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Large aperture VCSELs with a continuous-wave output power of 1.95 W

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Abstract

In this study, 980 nm high-power bottom-emitting vertical-cavity surface-emitting lasers (VCSELs) with large emission aperture are described. The devices have been fabricated by using oxidation confinement technology. Al_2O_3 film, instead of SiN_x film, is used as the passivation layer to enhance heat dissipation. A distinguished device performance is achieved. The maximum continuous-wave (CW) output power of the large emission aperture devices with active diameters up to 500 μm is as high as 1.95 W at room temperature.

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Keywords: VCSELs; Bottom emitting; 980 nm; Output power; Thermal resistance

1. Introduction

Recently, great attention has been paid to vertical-cavity surface-emitting lasers (VCSELs), owing to their merits such as high-power, high-efficiency coupling to fibers, single longitudinal mode operation, ability of being integrated to arrays on a single chip, and low fabrication cost. These advantages are essential for the applications such as laser pumping, medicine and materials treatment [1–5]. Especially, high-power VCSELs emitting at 940–980 nm are desired for pumping solid-state lasers and Er- or Yb-doped optical amplifiers. The highest optical output power reported for a single device by the University of Ulm is 180 mW for a top-emitting device with an aperture of 146 μm [6] and 890 mW for a bottom-emitting device with an aperture of 320 μm in continuous-wave (CW) operation. CW output power larger than 1 W at room temperature for a VCSELs 2-D array consisting 19 elements is also reported [7].

In order to obtain higher output power, a single device with larger emission aperture or a 2-D array should be employed. Since a 2-D array is more complicated than a single device in fabrication and application, we put our efforts on the fabrication of the single device with larger emission aperture. The heat dissipation of the VCSELs with enlarged emission aperture becomes a key problem. In order to resolve this problem, we use a new passivation layer with Al_2O_3 film instead of the conventional SiN_x film to minimize the thermal resistance of the VCSELs. By using this kind of device structure, the CW output power is improved significantly, the maximum output power as high as 1.95 W at room temperature can be reached for a single device with an active-area diameter of 500 μm.

2. Device fabrication and measurement

Fig. 1 illustrates the configuration of the investigated selectively oxidized VCSELs. The multi-layer system is grown by metal organic chemical vapor deposition (MOCVD) epitaxy on an n-GaAs substrate. The active region contains three $In_{0.2}Ga_{0.8}As$ quantum wells (QWs)

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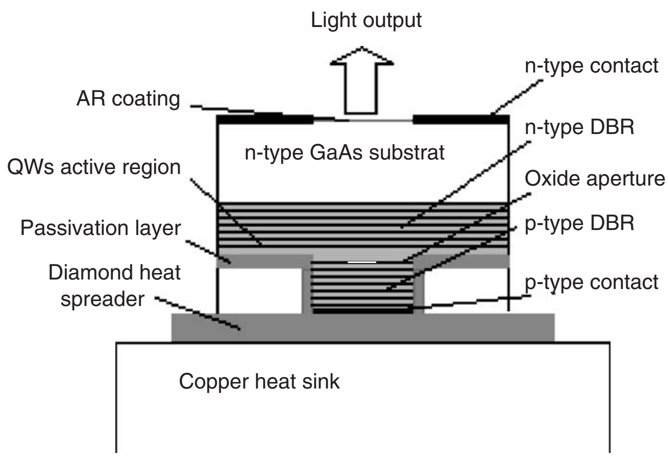

Fig. 1. A schematic diagram of the device structure.

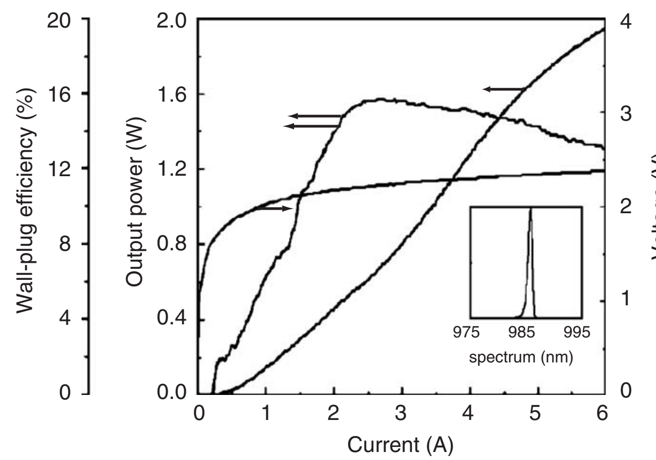

Fig. 2. Output power, wall-plug efficiency and voltage against driving current for a device with 500 μm active-area diameter. The inset is the lasing spectrum at a current of 6 A.

embedded in $GaAs_{0.92}P_{0.08}$ barriers for lasing at 980 nm. Two $Al_{0.3}Ga_{0.7}As$ cladding layers are introduced on both sides of the active region to improve longitudinal carrier confinement and to make the inner region one wavelength thick. The bottom Bragg reflector consists of 30 n-type Si-doped $Al_{0.9}Ga_{0.1}As$/GaAs quarter-wavelength layer pairs. The 25 pairs $Al_{0.9}Ga_{0.1}As$/GaAs p-type C-doped top Bragg reflector has an optimized doping profile to reduce the electrical series resistance. Current confinement is achieved by means of selective lateral oxidation of an extra AlAs layer about 30 nm thick placed directly above the top cladding layer. Oxidation is done in a water vapor atmosphere using nitrogen as the carrier gas at 420 °C, and the lateral oxidation rate is 0.5 μm/min. After oxidation, an Al_2O_3 passivation layer instead of the conventional SiN_x film is deposited on the mesa to avoid short circuits during soldering the device on heat sink. The thermal conductivity of Al_2O_3 is $36\,W\,m^{-1}\,K^{-1}$, which is much larger than that of SiN_x ($23.4\,W\,m^{-1}\,K^{-1}$). So in the same condition, more heat can be dissipated by using Al_2O_3 film. The p-type TiPtAu contact on the top of the mesa is evaporated and served as a metal pad for soldering. Before depositing an antireflection (AR) coating of HfO_2 film, the substrate is thinned and polished down to 150 μm in order to reduce absorption losses. Self-aligned lithography is used to define the n-type AuGeNi/Au substrate contact surrounding the emission aperture. Single devices are cleaved and then soldered p-side down with In-solder on metallized diamond heat sinks, providing thermal conductivities of larger than $1100\,W\,m^{-1}\,K^{-1}$ for effective heat spreading. Then the chip with diamond spreader is attached with indium paste on a copper submount.

3. Experimental results

The device is mounted on a micro-channel cooler, which increases the heat dissipation from the device so that the temperature difference between the copper submount and the active region is minimized. Fig. 2 shows the dependence of the CW light output and the voltage on injection current for a 500 μm-diameter device. A maximum CW output power of 1.95 W is achieved at room temperature, which is limited by the current source. The threshold current and threshold voltage are 0.88 A and 1.9 V, respectively. The maximum slop efficiency ($\Delta P/\Delta I$) is 0.4 W/A, and the differential resistance (R_d) is 0.05 Ω. The maximum wall-plug efficiency is 16% at the injection current of 2.3 A. However, as the injection current is further increased, the wall-plug efficiency decreases due to the internal heating in the active area. The inset shows the lasing spectrum measured at a current of 6 A. The peak wavelength is 985.7 nm and the FWHM of the spectrum is 0.7 nm.

Because of relatively low conversion efficiency and large series resistance, a large amount of the injection current is converted into heat in CW operation. The thermal resistance is suitably used to describe the heating of the VCSELs, which is defined as

$$R_{th} = \frac{\Delta T}{\Delta P_{diss}}, \quad (1)$$

where ΔT is the temperature increase in the device, and ΔP_{diss} is the dissipated electrical power:

$$\Delta P_{diss} = (ui - P_{out}), \quad (2)$$

where P_{out} is the optical output power, u and i are the voltage and the current applied to the device, respectively. The thermal resistance is determined experimentally by $R_{th} = C_1/C_2$ from two measurements, namely the wavelength shift with dissipated power $C_1 = \Delta\lambda/\Delta P_{diss}$, and the shift with varying heat-sink temperature $C_2 = \Delta\lambda/\Delta T_{hs}$, usually at pulsed operation. For a short optical resonator, as that in the VCSELs, the emission wavelength λ is determined by the cavity resonance, instead of the gain peak as that in the conventional F–P type edge-emitting lasers (EEls) [8]. The wavelength shift is mainly governed by changes of average refractive index in the resonator and to a lesser extent by the thermal expansion of the

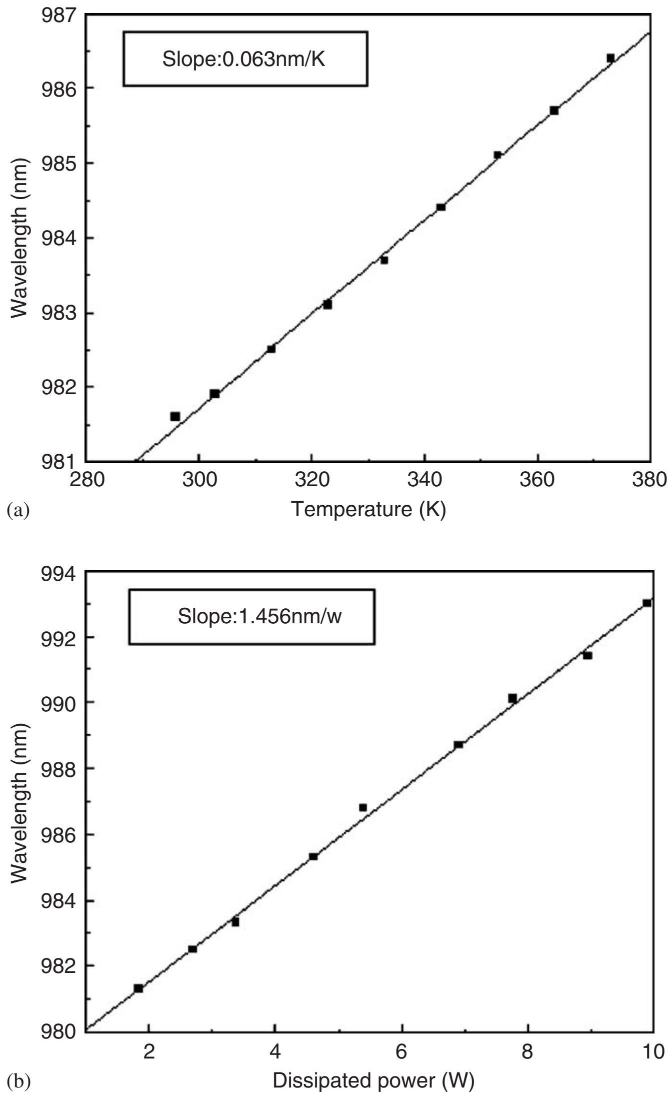

Fig. 3. Thermal resistance measurement of VCSELs: (a) wavelength versus temperature and (b) wavelength versus dissipated power.

semiconductor layers. Consequently, the wavelength shift of the mode depends on the material composition of the Bragg reflectors and the inner cavity. For our devices, the wavelength of the fundamental mode is measured as a function of heat sink temperature at a constant current of 2 A (Fig. 3(a)), the result of $\Delta\lambda/\Delta T_{hs}$ is 0.063 nm/K. The ratio of the wavelength shift to the dissipated power, $\Delta\lambda/\Delta P_{diss}$, is 1.456 nm/W (Fig. 3(b)). Finally, the experimental result of thermal resistance is 23.1 K/W. This result is in accordance with the result calculated with the analytic formula for the thermal resistance of a semi-infinite disk substrate $R_{th} = 1/(2\sigma_{th}D)$, where D is the active diameter of device [9]. The average material thermal conductivity σ_{th} is found to be 43.2 W m^{-1} K^{-1}, which is close to the value of 45 W m^{-1} K^{-1} for bulk GaAs.

4. Conclusion

In summary, the fabrication and performance characteristics of the large aperture high-power VCSELs have been reported. Al_2O_3 film is used as passivation layer instead of the conventional SiN_x film. The performance of device is significantly improved. A CW output power up to 1.95 W is demonstrated. The threshold current and threshold voltage are 0.88 A and 1.9 V, respectively. The maximum wall-plug efficiency is 16%, and the differential resistance (R_d) is only 0.05 Ω. At the injection current of 6 A, the lasing peak wavelength is 985.7 nm, and the FWHM of the spectrum is 0.7 nm. The thermal resistance of the VCSELs is analyzed in detail, the experimental result of the 500 μm aperture device is 23.1 K/W.

Acknowledgments

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