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Uniform Self-Formation of High-Density InAs Quantum Dots by InGaAs Embedding Growth

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1. Introduction

High density, high uniformity and high crystal quality of the self-assembled quantum dots (QDs) are requested for realization of high-performance optoelectronic device applications: QD lasers (QD-LDs) and QD semiconductor optical amplifiers (QD-SOAs) [1]. In general, however, there are trade-off relations between high uniformity, high density and high crystal quality of the QDs in the conventional Stranski-Krastanov (SK) growth. For example, the uniform QDs can be obtained by the low growth rate and low arsenic pressure conditions [2]. However, the QD density becomes to be lower (1-3×10^{10}cm^{-2}) because of a long migration length. In addition, self size-limiting (SSL) is one of important effects for highly uniform formation of the QDs, which are covered with the stable facets [3]. However, the excess surface concentration of the adatoms due to the SSL effect induces the coalescence between the neighboring QDs, which makes a giant dot structure and provides the dislocations. High-density nucleation of the QDs also induces the incoherent dot structure due to the coalescence because of a narrow separation distance between the neighboring QDs.

Recently, we have demonstrated high density and high uniformity InAs-QDs on the Sb-terminated GaAs(001) layer by molecular beam epitaxy (MBE) [4]. In this conference, we present a new method for getting the high-uniformity and high-density InAs QDs with keeping a high crystal quality on the GaAs(001) substrates by MBE. It is uniform self-formation of high-density InAs QDs during the InGaAs embedding growth. We demonstrated high QD density of about 7×10^{10} cm^{-2}, a narrow photoluminescence (PL) linewidth of about 24 meV and a strong PL intensity.

2. Experiments

The samples were prepared by using a solid-source MBE. The GaAs buffer layer was grown on the GaAs(001) substrate at 590^{o}C, and then the substrate temperature was cooled down to 480 ^{o}C (or 500 ^{o}C). The InAs QDs were grown under the low growth rate (0.035 ML/s) and low arsenic pressure (3×10^{-7} Torr) conditions. The InAs QDs were also grown on the Sb-terminated GaAs buffer layer [4]. After the QD growth, the growth interruption was done for 5 min, and then the 4-nm-thick $In_{0.2}Ga_{0.8}As$ and 100-nm-thick GaAs layer were capped at 460 ^{o}C.

3. Results and Discussion

In the SK growth of the InAs QDs, low growth temperature, high growth rate and high arsenic pressure induce high-density nucleation of the 3D dots. However, the inhomogeneous broadening in the QD structure and the coalescence between the QDs are enhanced as shown in figure 1(a), in which the InAs QDs with 2.7 ML were grown on the GaAs buffer layer at the growth temperature of 480^{o}C, the growth rate of 0.07 ML/s and the arsenic pressure of 9×10^{-7} Torr. At 480^{o}C, the low growth rate of 0.035 ML/s and low arsenic pressure of 3×10^{-7} Torr conditions effectively suppressed the coalescence (Fig.1(b)). In this case, the dot density is about 7×10^{10}cm^{-2}. However, the uniformity in the QD size was insufficient.

Figure 2(a) shows a PL spectrum of the InAs QDs (2.7 ML), covered with the GaAs capping layer. Since the InAs coverage is insufficient for getting uniform QDs due to the self size-limiting effect, the PL spectrum reveals a large linewidth of 39 meV. The main peak wavelength is 1150 nm at 12K, and the large shoulder appears at the short wavelength region. It means the smaller QDs, which do not reach the limited dot size. Next, the 4-nm-thick InGaAs capping layer was grown on the same InAs QDs (2.7 ML). The PL spectrum is shown in Fig. 2(b). Since the InGaAs capping layer plays a role for the strain reduction, the PL spectrum shifts toward a low energy side [5]: the main peak

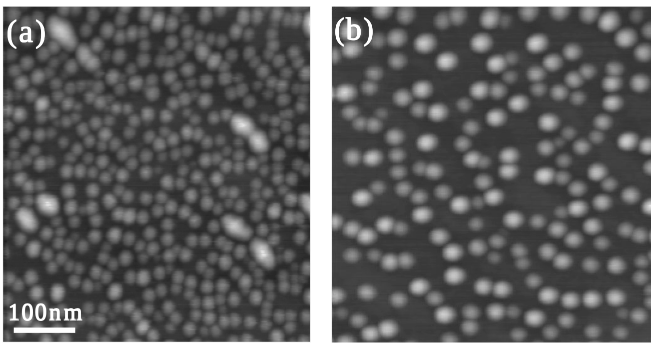

Fig.1. AFM images of InAs QDs grown at 480^{o}C. ((a): growth rate of 0.07 ML/s and As pressure of 9×10^{-7} Torr. (b): 0.035 ML/s and 3×10^{-7} Torr)

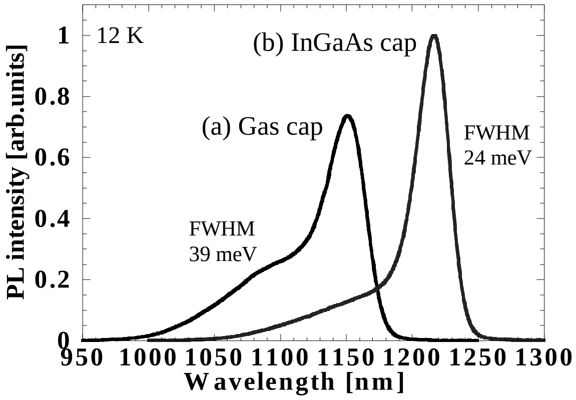

Fig.2. PL spectra of InAs QDs with GaAs capping layer (a) and InGaAs capping layer (b). The measurement temperature was 12 K.

wavelength is 1215 nm at 12K. Here it should be noted that the PL spectrum reveals a narrow linewidth of 24 meV. The short-wavelength shoulders due to the small QDs are suppressed, and the main peak intensity at 1215 nm increases relatively. Therefore, it can be predicted that the small InAs QDs become to be larger during the InGaAs embedding growth.

Figure 3 shows an (1-10) cross-sectional transmission electron microscopy (TEM) image of the double-stacked InAs QDs (2.7 ML). The 1st QD layer was covered with the 4-nm-thick InGaAs layer, and then the 50-nm-thick spacer layer of the GaAs was grown. The 2nd QDs was covered with the conventional GaAs layer. Here the 2nd QD growth was almost never affected by the underlying 1st-QDs because of the thick GaAs spacer layer. In Fig.3, one can see the larger size of the 1st QDs than that of the 2nd QDs in spite of the same InAs coverage of 2.7 ML. That is, during the InGaAs growth, In adatoms are preferentially grown on the InAs QDs. It can be explained by a strain effect: In adatoms are easily incorporated on the relaxed surface of the InAs dots compared with the strained wetting layer. In addition, a narrowing effect of the PL linewidth must be considered. As mentioned before, it

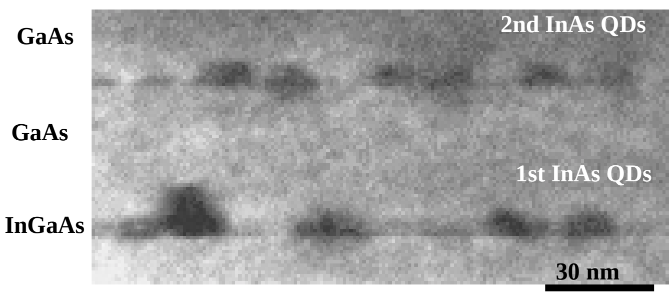

Fig.3. An (1-10) cross-sectional TEM image of double-stacked InAs QDs with 2.7 ML in coverage. 1st and 2nd QD layers were respectively covered with InGaAs layer and GaAs layer. The spacing layer between both QDs is 50-nm-thick GaAs layer.

suggests that the smaller QDs more increase in comparison with the larger QDs. As the result, the size uniformity improves. Although the surface of the larger QDs is more relaxed, the stable {110} facets appear on the side wall of the larger QDs. On such stable facets, the In adatoms are hardly incorporated. In short, it is possible that a self size-limiting effect of the InAs QDs progresses during the InGaAs embedding growth. Furthermore, in this growth process, it is expected to suppress the coalescence because the In-poor InGaAs capping layer is simultaneously grown on the wetting layer between the QDs. In fact, the PL intensity is enhanced for the InGaAs embedding growth.

From these results, we could obtain the high density of about 7×10^{10}cm^{-2} and a narrow PL linewidth (high uniformity) of 24 meV in the self-formation of the InAs QDs on the conventional GaAs(001). This uniform self-formation of the InAs QDs during the InGaAs embedding growth was also observed for the Sb/GaAs buffer layer, which induced higher QD density. This self size-limiting effect of the QDs during the embedding growth is one of promising techniques for achievement of the high-density and high-uniformity QDs with high crystal quality.

4. Conclusions

We studied the InGaAs embedding growth of the InAs QDs in the MBE growth. It was found that the In adatoms were selectively incorporated into the InAs QDs during the InGaAs embedding growth. In addition, the self size-limiting effect of the QDs was observed in the PL measurements. As the results, we successfully achieved the high QD density of about 7×10^{10}cm^{-2} and a narrow PL linewidth of 24 meV.

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