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Thermal Treatment of InGaAs/GaAs Self-Assembled Quantum Dots With SiN_x and SiO_2 Capping Layers

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Intermixing effects of MOCVD (metal organic chemical vapor deposition) grown InGaAs SAQDs (self-assembled quantum dots) covered with SiO_2 and SiN_x-SiO_2 dielectric capping layers were investigated. The intermixing of SAQDs was isothermally performed at 700 °C by varying annealing time under the N2-gas ambient. It was confirmed from the PL measurement after the thermal annealing that, the emission energy of SAQDs was blue-shifted by 190 meV, the FWHM (full width at half maximum) was narrowed from 76 meV to 47 meV and the PL intensity was increased. SiN_x-SiO_2 double capping layer have been found to induce larger PL intensity after the thermal annealing of SAQDs compared to SiO_2 single capping layer.

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I. INTRODUCTION

There has been considerable interest in the growth of SAQDs due to their fundamental physics of 3-dimensional quantum confinement together with the novel device functionality that they can provide [1–6]. Since QD structure is expected to have delta-function like density of states, higher differential gain, lower threshold current density, and higher temperature stability in QD laser, than in quantum well laser, are possible. However, inhomogeneous broadening in PL due to size distribution and composition distribution of QDs restrict their real applications.

The optical properties of SAQDs are important for their application to optical devices such as laser diodes (LDs). The optical properties of SAQDs are dependent not only on the growth condition but also on the post-growth process such as a thermal treatment [7].

The relatively large inhomegeneous broadening in photoluminescence (PL) spectrum, due to compositional distribution and size distribution, negates the advantages of QD as a active medium of QD-LDs and constitutes a technical barrier for the development of the QD-LDs. The blue-shift and narrowing in the PL spectrum of SAQDs after thermal annealing have been widely reported [7–9]. Therefore thermal annealing technique can be a good technical candidate to overcome this problem.

The growing temperature of InGaAs/GaAs SAQDs is relatively lower than the normal growing temperature of InGaAs/GaAs material system. This lower growing temperature would induce defects in SAQD structure, which degrade the optical quality of SAQDs. There have been some reports, such as Malik *et al.* [9], in which dielectric capping on the SAQD structure and subsequent thermal annealing enhanced the optical quality.

In this study, we have studied the effect of dielectric capping films such as SiO_2 and SiN_x on the optical properties after thermal annealing of dielectric capped InGaAs/GaAs SAQD structure grown by MOCVD method in order to improve their optical quality.

II. EXPERIMENT

The InGaAs SAQD structure used in this study was grown by MOCVD method on semi-insulating GaAs substrate at 530 °C by using TMG (trimethylgallium), TMI (trimethylindium), and AsH_3 as sources of Ga, In and As, respectively. The GaAs buffer layer was grown at 650 °C before the growth of $In_{0.5}Ga_{0.5}As$ quantum dot and finally a 120 nm thick GaAs layer was grown. The same SAQD structure except the 120 nm thick GaAs

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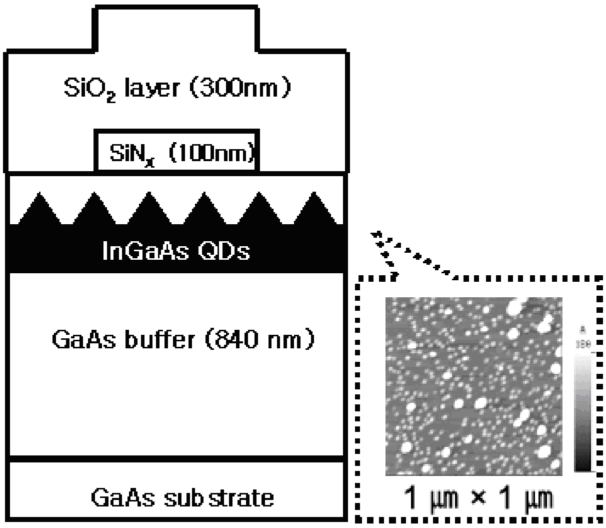

Fig. 1. Schematic diagram of sample structure used in the study.

layer was grown to get AFM (atomic force microscope) image. The density, the aspect ratio, and the lateral size of SAQD were 4.4×10^{10} cm^{-2}, 0.2, and about 30 nm, respectively, which was confirmed by AFM.

Two types of dielectric capping layers, such as SiO_2 and SiN_x-SiO_2 were deposited on the InGaAs SAQD structure by using plasma enhanced chemical vapor deposition (PECVD) method. Dilute silane (5 % SiH_4 in N_2), N_2O (99.999 %), and NH_3 gases were used as reactive gases for the growth of SiN_x and SiO_2 capping films. The pressure, applied RF power and the substrate temperate were 0.9 Torr, 30 watts and 200 °C, respectively. Sample structure shown in Fig. 1 was fabricated by using standard photolithography, wet chemical etching with a buffered oxide etchant and dielectric deposition by PECVD method. The thicknesses of SiO_2 and SiN_x capping film were 300 nm and 100 nm, respectively.

Thermal annealing of samples was carried out at 700 °C under N_2 gas ambient for the time range from 1 minute to 4 minutes. After the thermal annealing, photoluminescence (PL) measurement has been carried for the characterization.

III. RESULTS AND DISCUSSION

Figure 2 shows PL peak energy and FWHM of PL spectrum after the thermal annealing. As shown in Fig. 2, the PL peak of SAQDs was blue-shifted up to 190 meV as the annealing time increased from 1 minute to 4 minutes. The increase of a blue-shift with annealing time is attributed to the intermixing of Indium and Gallium atoms in SAQD structure [8]. The blue-shift for SiO_2-SiN_x capped sample is larger than that for SiO_2 capped sample at the same annealing time. Therefore one can

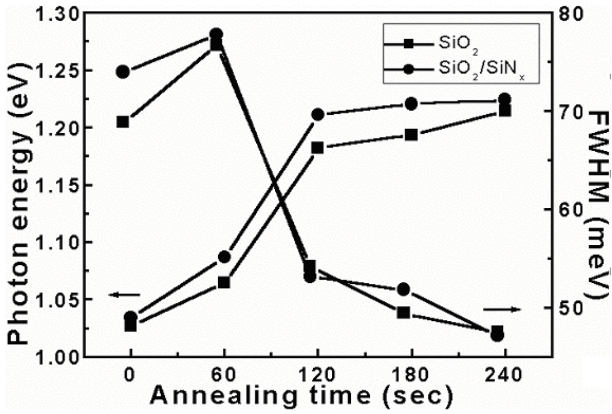

Fig. 2. PL peak energy and FWHM of PL spectrum.

conclude that SiO_2-SiN_x double capping induces larger In-Ga inter-diffusion than SiO_2 single capping.

As shown in Fig. 2, FWHM of PL spectrum was narrowed from 76 meV to 47 meV. This result is well coincident with the reported results [9–11]. The reduction of FWHM may be attributed to both the size and compositional changes in SAQDs [9–11].

Figure 3 shows the normalized PL intensity after thermal annealing. The PL intensities were increased as the annealing time increased up to 3 minutes, as seen in Fig. 3, not only for SiO_2 capped sample but also for SiN_x-SiO_2 capped sample. This kind of increase in PL intensity can be attributed to the reduction of nonradiative defect centers by thermal annealing [9]. However too long annealing time may degrade structural quality after full quenching of defects in the structure, and thus induces decrease in PL intensity over 3 minutes annealing as in Fig. 3. This kind of behavior was also reported by other researchers [7,9].

It is noted that, as seen in Fig. 3, the increase in integrated PL intensities for SiN_x-SiO_2 capped samples are larger than that those for SiO_2 capped samples. It has been well known that SiO_2 capping layer induces larger defects near interface than SiN_x capping layer.

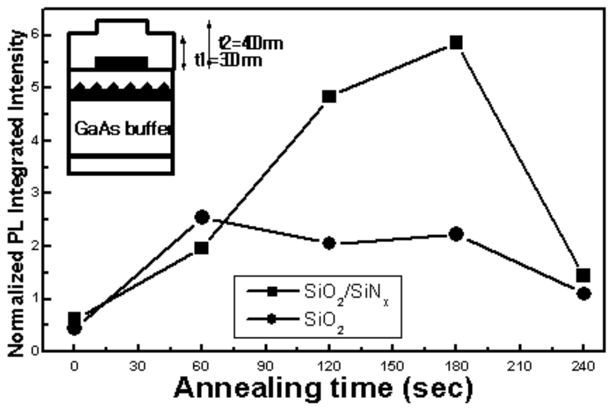

Fig. 3. Normalized PL intensity.

Furthermore, since thermal expansion coefficient of SiO_2 is smaller than that of SiN_x, the strain generated near interface during high temperature annealing process would be smaller for SiN_x-SiO_2 capped region than that for SiO_2 capped region because the thermal expansion coefficients of SiO_2 and SiN_x are smaller than that of GaAs. These facts may result in the reduction of strain induced defect indiffusion and consequently result in larger increase in the integrated PL intensity for SiN_x-SiO_2 capped sample.

IV. CONCLUSIONS

In this study, we have studied the effect of dielectric capping film on the optical properties after thermal annealing of dielectric capped SAQD structure grown by MOCVD method. A SiO_2 single layer and a SiN_x-SiO_2 double layer were employed as dielectric capping films. Thermal annealing of dielectric capped SAQD samples at 700 °C showed the increase of blue-shift in PL peak energy and also showed the narrowing of FWHM in PL spectrum as the annealing time increased. The maximum blue-shift of a 190 meV in PL spectrum and the narrowing of FWHM in PL spectrum from 76 meV to 47 meV were observed for 4 min. annealing.

It has been found out that the blue-shift for SiN_x-SiO_2 capped sample is larger than that for SiO_2 capped sample at the same annealing time. The increase of integrated PL intensity was also observed after thermal annealing of dielectric capped SAQDs. More than 6 times larger integrated PL intensity compared to virgin sample was obtained for SiN_x-SiO_2 capped sample. The SiN_x-SiO_2 double capping layer has been also found to induce much larger increase in integrated PL intensity than the SiO_2 single capping layer. Therefore one can conclude that SiN_x-SiO_2 double capping layer is better than SiO_2 single capping layer for the improvement of optical quality of SAQDs.

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