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Improved optical properties of low density InAs/GaAs quantum dots by controlling partial capping process

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Abstract

We investigated the density and the optical properties of InAs/GaAs quantum dots (QDs) as functions of partial capping layer growth temperature and thickness. We successfully obtained low density QDs with narrow linewidth emissions by controlling the growth temperature of the partial capping layer. Moreover, we reduced the background emission by increasing the thickness of the partial capping layer. The obtained low density QDs with such high optical quality emissions are suitable for cavity quantum electrodynamics experiments.

1. Introduction

InAs/GaAs self-assembled quantum dots (QDs) coupled to photonic crystal nanocavity is a powerful platform for research on cavity quantum electrodynamics (CQED) [1]. Especially when utilizing the quantum nature of single QDs, the growth of low density QDs with distinct narrow-linewidth emission is primarily required. In addition, the reduction of a broad background emission is desirable in order to reduce the unwanted optical absorption in the photonic nanostructures [2]. An emission wavelength of around 940 nm is also required for using highly sensitive Si photodetector and avoiding absorption from InAs wetting layer (~900 nm). So far, there is no report about the fabrication of the QDs satisfying all the above requirements. In this study, we fabricated such QDs by the fine-tuning of the conditions of a QD growth, a growth interruption after that and a partial capping process. In this paper, we especially focus on the partial capping process. Previously, several groups reported the morphology change of QDs during capping. Gong et al. reported that the higher capping temperature induced more segregation of In atoms from the QDs and caused a large Ga-In intermixing [3]. The growth temperature of the partial capping layer also affected the optical quality of the QD emissions [2]. Costantini et al. reported the intermixing was almost independent of the growth rate of the partial capping layer [4]. Thus, we investigated the density and the optical properties of the QDs as functions of the growth temperature and the thickness of the partial capping layer, and successfully obtained the low density QDs with narrow linewidth emissions and a low background emission.

2. Experimental

Sample preparation

We fabricated GaAs-capped InAs QD structures on GaAs (001) semi-insulate substrates by solid-source molecular beam epitaxy (MBE) with As_2 source. First, we grew a GaAs buffer layer after the thermal cleaning process in the MBE chamber. Then, we grew an $Al_{0.7}Ga_{0.3}As$ sacrificial layer for the fabrication of a photonic crystal nanocavity. After that, a 55-nm thick GaAs layer was deposited, followed by the growth of InAs QDs with a growth rate of 0.008 ML/s at 480 °C. After a short growth interruption of 10 s at the same temperature for wide size distribution of QDs, we lowered the substrate temperature to 430-465 °C and capped the QDs with a 3-nm-thick GaAs partial capping layer. After 50 s of raising the substrate temperature, we started the growth of 52-nm-thick GaAs capping layer. This sequence includes an In-flush [5], which reduces the height of QDs and shortens the wavelength of QD emissions. The cross-sectional schematic image of the grown structure is shown in fig. 1. We also fabricated the similar structures with the 2.7-3.2-nm-thick partial capping layer grown at 465 °C.

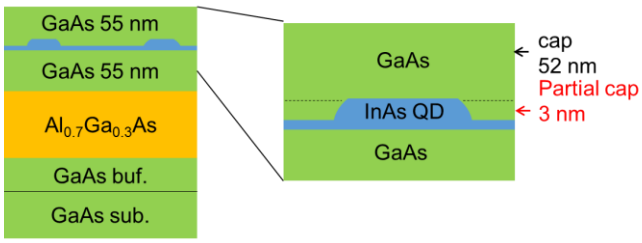

Fig. 1. Cross-sectional schematic image of fabricated structure.

Characterization

We characterized the grown QDs by low-temperature (15 K) micro-photoluminescence (μ-PL) spectroscopy. We also characterized the morphology of uncapped QDs by atomic force microscopy to check the wide size distribution of the QDs.

3. Results and Discussion

Figure 2(a) shows the evolution of μ-PL spectra by varying the growth temperature of partial capping layer ($T_{p.cap}$) from 430 to 465 °C. As $T_{p.cap}$ increases, the number of PL peaks decreases, together with a significant reduction of the background emission. These results suggest that $T_{p.cap}$ can be used to control the density of QD emission peaks as well as the amount of the background emission. Figure 2(b) shows a plot of linewidths and densities of QD emission peaks as a function of $T_{p.cap}$. When increasing $T_{p.cap}$, we observed a clear reduction of the linewidth by a factor of more than three. Note that the In-flush temperature (that is, the substrate temperature when the growth of the capping layer starts) varied from 465 °C to 490 °C with $T_{p.cap}$, due to the fixed time of In-flush in this experiment. Therefore, the strength of In-flush might also affect the linewidth and the number of PL peaks.

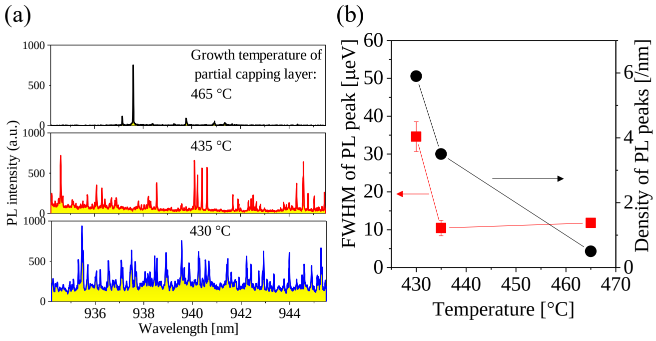

Fig. 2. (a) Micro-PL spectra of QDs with partial capping temperature of 430-465 °C (measured at 15 K). (b) Partial capping temperature dependence of FHWM and density of PL peaks.

We observed the degradation of a QD emission quality when using $T_{p.cap}$ of above 465 °C for QDs grown with a slightly different growth condition (not shown). This is probably because the excess annealing weakened the quantum confinement effect in the QDs by strong intermixing between the QDs and barriers as well as by the erosion of the QD shape [2]. Thus, we consider that $T_{p.cap}$ of 465 °C is the optimum value for obtaining low density and narrow emissions.

Next, we examined the effect of the thickness of the partial capping layer ($t_{p.cap}$) on the optical quality of QDs. We observed a broad background emission peak at around 960 nm for $t_{p.cap}$ of 3.0 nm (Fig. 3). Thus, the shorter wavelength side of that peak exists at around 940 nm, where the target PL peaks exists. By increasing $t_{p.cap}$ to 3.2 nm, the background emission peak shifted to longer wavelength and background intensity for target PL peaks decreased. In contrast, the background emission peak shifted to shorter wavelength and overlapped with target PL peaks when decreasing $t_{p.cap}$ to 2.7 nm.

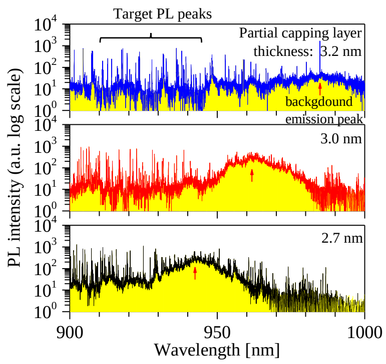

Fig. 3. Micro-PL spectra of QDs with the partial capping layer thickness of 2.7-3.2 nm (measured at 15 K). The partial capping temperature is fixed at 465 °C. Arrows indicate the peaks of broad background emissions from large InGaAs complex structures.

We consider that this broad background emission comes from large InGaAs complex structures, which are formed during partial capping. These complex structures have large lateral size, thus the emissions from these structures are broad. The peak of this broad emission shifted to longer wavelength by increasing $t_{p.cap}$, due to the increase of the heights of these structures.

By using the optimized $T_{p.cap}$ (465 °C) and $t_{p.cap}$ (3.2 nm), we obtained low-density low-background sharp emissions from neutral exciton (X^0) and biexciton (XX^0), confirmed by polarization-dependent (fig. 4) and excitation-power-dependent μ-PL spectra (not shown). Calculated FWHMs of X^0 and XX^0 peaks are 18 and 15 μeV, respectively. These emissions are suitable for the study of CQED.

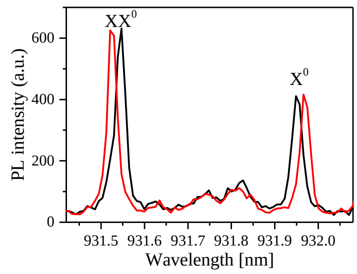

Fig. 4. Polarization-dependent Micro-PL spectra of QDs with partial capping layer growth temperature of 465 °C and thickness of 3.2 nm (measured at 15 K). Two spectra show two components of polarization directions perpendicular to each other.

4. Conclusions

We investigated the relation between the density and the optical properties of InAs/GaAs QDs with the partial capping process. We successfully fabricated low-density high-optical-quality QDs by controlling the growth temperature of the partial capping layer. We also reduced the background emission by increasing the thickness of the partial capping layer. The obtained QDs with such high-quality emission peaks are suitable for the study of CQED.

Acknowledgements

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