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MBE Growth and Characterization of InAlGaAs/GaAs Quantum Dots

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***Abstract*— InAlGaAs/GaAs quantum dots (QDs) are grown by molecular beam epitaxy and subsequently characterized to achieve emission <1 µm. Growth parameters are optimized to grow a new generation of homogeneous quaternary QDs with a PL FWHM of ~60 meV and a surface density of >10^{10} cm^{-2}.**

Keywords*— Quantum dot, photoluminescence, molecular beam epitaxy, AFM, energy states

I. INTRODUCTION

Semiconductor quantum dots (QDs) have received significant research interests in optoelectronic device applications due to carrier confinement in three directions and superior electronic band structure. Demonstration of delta-like density of state function enables numerous benefits such as enhanced temperature stability, narrow gain spectrum and low threshold current density [1-3]. Significant progress has been made in InAs/InP [4] and In(Ga)As/GaAs [5] QDs for diode lasers in the traditional C- and O-bands . However, relatively little success is achieved in the near-infrared (NIR) lasers emitting around 900 nm. This is primarily because of the growth challenges of self-organized QDs with a tailored geometry by the Stranski–Krastanov (S-K) method at this wavelength regime. In fact, growth of conventional InAs/GaAs QDs with small size and homogeneity to emit shorter wavelengths is challenging. Due to this inherent issue with the random alloy, ternary or quaternary alloys with the appropriate aluminum (Al) and indium (In)-composition is required to obtain ~900-nm QD-based active region [6].

Additionally, QD lasers, enabling carrier confinement in all directions, are a good choice for achieving temperature-insensitive operation [4]. However, for QDs emitting at shorter wavelengths, small-size QDs are required, and a little change of dot size introduces a large splitting of energy states [7]. As a result, active regions suffer from rather poor temperature stability due to significant change in emission wavelengths with dot geometry. In this work, a digital-alloy method is adopted to obtain quaternary InAlGaAs QDs with high homogeneity, targeting shorter emission wavelengths. A systematic study on the growth window for 3D transition is conducted by changing material compositions. The optical properties of the as-grown QDs are measured by photoluminescence (PL) and the results are then fitted with theory.

II. DEISGN AND METHODOLOGY

For the growth and characterization of QDs, all the samples were grown using solid-source molecular beam epitaxy. The QD PL structures, as schematically shown in Fig. 1(a) were grown on semi-insulating GaAs (001) substrate. The PL structures were composed of InAlGaAs QDs sandwiched by GaAs barriers. The growth was begun with a GaAs buffer layer at a temperature of 590°C. The InAlGaAs quantum dot layers were then grown by a digital alloy technique with periodic deposition of $Al_{0.71}In_{0.29}As$ and $Ga_{0.83}In_{0.17}As$ and InAs in sub-monolayers.

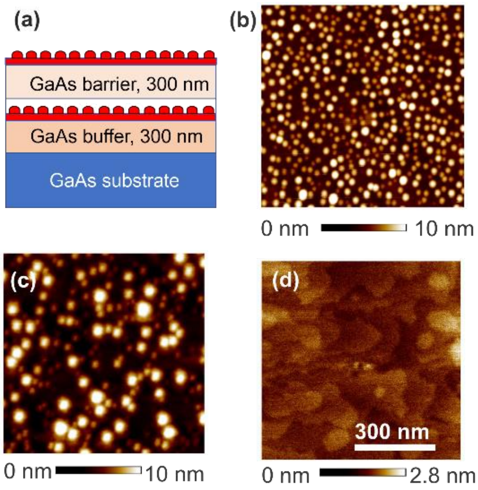

Fig. 1. (a) Structure for the growth of the QDs. AFM image of 1 µm × 1 µm for InAlGaAs/GaAs QDs with In composition of (b) 62% (c) 52% (d) 42%

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A 4.9 monolayer (ML) thick $Al_{0.15}In_{0.62}Ga_{0.23}As$ layer was grown at a temperature of 520°C. A 300-nm-thick GaAs barrier layer was then grown to embed the QDs and finally another identical QD layer as the embedded one was grown on top. The buried QDs was used to determine the optical properties during PL measurement. The surface QD layer was examined by atomic force microscopy (AFM) in order to measure the morphology and the distribution of dot density across the wafer.

III. RESULTS AND DISCUSSION

As the In-content has a pronounced effect on the quaternary QD homogeneity, 3 samples with different In-contents from 62% to 42% decremented by 10% were grown at 520°C without changing the other parameters. It is found that the sample with 62% In-content exhibits a better dot density and homogeneity. The mean height of the dots is 4.3 nm with a standard deviation of 1.2 nm. A dot density of as high as 5×10^{10} cm^{-2} was achieved as shown in Fig. 1(b). Though a reduced In-content was expected to provide a better homogeneity, the bimodal distribution of the QDs, as shown in Fig. 1(c), yields inhomogeneity with mostly two kinds of dot distribution, large and small. the density reduced by a factor of 2. With further reducing the In composition to 42%, the 3D transition began but a complete 3D nanoisland formation was not achieved. Fig. 1(d) shows the height variation of QDs which is on the order of 3 nm.

The low-temperature PL spectra are shown in Fig. 2(a) where a blueshift of the peak wavelength is seen for reducing the In-content. The broad PL spectrum for an In-content of 62% and 52% bears the testimony of achieving 3D transition while the PL spectrum was observed to be more 2D quantum-well-like for an In-content of 42%. Fig. 2(b) shows the measured the PL peak wavelength and FWHM as a function of the In-contents. The study concludes with the 3D growth transition window for the QDs indicated in Fig. 2(b).

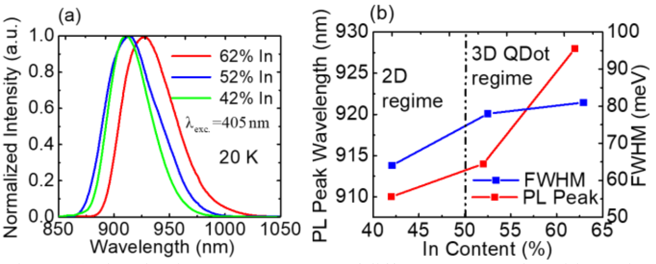

Fig. 2. (a) Photoluminescence spectrum of different QD samples with varying In-composition, (b) PL peak wavelength and FWHM as a function of In content, the dotted line indicates the boundary for 3D transition.

To determine the effects of growth temperature of the InAlGaAs QDs, two samples were grown at 540°C and 520°C. It is found that a slight variation of the growth temperature introduces a pronounced effect in the PL spectrum as the emission shift to 890 nm at 20 K. However, the AFM data does not confirm the QDs in the top layer but leaves with an indication that a high temperature can achieve shorter QDs due to an enhanced migration length of Al adatoms. In order to achieve more homogeneous QDs with a high density at this wavelength regime, a higher number of monolayer thick InAlGaAs or rapid thermal annealing will be attempted in the future.

All the measured PL data were carefully analyzed and compared with the calculated energy states of the QDs based on the 6-band *k.p* model. Fig 3(b) shows the schematic of a representative QD structure with the geometrical parameters where *h*, *D*, and *W* indicate the dot height, diameter and wetting layer thickness, respectively. These parameters introduced in the calculation were measured from AFM. GaAs and $Al_{0.4}Ga_{0.6}As$ were chosen as barrier materials for band diagram simulation at 20 K and room temperature, respectively. The band diagram of the QD structures with GaAs as a barrier material is presented in Fig. 3(c). The calculated photon energy levels match with the experimental PL results as shown in Fig. 3(d).

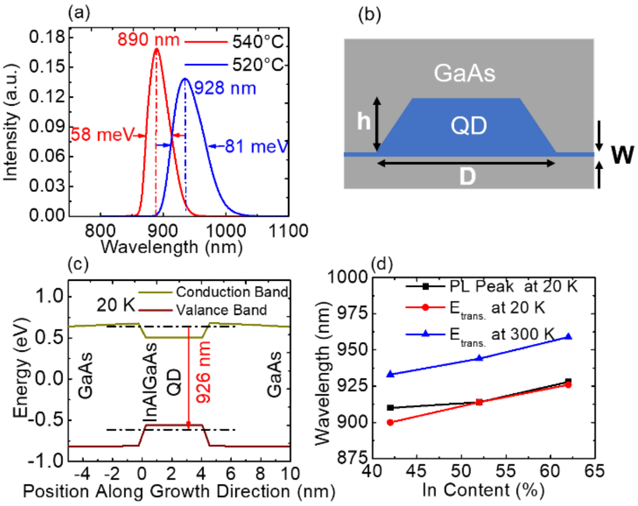

Fig. 3. (a) Measured PL spectra at 20 K for the two 62% In-containing InAlGaAs/GaAs QD test structures, (b) schematic, (c) band diagram, and (d) measured PL peak wavelengths of the QD structures as a function of the In-content and the results are fitted with theory.

IV. CONCLUSION

In summary, the optical properties of the InAlGaAs/GaAs QDs are experimentally investigated, and the results are fitted with theory. The extensive characterization studies of the QDs will help achieve a gain medium to be utilized in next-generation NIR diode lasers for a wide range of emerging application including LiDAR and sensing.

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