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# Effects of Double-cap Technique on the improvement of InAs/InAlGaAs/InP Quantum Dots Grown by Metal-organic Chemical Vapor Deposition

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**Abstract**

**We report the effects of applying a double-cap on the optical properties of an InAs/InAlGaAs quantum dots (QDs) system grown by metal-organic chemical vapor deposition. With optimized thickness and lattice constant of the high temperature second cap layer, the PL peak intensity and linewidth of the five-stack InAs/InAlGaAs QDs grown on a semi-insulating InP (100) substrate were significantly improved.**

## 1. Introduction

Self-assembled InAs quantum dots (QDs) by Stranski-Krastanow (SK) mode have been attracting intense interests, owing to their unique physical properties and great potential in optoelectronic device applications, especially QD semiconductor lasers [1]. Considerable efforts have been devoted to the InAs/GaAs system [2], while research on the InAs/InP system operating at 1.55 μm, is somewhat limited. However, InP-based quantum systems have been playing a vital role in the long wavelength laser application.

So far, InGaAsP and InAlGaAs have been the two mainstream material systems for quantum dot laser structures. Compared with the InGaAsP alloy, InAlGaAs possesses an advantage of a larger band-offset, leading to enhanced differential gain and better temperature characteristics [3]. To date, studies on InAs/InAlGaAs QD growth have mainly been dominated by molecular beam epitaxy [4]. In contrast, InAs QDs with InAlGaAs as a cap layer grown by metal-organic chemical vapor deposition (MOCVD) have not yet been reported.

In this work, an InAlGaAs double-cap procedure is reported in optimizing the optical properties of InAs QDs embedded in an InAlGaAs matrix. By adopting this double-cap technique, dot height dispersion can be dramatically reduced, providing more flexibility in tuning the emission wavelength of InAs QDs. Moreover, the negative effects of phase separation and non-radiative defects are minimized, compared with a single low temperature InAlGaAs cap in MOCVD growth.

## 2. Experiments

All samples in the study were grown on semi-insulating (SI) InP (001) substrates in a low-pressure (100 mbar) horizontal MOCVD system with a total gas flow rate of 15 slm. Trimethylindium (TMIn), trimethylaluminum (TMAl), and triethylgallium (TEGa) were used as the group III precursors, and tertiarybutylarsenic (TBA) and phosphine ($PH_3$) were used as the group V precursors. To start with, a 60 nm InP epi-layer was deposited at 600 ℃ on the InP substrate. A 2 nm $In_{0.4}Ga_{0.6}As$ wetting layer was grown at 600 ℃ prior to the InAs QD growth, and then the substrate was cooled down to 500 ℃ in arsenic ambient to prevent surface decomposition. After that, InAs was deposited, with a supply of 3.6 monolayers (MLs), a growth rate of 0.36 ML/s and a V/III mole ratio of 0.4. A 5 s growth interruption was immediately introduced with TBA flux for QDs formation. The quantum dots were subsequently capped by InAlGaAs double cap layers. In this regard, the first $In_{0.8-x}Al_{0.2}Ga_xAs$ cap growth was conducted at the same growth temperature as the QDs (500 ℃), with a thickness of 1.2 nm to keep the QD emission wavelength near 1.55 μm. Afterwards, the sample was heated up to 600 ℃ in five minutes, with TBA annealing to flush the uncapped QDs and flatten the growth front before the InAlGaAs second cap layer (SCL) deposition. Finally, an $In_{0.71-x}Al_{0.29}Ga_xAs$ SCL was grown at 600 ℃. The thickness of the SCL cannot be precisely determined and will be further optimized. The schematic of the structure is shown in Fig. 1.

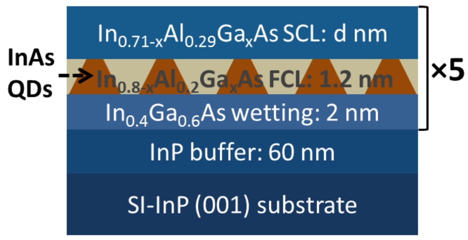


Fig. 1. Schematic of five-stack InAs QDs embedded in an InAlGaAs double-cap procedure.

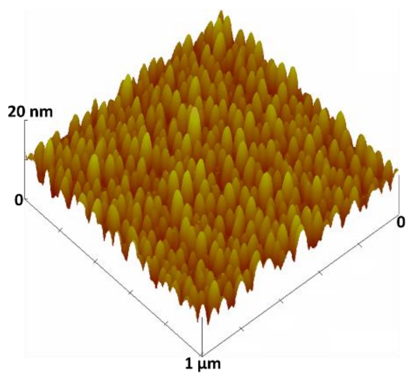


Fig. 2. Three dimensional 1× 1 $\mu m^2$ AFM image of surface InAs QDs.

The growth conditions for the InGaAs wetting layer and InAs QDs were optimized and examined by a three dimensional 1 μm × 1 μm atomic force microscopy (AFM) image, as shown in Fig. 2. A uniform QD distribution with an areal density of about 5 × $10^{10}$ $cm^{-2}$ was achieved, due to the smooth growth front of the strained $In_{0.4}Ga_{0.6}As$ wetting layer. The average diameter and height of the close-packed QDs were estimated to be 42 and 3.8 nm, respectively. Very few QDs are elongated into quantum dash geometries.

The impact of the SCL thickness d (as shown in Fig. 1) on the optical properties of stacked InAs/InAlGaAs QDs was first investigated by room temperature photoluminescence (RT-PL) microscopy, excited by a 300 mW solid-state 671 nm laser. The first cap layers (FCLs) were fixed at 1.2 nm $In_{0.52}Al_{0.2}Ga_{0.28}As$, and the compositions of SCLs were kept as $In_{0.51}Al_{0.29}Ga_{0.2}As$, while the thicknesses varied from 20 nm to 50 nm. The compositions of In and Al in the InAlGaAs alloy were determined by x-ray diffraction (XRD) fitting and RT-PL, respectively. Fig. 3(a) shows the PL spectra of the samples. It is noted that the PL intensity increased sharply when increasing SCL thickness from 30 nm to 40 nm. The normalized PL peak intensity and full-width at half-maximum (FWHM) as a function of the SCL thickness, are presented in Fig. 3(b). For five stacks of InAs/InAlGaAs, 50 nm InAlGaAs separation provides the best optical performance, with the strongest peak intensity (3.5 times over the 20 nm cap) and the lowest FWHM value (71 meV). This can be attributed to a smoother growth front and better surface morphology after the high temperature InAlGaAs capping. A higher kinetic roughness will inevitably reduce the QDs density in the subsequent QD layer growth.

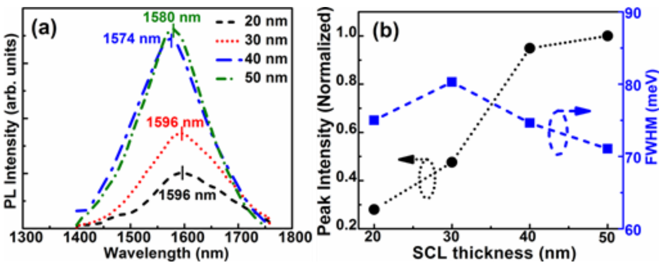


Fig. 3. (a) RT-PL spectra of five stacks of InAs QDs with different SCL thicknesses. (b) Normalized PL peak intensity and FWHM dependences on the SCL thickness.

Next, the influence of the lattice constant of the $In_{0.71-x}Al_{0.29}Ga_xAs$ SCL on the PL characteristics of QDs was investigated. To examine this, the FCLs were maintained at 1.2 nm $In_{0.52}Al_{0.2}Ga_{0.28}As$, and the SCLs thicknesses were fixed at the optimized 50 nm. Fig. 4(a) presents the PL spectra of QDs with different SCL lattice constants, by varying the Indium fraction in InAlGaAs. From Fig. 4(b), with an $In_{0.51}Al_{0.29}Ga_{0.2}As$ separation, the PL peak intensity of the five-stack InAs/InAlGaAs reaches its highest value, together with the smallest line width of 71 meV. The optical property improvement can be explained by a well-balanced stress [5]. More specifically, when the Indium composition is too low (too small lattice constant) in the SCL, the tensile strain generated from the InAs quantum dots beneath will be over-balanced. Therefore, the compressive stress along the sample will be more inclined to generate dislocations and other defects [6]. Similarly, for a certain thickness of the SCL, if the Indium fraction is larger than 53%, namely, the lattice constant of the InAlGaAs is even larger than that of InP, it is more difficult to compensate the tensile strain in the multi-stack QDs structure. The accumulated strain will lead to an obvious broadening in FWHM and degradation in PL intensity, as depicted in Fig. 4(b).

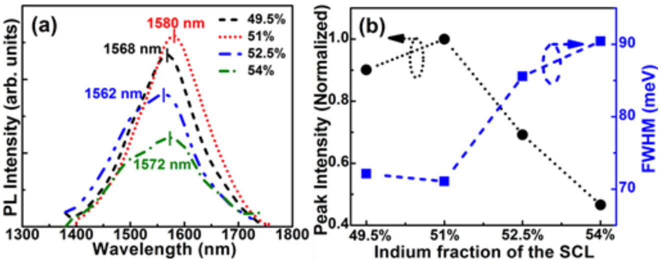


Fig. 4. (a) PL spectra taken at room temperature of five-stack InAs QDs with different Indium compositions in the SCL. (b) The evolutions of normalized PL peak intensity and line width with Indium fraction in the SCL.

## 3. Conclusions

In conclusion, the effects of InAlGaAs double cap layers on the optical performance of five-stack InAs/InAlGaAs grown by MOCVD were studied. By increasing the SCL thickness from 20 nm to 50 nm, the PL peak intensity was increased by a factor of 3.5, ascribing to a smoother growth front before the next QD growth. Moreover, the optical properties of multi-stack QDs were improved by adopting the strain compensation technique. The results pave the way to realizing high performance 1.55 μm QD lasers based on the InAs/InAlGaAs/InP system.

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