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Enhancement to Optical Gain Difference of Structures and Interdot Spacing in Multi-Stack Semiconductor Quantum Dots

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Abstract

A quantum dot (QD) laser is expected to have low threshold current density, high thermal stability, and high modal gain. In our study, we measured the optical gain of multi-stack QDs with different barrier thickness, and two different stacking structures, using the variable stripe length method. In the case of a close double stacked structure, optical gain increased with decreasing barrier thickness, owing to quantum coupling.

1. Introduction

A quantum dot (QD) laser is expected to have low threshold current density and high thermal stability. [1] However, problems arise. A QD laser may exhibit inadequate modal gain, inadequate transverse mode control, and other deficiencies. In our previous work, we created 1.3 μm high-density, high-uniformity QDs. These were used in our proposed gradient composition, along with an As_2 source, with a density of 1×10^{11} cm^{-2}. We also realized a high modal gain with 8 cm^{-1}/QD layer, using the current injection method. [2] Moreover, for high modal gain, we used multi-stack QD layers with thin barriers, introducing quantum coupling between vertical QDs. [3-4]

In this study, we measured the optical gain of multi-stack QDs with different barrier layers and of two different multi-stack QD structures, using the variable stripe length (VSL) method.

2. Experiments & Results

Self-organized $In_{0.4}Ga_{0.6}As$ multi-stack QDs were grown on an Si-doped GaAs(001) substrate using As_2 as the source. We grew eight-stack $In_{0.4}Ga_{0.6}As$ QD structures with GaAs interdot spacings of 3.5, 7, 10, and 15 nm. The dots were 5 nm high, 20 nm wide, and pyramidal in shape. In addition, we fabricated two differently stacked structures. Figures 1(a) and 1(b) show the schematic structures of the close stacked structure, and the close double stacked structure, respectively. The QD density was 3.0×10^{10} cm^{-2} for both structures.

Photoluminescence (PL) was investigated using a spectroscopy system. Laser light was focused on the QD samples through an objective lens. A Ti:sapphire pulse laser was used as an excitation source for the PL measurements. Modal gain was investigated using the VSL method. A source light with parallel beams was applied to the sample.

The PL(I_{ASE}) from QDs was calculated from the cross section of the samples. The modal gain was calculated from the interaction between the length of the parallel beams and the intensity of PL from the QDs. Fig. 2 shows the schematic of the VSL method.

Fig. 3 shows the PL spectrum of the close stacked structure for various stripe lengths used in the VSL method. The peak wavelength and the full-width half-maximum (FWHM) were approximately 1300 nm and 22 meV, respectively. Fig. 4 plots the PL peak intensity against stripe length.

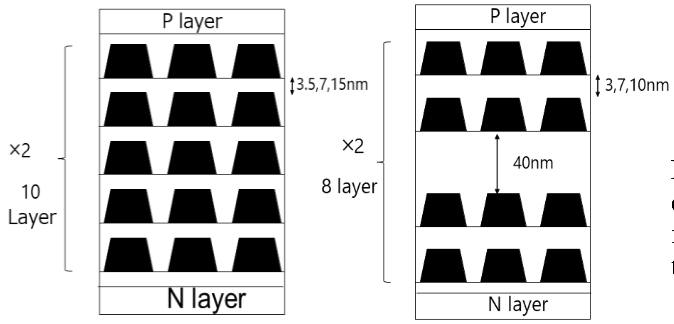
Optical gain was calculated to fit the experimental data to the theoretical equation: [5]

$$I_{ASE} = \frac{A}{g}\{exp(gL) - 1\} \qquad (1)$$

Fig. 5 shows the optical gain as a function of interdot spacing for each of the two different structures. We observed that the optical gain of the close stacked structure slightly decreases as interdot spacing decreases. However, in the close double stacked structure, optical gain is greatly increased by decreasing interdot spacing. We observed that optical gain is highest for an interdot spacing of 3.5 nm.

We expected these results for two main reasons. The first is internal loss. Thin interdot spacings cause increasing internal strain on QDs. However, the double close structure experiences lower strain than the close structure and is less affected.

The second reason is the superposition of the wavefunction. For interdot spacing of 10 nm or less, the wavefunctions of electrons become coupled owing to quantum mechanical interactions. However, at d = 3 nm, not only the electron wavefunctions, but also the holes in the medium, become coupled. Therefore, both the coherent volume and optical gain will be increased.



(a) (b)

Fig. 1 Structure of multi-stack QDs. (a) Close stacked structure with 10 layers and (b) Double close stacked structure with 8 layers.

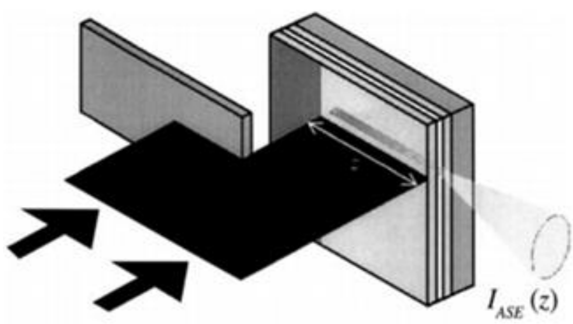


Fig. 2 Schematic images of the VSL method.

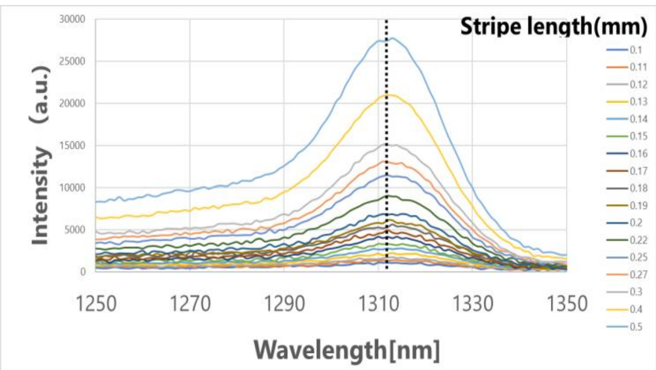


Fig. 3. PL spectra for various stripe lengths with a close double stacked structure. PL peak and FWHM are around 1310 nm and 22 meV, respectively.

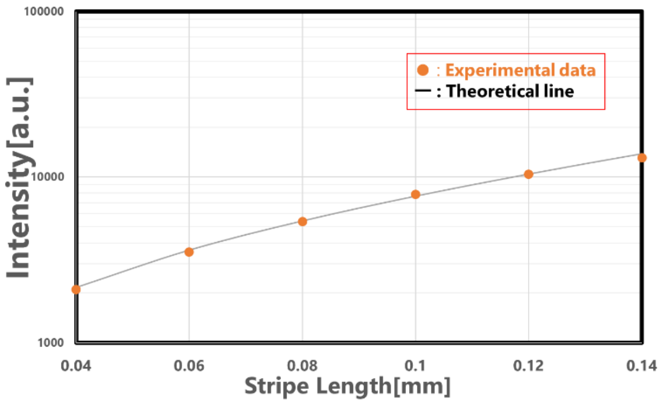


Fig. 4 PL peak dependence of stripe length with double close stacked structure. Circles show experimental data from PL spectra. The theoretical line a fit of Equation 1 to the experimental data.

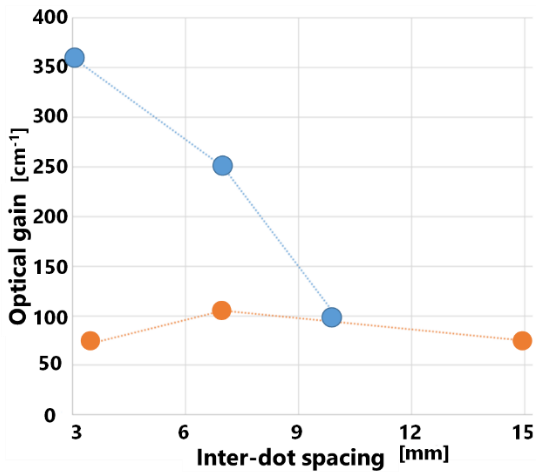


Fig 5. Optical gain dependence of interdot spacing, where orange and blue circles show the close stacked and double close stacked structures, respectively.

References;

[1] Y.Arakawa and H. Sasaki: Appl. Phys. Lett. **40** 939 (1982)

[2] A.Amano, T.Sugaya, and K.Komori: IEEE photonics Tecnol. let.**18** 619 (2006)

[3] T. Sugaya, T. Amano, M. Mori, S. Niki and M. Kondo, Jpn. J. Appl. Phys. 49, 030211 (2010).

[4] T. Sugaya, T. Amano, M. Mori and S. Niki, *J. Vac. Sci. Tech nol. B* **28**, C3C4 (2010).

[5] K.L. Shankee, R.F. Lehnny, Appl.Phys.Lett. **18** 475 (1971)