Dimensional magnetoplasma resonance detected by free-exciton photoluminescence in modulation-doped GaAs/$Al_xGa_{1-x}As$ heterojunctions

B. M. Ashkinadze and E. Linder
Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel

V. Umansky
Braun Center for Submicron Research, Weizmann Institute, Rehovot, Israel

(Received 18 May 2000)

We studied the effect of microwave (mw) irradiation on the low-temperature photoluminescence (PL) of high-quality, modulation-doped, wide GaAs/$Al_xGa_{1-x}As$ heterojunctions (HJ's) containing a two-dimensional electron gas (2DEG), in the density range of $(0.9–4)\times10^{11}\ cm^{-2}$. The PL arises from excitons that recombine radiatively in the GaAs buffer layer, far from the 2DEG which is confined close to the GaAs/$Al_xGa_{1-x}As$ interface. We observe that the exciton PL is affected by a mw heating of the 2DEG: the mw-induced PL intensity change increases with increasing 2DEG density as well as under a perpendicular magnetic field that corresponds to the 2DEG dimensional magnetoplasma resonance (DMPR) condition. Moreover, the exciton PL intensity shows a bistability at magnetic field strengths that are close to those observed in the DMPR mw absorption. The mw-induced PL modulation effects are interpreted as being due to the interaction of the excitons with low-energy, ballistically propagating acoustic phonons that are emitted by the mw-heated 2DEG. The exciton PL quenching is associated with an exciton drag by the phonon flux towards the opposite HJ interface where the excitons recombine nonradiatively. The rate of phonon emission is determined by the 2DEG state, and thus the exciton PL responds to the changes of the 2DEG parameters.

I. INTRODUCTION

A high-mobility two-dimensional electron gas (2DEG) is formed near the interface of a GaAs/$Al_{0.3}Ga_{0.7}As$ heterojunction by electron transfer from the selectively doped $Al_xGa_{1-x}As$ barrier layer into the undoped GaAs buffer layer.[1] A number of basic physical phenomena have been found in the heterojunctions containing an ''equilibrium'' 2DEG. The latter means that the 2DEG density and mobility do not change with varying the experimental conditions, and there is no electron transfer between the 2DEG and the nearby buffer and barrier layers (in the dark and at low temperature). The 2DEG can be easily excited to a nonequilibrium state either with application of an in-plane electrical field or under photoexcitation of the 2D electrons to higher-energy states by interband or intersubband radiation, whereby an electron energy distribution is modified. The 2DEG driven into a nonequilibrium state exhibits a variety of interesting phenomena, among which are modulation of longitudinal resistance by microwave (mw) or far-infrared (FIR) irradiation (photoconductivity-detected cyclotron and spin resonances),[2–5] and current, mw, or FIR-induced changes of the photoluminescence (PL).[6–9] Physical mechanisms producing these changes are not well understood,[2,4,6,8,10] and therefore processes related to athermal (hot) 2D electrons have to be explored. Recently, we observed a hysteretic cyclotronlike resonance (CR) of a laterally confined 2DEG that is heated by mw irradiation.[11] The hysteresis provides unambiguous evidence that the 2DEG density decreases with a moderate increase of the electron temperature $T_e=10–20$ K. Hot 2D electrons also emit nonequilibrium phonons[12,13] that can affect the spectroscopic and dynamic properties of photoexcited heterostructures.

The low-temperature radiative recombination of the 2DEG with photoexcited holes proved to be an effective optical probe of the many-body interactions and their modification under an applied magnetic field.[14] The 2DEG photoluminescence (PL) spectral shape, intensity, and decay time have been shown to strongly depend on the 2DEG-hole separation.[14–18] Therefore, whether photoexcited holes are free or bound and the degree of their localization are of central importance. In high-quality heterojunctions (HJ's) having a *p*-type GaAs buffer layer, the photoexcited electron-hole pairs are separated by the built-in HJ electric field that can spread throughout the entire (wide) buffer GaAs layer.[19] The holes drift away from the interface and the electrons accelerate towards the interface where the 2DEG is located (Fig. 1). The 2D electron-hole separation might be so large that no 2DEG–free hole radiative recombination is observed since electron and hole wave functions barely overlap. In order to study the 2DEG-hole PL in a HJ, the GaAs-buffer layer is intentionally *p*-type δ-doped in the vicinity of the 2DEG.[14] Without such a doping the PL spectrum of high-quality, wide HJ's (with a GaAs buffer layer width exceeding 100 nm) is dominated by exciton recombination in the GaAs buffer layer.[20] Nevertheless, the PL lines exhibit some specific 2DEG features: PL intensity oscillations that correlate with the 2DEG filling factor were observed under a magnetic field applied perpendicularly to the HJ plane;[8,9,16,21] PL modifications caused by a 2DEG heating were reported.[6–9] These observations lead to conflicting interpretations of the PL lines origin in HJ's. In the previous PL studies, the effects of phonon emission and decreased 2DEG density that accompany the nonequilibrium 2DEG state on the PL of the HJ's were not considered.

In order to elucidate these issues we studied the PL spectroscopy of modulation-doped GaAs-$Al_xGa_{1-x}As$ HJ structures by varying the 2DEG density (by cw optical depletion)

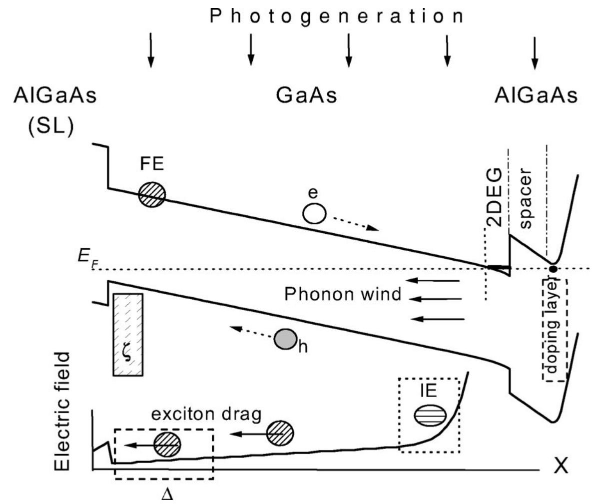

FIG. 1. Schematic band and built-in electric field profiles of the HJ. Free excitons are formed in flat GaAs region (Δ); they diffuse and drift in a built-in electric field towards the 2DEG. The exciton drag into the ζ region by the phonon wind emitted from the 2DEG is schematically shown.

and its electron temperature (by mw irradiation). Applying a perpendicular magnetic field (simultaneously with mw irradiation), a 2DEG dimensional magnetoplasma resonance (DMPR) is detected by the resonant PL intensity quenching. The latter shows a bistability (hysteretic dependence on the applied magnetic field) that corresponds exactly to the 2DEG bistability observed in the mw absorption of the 2DEG.[11] We attribute the PL to the radiative recombination of excitons in the GaAs buffer layer and the mw-induced PL spectral modifications to the strong interaction between the spatially separated buffer layer excitons and the 2DEG. This is an indirect interaction that we propose to be mediated by the nonequilibrium phonons emitted by the hot 2DEG.[7]

The paper is structured as follows: Section II presents the samples parameters and the experimental setup for the simultaneous study of microwave transmission and PL spectroscopy. The experimental studies of the 2DEG DMPR and of the PL spectral modifications under mw irradiation and applied magnetic field are presented in Secs. III and IV, respectively. The dynamic processes occurring under HJ photoexcitation and the PL lines origin are discussed in Sec. V. The interaction between the mw heated 2DEG and the excitons, mediated by the nonequilibrium phonons, and the bistablity observed in the PL intensity are considered in Sec. VI. Conclusions are given in Sec. VII.

II. HETEROJUNCTION SAMPLES AND EXPERIMENTAL PROCEDURE

Several modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ HJ's grown by molecular beam epitaxy on (001)-oriented, undoped GaAs substrates were studied. An undoped GaAs buffer layer (having a thickness of 1.5 μm) is grown on a superlattice that separates it from the substrate. An $Al_{0.3}Ga_{0.7}As$ layer is grown on top of the buffer layer. It contains a Si-doped layer that is separated from the GaAs/$Al_{0.3}Ga_{0.7}As$ interface by a spacer layer whose width varies in the range 30–70 nm (in different samples). The high-mobility 2DEG is formed in the potential notch near this interface (Fig. 1). The 2DEG density and the dc mobility, measured at $T_L=4$ K, for the various samples were in the ranges $n_{2D}^0=(0.9–2.6)\times10^{11}\,\mathrm{cm}^{-2}$ and $\mu_{dc}=(2.2–4.5)\times10^6\,\mathrm{cm}^2/\mathrm{V\,sec}$, respectively. All the studied samples show similar PL spectra and mw modulation. Most of the data presented here were obtained for one HJ, having $n_{2D}^0=2.6\times10^{11}\,\mathrm{cm}^{-2}$ and $\mu_{dc}=2.8\times10^6\,\mathrm{cm}^2/\mathrm{V\,sec}$. This sample was fabricated in the form of a small, round mesa with a diameter of $a=0.7$ mm in order to ensure linearity of the mw absorption signal for low mw power.

The sample was inserted in an 8-mm waveguide that was short-circuited at one end. A 36 GHz Gunn diode was used as a mw radiation source and the incident mw power was varied in the range of $P_{in}=10^{-3}$–10 mW. The sample was immersed in liquid He or in cold He gas, and the temperature was varied in the range of $T_L=1.8$–25 K. An external magnetic field B was applied either perpendicularly to the HJ plane (for 2DEG cyclotron resonance), or parallel to it (allowing a electron CR to occur only in thick layers such as the GaAs buffer layer). The magnetic field was slowly scanned ($\sim$50 G/min) back and forth in the range of $B=0-0.2$ T. The sample was illuminated by laser light (from a He-Ne or a tunable dye laser) through a pinhole in the waveguide. The incident laser intensity was varied in the range $I_L=0.001-50\,\mathrm{mW/cm}^2$. The cw PL and its modifications were analyzed by a standard spectroscopic technique. The mw radiation transmitted by the sample and reflected from the short-circuited end of the waveguide was measured as a function of scanned magnetic field.[11,22]

III. DIMENSIONAL MAGNETOPLASMA RESONANCE OF THE 2DEG

An electron resonantly absorbs mw radiation of a frequency $f=\omega/2\pi$, when the magnetic field satisfies the cyclotron resonance (CR) condition $\omega=\omega_{CR}=eB_{CR}/m^*c$, where m^* is the electron effective mass. For $f=36$ GHz (used here), the resonance field of free electrons in GaAs is $B_{CR}=0.086$ T. It is well known that the CR transforms into a dimensional magnetoplasma resonance (DMPR) with increasing electron density.[23] A similar DMPR was observed and studied in the laterally confined 2DEG (see the review in Ref. 24). When the electrons are confined to a mesa with a diameter a, DMPR takes place at a magnetic field given by

$$B_R=B_{CR}-\frac{3\pi^2ecn_{2D}}{2\kappa\omega a}, \tag{3.1}$$

where κ is the average dielectric constant value of GaAs and free space (~7).[24] By measuring B_R we can find the n_{2D} variation under varied experimental conditions (photoexcitation intensity and/or mw power). In addition to the n_{2D} determination, the resonance line shape is fitted to a Lorentzian that yields the 2D electron momentum relaxation rate, and thus the CR mobility, μ_{CR}, can be estimated.

Figure 2 presents the mw transmission versus B traces measured with a very low mw power at 2 K in the dark (curve a) and under He-Ne laser illumination with increasing I_L values. The DMPR line shape fit of the trace obtained in the dark, yields $B_R=0.02$ T and $\mu_{CR}=1.25\times10^6$ cm^2/V sec.

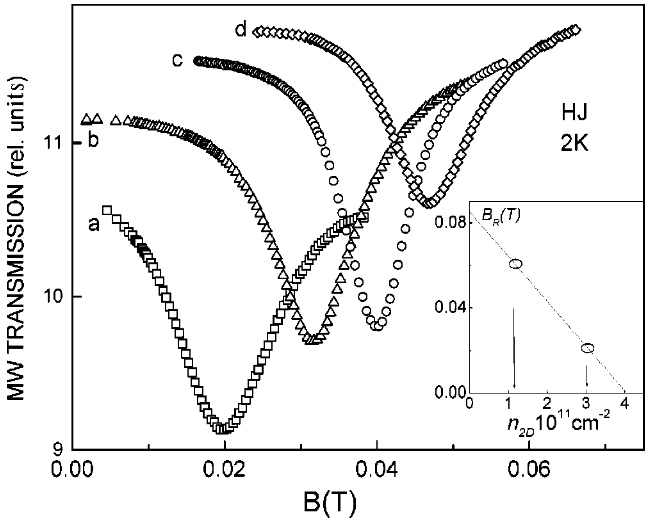

FIG. 2. MW transmission vs B at $P_{in}=0.01$ mW for photoexcitation of $I_L\,(\mathrm{mW/cm^2})$: (a) 0, (b) 10^{-3}, (c) 10^{-2}, and (d) 10^{-1}. Inset shows the calculated dependence of $B_R(n_{2D})$ [Eq. (3.1)]; the arrows indicate the available range of n_{2D} for the studied sample.

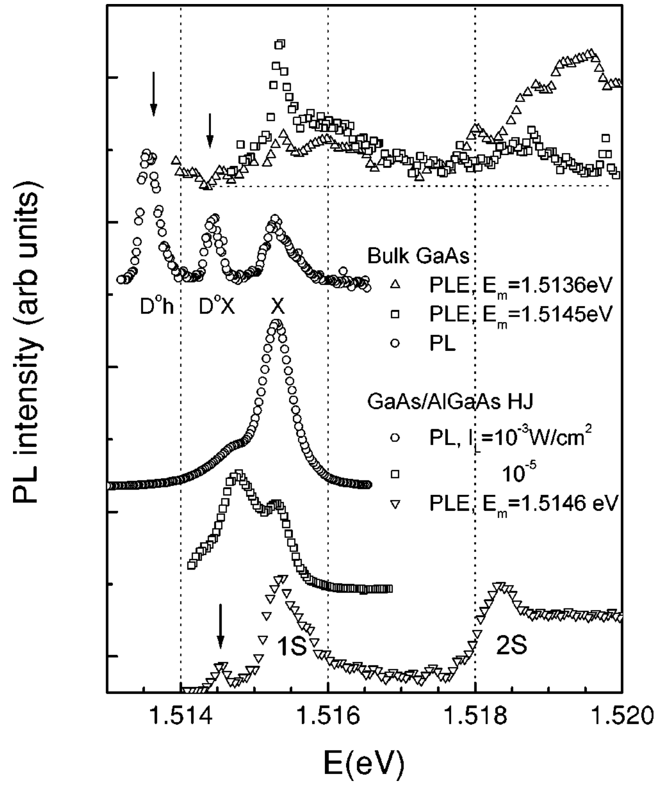

FIG. 3. PL and PL excitation (PLE) spectra of the bulk GaAs and of the wide GaAs/Al_xGa_{1-x}As heterojunction structure at 2 K; the monitored PL energies E_m are shown by arrows.

Illumination with laser energy $E_L > E_{g2}$, the $Al_{0.3}Ga_{0.7}$As energy gap, causes a 2DEG density decrease, namely, an optical depletion of the heterojunction,[14,19] and it results in a B_R increase. It should be noted that B_R shifts to 0.03 T under photoexcitation into the 2S FE state of GaAs (at $E_L = 1.5185$ eV). From these experiments we conclude that optical depletion is also caused by illumination with photon energies $E_L < E_{g2}$; however, its efficiency is much lower than that under light with $E_L > E_{g2}$. In the inset of Fig. 2 we plot $B_R(n_{2D})$ as computed using Eq. (3.1). The experimentally obtained B_R values determine the 2DEG density range (marked in the figure inset) that was achieved under optical depletion in our study. As the mw power increases the DMPR shifts to higher B_R and exhibits the hysteresis studied and analyzed in Ref. 11.

IV. EXCITON PHOTOLUMINESCENCE

All the studied HJ's having various 2DEG densities show similar PL spectra. Under the lowest photoexcitation intensities and at the ambient temperature $T_L = 2$ K, the PL spectrum consists of two lines at $E_x = 1.5153$ eV (marked X in Fig. 3) and at $E_b = 1.5146$ eV. Their relative intensities vary from sample to sample. In order to identify the origin of these lines, we compare in Fig. 3 the PL and its excitation (PLE) spectra for the HJ with those of an undoped GaAs layer of 10 μm thickness.[20,25] The three PL lines of the bulk GaAs are assigned to the free exciton (FE), the exciton bound to a neutral donor, D^0X, and the free hole-neutral donor, D^0h, recombination. (The latter is based on the differences between the PLE spectra monitored at D^0X and at D^0h lines.)[25] Note, that the X PL bands and the PLE spectra of both samples are similar, and the PL and PLE line shape difference is likely to be due to the various GaAs layer thickness in bulk and HJ samples.

The integrated PL intensity of the studied HJ's shows a superlinear increase with increasing He-Ne laser intensity and a simultaneous increase of the X line relative to the lower-energy line (Fig. 4, left panel, curves c to a). However, under photoexcitation at $E_L = 1.5185\,\mathrm{eV} < E_{g1}$ (below GaAs band gap) the integrated PL intensity increases nearly linearly with I_L, the PL band at E_b is stronger, and both PL lines are broader (curve c). We observe that both PL linewidths are unaffected by the 2DEG density when n_{2D} varies either in the different HJ's (having various n_{2D}) or by increasing I_L (Fig. 2) as it would be expected if the PL bands had resulted from the 2DEG.

At $T_L = 2$ K the PL spectral modification with increased mw power is shown in Fig. 4, right panel. Increasing mw power at very low I_L (curves c, c1) results in an increased X-line intensity (J_X) and a decreased intensity of the low-energy line. A further increase in P_{in} quenches the entire PL, as shown in Fig. 5 (for $I_L = 0.03\,\mathrm{mW/cm^2}$). The intensity of the X line decreases by 6 times and its width increases from 0.35 meV to 0.6 meV at $P_{in} = 4$ mW (Fig. 4, curves a and a1). At $T_L = 4$ K the X line always dominates in the PL spectrum, its spectral linewidth is about 0.5–0.6 meV, and increasing the mw power causes a J_X decrease without noticeable line broadening. Under higher He-Ne laser intensity the PL quenching with increasing P_{in} weakens (see Fig. 5), and the PL quench occurs only under resonant magnetic field strength (Fig. 6).

The mw-induced change of the X-line intensity depends on a magnetic field. The main finding is an observation of the 2DEG DMPR by means of the buffer layer PL.[7] In Figs. 6(a), 6(b), and 6(d) the $J_X(B)$ dependencies are shown for the three P_{in}. At low mw power one can see a complicated behavior of $J_X(B)$ around the resonant B_R. Below we will see that this behavior results from the J_X dependence on the

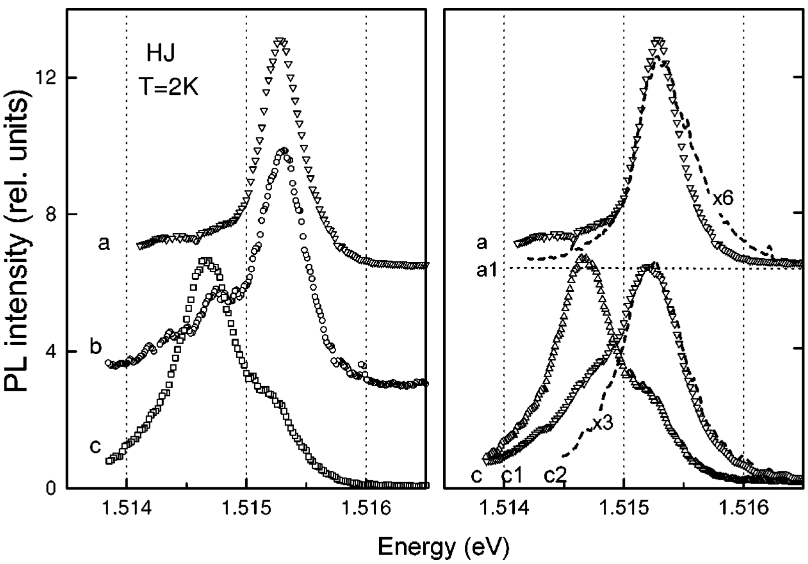

FIG. 4. PL spectra of the HJ under various experimental conditions: E_L (eV), I_L (W/cm^2), P_{in} (mW). (a) 1.96, 10^{-4}, 0; (a1) 1.96, 10^{-4}, 4; (b) 1.96, 10^{-5}, 0; (c) 1.519, 10^{-3}, 0; (c1) 1.519, 10^{-3}, 0.5; (c2) 1.519, 10^{-3}, 4. The PL spectra (a1) and (c2) are normalized to those obtained in the absence of mw irradiation.

absorbed mw power when J_X increases at the expense of the low energy PL band (see Fig. 5). At increased P_{in}, $J_X(B_R)$ exhibits a clear resonant quenching. The latter follows the n_{2D} variations: At lowest He-Ne light intensity [Fig. 6(a)] or under photoexcitation at $E_L=1.519$ eV [Fig. 6(d)] when optical depletion is weak and n_{2D} is highest, the resonant quenching is at low B_R, and it is very intense [Figs. 6(a) and 6(d)]. With increasing I_L the resonant quenching of J_X occurs at higher B_R, and the ratio $J_X(B=0)/J_X(B_R)$ decreases [Fig. 6(c)]. The resonant B values strictly correspond to those of the DMPR. Thus, an optically detected dimensional magnetoplasma resonance of the 2DEG is observed by monitoring the X-band PL intensity.

At more higher P_{in}, the $J_X(B)$ dependencies exhibit a hysteresis: they depend on whether B increases or decreases. The $J_X(B)$ hysteresis loop is wide for high n_{2D} [Figs. 6(d) and 6(a)], namely, under photoexcition at $E_L<E_{g2}$ or under very low He-Ne laser intensities. The hysteresis disappears for high I_L values [Fig. 6(c)]. The X PL intensity demonstrates a bistable behavior at the same P_{in}, B, and I_L as the hysteretic DMPR does.[11] For comparison, the mw transmission hysteresis is shown in the bottom of Fig. 6(b).

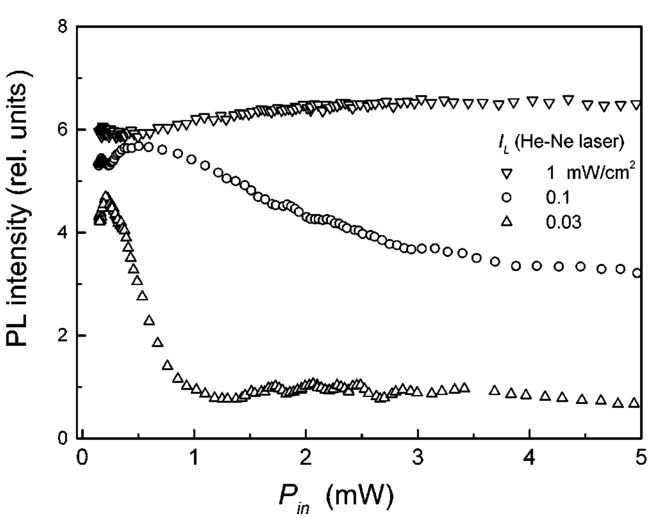

FIG. 5. Exciton PL intensity vs P_{in} at three photoexcitation intensities (I_L).

The mw-induced PL modification is also studied when a magnetic field is applied parallel to the heterojunction plane. At $B=0$ the X-line PL intensity either increases or quenches (see Fig. 5) under mw irradiation, but its value is independent of B. In contrast, the exciton PL in the thick undoped GaAs layer exhibits a clear resonant quenching (optically detected cyclotron resonance at B_{CR}) due to the effective heating of free photoelectrons in bulk GaAs at B_{CR}.[22] In the case of the HJ, the mw absorption by the 2DEG overwhelms that due to photoinduced electrons in the GaAs buffer layer, and there are no observable changes in the mw transmission versus B since the in-plane magnetic field does not affect the mw absorption by the 2DEG.

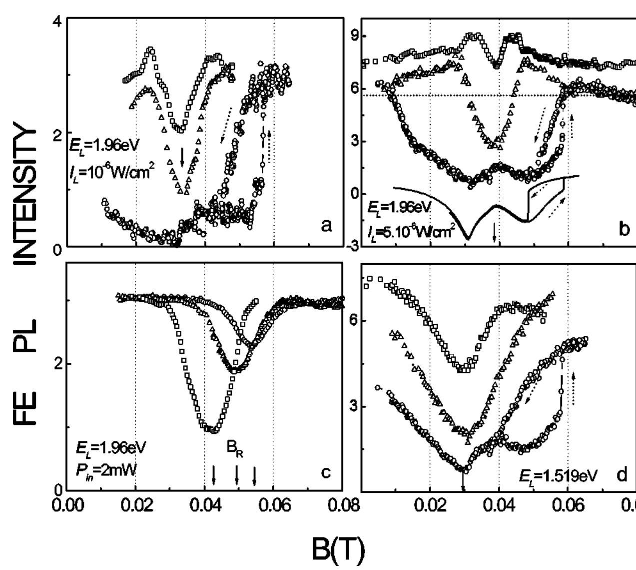

FIG. 6. Exciton PL intensity vs B monitored at the FE peak energy for various P_{in} (mW): (a) $I_L \sim 1\times10^{-6}$ W/cm^2 (He-Ne laser excitation) and $P_{in}=0.2$ (squares); 0.5 (triangles); 2 (circles). (b) $I_L \sim 5\times10^{-6}$ W/cm^2 (He-Ne laser excitation) and $P_{in}=0.2$ (squares); 0.5 (triangles); 2 (circles). (c) $P_{in}=2$ and He-Ne laser excitation at I_L (W/cm^2)$=10^{-5}$ (squares); 10^{-4} (triangles); 10^{-3} (circles). (d) Below band gap GaAs excitation and $P_{in}=0.2$ (squares); 0.5 (triangles); 2 (circles). The mw transmission hysteresis is shown in the bottom of (b).

V. EXCITON FORMATION IN THE PHOTOEXCITED HETEROJUNCTION

A GaAs buffer layer of a high-quality, modulation-doped HJ usually contains residual acceptor impurities with the density of the order of 10^{13}–10^{14} cm^{-2}. The built-in electric field in such a HJ exists in the entire, *p*-type GaAs buffer layer.[19] Schematic band and built-in electric field profiles are shown in Fig. 1. Free electron–hole pairs are photogenerated practically homogeneously throughout the structure since the light penetration length is about 1 μm. These pairs bind into excitons in the GaAs layer flat band region situated far from the potential notch (the Δ region in Fig. 1), and these excitons diffuse or drift to the higher field region. Most of the free electrons and holes photoexcited outside the Δ region are separated by the built-in electric field: the holes drift away from the HJ and the electrons drift towards the 2DEG. In samples having a high carrier mobility, the electron-hole (e-h) separation process lasts a short time so that the probability of a free, spatially indirect exciton formation from the separated electron and hole[8] is likely to be very low. The recombination of the 2D electrons with holes photogenerated in the $Al_xGa_{1-x}As$ layer and swept into the GaAs layer gives rise to 2DEG optical depletion.[14] The PL spectrum of such a recombination should be spectrally redshifted with respect to the GaAs FE PL spectrum, and the n_{2d} variation should lead to the spectral shift change.[14] A fast hole drift in the HJ built-in electric field away from the 2D electrons results in an inefficient 2DEG–free hole radiative recombination, and this PL is unlikely to be observed in high-quality HJ's having a wide (above 100 nm) GaAs buffer layer.

Under low photoexcitation intensities, as long as the HJ built-in electric field is not significantly modified, two PL channels originating from the free excitons should be considered: (a) GaAs free excitons and (b) interface excitons (IE's), the excitons driven by the electric field gradient close to the potential notch (Fig. 1).[20,26] The IE's are polarized by the electric field, and their energy is lower than that of the FE's.[26] The total luminescence intensity should be weak since the excitons can be formed from *e-h* pairs only in the small Δ region, where the bands are nearly flat. As the photoexcitation intensity increases the electron and hole separation results in decreased band bending,[19] and the Δ region widens. The total number of the formed excitons increases nonlinearly with I_L, and fewer are driven towards the potential notch since the built-in electric field gradient decreases. Thus, as I_L increases we expect a superlinear rise of the integrated PL intensity and a redistribution of the PL spectrum, with an increased FE PL intensity.

The experimental results (Figs. 3 and 4) allow us to conclude that the PL bands originate from the FE recombination (at E_x) and from the IE recombination (at E_b). An observation of the superlinear increase of the integrated PL intensity and the PL spectral redistribution with increasing I_L, as well as the different PL behavior under *e-h* pair photogeneration ($E_L = 1.96$ eV) and under direct FE generation ($E_L = 1.5185$ eV) support such an assignment (see also Ref. 20). Indeed, under photoexcitation with $E_L < E_{g1}$ the FE's are generated throughout the entire GaAs layer, and few free *e-h* pairs are photogenerated, thus, the built-in electric field weakly varies with I_L, the integrated PL intensity increases linearly with I_L, and the IE PL intensity is highest.

VI. THE INTERACTION OF NONEQUILIBRIUM PHONONS WITH THE EXCITONS

It is known that electron heating in dc or mw electric fields affects the exciton PL intensity in undoped, bulk semiconductors and in undoped quantum wells.[27] The physical mechanism of this PL modulation arises from the direct hot electron–hole (or exciton) interaction leading to a decreased exciton formation probability or to exciton heating and ionization as the electron temperature increases.[28] The FE PL mw-induced changes in HJ's containing a 2DEG cannot be explained in these terms because of the following differences: (a) It arises from a hot 2DEG that is located far away from the FE's. (b) It decreases as n_{2D} is reduced under intense He-Ne laser illumination (Figs. 5 and 6). (c) The 2DEG DMPR and its bistability clearly show up in the mw-induced FE PL modulation (Fig. 6). (d) PL mw-induced modulation is more effective compared to bulk GaAs and undoped GaAs QW's. Since we established that the PL is due to the free excitons in the wide buffer layer we must explain how excitons interact with the 2DEG situated far away.

We propose that this interaction is mediated by low-energy acoustic phonons that are ballistically propagating from the mw-heated 2DEG over a long distance.[12,13,29] Such nonequilibrium phonons were detected by using special bolometers[12] as well as by the exciton PL modulation in a Si field-effect transistor[13] when the 2DEG was strongly heated by the electric pulses. Below, we consider the physical processes that can lead to exciton PL modification under 2DEG heating in HJ's.

A. 2DEG temperature increase

As the 2DEG is subjected to an intense mw irradiation at low T_L, its effective temperature T_e increases in order to balance the gained Joule power to the power of energy losses due to phonon emission. The T_e dependence on the gained power per electron was widely studied, both theoretically[30,31] and experimentally.[32,33] It was shown for GaAs heterostructures containing a 2DEG that T_e reaches 15–20 K for a gained dc electric power of 10^{-13} W/electron at $T_L < 2$ K. In QW's, the similar estimate of T_e for the 2DEG heated by mw irradiation was obtained from the 2DEG–free hole PL spectrum analysis.[34] At the highest P_{in} used in our experiments the absorbed mw power by the mesa containing the 2DEG does not exceed 0.1 mW, and from this we estimate $T_e \leqslant 20$ K. For a fixed P_{in} the strongest electron heating occurs at B_R, thus, scanning magnetic field varies T_e.

An effective heating of the 2DEG can also occur under photoexcitation of the HJ, in the absence of mw irradiation. Indeed, due to the built-in electric field [it is of the order of 10^3 V/cm even under strong illumination of such a HJ (Ref. 19)], the photoelectron accelerating towards the notch, can acquire a high energy and transfer it to the 2DEG. Each electron transfers to the 2DEG an energy of the order of $h\Omega \approx 36$ meV, the LO-phonon energy. Then, the gained power per electron in the 2DEG can be estimated from the following expression (similar to the case of quantum well photoexcitation[34]):

$$\left\langle \frac{dE}{dt} \right\rangle \simeq \frac{\hbar \Omega I_L \alpha L}{n_{2D} \hbar \omega}, \tag{6.1}$$

where $\hbar\omega$, α, and L are the photon energy, absorption coefficient and GaAs buffer layer width, respectively. Here we assume that all electrons photogenerated in the buffer layer, $I_L \alpha L/\hbar\omega$, reach the 2DEG. For $I_L = 0.01\,\mathrm{W/cm^2}$, $\alpha L \sim 1$, and $n_{2D} = 2\times10^{11}\,\mathrm{cm^{-2}}$, Eq. (6.1) yields $\langle dE/dt\rangle = 10^{-15}$ W, and it results in $T_e \simeq 5$ K according to Ref. 33. Thus, a moderate photoexcitation of the wide HJ might result in the increased 2D electron temperature.

B. Nonequilibrium phonons emission by a hot 2DEG

The hot electrons at $T_e < 20$ K emit low-energy acoustic phonons that travel ballistically at low temperature.[12,29,35] The spectral distribution of phonons emitted by hot 3D electrons was calculated.[36] In this case the energy and the momentum conservation in the process of the electron-acoustic phonon interaction restricts the wave vector q and energy ε of the emitted phonons: $q \leqslant \sqrt{8kT_e m^*/\hbar^2} \approx 1.2\times10^6\,\mathrm{cm^{-1}}$, $\varepsilon = \hbar s q \leqslant 0.4$ meV. Here, we set $T_e = 20$ K, $m^* = 0.067 m_0$; $s = 5\times10^5$ cm/sec is the sound velocity. The phonons effectively interacting with the excitons at $T_L = 2$ K have $q \sim k_{ex} = \sqrt{2kT_L M/\hbar^2} \approx 5\times10^5\,\mathrm{cm^{-1}}$, where $M = m_e + m_h \sim 0.52 m_0$ is the exciton mass for GaAs. The population of the nonequilibrium low-energy phonons is proportional to the electron density, and if it exceeds that of the equilibrium phonons, the nonequilibrium phonons affect the FE PL.[35,37]

For 2D electrons the restriction associated with the conservation of the momentum component normal to the interface, $q_\perp$, is relaxed so that the 2D electrons emit phonons with $q \leqslant q_\perp + q_\parallel < \pi/D + q_\parallel$, where D is the width of the 2DEG layer. $q_\parallel$ is obtained from the conservation of the momentum component parallel to the interface: $q_\parallel \leqslant \sqrt{8\varepsilon_F m^*/\hbar^2}$, where ε_F is a 2DEG Fermi energy. This extends the range of the available energies for phonon emission, and the phonon emission rate as well as the electron energy and momentum relaxation rates is enhanced in the two-dimensional case.[30,31] Recently, calculations of the acoustic phonon emission rate by the hot 2DEG in GaAs were carried out.[38,39] It was shown that the acoustic phonon emission due to the deformation potential (DP) and piezoelectric (PE) interaction with the 2D electrons is characterized by specific spectral and angular distributions.[39]

C. The effects of nonequilibrium phonons on the exciton PL

The nonequilibrium phonons are absorbed or scattered by the excitons (as well as by the free electrons and holes). The excitons acquire energy and momentum resulting in exciton heating[37] and drag.[29] The effects of the nonequilibrium phonons on the exciton PL were observed and analyzed in bulk Si, CdS, and GaAs when the phonons were generated by a metal heater or from a hot spot appearing under strong photoexcitation.[13,35,37] In contrast to these experiments, the FE PL modulation studied here is observed at a much lower absorbed (mw) power ($W < 0.1\,\mathrm{W/cm^2}$). It is due to the fact that the energy distribution of the phonons emitted by the hot 2DEG matches quite well (as shown above) the energy (and momentum) range where the effective phonon-exciton interaction takes place.

The phonon-exciton interaction may be characterized by an absorption cross section σ averaged over the Maxwellian exciton distribution.[29] For the case of the DP interaction, σ can be estimated by using the averaged phonon absorption rate by electrons [see Eq. (3.4.4) in Ref. 36]:

$$\sigma_{DP}(q) = \frac{1}{V_T}\frac{dN_q}{dt} = \frac{E_1^2 M}{\hbar \rho s k T_L} \exp\left(-\frac{(\hbar q s - 2Ms^2)^2}{8Ms^2 kT_e} \right). \tag{6.2}$$

We use the same expression for the excitons: V_T is the exciton thermal velocity, and E_1 is an effective deformational potential for the excitons. Taking $E_1 = 7$ eV (the same as for the electrons[22]), we get $\sigma(q \approx k_{ex}) \cong 10^{-13}\,\mathrm{cm^2}$. In the case of the PA phonon-exciton interaction, the same cross section form holds, where E_1^2 should be replaced by $e^2 \rho s_L^2 K^2/\kappa q^2$ ($K^2 = 4\times10^{-3}$ is a dimensionless electromechanical coupling constant for GaAs,[22] and κ is a dielectric constant). For $q \approx k_{ex} = 5\times10^5\,\mathrm{cm^{-1}}$ we get $\sigma_{PE} = 5\times10^{-13}\,\mathrm{cm^2}$.

The absorption of the nonequilibrium DP and PE phonons causes a small increase of the exciton temperature. From the power balance equation for the exciton temperature T_{ex},

$$\sigma W = k\frac{T_{ex} - T_L}{\tau_p}, \tag{6.3}$$

one can obtain $T_{ex} - T_L \approx 0.7$ K at the phonon flux intensity of $W = 0.1\,\mathrm{W/cm^2}$ and for an exciton energy relaxation time $\tau_p \cong 2\times10^{-10}$ s.[40]

The FE PL band broadening observed under strong 2DEG heating (Fig. 4, right panel) is likely to be due to this slight exciton heating. In addition, the interface excitons are very sensitive to the temperature,[20,26] and the exciton temperature increase affects the PL intensity redistribution. The latter is observed in the experiments (Figs. 4 and 5). But, the strong FE PL quenching cannot be caused by such a temperature increase or by the direct FE dissociation due to the phonon absorption. The phonons active in the latter process must have energies exceeding the exciton binding energy (4 meV), and such phonons are not emitted by the hot 2DEG at $T_e \sim 20$ K.

Another known effect of nonequilibrium phonons on the PL is due to an exciton drag.[29,35,37] The force f exerted by the phonon flux on the exciton is given by[29]

$$f = \frac{\hbar k_{ex} \sigma W}{\hbar \omega}, \tag{6.4}$$

where $\hbar k_{ex} = (2kT_L M)^{1/2}$ is an average momentum transferred to each exciton and $\hbar\omega$ is the average phonon energy. The force causes an exciton drag with a velocity

$$V_d = \frac{f\tau_m}{M} \approx \frac{\sigma W \tau_m}{Ms}, \tag{6.5}$$

where τ_m is an exciton momentum relaxation time for the exciton scattering by the PE and DP phonons.

As follows from Eq. (6.5) V_d can exceed 5×10^4 cm/s at $W \sim 0.1\,\mathrm{W/cm^2}$. Here we use $\tau_m \cong D_{ex}M/kT \approx 10^{-10}$ s, as it is estimated using the exciton diffusion coefficient $D_{ex} \sim 100\,\mathrm{cm^2/s}$. The latter value is consistent with an estimate of τ_m based on the measured electron mobility in pure GaAs at 2 K.[22] Note that τ_m for the exciton scattering by the PE phonons at low temperature may exceed the electron momentum relaxation time.[35,40]

For bulk semiconductors it was shown that the exciton drag leads to an increased[29,35] or decreased[37] effective exciton diffusion length, and the total exciton number in the sample changes as a result of the exciton recombination on the sample surfaces. We associate the strong FE PL quenching in the HJ's with an exciton drag by the phonon flux towards the interface that is opposite to the 2DEG, and a subsequent fast nonradiative recombination there (the ζ-GaAs region in Fig. 1). The FE PL intensity reduces if the excitons with the drift velocity V_d reach the ζ-GaAs region in a time $t=\delta/V_d$ that is less than a FE radiative time, $\tau_R \approx 3\times10^{-9}$ s.[41] Here δ is the width of the Δ-GaAs region where the excitons are mainly generated. We set $\delta\leqslant 0.5\ \mu$m since the strongest PL decrease is observed under the lowest photoexcitation intensity (Fig. 5) when the Δ-GaAs region is small. Thus, we get $t\leqslant 10^{-9}$ s$<\tau_R$, and conclude that the exciton drag and fast nonradiative FE recombination in the buffer GaAs ζ-region may result in the PL quenching.

A more sophisticated analysis should take into account the spectral and angular distributions of the PE and DP phonons emitted by the 2DEG,[38,39] as well as the specific features of the PE phonon-exciton interaction.[35] Note, that the exciton interaction with low-q-vector PE phonons may even increase the cross section. (However, we should take into account that the exciton interaction reduces with increasing PE phonon wavelength.[35])

D. FE PL bistability

Recently it was shown that the 2DEG density reduces under moderate electron heating as a result of electron vertical transport in the QW structures.[11] It is the hysteretic mw DMPR in the laterally confined 2DEG that gives an unambiguous evidence of the n_{2D} decrease. Qualitatively, the DMPR hysteresis can be explained as follows. When the magnetic field increases and the DMPR evolves at B_R, the electron temperature increases. The latter leads to a decreased n_{2D}, and the DMPR shifts to the higher B [see Eq. (3.1)]. At $B_1\gg B_R$, a feedback mechanism (the decreased T_e results in larger n_{2D}, in the DMPR shift to lower B, and in a further T_e decrease) stimulates a sharp drop of T_e (and a sharp n_{2D} increase). Thus, for $B\geqslant B_1$ on the ascending branch, n_{2D} returns to its value at $B\ll B_R$. When the magnetic field scans back, the electrons begin to be effectively heated just at $B=B_2<B_1$ (when B approaches to B_R) since n_{2D} on the descendant branch is higher than that on the ascendant branch (even at $B<B_1$). The density of the heated 2D electrons decreases, the DMPR moves to meet B, and the mw absorption sharply increases (the mw transmission decreases at $B=B_2$). A quantitative analysis of the nonlinear DMPR has been done in Ref. 11. In the range of $B_2<B<B_1$, n_{2D} has two different values, and therefore the phonon flux emitted by hot 2DEG is also bistable, being proportional to n_{2D}. This gives rise to the FE PL hysteresis. The FE PL intensity demonstrates a bistable behavior at the same P_{in}, B, and I_L as in the hysteretic DMPR (Fig. 6). It is obvious that the nonlinear mw transmission and magneto-PL intensity dependencies on B are different.[22]

VII. CONCLUSIONS

We found that the 2DEG driven into nonequilibrium state by resonant (or nonresonant) microwave absorption strongly affects the photoluminescence of high-quality, wide $GaAs/Al_xGa_{1-x}As$ heterojunctions. The exciton PL intensity responds to the changes in the nonequilibrium 2DEG parameters. In particular, the PL bistability corresponding to the bistable behavior of the 2DEG density under the nonlinear resonance[11] is observed. Our results show that the photoluminescence in such HJ's originates from excitons that recombine radiatively in the GaAs buffer layer far from the 2DEG, which is confined in the potential notch close to the $GaAs/Al_xGa_{1-x}As$ interface. Thus, the indirect interaction appears between the excitons and the nonequilibrium 2DEG. We propose that this interaction is mediated by the low-energy nonequilibrium phonons emitted by the mw-heated 2DEG. The estimate shows that the exciton drag by the phonon wind due to the hot 2DEG is an appropriate physical mechanism leading to the mw-induced exciton PL change. We assume that the PL intensity oscillations observed in wide HJ's with increasing magnetic field[8,9,16,21] may be caused by a quantizing nonequilibrium phonon flux. Indeed, in the nonequilibrium (photoexcited) 2DEG the electron transitions between Landau levels are accompanied by the phonon emission, and the phonon flux intensity drastically reflects the quantum nature of the electron states.[42,43] The exciton drag by the quantizing phonon flux may give rise to the exciton PL intensity variations with increasing magnetic field. We conclude that the presence of nonequilibrium phonons has to be taken into account in many experiments where the 2DEG is driven into nonequilibrium state.

ACKNOWLEDGMENTS

We wish to thank Elisha Cohen and Arza Ron for many helpful discussions. The research at the Technion was done in the Barbara and Norman Seiden Center for Advanced Optoelectronics and it is supported by U.S.-Israel (BSF) Grant No. 509-501.

[1] C. Weisbush and B. Vinter, *Quantum Semiconductor Structures* (Academic, Boston, 1991).

[2] J.C. Maan, Th. Englert, and D.C. Tsui, Appl. Phys. Lett. **40**, 609 (1982).

[3] F. Thiele, E. Batke, V. Dolgopolov, and J.P. Kotthaus, Phys. Phys. Rev. B **40**, 1414 (1988).

[4] R. Meisels, I. Kulac, and F. Kuchar, Phys. Rev. B **61**, 5637 (2000).

[5] S. Tsujino, H. Nakajima, T. Noda, and H. Sakaki, Physica B **249-251**, 571 (1998).

[6] N.N. Zinov'ev, A.V. Andrianov, L.J. Chaillis, C.T. Foxon, and J.J. Harris, Phys. Rev. B **53**, 7945 (1996).

[7] B.M. Ashkinadze, A. Nazimov, E. Cohen, A. Ron, and V. Umansky, in *Proceedings of the International Conference on the Physics of Semiconductors*, ICPS24, edited by D. Gershoni (World Scientific, Singapore, 1998).
[8] J.X. Shen, Y. Oka, C.Y. Hu, W. Ossau, G. Landwehr, K. Friedland, R. Hey, K. Ploog, and G. Weimann, Phys. Rev. B **59**, 8093 (1999).
[9] K. Suzuki, K. Saito, K. Muraki, and Y. Hirayama, Phys. Rev. B **58**, 15 385 (1998).
[10] N.A. Mordovets and I.N. Kotel'nikov, Fiz. Tekh. Poluprovodn. **28**, 1971 (1994) [Sov. Phys. Semicond. **28**, 1080 (1994)].
[11] B.M. Ashkinadze and V. Yudson, Phys. Rev. Lett. **83**, 812 (1999); Physica E (Amsterdam) **6**, 182 (2000).
[12] L.J. Challis, A.J. Kent, and V.W. Rampton, Semicond. Sci. Technol. **5**, 1179 (1990); A. Kent, A. Gross, P. Hawker, and M. Henini, Phys. Status Solidi B **204**, 230 (1997).
[13] A.V. Akimov, L.J. Challis, J. Cooper, C.J. Mellor, and E.S. Moskalenko, Phys. Rev. B **45**, 11 387 (1992).
[14] I.V. Kukushkin and V.B. Timofeev, Adv. Phys. **45**, 147 (1996).
[15] N.R. Cooper and D.B. Chklovskii, Phys. Rev. B **55**, 2436 (1997).
[16] A.J. Turberfield, S.R. Haynes, P.A. Wright, R.A. Ford, R.G Clark, J.F. Ryan, J.C. Harris, and C.T. Foxon, Phys. Rev. Lett. **65**, 637 (1990); H.D. Davis, J.C. Harris, J.F. Ryan, and A.J. Turberfeld, *ibid.* **78**, 4095 (1997).
[17] B.B. Goldberg, D. Heiman, M. Dahl, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev. B **44**, 4006 (1991).
[18] R.J. Nicholas, D. Kinder, A.N. Priest, and C.T. Foxon, Physica B **249**, 553 (1998).
[19] J.G. Michels, R.J. Nicholas, J.C. Harris, and C.T. Foxon, Phys. Rev. B **52**, 2688 (1995).
[20] E.S. Koteles and J.Y. Chi, Superlattices Microstruct. **2**, 421 (1986).
[21] Y. Kim, C.H. Perry, K.S. Lee, and D.G. Rickel, Phys. Rev. B **59**, 1641 (1999).
[22] M. Kozhevnikov, B.M. Ashkinadze, E. Cohen, and A. Ron, Phys. Rev. B **52**, 17 165 (1995).
[23] G. Dresselhaus, A.F. Kip, and C. Kittel, Phys. Rev. **98**, 368 (1955).
[24] W. Hansen, J. P. Kotthaus, and U. Merkt, in *Semiconductors and Semimetals*, edited by M. Reed (Academic, San Diego, 1992), Vol. 35, p. 279.
[25] B.M. Ashkinadze and V. V. Rossin, in *Proceedings of the International Conference on the Physics of Semiconductors*, ICPS22 (World Scientific, Singapore, 1994); M. Kozhevnikov, B.M. Ashkinadze, E. Cohen, and A. Ron, Solid State Commun. **106**, 73 (1998).
[26] I. Balslev, Semicond. Sci. Technol. **2**, 437 (1987).
[27] M. Godlevski, W.M. Chen, and B. Monemar, CRC Crit. Rev. Solid State Mater. Sci. **19**, 241 (1994).
[28] B.M. Ashkinadze and I.M. Fishman, Zh. Éksp. Teor. Fiz. **78**, 1793 (1980) [Sov. Phys. JETP **51**, 899 (1980)]; B.M. Ashkinadze, V.V. Belkov, and A. Krasinskya, Fiz. Tekh. Poluprovodn. **24**, 883 (1990) [Sov. Phys. Semicond. **24**, 555 (1990)]; B.M. Ashkinadze and V.V. Bel'kov, Fiz. Tverd. Tela (Leningrad) **30**, 1084 (1988) [Sov. Phys. Solid State **30**, 628 (1988)]; B.M. Ashkinadze, E. Cohen, A. Ron, and L.N. Pfeiffer, Phys. Rev. B **47**, 10 613 (1993).
[29] V.S. Bagaev, L.V. Keldysh, N.N. Sibeldin, and V.A. Tsvetkov, Zh. Éksp. Teor. Fiz. **70**, 702 (1976) [Sov. Phys. JETP **43**, 362 (1976)].
[30] V. Karpus, Fiz. Tekh. Poluprovodn. **22**, 151 (1988) [Sov. Phys. Semicond. **22**, 268 (1988)].
[31] B.K. Ridley, Rep. Prog. Phys. **54**, 169 (1991).
[32] A. Straw, A.J. Vickers, and J.S. Roberts, Semicond. Sci. Technol. **7**, B343 (1992).
[33] N. Balkan, H. Celik, A.J. Vickers, and M. Cankurtaran, Phys. Rev. B **52**, 17 210 (1995).
[34] B.M. Ashkinadze, A. Nazimov, E. Cohen, A. Ron, and L.N. Pfeiffer, in *Proceedings of the International Conference on the Physics of Semiconductors*, ICPS24, edited by D. Gershoni (World Scientific, Singapore, 1998).
[35] N.N. Zinoviev, L. Ivanov, I.G. Lang, S.T. Pavlov, and I.D. Yaroshetsky, Zh. Éksp. Teor. Fiz. **84**, 1761 (1983) [Sov. Phys. JETP **57**, 1027 (1983)].
[36] E.M. Conwell, *High Field Transport in Semiconductors, Supplement 9 of Solid State Physics*, edited by F. Seitz, D. Turnbull, and H. Ehrenreich (Academic, New York, 1967).
[37] A.V. Akimov, A.A. Kaplyanskii, E.S. Moskalenko, and R.A. Titov, Zh. Éksp. Teor. Fiz. **94**, 307 (1988) [Sov. Phys. JETP **67**, 2348 (1988)].
[38] Cz. Jasiukiewicz and V. Karpus, Semicond. Sci. Technol. **11**, 1777 (1997).
[39] Cz. Jasiukiewicz, Semicond. Sci. Technol. **13**, 537 (1998).
[40] E. Vass, Z. Phys. B: Condens. Matter **90**, 401 (1993).
[41] J. Aaviksoo, I. Reinmand, V.V. Rossin, and V.V. Travnikov, Phys. Rev. B **45**, 1473 (1992).
[42] G.W. Slater and A.M.S. Tremblay, Phys. Rev. B **29**, 2289 (1984).
[43] L.J. Challis, Physica B **204**, 117 (1995).