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Fabrication of Quantum Dots for Wavelength Converter Using Four-Wave Mixing

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1. Introduction

The optical properties of self-assembled quantum dots (QDs) are currently a subject of intense investigation due to their fascinating physical properties and their strong potential for application in optoelectronics devices. As a promising wavelength conversion for wavelength-division multiplexed (WDM) networks, four-wave mixing (FWM) in semiconductor optical amplifiers (SOA) has been extensively investigated because of the significant advantages including strict bit-rate and modulation format transparency and multichannel operation. In addition, FWM enables other processing functions such as dispersion compensation and optical logic gates.

In this paper, we show the numerical calculation of the third-order nonliner susceptibility ($\chi^{(3)}$) and fabrication of the InAs/InP self-assembled QDs using Stranski-Krastanov (S-K) growth mode for the application to the wavelength converter using FWM in SOA.

2. Calculation of $\chi^{(3)}$ under FWM condition

The numerical calculation results of $\chi^{(3)}$ under FWM condition in QDs and a quantum well (QW) is shown in Fig.1. This calculation is used the density matrix formalism taking into account the spectrum-hole-burning. The shape of the QDs is cube, so-called quantum box. The calculated material system is GaInAs/InP, the career density is 5×10^{18}cm^{-3} and a difference in wavelength with the pumping-laser λ_p and the signal λ_q is 1nm.

As shown in Fig.1, $\chi^{(3)}$ becomes the largest when the size of the QDs is 10nm cube. And the maximum value of $\chi^{(3)}$ of QDs is about 10 times lager compared to the QW.

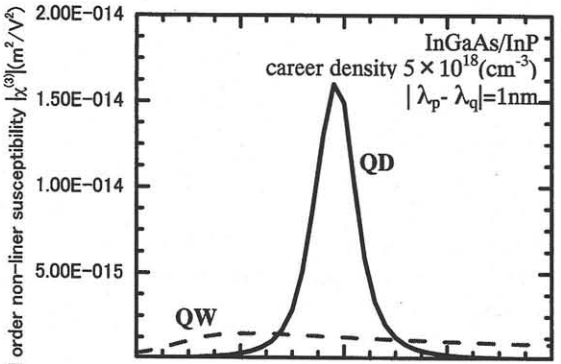

Fig.1 Theory calculation of $\chi^{(3)}$ under FWM condition

3. Fabrication of self-assembled InAs QD on InP subs

The self-assembled InAs QDs on the InP(001) substrate was grown under the S-K growth mode condition by using low pressure metal organic vapor-phase epitaxy (MOVPE). In the S-K growth mode condition, the three dimensional growth is appeared when the lattice mismatch between the growth material and substrate is large. In the InAs/InP material system, this lattice mismatch is about +3%, and this is smaller than the InAs/GaAs system (+7%). But it is possible to integrate other optoelectronics devices by using InP susbstrate.

Next, we show the growth process of the self-assembled dots. First, 3nm GaInAs was grown on the InP(001) substrate to prevent the phosphorus (P) removing from the InP substrate during the InAs dots growth. Then, the InAs was supplied. After that, the growth was interrupted about 1min. During this interruption, it is suggested that the S-K dot was self-formed. The structure of the sample is shown in Fig.2.

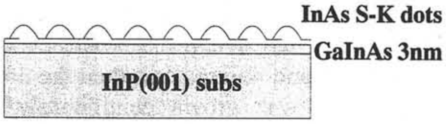

Fig.2 Structure of the sample

Fig.3 shows the growth temperature dependence of the average size, density and the standard deviation of the size of the InAs S-K dot. And typical AFM images of 2. m×2. m square are shown in the figure. By decreasing the growth temperatures from 600°C to 540°C, the dot size becomes half that is from 80nm to 40nm, and the dots density increases 5 times that is from 0.3×10^{10}cm^{-2} to 1.6×10^{10}cm^{-2}. This result suggests the possibility that dot size and density can be controlled by the growth temperature change.

Then we explain the other dependence of growth parameter. When the InAs supplied time was decreased to less than 10sec, the dot size became to small, and the dot density was decreased 1.5 times. The size of the dot is almost within the deviation, but we can control the dots density by changing the supplied time. When the amount of supplied species of TMIn was increased, the dot density was increased 2.5 times, so we can control the dots density by changing the amount of supplied species. As for the InAs V/III ratio dependence, we could not see the significant relation between the size and density of dots.

Under the optimum growth condition, the average dot size was 41.8nm, the dot density was 1.62×10^{10}cm^{-2} at the 540°Cgrowth temperature, the 20sec InAs supplied time, and the supplied species were TMIn=5.03×10^{-6}mol/min, tBAs=2.72×10^{-4}mol/min (V/III=54). The size of dot is the range of "dot like", and the density reaches an order 10^{10}cm^{-2}.

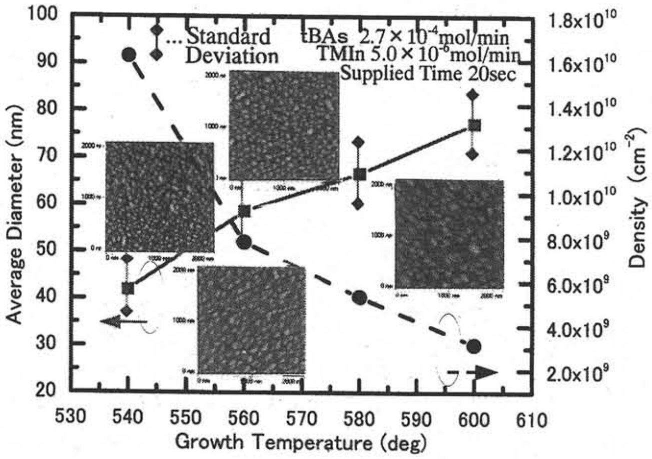

Fig.3 Growth temperature dependence of average size, density and size uniformity

4. Stacking of dots

For the application of SOAs, stacking of the dot layer is necessary to increase the volume of dots. Then we show the result of the stacking of InAs dots layer. The structure of the stacking sample is shown in the Fig.4. The growth process of the sample is as follows. After the self-formation of InAs S-K dots, GaInAs was overgrown where the thickness was varied between 0 and 4.5nm. And then the 30nm thickness InP spacer layer was grown continuously. The growth temperature was 540°C, the InAs supplied time was 5sec, the supplied species were TMIn=5.03 × 10^{-6} mol/min tBAs=2.72×10^{-4} mol/min (V/III=54).

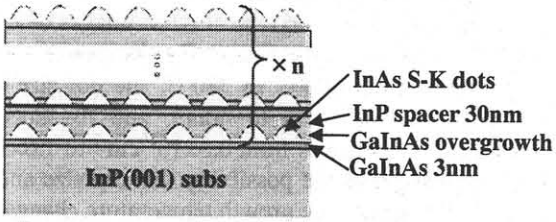

Fig.4 Structure of the stacking sample

Fig.5 shows the stacking layer dependence of the Photoluminescence (PL) spectrum. As can be seen from the AFM images that was on the top of the stacking layer, the dots was observed as the island-shape in the two stacking layers, but we could not observe the perfect dot-shape in the six and ten stacking layers sample. Because of the insufficient flatness after the InP spacer layer growth, the dots were grown along the step which had high chemical potential in the two stacking layers, and self-assembled dot formation was decreased due to the shortening of migration length in the six or ten stacking layers sample. And the intensity at 1650nm wavelength was increased by increasing the layer number.

Fig.6 shows the dependence of the GaInAs overgrowth layer thickness on the PL spectrum. The layer number was 10 in these samples. In the sample without the GaInAs layer, there was the PL intensity at the 1450nm wavelength. But this PL intensity was weakened by increasing the GaInAs layer thickness. Because of the GaInAs layer will work as the barrier layer to the InAs quantum dot, the thick GaInAs layer weakened the quantization of carriers by the decrease of band discontinuity compared to the InP. Hence the PL intensity at 1450nm wavelength is considered from the InAs dots.

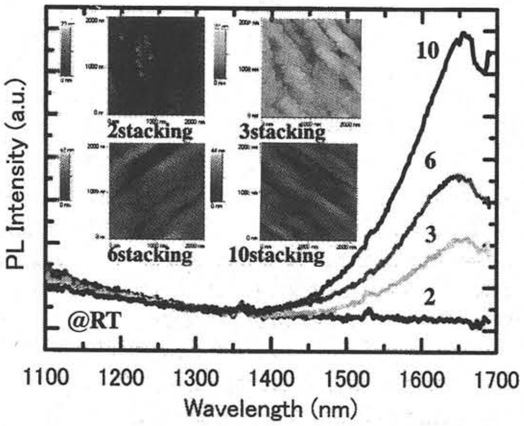

Fig.5 PL and the condition of the dot the change number of stacking

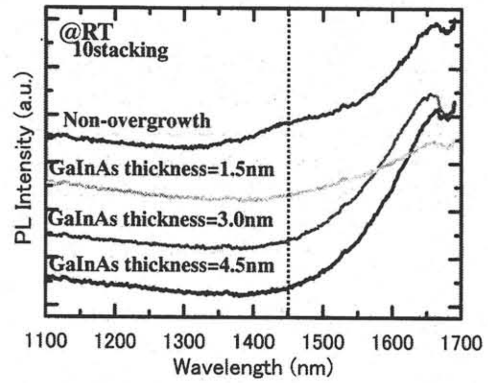

Fig.6 PL about the change in GaInAs overgrowth layer thickness

5. Conclusion

We show the numerical calculation of susceptibility of QDs and the experimental results of the self-assembled InAs QDs by using S-K mode growth condition in MOVPE.

From the experiment, we confirmed that the dot size and density could be controlled greatly by changing the growth temperature. And 41.8nm dot size, 1.62×10^{10}cm^{-2} dot density was obtained under the 540°C growth temperature, 20sec supplied time, and the supplied species were TMIn=5.03×10^{-6}mol/min tBAs=2.72×10^{-4}mol/min (V/III =54). We observed the change of the PL spectrum of the InAs dot by containing the GaInAs overgrown layer as the barrier layer.