Competition between confinement potential fluctuations and band-gap renormalization effects in $In_{0.53}Ga_{0.47}As/In_{0.525}Ga_{0.235}Al_{0.25}As$ single and double quantum wells

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We present the results of our studies on the emission properties of $In_{0.53}Ga_{0.47}As/In_{0.525}Ga_{0.235}Al_{0.25}As$ single and coupled double quantum wells (CDQWs) with different degrees of potential fluctuation. We have verified that the curve of the temperature (T) dependence of the emission peak energy (E_{PL}) is significantly influenced by the potential fluctuations (which are magnified by the presence of the internal barrier in the CDQW) as well as by the excitation density used in the photoluminescence (PL) measurements. As the excitation power increases, two effects occur simultaneously: the filling of the band-tail states related to potential fluctuations and the band-gap renormalization (BGR) caused by the increase in the density of photogenerated carriers. As the optical density increases, the E_{PL} can shift to either higher (blueshift) or lower (redshift) energies, depending on the temperature at which the measurements are carried out. The temperature at which the displacement changes from a blueshift to a redshift is governed by the magnitude of the potential fluctuations and by the variation of BGR with excitation density.

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I. INTRODUCTION

In the past decades, research on semiconductor heterostructures has been intensive, especially on their optical properties.[1–6] In particular, considerable attention has been given to InGaAs/InGaAlAs quantum wells due to the possibility of tuning their emission in the range between 1.3 and 1.6 μm, which is suitable for application in optoelectronic devices.[7–9]

The study of the optical properties of semiconductor heterostructures as a function of excitation density as well as of the temperature has revealed interesting aspects of the photogenerated carrier interaction among themselves and of the form and characteristics of the confinement potential, respectively.

High doping levels and/or high optical excitation densities result in the band filling and band-gap renormalization (BGR) due to the interaction among the many carriers, causing significant alterations in the emission spectra.[10–14] Experimental evidences of these phenomena were obtained from photoluminescence (PL) spectra of bulk materials and semiconductor heterostructures in samples with high doping levels[11,12] as well as at conditions of intense optical pumping, using pulsed[13] and continuous lasers.[14] The main characteristic of BGR is the observation of a redshift of the lower edge of the luminescence line and, generally, of the PL peak energy (E_{PL}) when there is an increase in the doping level or in the optical excitation intensity.[10]

On the other hand, carriers undergo a marked influence of the confinement potential fluctuations, mainly at low temperature and low excitation density, caused by the morphological disorder usually present in heterostructures, which is associated with the localized variations in the well thickness and/or the alloy chemical composition. Such fluctuations can generate a localization effect on the carriers that strongly affects the optical spectra.

Several groups have studied the influence of these fluctuations on the optical properties of quantum wells in detail.[15–20] These fluctuations lead to the formation of a band tail in the quasi-two-dimensional excitonic density of states. One consequence of this band tail on the PL spectra is the displacement of the E_{PL} to higher energies (blueshift) as the temperature increases up to a certain value, after which the E_{PL} undergoes the regular shift to lower energies (for more details, see, e.g., Ref. 21, and references therein). When the potential fluctuation is very large, the emission peak presents an anomalous behavior as the temperature increases, sometimes referred to as inverted S-shaped behavior, constituted by the following sequence: redshift-blueshift-redshift.[17] Depending on the magnitude of the potential fluctuations, the localization effects can affect the emission properties even at room temperature.[22,23]

Experimental results have shown that an increase in the excitation power can mask the localization effects due to the filling of the lower states of the potential fluctuations by the photogenerated carriers, which minimizes or even suppresses the fluctuation effects.[17,21,24] On the other hand, an increase in the excitation density (increase in the density of photogenerated carriers) can also generate the BGR phenomenon due to the carrier-carrier interaction. However, to our knowledge, there is no registration in the literature of any work that discusses, in a systematic way, the combined effects of the band-gap renormalization due to the optical excitation density and of the potential fluctuations on the optical properties of semiconductor heterostructures.

In this work, we have studied the emission properties of $In_{0.53}Ga_{0.47}As/In_{0.525}Ga_{0.235}Al_{0.25}As$ single and coupled double quantum wells (CDQWs) as a function of temperature and excitation intensity. The coupled double quantum well is produced by the insertion of a narrow barrier at the center of the InGaAs well. Due to the structure of the sample used in this study, it was possible to follow, in the same sample, the influence of the introduction of the internal barrier in the CDQW and of its thickness, which is directly related to the magnitude of the potential fluctuations, on the PL spectra. We have verified that the E_{PL} versus temperature (T) curve is strongly influenced by the potential fluctuations (magnified by the presence of the internal barrier) as well as by the intensity of the excitation power used in the PL measurements. We have analyzed these results by taking into account the competition between the effect of the potential fluctuations and the many-body effects caused by the increase in the density of photogenerated carriers.

II. EXPERIMENTAL DETAILS

The sample was grown by molecular beam epitaxy on a semi-insulating InP substrate and contains four 100-Å-thick $In_{0.53}Ga_{0.47}As$ quantum wells separated one from the other by 300-Å-thick $In_{0.525}Ga_{0.235}Al_{0.25}As$ barriers. The first 100-Å-thick InGaAs quantum well (labeled as QW100) does not contain any layer of the barrier material inserted in its interior, and it is used as a control well, while the other quantum wells contain 10-, 20-, and 30-Å-thick narrow barriers inserted at the center of the second, third, and fourth wells, respectively. More details, such as a sketch of the sample structure, are shown in Ref. 21. For the sake of simplicity, we call spike the narrow barrier inserted at the center of the well and the CDQWs with internal barriers of 10, 20, and 30 Å will be called SPK10, SPK20, and SPK30, respectively.

In the photoluminescence measurements, the 514.5 nm line of an Ar^+ laser was used as the excitation source, with the laser beam focused on a 260-μm-diameter spot. For measurements in the temperature range between 8.5 and 300 K, we have used a closed circuit He cryostat, in which the thermal contact between the sample and the cold finger was improved by using silver paint. As for the PL measurements carried out at 2 K, a liquid He immersion cryostat was used. A spectral analysis of the luminescence was carried out by a monochromator with 0.5 m focal length, and the detection was made by a thermoelectrically cooled InGaAs *p-i-n* photodiode, using a standard lock-in technique.

III. EXPERIMENTAL RESULTS

The PL spectrum of the sample used in this study, obtained at 8.5 K, shows four emission peaks that are due to the fundamental (e_1-hh_1) excitonic transitions related to the single quantum well (SQW) (0.853 eV) and to the CDQWs with internal barriers of 10 Å (0.904 eV), 20 Å (0.943 eV), and 30 Å (0.963 eV). This spectrum is shown in Ref. 21.

Figures 1 and 2 show the variation of the E_{PL} as a function of temperature (T), for all quantum wells in the sample,

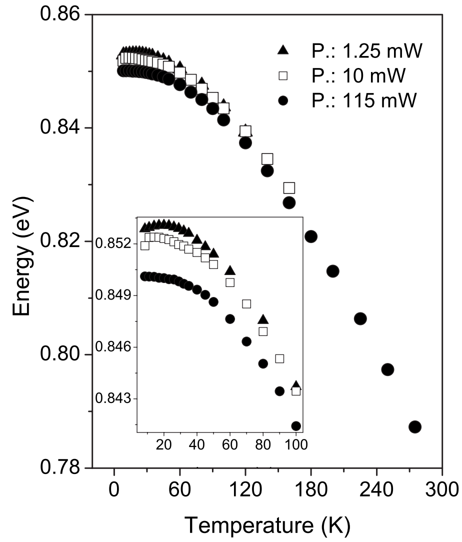

FIG. 1. PL peak energy (E_{PL}) for the QW100 well as a function of temperature for laser powers of 1.25 mW (triangles), 10 mW (squares), and 115 mW (circles). The inset is an amplification of the figure in the low temperature range (below 100 K).

obtained at three different excitation powers: 1.25, 10, and 115 mW. In each of these figures, an inset is included, which magnifies the low temperature region. Through these insets, it is possible to observe a general aspect of the E_{PL} versus T behavior: with the lowest power (1.25 mW), as the temperature is increased, the E_{PL} first moves to higher energies (blueshift) and, above a certain temperature T_M, E_{PL} moves to lower energies (redshift). The thicker the spike, the larger the amplitude of the blueshift as well as the value of T_M. These effects are related to the morphological disorder present in the sample, which causes fluctuations in the confinement potential. The increase in blueshift and T_M with increasing spike thickness is associated with the fact that this disorder is magnified by the increase in spike thickness.[21] However, the blueshift amplitude decreases with increasing excitation power and it is no longer observed when the power increases to 115 mW, independent of which quantum well is analyzed.

The inset in Fig. 1 (regarding the single quantum well) shows that the experimental points, relative to the same measurement temperature, undergo a systematic shift to lower energies as the excitation power increases.

On the other hand, the E_{PL} versus T curves for the wells with spike, shown in the insets of Figs. 2(a)–2(c), present a much more complex behavior with the power variation. There is a crossing of the curve described by the experimental points obtained with a power of 115 mW and the curves obtained with lower powers. These crossings occur between 10 and 15 K for the well with a spike of 10 Å [Fig. 2(a)], and between 30 and 35 K for the wells with spikes of 20 and 30 Å [Figs. 2(b) and 2(c)]. It is important to stress that, for temperatures beyond the crossing point, the experimental points obtained from measurements with higher powers are always shifted to lower energies in relation to those obtained with lower powers. So, the experimental results show that, starting from a certain temperature T_X (whose value depends

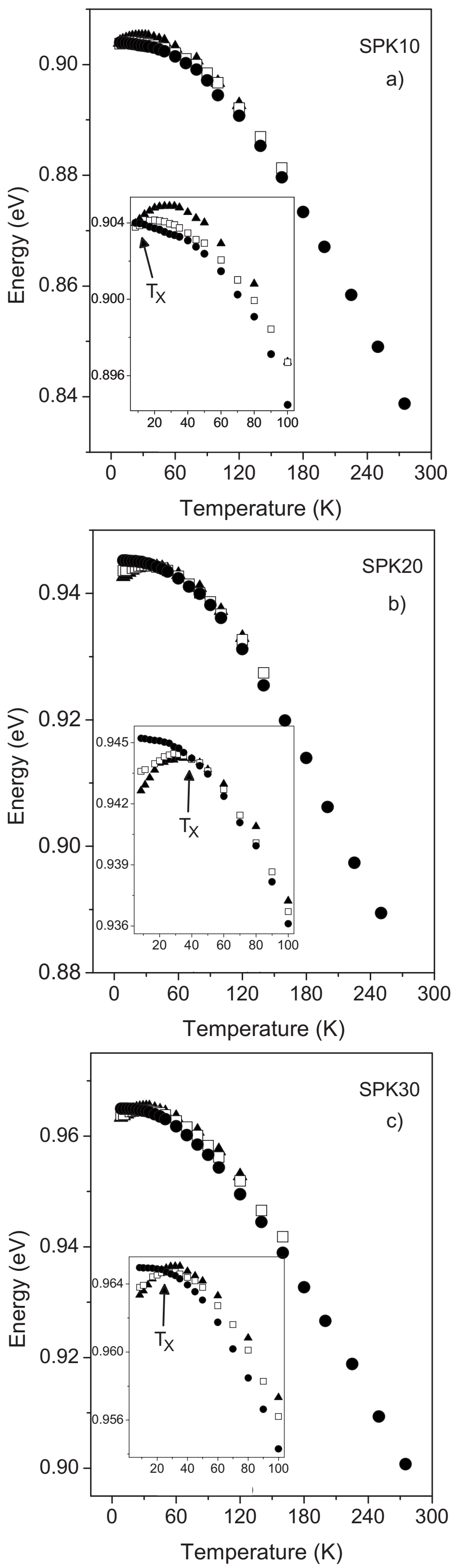

FIG. 2. E_{PL} as a function of temperature for the coupled double quantum wells (a) SPK10, (b) SPK20, and (c) SPK30, with powers of 1.25 mW (triangles), 10 mW (squares), and 115 mW (circles). The insets are amplifications of the figures in the low temperature range.

on the thickness of the spike), the E_{PL} versus T curve undergoes an almost rigid shift to lower energies when the excitation density is increased.

Figure 3 shows the PL spectra taken at 8.5 K using different excitation powers, from 50 μW up to 130 mW. The upper limit of 130 mW was adopted here since, for higher powers, the spectra of the DQWs start to overlap due to the enlargement of their linewidths. However, for the SQW, whose spectrum is farther from the others, we have accompanied the evolution of the emission up to 250 mW. The behavior of E_{PL}, which is taken from the data shown in Fig. 3, is shown in Fig. 4 as a function of the logarithm of the excitation power for each QW. Figure 4 shows that the E_{PL} for the SQW (lower curve) undergoes a redshift with the increase in the excitation power, while in the SPK10, the E_{PL} practically does not change in the power range analyzed. On the other hand, the E_{PL} of the SPK20 and SPK30 wells (upper curves) reveals a blueshift with increasing power. Figure 3 also shows an enlargement of the spectra to the lower energy side, as well as to the higher energy side, as the excitation power increases.

IV. DISCUSSION

Initially, we analyze the results presented in the previous section for the SQW and discuss the possible causes for the displacement to lower energies of the E_{PL} versus T curve with increasing power density (see inset in Fig. 1).

The natural tendency is to attribute this displacement of E_{PL} to the local lattice heating due to the continuous incidence of the laser beam, i.e., the lattice temperature would be higher than the measured one, which could cause a reduction in the effective band-gap energy of the quantum well and, consequently, the redshift of the emission. A way of trying to simulate this effect would be to translate to higher temperature, along the temperature axis, the E_{PL} versus T curve taken with the highest power in such a way that the value of E_{PL} at the lowest temperature of this curve lies exactly on the curve taken with the lowest power (in which we consider that the heating effects, if they exist, are negligible). This way, the temperature of the measurements obtained at the highest power would be approximately adjusted to the actual temperature of the crystal at the laser striking point. This procedure was carried out by taking into account the experimental points extracted from the PL measurements obtained with powers of 1.25 and 115 mW. The result is shown in Fig. 5. The first point of the measurements carried out at higher power lies on the curve obtained with a lower power at approximately 65 K. If the displacement of the emission peak to lower energies was only due to the effects of band-gap reduction by heating caused by the laser incidence, this result would indicate that the increase from 1.25 to 115 mW in power would result in an increase in the lattice temperature of about 57 K (value of the net displacement of the curve with highest power in the temperature scale from Fig. 5). If the effect was caused by the heating of the sample under illumination, the E_{PL} versus T curves for both powers should approximately coincide after the correction. However, as Fig. 5 clearly shows, this is not the case. This large mismatch

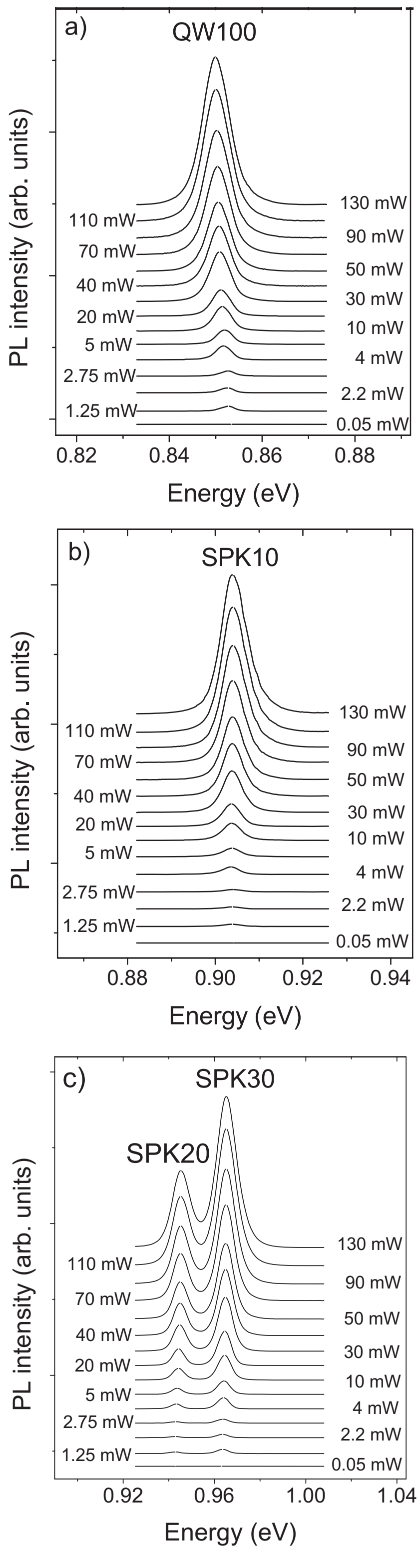

FIG. 3. PL spectra at 8.5 K as a function of power for (a) QW100, (b) SPK10, and (c) SPK20 and SPK30.

between the two curves occurs because if the lowest temperature of the high power curve was 65 K, the curve would begin in a region in which the dE/dT derivative is high (negative) and, in this manner, the values of E_{PL} related to the next temperatures should present a significant decrease

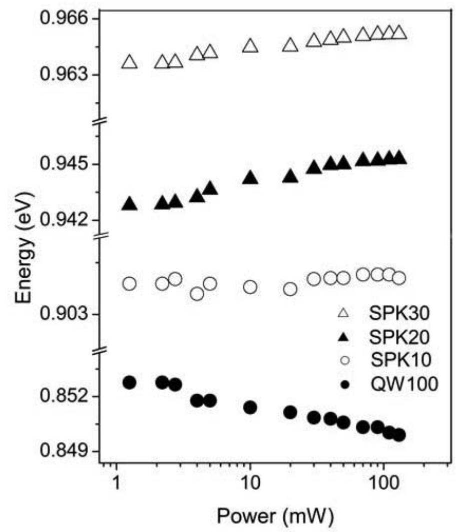

FIG. 4. E_{PL}, at 8.5 K, as a function of power for QW100 (filled circles), SPK10 (empty circles), SPK20 (filled triangles), and SPK30 (empty triangles).

with a small increase in temperature, but, instead of this, we observe that this curve has a plateau for approximately the same temperature range as the low power curve has, which is characteristic of the low temperature range.

We have also tried to verify the heating of the sample with increasing power density by measuring the temperature directly at the point of the laser beam incidence, making use of a thermocouple. In this test, the experimental conditions were the same as those in the PL measurements; however, we have changed the sample for a thermocouple, which was kept with the same thermal contact with the cryostat cold finger. By increasing the laser power from 1.25 to 115 mW,

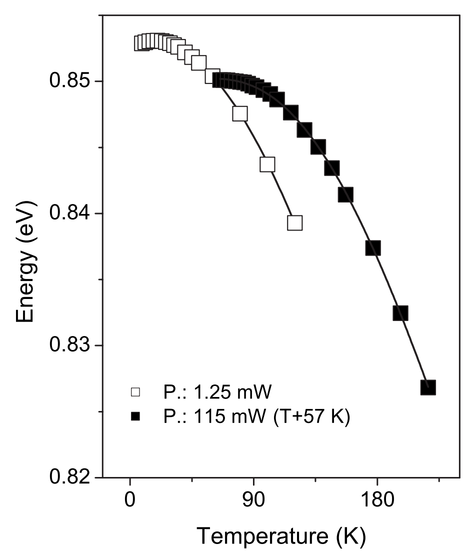

FIG. 5. E_{PL} for the QW100 well as a function of temperature, with powers of 1.25 mW (empty squares) and 115 mW (full squares), where the points relative to 115 mW were shifted by 57 K in the temperature scale. The continuous lines refer to the fits obtained using the Passler model from Ref. 22 for each of those curves.

we have observed an increase of about 2 K in the temperature measured by the thermocouple. On the other hand, when the thermocouple is not in thermal contact with the cold finger, the same power variation leads to an increase of about 30 K in the temperature. Once the sample was in good thermal contact with the cold finger during the PL measurements, and taking into account the good thermal conductivity of the InP substrate, we believe that, in our experimental setup, the heat generated in the samples by the laser incidence was quickly transferred to the cold finger, causing no significant increase in the lattice temperature.

For a further clarification, we have also estimated the increase in the sample temperature by taking into account the power and the spot of the laser, the thickness and the average thermal conductivity of the sample and its reflectivity. For an incident laser power of 115 mW, the estimated increases in temperature were about 0.2 K at the measurement temperature of 10 K and about 3.6 K for measurements taken at room temperature.

PL measurements as a function of the power density (not shown here) were also carried out at a temperature of 2 K, with the sample immersed in liquid helium, i.e., in a situation in which there is an effective heat exchange between the surface of the sample and the helium bath. Nevertheless, the same displacement of E_{PL} to lower energies is still verified as the power increases.

Finally, we compare the spectra related to the intersection point in Fig. 5, i.e., the spectrum obtained with a low power (1.25 mW) at $T=65$ K to that obtained with a power of 115 mW at $T=8.5$ K. This comparison is shown in Fig. 6(a). We can clearly see that the line shapes of both spectra are very different. In the spectrum obtained with a high power, we observe a broadening at the lower energy side, while in the spectrum obtained with a low power, at 65 K, a tail appears at the higher energy side, which extends to energies higher than those observed in the other spectrum, due to the thermal redistribution of the carriers into the conduction band.

Thus, we can conclude that the increase in the excitation power up to 115 mW in our experimental setup certainly does not cause an increase in the lattice temperature strong enough to cause the E_{PL} shift verified in our measurements. We attribute this shift to many-body effects.

When the excitation intensity of the laser beam hitting a semiconductor sample is changed from low to high intensities, the excitons make a transition from an insulating exciton gas, at low excitation densities, to a conducting electron-hole plasma (e-h plasma) at high densities. The e-h plasma phase occurs when the e-h pair density exceeds a critical density n_M, also called Mott threshold. At the critical density, the free carrier screening leads to the exciton breakdown.[10] So, the many-body interactions among the free carriers renormalize the electron-hole self-energy and the band gap shrinks. The main many-body processes responsible for the BGR are the correlation (due to the Coulomb repulsion among the carriers of the same species) and the exchange,[25] which depend strongly on the carrier density. As the carrier density increases, the band gap decreases due to the BGR, while electrons fill the conduction band and holes fill the valence band, up to the respective Fermi levels. The effect of BGR and band filling combined processes is the redshift of the low-energy edge of the emission line and the blueshift of the high-energy edge, resulting in a broadening of the emission spectrum on both sides. The critical density, for which the exciton stability is lost, was calculated to be in the range of $10^{10}-10^{11}$ cm^{-2}.[25,26] Recently, Kappei *et al.*[27] carried out a study of PL as a function of excitation power, the results of which indicated that a Mott-type transition gradually occurs when the carrier concentration rises from 1×10^{10} to 1×10^{11} cm^{-2}.

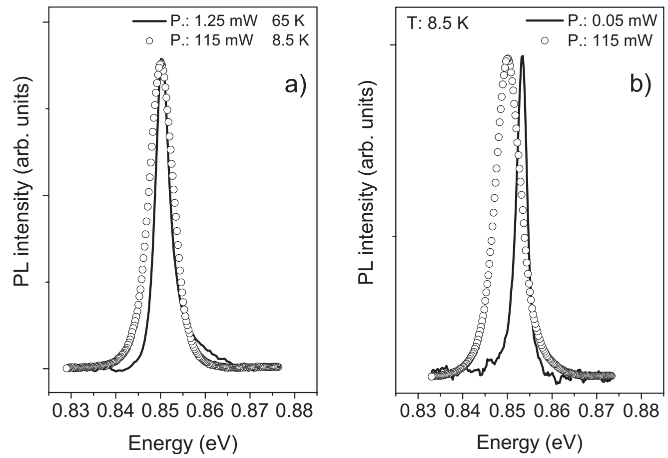

FIG. 6. (a) PL spectra of QW100. Dotted line, PL spectrum obtained at 8.5 K with a power of 115 mW; continuous line, spectrum obtained at 65 K with a power of 1.25 mW. (b) PL spectra of QW100 at 8.5 K obtained using excitation powers of 0.05 mW (continuous line) and 115 mW (dotted line).

Figure 6(b) shows the PL spectra of the QW emission obtained at 8.5 K with low (0.05 mW) and high (115 mW) excitation powers, where the spectrum obtained with the highest excitation density (estimated to be $n=5\times10^{10}$ cm^{-2}) is rescaled in order to compare the line shape of both spectra. As the excitation density increases, the low-energy edge shifts to lower energy, while the high-energy edge displaces to higher energy relative to the E_{PL}. The net result is a broadening of the line shape and a shift of the E_{PL} to a lower value. Thus, the broadening of the emission line as well as the E_{PL} redshift observed in our spectra as the excitation density increases are consistent with the band filling and BGR effects expected for the values of carrier concentrations produced in our measurements. So, we interpret this redshift as a manifestation of the BGR that occurs in the quantum wells as a result of the larger carrier-carrier interaction caused by the increase in the photogenerated carrier concentration.

To have a general idea of how the band edge and the Fermi level varies with the excitation power, we have plotted in Fig. 7 the energies taken at half maximum of the low-energy side and of the high-energy side of the luminescence peak, respectively, as a function of the logarithm of excitation power. For comparison, the E_{PL} values are also shown in this figure. The figure shows a continuous displacement of the low-energy edge to lower energies as well as a displacement to higher energies of the high-energy edge (relative to the E_{PL}) as the excitation power increases. This figure shows the results obtained with excitation powers up to 250 mW. In

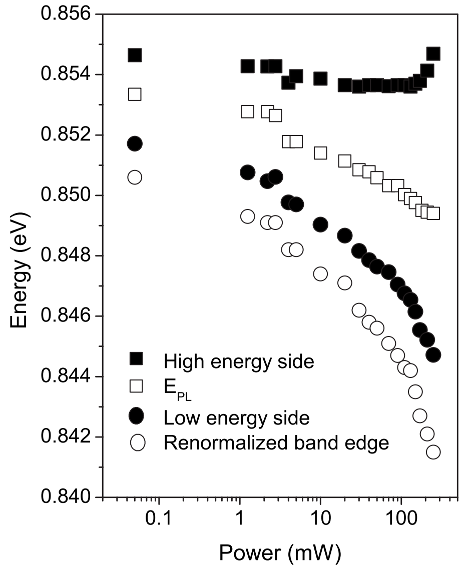

FIG. 7. PL spectral features for QW100 at 8.5 K versus the logarithm of the excitation power. Filled squares, high-energy edge at half maximum; empty squares, PL peak energy; filled circles, low-energy edge at half maximum; empty circles, renormalized band edge (see text).

order to have a better estimate of the renormalized band edge, we have determined it from the PL spectra by a linear extrapolation of the low-energy side of the spectrum to the background level, as proposed by Olego and Cardona.[28] These results are also shown in Fig. 7 (lower curve). To find the BGR coefficient in the expression $\Delta E_G = -a_R(n)^{1/3}$, where n stands for the carrier density (in cm^{-2}), we have performed a linear fit of this expression to the experimental data through a least square fitting program and we have found $a_R = (1.86 \pm 0.05) \times 10^{-3}$ meV $cm^{2/3}$, where the uncertainty only takes into account the fitting process. To compare this value with some theoretical result, we have calculated a_R by using the relation obtained by Schmitt-Rink and Ell,[25] $\Delta E_G \approx -3.1(na_0^2)^{1/3}E_0$, where E_0 stands for a two-dimensional exciton Rydberg, a_0 the exciton radius, and n the carrier density (in cm^{-2}), finding $a_R = 2.4 \times 10^{-3}$ meV $cm^{2/3}$. So, both the values are in reasonable agreement.

Next, we will focus on the results related to the quantum wells with spike. By analyzing the data presented in Fig. 2, we have observed a crossing of the E_{PL} versus T curves obtained with different excitation powers, which occurs at a temperature designated as T_X. Such behavior can satisfactorily be explained if we take into account the combination of the effects of potential fluctuations and BGR at the different excitation powers.

In the situation shown in the inset of Fig. 2(c) [double quantum well (DQW) with spike of 30 Å], at low temperatures and low excitation power, the carriers recombine starting from the minimum of the band tail of the density of states. When the power is increased, at low temperatures, the higher energy states of the band tail become populated and, thus, the luminescence peak moves to higher energies (blueshift). So long as the density of states of the band tail is small, mainly at the lower energies, this blueshift occurs with a small power variation and this is the effect that prevails at low temperatures and up to a certain value of power. When we increase the power even more, a competition between the blueshift and the redshift begins to occur due to the BGR effect discussed previously, with one effect being difficult to separate from the other.

In the following, we discuss the results shown in Fig. 2(c), taking into consideration the temperature dependence of E_{PL} at low and high excitation powers. At the lowest power, $P = 1.25$ mW, the E_{PL} versus T curve shows at low temperatures the blueshift characteristic of potential fluctuations, as discussed in the Introduction. For the curve obtained with the highest power, $P = 115$ mW, the blueshift does not take place since all the states generated in the band tail of the potential fluctuation are already occupied due to the large number of photogenerated carriers. However, in this curve, the BGR effect due to the interaction of the carriers is already perceptible and, starting from the temperature T_X, this effect begins to prevail over the effect of carrier localization (which has less and less influence as the temperature increases), placing this curve below the lower power curve.

Next, the competition between the two effects in the different wells is compared. As discussed in a previous work on the potential fluctuation of these same wells,[21] there is an increase in the potential fluctuation magnitude with the insertion of the spike and with the increase in its thickness.

For the SQW, as the effect of the potential fluctuation is practically negligible, the curves of E_{PL} versus T (Fig. 1) obtained with different excitation powers do not intercept; with the increase in excitation power, the curve undergoes a displacement, approximately as a whole, to lower energies under the effect of BGR (for the variation of excitation power from 1.25 to 115 mW, this displacement is approximately 3 meV).

For SPK10, where the potential fluctuation is small but their effects are already perceptible,[21] the three curves cross each other at a very low temperature ($T_X \sim 10-15$ K), which indicates that, at this temperature, as the power is increased, the effects of blueshift due to the potential fluctuations and the redshift due to BGR cancel each other out. At temperatures higher than T_X, the BGR effect prevails.

For SPK20 and SPK30 DQWs, which have levels of potential fluctuation similar between themselves but larger than the one for DQW SPK10,[21] the temperatures at which the curves cross each other (T_X) are higher. The fact that T_X is a little higher for SPK20 than for SPK30 can be explained if we take into account that the effect of BGR is larger for SPK30. We have verified, from the displacement of the experimental points with the increase in the power at high temperatures (around 150 K), that this is really the case: for SPK20, the curve taken at $P = 115$ mW undergoes a shift of 2.0 meV to lower energies relative to the one taken at $P = 10$ mW, while for SPK30, the displacement is 2.9 meV. Being larger, the effect of BGR pulls the curve more to lower energies for SPK30 than for SPK20, and T_X occurs at a lower temperature for SPK30.

Thus, in quantum wells with potential fluctuations, the E_{PL} versus T curves obtained at different excitation powers cross each other at a temperature T_X, which depends mainly on the magnitude of the potential fluctuations, increasing with the increase in the magnitude of the potential fluctuation and decreasing for a larger influence of BGR. The effect that prevails when the excitation power is increased depends on whether the temperature is above or below T_X: at temperatures below T_X, the blueshift resulting from the filling of the energy states of the potential fluctuation band tail prevails over the redshift due to the BGR, moving E_{PL} to higher energies; at temperatures above T_X, the redshift due to BGR prevails and there is an effective displacement of E_{PL} to lower energies. At the temperature T_X, the two effects have the same magnitude and cancel each other out, thus maintaining the position of E_{PL} as the excitation intensity varies.

These findings can be confirmed by Fig. 4, which shows the E_{PL} displacement for the four wells versus the logarithm of the excitation power, at 8.5 K. The lower curve, for the SQW, shows that as the excitation power increases, there is a displacement of the E_{PL} to lower energies, which is in agreement with the results previously obtained, showing that in the SQW the potential fluctuation is negligible and the redshift due to the BGR prevails in the whole temperature range. In the curve corresponding to the DQW SPK10, the E_{PL} practically does not change with the increase in the excitation power, in the whole range of power used, which is in agreement with the finding that the temperature T_X, at which the two opposed effects cancel each other out, is very close to the temperature at which these spectra were obtained ($T = 8.5$ K). In the two upper curves, we can see that the PL peaks, associated with the DQWs SPK20 and SPK30, move to higher energies as the excitation power increases due to the fact that the temperature at which the spectra were obtained is lower than T_X; in these cases, the temperatures T_X are higher because the fluctuation levels are larger than those of the wells treated previously.

V. SUMMARY AND CONCLUSIONS

In this work, we carried out a study on the emission properties of $In_{0.53}Ga_{0.47}As/In_{0.525}Ga_{0.235}Al_{0.25}As$ single and coupled double quantum wells with different degrees of potential fluctuations. E_{PL} versus T curves were analyzed as a function of excitation power for the different wells, thus allowing for a systematic analysis of the effects of the excitation density and of the magnitude of the confinement potential fluctuations on the emission spectra of the quantum wells. At low temperatures and low excitation densities, the carriers preferentially recombine from the lower energy band-tail states generated by the fluctuations of the confinement potential. By increasing the excitation power, two effects will occur at the same time: the filling of these band-tail states, which shifts the E_{PL} to higher energies, and the BGR, which shifts the E_{PL} to lower energies. With increasing temperature, the E_{PL} obtained with low powers develop a blueshift. However, this blueshift is not observed in the E_{PL} versus T curve obtained with the highest power because, in this case, the lower energy states are already filled out by the photogenerated carriers and the emission by the carriers of higher energy states prevails. At sufficiently high temperatures, at which the carriers have already acquired enough thermal energy to escape from the influence of the potential fluctuations, the only effect acting on E_{PL} is the BGR, which is evidenced by the redshift of the experimental points with increasing power. In short, the values of the emission peak energy of the quantum wells can shift to either higher or lower energies, depending on the magnitude of the potential fluctuations and on the temperature at which the measurement is carried out. The temperature at which the displacement changes from a blueshift to a redshift is governed by the magnitude of the potential fluctuations and by the variation of BGR with excitation density.

Generally, experimental investigations are concerned either with the potential fluctuation effects or with the BGR effects. However, it is necessary to take into account the combination of both effects for an appropriate interpretation of the influence of the excitation density and of the temperature on the optical spectra of semiconductor heterostructures or alloys.

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