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Ion beam studies of InAs/GaAs self assembled quantum dots

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Abstract

Self assembled InAs/GaAs quantum dots (QD's) emit in the wavelength range (1.3–1.55 μm) revealing an enormous potential to become the active elements of low threshold lasers and light emitting diodes for communication systems. However, the luminescence is dramatically quenched at room temperature (and even below) due to the defects in the GaAs matrix which open non-radiative recombination paths.

In this study we combine Rutherford backscattering/channelling (RBS-C) and high resolution X-ray diffraction (HRXRD) to study the structural properties of the InAs/GaAs structures. The InAs/GaAs QD heterostructures were grown by atmospheric pressure metal organic vapour phase epitaxy. Channelling measurements reveal a good crystalline quality along the main axial directions with minimum yields in the range of 4–6% through the entire capping layer. An increase on the dechannelling rate was observed in the region where the InAs quantum dots were buried. The channelling results also give evidence for the presence of defects preferentially oriented. Detailed angular scans in a structure with a 28 nm cap allowed the study of the In orientation with respect to the GaAs matrix and a perfect alignment was found along the growth direction. The strain in the dots shifts the angular curves along the tilt directions.

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Keywords: Channelling; InAs quantum dots; Defects

1. Introduction

A new class of optoelectronic devices is emerging based on the development of low dimensional structures. The space localization of carriers in these systems brings new challenges to solid state physics creating an enormous expectation of new technological breakthroughs. The zero dimensional confinement achieved in quantum dots (QD) is very much appealing both from the applications (photodetectors and laser diodes) and fundamental research point of view. Among the interesting properties are the low and temperature-independent threshold currents and the sharp optical transitions [1,2].

The growth of self assembled QDs is driven by the strain fields resulting from the lattice mismatch between the dots and the surrounding matrix. In the case of the InAs dots (lattice constant 0.605 nm) in GaAs (lattice constant 0.565 nm) the in-plane strain is 7%. The first layers grow strained and above the critical thickness the strain accumulated induces the spontaneous formation of the islands, the so called Stranski–Krastanov growth mode. The transition from the two dimensional growth to the three dimensional happen around 1–2 monolayers of InAs [3]. The growth

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conditions allow the control of the shape, composition, size and strain distribution in the dots which have a strong impact on the electronic properties of the nanostructures. However, defects created during the growth, in particular the over layer cap, can degrade the operating characteristics of the QD systems. Recently a new process to reduce the number of defects present in the cap and consequently the optical quenching was proposed [4]. In this process the growth of the cap is interrupted and tetrachloromethane inserted in the reaction chamber before finishing the growth.

In this work we will combine the channelling and high resolution X-ray diffraction techniques to study the strain and defects present in InAs/GaAs QD's structures. Channelling is a well established technique offering the possibility to study defects and lattice distortions at nanometer scale. The results reveal an increase of the dechannelling at the depth where the InAs QD's were embedded. The detailed angular scans along the major tilted axial directions show asymmetric In dips.

2. Experimental details

InAs/GaAs self aligned quantum dots (SAQD) heterostructures were grown by atmospheric pressure metal organic vapour phase epitaxy (AP MOVPE). Two kinds of samples were prepared with different cap thicknesses. One sample were grown in standard conditions [5] with the quantum dots overgrown by an $In_xGa_{1-x}As$ quantum well (QW) layer at 520 °C ($x = 0.2$–0.3, the thickness 2–3 nm) and covered with a 30 nm thick GaAs capping layer (CL), as illustrated in Fig. 1. The other samples (with both n and p types of doping) were grown slightly differently. After the deposition of 2–3 nm of InGaAs (QW) and 5 nm of GaAs onto the QD layer, the growth was interrupted and tetrachloromethane was introduced into the reactor at 580 °C for 20 s. Finally, the rest of the capping layer (with variable thickness) was grown at a temperature somewhat higher than for other samples.

The crystalline quality, composition and strain were accessed both with high resolution X-ray diffraction (HRXRD) and Rutherford backscattering/channelling spectrometry (RBS/C). The RBS/C measurements were performed with 1 mm collimated $^4He^+$ beam with 2.0 MeV. The samples were mounted in a computer controlled two-axis goniometer with an accuracy of 0.01°. The backscattered particles were detected by two surface barrier silicon detectors placed at 160° and close to 180° with respect to the beam direction (Cornell geometry) and with 13 and 16 keV energy resolutions, respectively. The strain in the layers was studied performing detailed angular scans of the <1 0 1> and <1 1 1> directions along the (0 1 0) and (1–10) planes, respectively. The XRD studies were done with a double-crystal diffractometer with a resolution of the order of 30 arc sec.

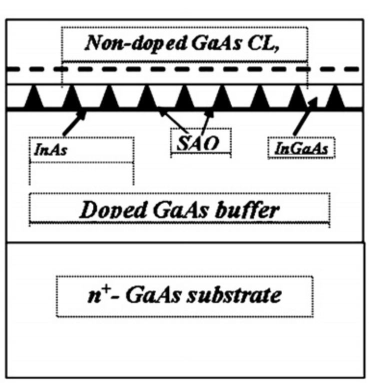

Fig. 1. Schematic diagram of the sample structure used in these studies.

3. Results and discussion

The presence of the InAs dots and the depths and thickness of the In doped layer was measured by grazing incidence RBS analysis. The spectra were simulated using the NDF code to model the presence of the quantum dots [6]. The results are shown in Fig. 2 and the best results were obtained assuming a thickness of 28(3) nm for the cap layer (we did a self-consistent analysis enforcing the same energy calibration on the two angles and considering bulk densities) and 4 nm for the QD height. In this case, the volume fraction of the QDs is 38 vol.% and the surface roughness (or inhomogeneity of the cap layer thickness) is around 3.5 nm. Small deviations from these values also give good fits but our results are in excellent agreement with the AFM analyses of similar samples [5]. For the sample with a thicker GaAs cap the In signal is shadowed by the Ga and As signals. Fig. 3 shows the random, (1–10) plane and <1 1 1> axis aligned spectra where is visible the kink due to the dechannelling in the region of the buried InAs QD's. The continuous line is the result of the simulation

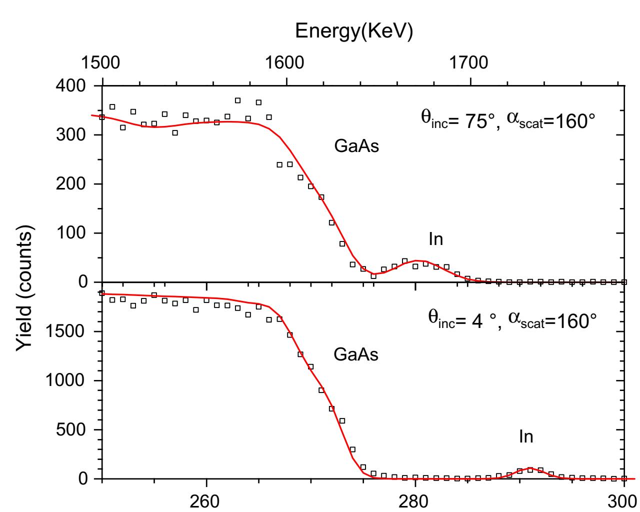

Fig. 2. RBS spectra and simulated results (continuous curve) obtained for two incident angles.