Thermal Analysis of Self-heating Effect in GaInAsP/InP Membrane DFB Laser on Si Substrate

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***Abstract* — Toward realization of an ultra-low-power-consumption semiconductor light source for on-chip optical interconnection, thermal characteristics of a membrane DFB laser were theoretically investigated. From numerical analysis, the thermal resistance of the membrane laser was estimated to be 6100 K/W, which does not affect to lasing characteristics of the membrane DFB laser due to low power operation capability.**

I. Introduction

Recently, in LSI global wiring, an increase of RC delay time and large power consumption become serious problems, and an introduction of optical interconnections is expected as one of the methods to solve them. For such on-chip optical interconnection, available pulse energy for the light source is expected to be less than 100 fJ/bit, which means a driving current is limited less than 1 mA when direct modulation speed and driving voltage are assumed to be 10 Gb/s and 1 V, respectively [1]. Hence, ultra-low-power-consumption semiconductor light source are strongly required. To meet this requirement, we proposed and have been investigating semiconductor membrane DFB lasers, which have a thin semiconductor core layer and low refractive-index cladding layers such as SiO_2, BCB or Air [2]. Due to strong optical confinement effect of the membrane DFB laser, ultra-low threshold current operation can be realized. Previously, we have reported an optically pumped membrane DFB laser with low threshold pump power of 0.34 mW [3]. In addition, an electrically pumped membrane DFB laser with threshold current of 11 mA was demonstrated by introducing a lateral-current-injection (LCI) structure [4,5].

However there is an anxiety about continuous-wave (CW) operation due to poor thermal conductivity inherent to the membrane structure. In this paper, we estimated the thermal resistance of the membrane DFB laser from the numerical analysis, and proved that the self-heating has very small effect on the operation of the membrane DFB laser because of its low-power consumption feature.

II. Thermal Resistance Simulation

Figure 1 shows the schematic structure of the GaInAsP/InP LCI-membrane-DFB laser with surface grating structure used for the calculation. A GaInAsP core layer in the LCI structure consisting of compressively strained 5QWs which sandwiched optical confinement layers (OCLs) was laterally sandwiched by p-InP and n-InP

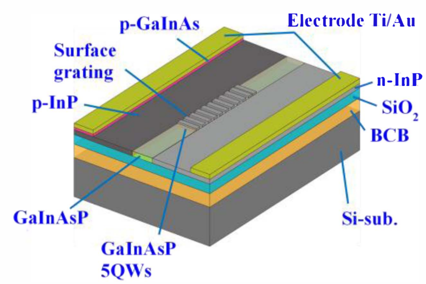

Fig. 1 Structure of membrane DFB laser.

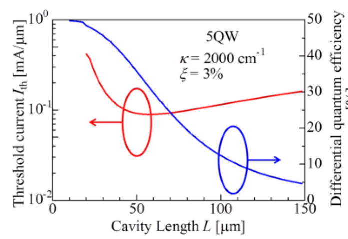

Fig. 2 Calculated threshold current and differential quantum efficiency as a function of cavity length.

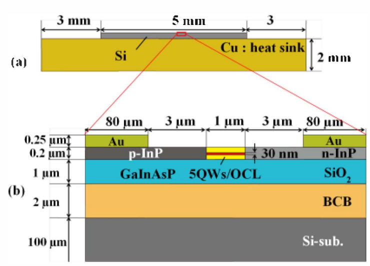

Fig. 3 (a) overview of the simulation model and (b) detailed drawing around the active layer.

cladding layer. The surface grating structure was formed on the top of the laser stripe.

From this assumption, the calculated threshold current and external differential quantum efficiency as a function of the cavity length are shown in Fig. 2. The minimum threshold current and the external differential quantum efficiency were 0.1 mA and 33%/facet, respectively when the cavity length was 50 μm. The temperature distribution in the active region was simulated using the finite element method with the model shown in Fig. 3. A thermal resistance R_{th} was calculated by using following expression.

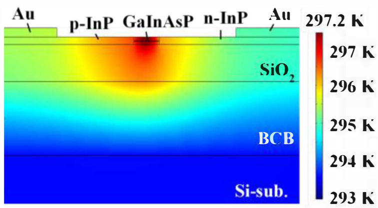

Fig. 4 Simulated result of temperature distribution in the membrane laser at a driving current of 1 mA.

$$R_{th} = \Delta T / P_{eff}$$

Where, the ΔT and P_{eff} are the change of temperature and the dissipated power, respectively. In this model, the QWs were replaced by bulk material with an equivalent thermal conductivity. With respect to the heat sources, the absorption of spontaneous emission, the nonradiative recombination and the Joule heat were given in the active layer. The Joule heat due to the sheet resistance was given in the p-InP layer because the sheet resistance in the p-InP region dominated large part of the total series resistance of the LCI structure. When a driving current was assumed to be 1 mA, the heat generations in the active layer and the p-InP layer were 0.54 mW and 0.15 mW, respectively. In this condition, the temperature distribution in the membrane laser is shown in Fig. 4. And the change of temperature ΔT and the thermal resistance R_{th} are calculated to be 4.2 K and 6100 K/W, respectively. The value of the thermal resistance is a very high compared with that of typical semiconductor laser of about 50 K/W.

III. Lasing Characteristics

Figure5 shows the output power at 293 K as a function of injection current in consideration of self-heating. In this calculation the output power was calculated with the following expression [6].

$$P_{out} = 0 \quad (I \leq I_{th})$$
$$= \eta_d(T_{room}) \exp\left(-\frac{R_{th}P_{eff}}{T_1}\right) E_g \left\{ I - I_{th}(T_{room}) \exp\left(\frac{R_{th}P_{eff}}{T_0}\right) \right\} \quad (I \geq I_{th})$$

Figure 6 shows the change of temperature of the active region. The parameters which are used for this calculation are as follows, η_d (T_{room}) = 0.33, I_{th}(T_{room}) = 0.1 mA, R_{th} = 6100 K/W, E_g = 0.8 eV, T_0 = 50 K, and T_1 = 100 K. As can be seen, the saturation of the output power due to self-heating was very small, and then the change of temperature of the active layer was less than 5 K when injection power was 1 mW. Therefore the self-heating caused by continuous operation have a very small effect on the output power. Due to the small driving power of the membrane laser, the change of temperature is the same or less in comparison with typical laser although the expected thermal resistance of the membrane laser is relatively high.

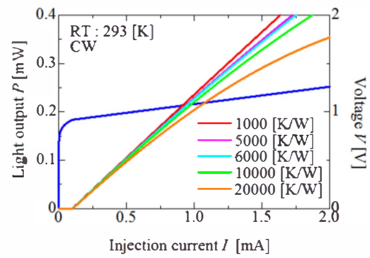

Fig. 5 Calculated results of output power and voltage as a function of injection current at 293 K for various thermal resistances.

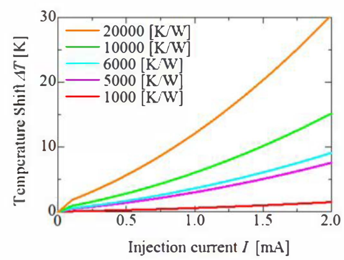

Fig. 6 Calculated temperature at the active region as a function of injection current for various thermal resistances.

IV. Conclusion

The expected self-heating caused by continuous operation have a very small effect on a lasing characteristics of the membrane DFB laser in spite of the high thermal resistance of 6100 K/W due to the small driving power.

This research was financially supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan,the JSPS through Grants-in-Aid for Scientific Research (#24246061, #19002009, #22360138, #21226010, #23760305, #10J08973) and also by the Ministry of Internal Affairs and communications through SCOPE, and the Council for Science and Technology Policy (CSTP), JSPS through FIRST program.

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