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Research Article

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Hydrostatic and Biaxial Strain Effect on Electronic Properties of (In,Ga)As Capped InAs/GaAs (113)A Quantum Dots

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Abstract

Optical properties of InAs/GaAs (113)A quantum dots grown by molecular beam epitaxy (MBE) capped by (In, GA)As. Have been investigated. The photoluminescence spectroscopy has been used to explain the optical properties of InAs QD. The reflection high-energy electron diffraction (RHEED) is used to develop the formation process of InAs quantum dots (QDs). A broadening of the PL emission due to size distribution of the dots when InAs dots are capped by GaAs and separation between large and small quantum dots, when they are encapsulated by Ingas has been showed. The PL polarization measurements, have shown that the small dots, require an elongated form, but the large dots present a quasi-isotropic behavior. These results are due to hydrostatic and biaxial strain action on large and small dots grown under specifically growth conditions.

Keywords: High Index, MBE, Strain, Photoluminescence, QDs, InAs, GaAs

1. Introduction

Self-assembled quantum dots (QDs), have been studied intensively, for more than a decade, due to their unique physical properties, arising from the three-dimensional quantum confinement of carriers and delta-like density of state [1-3]. QDs find many applications in optoelectronic devices However, the stochastic nature of the QDs, makes it difficult to obtain dots, with uniformity in both their size and their spatial distribution [2,3]. This behavior, constitute the most dramatic problem that prevents the production of optoelectronic devices, with a high quality of dots. Since, it is incompetent to provide the prospect of temperature independent low threshold lasers [4,5]. The physical properties, strongly depend on growth conditions, such as growth temperature growth rate, and the capping layer material. To improve or adjust the QDs properties, is the utilization of high-index substrates which exhibit some interesting phenomena with respect to (001) orientation. To date, there are few reports about successful growth of self-organized QDs on high-index substrates comparable to those with (001) orientation [6,7].

Growth studies have also been realized with the intention of controlling morphologic and density of the QDs [8]. The growth control and the valid results obtained on these structures which are elaborated on high-index substrates have permitted to improve optical and electrical properties of many compounds [9,10]. Prior to understanding how the capping layer influences the optical property of [11 k] grown InAs QDs. One has to know the effect on the transition energies of QD growth on [11 k] substrates (k = 1, 2, 3). The origin of the evolution of the transition energy, with the substrate orientation, can be traced back to the competition of several effects: (i) hydrostatic component of the strain tensor is responsible for a shift of the conduction band upwards and the valence bands downwards. (ii) biaxial component of the strain tensor influences the degree of the valence band mixing. (iii) variation of the hole effective mass, with the substrate orientation, can significantly alter the effects of the size of the QD. Theoretically, Mlinar et al. have shown that the QD size in the growth direction determine which of the three above-mentioned effects will be the dominant one, regardless of the dot shape [8,9]. In this work we reported the experimental details of the polarized photoluminescence spectroscopy on the InAs/GaAs (113) capped by GaAs and Ingas epilayers. We investigated the effects of the hydrostatic and biaxial strain on the transition energy when the dots are encapsulated by Ingas layer.

1.1. Experimental Details

The samples under investigation in this study, were grown on semi-insulating, (113)A-oriented GaAs substrates, using MBE system equipped with conventional solid- source diffusion cells. The substrate native oxides were removed from the surface at grown temperature 580◦C under an arsenic flux. The GaAs growth rate was set to 0.71 monolayer (ML)/s. After that the growth rates were calibrated with Stranski-Krastanov (SK) transition and RHEED oscillations during epitaxial growth of InAs and GaAs layers on GaAs (113)A, respectively. The growth temperature of InAs QDs was fixed at 500◦C, the substrate temperature was measured by an infrared pyrometer. The RHEED pattern was recorded using our newly developed digital image analysis system, which combines a very sensitive CCD camera and a frame grabber as well as dedicated software. The 3 MLs InAs QDs samples were capped by a thin GaAs and InxGa1−xAs (x = 0.3) layers, respectively. An in-situ reflection high-energy electron diffreaction (RHEED) pattern was used to show the formation process of the InAs quantum dots.

Photoluminescence measurements were carried out, between 10 and 300 K, while keeping the samples in a closed-cycle helium circulation cryostat. The excitation wavelength used is the 514,5 nm line of the cw Ar+ laser. The emission was dispersed by a high-resolution spectrometer and detected by a thermoelectrically cooled Ingas photodetector. The PL polarized measurements were performed on the PL emission normal to the surface via a Glan-Thompson near infrared polarizer at the entrance slit of the monochromator followed by a quarter wave plate in order to get the PL signal independent of any light polarization effect of the optical system response.

2. Results and Discussions

In order to properly confine the carriers in quantum dots it is essential that these dots are encapsulated. The problem that arises is to choose the material suitable for encapsulation. When encapsulating quantum dots with a few monolayers of GaAs for example, Ga atoms diffuse into the dot, which decreases their sizes. In fact, the heart of the dots remains in InAs while the edges are composed of ternary Ingas, this process can modify the structural and optical properties of QDs. Moreover, it is known that the growth of Ingas layer on InAs quantum dots on (001) GaAs substrates, reduces the stress in quantum dots due to the decrease of hydrostatic strain. This phenomenon, shifts the emission energy of QDs to the red [8]. But the question that arises here is the following: What have we observed when the InAs QDs are elaborated on high-index GaAs substrates?

To answer this question, we studied two structures. The first one is InAs QDs encapsulated by GaAs. The second is capped by Ingas. Figure 1 show the photoluminescence spectra of these two structures, made at low temperature. For sample covered by GaAs, the PL emission has an systematic form at the low-energy side. The spectrum can be decomposed into two Gaussians:

the first peak is centered on 1.26 eV. The second peak is located at 1.3 eV. Both peaks have the same FWHM (60 meV). To explain the asymmetry of the spectrum a study of PL as a function of excitation density can be investigated.

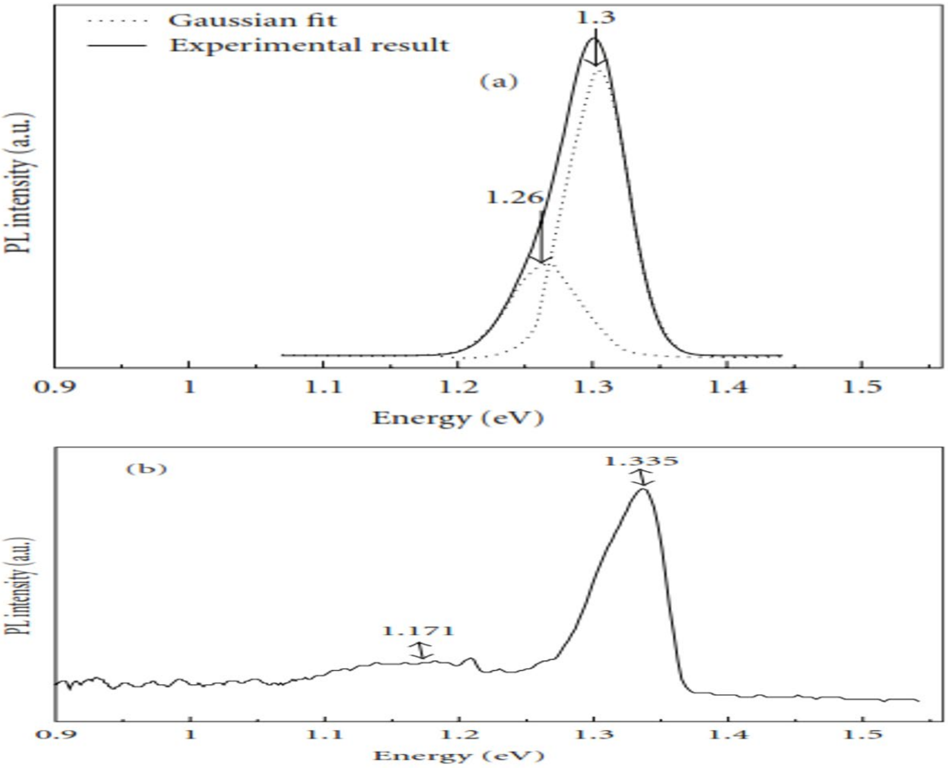

Figure 1: 10 K Pl Spectra of Inas/Gaas (113) Quantum Dot Capped by Gaas Epilayer (A) and Ingas Epilayers (B)

The variation of PL spectra as a function of excitation density is shown in figure 2. The PL intensity increases with excitation density. But, the energy position and width at half maximum does not exhibit significant variations. Secondly, we observe that the PL spectra retain their asymmetry at low-energy side. This resulted indicating an effect of simultaneous filling of energy states when increasing power densities. We can therefore attribute the two Gaussian peaks (Figure 1) to the two ground states of two quantum dot sizes. Small dots with energy emission at 1.3 eV and large dots emitting at 1.26 eV. The shape of the spectrum is a direct result from dispersion in quantum dot sizes. PL and AFM have been carried out for Ingas QDs prepared on high-index GaAs substrates that confirm this size dispersion [8-15]. These phenomena are explained by the presence of surface steps in GaAs (113) substrates which could influence that the difffusion length of adatoms is a strong factor in determining the shape size and density of QDs.

For the sample covered by Ingas epilayer, an abnormal blue shift of about 35 meV have been observed, compared to the emission of the sample encapsulated by GaAs. Moreover, we observe the appearance of another PL band at the low-energy side centered at 1.17 eV. We have an asymmetry of the two PL bands with an FWHM of about 30 meV which may be due to the changes of the indium compositions in the quantum dot.

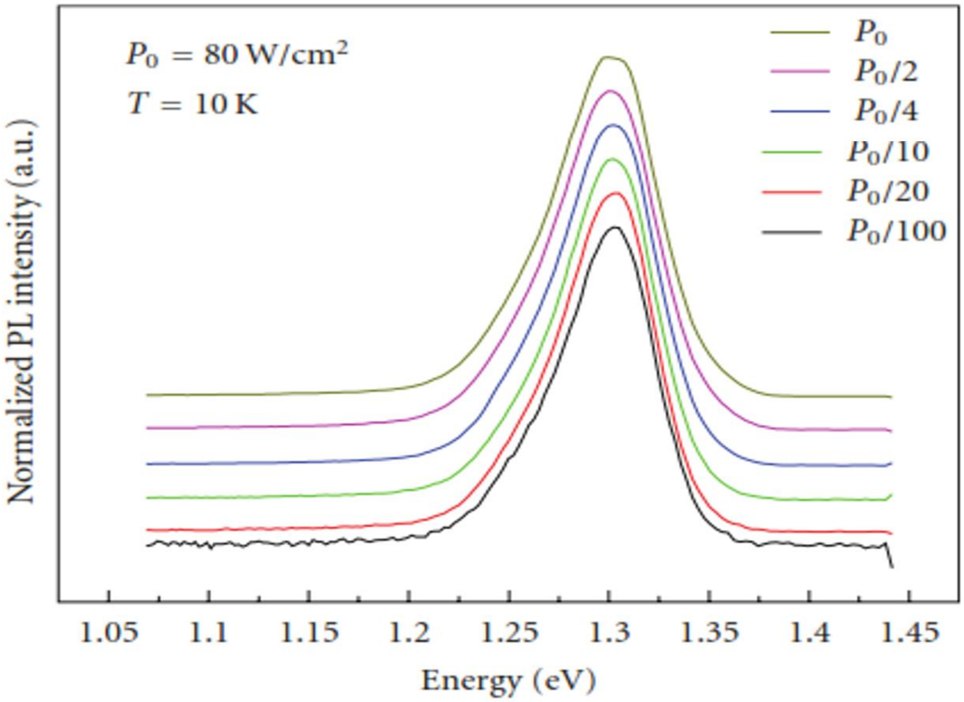

Figure 2: Evolution of Pl Spectra as a Function of Excitation Density of InAs QDs Capped by GAAs

These results were shown theoretically by Mlinar et al., [8, 9]. They show that the emission of InAs quantum dot covered by Ingas and GaAs substrates prepared on (111), (112), and (113) would be shifted to high energies when growth conditions (size, composition) is prepared. Mlinar et al. showed that for InAs QDs small size dots the fundamental transition decreases with the indium concentration and substrates orientation. While, the large InAs QDs the transition energy increases to a threshold value then it decreases for GaAs substate high-index orientations. Since, it decreases continuously for the orientation (001). The shift to high energies side is the competition between the hydrostatic and biaxial strain [5-11]. In fact, the hydrostatic strain decreases with the indium content for the small InAs QDs size dots whatever the orientation of the substrate. The monotonic decrease; in the energy transition as a function of the indium content in InxGa1−xAs. However, the biaxial strain is responsible for the decrease of the discontinuity of the valance band (VB) which increases with the indium composition. In the case of GaAs high-index substrates the biaxial strain is greater than the hydrostatic strain. The transition energy, increases when the InAs dots are covered with Ingas which is not the case for the orientation (001) where the hydrostatic strain is the most important [8,9]. About width at half maximum of PL spectra figure 1 show that this parameter decreases from 60 to 30 meV when the dots are capped by the Ingas. This decrease reflects an improvement in uniformity of quantum dots. These results are explained by the fact that for small quantum dots when they are encapsulated by Ingas their biaxial strain increases which enhances their emission efficiency. But hydrostatic strain of large InAs quantum dots encapsulated by Ingas decreases with decreasing their emission energy.

The biaxial component of the strain tensor is responsible for the decrease of the valence band. The decrease of the hydrostatic strain with increasing the indium content affect the transition energy.

Also, that even for [001] grown small InAs QD size biaxial strain is increased. But the hydrostatic strain has a dominant influence on the transition energy [8,9].

In fact, the broadening of the PL emission is due to size distribution of the InAs quantum dots. So, when InAs quantum dots are capped by GaAs is observed. A separation between large and small quantum dots when they are encapsulated by Ingas. These phenomena are due to hydrostatic and biaxial strain action on large and small dots grown under specifically growth conditions. PL polarization measurements were realized in the linear response regime. The degree of linear polarization P of the emitted light is classically defined by the following equation:

$$P = \frac{I_{[33-2]} - I_{[-110]}}{I_{[33-2]} + I_{[-110]}}, \qquad (1)$$

where I[33–2] and I[−110] are the PL intensities along the two orthogonal directions [33–2] and [–110].

No PL polarization anisotropy is showed (P 0%) for InAs quantum dots capped with GaAs layer (Figure 3(a)) which is due to the dispersion in size and shape of the quantum dots. Indeed, the luminescence is identical in all directions because of the dispersion in size and shape of InAs quantum dots. For the InAs QDs capped by Ingas, a small anisotropy is observed (P~ 8%) at the high-energy side. Since the PL peak intensities observed in the [–110] direction of the polarizer is smaller than those showed in the [33–2] direction. The degree of linear polarization is found to be around 10% (Figure 3(b)). This result is the clear signature of elongated quantum dots [16-18]. Although, the small InAs quantum dots require an elongated form, but the large InAs dots present a quasi- isotropic behavior.

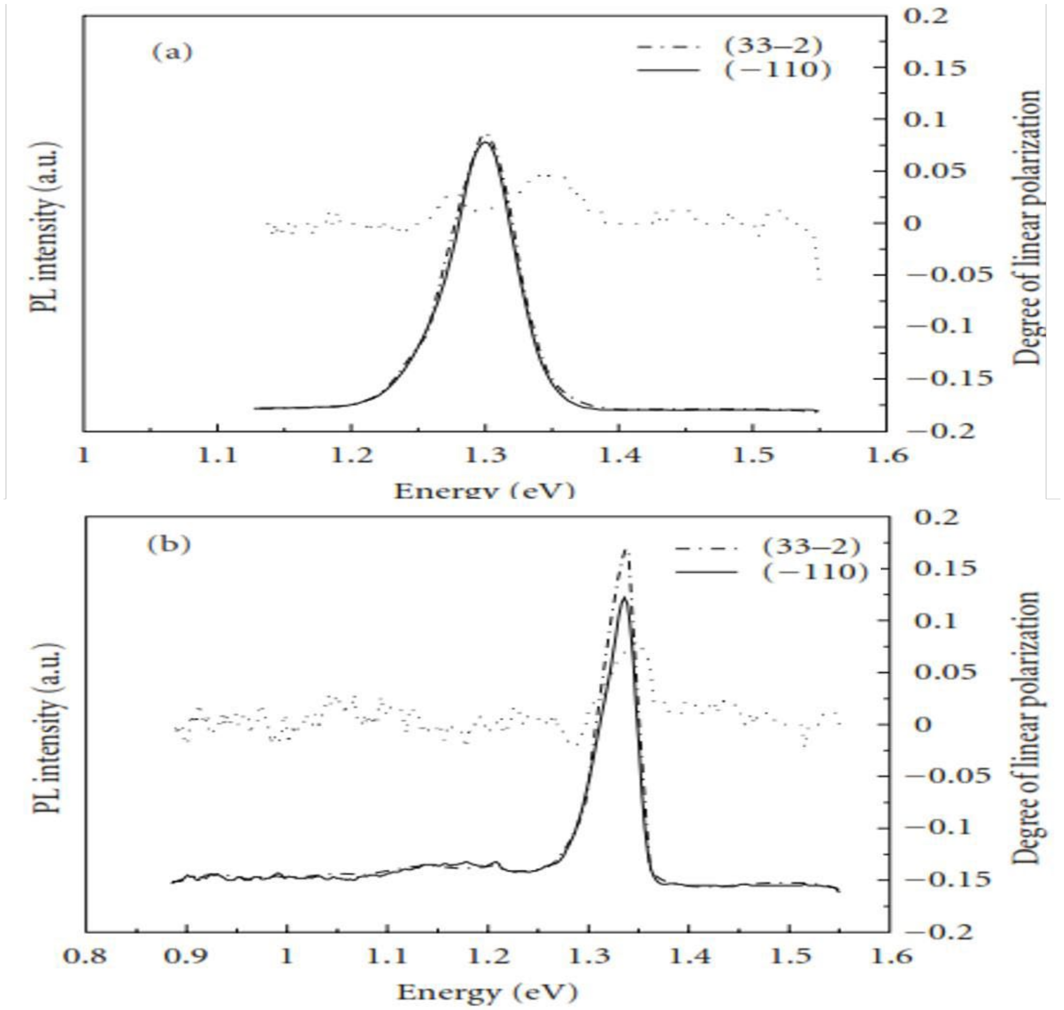

Figure 3: Polarization Pl Spectra at 10 K and Degree of Linear Polarization for the Inas Capped by Gaas Sample (A) and InGaAs Sample (B)

3. Conclusion

We have investigated the optical properties of InAs/GaAs (113) A quantum dots, grown by molecular beam epitaxy (MBE), capped by (In, GA)As. A broadening of the PL emission due to size distribution of the InAs quantum dots when they are capped by GaAs have been shown. A separation between large and small InAs quantum dots when they are encapsulated by Ingas has been demonstrated. Hydrostatic and biaxial strain affect the optical properties of large and small InAs dots grown under specific growth conditions. The PL polarization measurements have been investigated to show the strain effect. We have explained that the small dots require an elongated form but the large dots present a quasi-isotropic behavior.

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