Microwave modulation of circularly polarized exciton photonluminescence in GaAs/AlAs multiple quantum wells

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(Received 25 September 1995)

This study describes microwave (mw) modulated circularly polarized photoluminescence (MPL) of the inhomogeneously broadened $(e1\text{:hh}1)1S$ exciton, in undoped GaAs/AlAs multiple quantum wells, at $T=1.4$ K. A circularly polarized excitation creates spin-oriented excitons and free carriers, and the latter are heated by the absorption of mw radiation. The degree of PL circular polarization (P_{cir}) and of the MPL signal (ΔP_{cir}) is measured under a magnetic field, applied normal to the quantum well plane. This experimental procedure enables us to investigate the influence of the spin-oriented mw-heated free electrons on the exciton transfer among the localized exciton sites. The modulated spectrum resolves the inhomogeneously broadened PL band into a fine structure corresponding to different exciton localizations: delocalized, localized, and impurity-bound excitons. Each resolved MPL band has a distinct intensity dependence on the mw power and on the magnetic-field strength, which is due to the different exciton trapping rate and the restricted electron motion (induced by a magnetic field). We studied the effect of the magnetic field on the degree of MPL polarization (ΔP_{cir}) of the various excitons, and found the MPL of delocalized excitons to be completely unpolarized, that of localized excitons partially polarized, and of impurity-bound excitons completely polarized. The observation of $\Delta P_{\text{cir}}\sim 1$ for strongly localized excitons is explained by a preferred exciton localization on acceptors that were neutralized by spin-oriented holes. The other observed ΔP_{cir} values indicate that the change in the exciton spin orientation, induced by the hot-carrier–exciton interaction, depends on their mutual spin orientation.

I. INTRODUCTION

Many studies have shown that the excitons in quantum wells (QW's) are subjected to spatial potential fluctuations, arising mainly from interface roughness. In high-quality QW's, the long-range in-plane variation of the QW potential is uniform on a scale larger than the exciton area $(\sim \pi a_B^2)$. Such areas are commonly described as in-plane ''islands.''[1] The $(e1\text{:hh}1)1S$ exciton spectroscopic and dynamic properties are then affected by their degree of localization at these interface islands. For example, the exciton photoluminescene (PL) band is inhomogeneously broadened[2–5] and is Stokes shifted with respect to its excitation spectrum.[6] Excitons moving over interface islands whose area is much larger than that of the exciton are considered to be delocalized. Those confined to islands with a diameter about the size of the exciton are localized, and excitons bound to the impurity sites are considered to be strongly localized excitons.[7,8] Various spectroscopic methods were employed in order to learn about the degree of exciton localization. Of these we refer to resonant light scattering (both Rayleigh[9] and Raman[10]) and to near-field spectroscopy[11] that maps the spatial distribution of excitons that recombine at an energy determined by their localization.

This report describes microwave (mw) modulated circularly polarized photoluminescence (MPL) studies of the inhomogeneously broadened $(e1\text{:hh}1)1S$ exciton in undoped GaAs/AlAs multiple QW's. Godlewski, Chen, and Monemar[12] showed that the mw radiation interacts only with free electrons in semiconductors. Thus, in the MPL experiment, the photogenerated free carriers are heated by absorption of the mw electric-field component. The hot carriers are then free to move in the QW plane and are scattered by the photogenerated excitons. This scattering process induces a redistribution among the localized excitons, as well as exciton spin relaxation processes, and these are observed as a modulation of the luminescence intensity and its polarization. The mw absorption effect on the unpolarized PL spectra of various bulk crystals and MQW's has already been discussed in several reports.[13–17] Romestain and Weisbuch[18] and Cavenett and Pakulis[14] studied the electronic cyclotron resonance and its effect on the PL. DeLong *et al.*[19] interpreted the PL modulation due to mw absorption as a Joule heating effect. Ashkinadze, Bel'kov, and Krasinskaya[20] and Wang, Monemar, and Ahlstrom[21] attributed the modulation effect to either impact ionization, impact activation, or a reduction of the cross section for formation of excitons and neutralization of shallow donors by the hot free carriers. A further detailed discussion about the nature of the mw mechanism of the interaction with the carriers is found in Sec. III A.

While the unpolarized MPL was studied in previous reports, here we utilize circularly polarized excitation and detection of the MPL spectra. Moreover, the excitation is done resonantly and in the presence of an external magnetic field. This experimental procedure creates spin-oriented hot carriers and excitons.[22–26] Several recent publications describe the delocalized exciton relaxation in MQW's, utilizing linear and circularly polarized PL[25–29] or unpolarized MPL.[13–16,27] In the present experiments, the utilization of the circularly polarized MPL method enables us to resolve the $(1e{:}\mathrm{hh}1)1S$ exciton band into several bands due to delocalized, localized, and impurity-bound excitons and to follow the spin-orientation relaxation processess of the excitons at various localized states. Each MPL band shows a different degree of circular polarization and a distinct dependence on the microwave power, relating to the degree of exciton localization. Furthermore, the detection of the circularly polarized components of the MPL spectra provides information about the change in the exciton spin orientation, due to the hot-carriers–exciton interaction.

This paper is laid out as follows. Section II describes the experimental procedure. Section III reports the experimental results and analysis of the MPL spectra and the change in the degree of the polarization of various excitons. Section IV summarizes the paper.

II. EXPERIMENTAL PROCEDURE

We studied undoped GaAs/AlAs multiple QW samples grown without interruption on (001)-oriented GaAs substrates by molecular-beam epitaxy (MBE). The MQW has 50 periods of 70-Å wells and 200-Å barriers. The samples were mounted in a TE_{111} mw cavity, resonating at $\nu_{\mathrm{mw}}=10.8$ GHz. The cavity itself was located at the center of a split-Helmholtz coil superconductor magnet with $\mathrm{B}\|(001)$. The samples were immersed in liquid He at 1.4 K in a capillary-like cryogenic Dewar. The PL was resonantly excited ($E_L=1.6196$ eV) by a cw titanium-sapphire laser pumped by an Ar^+ laser and the excitation power at the sample surface did not exceed 0.2 W/cm^2. The incident laser beam was σ^+ circularly polarized and the PL was analyzed in σ^+ and σ^- orientations and dispersed by a holographic grating monochromator equipped with a photomultiplier. The modulated emission was monitored in the direction $\mathbf{k}\|B$ (Faraday configuration).

The samples were placed in the cavity in the region of minimal electric field that is polarized in the QW plane. The mw source was a synthesizer sweeper, amplified by a solid-state amplifier. The amplified source was directional coupled to the cavity via a low-loss, cryogenic coaxial cable, with the mw being loop coupled at the entrance to the cavity. The mw power output was amplitude modulated at a frequency of 120 Hz, and the induced changes in the PL were detected, using a lock-in amplifier. The MPL was measured at mw power levels 0.3–300 mW and examined in the presence of an external static magnetic field, ranging from 0 to 2.8 T. The mw power was measured at the entrance to the mw cavity. We estimate that only about 5% of the incident power was absorbed by the entire sample (MQW and substrate).[13] The mw power indicated in the figures is that absorbed by the sample.

III. RESULTS AND DISCUSSION

A. Microwave modulated photoluminescence

Figure 1 shows the PL (a), MPL (b), and MPL fraction (c) spectra that were obtained under resonant and optically oriented excitation (σ^+) at $E_L=1.6196$ eV. The PL was analyzed in σ^+ (right) and σ^- (left) orientations, either with or without an external magnetic field. The unpolarized spectra that are shown in Figs. 1 and 2 were obtained by summation of the PL or MPL circular components [as defined in Eqs. (1) and (3) below].

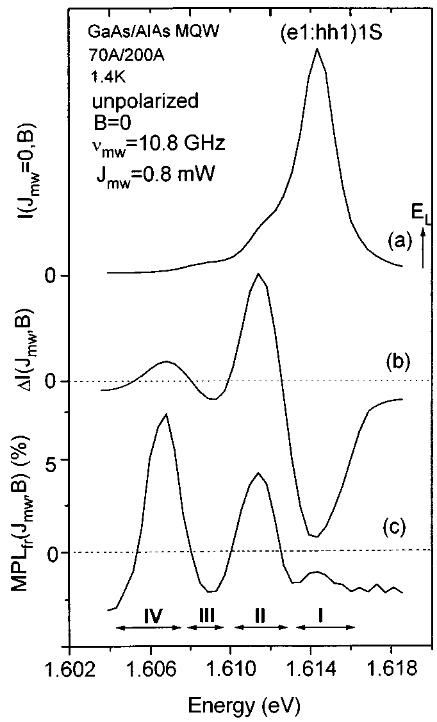

FIG. 1. (a) PL, (b) MPL, and (c) MPL fraction spectra. The excitation is σ^+ polarized and done resonantly at 1.6196 (E_L is labeled by the vertical arrow). All the spectra are a numerical summation of σ^+ and σ^- PL or MPL components (''unpolarized''). The horizontal arrows indicate the energy range of the resolved bands: band I—delocalized excitons; bands II, III, and IV—localized excitons.

Figure 1(a) shows the inhomogeneously broadened unpolarized PL spectrum of the $(e1{:}\mathrm{hh}1)1S$ exciton band of undoped GaAs/AlAs MQW's. This spectrum is given by

$$I(J_{\mathrm{mw}}=0,B)=I_{\sigma^+}(J_{\mathrm{mw}}=0,B)+I_{\sigma^-}(J_{\mathrm{mw}}=0,B). \quad (1)$$

J_{mw} denotes the mw power. $I_{\sigma^\pm}(J_{\mathrm{mw}}=0,B)$ are the circular PL intensity components analyzed in σ^+ or σ^- orientations, and $I(J_{\mathrm{mw}}=0,B)$ is the PL intensity observed in the absence of the mw radiation for a given applied magnetic field (B). As discussed in the Introduction, the excitons are subjected to spatial potential fluctuations, arising mainly from interface roughness. Consequently, the PL exciton band is inhomogeneously broadened due to exciton localization at various interface islands.

In the MPL experiment, one measures the change in the PL intensity, $\Delta I(J_{\mathrm{mw}},B)$, induced by the absorption of the amplitude modulated mw radiation:

$$\Delta I(J_{\mathrm{mw}},B)=I(J_{\mathrm{mw}}\neq 0,B)-I(J_{\mathrm{mw}}=0,B). \quad (2)$$

$I(J_{\mathrm{mw}}\neq 0,B)$ is the PL intensity observed in the presence of mw radiation.

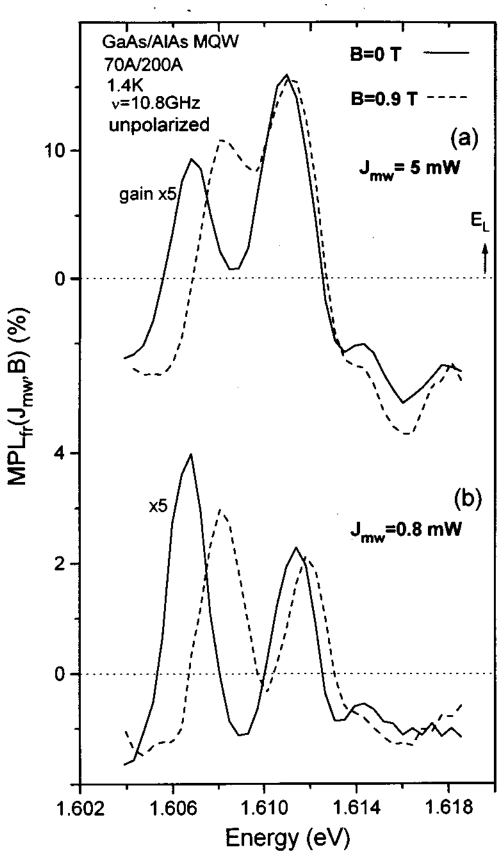

FIG. 2. Representative unpolarized MPL fraction spectra, modulated by mw power of (a) 5 mW and (b) 0.8 mW. The solid and dashed curves indicate spectra recorded in the absence and presence of the magnetic field, respectively. The excitation is σ^+ polarized and done resonantly at 1.6196 eV.

Figure 1(b) displays a typical unpolarized MPL spectrum given by

$$\Delta I(J_{\rm mw},B) = \Delta I_{\sigma^+}(J_{\rm mw}\neq 0,B) + \Delta I_{\sigma^-}(J_{\rm mw}\neq 0,B). \quad (3)$$

$\Delta I_{\sigma^\pm}(J_{\rm mw}\neq 0,B)$ denote the circularly polarized components of the MPL signal. The resonantly excited MPL spectra consist of a negative modulation band at the high-energy part of the exciton luminescence (labeled I), a positive band (labeled II) just below band I, and two other bands (labeled III and IV) at the lower-energy part. Our analysis (see below) indicates that the MPL spectra can be explained by the following characterization of these bands: the excitons in band I are delocalized over large interface islands, with area larger than πa_{1S}^2 (where a_{1S}^2 is the two-dimensional exciton Bohr radius in its $1S$ state). Band II is due to excitons localized on interface fluctuation sites with an island radius of close to that of the exciton. At the low-energy tail, bands III and IV correspond to the strongly localized excitons, most probably at impurity sites.[30] Evidently, the MPL spectra exhibit quenching of the delocalized exciton PL intensity and enhancement of the localized exciton intensity. It should be noted, however, that the signs of the MPL bands, as shown in Fig. 1(b), were reversed when the excitation was above the band-gap energy ($E_{\rm gap}$). The excitation energy dependence is in agreement with the observations reported by Ashkinadze *et al.*[13] (done at $\nu = 36.5$ GHz). However, the present work is restricted to resonant excitation only.

The MPL fractional change is shown in Fig. 1(c). It was obtained by dividing the MPL [Fig. 1(b)] by the PL spectra [Fig. 1(a)], when

$$\mathrm{MPL}_{\rm fr}(J_{\rm mw},B) = \frac{\Delta I(J_{\rm mw},B)}{I(J_{\rm mw}=0,B)}. \quad (4)$$

We obtained the degree of the modulation from the fractional change in the luminescence intensity, governed by the interaction between the excitons and the hot carriers. As observed in Fig. 1(c), hot-carrier–exciton interaction results in a small fractional luminescence change for the delocalized excitons, but exhibits a much stronger effect as the excitons become more localized. The MPL fraction indicates that the modulation is 20% in band I, 40% in band II, and about 75% in band IV. Apparently, the scattering process of the hot carriers, with delocalized excitons, is sufficient in order to activate the exciton migration and retrapping at localized sites.

Different microwave-induced mechanisms could be considered in order to explain the observed MPL spectra: (1) a direct interaction between the mw electric field and the excitons, (2) exciton impact ionization by the hot free carriers, (3) Joule heating of the entire sample, and (4) exciton impact activation or change in the cross section of exciton localization. Mechanisms (1)–(3) can be disregarded for the following reasons. The excitons are neutral particles and therefore they do not interact directly with the mw electric field. The MPL spectra, shown in Fig. 1, are in the spectral range corresponding to the PL spectrum. This indicates that the interaction with mw radiation does not ionize the excitons into separate *e-h* pairs. Reference 13 explains that the value of the ratio between the integrated intensity of the negative band and the sum of the positive bands, given by

$$R = \frac{\mathrm{MPL}_{\rm fr(band\ I)}}{\mathrm{MPL}_{\rm fr(band\ II)} + \mathrm{MPL}_{\rm fr(band\ IV)}} \quad (5)$$

can differentiate between the Joule heating effect ($R<2$) and the impact activation process ($R=3$). Examination of the MPL spectra indicates that $R\sim 3$ for all those obtained under various values of B and $J_{\rm mw}>2$ mW. This excludes the possibility of Joule heating and supports the mechanism of impact activation. It proceeds as follows: Resonant photoexcitation with $E_{\rm exc}<E_{\rm gap}$ generates enough free carriers from deep traps and these are heated by applying the mw electric field. They are free to move in the QW plane, impact activating the excitons, resulting in a redistribution of the excitons among various localized and delocalized sites. Thus, the hot carriers must be free, in order to move over a distance at least as large as the interface island of the delocalized excitons, in order to activate them. The localizing sites can be islands with radii close to the exciton Bohr radius or impurity sites and, therefore, exciton migration is restricted.

Figure 2 shows typical $\mathrm{MPL}_{\rm fr}(J_{\rm mw},B)$ spectra, recorded at two different $J_{\rm mw}$ and B strengths. All the studied MPL spectra recorded at $B\neq 0$ were multiplied numerically by the ratio $I(J_{\rm mw}=0,B=0)/I(J_{\rm mw}=0,B\neq 0)$, in order to adjust for the variation of the overall PL intensity, due to the applied magnetic field. One can see that $\mathrm{MPL}_{\mathrm{fr}}\ (J_{\mathrm{mw}},B)$ changes substantially, when the mw power and the magnetic field are varied. A low mw power with a high magnetic field has a similar effect on MPL, as that of a high mw power in the absence of a magnetic field. It should be noted that band III appears as a negative band when measured with $J_{\mathrm{mw}}<2$ mW. However, it reverses its sign when measured with $J_{\mathrm{mw}}>2$ mW. Moreover, under the latter conditions bands III and IV overlap and only their spectral envelope can be measured. Thus, an apparent blueshift is observed in the spectral region of bands III and IV. The unusual behavior of band III will be further discussed in the next section. Since band III is unresolved for all J_{mw} and B values, the following discussion will mainly concentrate on bands I, II, and IV.

In order to examine the $\mathrm{MPL}_{\mathrm{fr}}$ intensity dependence on the incident mw power, we measured the integrated intensity of each band of the delocalized and localized exciton bands, as a function of J_{mw} for various magnetic fields. This is defined by

$$I\mathrm{MPL}_{\mathrm{fr}}=\frac{1}{N_j}\int_{\varepsilon_1}^{\varepsilon_2}\mathrm{MPL}(J_{\mathrm{mw}},B,\varepsilon)_j d\varepsilon, \quad j=\mathrm{I,II,IV}. \tag{6}$$

The normalization factor N_j is the maximal $I\mathrm{MPL}_{\mathrm{fr}}$ value of each band, and ε_1 and ε_2 are the high- and low-energy limits of integration for the various MPL bands. Figure 3 shows the $I\mathrm{MPL}_{\mathrm{fr}}$ dependence on J_{mw}, with that of band I plotted as the negative in order to emphasize the fact that its PL emission was quenched by the mw radiation [cf. Fig. 1(b)]. All three bands exhibit a nonlinear behavior and can be fitted by

$$I\mathrm{MPL}_{\mathrm{fr}}(J_{\mathrm{mw}},B)=A[1-\exp(-\alpha J_{\mathrm{mw}})]. \tag{7}$$

The slopes of all the curves are less steep between $B=0$ and ~ 1.1 T than between $B=1.3$ and 2.8 T. In the latter range, the dependence becomes nearly linear for delocalized and localized excitons (bands I and II), while still remaining sublinear for the impurity-bound excitons (band IV). The parameters A and α are obtained from the best fit. Parameter α represents the efficiency of interaction between the hot carriers and the excitons. The α values are similar for bands I and II ($\sim$0.18–0.23 mW^{-1}). However, its value is almost four times larger for band IV ($\sim$0.7–0.9 mW^{-1}). α of bands I and II does not show a pronounced change for the MPL taken at $B=0$–1.1 T. However, this value drops by a factor of $3-5$ above $B=1.1$–1.2 T, thus indicating that the efficiency of the hot-carrier–exciton interaction decreases when the magnetic-field strength increases above 1.1 T. The distinct difference between α values of delocalized, localized, and impurity-bound excitons may be explained in the following manner: If all the delocalized excitons under mw radiation are evenly redistributed among the localizing sites, then the α values could be similar for all bands. However, the experimental results exclude this possibility and show that the delocalized excitons, undergoing scattering by hot carriers, are trapped at impurity sites more efficiently than in any other sites.

The $I\mathrm{MPL}_{\mathrm{fr}}$ dependence on magnetic field is presented in Fig. 4. The intensities of the three exciton bands increase with increasing magnetic field up to $B=1.1$ T and then gradually decrease. If we assume that the B value at maximum of the curve in Fig. 4 corresponds to a cyclotron resonance, then the particle involved has an effective mass of 2.4 m_e. Such a large value corresponds neither to the valence nor to the conduction band of GaAs/AlAs. Thus, an interpretation of a cyclotron resonance phenomenon must be excluded.

The results which show that a shift in the α values of bands I and II and a sign change in the B dependence slope

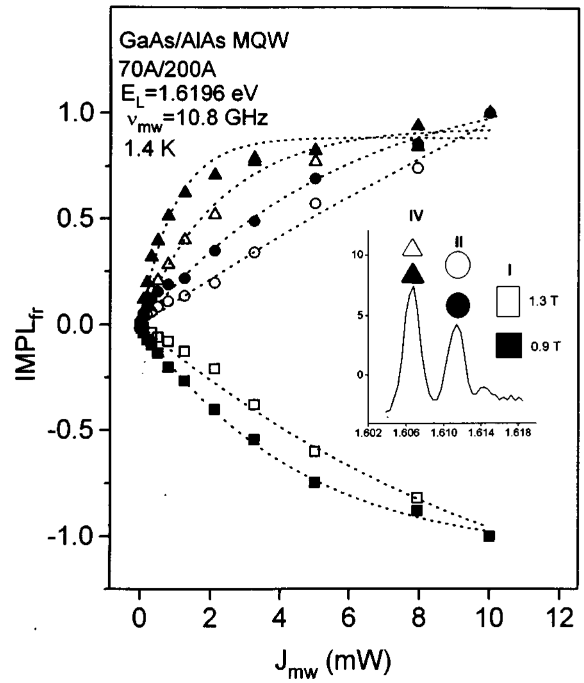

FIG. 3. Integrated intensity dependence of the unpolarized MPL fraction spectra on mw power of bands I (squares), II (circles), and IV (triangles) measured at 0.9 T (full symbols) and 1.3 T (open symbols), as indicated in the inset. Dashed lines are the best-fit theoretical curves calculated according to Eq. (7).

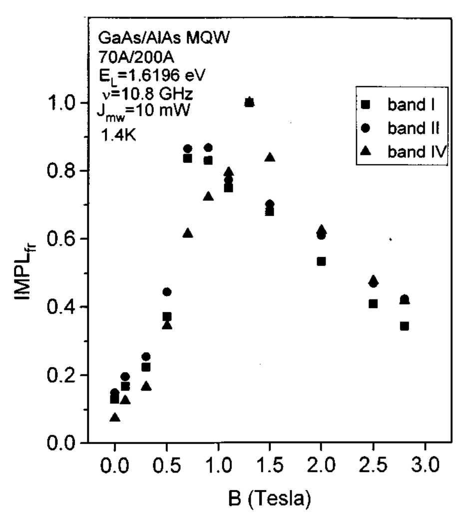

FIG. 4. Integrated intensity dependence of the unpolarized MPL fraction spectra on a magnetic-field strength of bands I (squares), II (circles), and IV (triangles).

(Figs. 3 and 4) both occur around 1.1 T obviously indicate a reduction in the electron-exciton interaction efficiency. We propose to explain these phenomena in the following way: Hot free carriers perform a precessional motion in the plane of the interface around the B axis, which is normal to the interface. The corresponding magnetic radius is

$$\lambda=(\hbar c/Be)^{1/2}. \tag{8}$$

Apparently, at low B the magnetic radius of the hot electrons is much larger than the exciton Bohr radius in GaAs/AlAs MQW's ($\sim$200 Å). Then scattering is highly probable and therefore the impact activation process of the excitons is effective. However, for $B\geqslant 1.1$ T the precession radius of the hot carriers becomes smaller than the exciton Bohr radius. The scattering becomes substantially less effective with both delocalized and localized excitons, since the latter is localized on islands whose radius is close to that of the exciton (band II). As a result, we observe a decrease in α values (bands I and II) and slope reversal in the $I\mathrm{MPL}_{\mathrm{fr}}$ dependence curve on B. These results are consistent with the magnetic freeze-out of excitons observed by Jiang *et al.*[31] They found that magnetic fields as low as 2 T induce localization or reduction in the exciton mobility. The diffusion coefficient of $(e1\text{:hh}1)1S$ excitons at 2 K is reduced by a factor of 8 under an applied magnetic field of 2 T. This enhances the exciton localization on interface islands and on impurities.[31]

B. Circularly polarized microwave modulated photoluminescence

The polarization properties of the excitons, electrons, and holes are based on the following considerations:[19] For $B=0$ and $\mathbf{k}=0$, the electron states are $|\pm\frac{1}{2}\rangle_e$ and the heavy-hole states are $|\pm\frac{3}{2}\rangle_{\mathrm{hh}}$, where the quantum numbers are those of the angular momentum projected along the growth direction ($J_z=\pm\frac{1}{2}$ and $J_z=\pm\frac{3}{2}$, respectively). The radiative transition requires $\Delta J_z=\pm 1$. Therefore, circularly polarized light propagating along the z direction can induce the following optically allowed (Γ_5 symmetry) transitions: $|-\frac{3}{2}\rangle_{\mathrm{hh}}\rightarrow|-\frac{1}{2}\rangle_e=|+1\rangle$ is σ^+ polarized; $|+\frac{3}{2}\rangle_{\mathrm{hh}}\rightarrow|+\frac{1}{2}\rangle_e=|-1\rangle$ is σ^- polarized. Since the spin relaxation time is generally much shorter than the radiative recombination lifetime,[23] the excited carrier will relax before recombining radiatively. The selection rules for recombination are the same as for excitation, and therefore, the polarized PL depends on the population of electrons and holes in the respective $|J_z\rangle$ states. The optically allowed $(e1\text{:hh}1)$ exciton states are $|+1\rangle=|-\frac{1}{2},+\frac{3}{2}\rangle$ and $|-1\rangle=|+\frac{1}{2},-\frac{3}{2}\rangle$. The spins of the electrons and holes are coupled by exchange, and since the spin relaxation of the hole is faster than that of the electron,[28,32,33] P_{cir} in undoped QW's is determined by the more slowly relaxing electron.

We investigated the degree of circular polarization change induced by the mw modulation under σ^+ excitation. This excitation creates two spin-oriented species: excitons and free carriers. It is essential to demonstrate the results of the polarized PL prior to those of the polarized MPL. The circular polarization is defined by

$$P_{\mathrm{cir}}=\frac{I_{\sigma^+}(J_{\mathrm{mw}}=0,B)-I_{\sigma^-}(J_{\mathrm{mw}}=0,B)}{I_{\sigma^+}(J_{\mathrm{mw}}=0,B)+I_{\sigma^-}(J_{\mathrm{mw}}=0,B)}. \tag{9}$$

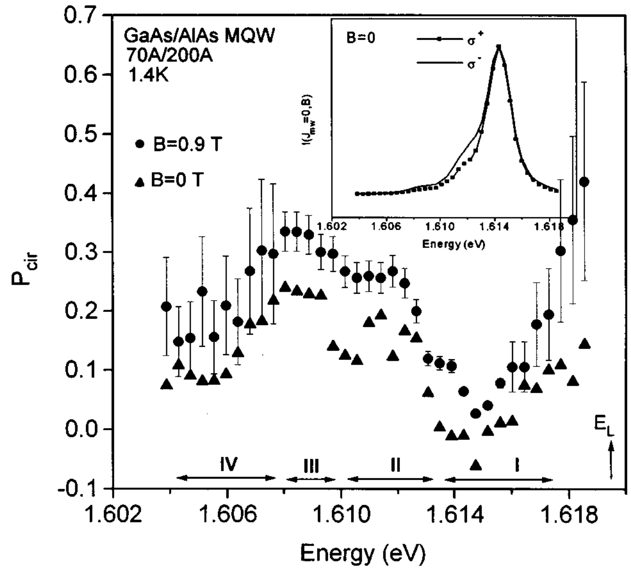

FIG. 5. The exciton P_{cir} spectra dependence recorded at two representative magnetic fields: 0 T (triangles) and 0.9 T (circles). The inset shows σ^+ (dotted line) and σ^- (solid line) PL components in the absence of magnetic field.

Figure 5 displays the PL circular polarization (P_{cir}) spectrum, without, and under, an applied magnetic field. It is clearly seen that part of band I is completely unpolarized, except for its high-energy part which is partially polarized. The PL of the localized excitons is polarized (bands II and III), and their polarization increases with magnetic-field strength. The polarized PL signal, associated with band IV, is very weak (see inset in Fig. 5).

Figure 6 displays the MPL fraction spectra, analyzed in the σ^+ and σ^- orientations at various mw powers, given by

$$\mathrm{MPL}_{\mathrm{fr}_{\sigma^\pm}}(J_{\mathrm{mw}},B)=\frac{\Delta I_{\sigma^\pm}(J_{\mathrm{mw}}\neq 0,B)}{I_{\sigma^\pm}(J_{\mathrm{mw}}=0,B)}. \tag{10}$$

Figure 7(a) displays the ΔP_{cir} dependence on the magnetic-field strength for the delocalized and impurity-bound excitons, and Fig. 7(b) that of localized excitons. The change of circular polarization induced by the mw modulation and under optically oriented excitation is defined as

$$\Delta P_{\mathrm{cir}}=\frac{I\mathrm{MPL}_{\mathrm{fr}_{\sigma^+}}-I\mathrm{MPL}_{\mathrm{fr}_{\sigma^-}}}{I\mathrm{MPL}_{\mathrm{fr}_{\sigma^+}}+I\mathrm{MPL}_{\mathrm{fr}_{\sigma^-}}}. \tag{11}$$

$I\mathrm{MPL}_{\mathrm{fr}_{\sigma^\pm}}$ is defined in a similar way to that in Eq. (6). The double difference (Δ) of P_{cir} arises from (1) the mw modulation and (2) the difference between MPL circular components.

In Fig. 7(a), delocalized excitons (band I, indicated by squares), exhibit $\Delta P_{\mathrm{cir}}\sim 0$, independent of B strength and J_{mw}. In other words, their MPL is unpolarized. Due to their delocalized nature, these excitons are subjected to scattering by impurities that cause their dephasing.[26,28] These dynamic processes are faster than the exciton radiative decay rate.[6,34] Therefore, delocalized excitons lose their primary spin angular momentum orientation ($|+1\rangle$) immediately after σ^+ excitation, resulting in an unpolarized PL spectrum,

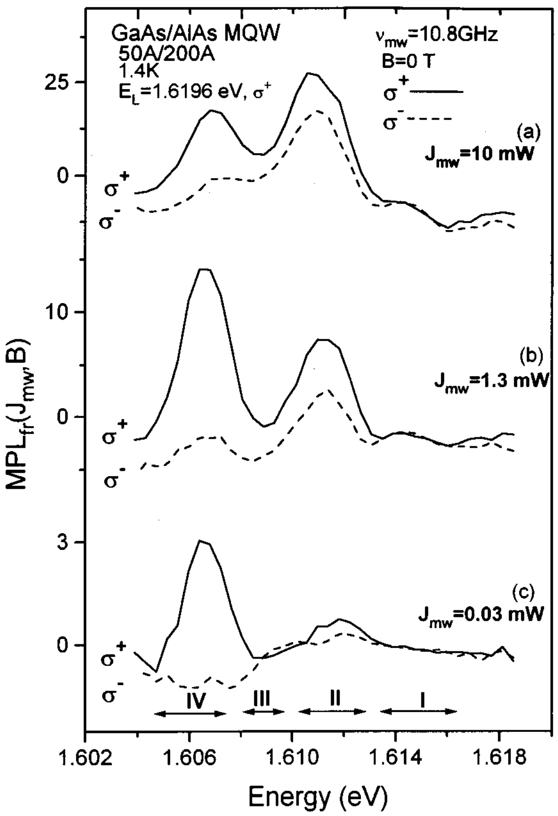

FIG. 6. Representative polarized MPL fraction spectra modulated by mw power of (a) 10 mW, (b) 1.3 mW, and (c) 0.03 mW. The solid and dashed lines indicate σ^+ and σ^- MPL components, respectively. The excitation is σ^+ polarized and done resonantly at 1.6196 eV.

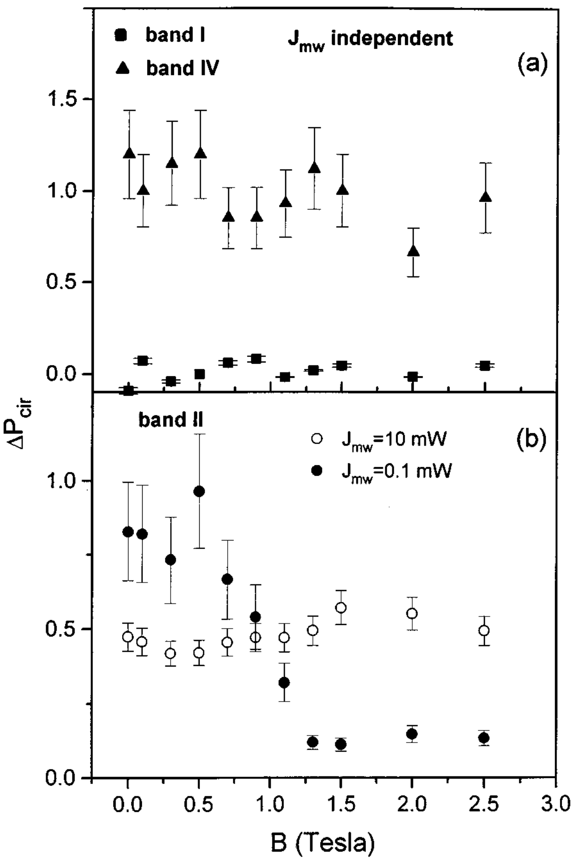

FIG. 7. (a) The dependence of $\Delta P_{\rm cir}$ of bands I (squares) and IV (triangles) on a magnetic-field strength; (b) the dependence of $\Delta P_{\rm cir}$ of band II on a magnetic-field strength, for two representative values of mw power (10 and 0.1 mW, presented by the full and open circles, respectively).

$(P_{\rm cir}\sim 0)$. Hence, the effect of spin-oriented hot-electron interaction on the spin orientation of the excitons is negligible, and we monitor no difference between the σ^+ and σ^- orientations of the MPL spectra.

The MPL emission, associated with excitons localized at impurity sites (band IV), is completely polarized, with $\Delta P_{\rm cir}\sim 1$. We cannot compare it to the PL polarization, because it is very weak (see inset in Fig. 5). In other words, there is a microwave-enhanced signal of one of the components of the circularly polarized emission, as a result of the interaction with spin-oriented carriers. It is known that MBE-grown undoped GaAs/AlAs QW's tend to be p type, with a high degree of compensation.[30,35] Indeed, it was shown[30,35] that the spectral region of bands III and IV corresponds to excitons bound to neutral acceptors, (A^0,X). As $J_{\rm mw}$ increases, hole migration and trapping are enhanced, causing neutralization of the acceptors. If the holes are trapped and retain their orientation, then the high value of the polarized MPL indicates that $|-\frac{1}{2},+\frac{3}{2}\rangle$ excitons are trapped more efficiently on the spin-orientated A^0 sites. As discussed earlier, free carriers preserve their spin orientation for a relatively long time. According to the observation of the complete mw-enhanced polarization of these bands, it is plausible that free holes indeed retain their spin orientation, $|+\frac{3}{2}\rangle$, and induce, in particular, spin-oriented trapping of the excitons.

Figure 7(b) displays the $\Delta P_{\rm cir}$ of localized excitons (band II) for two representative values of $J_{\rm mw}$. $\Delta P_{\rm cir}$ is independent of magnetic field at high mw powers ($J_{\rm mw}>2$ mW, indicated by open circles), and this is explained in the following way: For high $J_{\rm mw}$, hot carriers are generated, and so the excitons undergo effective impact activation and redistribution between the sites, even when the magnetic radius of the hot-carrier motion is reduced with increasing B. At low mw power ($J_{\rm mw}<2$ mW), $\Delta P_{\rm cir}$ decreases with increasing B, until it reaches an almost zero value, as seen in Fig. 7(b) (indicated by full circles). The value of $\Delta P_{\rm cir}=0$ means that the PL polarization, equal to 0.2–0.3 (see Fig. 5), did not change as a result of mw modulation. The decrease in the MPL polarization may be caused by several mechanisms: There is a mutual spin orientation of hot electrons and excitons, in which their interaction may cause a more effective trapping of the $|+1\rangle$ excitons at $B\leqslant 1$ T, rather than at $B\geqslant 1$ T. High magnetic fields cause substantially less effective scattering between localized excitons and hot carriers, as previously explained [see Eq. (8)].

The change in the spin orientation of the excitons localized on islands of about the size of the exciton points out when the radius of the precession motion of the hot carriers reaches this value. While the α parameter is not sensitive enough to distinguish between band I and band II, the MPL polarization differentiates between the character of the delocalized and localized excitons.

Although localized and delocalized exciton bands were resolved, this effect does not lend itself to an analysis as was done by Uenoyama and Sham[29] and Damen *et al.*[34] for the polarized spectra observed in undoped and doped QW's. This results from the fact that only the relative change in the population of each band is measured by the polarized MPL.

IV. SUMMARY

We presented an experimental study of the circularly polarized microwave modulated photoluminescence technique, enabling us to resolve the various types of excitons localized on the GaAs/AlAs QW's interface roughness. For the first time, we have clearly resolved several localized exciton bands, in the inhomogeneously broadened PL band, by the MPL technique. We found that each band shows a distinct intensity and ΔP_{cir} dependence on the microwave power and on the magnetic-field strength. We interpret these observations as due to the effect of mw heated carriers on the population, and polarization of the various excitons is dependent on (1) the degree of their localization on the particular site, (2) the change in the hot-carrier motion induced by a magnetic field, and (3) the mutual spin orientation of the hot carriers and the excitons. The circularly polarized MPL is thus a powerful tool to explore the hot-carrier–exciton interaction, and to follow the exciton relaxation dynamics.

ACKNOWLEDGMENTS

The work at Technion was supported by the United States–Israel Binational Foundation (BSF), Jerusalem, Israel, and was done at the Barbara and Norman Seiden Center for Advanced Opto-Electronic Research.

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