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Athermal and tunable operations of 850 nm vertical cavity surface emitting lasers with thermally actuated T-shape membrane structure

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We demonstrate the athermal operation and the wavelength tuning of 850 nm GaAs-based vertical cavity surface emitting lasers with a thermally actuated cantilever structure. The thermal actuation of a top distributed Bragg reflector mirror enables us to compensate the temperature drift of lasing wavelengths. The temperature dependence of lasing wavelengths could be controlled from −0.011 nm/K to −0.18 nm/K by changing the cantilever length. In addition, a T-shape membrane structure was introduced for efficient electro-thermal tuning. A small temperature dependence of −0.011 nm/K and wavelength tuning of 4 nm were obtained. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4753807]

Vertical cavity surface emitting lasers (VCSELs) have been attracting great interest as light sources with low power consumption and small footprint for use in high-speed optical interconnects. A wavelength division multiplexing (WDM) is one way for further increase of transmission capacities in optical interconnects. The temperature dependence of lasing wavelengths in single-mode semiconductor lasers, which is typically 0.1 nm/K, is a remaining problem to be solved for WDM optical interconnects with narrow channel spacing. It has been difficult to realize wavelength athermalization for semiconductor lasers and therefore a precise temperature controller is necessary for dense WDM interconnects. The elimination of costly and bulky thermoelectric controllers is required for use in WDM interconnects. If we are able to realize athermal semiconductor lasers exhibiting a fixed wavelength even under ambient temperature changes, we expect low power consumption and small packaging in WDM transmitter modules. A number of groups have reported various methods of eliminating the wavelength drift, including the use of an external cavity,[1] applying hydrostatic pressure,[2] and the use of alternative materials.[3]

In the past years, VCSELs using micro electro mechanical systems (MEMS) have been studied intensively for wavelength tuning in different spectral ranges.[4–12] A VCSEL with a thermally actuated cantilever based on a bimorph effect enables us to compensate the expansion of an optical cavity length, which leads to the control of the temperature dependence of lasing wavelengths.[13] We demonstrated an athermal InP-based VCSEL with a fixed wavelength even under ambient temperature changes thanks to the self-compensation based on a thermally actuated cantilever structure.[14] In addition, we demonstrated the athermal operation of GaAs-based VCSELs with a thermally actuated cantilever.[15] We obtained an extremely low temperature dependence of 0.002 nm/K, which is 40 times smaller than that of conventional single-mode lasers.

However, it has been difficult to realize the athermal and tunable operations at the same time for semiconductor lasers. The wavelength of athermal VCSELs cannot be controlled with a thermoelectric controller due to their athermal nature. We need the wavelength tuning for precise wavelength allocations. In this paper, we demonstrate the athermal operation and wavelength tuning of single-mode 850 nm VCSELs with a T-shape membrane structure.

Figures 1(a)–1(d) show the cross-sectional schematic view, the schematic top-view, the micro-scope top-view image, and the scanning electron microscope image of the fabricated athermal and tunable VCSEL, respectively. The device consists of a top AlGaAs MEMS mirror, an active region including GaAs/AlGaAs quantum wells, and an AlGaAs bottom p-type distributed Bragg reflector (DBR) including an oxide aperture which provides optical and electrical confinement. The top MEMS mirror is a freely suspended AlGaAs n-DBR including a 4λ-thick (1.1 μm) $Al_{0.85}Ga_{0.15}As$ stress control layer at the bottom. The thermal expansion coefficient of the stress control layer is smaller than the average of the semiconductor DBR. Thanks to different thermal expansion coefficients in different AlGaAs compositions, we are able to obtain the thermal actuation of the DBR for self-compensation of the temperature dependence of a resonant wavelength. In conventional MEMS VCSELs, the wavelength control can be realized by changing the air gap. In order to enhance the tuning efficiency $\Delta\lambda/\Delta d$ (d: the thickness of the air gap), the reflection at the interface between the air gap and the semiconductor should be reduced.[10] Our structure has an Al_xO_y anti-reflection (AR) layer at the interface.[15] The refractive index of Al_xO_y is about 1.5 which is close to that of a perfect AR coating. The structure leads not only to the enhancement of wavelength tuning efficiencies but also to the increase in the temperature range of athermal operations. This is because the tuning efficiency $\Delta\lambda/\Delta d$ can be nearly constant against air-gap changes by inserting the Al_xO_y layer.

In addition, the wavelength tuning can be realized by heating a cantilever structure which is thermally isolated from an active region. We designed a T-shape membrane structure for enhancing the tuning efficiency. The membrane consists of a cantilever and a bridge which are perpendicular to each other. Both of cantilever and bridge areas are released by selective etching of a GaAs sacrificial layer as shown in Fig. 1(b). In our T-shape membrane structure, its two ends are suspended by two supporting mesas with tuning electrical contacts. By injecting current laterally through the bridge part

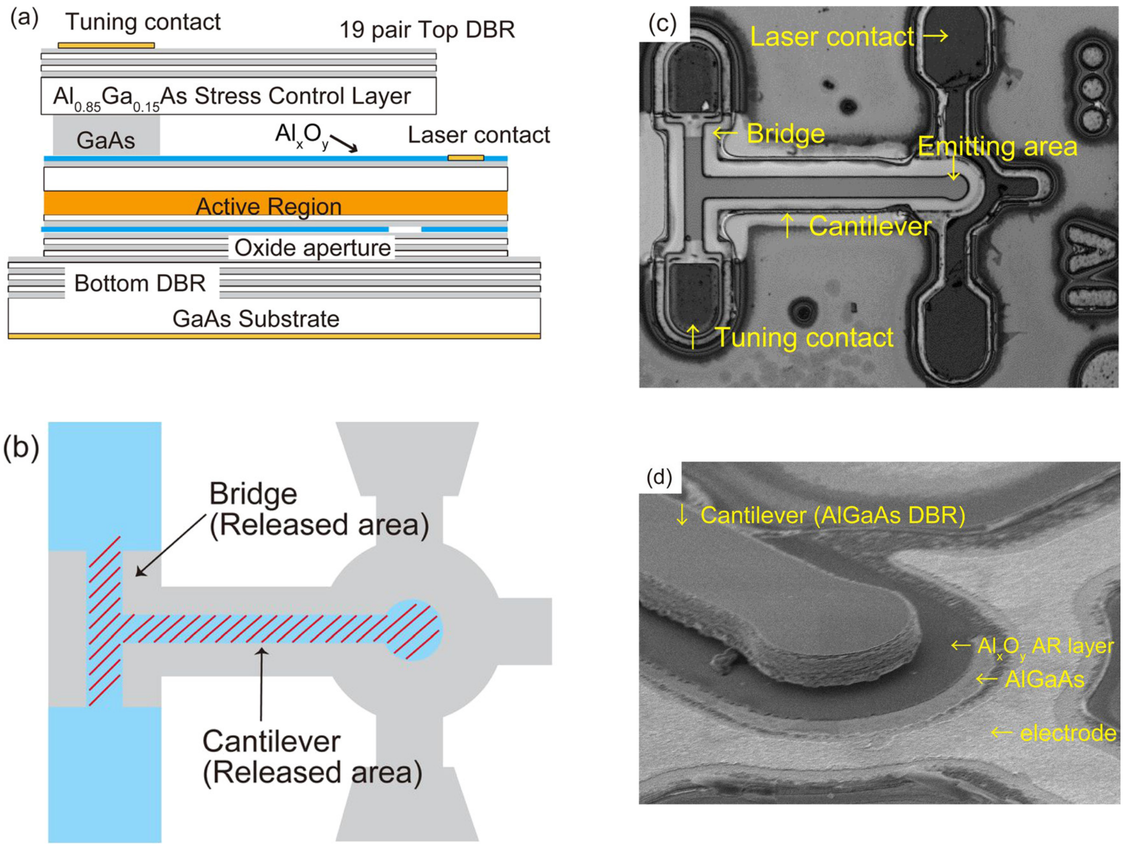

FIG. 1. The proposed athermal and tunable 850 nm MEMS VCSEL: (a) Schematic cross-sectional view, (b) schematic top-view, (c) micro-scope top-view image, and (d) scanning electron microscopic image of a fabricated VCSEL with Al_xO_y anti-reflection layer.

of the T-shape semiconductor membrane structure, we are able to obtain efficient heating of the cantilever with keeping athermal operations. We calculated the thermal distribution in the cantilever structure by using a finite element method as shown in Fig. 2. The heating power at the membrane bridge is assumed to be 10 mW. The temperature increase at the bridge is as large as 84 K. The movable cantilever part which is located at the center of the bridge is efficiently heated. We estimated the electro-thermal tuning efficiency could be as high as 0.4 nm/mW. We also confirmed that the temperature increase at an active region is below 5 K.

The fabrication process includes the formation of a cantilever structure, VCSEL mesa etching, an oxidation process which forms an oxide confinement structure and an AR layer, metal deposition, and finally cantilever release by selective etching of a GaAs sacrificial layer. Cantilever structures and VCSEL mesas were formed by inductively coupled plasma (ICP) dry etching. The Al_xO_y AR layer can be formed by a lateral wet-oxidation of a 140-nm-thick epitaxial $Al_{0.98}Ga_{0.02}As$ layer during the formation of an oxide aperture for optical and electrical confinement. No extra fabrication process is needed to form the Al_xO_y AR layer. The diameter of a freely suspended DBR mirror at the head of the cantilever is 18 μm and the diameter of bottom mesas is 60 μm. The entire $Al_{0.98}Ga_{0.02}As$ AR layer was oxidized at 500 °C leaving an unoxidized aperture ($\sim$4 μm in diameter) at the center of a larger bottom mesa. We deposited Ni/AuGe/Au as a top laser contact after removing the surface Al_xO_y AR layer by buffered hydrofluoric acid and Au/Zn/Au as a bottom contact, respectively.[16] A T-shaped membrane was released by highly selective citric-acid-based chemical etching of a GaAs sacrificial layer followed by a critical point drying process.[17] The micro-scope top view image of the fabricated MEMS VCSEL is shown in Fig. 1(c). The Al_xO_y AR layer was formed with a smooth surface as shown in Fig. 1(d).

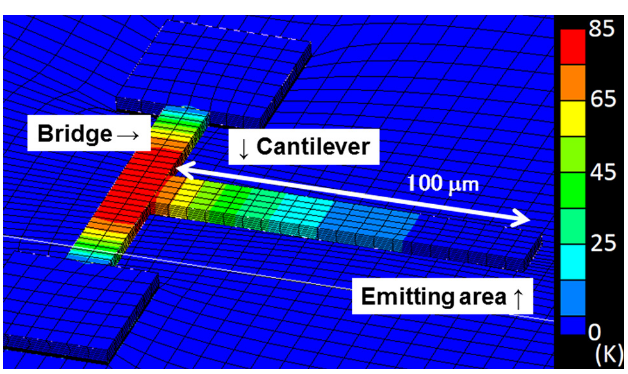

FIG. 2. Calculated temperature distribution in T-shape membrane structure with heating the bridge part.

Figure 3 shows the current/voltage (I-V) and current/light output power (I-L) characteristics of a fabricated VCSEL with different electrical powers in electro-thermal tuning. The threshold is below 2 mA under room temperature continuous-wave operations. Noticeable changes between 1.1 and 1.7 mA in threshold current can be seen with heating the cantilever, which would be due to the wavelength shift resulting in increased wavelength off-set from a gain peak. A rather high operating voltage is due to our poor lift-off

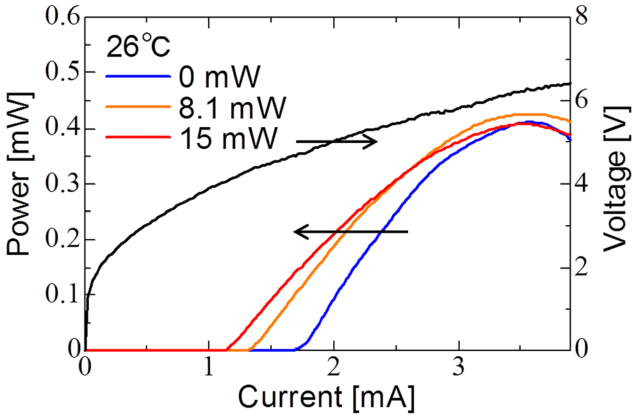

FIG. 3. I/L and I/V characteristics with various power consumptions for heating a membrane bridge.

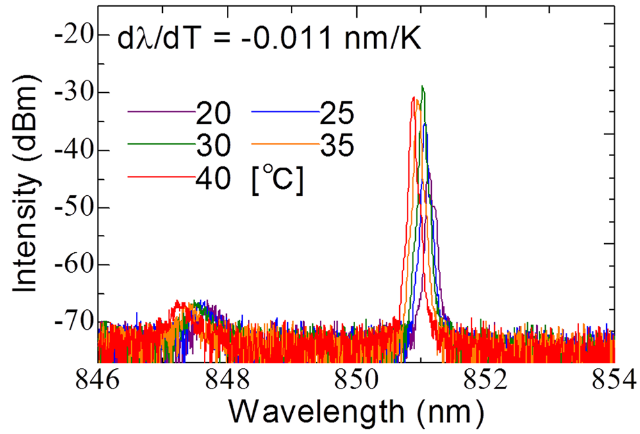

FIG. 5. Athermal operation of 850 nm VCSEL with a thermally actuated T-shape cantilever structure.

process of the n-type contact, which can be improved. The maximum power could be improved by reducing the operating voltages and optimizing the top mirror reflectivity. We also expect higher output power by optimizing their resonant wavelength off-set from a gain peak.

Figure 4 shows the measured temperature dependence of wavelengths for VCSELs with different cantilever lengths from 100 to 200 μm. The temperature dependence of MEMS VCSEL having different cantilever lengths was measured from the thermal wavelength shift of a dominant lasing mode. The length of the bridge part is fixed at 80 μm. The temperature dependence could be controlled from -0.011 nm/K to -0.18 nm/K by changing the cantilever length. As can be seen, the dependence can be precisely controlled by adjusting the cantilever length as shown in Fig. 4. Our T-shaped membrane structure enables the precise control of the cantilever length, which makes the precise control of the temperature dependence of lasing wavelengths. Figure 5 shows the lasing spectra with a cantilever length of 100 μm for different temperatures from 20 to 40 °C. The device was operated at a constant current of 1.8 mA to avoid the effect of self-heating. A small temperature dependence of -0.011 nm/K of a single-mode VCSEL was obtained with a 100 μm-long cantilever. The temperature dependence is 8 times smaller than that of conventional VCSELs. A smaller temperature dependence which was preliminarily obtained in our previous work[15] could be realized by precise adjustment of the cantilever length to meet the athermal condition.

We carried out the wavelength tuning of the athermal VCSEL with a cantilever length of 100 μm under continuous-wave operations at a stage temperature of 30 °C. We injected current laterally through the bridge part of a T-shape membrane structure. The electrical isolation could be obtained between the laser contact and the tuning electrode with the Al_xO_y AR layer. Figure 6 shows the lasing spectra with different electrical power consumptions from 0 to 22 mW. We obtained continuous wavelength tuning of 4 nm with an electrical heating power of 22 mW by utilizing the mechanical actuation of a cantilever. Figure 7 shows the wavelength tuning characteristics of an athermal VCSEL at different temperatures of 20 °C and 35 °C, respectively. The lasing wavelengths are plotted as a function of electrical power consumption for heating the cantilever. We observed no significant change of the tuning characteristic while conventional VCSELs show a wavelength drift of over 1 nm with the same temperature change. We realized the athermal operation with a wavelength drift of -0.011 nm/K and the continuous wavelength tuning of 4 nm at the same time.

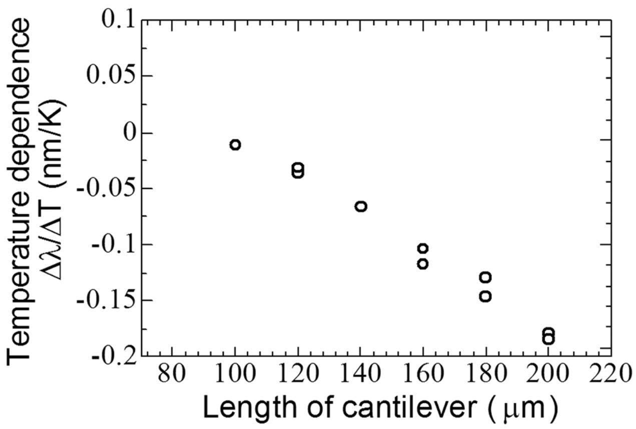

FIG. 4. Measured temperature dependence as a function of the length of T-shape cantilever structure.

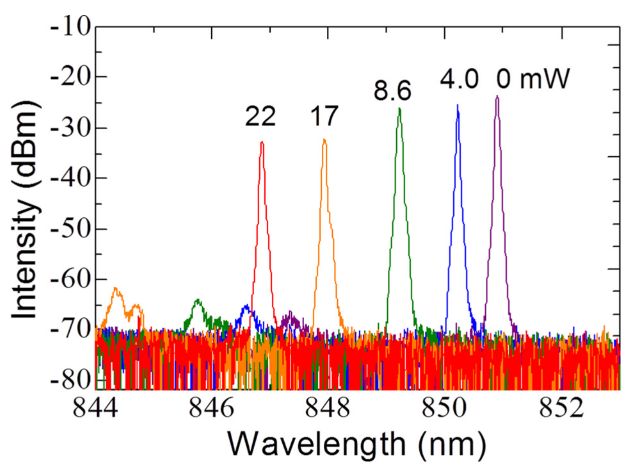

FIG. 6. Wavelength tuning with various power consumption by heating a micromachined mirror at a stage temperature of 30 °C.

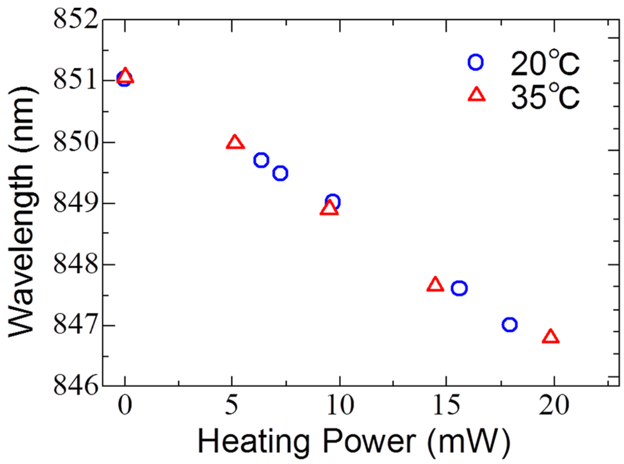

FIG. 7. Measured tuning characteristics at stage temperatures of 20 °C and 35 °C.

We demonstrated the continuous wavelength tuning of athermal single-mode GaAs VCSELs with a thermally actuated MEMS structure. A precise control of the temperature dependence of wavelengths was realized with a T-shape membrane structure. The temperature dependence could be controlled from −0.011 nm/K to −0.18 nm/K. In addition, our T-shape membrane structure enables us to realize efficient electro-thermal tuning of a cantilever structure. A continuous wavelength tuning of 4 nm was obtained with an electrical power consumption of 22 mW. For further reduction of the electrical tuning power, one potential approach will be to reduce the area of a micro-heater. The present structure has not been optimized for this purpose. The length of a bridge part of our T-shape structure can be reduced for reducing the power consumption. Another approach will be to use an electrostatic force for wavelength tuning, which will be opened for future study. The result shows a potential of tunable and athermal VCSELs for use in high capacity WDM optical interconnects with low power consumption. By making temperature controllers unnecessary, our athermal and tunable VCSELs may enable low power consumption in short-reach uncooled WDM applications.

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