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Ground and Excited States Energy in InAs Quantum Dots in a Well InGaAs/GaAs Structures

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Abstract

This paper presents the photoluminescence study at 80 K and scanning photoluminescence spectroscopy investigation of the ground and multiexcited states at 80 and 300 K in InAs quantum dots (QDs) inserted in symmetric $In_{0.15}Ga_{0.85}As$/GaAs QW structures created at different QD growth temperatures. It is shown that some of the structures investigated exhibit a spatial long range variation of the average QD size in the QD ensemble across the sample. This long range QD size inhomogeneity was used for an investigation of the multiexcited state energy trend versus ground state energy (or QD sizes). Experimental results were compared with the electron-hole level energy trend versus QD size predicted theoretically on the base of the 8-band $k{\cdot}p$ approach. Some correlation between experimental and theoretical results has been revealed and discussed.

Key words: QD sizes, ground state, multi excited state energy, growth temperatures.

Resumen
(Comportamiento de la energía elástica para el estado base y estados excitados en puntos cuánticos de InAs en estructuras de pozos de InGaAs/GaAs)

En este trabajo se presenta el estudio de fotoluminiscencia a 80 K e investigación de espectroscopia de fotoluminiscencia de barrido del estado base y de varios estados excitados a 80 y 300 K en puntos cuánticos (QD) de InAs embebidos en estructuras simétricas $In_{0.15}Ga_{0.85}As$/GaAs de pozos cuánticos (QW) creadas a diferentes temperaturas de crecimiento de QD. Se muestra que algunas de las estructuras investigadas presentan una variación espacial de largo alcance del tamaño promedio de los QD a través de la muestra. Esta falta de homogeneidad de largo alcance en el tamaño de los QD se utilizó para la investigación de la energía de los estados multiexcitados con la energía del estado base (o tamaño del QD). Los resultados experimentales se compararon con la tendencia de la energía del nivel electrón-hueco en comparación con el tamaño de los QD predicho teóricamente en la base de la aproximación de las ocho bandas $k{\cdot}p$. Cierta correlación entre los resultados experimentales y teóricos han sido revelados y se discuten.

Palabras clave: tamaño de los puntos cuánticos QD, estado base, energía de los múltiples estados excitados, temperatura de crecimiento.

1. Introduction

It was shown ten years ago that the growth of a highly lattice mismatched semiconductor layer of InAs on a GaAs substrate (Stranski-Krastanow (SK) growth mode) could lead to the spontaneous formation of semiconductor islands with sizes in the quantum range [1, 2]. At the end of the nineties different technological methods were used for the modification of electronic quantum dot (QD) parameters in MBE and MOCVD growth of InAs/GaAs QDs [3]. As result of this work, SK QD structures have been obtained with high quality suitable for laser device applications [4]. It was revealed, however, that SK QDs exhibit inhomogeneity and random distribution on the surface of heterostructures [5]. A very promising method for QD parameter investigation is PL scanning spectroscopy [6]. This method enables a precise investigation of ground and multiexcited optical transition variations along the same structure. This paper presents the PL investigation at 80K at different excitation light intensities, as well as a complementary ground and multi excited state PL scanning study performed at 80 and 300K on symmetric DWELL (dot-in-a-well) laser structures created at different InAs QD growth temperatures with the aim to study the ground and multiexcited states luminescence variations and their trend as a function of the QD GS energy or InAs QD sizes.

2. Samples and experimental setup

The DWELL laser structures were grown by elemental source MBE method as was described in [5-7]. Five different QD structures were created: QDs and QW were grown at 470 (1), 490 (2), 510 (3), 525 (4) and 535ºC (5), and at 590-610 ºC for the other layers of the structure. The individual dots are of 12-18 nm in base diameter and ~ 6-9 nm in height. It was shown earlier in [7] in an AFM investigation of the same type of uncapped InAs QDs that the density of QDs changed from 1.1×10^{11} down to 1.4×10^{10} cm^{-2} when the QD growth temperature increases from 470 to 5350 C. The scanning PL spectroscopy of the QD ground state was performed at 80 and 300 K using a pulsed solid state 800 nm IR laser at an excitation power density of ~170 W/cm^2. Multiexcited state PL mapping was performed at 80 K as well using an Ar+ laser with a wavelength of 514.5 nm and the excitation power density up to 1.0 kW/cm^2. The PL measurement setup was described in [5, 6].

3. Experimental results and discussion

Figure 1 represents PL spectra measured at different excitation power densities for sample #5. The variation of PL band intensities with the change of excitation power indicates that the low energy PL band can be attributed to the carrier recombination between the ground states (GS) in the QDs. The higher energy PL band appears at the higher excitation densities (> 50-100 W/cm^2), indicating that they represent optical transitions via excited states (1ES, 2ES, 3ES).

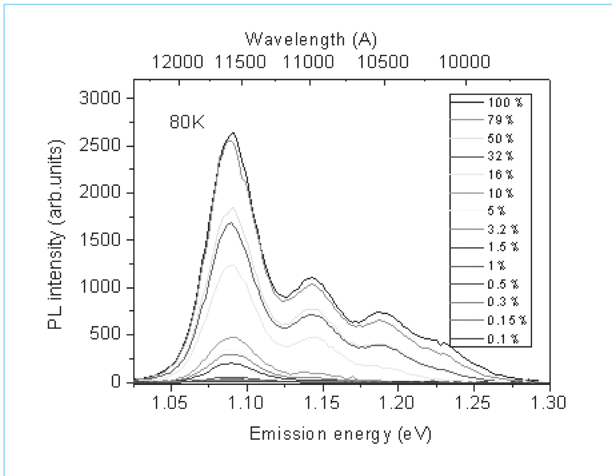

Fig. 1. PL spectra measured at different excitation powers; the highest one is 500 W/cm^2, for QD structures, obtained at the temperature 535ºC.

The full-width at half maximum (FWHM) of PL bands is: 38-40 meV for GS and 36, 32 and 27 meV for 1, 2 and 3 ES PL bands, which is typical for highly homogeneous QD structures. The highest PL intensity is characteristic of structures with QD layers grown at 490-510ºC. With increasing growth temperature up to 5100 C, the GS peak shifts into low energy spectral range, but at higher temperatures (525-535ºC) its shifts to higher energy side again (Fig. 2). PL intensities in QD samples show a noticeable inhomogeneity across the sample area, which in some QD structures is accompanied with a spectral shift of the principal PL maximum (Fig. 2).

We have explored this effect in more detail using a spectroscopic PL mapping technique. On the semi log plot of GS PL intensity vs. its GS energy position the fitting of this trend is very close to a straight line. As we have shown earlier [5,6], this type of dependence testifies on the GS binding energy decrease, apparently, due to decreasing QD sizes.

Multiexcited PL band mapping was performed at 80K on the same line-scan where the QD size decreases (Fig. 3). The energy difference between GS-1ES, 1ES-2ES and 3ES-2ES peaks do not equidistant and equal to 56, 51 and 47 meV, respectively, at a GS position of 1.080 eV (bigger QDs), and monotonically decreases to 48 , 31 and 29 meV, respectively, with increasing GS peak energy up to 1.131 eV (smaller QDs). The analysis of the results of the multiexcited state energy

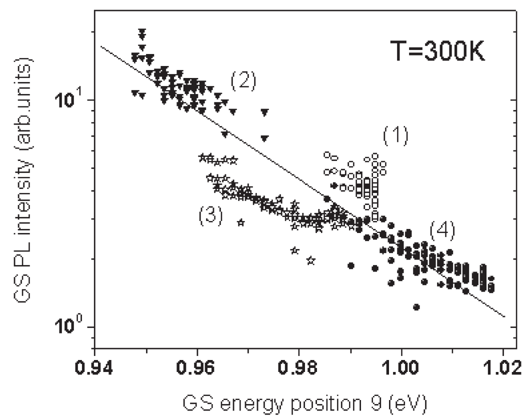

Fig. 2. GS PL intensity versus GS maximum position for QD structures grown at temperatures: (1) 490, (2) 510, (3) 525 and (4) 535ºC.

trend in InAs/InGaAs QDs presented in Fig. 3 we will perform in comparison with the predicted electron-hole energy gap trend for different electronic levels versus QD sizes calculated in Ref. [8] using the 8-band k·p approach. We estimated GS and 1-2 ES optical transitions as the electron hole recombination between the levels with the same quantum numbers: E0-H0, E1-H1, E2-H2.

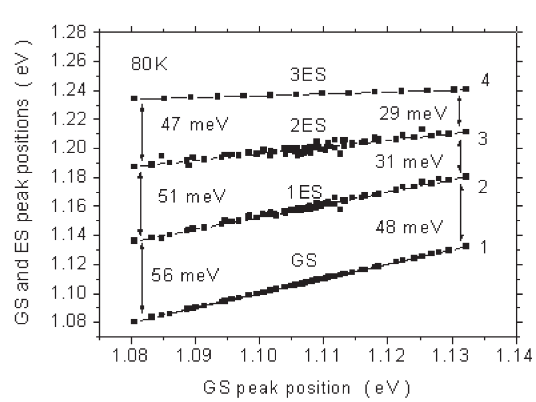

Fig. 3. Experimentally measured GS, 1ES, 2ES and 3ES optical transition energies versus GS transition energy for the sample 5.

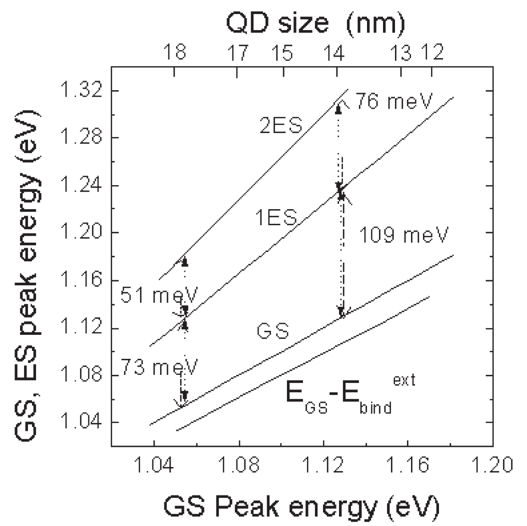

Fig. 4. Energy gap between E0-H0, E1-H1, E2-H2 electron-hole levels in QDs calculated on the base of the theoretical results presented in [8].

Figure 4 presents theoretically calculated energy differences between E0-H0, E1-H1, E2-H2 electron-hole levels in QDs based on Ref. [8]. For further comparison it is necessary to correct the presented electron-hole energy gaps taking into account the exciton binding energies for different states and various QD sizes. Ground state exciton binding energies were computed in the Hartree approximation using 8-band solutions for both electrons and holes in the QDs with sizes from 13-18 nm [8]. The GS transition E0-H0 corrected for exciton binding energy for different QDs is presented in figure 4 as well.

As one can see in figure 3 the experimental energy spacing between the 1ES-GS transition is higher in comparison with the 2ES-1ES and 3ES-2ES values. The theoretically predicted energy spacing for the same transition 1ES-GS is higher than for the 2ES-1ES one as well. So, in this case we can see a correlation between experimental and theoretical results. The experimental values of 1ES-GS, 2ES-1ES and 3ES-2ES decrease with GS energy increasing (smallest QD sizes) (Figure 3). Theoretically predicted values on the contrary have increased significantly (Figure 4) from 73 meV up to 109 meV for 1ES-GS and from 51 meV up to 76 meV for 2ES-1ES, with the QD size decreasing. So, the optical transition energy trend versus QD sizes observed experimentally and predicted theoretically is different.

4. Conclusions

The main reason for different electron-hole energy trends versus GS energy (QD sizes) for experimental and theoretical results may be related to the different shape of the confinement potential and its changes with QD sizes and geometry in investigated QDs in comparison with theory. Non-equidistant energy spacing between GS and ES indicates that a harmonic-oscillator model is not applicable very much in QDs studied. As we have shown in [9], the formation of ES energy levels in QDs, apparently due to a non-parabolic shape of the well profile, is non-harmonic.

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