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Vertical-cavity surface-emitting lasers with periodic gain structure

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Abstract

The periodic gain structure is used as the active region of vertical-cavity surface-emitting lasers, which can enhance the effective coupling between gain regions and internal optical field. The high device performance is achieved. The maximum continuous-wave output power of large aperture device with active diameter up to 400 μm is as high as 1.41 W at room temperature. The low threshold current is only 0.5 A, which is lower than that of the conventional device with three quantum wells.

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Keywords: Periodic gain structure; VCSELs; High power; Low threshold

1. Introduction

In the past few years, vertical-cavity surface-emitting lasers (VCSELs) have been intensively studied because of their attractive features such as low divergence angles compatible with optical fibers, on-wafer testing, inherent single longitudinal mode operation, and high-density two-dimension arrays. Now the applications of high-power VCSELs in the regime of watts, such as laser pumping, medicine and material treatments are revealing a growing market [1–5]. However, threshold current and light output power have some conflicting dependence on each other. One of the significant dependence is that the enhancement of the reflectivity of the distributed Bragg reflector (DBR) reduces the threshold current, but also causes a reduction of light output power.

In 1988, Kaja et al. first reported a novel periodic gain structure, which overcame the

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above-mentioned deficiency satisfactorily [6]. Using the periodic gain structure as the active region of surface-emitting laser has the advantage of effective coupling between gain region and internal optical field, which contributes to the reduction of threshold current density without deteriorating the output power characteristics. Now, the periodic gain structure in optical-pumped VCSELs has achieved satisfying performance, the threshold of device can be reduced over 50%, the maximum operating temperature increased 20 °C [7], and the maximum output power is as high as 0.5 W for single transverse-mode VCSELs [8]. In long-wavelength (1.5 μm) electrical pumped VCSELs [9,10] have been already carried out. In this paper, we use the periodic gain structure as the active region of 980 nm wavelength electrical pumped VCSELs. A distinguished device performance has been also achieved.

2. Active region with periodic gain structure

The wafer has been grown by metal-organic chemical vapor deposition (MOCVD) on n-type GaAs substrates. The active region is a 2λ thick cavity, which contains 9 strain-compensated InGaAs/GaAsP quantum wells (QWs). These QWs are divided into three groups separated by lattice-matched spacers. The each group is composed of three 10-nm-thick $GaAs_{0.92}P_{0.08}$ barriers and 8-nm-thick $In_{0.2}Ga_{0.8}As$ wells with an emission wavelength of 980 nm. The spacing layers are made of lattice-matched AlGaAs as shown in Fig. 1.

In this geometry, the periodic QW gain medium is aligned at the antinodes of the electric field of the standing-wave pattern. When the QW period is matched to the emission wavelength, there is no possibility of longitudinal spatial hole burning because the gain medium coincides with the peaks of optical field. The special overlap integral between an optical field and the gain elements is enhanced in the vertical direction at a specific wavelength determined by the period of the gain medium, hence the gain in this structure is both anisotropic and wavelength selective which should favor single longitudinal mode operation. The

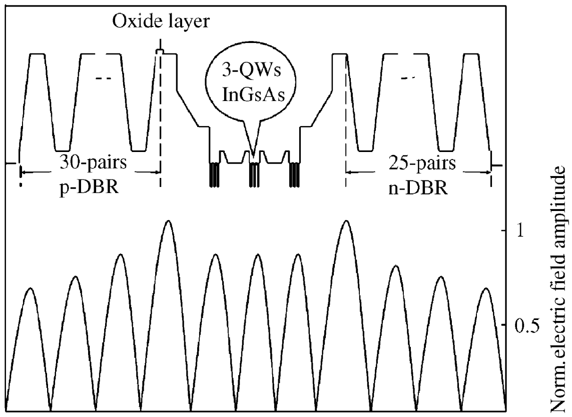

Fig. 1. Material composition and electric-field-squared standing wave profiles of the epitaxial wafer.

usual spatial average over a squared sinusoidal function to determine the effective gain along the resonator axis does not apply to this structure. At threshold, the material gain can be simply written as

$$g_{\rm th} = \frac{1}{\Gamma}\left(\alpha_{\rm i} + \frac{1}{L}\ln\left(\frac{1}{R}\right)\right), \qquad (1)$$

where R is the mirror reflectivity, L the cavity length, Γ the total confinement factor, and $\alpha_{\rm i}$ the internal loss. Compared to the $\Gamma(\approx 1)$ of the conventional three-QWs structure, the value in this periodic gain structure, $\Gamma \approx 2$, increases almost by a factor of two [11].

Furthermore, the external efficiency $\eta_{\rm d,}$ is defined by

$$P_0 = \eta_{\rm d}\frac{hv}{q}(I - I_{\rm th}), \qquad (2)$$

in which P_0 is the power out, hv the photon energy, q the electron charge, I the bias current, and $I_{\rm th}$ the threshold current. For the lasers with this structure, it can be shown that

$$\eta_{\rm d} = N_{\rm A}\eta_{\rm i}\frac{\alpha_{\rm m}}{\alpha_{\rm i} + \alpha_{\rm m}}, \qquad (3)$$

where $N_{\rm A}$ is the number of active groups, $\eta_{\rm i}$ the injection efficiency, and $\alpha_{\rm m}$ the mirror loss. This linear scaling of the differential efficiency with the number of active groups is valid when all groups are under the same mode. The familiar threshold current equation can be modified, i.e.

$$I_{\rm th} = I_{\rm tr} \exp\left(\frac{\alpha_{\rm i} + \alpha_{\rm m}}{\Gamma g_{\rm th}}\right). \quad (4)$$

Due to the transverse roll off of the mode, the confinement factors for the outer active region groups are smaller than that of the center group, the total confinement factor dose not scale with $1/N_{\rm A}$ [12]. Moreover, the gain does not linearly change as current increases. Thus, the threshold current is also reduced with multiple active regions, but does not scale with $1/N_{\rm A}$.

3. Device structure and fabrication

A schematic cross-section of VCSELs structure is displayed in Fig. 2. The high reflective p-DBR is built of 30 pairs of quarter-wavelength thick $Al_{0.9}Ga_{0.1}As/GaAs$ with a graded interface providing a reflectivity of 99.9%. To reduce the series resistance of the thick multi-layer stack, carbon as p-type dopant is employed using extra modulated doping near interfaces to decrease the voltage drop without increasing absorption losses. The silicon-doped n-DBR consists of only 25 pairs of the same material composition providing a reflectivity of 99.6%. Current confinement is achieved by the means of selective lateral oxidation of an about 30 nm thick extra AlAs layer placed directly above the top cladding layer. Oxidation is done in a water vapor atmosphere using nitrogen as the carrier gas at 420 °C. An Al_2O_3 passivation layer is deposited on the mesa to avoid short circuits when soldering the device on heat sink. 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 junction-down with AuSn-solder on a metallized diamond heat spreader. Then the chip with diamond spreader is attached with indium paste on a copper submount.

4. Optical properties

The devices are mounted on a micro-channel cooler, which increases the heat dissipation from the devices so that the temperature difference between the copper submount and the active region is minimized. Fig. 3 shows the dependence of continuous-wave (CW) light output, applied voltage and wall-plug efficiency on injection current for a 400-µm-diameter device. A maximum output power of 1.41 W is achieved at room temperature, which is limited by the current source. The threshold current and threshold

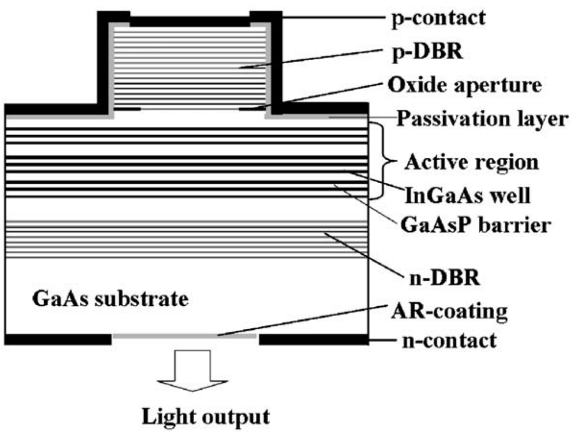

Fig. 2. A schematic diagram of the device structure.

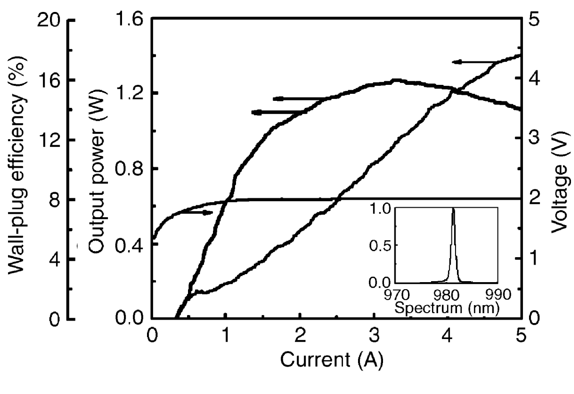

Fig. 3. Output power, wall-plug efficiency and voltage against driving current for a device of 400 µm active diameter. The inset is the lasing spectrum at a current of 6 A.

Table 1
The characteristics of three-QWs and periodic gain QWs structure VCSELs

	Output power (W)	Threshold current (A)	Wall-plug efficiency (%)	Peak wavelength (nm)	FWHM (nm)
Three-QWs	1.08	0.61	14.3	987	0.9
Periodic gain QWs	1.41	0.5	16	981.3	0.7

voltage are 0.5 A and 1.8 V, respectively. The maximum slop efficiency ($\Delta P/\Delta I$) is 0.44 W/A, and the differential resistance (R_d) is 0.05 Ω. The maximum wall-plug efficiency is 16% at the injection current of 3.3 A, but the injection current is further increased, the wall-plug efficiency decreased due to the internal heating in the active area. The inset shows the lasing spectrum measured at a current of 5 A. The peak wavelength is 981.3 nm and the full-width at half-maximum (FWHM) of the spectrum is 0.7 nm.

High-power VCSELs with conventional three-QWs structure has been reported in our previous paper [13]. The characteristics of the VCSELs with three-QWs and periodic gain structure are compared in Table 1. The diameters of the devices are 400 μm. The output power of the device with periodic gain structure active region has been increased nearly a half compared to the conventional three-QWs device, the decrease is 0.11 A of the threshold current than that of three-QWs structure, the wall-plug efficiency is also improved to be 1.7% higher, and the peak wavelength shows a smaller blue shift which shows less heat occurred in active region. These results agree with the theoretic predictions discussed earlier, so these improvements can be attributed to the application of the periodic gain structure in our device.

5. Conclusion

The high-power and low-threshold bottom emitting VCSELs are achieved by using periodic gain structure as the active region. The device with 400 μm aperture size operates at room temperature with CW condition. The threshold current is only 0.5 A, and the maximum output power is up to 1.41 W with a wall-plug efficiency of 16%. The lasing peak wavelength is 981.3 nm, and the FWHM is 0.7 nm. These results suggest that the performance of VCSELs has been improved by using the periodic gain structure.

Acknowledgments

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