CHAPTER V

CONCLUSIONS

This work presents the fabrication of InGaAs ring-like nanostructures by droplet epitaxy using solid-source molecular beam epitaxy. The growth started with the formation of InGa droplets on GaAs surface and followed by the crystallization of the InGa droplets under As_4 pressure to form InGaAs quantum rings. During the growth, the evolution of surface structures was monitored by *in situ* RHEED observations. The formation mechanism of InGaAs quantum rings from metallic InGa droplets is investigated. After the crystallization, the surface morphology of the samples was characterized by ex situ atomic force microscopy. Low-density of $10^8/cm^2$ InGaAs quantum rings have been observed. The quantum rings are not perfectly circular due to anisotropy surface diffusion during the crystallization.

Furthermore, the growth conditions have been varied by changing the droplet forming parameters, i.e.; 1) substrate temperature during $In_{0.5}Ga_{0.5}$ deposition, 2) $In_{0.5}Ga_{0.5}$ amount deposited, and 3) In-mole-fraction of In_xGa_{1-x} droplets. The effects of each parameter on the morphological properties of the InGaAs quantum rings are investigated.

For the effects of substrate temperature during the deposition, it is found that increasing substrate temperature results in InGaAs quantum rings of a larger size but lower density. Greater migration length of In and Ga atoms leads to 2-dimensional expansion and coalescence of InGa into larger droplets. Thus, larger but fewer quantum rings are formed after the crystallization.

Regarding the effects of $In_{0.5}Ga_{0.5}$ amount, increasing the deposited $In_{0.5}Ga_{0.5}$ amount also results in changing of quantum ring size and density. At low substrate temperature, the quantum ring size increases with increasing $In_{0.5}Ga_{0.5}$ amount. However, the quantum ring density oscillates with increasing $In_{0.5}Ga_{0.5}$ amount. The oscillation is due to merging of numerous small droplets into a full layer instead of individual droplets. At higher substrate temperature, on the other hand, the increment of $In_{0.5}Ga_{0.5}$ amount results in quantum rings of a greater height, higher density but smaller diameter. The decrease of diameter is supposed to be caused by accumulating compressive strain inside the larger quantum rings and the partial relaxation.

Varying indium-mole-fraction of InGa droplets strongly leads to a variation of crystallized quantum rings. When indium content of InGa droplets is less than 0.5, high density tiny-size quantum rings are obtained after the crystallization. Whereas, when indium content is equal or more than 0.5, low density large-size quantum rings are formed after the crystallization.

The photoluminescence measurement was also performed to characterize the optical properties of the quantum rings. The InGaAs quantum rings were grown under selected conditions of 2-5 ML $In_{0.5}Ga_{0.5}$ droplets deposition at 210°C substrate, with additional 100-nm GaAs capping layers. The capping layers were grown by migration-enhanced epitaxy at lower growth temperature and followed by the conventional method at higher temperature. The optical properties of the quantum rings were examined by photoluminescence spectra of the respective samples. The photoluminescence intensities are relatively low due to low density of the quantum rings. In particular, photoluminescence emissions for 2 ML and 5 ML conditions are too low due to very low density of QRs and accumulating strain, respectively. However, the photoluminescence emissions for 3 ML and 4 ML conditions can be examined. The photoluminescence peak of the 4 ML sample is centered at a little shorter wavelength than that of the 3 ML sample. This corresponds with the relatively smaller size of 4 ML-condition quantum rings. The photoluminescence intensity of the 4 ML condition is about 3 times higher than that of the 3 ML. This is due to higher density quantum rings in the 4 ML sample. Moreover, the full-width at half-maximum is slightly broad due to quantum ring-size distribution and composition distribution.

The photoluminescence measuring parameters including excitation intensity, measuring temperature, and polarization have been varied. As the excitation intensity is raised, the photoluminescence intensities increase without shifting. The ground-state energies of the InGaAs quantum ring systems are identified from the emission peaks. When the measuring temperature increases, the photoluminescence intensities decrease without thermal broadening. It is also observed that the photoluminescence peaks of the 3 ML sample are not shifted. This can attribute to the strain-free quantum rings which create no strain effect on the energy band structures. On the other hand, the peaks of the 4 ML sample are red-shifted. This shift can attribute to the existence of the strain field, which complicates the energy band structures and decreases the stability of the carriers. This increases the possibility to emit the longer-wavelength photon with increasing the thermal excitation. Finally, the elongation of the quantum rings is confirmed by the polarization resolved spectra. It is found that the polarized spectra along the perpendicular crystal directions exhibit the maximum difference of intensity. This corresponds to the anisotropy of the quantum rings.

Recommendations for further works

Due to the density of quantum rings grown by droplet epitaxy is relatively low, it is difficult to clearly study the optical properties of the quantum rings grown under some conditions. The multi-stack growth can increase the number of quantum rings per unit volume. However, the stability of ring shape in each stack should be confirmed. Also, the rapid thermal annealing (RTA) can improve the crystal quality of such low-temperature-crystallized quantum rings to obtain higher photoluminescence intensity.