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Effect of Reduced Stacking Periods on Modulation Bandwidth of Self-Assembled Quantum-Dot Lasers: Theoretical Study

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1. Introduction

Quantum-dot (QD) lasers [1] are one of the promising candidates for next-generation low-power-consumption light sources in photonic networks owing to their excellent temperature stability [2-4]. However, as for the modulation speed, further extension of the modulation bandwidth is desirable to meet the continuously increasing demands of network traffic.

For several years, we have been extending the modulation bandwidth by enhancing the maximum modal gain by increasing the sheet density of QDs and stacking number of QD layers. Very recently, by increasing the stacking number of high-density QD layers (density = 5.9×10^{10} cm^{-2}) up to 8, we demonstrated room-temperature 25-Gbps eye-opening of QD lasers, which was the record high for 1.3-µm QD lasers [5].

Further increase in the stacking number for a high maximum modal gain does not improve the modulation bandwidth. For example, when we further increased the stacking number up to 10, the modulation bandwidth became narrower than that of 5-layer lasers although the maximum modal gain of 10-layer lasers was higher than that of the 5-layer lasers [6].

According to the analyses using the novel model considering carrier transport [6], we found out that the reason for this observation was both long carrier transport time along the QD-stacking direction and long effective carrier capture/relaxation time originating from the scale-up factor [7] with small effective-QD ratio. To improve them, the total thickness of active layers should not be very large, which requires reduction in the stacking period of QD layers.

In this report, by using the novel model, which agrees with the experiment, we theoretically estimated the effect of reduction in stacking period on the modulation bandwidth of QD lasers.

2. Model describing maximum modulation bandwidth of QD lasers

By referring to the layer structure of 5- and 10-layer lasers [6], the layer structure model we used in this report is shown in figure 1. It consists of QD layer(s) with a stacking number, N_{stack}, and a stacking period, L_{stack}, sandwiched between the p- and n- cladding layers with a distance of $L_{\mathrm{p\text{-}n}}$ (nm) = $N_{\mathrm{stack}}L_{\mathrm{stack}}$+85. Since the modulation bandwidth of QD lasers is limited by the strong damping characterized by the K-factor (K) [6], it can be given as follows.

$$f_{3dB\_max} = 2\sqrt{2}\pi / K \qquad (1).$$

The K-factor can be given as follows under the assumption that each QD layer is located at the center of p-/n-cladding layers and surrounded by SCH/barrier material with a diffusion coefficient of $D_{\mathrm{diffusion}}$.

$$\frac{K}{4\pi^2} = \tau_p + \frac{\tau_0}{1-P} + \frac{L_{p\text{-}n}{}^2}{8D_{diffusion}} \qquad (2).$$

Here, τ_{p} is the photon lifetime. P is the average carrier population ratio at the QD ground state, which is given as $\{1+(G_{\mathrm{th}}/G_{\mathrm{max}})\}/2$ with threshold modal gain G_{th} and maximum modal gain G_{max}. τ_0, the intrinsic capture/relaxation time when P = 0, is given as follows.

$$\tau_0 = \tau_{i0}\left[\frac{L_{p\text{-}n}}{N_{stack}D_{1QDlayer}V_{1QD}R_{activeQD}}\right] \qquad (3).$$

Here, τ_{i0} is intrinsic capture/relaxation time for single QD, and the term inside the square brackets is the scale-up factor [7], where D_{1QDlayer}, V_{1QD}, and R_{activeQD} are the sheet QD density, averaged volume for single QD, and effective QD ratio contributing to gain, respectively.

We used the following experimentally extracted parameters for the calculation [6]. We determined τ_{p} and P to minimize the K-factor [8]. For the maximum modal gain G_{max}, we used a value of 35.2 cm^{-1} at 5-layer stacked QD laser with a stacking period of 40 nm and other values for different stacking numbers, and the stacking period are estimated in proportion to the optical confinement factor by assuming $Al_{0.4}Ga_{0.6}As$/GaAs material system. For the capture/relaxation time, we used a value of 2.7 ps at the 5-layer stacked QD laser with a stacking period of 40 nm, and other values are calculated according to Eq. (3) with effective QD of unity for simplicity. For the calculation of carrier transport time, a diffusion coefficient of 94 cm^2/s is used.

3. Evaluation of enhancement of modulation bandwidth with reduced stacking period of QD layers

Figure 2 shows the calculated intrinsic capture/relaxation time as a function of N_{stack} for various L_{stack} values, which was later used for the calculation of the modulation bandwidth. The degree of the reduction in the intrinsic capture/relaxation time with stacking period is nearly fifty percent from stacking period of 40 nm down to 15-20 nm, suggesting large contribution to the modulation bandwidth [8].

Figure 3 shows calculated K-factor-limited bandwidth as a function of N_{stack} for various values of L_{stack} ranging from 50 nm to 15 nm. In the case, when stacking period is maintained at 40 nm corresponding to the experiment [6], the calculated K-factor-limited bandwidth is maximized at 9 layers as shown in Fig.3. Therefore, published data for 8 layers is almost optimized in terms of stacking numbers. Compared with the case of the 40-nm stacking period, if we reduce stacking period down to 30 nm, then we can expect enhancement of modulation bandwidth by about 3 GHz at around 11 layers. With a stacking period of 25 nm, enhancement of modulation bandwidth is about 6 GHz at 12 layers. Furthermore, with a stacking period of 15–20 nm, the enhancement of modulation bandwidth is more than 10 GHz. These improvements originate from not only the reduction in carrier transport time but also the reduction in intrinsic capture time, as shown in figure 2.

4. Summary

We theoretically evaluated the improvement in maximum modulation bandwidth with reduced stacking period of QD layers on the basis of the model considering the carrier transport issue. We have shown examples of calculation with stacking period between 50 nm and 15 nm. There is sufficient room for improvement in the modulation bandwidth by more than 10 GHz with the reduced stacking period.

Acknowledgements

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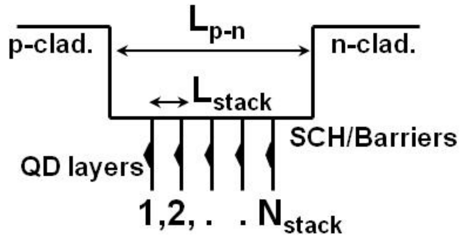

Fig.1 Schematic layer structure of QD lasers.

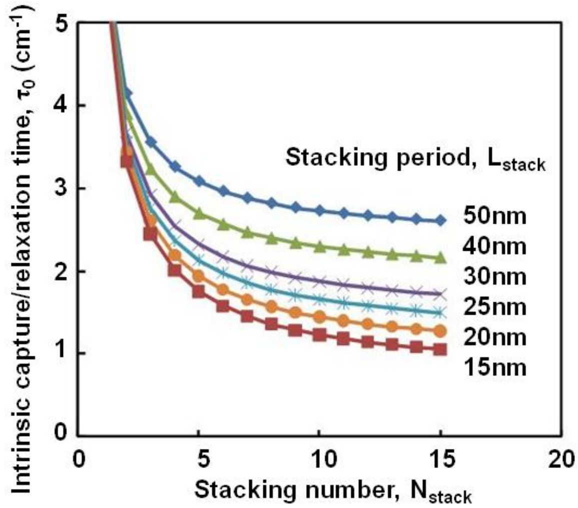

Fig.2 Intrinsic capture/relaxation time τ_0 (see Eq.3 in the text) as a function of stacking number for various stacking periods of the QD layer.

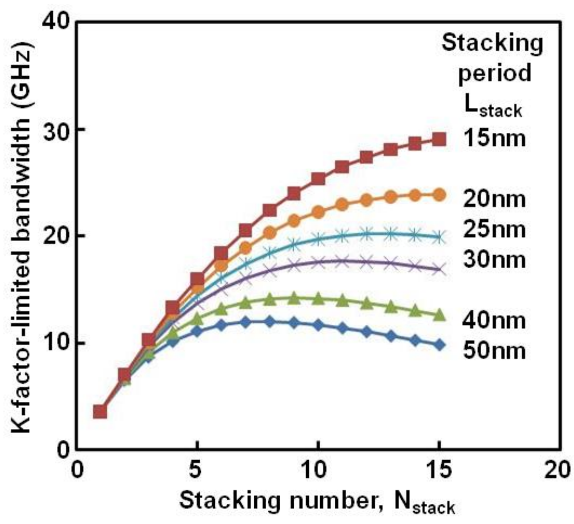

Fig.3 K-factor-limited bandwidth as a function of stacking number for various stacking periods of the QD layer.