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E-1-2 (Invited)

MOCVD Growth of Quantum-Dot Optical Devices

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1. Introduction

Quantum dots (QDs) grown on InP substrates are attracting research attention for providing telecom devices with high performance. A semiconductor optical amplifier (SOA) is one possible application, since SOAs with self-assembled QDs have excellent characteristics [1]. In QD SOAs, polarization insensitivity is a remaining issue for use in common, and QDs that are sensitive to lights of both transverse-electric (TE) mode and transverse-magnetic (TM) mode are required. Since the polarization properties of QDs are expected to be changed by their shape and strain, we have proposed columnar QDs formed by close stacking QD layers with tensile-strained barrier layers as a structure of controlling polarization properties [2]. In this paper, we report MOCVD growth of columnar InAs QDs with InGaAsP barriers on InP(001) and their optical polarization properties aiming at an increase in the sensitivity to the TM mode. Also, columnar-QD SOA with large TM gains is demonstrated.

2. Growth and Polarization Control of Columnar QDs

Columnar QDs were formed on an unstrained $In_{0.85}Ga_{0.15}As_{0.33}P_{0.67}$ (λ = 1.1 μm) layer on InP(001) substrate by alternately growing InAs QD layers with a nominal deposition amount of 2 ML and InGaAsP barrier layers. A low growth temperature of 430°C was used in order to form small QDs. A typical size of QDs was as small as 15 nm in the [110] direction, 22 nm in the [1-10] direction and 1.2 nm in the height. The columnar-QD height was controlled by the stacking numbers, and the strain in the QDs was controlled by the thickness and strain of the barrier layers. Polarized PL was measured from the (110) cleaved edge of the samples with 3-μm-thick InP capping layers that have close optical confinement to actual devices.

(1-10) cross-sectional TEM images of columnar QDs with nominal 2-ML barriers are shown in Fig.1. When the barriers with tensile strain of 2.0% were used, dislocations were observed at 13 folds due to the accumulation of compressive strain of InAs, and the height of columnar QDs fluctuated (Fig. 1(a)). By means of increasing tensile strain to 3.7% and enhancing strain compensation, the QD layers were observed to be uniformly stacked without generating any dislocations even for the large stacking numbers of 22, and columnar QDs with high aspect ratios were obtained (Fig. 1(b)). Also, 3.7% tensile-strained-barrier samples showed good optical quality without a significant decrease in PL intensity up to 25 folds.

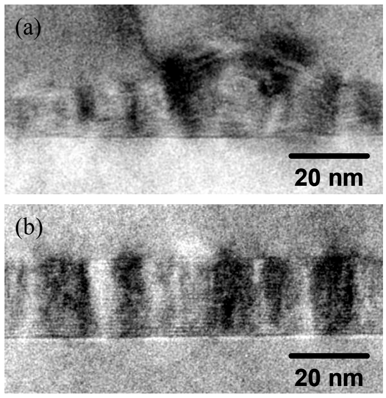

Fig. 1 TEM images of columnar QDs with (a) 13 folds, 2.0%-strained barrier, (b) 22 folds, 3.7%-strained barrier.

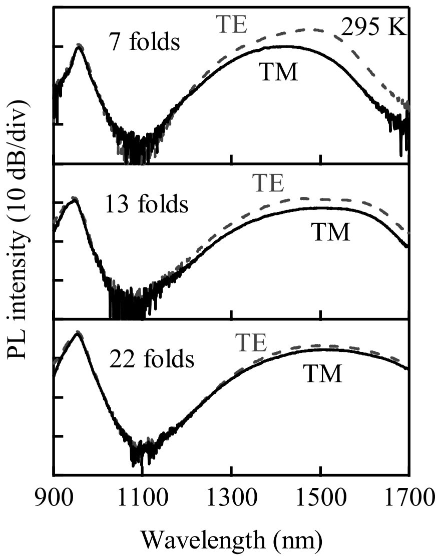

Fig. 2 Polarized-PL spectra of columnar QDs with varying stacking numbers.

Polarized PL spectra of columnar QDs with varying stacking numbers are shown in Fig. 2, where 2-ML-thick barriers with a tensile strain of 3.7% were used [3]. As the stacking number was increased from 7 to 22, the ratio of TM modes to TE modes increased, and difference in the polarization are largely suppressed. The effect of the increase in the height, however, saturated at around 22 folds. We consider that remaining biaxial strain in QDs dominates polarization, which was due to that wetting layers work as maintaining biaxial strain in QDs strongly for small QDs.

Effects of strain in QDs on polarization properties were investigated by changing the volume of tensile-strained barriers, that is, barrier thickness. Polarized PL spectra of 22-fold columnar QDs with varying thickness of tensile-strained barriers are shown in Fig. 3. As the barrier thickness was increased from 2 to 3 ML, the TM mode exceeded the TE mode, and it was confirmed that an increase in tensile stress to QDs also enhances the proportion of TM modes. From these results, we found that polarization properties of QDs can be controlled by changing QD height and strain.

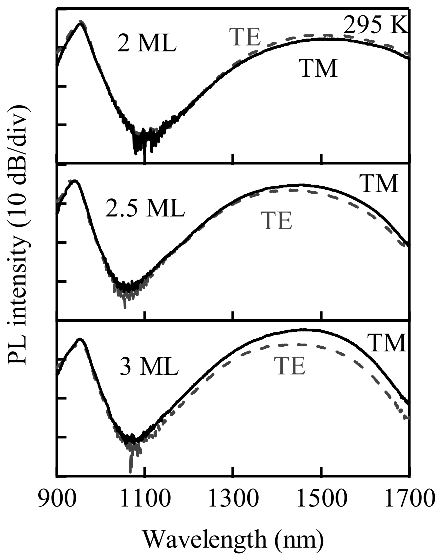

Fig. 3 Polarized-PL spectra of 22-fold columnar QDs with varying barrier thickness.

3. Fabrication of Columnar-QD SOAs

We fabricated buried-heterostructure-type SOAs with columnar QDs [4]. The SOAs have tilted waveguides with 8 degrees and window structures to suppress lasing action. Amplified spontaneous emission (ASE) spectra for a 1-mm-long chip with the 22-fold columnar QDs stacked by 2.5-ML barriers are shown in Fig. 4(a). TM-mode emissions were higher for all injection currents, which was consistent with the polarized PL measurements. Chip gain characteristics of a columnar-QD SOA at a wavelength of 1.55 μm are shown in Fig. 4(b). 2-columnar-QD layers were used for the active region in order to generate large gains. The TM-mode and TE-mode gains at an injection current of 300 mA were 17.3 dB and 11.1 dB, and TM-gain-dominant operation was successfully demonstrated. A chip-out 3-dB saturation output power of 19.5 dBm was obtained for the TM mode.

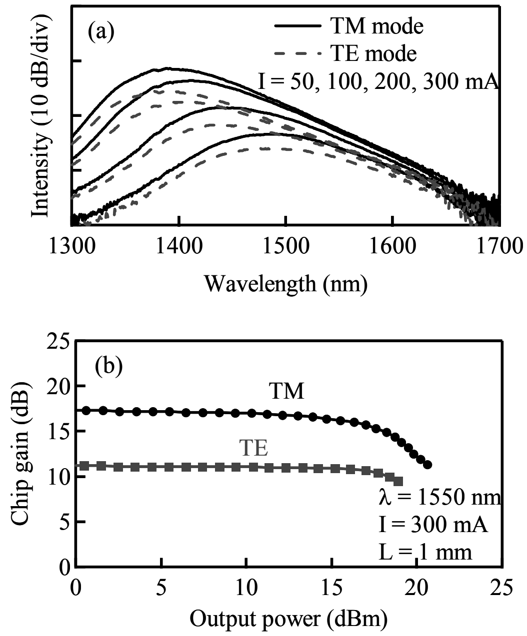

Fig. 4 (a) ASE spectra and (b) gain properties of columnar-QD SOA.

4. Conclusions

In summary, we successfully controlled polarization sensitivities of columnar QDs and obtained QDs that have nearly the same sensitivities to the TE and TM modes in the 1.55-μm telecom region. In addition, we demonstrated TM-gain-dominant QD SOA using columnar QDs, which leads to realization of polarization-insensitive QD SOAs.

Acknowledgements

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References

[1] T. Akiyama, M. Ekawa, M. Sugawara, K. Kawaguchi, H. Sudo, A. Kuramata, H. Ebe and Y. Arakawa, IEEE Photonics Technol. Lett. **17** (2005) 1614.

[2] H. Ebe, A. Uetake, T. Akiyama, K. Kawaguchi, M. Ekawa, A. Kuramata, Y. Nakata, M. Sugawara and Y. Arakawa, Jpn. J. Appl. Phys. **44** (2005) 6312.

[3] K. Kawaguchi, N. Yasuoka, M. Ekawa, H. Ebe, T. Akiyama, M. Sugawara and Yasuhiko Arakawa, Jpn. J. Appl. Phys. **45** (2006) L1244.

[4] N. Yasuoka, K. Kawaguchi, T. Akiyama, H. Ebe, M. Ekawa, S. Tanaka, K. Morito, A. Uetake, K. Otsubo, M. Sugawara, and Y. Arakawa, *The 19th Annual Meeting of the IEEE LEOS, post-deadline paper,* 2006.