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Photoluminescence hysteresis of the optically detected cyclotron-like resonance of a two-dimensional electron gas

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A significant reduction of the two-dimensional electron gas (2DEG) density n_{2D} in a modulation doped GaAs/AlGaAs quantum well is observed when the 2D-electrons are heated by microwave (mw) irradiation at 1.8 K. A dependence of n_{2D} on the effective electron temperature T_e leads to a remarkable hysteresis of the optically detected dimensional magnetoplasma (cyclotronlike) resonance, namely, to a bistability of the 2DEG-free hole photoluminescence (PL) spectrum as the magnetic field is scanned back and forth. The n_{2D} and T_e values for the nonequilibrium 2DEG are obtained from the PL spectrum analysis. The PL time-resolved study shows that n_{2D} depends on the mw pulse duration and has a long recovery time $\sim 10^{-2}$ sec. This phenomenon is attributed to an increased vertical transport of the warm electrons out of the quantum well.

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A high mobility two-dimensional electron gas (2DEG) in a semiconductor modulation doped quantum well (MDQW) and heterojunction (HJ) can be easily heated by dc current, far-infrared (FIR), microwave (mw) or visible irradiation, and its low-temperature properties are thereby modified. This was observed in several cases: a breakdown of the quantum Hall effect with increasing dc current,[1] a change in the 2DEG magnetoresistance under FIR or mw irradiation,[2–4] and the effects of increased light or FIR/mw intensities on the 2DEG photoluminescence.[5–8] These phenomena were interpreted as caused by an increased electron temperature of the 2DEG.

Recently, a hysteresis of the dimensional magnetoplasma (cyclotronlike) resonance (DMPR) was observed in quantum heterostructures containing a laterally confined 2DEG.[9] It is well known that the cyclotron resonance (CR) transforms into a DMPR with increasing electron density (if the electrons are spatially confined in a small area with dimensions, a, less than the mw radiation wavelength).[10,11] The resonant magnetic field strength B_R is shifted from the classical electron CR value B_{CR}:

$$B_R = B_{CR} - 3\pi^2 ec n_{2D}/2\kappa\omega a.$$

Here, ω is the mw frequency; $B_{CR}=\omega m^* c/e$; κ is the average dielectric constant value of the sample and free space. A remarkable feature of the DMPR is its B_R-dependence on n_{2D}. By measuring B_R one can measure the n_{2D}-value in a nonequilibrium state, for example, under photoexcitation intensity variation. This approach has been used in studying the PL spectral evolution from a 2DEG state to excitons when n_{2D} was varied by optical depletion.[8,12,13]

At the resonant magnetic field B_R, the electrons gain the largest energy amount from the mw radiation and, thus, reach the highest T_e under intense mw power. The observed DMPR hysteresis was interpreted[9] as a nonlinear resonance resulting from a decrease of n_{2D} with increasing electron heating. The developed model of the DMPR hysteresis allowed for a phenomenological relation between n_{2D} and the absorbed mw power causing the electron heating.[9] However, the dependence of n_{2D} on T_e cannot be reliably extracted from the mw absorption experiments, since the lineshape of the nonlinear DMPR is determined by both n_{2D} and T_e values.

The heated 2DEG goes through several nonequilibrium regimes. At low temperatures, the energy gained by the electron is rapidly redistributed within the 2DEG due to the very efficient electron-electron (hole) scattering. On the other hand, the cooling of the warm 2DEG occurs by emission of low-energy acoustic phonons that is not efficient for the degenerate 2DEG at low temperature.[14] Consequently, the 2DEG temperature T_e becomes higher than the lattice temperature T_L, and, simultaneously, the density of nonequilibrium acoustic phonons increases. After the electron heating is turned off, T_e relaxes with a characteristic energy relaxation time of the order of 10^{-9} sec, while the lifetime of the nonequilibrium acoustic phonons generated by the warm 2DEG, is determined by their ballistic propagation through the entire sample and their leaving into liquid He. The latter lifetime is of the order of 10^{-6} sec.[15]

The specific feature of a GaAs/AlGaAs quantum heterostructures that allows a change in n_{2D} with T_e, are the AlAs or AlGaAs layers adjacent to the 2DEG. Under electron heating, a redistribution of the nonequilibrium 2D-electrons between the QW and resonant (or nearly resonant) impurity states in the spacer or in the doping AlGaAs layers can occur by an electron vertical tunneling (probably, assisted by nonequilibrium acoustic phonons). As the electron heating is turned off, the electrons return into the QW, and the expected recovery time can be quite long. In a number of experiments with a nonequilibrium 2DEG (Refs. 2, 3, and 16) relaxation times of $10^{-4}-10^{-1}$ sec were observed. However, these long times were not convincingly explained.

Here we report on the photoluminescence (PL) study in a modulation doped GaAs/AlGaAs quantum well subjected to mw electron heating. The PL of the studied samples is due to

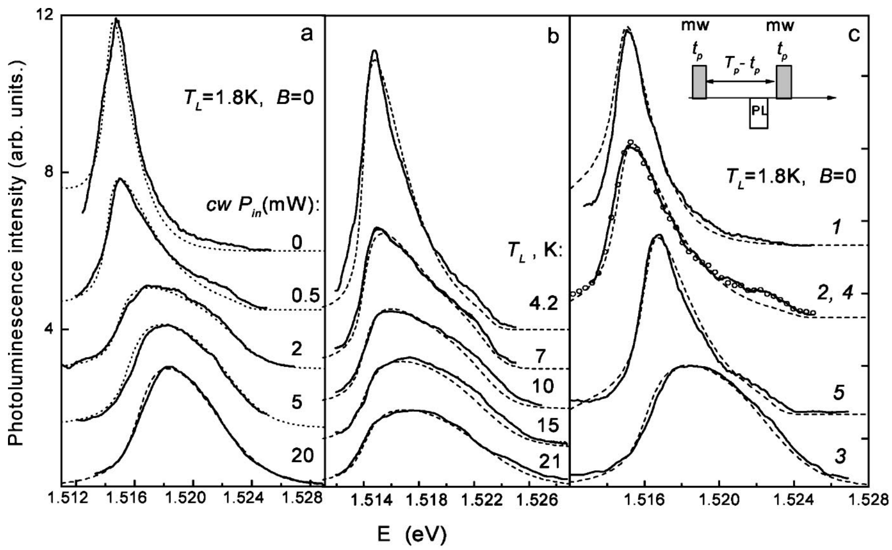

FIG. 1. The 2DEG-free hole PL spectra of the 25 nm MDQW with $n_{2D}=2.3\times10^{11}$ cm^{-2} (solid lines) and the fitted PL spectra (dash lines). (a) vs cw P_{in}. (b) vs lattice temperature T_L. (c) The PL spectra 1, 2 (shown by circles) and 3 are measured under cw $P_{in}=0$, 0.1, and 10 mW, respectively; 4 and 5 at 10 mW mw pulse having $t_p=10^{-5}$ and 2.8 $\times10^{-3}$ sec, respectively.

the 2DEG-free hole radiative recombination. The 2DEG heating modifies the PL spectrum, and the PL change is enhanced at the resonant magnetic field. This is the basis of the optically detected resonance (ODR) technique. In the case of DMPR, the resonant PL modifications can be caused by the n_{2D} as well as T_e variations, and this allows us to observe a hysteretic optically detected DMPR. We use pulse modulated mw heating and time-resolved PL detection techniques in order to investigate the different processes that are related to electron heating. The optically detected DMPR is studied as a function of the mw power and of the mw pulse duration t_p. The 2DEG parameters n_{2D} and T_e are reliably estimated from the analysis of the 2DEG-free hole PL spectrum, and the dependence of n_{2D} on T_e is obtained. A long recovery time ($\sim10^{-2}$ sec) of the decreased n_{2D} is observed.

The MDQW samples were grown by molecular-beam epitaxy, and they have the following layer structure: a 500 nm thick GaAs buffer, a 3/10 nm GaAs/$Al_{0.33}Ga_{0.67}As$ superlattice (100 periods), a 25 nm-thick GaAs QW, a 80 nm-thick $Al_{0.33}Ga_{0.67}As$ spacer layer, a 350 nm-thick Si-doped $Al_{0.33}Ga_{0.67}As$ layer, and a 10 nm-thick GaAs cap layer. The 2DEG densities and dc mobilities for samples from several different wafers, varied in the ranges $n_{2D}=(1.1\text{–}2.4)\times10^{11}$ cm^{-2} and $\mu_{dc}=(1-4)\times10^6$ cm^2/V sec at 4 K. The samples were fabricated in the form of round mesas (0.5–0.7 mm in diameter) that contain a laterally confined 2DEG. Large area samples 2×2 mm^2 were also studied. The sample was inserted in an 8-mm waveguide. The mw power from a 36 GHz Gunn-diode varied in the range of $P_{in}=(10^{-3}-50)$ mW, and it was modulated by a p-i-n diode. The mw pulse duration t_p and the repetition frequency $f=T_p^{-1}$ were controlled in the range of $(10^{-7}\text{–}10^{-2})$ sec and $(10^2\text{–}10^5)$ Hz, respectively. The magnetic field B was applied perpendicularly to the sample plane, while the mw electric field was in the plane. The sample was photoexcited at 1.56 eV with Ti-sapphire laser light, and the incident intensity was kept below 10^{-3} W/cm^2. The PL was detected with a spectrometer equipped with a photomultiplier. Time-resolved PL experiments were performed by using a photon counter with a variable gate (θ). The sample temperature T_L was varied in the range 1.7–30 K, however, the mw irradiation experiments were performed with the sample immersed in liquid He at 1.8 K.

Figure 1(a) displays PL spectra obtained under the lowest photoexcitation intensity (that does not affect the PL spectrum), at $B=0$ and at several P_{in} values. PL spectra taken at various lattice temperatures are shown in Fig. 1(b). A comparison between Figs. 1(a) and 1(b) reveals an essential difference between the PL spectral modification with increased T_L and with increased P_{in} at $T_L=1.8$ K: the PL spectra are blue-shifted and become narrower with increasing P_{in}. Since the PL of the studied high quality MDQW originates from the 2DEG-free hole radiative recombination it is an evidence that the observed PL modification under cw mw irradiation can result from both T_e and n_{2D} changes.

In order to exclude the PL spectral modification that is due to the increased T_e, the PL spectra were measured within the gate $\theta=3\times10^{-3}$ sec after an intense mw pulse irradiation of $P_{in}=10$ mW [see time diagram in Fig. 1(c)]. Such PL spectra (curves 4 and 5) are shown in Fig. 1(c) for mw pulse of $t_p=10^{-5}$ sec and 2×10^{-3} sec (with a pulse cycle $T_p=7\times10^{-3}$ sec), respectively. These spectra should be compared with those obtained under cw mw power of $P_{in}=0$, 0.1, and 10 mW (spectra 1, 2, and 3, respectively).[17]

A remarkable PL modification occurs with increasing t_p, namely, the spectrum 5 (taken at long mw pulses) is blue-shifted and narrow when compared with the spectrum 4. This indicates that the mw pulse causes a n_{2D} decrease which does not recover during the time interval of T_p-t_p (of the order 10^{-2} sec) after the pulse turns off. We found that the n_{2D} value that determines the PL spectrum, decreases with increasing t_p until it reaches the same value as observed under cw mw irradiation (see below). The n_{2D} vs t_p dependence varies with T_p, and this allows us to estimate the characteristic relaxation times for the processes of the n_{2D} decrease and recovery.[18]

Figure 2 shows an optically detected DMPR for the MDQW mesa of 0.5 mm diameter. The PL intensity at $E_{mon}=1.517$ eV is measured as a function of the magnetic

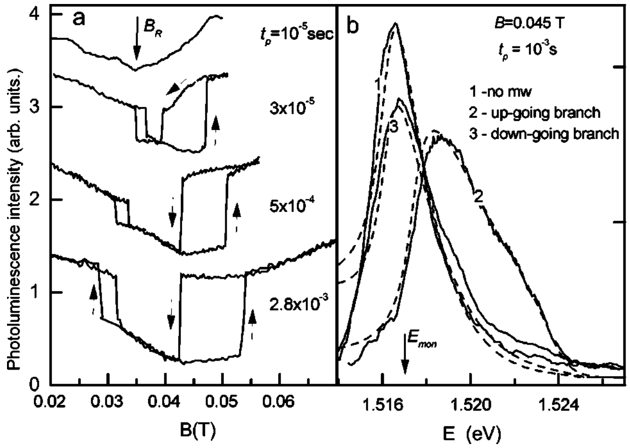

FIG. 2. (a) ODR at $P_{in}=1$ mW and at various mw pulse duration t_p. Hysteretic curves are vertically shifted for clarity. (b) PL spectra obtained at two hysteresis branches (solid lines) and the fitted PL spectra (dash lines) with n_{2D} and T_e values shown in Fig. 3.

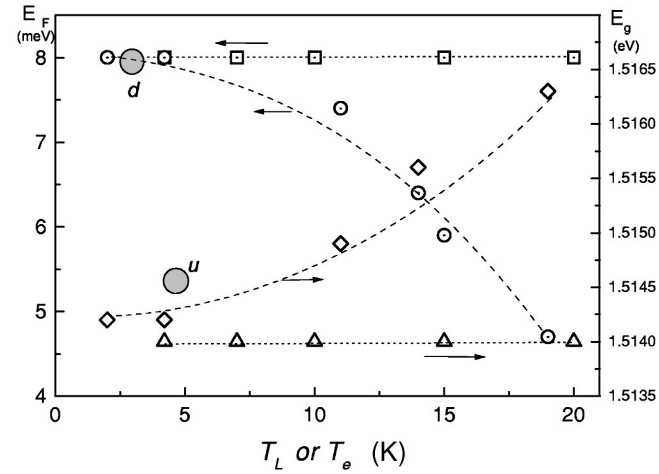

FIG. 3. The 2DEG parameters obtained by fitting the measured PL spectra. ⊡, ⊙ and △, ◇ are the $E_F=3.6\times(n_{2D}/10^{11})$ and E_g values for lattice and mw heating, respectively. The circles denoted by d and u correspond to the values of E_F and T_e at $B=0.045$ T extracted from the PL spectra 2 and 3 of Fig. 2(b) (on the down and up-going hysteresis branches, respectively).

field (B) when B is slowly scanned back and forth. The θ-gated PL is taken after termination of mw irradiation pulses at several t_p ($P_{in}=1$ mW). Under short mw pulses, the ODR occurs at $B_R=0.035$ T and it is similar to that observed at low cw mw power of 0.01 mW,[12,13] as a result of the mw power leakage.[17] At $t_p>2\times10^{-5}$ sec, the PL intensity exhibits a hysteretic dependence on B with sharp discontinuities in both hysteresis branches. The hysteresis loops become wider with increased t_p, and the PL hysteresis at $t_p=10^{-3}$ sec is similar to that observed under cw $P_{in}=1$ mW. Also, the appearance of two loops is due to the complexity of the nonlinearity.[9]

The PL spectra obtained under the ODR conditions are presented in Fig. 2(b). A clear difference exists between the PL spectra measured for the same B within the hysteresis loop: on the up-going branch (curve 2) and then, on the down-going branch (curve 3). Thus, the hysteresis of the PL lineshape unambiguously shows the 2DEG density decrease under the electron heating on the up-going branch.

The PL hysteresis is also observed under cw mw irradiation. However, the presence of hot electrons as well as of the nonequilibrium phonons makes the observation and interpretation of the experiment more complicated.[18] The combined time-resolved technique allowed us to measure the PL hysteresis and to estimate n_{2D} in the absence of the hot electrons and of the nonequilibrium phonons since both T_e and nonequilibrium acoustic phonon population has completely relaxed before the PL-gating.

The PL spectra were fitted by a simple, noninteracting electrons model[19] in order to obtain n_{2D} and T_e parameters of the nonequilibrium 2DEG subjected to mw heating as well as at an equilibrium with a high T_L. The fitted spectra shown in Figs. 1 and 2, yield the n_{2D}, T_e and the renormalized band gap E_g values that are presented in Fig. 3. As one can see n_{2D} and E_g do not vary with lattice temperature T_L. In contrast, the n_{2D} and E_g values for the mw heated nonequilibrium 2DEG vary with the 2DEG effective temperature T_e. The T_e values were estimated from the PL spectra measured under cw mw irradiation at various P_{in} [e.g., curve 3 of Fig. 1(c)], while n_{2D} were obtained from the time-resolved PL spectra measured with delay of 2×10^{-3} sec after the mw pulse of 2.8×10^{-3} sec terminated [e.g., curve 5 of Fig. 1(c)]. As the shorter mw pulse is used the PL spectrum is shifted to lower energy [curve 4 of Fig. 1(c)], and the n_{2D} value increases. It should be noted that T_e values extracted from the fitting of the gated PL spectra are slightly higher than $T_L=1.8$ K due to the mw leakage.[17]

The estimated 2DEG parameters on both hysteresis branches [extracted from Fig. 2(b)] are also given in Fig. 3. We conclude that n_{2D} decreases by $\sim$40% on the up-going hysteresis branch when the temperature of the mw heated 2DEG reaches $T_e\sim15$ K. As the magnetic field is scanned, T_e increases due to the DMPR, and n_{2D} decreases. Since the DMPR position B_R depends on n_{2D} the nonlinearity of the absorbed mw power arises, and this leads to the observed hysteresis.[9]

We thus have a conclusive proof of a long-lived 2DEG density decrease when the high mobility 2DEG is driven into a nonequilibrium state by heating the electrons. Now, we propose that this decrease occurs by a warm electron vertical tunneling out of the QW into the electronic states in the layers surrounding the QW. Since the time of the direct electron tunneling between the 2DEG and Si-doped layer (separated by a 80 nm-thick spacer layer) in the studied samples is extremely long, 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 nonlinear dependence of n_{2D} on T_e (Fig. 3) is an inherent property of the nonequilibrium 2DEG since there is no such dependence with increased T_L (for the equilibrium state). This strong nonlinearity can result from the electron vertical tunneling assisted by the nonequilibrium acoustic phonons,[20] as well as from a redistribution of the built-in HJ electric field with decreasing n_{2D}.

In conclusion, we have observed a hysteresis of the 2D-electron-free hole PL intensity and spectrum in laterally confined GaAs/AlGaAs MDQW. The hysteresis is a new manifestation of the 2DEG nonlinear dimensional magnetoplasma resonance induced by intense microwave irradiation. The time-resolved study of the PL change under the optically detected DMPR as well as at $B=0$, reveals a decrease of the 2DEG density with increasing the 2D-electron temperature. A long recovery time of the density change is observed. We attribute this phenomenon to a modification of electron vertical transport processes in the heterostructure under heating of the 2DEG.

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