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InAs/GaAs quantum dot structures covered by InGaAs strain reducing layer characterized by photomodulated reflectance

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Abstract

Optical properties of metalorganic vapor phase epitaxy grown InAs quantum dots in GaAs covered by thin $In_xGa_{1-x}As$ strain reducing layer were studied by photomodulated reflectance and photoluminescence spectroscopy. Results show that the increasing In content in the strain reducing layer shifts the luminescence of quantum dots from 1.25 to 1.46 μm and narrows the photoluminescence linewidth. To interpret photoluminescence data, we developed a simulation model of our quantum dot structure, which was calibrated using results of atomic force microscopy, photoluminescence and photoreflectance measurements. Simulations have shown that the strong photoluminescence red shift is caused both by the change of the band structure and the height of quantum dots which is significantly increasing when the In content in the strain reducing layer grows.

Keywords: Optical properties; Metalorganic vapor phase epitaxy; Indium arsenide; Gallium arsenide; Quantum dots

1. Introduction

Nowadays, self-assembled InAs/GaAs quantum dots (QDs) are intensively studied to become a base of low-threshold, high-output and heatsink-free lasers dedicated for optical communication at 1.55 μm. To extend the emission wavelength of InAs/GaAs QDs above 1.3 μm, the elastic strain in QD structures should be more relaxed and the size of QDs should be further increased. One approach, which was successfully used for this purpose, is based on either covering or embedding InAs QDs with $In_xGa_{1-x}As$ layers [1,2]. Covering of QDs by a ternary strain reducing layer (SRL) reduces strain component in the growth direction and brings a strain-driven phase separation of the heterocapping alloy. This enables the diffusion of In atoms to the QDs and enhances their size. Up to now, majority of experiments in this field was performed with structures grown by the molecular beam epitaxy method.

In this contribution, we present results obtained on QDs prepared by metalorganic vapor phase epitaxy (MOVPE) and covered by $In_xGa_{1-x}As$ layers containing up to 29% of In. Detailed simulation of electronic states in QD structures is applied for the analysis of optical data obtained by a combination of room temperature photoluminescence (PL) and photomodulated reflectance (PR) measurement. We show that this approach provides valuable information about the effect of SRL.

2. Experimental

QD structures were prepared by low-pressure MOVPE in a RAS LayTec equipped AIXTRON 200 machine, using Stranski–Krastanow growth mode on semi-insulating GaAs (1 0 0) substrates. Trimethylgallium (TMGa), trimethylindium (TMIn) and arsin (AsH_3) were used as precursors for the growth of GaAs, InAs and $In_xGa_{1-x}As$ layers. The structures were grown at 70 hPa total pressure and at a total flow rate through the reactor of 8 slpm. The first GaAs buffer layer was grown at 650 °C then the temperature was decreased to 500 °C for the growth of the rest of the structure. All InAs layers were grown under the same conditions: a growth rate of 0.2 ML/s, a V/III ratio of 83 and a growth time of 9 s. The growth interruption after the InAs layer growth for QD formation was 30 s. The composition of the 5 nm thick $In_xGa_{1-x}As$ SRLs was changed from 0 to 29% of In. AsH_3 and TMIn partial pressures in the

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reactor were the same as for InAs growth; only the TMGa partial pressure was changed. Samples prepared for PL measurement were provided with 15 nm thick GaAs capping layer.

QD structures were analyzed with atomic force microscopy (AFM)—Veeco Dimension 3100 system operated in the tapping mode with simultaneous detection of the phase signal using the super sharp diamond-like carbon tips with typical radius of 1 nm. Optical measurements were performed at room temperature. PL was excited by semiconductor lasers (808 and 980 nm) with excitation density of about 5 W cm^{-2}. PR spectra were measured using a setup where a 5 mW HeNe laser was used as the modulating source and a 30 W tungsten–halogen lamp filtered by a JY640 grating monochromator provided the monochromatic light. In both cases, the emitted (PL) or reflected (PR) light was detected by a cooled Ge detector and the resulting signal was processed by standard lock-in technique.

The interpretation of measured optical data was based on simulation of electronic states in InAs and InGaAs layers using the nextnano^3 simulator [3]. For a given structure, the computation started by minimizing the total elastic energy using a conjugate gradient method. This yielded the local strain tensor, which in turn determined the band offsets and light/heavy holes splitting. Subsequently, the multi-band-Schrödinger and Poisson equations were solved using the GaAs, InAs and InGaAs band parameters from [4].

3. Results and discussion

AFM shows that the layer of uncovered QDs is formed by lens shaped QDs with slightly elongated basis in the [−1 1 0] direction. Example of the typical QD height profile measured in [1 1 0] and [−1 1 0] directions is shown in Fig. 1. This elongation is explained by the higher sensitivity of the growth rate in the [1 1 0] direction on the AsH$_3$ partial pressure, which is kept low during QD formation. QDs exhibited good uniformity and an average density of 2×10^{10} cm^{-2}. To interpret AFM and optical data, a 3D model of a lens shaped QD embedded in GaAs was proposed. First, we supposed a structure consisting of a pure InAs QD and 0.3 nm thick InAs wetting layer (WL) [5] covered by 15 nm thick GaAs cap. Then we simulated electronic states in lens shaped QDs with different dimensions and compared them with results of PL measurements which provided energy separation between the ground and excited states in QDs. The best fit was obtained for QD height of 4 nm and 20 nm × 15 nm base, which is in good agreement with AFM data.

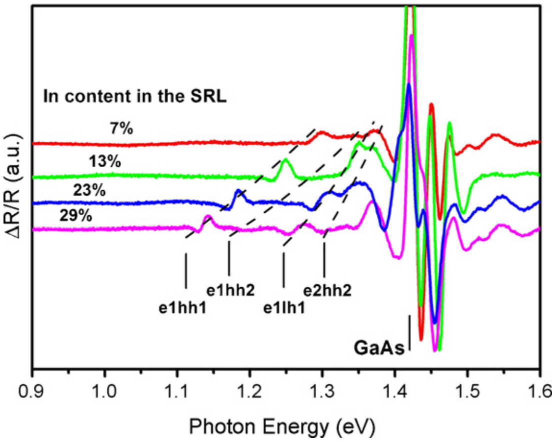

Fig. 2. Room temperature photoreflectance spectra of samples with a single QD layer covered by SRLs with different indium content. Theoretical values of quantum transitions in the SRL/WL identified by simulation are also indicated.

To cover also the influence of SRL in the model (see the inset in Fig. 1) we first analyzed the In content in our SRLs by PR which is a sensitive tool for the characterization of quantum wells and WLs [5]. Results are shown in Fig. 2 where corresponding PR spectra are presented together with theoretical simulation values of quantum transitions in the SRL/WL structure. Spectra are dominated by GaAs band gap bulk-like signal at 1.42 eV and resonances corresponding to the optical transitions in the SRL/WL. The arrows indicate the transition energies obtained from fitting the PR data with the first derivatives of the Gaussian line shape, which is the appropriate form for fitting the PR signal originating from bound states [6]. Fig. 2 shows that with increasing In content transitions between the lowest electron and heavy-hole (e1-hh1) or light-hole (e1-lh1) states shift to

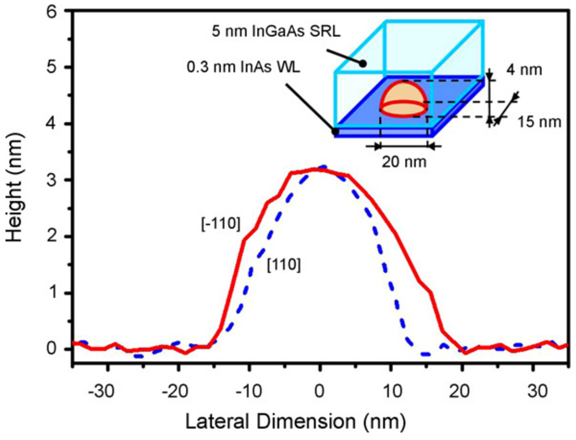

Fig. 1. Height profile of a typical InAs QD measured in two ([−1 1 0]: solid and [1 1 0]: dashed) perpendicular directions (bottom) and corresponding model used for simulation (inset).

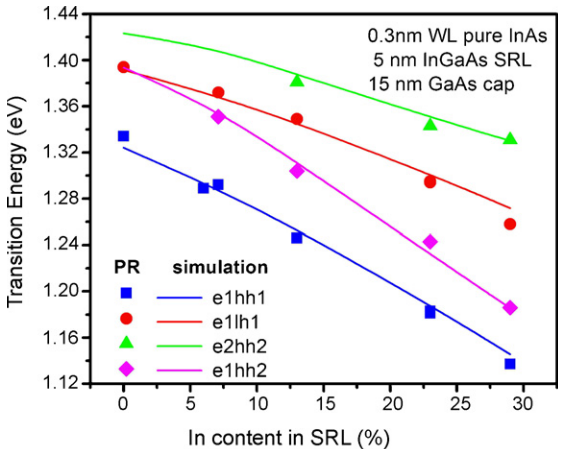

Fig. 3. Comparison of simulated transition energies in the SRL/WL (lines) with those obtained from PR measurement (points) at room temperature—samples with a single QD layer covered by SRL with different indium content.