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MOCVD Growths of the InAs QD Structures for Mid-IR Emissions

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In this research, InAs quantum dot structures for mid-infrared emission were self-assembled on InP substrate by using metal-organic chemical vapor deposition. To improve the grown quantum dot's shape, the dot density and the dot size uniformity, a two-step growth method has been used and investigated. By changing the composition of the $In_xGa_{1-x}As$ matrix layer of the $InAs / In_xGa_{1-x}As / InP$ quantum dot structure, emission wavelength of the InAs quantum dot structure has been extended to the longest > 2.35 μm measured at 77 K.

Keywords: MOCVD, Quantum dot, InAs, Mid-infrared.

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1. INTRODUCTION

Quantum dots (QDs) structure based optoelectronic devices, e.g. semiconductor lasers, show many advantages when compared with their counterpart quantum well based devices, including ultra-low threshold current, temperature independent and very high differential gain, etc. Attempts to use InAs quantum dots grown on InP substrates to extend their emission wavelength into mid-infrared (mid-IR) region of 2-3 μm has been attracting much attention, where mid-IR lasers are very important in defense, biomedical, environmental and industrial applications, including range finding, lidar atmospheric detection, laser surgery, molecular spectroscopy and remote sensing of atmospheric and planetary gases, etc. InAs quantum dots and quantum-dash lasers have been demonstrated at various wavelengths from 1.60 to 2.04 μm [1-4].

In this paper, metal-organic chemical vapor deposition(MOCVD) growths of the InAs QDs structures emitting at ~ 2.0 μm have been reported.

2. EXPERIMENTS AND RESULTS

All the samples were grown in a horizontal low-pressure MOCVD reactor (Aixtron, AIX200) with a gas foil rotation of the susceptor. In this research, all the sources used in the growths were metal-organic sources. Conventionally, in MOCVD growths of III-V semiconductors, high toxic hydride arsine(AsH_3) and phosphine (PH_3) are used as group V As- and P-precursors. In this research, less toxic organo-arsine and phosphine, tertiarybutylarsine (TBA) and tertiarybutylphosphine (TBP), are used for replacing AsH_3 and PH_3 in the growths. Other sources used are trimethylantimony(TMSb), trimethylgallium (TMGa) and trimethylindium (TMIn). The reactor pressure for all the growths was set at 20 mbar for growing the QDs, and it was set at 100 mbar for growing the InP buffer and $In_xGa_{1-x}As$ barrier layers. The total gas flow in the reactor was $Q_{tot} = 3.1$ slm. Epi-ready InP semi-insulating substrates oriented in (001) ± 0.1° direction were used for all the growths.

Before starting the epitaxy growth, the InP substrate was annealed inside the reactor under H_2 environment at 680 °C for 5 min. Then a 0.3 μm InP buffer layer was grown on the InP substrate at 630 °C. The reactor temperature was then lowered down for growing the QDs structures. Atomic Force Microscopy (AFM) was used to take the surface morphology of the QDs. Photoluminescence (PL) was carried out on the QDs structure samples to measure their emission. For the PL measurement, the samples were excited by a 488 nm Ar^+ laser, and the emission spectrum of the samples was spread by a monochromator and detected by a cooled PbS photodetector.

2.1 Stranski-Krastanow (S-K) Self-assembled InAs QDs

In the MOCVD S-K self-assembled InAs QDs, a highly strained InAs thin layer, few monolayers (MLs), was grown on a smaller lattice constant InP substrate. When the InAs layer reached certain thickness, the TMIn

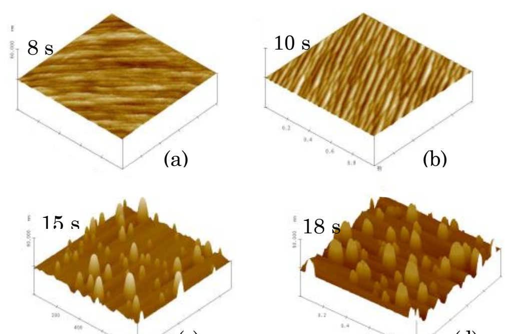

Fig. 1 – The 1 × 1 μm^2 AFM images of the InAs QD samples grown with different InAs layer thickness. The InAs layer of sample (a), (b), (c), (d) was 1.2 ML, 1.5 ML, 2.25 ML and 2.7 ML, respectively

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source was closed to stop the InAs growth while keeps the substrate temperature for few seconds for the post-growth interruption. The InAs QDs were formed self-assembly during this interruption because of the high strain accumulated in the lattice mismatched InAs layer Fig. 1 compares the surface morphology of thefour samples with different InAs layer thickness by changing the InAs layer growth time. The InAs layer thickness of the four samples is 1.2 ML, 1.5 ML, 2.25 ML and 2.7 ML, respectively. It is observed that when the InAs layer is below 1.5 ML, no QD is formed. The InAs QDs started form when the InAs layer is above 2.25 ML as shown in Fig. 1(c). The average dot height and diameter of sample (c) is 10.0nm and 35.5nm, respectively.

To study the effects of the growth temperature on the QDs formation, four QDs samples, sample (j) to (m), were grown at different temperature. The total grown InAs layer thickness of the four samples was kept 2.25 ML and the post-growth interruption time was 5 seconds. Fig. 3 shows the top-view AFM images of the four samples. High QD density of around 1.3×10^{10} cm^{-2} is obtained from the samples grown at the temperature ~ 460 °C. Out of this temperature range, when the sample was grown at either higher or lower temperature, the grown QD density reduces dramatically to around 0.5×10^{10} cm^{-2}.

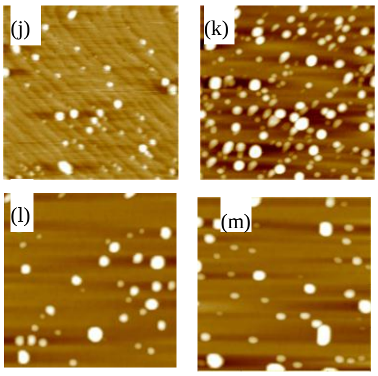

Fig. 2 – Top-view $1 \times 1 \mu m^2$ AFM images of the InAs QD samples grown at different temperatures. Sample (j), (k), (l) and (m) was grown at 420 °C, 460 °C, 500 °C and 520 °C, respectively

2.2 A two-step growth of QDs method

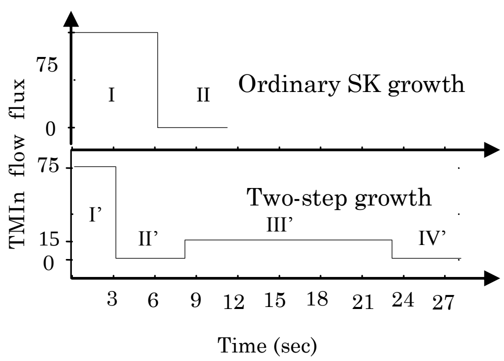

Fig. 3 – Schematic diagrams of the TMIn source flow settings during the InAs QDs growths for ordinary S-K growth and the two-step growth

In order to grow high crystal quality QDs with high dot density and good size uniformity, a two-step growth of InAs QDs method is proposed in this research. In this two-step QDs growth method, InAs growth is divided into two steps as shown in Fig. 3

In step-1 growth, including stages I' and II', a thin InAs layer is deposited with high TMIn source flux, and then the growth is stopped by closing for an internal interruption by closing the TMIn source. InAs nuclei are formed during the internal interruption. After the internal interruption, the TMIn source is opened again for the step-2 growth which consists stages III'and IV' as shown in Fig. 3. In the step-2 growth, the InAs layer is grown with lower growth rate. When the InAs target layer thickness is reached, the TMIn source is closed for post-growth interruption and the InAs QDs are finally formed self-assembly.

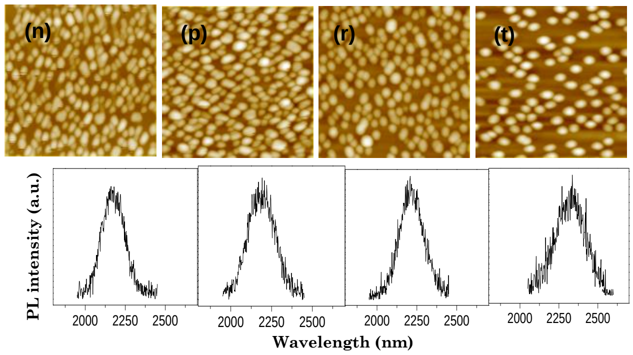

Fig. 4 – $1{\times}1 \mu m^2$ AFM top-view images and the 77 K PL spectra of samples (n), (o), (p), (q), (r), (s), (t) and (u)

We tried to increase the dot density by optimizing the inlet source flux of group-V source TBA flux in step-1 growth of the two-step growth of InAs QDs. The TMIn group-III source flux and all the other growth conditions were kept unchanged for growing the samples (n), (p), (r), and (t). In this study, only the group-V source flux of TBA for the step-1 growth was changed from 0 to 4.52×10^{-4} mol/min, with the V/III ratio correspondingly changed from 0 to 11, in these two-step growths of InAs QDs.

Optical and crystal properties of the InAs QDs samples grown with different input V/III ratio in step-1 growth has been studied using PL measurement. The measured PL spectra of the QD samples are also shown in Fig. 7. The emission peaks of all the samples are at ~ 2.18 μm.

3. CONCLUSIONS

In summary, InAs QDs for mid-IR emission have been self-assembly grown on InP substrate. The effects of the growth conditions on the QDs growths have been investigated and optimized. High coverage and uniform InAs QDs for mid-infrared emissions have grown on $In_xGa_{1-x}As$ / InP matrix with different indium compositions by MOCVD using a two-step growth method. By embedding the InAs QDs in graded $In0.53 \rightarrow (0.53 + y)Ga0.47 \rightarrow (0.47 - y)As$ barriers, we have demonstrated the InAs QDs emitting in mid-IR range at the longest wavelength of 2.35 μm measured at 77 K.

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