Fabrication of high-power VCSEL with radial bridge electrodes

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We report the fabrication of a novel high-power vertical-cavity surface-emitting laser (VCSEL) with radial bridge electrodes in this letter. The analysis shows that the radial bridge electrodes can reduce the p-type distributed Bragg reflector (p-DBR) electric and thermal resistance, and improve the device beam quality. The high-power radial brigde electrode VCSELs with 200-μm aperture have been made and tested. The testing results show that the differential resistance of the VCSEL is 0.43 Ω and the maximal continuous-wave (CW) output power is 340 mW, 1.7 times higher than the conventional electrode device. Its thermal resistance is 0.095 °C/mW, and its near-field pattern exhibits a homogeneous distribution. The high-power radial bridge electrode VCSEL has better temperature and opto-electric characteristics.

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Vertical-cavity surface-emitting lasers (VCSELs) have many advantages over conventional edge-emitting lasers, such as lower divergence, circular beam, single longitudinal mode operation, and a high packing density for two-dimensional arrays[1], and so on. So VCSEL devices have many potential applications in optical communications, optical interconnects, and optical integration. In recent years, along with the applications of high-power semiconductor lasers in medicine, material treatment, free space communication, and laser pumping, the fabrication of high-power VCSELs has got much attention and development[2]. But the output power of high-power VCSEL single devices and arrays is much lower than high-power edge-emitting lasers at present because of distributed Bragg reflector (DBR) structure in VCSEL resonance cavity. The DBR induces the increase of Joule's heat and thermal resistance[3], and so the thermal characteristics of surface-emitting laser are much worse than those of edge-emitting lasers. A great amount of heat occurring in VCSEL would increase the threshold current and reduce the output power of the device. Thermal problem has become a key difficult issue in the fabrication of high-power VCSELs.

In this letter, the novel high-power radial bridge electrode (RBE) VCSEL has been fabricated to solve the thermal problem. The device structure, just as traditional high-power VCSEL, is emitting from the n-side; while the heat sink is on the p-side[4]. And the RBEs instead of conventional circular electrodes are used on the p-side of the device. The analysis on the model of high-power RBE VCSEL shows that the RBEs can reduce the electric and thermal resistances and the Joule's heat of VCSEL, enhance the ability of heat dissipation, so the thermal characteristic of the device will be improved, and the output power will be increased. On the other hand, using the RBEs can increase the device beam quality, effectively avoiding near-field inhomogeneous distribution for spatial hole-burning effect in large-aperture VCSEL. The high-power RBE VCSELs with 200-μm aperture have been made and tested in experiments. The testing results show that the high-power RBE VCSELs have better temperature and opto-electric characteristics, and the device beam quality is very well.

In order to solve the thermal problem of high-power VCSEL, reduce the self-heating in the device, and improve the device heat dissipation, we design the high-power RBE VCSEL, where the conventional circular injection electrode of p-side in bottom emitting high-power VCSEL[5] is turned into a RBE. The center part of the RBE is still circular, and has the same area as the conventional circular electrodes. At the same time, RBE can avoid the near-field inhomogeneous distribution, as usual in the conventional electrode, when the injected current is increased. It is in favor of obtaining high output power. Sketches of high-power VCSEL electrodes are shown in Fig. 1.

The current of high-power conventional electrode VCSEL is injected through the circular electrodes, and the ring trench between the circular electrodes and ring leading electrodes acts as oxidation window. But the current of high-power RBE VCSEL is injected directly through

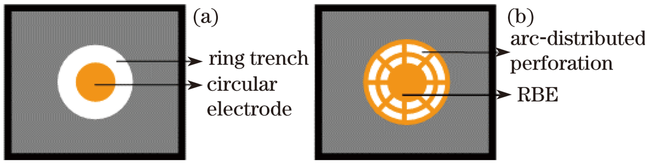

Fig. 1. Sketches of high-power VCSEL electrodes. (a) Conventional electrode; (b) RBE.

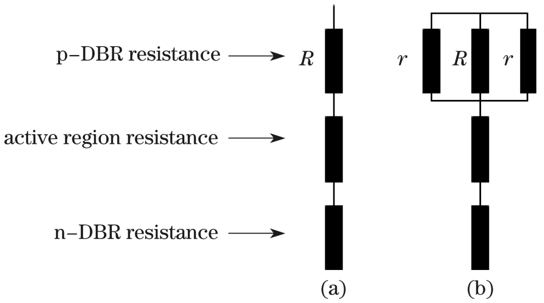

Fig. 2. Sketches of high-power VCSELs and their equivalent resistances. (a) Conventional electrode VCSEL; (b) RBE VCSEL.

the electrode, and the arc-distributed perforations among the radial bridge circuit act as oxidation window.

The central circular electrode is joined with the two ring electrode for the radial bridge shape electric channels, and the etch depth of all arc-distributed perforations can reach the active region when a device is made, so three electrical branches are founded between the injection electrode and the active region. The resistance R between the conventional circular electrode and the active region is connected in parallel with the resistance r between two ring electrodes and the active region, so that the whole resistance of the p-type DBR (p-DBR) can be reduced. Sketches of equivalent resistance of high-power VCSELs are shown in Fig. 2. The whole resistance of VCSEL is made up of p-DBR resistance, active region resistance, and the n-type DBR (n-DBR) resistance, and so the whole resistance of VCSEL can be reduced with the RBE structure and the Joule's heat in device will be reduced.

The heat source center of high-power RBE VCSEL lies in the active region, and the heat transmits through p-DBR to the heat sink. We assume that the temperature of the active region is T, the temperature of the heat sink is T_0, and other heat dissipation modes are ignored, and then we can obtain from the heat conduction theory that

$$T - T_0 = R_\mathrm{t} Q, \tag{1}$$

where R_t is the thermal resistance, and Q is the heat flux. Comparing Eq. (1) with the Ohm law formula, we find that the temperature difference $T - T_0$ equates the voltage difference, and the heat flux equals electric current I, so the thermal resistance R_t equals the resistance R. The p-DBR thermal resistance is made of three branches of thermal resistance connected in parallel, so the whole thermal resistance can be reduced, and the device ability of thermal conduction can be increased.

The center part of RBE is still a circular electrode, and current can be injected into the active region so that all the photons in the light aperture emit, and thus the electrode can avoid near-field inhomogeneous distribution for spatial hole-burning effect and improve the beam quality of the device.

The epitaxial wafer of the high-power RBE VCSEL is grown on a (100) GaAs substrate by using low pressure metal-organic chemical vapor deposition (MOCVD). The active layer contains three 6-nm-thick $\mathrm{Ga_{0.7}In_{0.3}As}$ quantum wells embedded in 8-nm-thick $\mathrm{GaAs_{0.92}P_{0.08}}$ barriers. The carbon-doped p-DBR consists of 31.5 $\mathrm{Al_{0.12}Ga_{0.88}As/Al_{0.9}Ga_{0.1}As}$ pairs with graded interfaces to reduce the series resistance. The silicon-doped n-DBR has only 23 $\mathrm{Al_{0.12}Ga_{0.88}As/Al_{0.9}Ga_{0.1}As}$ pairs for light bottom emission through the GaAs substrate. The center wavelength of DBR reflection spectrum is 980 nm. There is a 30-nm-thick $\mathrm{Al_{0.98}Ga_{0.02}}$ As layer located between the active region and the p-DBR. This layer is oxidized and converted to $\mathrm{Al}_x\mathrm{O}_y$ later in the fabrication process for current and optic confinement.

The main processes of the RBE VCSEL are as follows. Firstly, the photolithographic and wet chemical etching were used to form the oxidation window as shown in Fig. 1. The etching reached the $\mathrm{Al_{0.98}Ga_{0.02}As}$ oxidation layer, and the active layer should not be etched. Secondly, the exposed $\mathrm{Al_{0.98}Ga_{0.02}As}$ layer was oxidized at 420 °C with nitrogen carrier gas bubbled through water at 95 °C[6]. After oxidation, a thin $\mathrm{SiO_2}$ passivation layer was coated on the wafer, and an electrode window formed by secondary photolithography was opened for evaporating Ti-Pt-Au to form p-type electrode. The GaAs substrate was mechanically thinned and chemically polished down to about 150 μm. In order to increase the output power of the device, an antireflection (AR) coating of $\mathrm{ZrO_2}$ with a quarter-wavelength thickness was deposited. An n-type Ge-Au-Ni-Au electrode was evaporated surrounding the emission windows. Finally, the p-side of the cleaved chip was soldered onto a small copper heat sink with indium solder to form high-power RBE VCSEL single device.

The devices were tested under continuous-wave (CW) operation. The room-temperature light power-current-voltage (P-I-V) characteristic of high-power RBE VCSEL is shown in Fig. 3. The device with 200-μm aperture has a threshold current of 390 mA, the maximal output power is up to 340 mW at I = 2.45 A limited by thermal rollover, the output power is 1.7 times higher than the conventional electrode device fabricated with the same epitaxial wafer and the same aperture. The

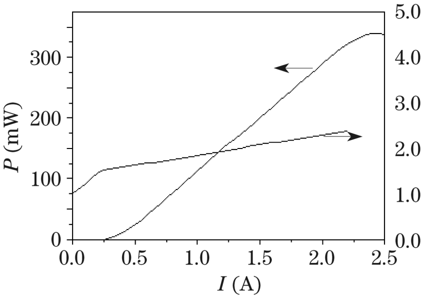

Fig. 3. P-I-V characteristics of high-power RBE VCSEL.

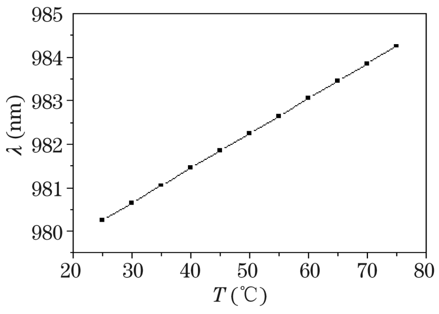

Fig. 4. Wavelength versus temperature for the RBE VCSEL.

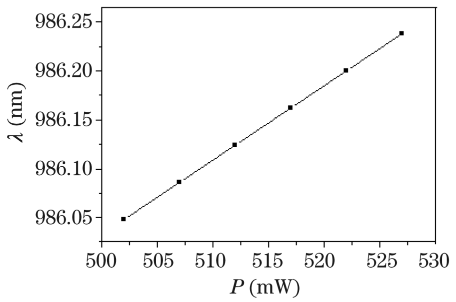

Fig. 5. Wavelength λ versus injection electrical power P of RBE VCSEL.

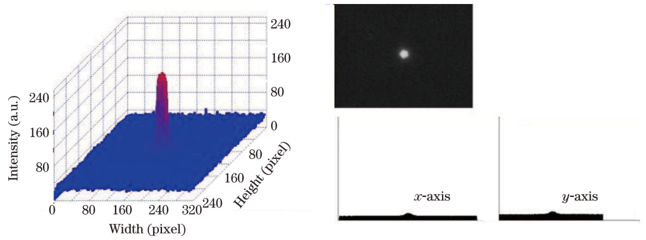

Fig. 6. Near-field pattern of high-power RBE VCSEL.

operating voltage at threshold is 1.68 V and the differential resistance reaches 0.43 Ω, the whole resistance of the device is low, so the Joule's heat decreases, and the opto-electric characteristics of high-power RBE VCSEL are well.

The wavelength change of the device with temperature was measured at $I = 1.8$ A, and the curve of wavelength versus temperature of high-power RBE VCSEL is shown in Fig. 4. The wavelength shifts to red with the increase in heat sink temperature due to the self-heating in the device. The red shift rate $\frac{\Delta\lambda}{\Delta T}$ is 0.08 nm/°C from Fig. 4.

We can obtain the curve of wavelength versus injection electrical power of high-power RBE VCSEL from the driving current and voltage-current (V-I) curve of device. The wavelength change depending on the injection power is shown in Fig. 5. Under a fixed temperature, the lasing wavelength increases by increasing the injection power owing to the self-heating. The injection power is calculated by subtracting the laser output power from the electric injection power $I \times V$, where I is the injection current and V is the applied voltage. From Fig. 5 we can see that red shift rate of the wavelength with the injection power $\frac{\Delta\lambda}{\Delta P}$ is 0.0076 nm/mW.

The thermal resistance R_t of the VCSEL is also given as

$$R_\mathrm{t} = \frac{\Delta T}{\Delta P}, \tag{2}$$

where ΔT and ΔP are the temperature change and the change in injection power, respectively[7]. Equation (2) can be turned into

$$R_\mathrm{t} = \frac{\Delta\lambda}{\Delta P}\frac{\Delta T}{\Delta\lambda}. \tag{3}$$

Substituting $\frac{\Delta\lambda}{\Delta T}$ and $\frac{\Delta\lambda}{\Delta P}$ into Eq. (3), we can obtain that the thermal resistance of high-power RBE VCSEL is 0.095 °C/mW. The thermal resistance is smaller, so the heat dissipation of the device is better. It agrees with the theory.

The near-field pattern of the device is shown in Fig. 6. The near-field distribution is more homogeneous from the two-dimensional (2D) near-field image. The device beam from three-dimensional (3D) image shows Gaussian distribution and the beam quality is very well.

In conclusion, the novel high-power RBE VCSEL has been fabricated and tested. The testing results show that using the RBE in the high-power VCSEL can reduce the electric and thermal resistance and the Joule's heat. It can also enhance the heat dissipation of the device. On the other hand, this kind of electrode can improve the beam quality and the characteristics such as the output power, the thermal characteristic, and the temperature characteristic. The RBE structure will be a new way to fabricate high-power VCSELs with high performance.

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