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Microwave photoresponse in the two-dimensional electron system caused by intra-Landau-level transitions

S. I. Dorozhkin,[1,2] J. H. Smet,[1] V. Umansky,[3] and K. von Klitzing[1]
[1]*Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, D-70569 Stuttgart, Germany*
[2]*Institute of Solid State Physics, Chernogolovka, Moscow district, 142432, Russia*
[3]*Braun Center for Submicron Research, Weizmann Institute of Science, Rehovot 76100, Israel*
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The influence of microwave radiation on the dc magnetoresistance of two-dimensional electrons is studied in the regime beyond the recently discovered zero resistance states when the cyclotron frequency exceeds the radiation frequency. Radiation below 30 GHz causes a strong suppression of the resistance over a wide magnetic field range, whereas higher frequencies produce a nonmonotonic behavior in the damping of the Shubnikov–de Haas oscillations. These observations are explained by the creation of a nonequilibrium electron distribution function by microwave induced intra-Landau-level transitions.

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The recent interest in the microwave photoresponse of high-quality two-dimensional electron systems (2DES) has been triggered by the report[1,2] (also Refs. 3–7) of zero-resistance states in the vicinity of the cyclotron resonance harmonics. These states developed out of minima of earlier reported microwave-induced magnetoresistance oscillations.[8,9] Theories capable of accounting for these oscillations are based on several different approaches. They include (i) indirect inter-Landau-level transitions, which involve absorption of microwave quanta and are accompanied by scattering processes that alter the electron momentum[10–17] (more general considerations in terms of the quantum Boltzmann equation were given in Ref. 18), (ii) the establishment of a nonequilibrium electron energy distribution function, including inverted occupation of the electronic states under appropriate conditions,[3,19,20] (iii) photon-assisted quantum tunneling,[21] and (iv) nonparabolicity effects.[22] Most of the cited papers treat the magnetoresistance of a homogeneous state and conclude that it may become negative. Additional theoretical activity concentrated on explaining the appearance of zero resistance in experiment instead. It is argued that negative values of the dissipative conductivity lead to instabilities.[23] As a result, an inhomogeneous domain structure that produces zero resistance may form, as discussed in this context in Ref. 24 and later in Refs. 18, 21, and 25–27.

So far, considerations were limited mainly to the weak magnetic fields (B) where the microwave frequency ω exceeds the cyclotron frequency ω_c and inter-Landau-level transitions are of great importance. Here, we address the influence of microwaves on the magnetoresistance and the amplitude of the Shubnikov–de Haas (SdH) oscillations in the opposite regime when $\omega < \omega_c$.[28,29] Inter-Landau-level transitions then no longer play a role. At comparatively low-frequency radiation, we experimentally observe a strong suppression of the magnetoresistance accompanied by a drop in the amplitude of the SdH oscillations.[30] At higher radiation frequencies, the SdH oscillations are also strongly damped except for a narrow region of the B, where the amplitude is rather insensitive to the radiation. We attribute the magnetoresistance and the SdH oscillation suppression to the nonequilibrium electron occupation caused by microwave-induced intra-Landau-level transitions. The unusual nonmonotonic damping of the SdH oscillations at higher ω reflects the crossover from the inter- to the intra-Landau-level transition regime in the case of nonoverlapping levels.

Hall bar samples were measured from two different wafers containing a remotely doped GaAs/AlGaAs heterojunction with an 80-nm spacer width. The mobility after illumination reached $6-15\times10^6$ cm^2/V s at a saturated density of $\approx 3\times10^{11}$ cm^{-2}. The channel widths of the samples were equal to 0.05, 0.2, and 0.4 mm. All samples demonstrated qualitatively the same behavior except for differences in the amplitude of the microwave-induced oscillations. They were mounted in a waveguide with a cross section of 16×8 mm^2 (WG18) and submerged in pumped ^{3}He. The ρ_{xx} and ρ_{xy} magnetoresistivity components were measured at 10 Hz with a lock-in technique.

Typical experimental curves are shown in Fig. 1. In the absence of radiation, ρ_{xx} exhibits the usual SdH oscillations. Radiation with frequency ω dampens these oscillations at low B and gives rise to the microwave-induced magnetoresistance oscillations (see also Fig. 2) with minima located where $\omega \approx \omega_c(k+1/4)$ (here $k=1,2,\ldots$). As seen in Fig. 1 low-frequency radiation (for our samples, less than 40 GHz)

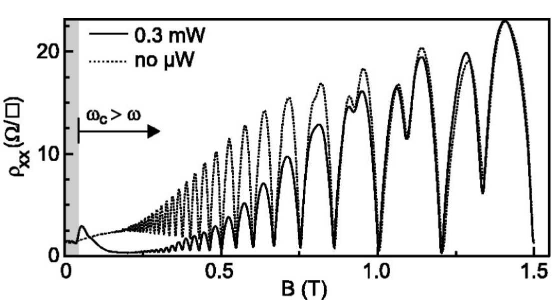

FIG. 1. Magnetoresistivity ρ_{xx} vs B in the absence of radiation (dotted line) and under 17 GHz radiation (solid line) at $T=0.4$ K and density $n_s=2.92\times10^{11}$ cm^{-2}. The microwave power $P=0.3$ mW was measured at the oscillator output. The microwave electric field is perpendicular to the current.

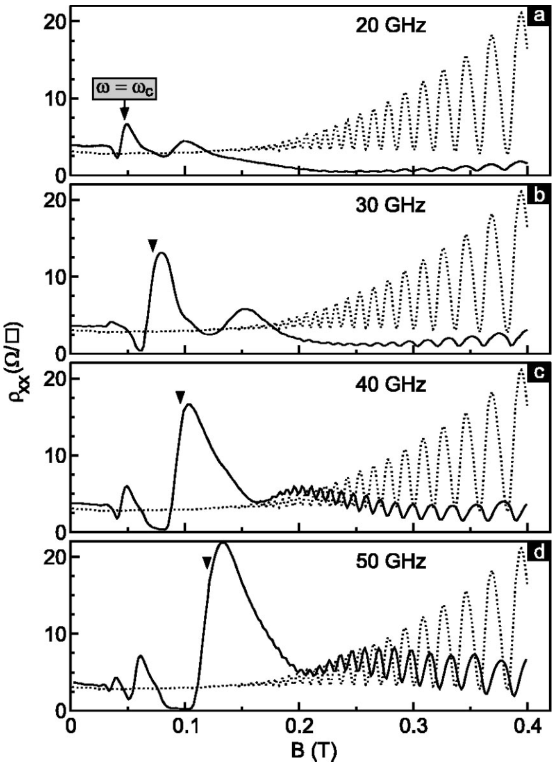

FIG. 2. Magnetoresistivity ρ_{xx} vs B without radiation (dotted lines) and under microwave radiation (solid lines) for the marked frequencies at $T=0.4$ K and $n_s=2.8\times10^{11}$ cm^{-2}. The oscillator output power P was equal to 2 mW. The positions of the cyclotron resonance are marked by arrows.

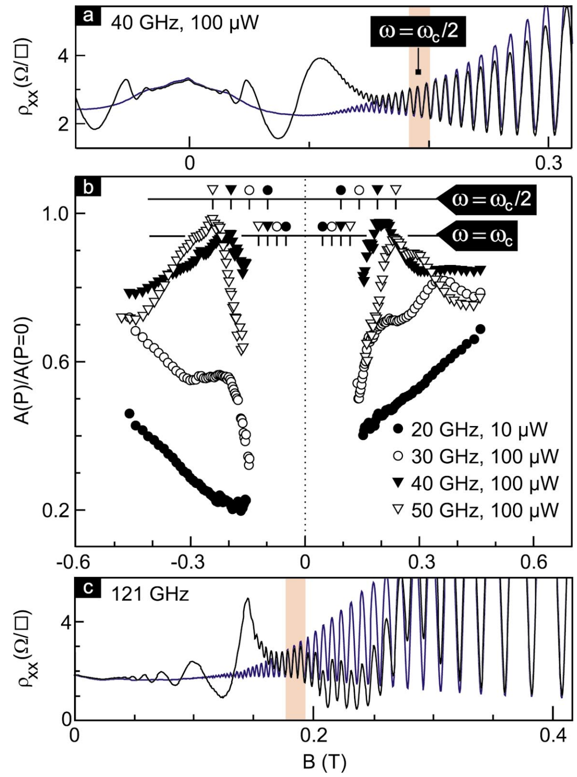

FIG. 3. (Color) (a) ρ_{xx} vs B without (blue) and with 100 μW of 40 GHz radiation. (b) The amplitude of each SdH oscillation under microwave radiation with power P, $A(P)$, normalized to its dark value, $A(P=0)$, is plotted for different microwave frequencies. The location of the cyclotron resonances and second cyclotron resonance subharmonics are marked. (c) ρ_{xx} vs B without (blue) and with 121 GHz radiation. The red-shaded box, where $\omega\approx 3\omega_c/2$, demarcates as in (a) the region where SdH oscillations do not respond to microwaves.

also dramatically suppresses the average magnetoresistivity within a wide range of B and even when $\omega_c \gg \omega$. In Fig. 1, the magnetoresistivity ρ_{xx} at, for instance, 0.2 T ($\omega_c/\omega\approx 5$) is reduced by one order of magnitude and becomes less than the zero-field resistivity by about a factor of 5. In the single mode regime, the effect is insensitive to the linear polarization direction. The Hall resistance is not affected in this regime, apart from a weakening of the plateau precursors. It is correlated with the damping of the SdH oscillations.

Figure 2 depicts how this ρ_{xx} suppression evolves with microwave frequency.[31] It reduces at higher ω and disappears near 40–50 GHz. At these higher frequencies, plotting the magnitude of each SdH oscillation, $A(P)$, normalized to its amplitude in the absence of radiation, $A(0)$, reveals a nonmonotonic behavior as a function of B as seen in Fig. 3(b). Note that data presented in Fig. 3 have been measured at more than one order of magnitude smaller power than data in Fig. 2. Figure 3(a) shows such low-power data for 40 GHz. The maxima of $A(P)/A(0)$ in Fig. 3(b), nearly symmetrically arranged around $B=0$, are located in the vicinity of the second cyclotron resonance subharmonic, i.e., when $\omega=\omega_c/2$. The asymmetry of the curves (especially at lower ω) with respect to $B=0$ is tentatively assigned to the excitation of chiral edge magnetoplasmons by the radiation.[28] At the maxima, $A(P)/A(0)\approx 1$, i.e., the SdH oscillation amplitude is insensitive to the applied low-power radiation. The red-shaded box in Fig. 3(a) highlights this region for the 40 GHz data.

Note that a drop of ρ_{xx} below the SdH minima in the absence of radiation can not be explained simply by electron heating. Heating can only dampen the SdH oscillations or causes an overall increase of ρ_{xx}. To account for our observations, we first address qualitatively what microwave absorption processes can take place when considering energy conservation, while assuming other selection rules are relaxed due to the inevitable disorder in samples. In Fig. 4, the regions in the (ω_c,ω) plane, where inter- and intra-Landau-level transitions can occur, are color coded. These areas are bounded by two lines: $\omega=\omega_c-2\Gamma/\hbar$ and $\omega=2\Gamma/\hbar$. Here, Γ is half the width of a broadened Landau level. These boundaries should not be interpreted as sharp cutoffs. They are valid at temperatures $kT\gtrsim\Gamma$, which corresponds to our experimental conditions. At very low temperatures $kT\ll\Gamma$, these border lines acquire additional oscillatory structure depending on the Landau-level filling (for an example of possible transitions, we refer to Ref. 3). When the cyclotron radius r_c exceeds the characteristic length scale, λ, of the random potential, Γ increases with $\sqrt{B}$.[32,33] The border lines for inter- and intra-Landau-level transitions then intersect when $\omega_c=\omega_{c0}$ and $\omega=\omega_0=\omega_{c0}/2$. For $\omega<\omega_0$, there are always transitions possible. They may modify the electron distribution function, which affects the conductivity (resistivity)

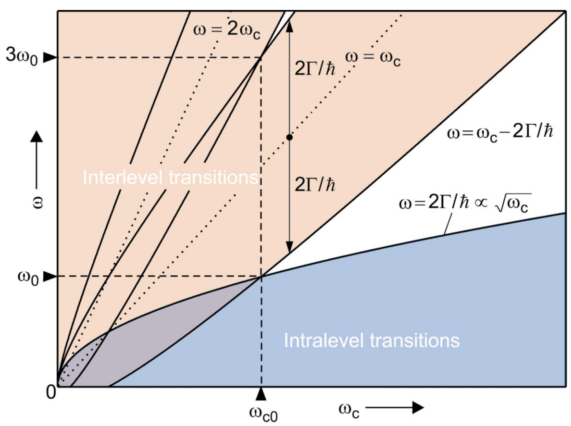

FIG. 4. (Color) The (ω_c,ω) plane. Regions where inter- and intra-Landau-level transitions can occur under microwave radiation are color coded. The main boundaries are formed by $\omega=\omega_c-2\Gamma/\hbar$ and $\omega=2\Gamma/\hbar$. They intersect at $\omega=\omega_0=\omega_{c0}/2$. In the white regions energy conservation prohibits transitions. The position of the cyclotron resonance and its second harmonic (straight dotted lines) are also shown.

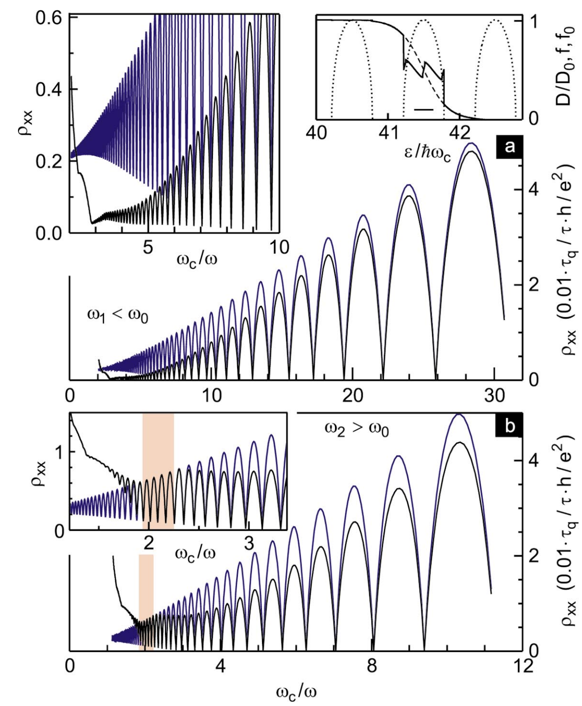

FIG. 5. (Color) Calculation of ρ_{xx} vs ω_c/ω (or B) (black solid lines) for frequencies (a) $\hbar\omega_1\approx 0.42\hbar\omega_0\approx 6.5\times10^{-3}\epsilon_F$ and (b) $\hbar\omega_2=1.15\hbar\omega_0\approx 0.018\epsilon_F$, and for the dimensionless microwave powers $P_\omega^{(0)}$ (Ref. 20) (proportional to ω^{-4}) of 100 and 10, respectively. The temperature $T\approx 4.0\times10^{-3}\epsilon_F$. Here ϵ_F is the Fermi energy at zero B field. Blue lines present the calculated magnetoresistivity in the absence of radiation. The left insets are expanded views (the same units as main panels). The right inset in the top panel depicts the semielliptical density of states D/D_0 (dotted line) (Ref. 32) and calculated distribution function $f(\epsilon)$ (solid line) under microwave radiation for the point $\omega_c/\omega\approx 3.7$, corresponding to a filling factor of 83. Here, $f_0(\epsilon)$ (dashed line) is the Fermi distribution function, with $D_0=2/\pi^2 l_B^2\Gamma$ and l_B the magnetic length. The value ω_1/ω_c for the chosen magnetic field is plotted in the inset as a line segment. In the bottom panel, the magnetic field interval where the SdH oscillations are not affected by radiation is demarcated by the red-shaded box.

and the SdH oscillation amplitude,[3,19,20] and also produces the dramatic drop in ρ_{xx} as shown later. However, when scanning B at a fixed microwave frequency exceeding ω_0, the white region, where we anticipate very weak absorption, is entered. It is likely responsible for the maxima in the 40 and 50 GHz curves of Fig. 3(b) where the amplitude of the SdH oscillations is only weakly influenced by the radiation. A similar nonmonotonic behavior of the SdH-oscillation amplitudes is expected from Fig. 4 at $\omega_c=\omega_{c0}$ and $\omega=3\omega_0$. This was indeed confirmed in experiment. For $f=121$ GHz in Fig. 3(c) near $B\approx 0.18$ T, the SdH oscillations are insensitive to radiation. Surprisingly, such straightforward considerations explain quantitatively the experimentally observed position of the maxima. It is worth noting that, within this picture, the decay of $A(P)/A(0)$ beyond the maxima in Fig. 3(b) at higher absolute values of B implies that the Landau-level width increases with B. Then, for frequencies exceeding ω_0 the low-field region with predominant inter-Landau-level transitions is followed by no transitions and finally by a field regime where intra-Landau-level transitions occur. This field-dependent broadening is distinctive of a short-range random potential for which $\lambda\leqslant r_c$.[32,33] In remotely doped heterojunctions, the shortest range of the random potential is frequently given by the spacer width. In our samples the cyclotron radius becomes smaller than the spacer width at $B>1$ T. The presence of fluctuations on a length scale $\lambda<r_c$ at low fields allows intralevel transitions.

To substantiate the assertion that the strong reduction of the average magnetoresistance for $\omega\ll\omega_c$ can be attributed to changes in the electron distribution function, we have analyzed whether the recently proposed theory in Ref. 20 is capable of reproducing this phenomenon. As initially suggested in Ref. 3, this theory considers the nonequilibrium population of electronic states. In addition, it allows for nonzero T and inelastic relaxation. We have solved numerically the equation for the nonequilibrium distribution function of Ref. 20 [Eq. (9)] for the case of nonoverlapping Landau levels, while omitting the term describing non-Ohmic effects. We further assume that spin splitting is not resolved. Calculated traces of ρ_{xx} for frequencies $\omega_1<\omega_0$ and $\omega_2>\omega_0$ are shown in Fig. 5. A damping of the SdH oscillations at intermediate values of ω_c/ω accompanied by a strong suppression of the average magnetoresistivity is apparent in Fig. 5(a) for $\omega_1<\omega_0$, qualitatively confirming observations in Figs. 1 and 2. The ρ_{xx} suppression is a result of the strong modification of the distribution function mainly within the highest occupied Landau level caused by intralevel transitions as evident from the right inset. Even in the presence of inelastic relaxation, energy ranges with inverted electron populations exist, which yield a negative contribution to the magnetoresistance not unlike what occurs at $\omega>\omega_c$ where the zero resistance states develop. Figure 5(b) for $\omega_2>\omega_0$ demonstrates the insensitivity of the SdH oscillations to the microwave power in a narrow B-field region when $\omega=\omega_c/2$, highlighted in red. This is consistent with the data in Fig. 3.

From the appearance of the maxima in $A(P)/A(0)$ at 40 GHz and their location in Fig. 3(b), the Landau-level width can be estimated. The data suggest $2\Gamma/\hbar\omega_c=0.5$ when $B\approx 0.18$ T. This estimate is in reasonable agreement with the lower B-field limit where we are able to resolve the SdH oscillations (0.1 T at $T=0.4$ K).

In summary, we have presented experimental data showing a dramatic suppression of the magnetoresistance across a wide field range where microwaves can, under the condition of single photon absorption, only induce intra-Landau-level transitions. The regime where intra-Landau-level transitions start to take over from inter-Landau-level transitions is detected from the anomalous damping behavior of the SdH oscillations. This anomaly allows us to estimate the Landau level width.

Recently, Ref. 34 has come to our attention. It explains our experiment in terms of intra-Landau-level transitions and modifications to the impurity scattering in the presence of a microwave electric field. Maximal suppression of the magnetoresistance is predicted for $\omega_c \gtrsim \omega$. This disagrees with both our experiment and model. In its present form, this model does also not explain the behavior of the SdH oscillation amplitude in Fig. 3.

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