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Room Temperature Pulsed Operation of 1.5μm VCSELDs with an Optimized MQW Active Layer

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Room temperature, pulsed operation of 1.5 μm InGaAs/InGaAsP MQW-VCSELD is demonstrated by the optimization of an MQW active layer, especially the number of quantum wells and the barrier thickness considering matched gain effect. Low threshold currents of 17 mA in 5 μm-devices and 25 mA in 7 μm-devices were achieved, and low series resistance of 40 Ω was obtained for 10 μm-devices. In addition, spontaneous emission enhancement/inhibition was discussed in these 1.5 μm MQW-VCSELDs.

1. INTRODUCTION

Vertical-cavity surface-emitting laser diodes (VCSELD) are attractive light sources including optical interconnections, fiber in the loop, and optical signal processing. Up to now, there have been numerous reports on low threshold, room-temperature (RT), CW operation of VCSELDs at 0.85-0.98 μm. At long wavelength, however, a few studies demonstrated RT, pulsed operation (50 mA[1], 34 mA[2]) of VCSELDs based on bulk active regions. Very recently, a first RT, CW operation of 1.3 μm VCSELD was reported[3]. In this paper, we report RT, pulsed operation of 1.5 μm VCSELDs with a theoretically optimized InGaAs/InGaAsP MQW active layer.

2. THEORETICAL DEVICE DESIGN

The optimization of MQW active layer in MQW-VCSELDs, especially the number of quantum wells N_w and the barrier thickness L_b, is important to achieve low threshold operation from the viewpoint of gain matching[4]. The threshold gain g_{th} of VCSELDs with internal loss and with gain matching is expressed by

$$\xi_m N_w L_w g_{th}= \frac{1}{2}\ln\left(\frac{1}{R_1R_2}\right)+\sum_{w,B} \xi_m N_i L_i \alpha_i + \left(L_c-\sum_{w,B} N_i L_i\right)\alpha_c \quad (1)$$

$$\xi_m=1+\frac{\sin 2\pi\sigma}{2\pi\sigma}, \qquad \sigma=\frac{1}{\lambda}\sum_{w,B} n_i L_i \quad (2)$$

where L_w is well thickness, R_i is mirror reflectivity, ξ_m is gain matching factor[4], α_i is optical loss, and L_c is cavity length. To estimate g_{th}, eq. (1) was self-consistently solved considering carrier density dependence of gain and optical loss including intervalence-band absorption.

Figure 1 shows an example of calculated N_w dependence of J_{th} in 1.5 μm unstrained MQW-VCSELDs with L_w of 7 nm and L_b of 6 nm. Note that lowest J_{th} is achieved when total MQW layer thickness is between $\lambda/4n$ and $\lambda/2n$ (N_w: 8-17, especially N_w=12), as is expected from matched gain effect[4]. Figure 2 shows the monotonic J_{th} dependence on L_b for 1.5 μm unstrained and strained MQW-VCSELDs when N_w is optimized. As is seen in this Fig. 2, it is found that J_{th} decreases with the decrease of L_b due to large confinement factor. However, L_b should be designed to be 5-6 nm to reduce the coupling of 2-D electrons between neighboring wells. The calculated mirror reflectivity R dependence of J_{th} shown in Fig. 3 indicates that RT, CW operation (<7 mA for 10 μm device) is possible for the optimized 1.5 μm MQW-VCSELDs if average R is larger than 98.5%.

3. EXPERIMENTAL

The schematic of 1.5 μm MQW-VCSELDs with an etched well structure used in this study is shown in Fig. 4. The laser structure consists of an n-InP clad layer, an unstrained MQW active layer, and a p-InP clad layer, grown by OMCVD, sandwiched between two 5-pair Si/SiO_2 mirrors with the measured R of 99.2 %[5] deposited by reactive ion sputtering. The MQW active layer was theoretically optimized to be composed of twelve 7-nm InGaAs wells separated by 6-nm thick InGaAsP barriers, as discussed in §.2. MQW total thickness was about 3/4λ. Total effective cavity length was designed to be 9×λ/2 (~2 μm) to decrease a diffraction loss in InP clad layers. The MQW layer was located at the peak of the optical standing wave to achieve matched gain. Active areas with diamond shape of 5, 7, 10, 15, 20 μm, formed by selective undercut just below the p-side mirror, were completely controlled using a self aligned process. The size of p-side mirror was slightly larger than that of active layer in order not to decrease R.

Figure 5 shows the emission spectra of a 5 μm device under CW 2 mA current at RT. Two longitudinal mode with mode spacing (FSR) of 165 nm was clearly observed. The Finesse value evaluated from FSR and spectral width (0.7 nm) is about 240, which corresponds to one-round-trip R_{total} of 98.7 %. The difference between R and R_{total} was 0.5 %, which resulted from the diffraction loss in clad layers and the scattering loss in active layer. Low series resistance of 40 Ω was obtained for 10 μm devices, which mainly resulted from small lateral diffusion resistance in p-InP clad layer due to the self-aligned structure and from the relatively large p-side contact area (400 μm^2). Lasing actions were observed in 5 μm devices with I_{th} of 17 mA and in 7 μm devices with I_{th} of 25 mA, under pulsed operation (200 ns, 5 kHz) at RT, as shown in Fig. 6.

4. SPONTANEOUS EMISSION ENHANCEMENT

Finally, we discuss spontaneous emission enhancement due to matched-gain effect and microcavity effect in our long-wavelength VCSELDs. Here, gain matching condition was intentionally controlled by adjusting the thicknesses of first SiO_2 layers in both Si/SiO_2 mirrors[6]. Figure 7 shows an example of spontaneous emission spectra with/without mirrors under the same electrical excitation at RT. Note that the intensity of $9\times\lambda/2$-mode is larger than that of $8\times\lambda/2$-mode, although the filtered intensity of $8\times\lambda/2$-mode without mirrors is higher than that of $9\times\lambda/2$-mode. This indicate that the cavity does not simply filter the spontaneous emission. Figure 8 shows the emission intensity ratio between the two modes after calibrating for the pure spontaneous emission intensity, as a function of the longitudinal-confinement factor ratio, which corresponds to gain matching condition. The emission intensity ratio is somewhat larger than the expected value from gain matching. This discrepancy indicates that spontaneous enhancement/inhibition due to the microcavity effect[7] might be occurring in spite of relatively wide emission spectrum, which may result from only two mode being allowed in the wide spectrum.

5. CONCLUSION

In conclusion, we have demonstrated first lasing operation of long wavelength MQW-VCSELDs through the optimization of an MQW active layer, especially the number of quantum wells and the barrier thickness, considering matched gain effect. Spontaneous emission enhancement was also discussed in these 1.5 μm MQW-VCSELDs.

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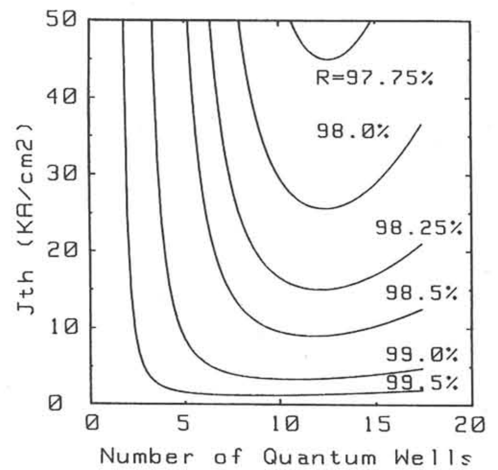

Fig. 1 Calculated Nw dependence of Jth at different R

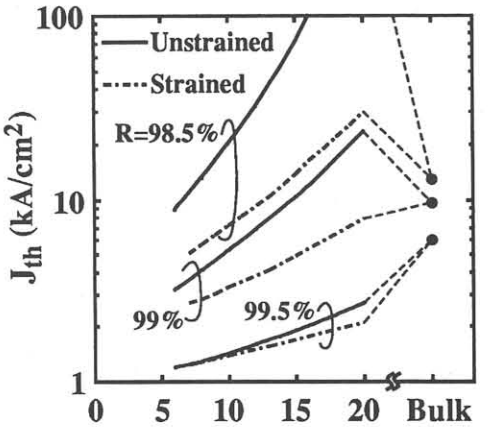

Fig. 2 Calculated LB dependence of Jth of unstrained and strained MQW-VCSELDs

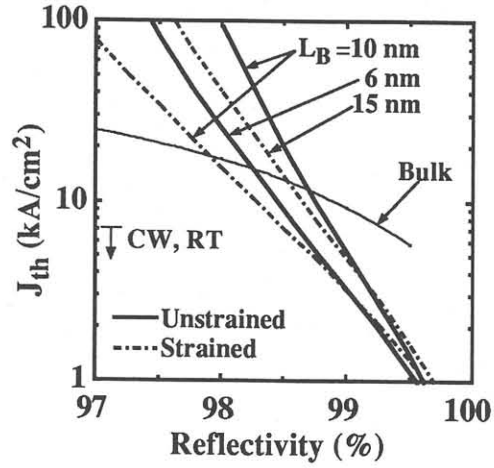

Fig. 3 Calculated R dependence of Jth of unstrained and strained MQW-VCSELDs and that of bulk-VCSELD

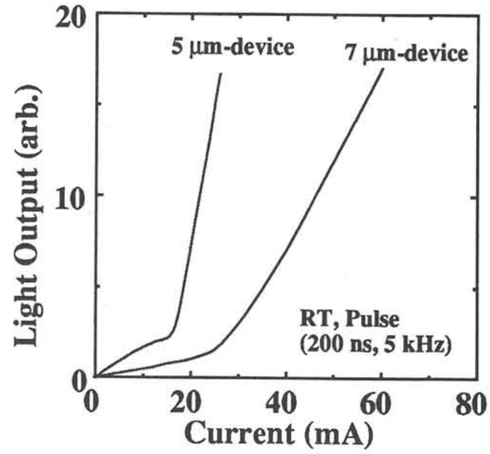

Fig. 6 Light-output power versus current (L-I) characteristics for 5 μm and 7 μm devices

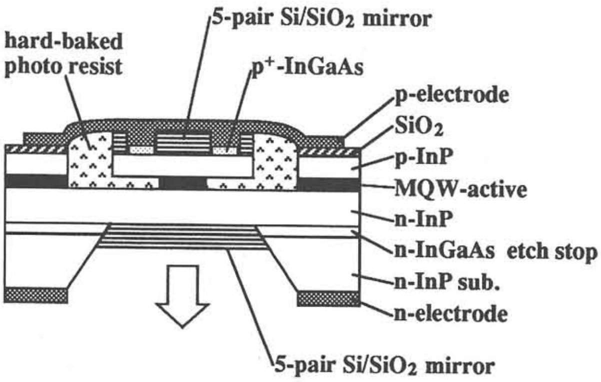

Fig. 4 Structure of 1.5 μm MQW-VCSELD

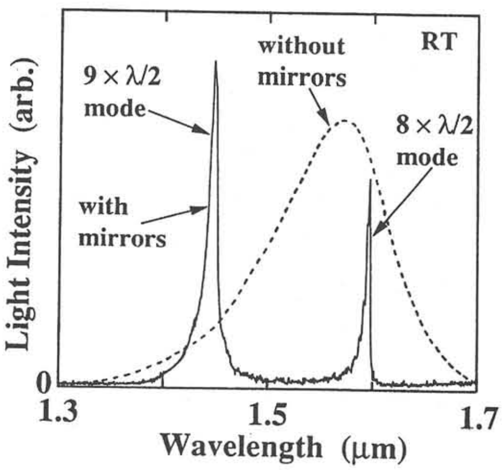

Fig. 7 Emission spectar with/without mirrors

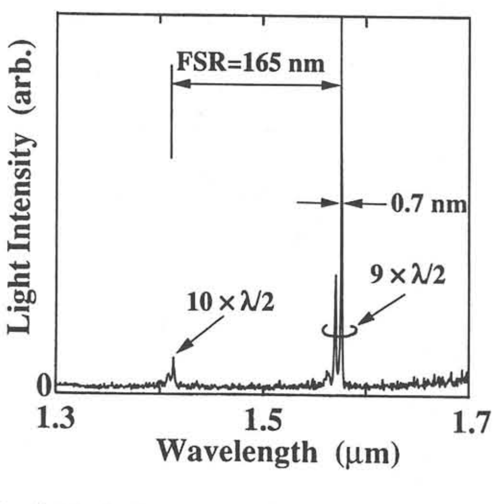

Fig. 5 Emission spectra of 5 μm device with current of 2 mA under CW at RT

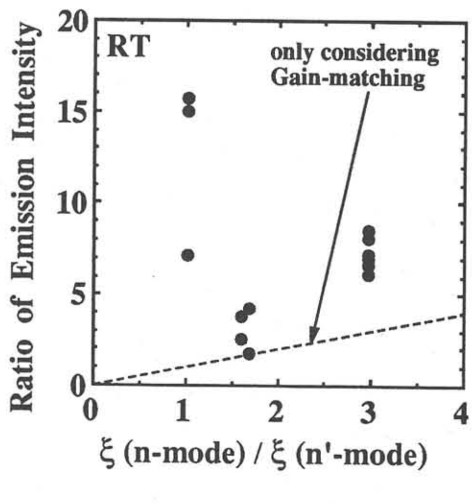

Fig. 8 Spontaneous emission enhancement/inhibition ratio