Thermal Analysis for Quantum Cascade Lasers using Experiments, Simulations and Structure Function Obtained by Static Measurement

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Abstract: In order to increase the output of quantum cascade lasers (QCLs), it is important to improve the heat dissipation. For investigating the relationship between the device structure and heat dissipation properties, three kinds of different QCL devices were prepared as follows. One is a device which has the ridge covered with SiO_2 and thin Au, another is a device which has the ridge covered with SiO_2 embedded with Au, and the other is a device which has the ridge covered with SiO_2 embedded with Cu. The temperature distributions was measured with a thermos-viewer. In addition, relationship between structure and heat dissipation properties in these structure devices are analysed with a three-dimensional model. As a result, it was clarified from experiments and simulations to improve heat dissipation properties by embedding ridge with Au or Cu. Furthermore, the thermal properties of the QCL device was measured by the statics method to separate the thermal resistance of the ridge, that of substrate, and that of mount parts. It was shown that the thermal resistance improves by more than 2 K/W from 9.3 K/W to 6.9 K/W by embedding ridge with Au or Cu.

1 INTRODUCTION

Quantum cascade lasers are n-type semiconductor lasers in which two types of semiconductor films are alternately stacked, and the laser light in the infrared region can be obtained (Faist et al., 1994). Conventional semiconductor lasers (LD) are limited to visible wavelengths below 3 μm, and semiconductor type lasers do not exist in the infrared region beyond that. QCLs oscillate in this region, and desired wavelength can be obtained just by changing the film thickness of the multilayer film using two kinds of materials.

In the latter half of the 2000s, commercially available lasers have been provided, and steadily commercialization is progressing with the detection of trace substances and gas detection in the distance. Particularly in the field of detection of trace substances, since the oscillation wavelength of QCLs is in the infrared region, it is possible to measure many gases with high sensitivity. With such trace substance detection and gas detection in the distance, higher sensitivity is expected by increasing the output. Since the amount of the laser absorption is measured in the detection of trace substances, it is necessary to propagate a long optical path length. Also, in far-field gas detection, a high-power laser is required since it detects weakly reflected light during laser light propagation.

As a high-power laser, watt-class laser oscillation has been reported by A. Evans et al., (2007; Bai et al., 2008). In order to further increase the laser output, a film structure with high oscillation efficiency and a device structure with high heat dissipation property are important. In this report, we focused on heat dissipation in QCLs. As a method for evaluating the heat dissipation property of QCLs, a method of embedding a ridge with InP has been adopted.

Several reports on the heat distribution of QCLs have been made. Sood et al. systematically measured the relationship between film thickness and thermal conductivity in super lattices of InGaAs and InAlAs (Sood et al., 2014). Evans et al. reported the analysis for temperature dependence of waveguide loss of QCLs (Evans et al., 2012). G. K. Veerabathran et al. have measured the thermal resistance by inputting pulsed power to QCL, which is called Dynamic method (Veerabathran et al., 2017).

On the other hand, V. Székely proposed a new method of extracting the thermal resistance from the

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voltage-current characteristics at the time of cooling has been introduced (Székely, 1997). This method is called the Statics method, and is widely used for measuring the thermal resistance of power devices. In this method, by using the inflection point of the thermal resistance (structure function), it is possible to separate the thermal resistance of the ridge, that of substrate, and that of mount parts.

In this paper, we applied this method to three kinds of QCLs with different structures, and separated the resistance for each constituent element such as ridge, substrate, and mount. In addition, we report on the thermal analysis using three-demensionsl simulations which reproduce the thermal characteristics of actual devices.

2 DEVICE STRUCTURE AND CHARACTERISTICS

Figures 1 (a) - (c) show three kinds of device structures comparing the temperature characteristics. In all devices, the QCL device forms an active layer (ridge portion) in which 22 layers of alternating layers in the device structure (a), thin SiO_2 and Au film are formed on the cladding layer. In the structure (b), gold of 10µm in thickness is plated on the structure (a). In the structure (c), Cu of 10 µm in thickness is plated on the SiO_2 film of (a). The result of laser operation for the device in the structure (c) is shown in Fig.2. At an operating temperature of 0 ℃, an oscillation wavelength of 4.41 µm and a laser peak output of 100mW have been obtained.

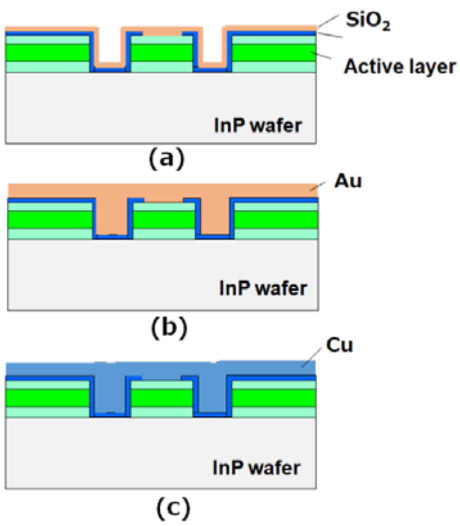

Figure 1: Devices structures. (a) Ridge covered with thin SiO_2 and thin Ti/Au, (b) Ridge embedded with Au, and (c) Ridge embedded with Cu.

In structures (a) - (c), the CuW mount was cooled to 10℃. Power up to 4 W was applied and the device temperature was measured with a thermos-viewer. The thermos-viewer FSV-210L (Apiste Corp.) is used for the measurement, and it can be measured the temperature with a space resolution of 12.5 µm or less with 25 µm lens and digital zoom. Fig.3 (A) shows the measurement results without operating, and (B) shows the result in the case of inputting 3 W of power.

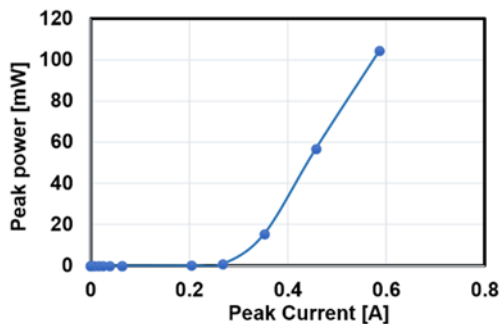

Figure 2: QCL output power.

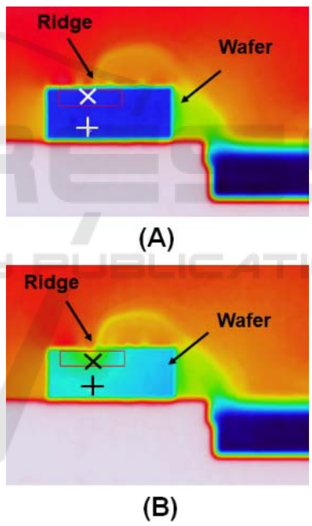

Figure 3: Temperature measurement with thermo-viewer, (A) without power and (B) input power of 3W.

Temperatures at two points “x” and “+” in Fig. 3 (A) were measured, and the supplied electric power was varied to obtain the temperature difference ΔT between “x” and “+”. “x” is just under the ridge portion, and “+” is a position 50 µm above the lower surface of the substrate. These results are shown in Fig.4. The measured values fluctuated by about 10% depending on the experimental setup. The variation ranges are shown as error with error bar. In the structure (a), the upper surface is covered with SiO_2 with a thickness of 0.2 µm and Au with a thickness of 0.5 µm, and the heat dissipation property for releasing heat into the atmosphere is lowered, and ΔT is large. On the other hand, in structures (b) and (c), heat is released to the atmosphere via Au or Cu on SiO_2, and ΔT decreases.

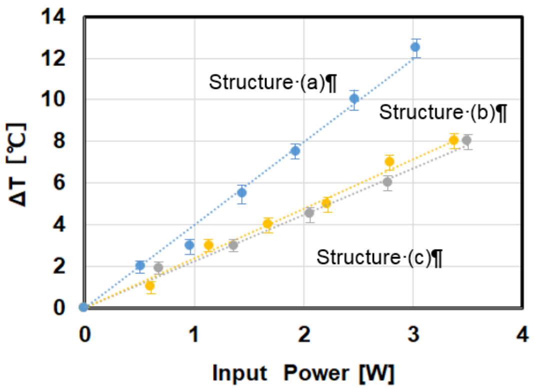

Figure 4: Temperature difference ΔT between the ridge bottom and the bottom of the wafer (Experiment).

3 THERMAL ANALYSIS

For thermal analysis inside the QCL element, a thermal airflow analysis software FloTHERM (Mentor Graphics Japan Co., Ltd.) was introduced to calculate the temperature distribution in the structures of (a), (b) and (c). 3-demensional model of the structure (a) of is shown in Fig.5.

Assuming that the electric power applied to the active layer in the ridge is a heating source, the inputting powers to the active layer were changed from 0 to 4 W. In addition, the surrounding air current is a natural convection model in which air is heated and rises. Because we can assume that the Cu/W mount was cooled to 10 ℃, the temperature of Cu/W was fixed at 10 ℃.

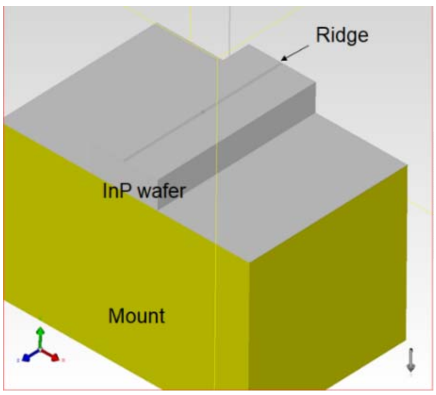

Figure 5: 3-Dimensional simulation model.

Figure 6 shows the calculation results. The temperature distributions at 3 W input power are displayed as contours. The maximum temperatures of the ridge portion in the structures of (a), (b), and (c) are 42.9, 29.7, and 29.7 ℃, respectively.

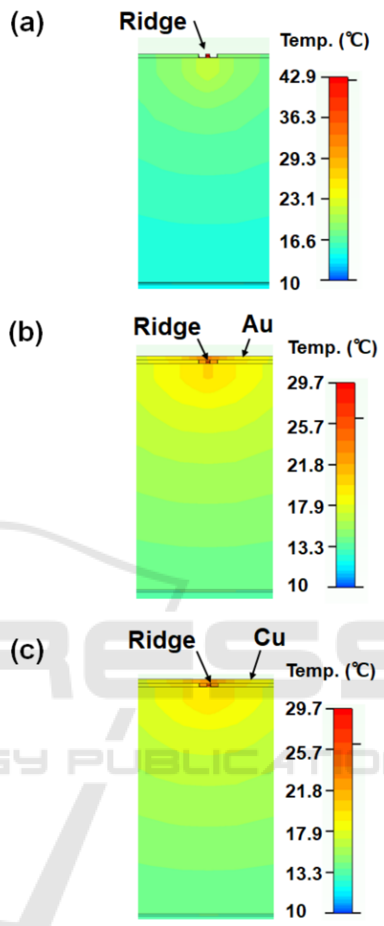

Figure 6: Simulation results. (A) Ridge covered with SiO_2 and thin Ti/Cu, (B) Ridge embeded with Au and (C) Ridge embeded with Cu.

In the three-dimensional simulation, the temperature distribution in the QCL was calculated by changing the input to the active layer. The temperatures in the temperature distribution were measured at the positions of “x” and “+” corresponding to those of Fig. 3, and the temperature difference ΔT was obtained. Fig. 7 shows the relationship between the input and the temperature difference ΔT. The ΔT in the structure (a) becomes larger than the ΔT in the structures (b) and (c). This tendency of the ΔT coincides with that of ΔT. It is considered that the absolute value differs because the measurement positions of the thermos-viewer does not accurately match the measurement positions in the calculation.

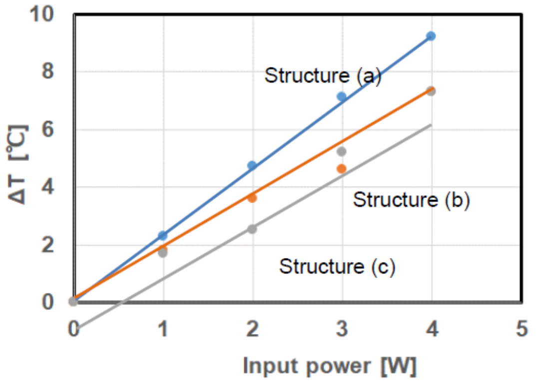

Figure 7: Temperature difference between the ridge bottom and the bottom of the wafer (Simulation).

4 MEASUREMENT OF THERMAL RESISTANCE AND STRUCTURE FUNCTION BY STATICS METHOD

Dynamic method and statics method are available for measuring thermal resistance of semiconductor devices. In the dynamics method, pulsed electric power is supplied to a semiconductor device to heat it, and the thermal resistance is measured. On the other hand, the statics method is a method in which a device is heated and the thermal resistance is measured from the voltage-current characteristic during cooling (Székely, 1997). Compared with the dynamics method, the measurement time is short, and it is possible to obtain highly reproducible results, and it has been widely used as a measurement method of thermal resistance.

In order to measure the thermal resistance of QCL accurately, statics method was adopted. For the measurement, T3Ster (Siemens AG) was used. The mounting part of the QCL device was cooled at 20 ℃ , and about 0.8 W of electric power was supplied to the QCL device to heat it. After stopping the power supply, the thermal resistance was calculated from the voltage-current characteristic flowing in the device.

The measurement results are shown in Fig.8. In the figure, the mark (A) shows the value of thermal resistance to the periphery of the ridge. Also, the mark (B) shows the thermal resistance value up to the InP wafer edge. It suggests that the thermal resistance improves by more than 2 K/W from 9.3 K/W to 6.9 K/W around the wafer edge of (B).

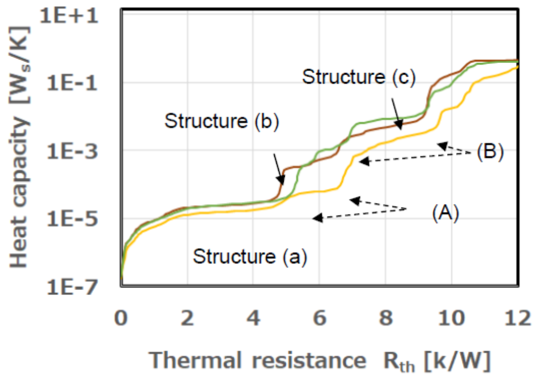

Figure 8: Thermal resistance vs. Heat capacity (Structure function).

5 CONCLUSIONS

The relationship between the device structure and heat dissipation were investigated in quantum cascade lasers. Three types of devices were prepared as follows. One is a device which has the ridge covered with SiO_2 and thin Au, another is a device which has the ridge covered with SiO_2 embedded with Au, and the other is a device which has the ridge covered with SiO_2 embedded with Cu.

From the results of the temperature measurement with the thermos-viewer and the three-dimensional thermal simulations, the effect of embedding Au and Cu was clarified. Furthermore, the heat properties of QCL devices were measured by the statics method using T3Ster. As a result, the thermal resistance of the ridge, that of InP wafer, and that of the mount were separated from the total thermal resistance. The improvement of thermal resistance with more than 2 K/W was attained by using Au or Cu embedding.

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REFERENCES

Bai, Y., Darvish, S.R., Slivken, S., Zhang, W., Evans, A., Nguyen, J., and Razeghi, M., 2008. *Appl, Phys. Lett.*, 92, 101105.

Evans, A., Darvish, S.R., Slivken, S., Nguyen, J., Bai, Y., and Razeghi, M., 2007. *Appl. Phys. Lett.*, 91, 071101.

Evans, C.A., Indjin, D., Ikonic, Z., and Harrison, P., 2012, *J. Comput. Electron*, 11, 137.

Faist, J., Capasso, F., Sivco, D.L., Sirtori, C., Hutchinson, A.L., Cho, A.Y., 1994. *Science*, 264, 553.

Sood, A., Rowiette, J.A., Caneau, C.G., Bozorg-Graeli, E., Asheghi, M., and Goodeson, K.E., 2014. *Appl. Phys. Lett.*, 105, 051909.

Székely, V., 1997. *Microelectronics Journal*, 28, 277

Veerabathran, G., K., Sprengel, S., Kari, S., Andrejew, A., Schmelauch, H., and Amann, M., C., 2017. *AIP Advances*, 7, 025208.