivity in the case of linear polarization [24]. It can also not be reconciled with the two most frequently cited theories, for which the influence of the circular polarization sense can easily be analyzed with analytical formulas reported in the literature [21]: the non-equilibrium distribution function scenario [3, 20, 21, 22] and the picture based on impurity- and phonon assisted indirect inter-Landau level transitions [11, 12, 13, 14, 15, 16, 17, 18, 19]. As an example, in the linear response regime and for a not too strong microwave field, the correction to the dark dc dissipative conductivity is a factor  $(\omega - \omega_c)^2 / (\omega + \omega_c)^2$  smaller for the CRI polarization sense (Eq. 16 and 17 in Ref. [21] with  $\mathcal{P}_\omega$  adapted for circular polarization. See also Eq. 6.11 in Ref. [19]). This factor originates in essence from the difference in the ac Drude conductivity for both circular polarization directions. For the second and third maximum (or minimum) this amounts to a factor of about 9 and 4 respectively! For larger microwave fields these corrections no longer obey a linear but rather a sublinear dependence on the microwave power and these factors are expected to be somewhat reduced. The dramatic disparity with the experiment of Fig. 2 however remains. There clearly is a strong need to analyze the polarization dependence of other proposed theoretical mechanisms.

The primary maximum does depend on the sense of circular polarization, likely because resonant heating at the cyclotron resonance produces a second contribution to the photoresistivity. In much older microwave photoconductivity experiments prior to the discovery of the zero resistance phenomenon, the cyclotron resonance absorption was already detected as a small resistance increase [8]. In the context of the recently discovered microwave induced resistance oscillations, signatures of the cyclotron resonance absorption in the magnetoresistivity remained unidentified, presumably because they were

masked by the much larger microwave induced resistance oscillations. The insensitivity of these oscillations on the polarization state and the ability to in-situ alter the circular polarization direction make it straightforward to reveal this bolometric contribution to the photoresistivity. More striking examples appearing at high power are illustrated in Fig. 3 for frequencies of 243 and 254 GHz (data at 183 and 200 GHz at three times larger power than in Fig. 2 also show a similar feature). The resistance enhancement can be surprisingly large and develops fine structure at these power levels. Its close connection to the cyclotron resonance is established by comparing with transmission data. The cyclotron resonance lineshape is distorted as a result of standing waves in the sample as well as in windows and other optical components as can be verified by investigating transmission data for a large frequency range. The power dependence of one such resistance peak is depicted in the bottom insert of Fig. 3. We interpret the threshold like behavior as a confirmation for the existence of two contributions to the resistance peak: the bolometric resistance enhancement with a nearly linear but steep power dependence and the contribution related to the oscillatory photoresistivity.

In summary, investigations in an all quasi-optical setup offering full control over the polarization properties of microwave radiation disclosed in discord with common theoretical pictures a complete immunity of the microwave induced resistance oscillations to the polarization state. Only the bolometric signal associated with cyclotron resonance absorption itself is strongly polarization dependent. This puzzling discrepancy between theory and experiment will likely reinvigorate the controversy on the origin of the microwave induced oscillations.

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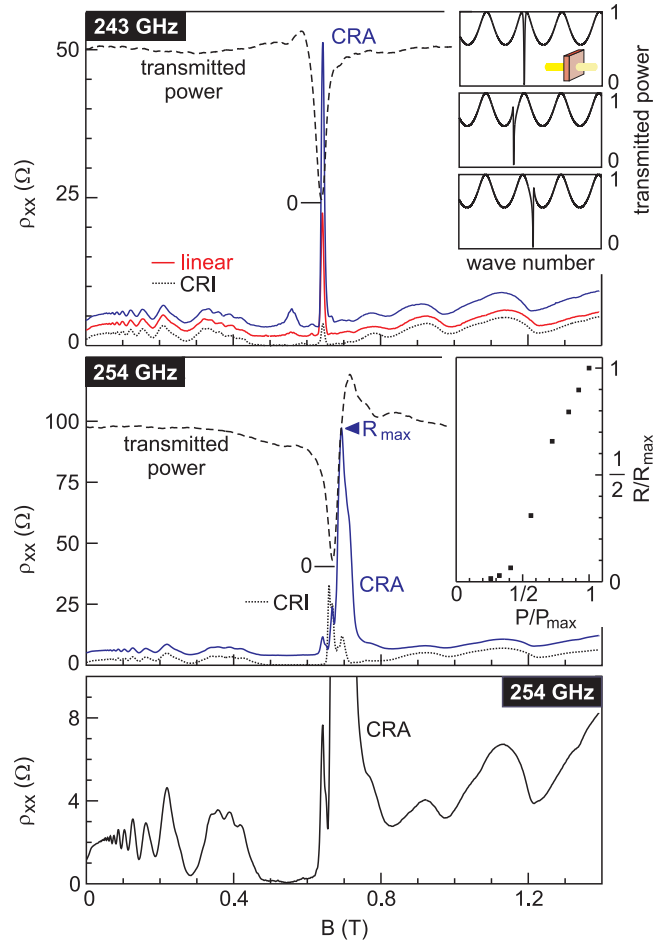


FIG. 3: Top: The magnetoresistivity for various polarizations under 243 GHz and 254 GHz radiation. Curves are offset for clarity. The dashed line represents the transmitted microwave power (no ordinate shown). The bottom panel is a blown up version of the 254 GHz data. The top inset schematically illustrates the influence of the unavoidable standing waves within the substrate on the lineshape of the cyclotron resonance line. The bottom insert plots the resistance maximum marked by a blue triangle as a function of the microwave power. The maximum incident power and the corresponding peak height are denoted as  $P_{\max}$  and  $R_{\max}$ .

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