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Excitons in undoped AlGaAs/GaAs wide parabolic quantum wells

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Abstract. In this work the electronic structure of undoped AlGaAs/GaAs wide parabolic quantum wells (PQWs) with different well widths (1000 Å and 3000 Å) were investigated by means of photoluminescence (PL) measurements. Due to the particular potential shape, the sample structure confines photocreated carriers with almost three-dimensional characteristics. Our data show that depending on the well width thickness it is possible to observe very narrow structures in the PL spectra, which were ascribed to emissions associated to the recombination of confined 1s-excitons of the parabolic potential wells. From our measurements, the exciton binding energies (of a few meV) were estimated. Besides the exciton emission, we have also observed PL emissions associated to electrons in the excited subbands of the PQWs.

1. Introduction

Recent advances in the semiconductor growth techniques have offered the opportunity to fabricate structures with potential profiles of almost any shape. For instance, the growth of short period superlattices with the digital alloy technique makes possible to synthesize semiconductor structures with any arbitrary potential profile. Closely perfect parabolic effective potential profiles have been grown by this technique. Parabolic quantum wells are very interesting structures both from fundamental and technological points of view. In these structures it is possible to form an almost homogeneous electron gas within a three-dimensional space that moves in a uniformly distributed background of positive charge [1]. Moreover, PQWs have the particular property of equally spaced electronic states, which makes possible an accurate determination of the band offset parameters [2]. From the technological point of view, PQWs can be used as polarization insensitive electro-absorptive modulators [3] and far-infrared resonant tunnelling devices [4]. Finally, PQWs demonstrated to be a very good candidate for the electric control of the electron spin [5], essential for the development of spintronic devices. Since the experimental realization of a GaAs/GaAlAs PQWs by Sayegan and co-workers [6], the properties of PQW structures have been discussed in an expressive number of works. However, most of them are theoretical ones [1,7] and/or associated to transport properties [8,9]. A very few works are addressed to the optical properties of PQWs. Recently, we reported on the optical properties of doped parabolic quantum wells [10]. In the present work, we are concerned with the optical properties of excitons and excited states on undoped AlGaAs/GaAs wide PQW.

2. Sample, experimental details and theoretical calculations

All the samples here investigated were grown in a Gen II Molecular Beam Epitaxy system on top of epi-ready semi-insulating GaAs (001) substrates. The structure of the PQW is the follow: first, an 1- μm -thick GaAs buffer was grown followed by a $20\times (\text{AlAs})_5(\text{GaAs})_{10}$ superlattice in order to improve the crystal purity and quality. Then a 500 \AA -thick AlGaAs layer was grown with the Al content varying linearly from 0% to 31% using the digital alloy technique, after which it was grown a 1000- \AA -thick $\text{Al}_{0.31}\text{Ga}_{0.69}\text{As}$ layer. Then, the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ parabolic quantum well was grown with the Al content varying from $x=0$ in the center of the parabola to $x=0.20$ at the edges of the parabola. Inside the well, the parabolic potential profile was achieved by the digital-alloy technique using a 20- \AA -period superlattice in which the respective thickness of GaAs and AlAs were varied accordingly. Finally, it was grown a cap layer consisting of a 400- \AA $\text{Al}_{0.31}\text{Ga}_{0.69}\text{As}$ layer followed by a 100- \AA -thick GaAs layer. PL measurements were performed in a closed circuit optical cryostat operating with helium from 8.5 K to 300 K. The samples were excited with the 5145 \AA line of an argon laser with spot size of 300 μm . The signal was analyzed by a monochromator and detected by a cooled charge coupled device. In order to determine the electron and hole energy levels of the subbands, we have performed theoretical calculations. In our calculations we considered background concentrations of electrons and holes equal to 10^{-10} cm^{-2} . These carrier concentrations represent the photogenerated carriers during our PL experiments [11]. In the calculations we have considered the ideal case of $T = 0 \text{ K}$ and a constant electron effective mass equal to $0.066 m_0$, as a mean value across the parabolic quantum well.

3. Results and discussion

Figure 1 shows the low temperature PL spectra for undoped PQWs with 1000 \AA and 3000 \AA well widths. We see that the spectrum can be divided by two spectral regions. One dominated by the GaAs bulk emissions (left side) and the other by the PQW emissions (right side). For the sample with 3000- \AA -well width, the PL spectrum is dominated by one emission associated to the bulk of GaAs. A small shoulder is also observed at the high energy side and is probably associated to the fundamental transition of the PQW (peak A). For the 1000 \AA sample a more complex PL spectrum is observed with at least three emissions related to the GaAs material and other three in the PQW layer. Based on our PL measurements as a function of temperature and excitation power, we ascribe the peak at 1.5164 eV to a GaAs band-to-band recombination. The peaks at 1.5158 eV and 1.5142 eV are associated to the free exciton and to a neutral donor to bound exciton emissions, respectively.

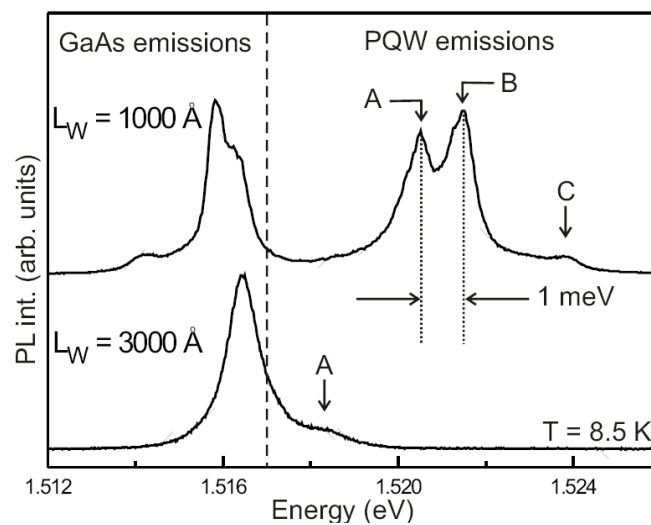


Figure 1. Low temperature PL spectra for undoped PQWs with 1000 \AA and 3000 \AA well widths. The vertical dashed line separates the GaAs and the PQW regions of the spectrum.

Now, we will describe the PQW emissions, in the right side of the Fig. 1. The spectra at low temperature and low excitation condition clearly show the difference between the two samples. For the sample with $L_w=1000$ Å three different PL emissions are present: one at 1.5205 eV, the other at 1.5215 eV and the last one at 1.5238 eV, labelled in Fig. 1 as A, B and C, respectively. For the $L_w=3000$ Å sample, instead of several peaks we observed only a small shoulder at 1.518 eV (peak A). In Fig. 2(a) we show the evolution of the PL response as a function of temperature for the $L_w=3000$ Å sample. We observe that with increase of temperature the transition associated to the A peak becomes well defined and a new transition shows up at 1.5183 eV (B peak) in the spectrum taken at $T=40$ K. We associate this new emission to an excited state of the PQW. In PQWs, owing to the parabolic shape of the potential, the probability of these kinds of transitions is no more zero and excited states are then possible to be observed. Definition of the fundamental transition (peak A) and the observation of excited levels (peak B) of the PQW with the increase of the temperature is an effect originated by the promotion of carriers from the GaAs bulk material to the excited levels of the PQWs and also from the fundamental PQW state to its excited states. However, with further increasing of the temperature due to scattering and non radiative processes the PL signal from the PQW quenches and it almost vanishes for temperature higher than 150 K.

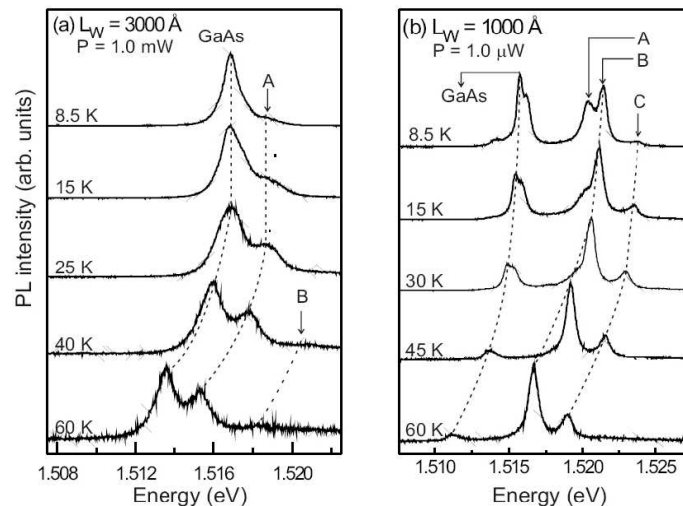


Figure 2. PL spectra at several temperatures for PQWs with different well widths: (a) $L_w = 3000$ Å and (b) $L_w = 1000$ Å. The dashed lines are guide to the eye.

From the theoretical calculations we verified that the fundamental electron (e1) to fundamental heavy hole (hh1) transition (e1-hh1) of the PQW is approximately 3.2 meV above the fundamental GaAs bulk emission. Using the spectrum at 60 K, where excitonic effects can be disregarded, we decomposed the PL spectrum using a multi-Gaussian fitting. From this fitting we determined that the separation between these two emissions is approximately 2.8 meV, in good agreement with the theoretical value of 3.2 meV. So we ascribed peak A to the e1-hh1 PQW recombination energy. Our calculations also indicate that the splitting between the hh1 and lh1 (light hole fundamental level) energies is ~ 1 meV. In this way, we believe that the transition e1-lh1 is present in the high energy tail of the A peak. To analyze the emission involving the excited state, we have to consider that from the parity selection rules, only transitions with the quantum numbers of the initial and final states differing by even numbers or zero can be observed. In this way, the best candidates for the B emission are the e1-hh3, e2-hh2 or e1-lh3 transition energies. The theoretical separation between these transition energies and the GaAs gap determined by our calculations are 6.7 meV, 9.4 meV and 11.9 meV, respectively. The experimental separation between the B emission and the GaAs peak is ~ 5.8 meV. So it is likely that the excited state (B emission) is associated to e1-hh3 transition.

In the Fig. 2(b) we show the PL spectra for the thinner PQW ($L_w = 1000\text{\AA}$) at different temperatures. We observe that the emission of the PQW is quite complex. As we have pointed out in the Fig. 1, three emissions (A, B and C) are present. We can notice that the emission A has its intensity rapidly decreased as the temperature increases and it is not observed anymore for $T > 30\text{ K}$. At $T = 30\text{ K}$, the emission B becomes dominant and the emission C rises in intensity. Also at $T = 30\text{ K}$, a very weak signal seems to be present in the high energy side of the spectrum. At $T = 60\text{ K}$, the peak is better perceived. Like in the wider PQW, emissions A, B and C also have a thermal quench for $T > 150\text{ K}$. It is important to notice that the B emission is the last one to vanish. By its behaviour as a function of the temperature it is quite clear that the emission B is the fundamental transition (e1-hh1) of the PQW. This transition is $\sim 5.6\text{ meV}$ above the band-to-band GaAs emission (the difference was taken in the spectrum at 60 K to avoid excitonic effects) in relatively agreement with the theoretical value of 7.2 meV . The experimental splitting between the A emission and the e1-hh1 transition energy is $\sim 1\text{ meV}$. Based on the temperature evolution of peak A we ascribe this emission to the 1s-excitonic transition of the PQW with a binding energy of approximately 1 meV . It is observed that the experimental separation between the emission C and the e1-hh1 transition energy is $\sim 2.5\text{ meV}$, which is very close to the theoretical value of the fundamental heavy and light hole splitting energy of 2.8 meV found in our calculation. Finally, our theoretical calculation also indicates that peak C is related to the e1-hh3 transition energy of the PQW.

4. Conclusion

Photoluminescence measurements at different temperatures have been performed to investigate the optical response of wide parabolic quantum wells with different well widths (1000 \AA and 3000 \AA). Due to the particular potential shape of the PQWs, these systems confine photocreated carriers with almost three dimensional characteristics. Depending on the well thickness, it was possible to observe narrow emissions in the PL spectra. For both samples the fundamental and also excited transitions of the PQWs were observed. For the thinner PQW we have observed that the optical transitions obey the parity selection rules and we have detected besides the e1-hh1 transition, the e1-lh1 and the e1-hl3 excited states. Finally, for the sample with $L_w = 1000\text{ \AA}$, we were able to observe 1s-excitonic emission with a binding energy of 1 meV . All these assignments were corroborated by theoretical calculations.

Acknowledgments

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