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InP Ring-shaped Quantum-dot Molecules Grown by Droplet Molecular Beam Epitaxy

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1. Introduction

The formation and characterization of nanoscale self-assembled dots due to the epitaxial growth of lattice mismatched heterostructures has been recently investigated for many different fabrication methods. In this paper, we report the preparation of InP ring-shaped quantum-dot molecules (QDMs) on $In_{0.49}Ga_{0.51}P$ layers by droplet epitaxy technique using solid-source molecular beam epitaxy. This technique is simple and flexible. It does not require additional complicated substrate processing and has a potential in developing quantum structures. [1-7] We have investigated the formation of InP ring-shaped QDMs by reflection high energy electron diffraction (RHEED). Atomic force microscopy (AFM) and Photoluminescence (PL) measurements are performed to characterize the physical and optical properties of the InP ring-shaped QDMs. For the application, they can be utilized in quantum computation applications owing to their circular shape of the InP ring-shaped QDMs such as extended quantum cellular automata (EQCA) cell. The electron configurations in the EQCA can be increased more from two to three, giving the EQCA cell ability to encode the logic values (0, 1/2 and 1). [8-9]

2. Growth and Characterization

The samples investigated in this work were grown by RIBER 32P solid-source molecular beam epitaxy system on semi-insulating GaAs (100) substrates. The growth was monitored in situ by RHEED system operated at 20 kV. The transition from a 2-dimension (D) to a 3D growth mode is illustrated by in situ recorded RHEED patterns in $[1\bar{1}0]$ azimuth and [110] azimuth as shown in fig. 1. The desorption of oxide on surface was done under As_4 flux pressure of 6×10^{-6} Torr at substrate temperature of 610 °C. During this step, RHEED pattern indicated rough surface. Then, the substrate was cooled down to 580 °C and a 300-nm-thick GaAs buffer layer was first grown with a growth rate of 0.5 ML/s. The sharp and clear 2×4 RHEED pattern or streaky pattern was observed and represented the smooth 2D surface. These were followed by the growth of 200-nm-thick $In_{0.49}Ga_{0.51}P$ layer which is lattice matched to GaAs at substrate temperature of 470 °C with a growth rate of 0.5 ML/s and V/III ratio of 10. During the growth of $In_{0.49}Ga_{0.51}P$ layer, RHEED pattern showed a 2×1 surface reconstruction. Then, the substrate temperature was reduced to 250 °C without P_2 beam to minimize the excess P on the surface

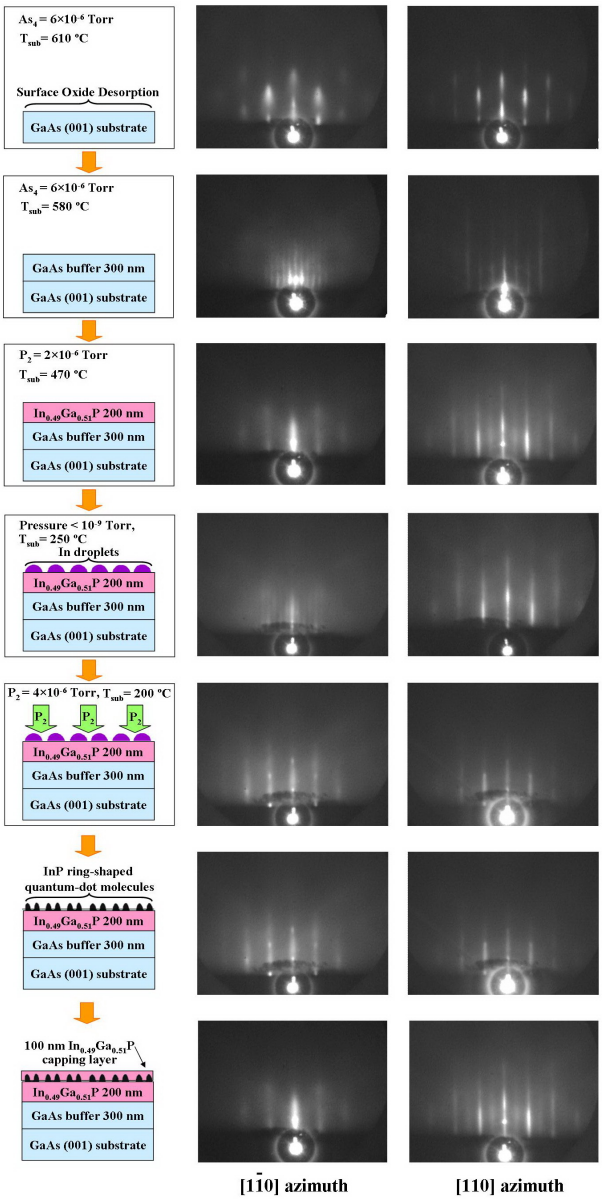

Fig. 1 Experimental procedures and RHEED pattern of each step in $[1\bar{1}0]$ azimuth and [110] azimuth.

and waiting untill the background pressure less than 10^{-9} Torr to minimize the initial interaction between In and P

during the In deposition. After that, An In amount of 3.2 ML was deposited at In deposition rate of 0.8 ML/s with substrate temperature of 200 °C. In this step, the RHEED pattern showed the elongated streaks that demonstrated the 2D characteristic of the surface. Finally, the crystallization processing was performed under 4×10^{-6} Torr of P_2 beam at 200 °C for 5 minutes. During crystallization, a more and more spotty RHEED pattern developed that illustrating 3D island. The AFM images were examined by a tapping mode in air shows that the InP ring-shaped QDMs were formed after crystallization. Figure 2 shows the AFM images in 2D and 3D of surface morphology. The densities of rings and dots are 9.2×10^{9} cm^{-2} and 7.13×10^{10} cm^{-2}. The average outer and inner diameters are 186.7 nm and 89.9 nm. The statistics of number of dots per ring and height of dots are shown in fig. 3. The average number of dots per ring is 7.7 dots and the average height of dot is 2.1 nm.

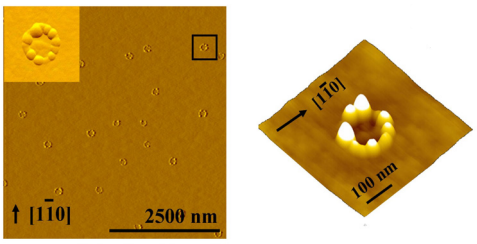

Fig. 2 Surface morphology [2-dimensions and 3-dimensions] by AFM of InP ring-shaped QDMs with In droplet conditions of In amount of 3.2 ML, In deposition rate of 0.8 ML/s and substrate temperature of 200 °C.

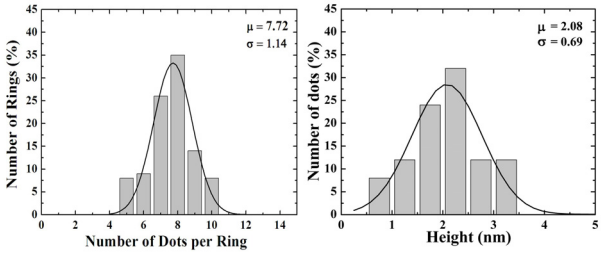

Fig. 3 Statistic of number of dots per ring and height of dots of InP ring-shaped QDMs with In droplet conditions of In amount of 3.2 ML, In deposition rate of 0.8 ML/s and substrate temperature of 200 °C.

For PL measurement, the 100-nm-thick $In_{0.49}Ga_{0.51}P$ capping layer was growth after crystallization. A 10-nm-thick $In_{0.49}Ga_{0.51}P$ was grown by migration enhanced epitexy (MEE) technique at 300 °C with 0.5 ML/cycle and a 90-nm-thick $In_{0.49}Ga_{0.51}P$ was grown by conventional epitexy growth at 470 °C. The micro-PL was achieved by a 532 nm laser with 150 mW and CCD detector at 300 K. Figure 4 shows the photoluminescence spectrum, a sharp peak of InP ring-shaped QDMs is observed at 1.67 eV (740.7 nm) with FWHM 72.9 meV. This sharpness of PL peak can be attributed mainly to the good crystal of InP ring-shaped QDMs.

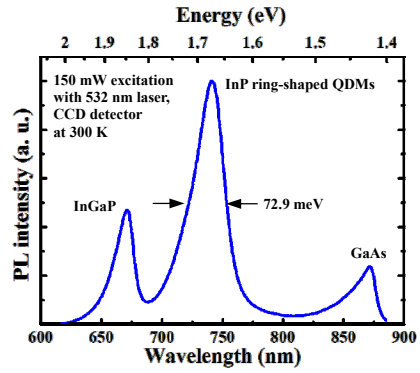

Fig. 4 PL spectrum at room temperature of InP ring-shaped QDMs with In droplet conditions of In amount of 3.2 ML, In deposition rate of 0.8 ML/s and substrate temperature of 200 °C.

3. Conclusions

RHEED investigation shows the changing from 2D to 3D structure of InP ring-shaped QDMs formation. It is demonstrated by AFM measurement that the InP ring-shaped QDMs were formed by droplet epitaxy technique. The AFM images review the physical structure of InP ring-shaped QDMs, hence circular ring-shaped QDMs could be achieved. The densities of rings and dots, average outer and inner diameters, the number of dots per ring and height of dots were investigated. Photoluminescence (PL) spectrum of InP ring-shaped QDMs shows a peak at 1.67 eV with FWHM 72.9 meV at room temperature.

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