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Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1283-1284

Enhanced Photoluminescence Properties from Self-Assembled InAs Surface Quantum Dots by Antimony Incorporation

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1. Introduction

Self-assembled InAs quantum dots (QDs) are of great interest for practical applications and scientific studies. Motivated by the beneficial results of the incorporation of antimony (Sb) as a surfactant into a strained InGaAs quantum well to delay three-dimensional growth and thus extend the emission wavelength by reducing the surface faceting and delay the formation of dislocations [1]. Dilute Sb incorporation into InAs buried quantum dots (BQDs) was demonstrated to emit at 1.3 μm at room temperature. Recent interest has been focused on the properties of uncapped In(Ga)As QDs due to their potential for biological sensing applications because of surface-sensitive properties [2-5]. However, application of uncapped QDs has been limited due to relatively poor PL performance compared with BQDs. Liang *et al.* observed that the optical performance of the surface quantum dots (SQDs) was improved by tuning the number of stacked QD layers or the GaAs spacer thickness [6]. In this work, we sought to improve the PL performance of InAs SQDs by directly incorporating various amounts of Sb into InAs SQDs, and characterized their optical and structural properties using photoluminescence (PL), atomic force microscopy (AFM), and transmission electron microscopy (TEM).

2. Experiment

InAs(Sb) QDs were grown on n^+-GaAs (100) substrates by molecular beam epitaxy in a Riber Epineat machine. Four samples were grown with beam equivalent pressures (BEP) of 0, 1.4 $\times10^{-8}$, 1.8×10^{-8}, and 6×10^{-8} torr, respectively, supplied from a Sb cracker, as shown in Fig. 1. The QDs (2.72 ML) were capped with a 50-Å $In_{0.15}Ga_{0.85}As$ layer and a 0.3 μm-thick Si-doped GaAs top layer. Similar QDs capped with a 50 Å $In_{0.15}Ga_{0.85}As$ layer were also grown on sample surface.

3. Results and Discussion

Fig. 2(a)-2(d) show the representative 1×1 μm^2 AFM images of InAs SQDs with Sb BEPs of 0, 1.4×10^{-8}, 1.8×10^{-8}, and 6×10^{-8} torr. Without Sb, random QDs with density of 3×10^{10} cm^{-2} can be seen. For a low Sb BEP of 1.4×10^{-8}, the QD density is approximately 3.5×10^{9} cm^{-2}. An Sb BEP of 1.8×10^{-8} torr can reduce the dot density to 6×10^{8} cm^{-2}. Further increasing Sb BEP to 6×10^{-8} torr changes the surface morphology to ellipsoid terraces, as shown in Fig. 2(d). The density is more than two orders of magnitude lower than that of the Sb-free QDs. This AFM result indicates that incorporating Sb effectively reduces the density of the SQDs, as previously observed [7]. These results show a significant Sb surfactant effect affecting the growth of the SQDs. In order to verify the density of QDs as a function of Sb concentration, further investigation is needed to clarify the low density SDQs for Sb BEP of 6×10^{-8} torr. Cross-sectional TEM image reveals only two QDs in the range about 850 nm with a height of ~7 nm and a

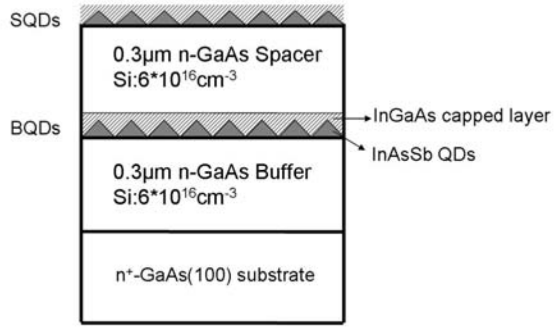

FIG. 1. Schematic illustration of the layered InAsSb/InGaAs nanostructure, emphasizing the structural correlation between InAsSb BQDs (buried quantum dots) and SQDs (surface quantum dots).

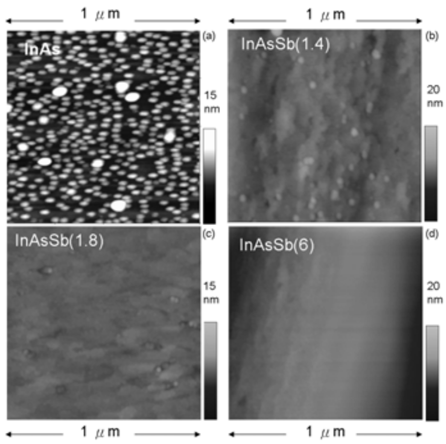

FIG. 2. (a)-(d). Representative 1x1 μm^2 AFM images of exposed QDs with Sb BEPs of 0, 1.4×10^{-8}, 1.8×10^{-8}, and 6×10^{-8} torr, respectively.

diameter of ~25 nm, as shown in Fig. 4. Therefore, the decrease in the dot density is explained by an Sb surfactant effect that can extend two dimensional growth and suppress dot formation. Fig. 3 shows the 300 K PL spectra for Sb

BEP of 0, 1.4 $\times 10^{-8}$, 1.8 $\times 10^{-8}$, and 6 $\times 10^{-8}$ torr, respectively. Etch spectrum exhibits two groups of peaks. The peaks at 0.95~1.05 eV are from the BQDs, and the peaks at ~0.77 eV are from the SQDs. The BQDs spectra show a doublet feature similar to the ground and first-excited transitions of the BQDs. The PL spectrum of Sb-free QDs exhibits a BQDs signal without SQDs signal. Hence, A significant enhancement of the PL for SQDs is observed with the incorporation of Sb into the QDs, as shown in Fig. 3.

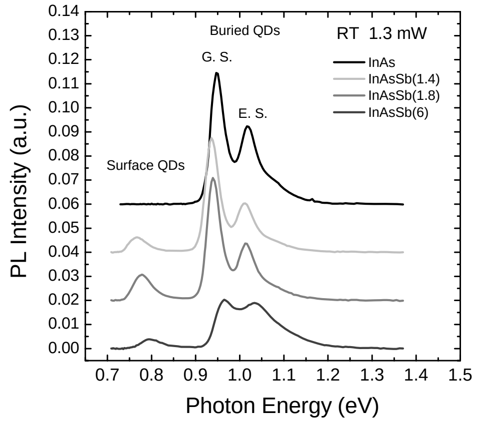

FIG. 3. Room-temperature PL spectra for Sb BEPs of of 0, 1.4$\times 10^{-8}$, 1.8$\times 10^{-8}$, and 6$\times 10^{-8}$ torr at an excitation power of 1.3 mW.

Spectrum InAsSb(1.4) shows PL emission peak centered around 0.936 eV from BQDs, and a long-wavelength emission peak around 0.765 eV from SQDs. When the QDs are covered by 0.3 μm GaAs cap layer, the emission energy from the BQDs is blueshift about 171 meV, which is expected due to the strain change before and after the growth of the GaAs capping layer[3 4]. In particular, sample InAsSb(1.8) has the highest PL intensity, which is approximately 4.5 times less than BQDs at 300K. This result is distinctly different from the results in [3], where they were reported that the approximately 1~2 orders of magnitude less than BQDs. Future increasing Sb BEP to 6 $\times 10^{-8}$ torr, spectrum InAsSb(6) shows a long-wavelength emission peak around 0.795 eV. It is found that the PL intensity decreases with increasing Sb BEP from 1.8$\times 10^{-8}$ to 6$\times 10^{-8}$ torr. This phenomenon can be interpreted as the change of SQD density. In particular, incorporation of the Sb from 1.4$\times 10^{-8}$ to 6$\times 10^{-8}$ torr can reduce the density of the SQDs by more then one order of magnitude, however, the PL intensity of the SQDs decreased only slightly. The literature has been shown that In segregation at the surface of InGaAs QDs led to greater PL intensity even at room temperature due to the suppression of nonradiative surface recombination [4]. GaAs and InAs surface recombination velocity are near 10^6 and 10^5 cm/s respectively [4], resulting in vanishing carrier at the GaAs and InAs surface. However, InSb has smaller surface recombination velocity of around 10^3 cm/s [8], indicating low carrier loss at the surface. Fig. 4 shows the cross-section TEM image of the InAsSb QDs for Sb BEP of 6$\times 10^{-8}$ torr. It is observed that the InAsSb SQDs has high Sb composition near the surface. The Sb passivation on the surface led to greater PL intensity in the SQDs due to reduction surface recombination velocity and suppressing carrier loss at the surface QDs even at room temperature.

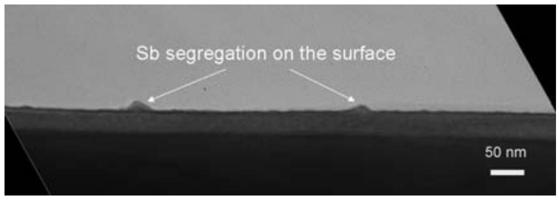

FIG. 4. Cross-section TEM image of the InAsSb QDs for Sb BEP of 6x10-8 torr.

4. Conclusions

We present a study of surfactant effect from self-assembled InAs surface quantum dots (SQDs) grown on GaAs substrate by incorporating antimony (Sb) into the QD layers with various Sb beam equivalent pressure (BEPs). Photoluminescence (PL) reveals an enhancement in the optical properties of InAs SQDs by the incorporation of Sb flux during growth. Atomic force microscopy and transmission electron microscopy analyses indicate that incorporation of the Sb BPE from 0 to 6$\times 10^{-8}$ torr can reduce the density of the SQDs by more then two orders of magnitude, however, the PL intensity of the SQDs enhances considerably. This improvement is attributed to the Sb passivation on the surface led to greater PL intensity in the SQDs due to reduction surface recombination velocity and suppressing carrier loss at the surface of QDs even at room temperature. These results indicate a mark Sb surfactant effect that can be used to improve surface-sensitive properties of SQDs for biological sensing.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC-97-2112-M-009-014-MY3, as well as the MOE ATU program for its partial support.

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