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Comprehensive investigation of optical and electronic properties of tunable InAs QDs optically active at O-band telecommunication window with (In)GaAs surrounding material

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ABSTRACT

In this paper, we report on the impact of InAs quantum dots' (QDs) position within InGaAs strain reducing layer on their structural and optical properties. Morphological investigation revealed that the QD' size and density are strongly dependent on the InGaAs underlying layer's thickness. Additionally, comprehensive spectroscopic study by room temperature photoreflectance spectroscopy (PR) and temperature dependent photoluminescence (PL) showed that indium segregation and strain driven alloy phase separation alter both the QDs and their surrounding materials. Embedding or covering the InAs QDs by InGaAs has been found to improve their overall properties including an extended emission wavelength up to 1.3 μm. However a pronounced degradation has been observed when growing them on the top of the strain reducing layer, resulting in a broadened size distribution and atypical temperature dependent emission energy and linewidth.

1. Introduction

Self assembled quantum dots (QDs), formed by Stranski–Krastanow (SK) growth mode, with three dimensional quantum confinements have attracted great attention in the past decades due to their atomic-likes properties. This makes them suitable in widely potential applications such as solar cells [1], micro-cavity light-emitting-diodes [2], infrared photodetectors [3] and lasers [4,5]. The studies of various QDs' structure has been conducted in a wide range of high performance optoelectronic devices and the identification of unique physical phenomena such as lower threshold current density, ultrahigh characteristic temperature and high differential gain [6,7]. In particular, the incorporation of InAs/GaAs QDs as the active medium open new perspectives of obtaining QDs' light emission in the International Telecommunication Union (ITU) O-band (1.26–1.36 μm) window operating at room temperature [8].

Accordingly, several groups have reported that the performance of the QDs' light emission can be improved significantly by either using InGaAs strain reducing underlying layer (SRUL) [9,10] or strain reducing capping layer (SRCL) [11–13]. Combining the two approaches, advanced quantum dot-in-a-well (DWELL) structure can be configured and offer better performance devices [14,15]. Furthermore, replacing the GaAs capping layers by InGaAs layers leads to partial strain relief-induced modification of confinement potential allowing to manipulate inter and intraband transitions in InAs QDs. It has been demonstrated that changing the compositions of barriers leading to a modification in the physical properties of QDs. These works mainly investigated the different approaches separately and are usually focused on the transitions in QDs whereas less attention has been devoted to the characteristics of quantum well (QW) barriers. However, the properties of InGaAs surrounding material are crucial for the design of optoelectronic devices operating at room temperature. This becomes more complicated because discrete levels in the zero-dimensional QDs are combined in the two-dimensional InGaAs QW. In that case, the QW is usually optically inactive in emission type of experiment since the majority of radiative recombination goes through the QDs states.

In this work, we systematically study the optical properties of both QD and QW transitions in quantum dot strain engineered InAs/(In)GaAs nanostructures designed for room temperature emission in the ITU O-band. By combining photoluminescence (PL) and photoreflectance spectroscopy (PR), detailed understanding of the critical energy states is investigated. An atomic force microscope (AFM) images are used to confirm the optical results. The aim of these experiments is to identify the carrier escape process; in particular the final states of the thermal transitions which are highly attractive for future QDs based optoelectronic components.

2. Experiments

The samples under investigation consist of a single InAs QDs layer grown by molecular beam epitaxy on Si-doped (0 0 1) GaAs

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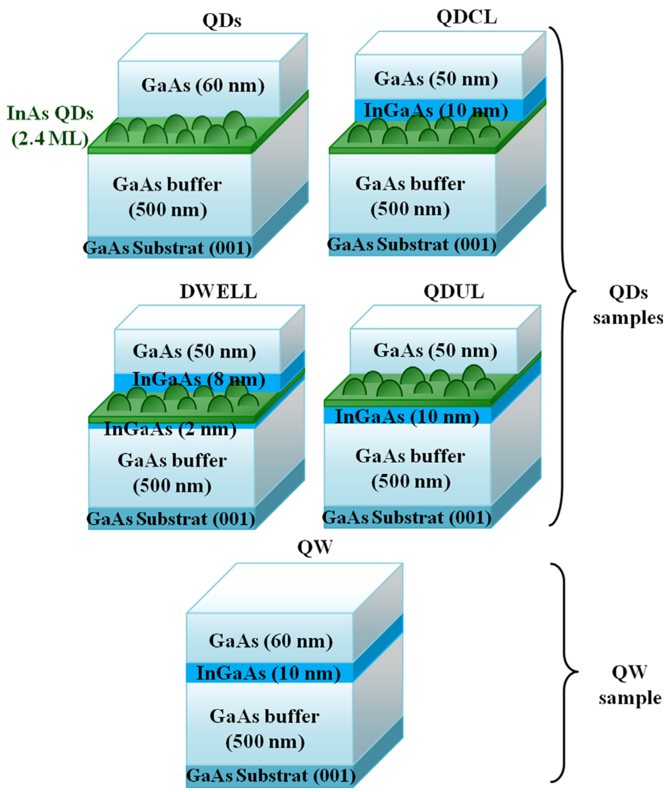

Fig. 1. The schematic representation of the investigated samples.

substrate. Fig. 1 symbolizes the graphic design of the samples. They consist of 500 nm GaAs buffer layer deposited at 580 °C. To investigate the effects of various InGaAs structures on the structural and optical properties of InAs QDs, two structures with the QDs and QW only were grown as reference. However, the other samples were grown with different position of the InGaAs layer with 15% In composition. In the QDCL (QDs with SRCL) sample, the QDs were directly covered by 10 nm InGaAs. For the DWELL sample the InAs QDs layer was embedded in 10 nm thick InGaAs layer (2 nm at the bottom and 8 nm at the top). Finally, the InAs QDs layer of the QDUL (QDs with SRUL) sample was directly deposited on a 10 nm InGaAs. The InAs QDs layer in QDs samples, having a nominal thickness of 2.4 monolayer (MLs), has been deposited at a growth rate of 0.028 ML/s (0.08 Å/s) and followed by 30 s growth interruption under As flux. The growth rate of InGaAs and GaAs materials are 0.19 ML/s (0.54 Å/s) and 0.85 ML/s (2.4 Å/s), respectively. The GaAs capping layer thickness was 60 nm for the QDs and QW samples and 50 nm for QDCL, DWELL and QDUL samples. Similar uncapped samples QDs, DWELL and QDUL have been grown for morphological investigation by AFM. For the PL measurements, the samples were excited with 514.5 nm line of an Ar^+ laser with 0.2 mm of diameter and the spectra were collected using a thermoelectrically cooled InGaAs photodetector using conventional lock-in technique.

3. Results and discussion

3.1. Effect of the InGaAs strain reducing layer on the property of QDs

Fig. 2 shows the low temperature PL spectra of the investigated samples recorded at various excitation densities. By increasing the excitation density in the 12-1200 W/cm^2 range, a clear band filling effect is observed, Therefore, we could attribute the high energy side peaks to the excited states (ES_n) ($n=1$, 2) emission associated

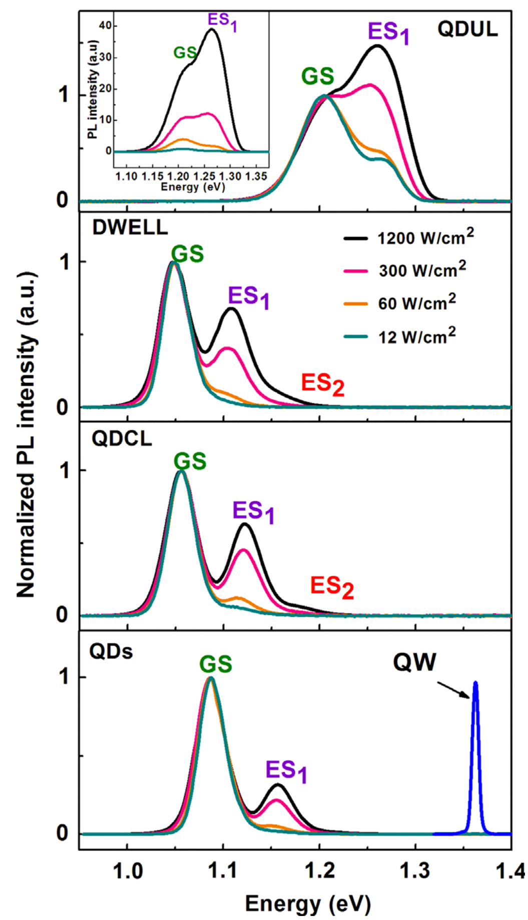

Fig. 2. 12K-PL spectra of the samples measured at different excitation power normalized with respect to the first peak. The inset shows the PL intensity of the QDUL sample without normalization.

to the ground state (GS) emission [16]. Moreover, the GS emission energy of the QDs with SRCL structure is redshifted by approximately 34 meV with respect to those grown on the pure GaAs matrix.

In fact, the presence of the SRCL is expected to reduce the strain around QDs, which induces a reduction of the effective energy gap [17,18]. Additionally, this redshift can be explained by the redistribution of In and Ga atoms during the deposition of the InGaAs capping layer on InAs QDs. The strain field caused by InAs QDs induces the preferential migration of In atoms to InAs QDs and Ga atoms from the dots which leads to a bigger dot size [19]. When the InAs QDs are embedded inside the asymmetric InGaAs/GaAs QW (DWELL sample), larger redshift about 40 meV is obtained with respect to the QDs reference sample. When the InAs are deposited on the QW, QDs' nucleation occurs on indium rich regions induced by In segregation increasing the total amount of InAs material. Furthermore, the decrease of the energy level spacing (ΔE) between the GS and the first excited state (ES_1) can also be explained by the changes of the QDs aspect ratio (height/diameter), depending on the QDs' environing material's composition. It is found to be 72 meV for InAs/GaAs QDs structure, 66 meV for QDs with SRCL (QDCL structure) and 60 meV for DWELL structure.

On the contrary, for InAs QDs with SRUL (QDUL sample) the spectra show an unexpected blueshift and broadening of the PL peaks. In order to clarify the PL behavior observed above, we investigate the morphological properties of uncapped InAs QDs by AFM. Fig. 3 presents typical 1 μm^2 AFM images of uncapped reference QDs directly formed on GaAs QDs (Fig. 3a), with InGaAs