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Hysteretic Microwave Cyclotronlike Resonance in a Laterally Confined Two-Dimensional Electron Gas

B. M. Ashkinadze and V. I. Yudson*

Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel

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A hysteretic cyclotron resonance (CR) is discovered in a laterally confined high-mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures. The hysteresis and switching phenomena are observed in microwave radiation absorption at temperatures below 25 K. The effect is accompanied by long-lived changes of the 2DEG density. We attribute these changes to modifications of vertical electron transport processes in heterostructures under microwave heating of the 2DEG. A phenomenological model based on the 2DEG density-dependent CR describes the main experimental findings.

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A free electron nonlinear cyclotron resonance (CR), with hysteresis occurring under intense irradiation, was predicted by Kaplan [1]. The nonlinearity considered is caused by the dependence of the cyclotron frequency on the electron relativistic mass which increases with the gained electron energy. The effect resembles a hysteresis in a classic nonlinear oscillator [2]. A hysteretic CR in semiconductors associated with the conduction band nonparabolicity was also proposed [1]. To the best of our knowledge, the hysteretic CR has not been observed in semiconductors yet.

Here we report on the hysteretic CR and switching phenomena found in a laterally confined, high-mobility, two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures. The effect is observed in a microwave radiation absorption at temperatures below 25 K and is accompanied by a reduction of the 2DEG density. This introduces a new mechanism of nonlinearity which is different from that discussed in Ref. [1]. A model is proposed to describe the nonlinear hysteretic CR in the laterally confined 2DEG.

The cyclotron resonance is of considerable current use in the study of high mobility 2D electrons in modulation doped GaAs-AlGaAs heterostructures [3–8]. Experiments are usually performed at low temperatures and under low-intensity far-infrared (FIR) or microwave (mw) irradiation that does not affect the 2DEG parameters. Increasing FIR or mw intensity leads to electron heating that becomes more efficient under CR condition. This results in the CR line shape modification [9], and gives rise to the optically detected resonance [10–13], as well as to the mw/FIR photoconductivity [14,15].

We have performed microwave CR absorption measurements on high quality single-sided modulation n-doped GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructures grown by molecular beam epitaxy, in a wide range of mw powers. We present results for two samples: a single, 25 nm wide quantum well (QW) and a heterojunction (HJ). A Si-doped layer is separated from the interface by a 80 nm (QW) or 30 nm (HJ) Al$_{0.3}$Ga$_{0.7}$As spacer. At 2 K, the dc measured 2DEG density, $n_{2\mathrm{D}}^{0}$, and mobility, μ, vary in the range of $(1.6-4) \times 10^{11}$ cm^{-2} and $(1-4) \times 10^{6}$ cm^{2}/V s, respectively. Electron density can be changed by light illumination either due to optical depletion [16] or due to persistent photoconductivity. The lateral dimension of the samples is reduced by fabricating mesas with the diameter a of 0.5–1.2 mm. The small sample size ensures the linearity of the mw absorption (MWA) at low mw power. An external magnetic field B is applied perpendicular to the heterointerface, and is scanned back and forth in the range of 0–0.3 T at a rate of 0.01 T/min.

The samples are placed in an antinode of the microwave electric field in a 8-mm waveguide which is short-circuited at one end. The mw frequency used is 36 GHz and the mw power in the waveguide, P_{in}, can be controlled in the range of 10^{-3}–5 mW. The waveguide is immersed in liquid He or in cold He gas so that the temperature is varied in the range of $T = 1.8$–30 K. Most experiments are carried out under cw mw irradiation. Time-resolved measurements are performed using pulsed mw power and a gated boxcar integrator.

Figures 1a and 1b present mw transmission (MWT) traces obtained at several P_{in} values for the single 25 nm QW and for the heterojunction, respectively. The MWT is measured as a function of a magnetic field, when the latter is scanned up and down. At low P_{in}, both MWT traces, for scanning up and down, coincide and exhibit a resonance at B_R which is lower than the resonant value $B_{\mathrm{CR}} = 0.086$ T expected for a free electron CR in GaAs at $f = 36$ GHz [17]. The resonance field B_R shifts to higher values with increased P_{in}. Above a certain threshold value of P_{in}, hysteresis occurs: there appears a difference between the MWT traces obtained at increasing and at decreasing magnetic fields. At still higher P_{in} a sudden MWT switching is observed.

A surprising finding is the persistence of the CR hysteresis also under modulated mw irradiation (see Fig. 1a, upper curve). The pulse modulated microwave radiation is used. Both pulse duration t_p and time interval

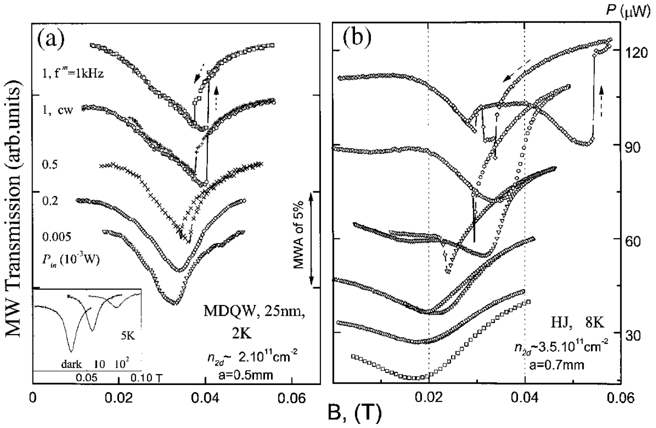

FIG. 1. The microwave radiation transmission traces measured at several input mw power values P_{in}: (a) Traces obtained for the MDQW are shifted vertically for clarity; P_{in} is shown near the traces; (b) the traces obtained for the HJ are presented for mw power given in absolute units (10^{-6} W). Arrows indicate the scanning direction of the magnetic field. The inset demonstrates the DMPR line shift under light illumination (incident intensity is given in $\mu\text{W/cm}^2$).

θ between the pulses are varied. We find that the hysteresis loop depends only slightly on θ as long as $\theta < 10^{-3}$ s and $t_p > 10^{-5}$ s. Since the hysteresis exists even for a small duty cycle ratio t_p/θ, it means that the intense mw irradiation induces a long-lived modification in the 2DEG state. This modification lasts after the mw pulse, and the 2DEG reaches its new steady state after a certain number of mw pulses. The 2DEG changes recover with a characteristic time of 10^{-2} s at 1.8 K.

Before interpreting the nonlinear resonance occurring at intense mw irradiation, let us underline the peculiarity of the linear CR for a laterally confined 2DEG where a depolarization of the 2DEG results in the CR resonance frequency shift. This was observed by Allen *et al.* and interpreted as a dimensional magnetoplasma resonance (DMPR) [6]. The DMPR line shape can be obtained from the equation of electron motion in an external magnetic field in the presence of a linearly polarized mw electric field,

$$P_{\text{MWA}}(B) = z\sigma_0 P_{\text{in}} \frac{1 + (\omega_B^2 + \omega_R^2)\tau_m^2}{[1 + (\omega_B^2 - \omega_R^2)\tau_m^2]^2 + 4\omega_R^2\tau_m^2} . \tag{1}$$

Here $P_{\text{MWA}}(B)$ is an absorbed mw power, z is a factor which takes into account the waveguide and sample geometry, σ_0 is a dc conductivity, $\omega_B = eB/(m^*c)$ is the cyclotron frequency, τ_m is an electron momentum relaxation time, $\omega_R = \omega - \omega_p^2(n_{2\text{D}})/\omega$, $\omega_p(n_{2\text{D}}) = [3\pi^2 e^2 n_{2\text{D}}/(2a\epsilon m^*)]^{1/2}$ is the plasmon frequency for the 2DEG confined within the mesa, a is the mesa diameter (a is smaller than the mw wavelength), and ϵ is an averaged value for the dielectric constant of free space and GaAs [7]. At a given mw frequency $\omega = 2\pi f$, the DMPR occurs at the magnetic field $B_R = B_{\text{CR}} - 3\pi^2 ecn_{2\text{D}}/(2\epsilon\omega a)$ which depends on $n_{2\text{D}}$ and differs from the standard CR magnetic field $B_{\text{CR}} = m^* c\omega/e$.

For the case of a low mw power ($P_{\text{in}} \sim 10^{-6}$ W), a shift of the DMPR line as $n_{2\text{D}}$ changes is shown in the inset of Fig. 1a. The MWT curves are measured in dark and at two intensities of He-Ne laser illumination which leads to decreased $n_{2\text{D}}$ due to optical depletion. Fitting the measured DMPR line shape to Eq. (1) electron mobility and density as a function of illumination intensity can be deduced [18].

To interpret the nonlinear and hysteretic CR we assume that an intense mw irradiation induces a long-lived reduction of the 2DEG density. This is consistent with the observation of the DMPR shift to higher B_R with increasing P_{in} (see Fig. 1) as well as with the observed long-lived 2DEG state modification. The only proper 2DEG parameter that can be characterized by such long relaxation times is the 2DEG density determined by slow vertical electron transport (tunneling) processes [19].

How can an intense mw field affect this vertical transport? The electron kinetic energy increases at the mw field, and this results in an increased 2DEG temperature T_e due to fast electron-electron scattering in the 2DEG. The electron heating experiments carried out in a dc electric field [20] allow one to estimate T_e for a given mw power absorbed per electron. Measuring the total mw power absorbed by the mesa, we deduce that T_e does not exceed 30 K in our experiments. The hot electrons emit low-energy acoustic phonons that are ballistically propagated at low temperature in GaAs [20]. Thus, the mw-induced 2DEG density decrease should be associated with the increase of the electron temperature (and, perhaps, with a flux of nonequilibrium acoustic phonons). We assume that the 2DEG heating modifies the rates of electron transport into and out of the 2DEG so that the 2DEG density reduces.

As a simple phenomenological model, we suppose that the rate of electron escape from the 2DEG increases linearly with the mw power absorbed per electron, $P_{\text{MWA}}(B)/n_{2\text{D}}$, whereas the electron return rate τ^{-1} is unaffected by mw radiation. This scenario implies that only the 2DEG temperature is changed under mw irradiation, while the lattice subsystem and the electrons of the rest of the sample remain in their equilibrium state. The balance equation for $n_{2\text{D}}$ takes in the form

$$\dot{n}_{2\text{D}} = -n_{2\text{D}}(1 + \beta P_{\text{MWA}}/n_{2\text{D}})/\tau + n_{2\text{D}}^0/\tau , \tag{2}$$

where β is a coefficient of mw-induced nonlinearity.

The steady-state solution of Eq. (2) reads $n_{2\text{D}} = n_{2\text{D}}^0(1 - \beta P_{\text{MWA}}/n_{2\text{D}}^0)$. For a linearly polarized mw field, P_{MWA} is given by Eq. (1), where $n_{2\text{D}}$ and ω_R depend now on P_{MWA} according to Eq. (2). Thus, Eq. (1) becomes a nonlinear equation which determines the nonlinear CR absorption in the steady-state regime. For a circularly (electron CR-active) polarized mw field, conditions for the hysteresis can be analytically found since the nonlinear Eq. (1) is replaced by a simpler one,

$$P = \frac{(1 - P)I}{1 + (x - \Delta P)^2}, \qquad (3)$$

where P, I, Δ, and x are dimensionless quantities: $P = \beta P_{\mathrm{MWA}}/n_{2\mathrm{D}}^0$, $I = z\beta\sigma_0 P_{\mathrm{in}}/n_{2\mathrm{D}}^0$, $\Delta = \omega_p^2(n_{2\mathrm{D}}^0)\tau_m/\omega$, and $x = (\omega_B - \omega + \Delta)\tau_m$; x varies with B. For given values of I and Δ, Eq. (3) determines P as a function of x.

An analysis shows that for $\Delta < \Delta_c = 3$, Eq. (3) has a single-valued solution $P(x)$ for any I; hence there is no hysteresis. For $\Delta > \Delta_c$, there appears a range of I where $P(x)$ has three solutions within some interval of x. In other words, the upper branch of the inverse function $x(P)$ has two extreme points: P_1 and P_2. A stability analysis shows that the $P(x)$ is unstable in the interval between $x_1 = x(P_1)$ and $x_2 = x(P_2) > x_1$, and the system demonstrates a hysteretic behavior with MWT switching at points x_2 (when x increases, i.e., magnetic field is scanned up) and x_1 (when x changes in the opposite direction). The range of I, where the hysteresis takes place, is determined by the inequality

$$(I + 1)^3 > (3/4)\Delta^2 I^2.$$

For $\Delta \gg \Delta_c = 3$, the lowest I value is estimated as $I \approx 2/(\sqrt{3}\,\Delta)$. Hence, the threshold mw power, where the hysteresis arises, $P^* \propto 1/\Delta$, i.e., P^* decreases with increasing $n_{2\mathrm{D}}^0/a$. Note that for our samples the experimentally found magnitude of Δ is about 7 for $T = 2$ K.

The above analysis is applicable for linear polarized radiation as long as the CR line is relatively narrow ($\omega\tau_m \gg 1$), so that the mw absorption due to the CR-inactive component can be neglected. Indeed, a numerical solution to Eq. (1) demonstrates the same hysteretic phenomena (Fig. 2) as those revealed in the above analysis. One can see that the Lorentz DMPR absorption line transforms into the hysteretic mw absorption as P_{in} increases. The 2DEG density also exhibits a hysteretic behavior with sharp jumps near the switching points. The smaller the DMPR shift, the narrower is the hysteresis loop (see Figs. 2a and 2b).

Comparison of the experimental results (Fig. 1) with the calculated curves shows that our model explains the main features of the nonlinear hysteretic CR found in the laterally confined 2DEG systems. However, the observed hysteresis becomes more complicated at still higher P_{in} as well as in the presence of weak illumination by light (see Figs. 1b and 3). These additional peculiarities are typical for combined dispersive-absorptive bistable phenomena and may result from higher order nonlinearities not included in our model.

The time-resolved mw experiments allow one to measure the phenomenologically introduced time (τ) of the electron transport between the 2DEG and adjacent layers. We have found that τ varies from sample to sample and depends on the ambient temperature as well as on illumination by light. Figure 3 presents the MWT traces obtained under weak illumination for various t_p and θ. Illumination leads to the DMPR line shift, to the sharper hysteresis, and to the relaxation time decrease. τ becomes less than 10^{-3} s when compared to its dark value of 10^{-2} s. Detailed results of the time-resolved experiments will be published elsewhere.

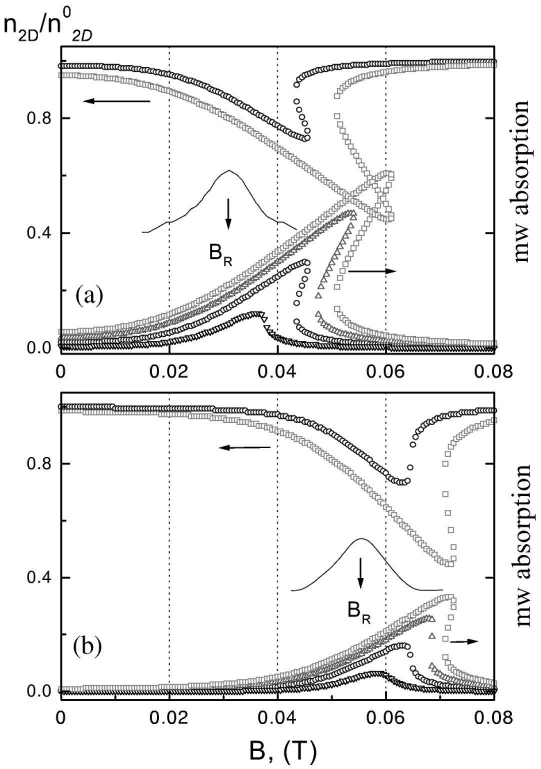

FIG. 2. mw absorption traces vs B calculated according to Eqs. (1) and (2) for two values of ω_R, a higher one (a) and a lower one (b). The nonlinear coefficient $\beta = 0.05$; the 2DEG mobility $\mu = 1.4 \times 10^6$ cm^2/V s; dimensionless input mw power values are 1, 5, 15, 30, 50. The 2DEG density vs B is presented for input mw power of 15 and 50. The DMPR positions are marked by arrows.

At present we do not specify the mechanisms of the mw-induced vertical electron transport. Note that in the studied samples, the time of the direct electron tunneling between the 2DEG and Si-doped layer is so long that some other vertical transport channels should be considered. Among them one may consider electron tunneling through impurity clusters or redistribution of the heated 2DEG electrons over deep impurities (e.g., DX centers) in the AlGaAs spacer layer. The revealed 2DEG density decrease caused by the electron heating is likely to be important also for interpreting the optically detected resonance experiments carried out with heterostructures [11,13–15].

In conclusion, a novel hot-electron nonlinear phenomenon—the hysteretic cyclotron resonance under intense microwave irradiation—is observed for the 2DEG in

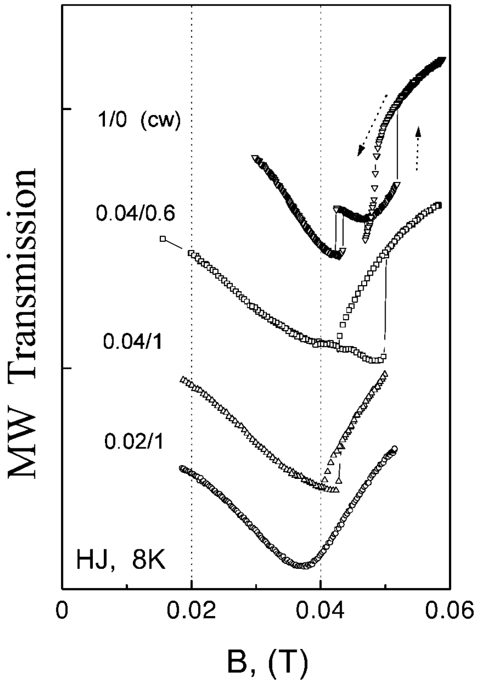

FIG. 3. MWT as a function of t_p/θ. t_p and θ (10^{-3} s) are shown near the curves. The traces are measured on the HJ at fixed $P_{\text{in}} \sim 0.1$ mW and under weak illumination.

laterally confined GaAs/AlGaAs heterostructures. The time-resolved study shows a long recovery time of the mw-induced nonlinearity. We assign the nonlinearity to the 2DEG density change caused by a modification of electron vertical transport processes under intense mw irradiation. A simple phenomenological model based on the 2DEG density-dependent CR, describes reasonably the experimental findings. Further research is required for understanding microscopic mechanisms of the revealed fast vertical electron transport processes.

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*Permanent address: Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow r-n, 142092 Russia.

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