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Photoluminescence characterization of GaAs quantum well laser structure with AlAs/GaAs superlattices waveguide

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Dependence on the excitation power and temperature of the photoluminescence emission of GaAs quantum well laser structures using GaAs/AlAs superlattices in the waveguide is reported. The effects related to a quality reduction due to the presence of a thick ternary AlGaAs cladding layer in the bottom of the laser structure were elucidated by comparing to the photoluminescence of a similar waveguide structure, except for the AlGaAs bottom layer. The excitation power dependence shows the strong excitonic origin of the light emission in the temperature range 4–300 K in both structures. Carrier transport mechanisms through the superlattices is analyzed from the evolution of the photoluminescence of the quantum well and the superlattice confining layers; a structure dependent transparency temperature is defined, at which transport changes from tunneling assisted to extended minibands regime. The value of this parameter depends on the localized states in the superlattice minibands, caused by interface roughness.

I. INTRODUCTION

The original structure of graded index separate confinement heterostructure single quantum well (GRIN-SCH-SQW) lasers[1] is at present undergoing continuous modifications, with the aim of improving both its crystalline structural perfection and its optical performance. The introduction of GaAs/AlGaAs (or GaAs/AlAs) superlattices in different parts of the laser structure has been the fows of great interest. It has been shown[2,3] that the introduction of a GaAs/AlAs superlattice buffer layer embedded at different depths between the GaAs substrate and the active layers clearly improves the device performance at the active region, in terms of lower threshold currents and higher quantum efficiency. All binary (AlAs)/(GaAs) short-period superlattices have been used to synthesize the cladding layer and optical cavity[4,5] of a GRIN-SCH-SQW laser. Also, these superlattices have been used[6] for the waveguide in the same type of laser.

The origin of the improvements promoted by the introduction of the superlattices are linked to either a reduction of impurity flow coming from the thick AlGaAs layer growth front, or to a higher interface abruptness at the active region.[7,8] However, to our knowledge, there is not any detailed study of the transport mechanisms and recombination processes of these laser structures, which could be due to the introduction of superlattices.

We present in this work a detailed analysis of the photoluminescence (PL) emission from laser structures with GaAs/AlAs superlattices in the waveguide in order to gain deeper insight into the recombination and carrier transfer processes of these laser structures.

Experimental conditions are described in Sec. II. Section III is devoted to a detailed analysis of the photoluminescence (PL) emission and its dependence with temperature and excitation power. In Sec. III A the excitation power dependence of the QW related PL signal is studied in order to distinguish excitonic versus free carrier recombination in the structures. In Sec. III B, we analyze the temperature dependence of the QW and SLs luminescence peak energies. The evolution of the intensity of the different peaks as a function of the temperature, is studied in Sec. III C to elucidate the transport mechanisms. Finally, in Sec. III D we study the different effects that contribute to the linewidth of the QW peak in the range 4–300 K.

II. EXPERIMENT

GRIN-SCH-SQW GaAs laser structures were grown by MBE on (001) Si-doped GaAs substrates. The waveguide is a GRIN structure consisting in all binary $(AlAs)_m/(GaAs)_n$ superlattices of constant AlAs barrier layer thickness $m=5$ monolayers (ML), and graded GaAs layer thickness $n=5$ ML (4 periods, SL3), $n=7$ ML (6 periods, SL2), and $n=9$ ML (25 periods, SL1). Both the superlattice waveguide and the 110 Å-thick GaAs active QW were undoped. Both $Al_{0.7}Ga_{0.3}As$ cladding layers are 1.2 μm thick, $n=2\times10^{18}$ and $p=2\times10^{18}$ cm^{-3}, respectively [structure A, Fig. 1(a)]. We have studied comparatively a GRIN structure without the alloy cladding layers, grown under the same experimental conditions, in order to discriminate the effects due to the thick AlGaAs barriers [structure B, Fig. 1(b)]. This GRIN structure has thicker (310 periods) SL3 top superlattice in order to have enough material thickness for absorbing the radiation to yield significant emission intensity even at room temperature. 40-μm-wide broad area lasers were fabricated. Typical J_{th} values for a 400-μm-long laser are 420 A/cm^2, comparable to those obtained by Tokuda *et al.*,[6] with temperature characteristic $T_0=300$ K in the temperature range 240–300 K and anomalous higher values (500 K) at lower temperatures.

In order to make PL measurements, the samples were mounted in a variable temperature cryostat, and the tem-

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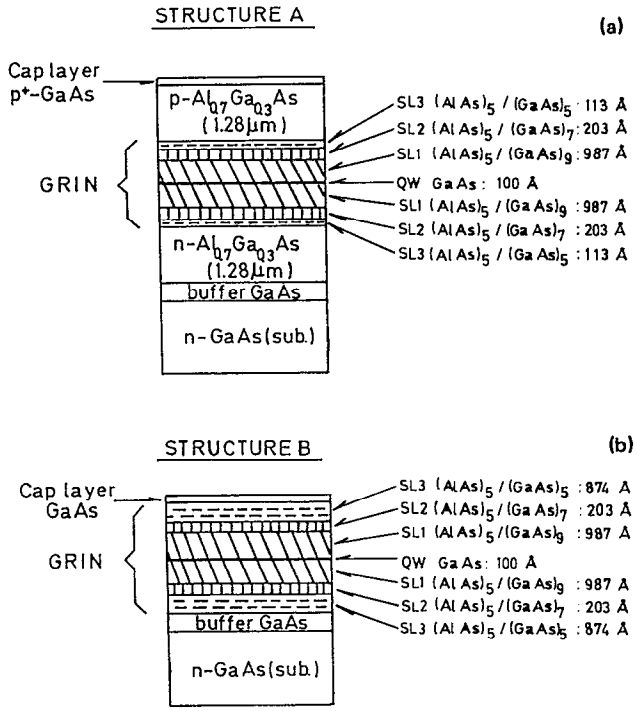

FIG. 1. (a) Schematic diagram of the laser structure or structure A. (b) Schematic diagram of the GRIN structure or structure B.

perature varied in the range 4–300 K. Excitation light was the 488.0 nm line of an Ar^+ laser (with energy above the band gaps of the $Al_{0.7}Ga_{0.3}As$ and the SLs). The emission was dispersed by a 0.8 m double monochromator and finally detected by a cooled GaAs photomultiplier.

III. PHOTOLUMINESCENCE RESULTS AND DISCUSSION

PL spectra from structures A and B, in the range 4–300 K are shown in Figs. 2(a) and 2(b). According to the energy position, the well widths are 110 and 85 Å for samples A and B, respectively.[9]

At low temperatures (13 and 17 K) the GRIN constituent SLs are observed (labeled SL1, SL2, and SL3 in Figs. 2(a) and 2(b)) as well as the QW. The relative intensity of the three superlattice peaks can be directly related to their respective thicknesses in both samples. In structure A, the emission from the thick $Al_{0.7}Ga_{0.3}As$ cladding layer is observed at very low temperatures (13 K), and rapidly disappears with increasing temperature. It can be noticed that in this A structure the SL1 peak remains intense even at room temperature.

In structure B, a double peak can be observed in the QW emission, separated 22 meV in energy. The origin of the high-energy contribution comes from recombinations involving the light-hole (LH) band and the main QW peak is linked to the heavy-hole (HH) band. The 22 meV energy difference are in agreement with the theoretically ex-

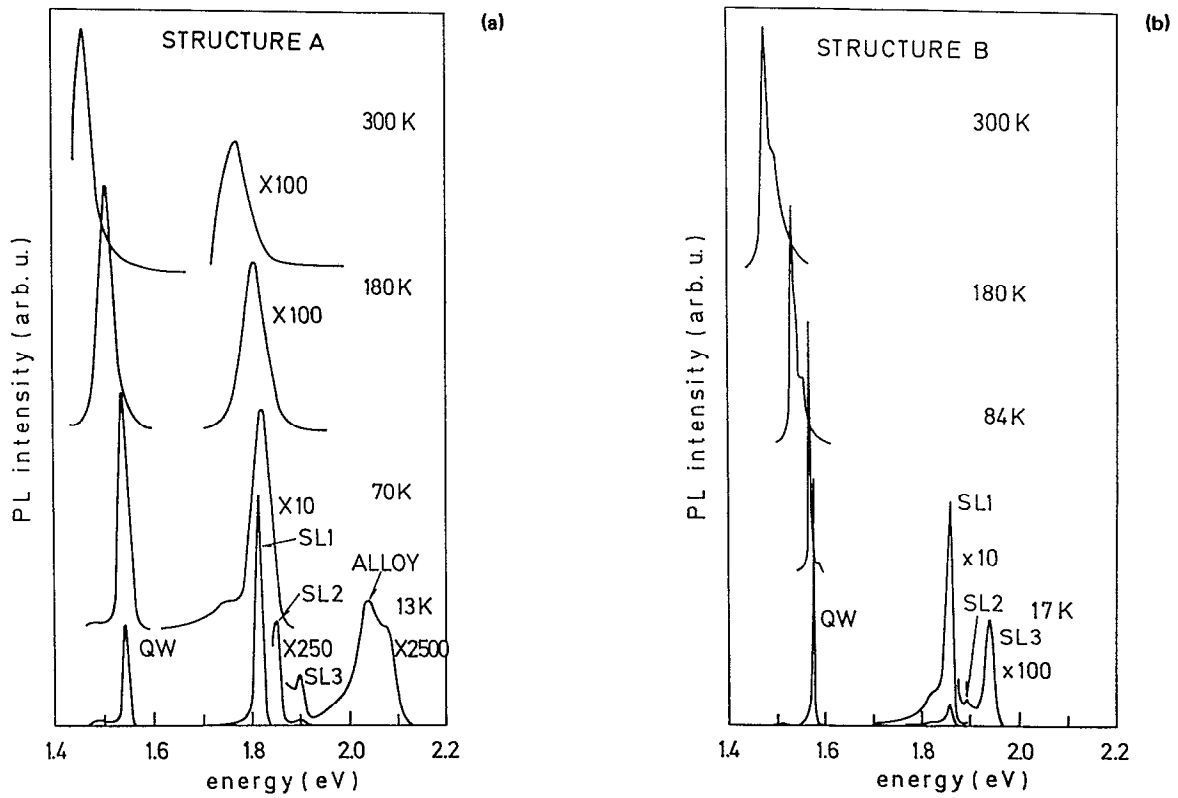

FIG. 2. (a) Photoluminescence spectra of structure A at different temperatures. (b) Photoluminescence spectra from structure B at different temperatures.

TABLE I. Values of α vs temperature for the structure A and structure B (α is given by the expression $dF/dt \propto P^{\alpha}$, where dF/dt is the number of photon per time unit and P the excitation power).

T (K)	Structure A	Structure B
4	1.17	...
25	1.13	...
70	...	1.21
90	1.08	...
170	1.20	1.23
245	1.23	1.41
300	1.20	1.42

pected results.[9] However, the HH and LH contributions cannot be resolved in structure type A due to its larger QW linewidth.

A. Excitation power dependence

A simple way to analyze the origin of the PL emission from undoped semiconductor structures, is to study the evolution of its excitation power dependence. Following the model of Fouquet *et al.*,[10] which describes the time dependence of electron and hole populations in an undoped semiconductor, the number of emitted photons per time unit after an excitation (dF/dt) is proportional to P^{α}, being P the excitation power and α the slope in a logarithmic plot of dF/dt vs P; α will give information on the recombination processes at each temperature. For $\alpha=1$ the recombination processes are purely excitonic, while $\alpha=2$ indicates that free carrier recombination processes are dominant.

We have performed the corresponding PL experiments and measured the integrated intensity of the QW PL peak as a function of the excitation power in a range of three orders of magnitude of P. The values of α for both structures are displayed in Table I. The values are close to $\alpha=1$, in the whole 4–300 K temperature, therefore, excitonic recombination processes remain are dominant in both structures, even at room temperature. Similar results have been obtained from excitonic absorption[11,12] and time resolved PL experiments[13] in GaAs-AlGaAs multiple QW structures with well widths ranging from 50 to 150 Å.

B. Energy shift of the photoluminescence peaks with the temperature

The transition energy of the QW and SL1 versus temperature is plotted in Fig. 3 in the range 4–300 K for both structures. The SL1 peak remained appreciable up to room temperature only in structure A. SL1 is a $(GaAs)_9/(AlAs)_5$ superlattice; its 4 K fundamental band gap, observed in PL, is type II (pseudoindirect);[14] as the temperature is raised up to 100 K, the type I (direct) transition approaches and, eventually, equals the type II transition, and will dominate at higher temperature.[15] The low intensity emission of SL2 and SL3 do not allow us to follow their temperature evolution.

We have represented in Fig. 3, for comparison, the band-gap temperature evolution of bulk GaAs, which has

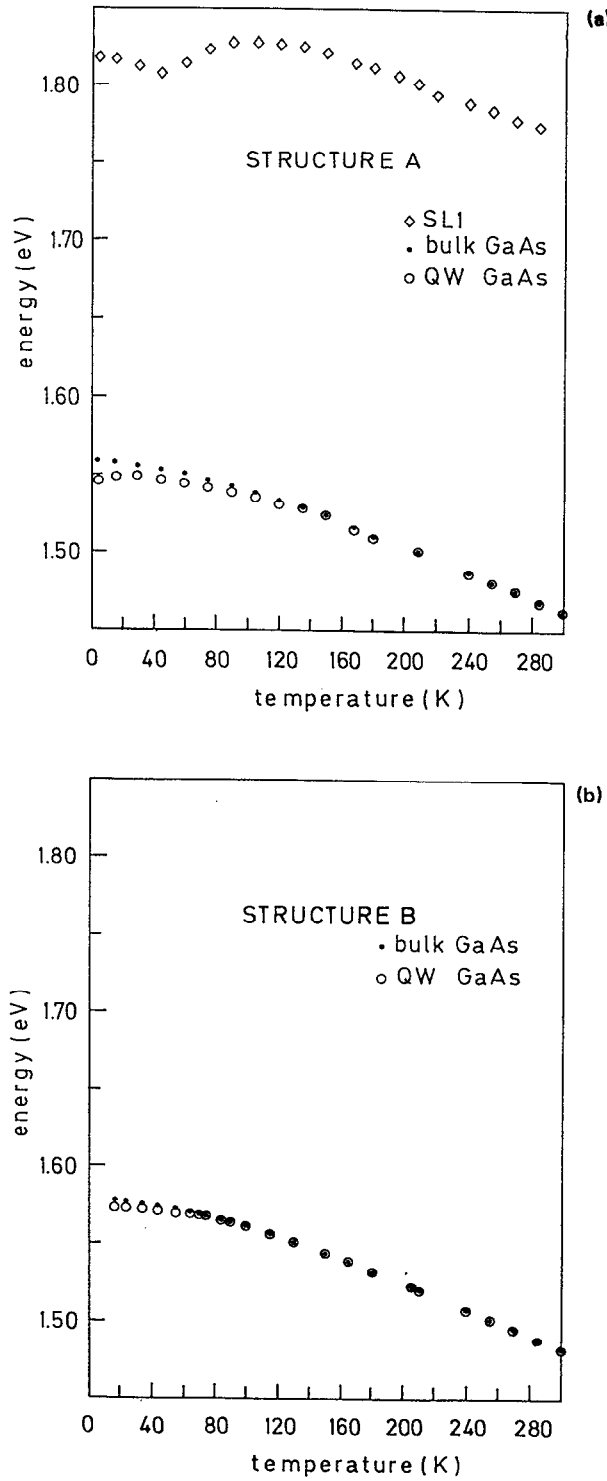

FIG. 3. Transition energy vs temperature: (a) Corresponding to the quantum well (QW) and the superlattice (SL1) of structure A, (b) corresponding to the quantum well of structure B.

been fitted to the experimental QW curves in the high energy temperature range. In both A and B structures, the QW fundamental transition closely follows the bulk GaAs curve down to 100 K. Below this temperature it deviates from the GaAs plot, remaining nearly constant in the 4–100 K range. Two possible explanations could be argued for this behavior: (a) The recombination slowly changes

from excitonic to free carrier type in the range 4–100 K and the shift amounts the exciton binding energy,[12] and (b) the change takes place from bound exciton to free exciton states in the range 4–100 K, shifting the PL peak an amount equivalent to the exciton-defect binding energy.[16] The observed Stokes shift in both structures is in the order 3–5 meV, which is much smaller than the expected QW exciton binding energy (9–13 meV).[17] Results obtained by Delalande *et al.*[18] and Zucker *et al.*[19] on studies of the exciton trapping effects in QW, demonstrate that the traps involved have their origin in interface defects and a typical exciton binding energy on these defects lies in the 2–5 meV range, in agreement with our experimental Stokes shift at 4 K. Therefore, we conclude that the temperature evolution of our samples, according to the hypothesis (b), indicated that at temperatures above 100 K the QW peak originates from free exciton recombinations and below that temperature excitons trapped to interface defects represent an important contribution to the overall recombination process. This result is consistent with the excitation power dependence of the QW PL intensity exposed in Sec. III A.

As shown in Fig. 3(a), the QW peak energy from structure A, undergoes a small blue shift of about 2 meV in the range 4–40 K. The origin of this observed blue shift can be interpreted as follows: Fluctuations of the QW width will produce an effective band-gap modulation in the directions parallel to the QW plane.[20] At low temperatures (4–40 K), the modulation related band-gap minima will act as active recombination sites, because photogenerated carriers will drift towards them as drift times are much smaller than radiative recombination times.[21] As temperature is raised, more carriers will be able to occupy states at higher energy in the band-gap modulation scheme and QW peak should broaden and shift towards higher energies. The shift will be approximately proportional to KT. This shift, described by Jiang *et al.*,[20] is not usually observed if the fluctuations are smaller than a single monolayer, due to the competitive red shift induced by the band-gap shrinkage with temperature. In this way, this result suggests that structure A, with an 1.28-μm-thick underlying $Al_{0.7}Ga_{0.3}As$ epitaxy, has fluctuations of the QW width higher than one monolayer; in structure B the blue shift is not observed, suggesting that well width fluctuations are smaller than a single monolayer.

C. Temperature dependence of the photoluminescence intensity

Figure 4 shows the dependence of the value of $I(QW)/I(SL)$ as a function of the temperature for structures A and B, $I(QW)$ and $I(SL)$ being the integrated intensities of the QW and SL1 peaks. As observed in Fig. 4, at low temperatures, the ratio of intensities is very small; when a certain critical temperature is exceeded, this parameter increases rapidly, the slope in structure B being higher than the corresponding slope in structure A. This means that, in structure B, the carriers (or excitons) are more efficiently transferred through the GRIN into the QW than in structure A. Two well-defined transport regimes can be deduced from the plot in the 4–300 K range. These are the

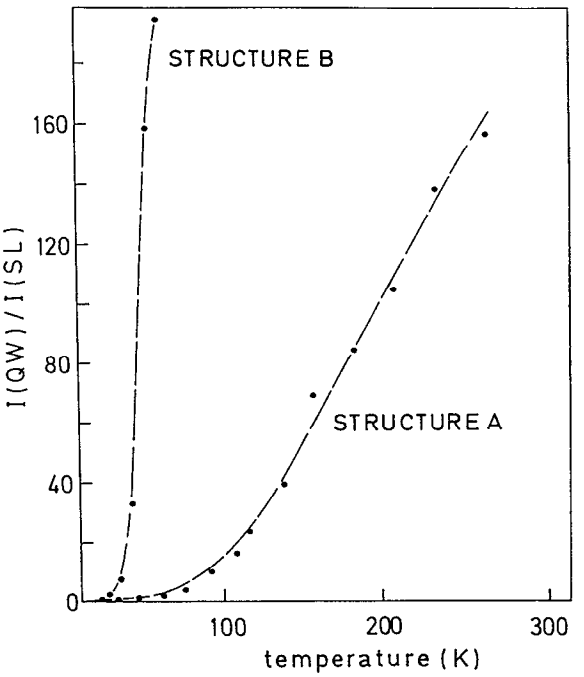

FIG. 4. Ratio of the integrated luminescence intensity of the quantum well to the integrated luminescence intensity of the superlattice as a function of temperature for structures A and B.

tunneling-assisted[22] and the miniband[23] regimes. We will define a transparency temperature T_t as the temperature at which transition between both regimes occurs. The transport in the tunneling-assisted regime takes place via localized states while in the miniband regime it takes places via Bloch states that are extended throughout the whole superlattice. The T_t value in structure A (around 120 K) is higher than the one in structure B (around 40 K). According to recent results from Fujiwara *et al.*,[24] this difference may be due to the fact that the composition of SL1 is not exactly the same in both structures (the GaAs content of SL1 in structure A is slightly larger than in structure B). Furthermore, fluctuations in the thickness of the SL layers, in their potential, or interface imperfections that will cause localization of the wave function in the superlattice.[25–27] This partial localization of carriers causes higher recombination within the confining layers, thus diminishing injection in the QW and limiting the transparency of the superlattice.

The PL intensity corresponding to SL1 in structure A at high temperatures may be ascribed to high localization of excitons. This is not observed in the structure B. We think this higher density of localized states in structure A as compared to B is due to a lower superlattice quality, caused by the growth of the 1.28-μm-thick $Al_{0.7}Ga_{0.3}As$ layer. This can affect the characteristics of lasers such as threshold current, causing it to be slightly higher than the conventional lasers constructed with ternary alloy waveguide. Also, for the same lasers, the values of T_0 are as high as 570 K for $T < 240$ K, due probably to the effect of no total transparency of the confining superlattice.

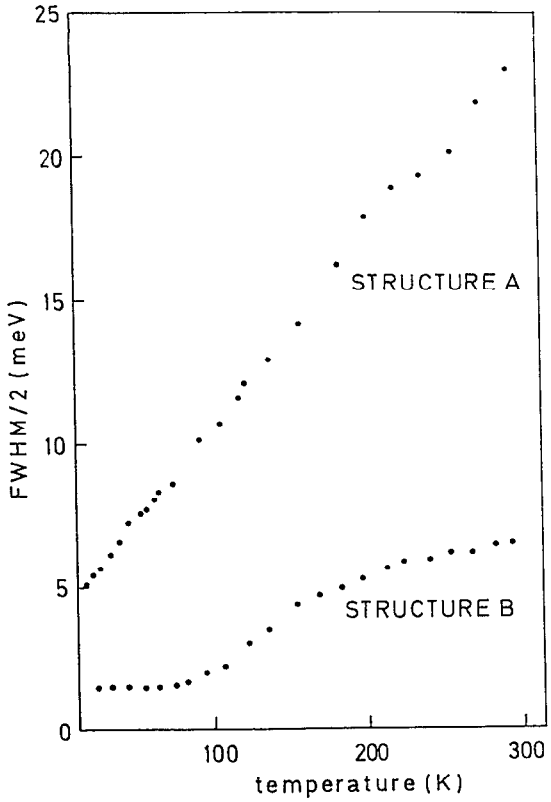

FIG. 5. The halfwidth at half maximum (FWHM/2) of the quantum well photoluminescence peak as a function of temperature for structures A and B.

D. Temperature dependence of the photoluminescence linewidth

Dominant contributions to the linewidth of the QW excitonic peak are due to the exciton-crystalline lattice interaction via polar optical phonons and to the fluctuations of the QW thickness.[12,28,29] Also interactions with acoustical phonons, and ionized impurities have to be considered in the low temperature range ($T<100$ K).

The spectral lineshape of the excitonic line in a QW structure can be fitted by a Gaussian curve with a broadening parameter Γ, approximately equal to the half width at half maximum FWHM/2 of the PL peak.[12] The value of Γ can be decomposed, in a first approximation, into four different contributions: Interactions with acoustical phonons (Γ_{LA}), interactions with ionized impurities (Γ_I), fluctuations of the confinement energies caused by well thickness variations ($\Gamma_{\Delta L}$) and interaction with LO phonons (Γ_{LO}). Consequently, the broadening parameter can be written as: $\Gamma=\Gamma_{LA}+\Gamma_I+\Gamma_{\Delta L}+\Gamma_{LO}$. In the low-temperature range, the Γ_{LA} term dominates over the Γ_{LO} term, and the reason for it is that the LA phonon population goes linearly with temperature while LO phonon scattering increases with temperature as follows: $\Gamma_{LO}=\Gamma^0_{LO}/[\exp(\hbar W_{LO}/KT)-1]$, and is negligible at low temperatures. The opposite reasoning holds for the high-temperature range.

Consistent with this scheme, and assuming that for a low density of residual impurities the term Γ_I becomes negligible, at low temperatures ($T<100$ K) the Γ_{LA} and $\Gamma_{\Delta L}$ terms dominate in Γ and, as the temperature is raised, Γ_{LO} and $\Gamma_{\Delta L}$ will be the only important contributions. Moreover, according to previous results in QW structures,[29] the contribution of the LA phonon scattering to Γ at 4 K is as small as 0.1 meV and, therefore, it can be stated that the $\Gamma(4\text{ K})$ of the QW PL peak can provide a direct indication of the degree of thickness fluctuation in the well, that is, $\Gamma(4\text{ K})\approx\Gamma_{\Delta L}$.

In Fig. 5, we present the FWHM/2 of the QW PL peaks as a function of the temperature. At 4 K, the QW peak of structure B shows a FWHM/2 of 1.5 meV, originated by a fluctuation of the potential well thickness of a magnitude smaller than a single monolayer. This result reflects the very high smoothness achieved at the QW interfaces of the structure. It is worth pointing out that in the interval 4–100 K the linewidth of the QW peak remains nearly constant, which indicates that even through the thermal energy (KT) is growing there are not available levels (induced by QW zones with different thicknesses) between the $n=1$ and $n=2$ sublevels. As the temperature is raised over 100 K the broadening due to LO-phonon scattering becomes significant and rapidly increases with T. The 7 meV value of the FWHM/2 at room temperature has the contribution of both $\Gamma_{\Delta L}$ and Γ_{LO}. This value is slightly smaller than the exciton binding energy[12,17] and it holds in the whole 4–300 K range, which confirms that excitonic states are not ionized and that it is possible to have predominantly excitonic recombination even at room temperature.

Based on the results found in structure B, we study the QW peak linewidth in structure A. At 4 K, the FWHM/2 of 5 meV indicates a larger interface roughness ($\Gamma_{\Delta L}$) in the range between one and two monolayer fluctuation. As temperature is raised in the range 4–300 K, the QW peak continuously broadens achieving values of $\Gamma=23$ meV at room temperature. In order to properly understand the magnitude of the Γ value, an extra contribution to the QW peak linewidth has to be added that was not present in structure B. The HH and LH related peaks, clearly resolved in B, Fig. 2(b), contribute simultaneously to the QW peak in structure A because both contributions cannot be resolved. For the 110 Å well in structure A, the energy difference between both transitions is 17 meV. Therefore, this extra broadening parameter, that we will note $\Gamma_{HH\text{-}LH}$ will play a fundamental role, together with the $\Gamma_{\Delta L}$ and Γ_{LO} terms, and the weight of each one of the three terms in the total Γ value cannot be accurately obtained.

IV. CONCLUSIONS

The recombination and carrier transport processes in a SL-GRIN-SCH-SQW laser structure have been analyzed from its photoluminescence emission. The GRIN layers of these laser structures were fabricated with all binary AlAs/GaAs short period superlattices.

We have shown that radiative recombinations have strong excitonic origin, even at room temperature; a transition from bound exciton to free exciton emission takes place for temperatures above 100 K.

We have observed a blue shift of about 2 meV in the range 4–40 K, in the PL emission of the laser structures. This shift is attributed to an effective band-gap modulation caused by fluctuations of the QW width, which we estimate to be on the order of two monolayers; in a similar structure, but without the underlying ternary material, results imply submonolayer fluctuation for the QW width.

Depending on the temperature, we have discriminated two regimes for the vertical transport through the superlattices to the QW. At low temperature, carrier transport is tunneling assisted, via localized states, and when a transparency temperature is reached, transport occurs via extended minibands. This transparency temperature depends on the superlattice composition and interface quality. The roughness of the thick ternary alloy underlying the waveguide structure causes transparency to be reached at higher temperature, and this transparency is not total, as photoluminescence from the SL is observed even at room temperature. These results indicate that flatness of this bottom layer is mandatory to get the expected improvement by using superlattices to synthesize the waveguide material of a SCH-QW laser.

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