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High Performance 9xx nm High Power Semiconductor Laser

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Abstract: To improve the performance of 9xx nm high power semiconductor lasers, the doping profile of n-cladding layer and p-cladding layer is adjusted to reduce the internal loss. A high energy band gap GaAsP was introduced between the active region and the waveguide layer to reduce the leakage of carriers in the active region. A broad area laser with internal loss of 1.25 cm^{-1} is designed and fabricated. The device with maximum output power of 26.5 W is obtained. The maximum electrical-optical power conversion efficiency is 72.4%, which is obtained when the output power is 10.5 W. The slope efficiency is 1.16 W/A.

Key words: laser diode; internal loss; free carrier absorption
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高性能9xx nm大功率半导体激光器

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摘要: 为了改善9xx nm高功率半导体激光器的性能,对n包层和p包层的掺杂分布进行了调整,以减小激光器的内部损耗。同时为了减小有源区载流子的泄漏,在有源区和波导层之间引入了高能量带隙GaAsP。设计并制作了内部损耗为1.25 cm^{-1}的高功率激光器。器件可靠性工作的最大输出功率为26.5 W。当输出功率为10.5 W时,最大电光功率转换效率为72.4%,斜率效率为1.16 W/A。

关 键 词: 激光二极管; 内部损耗; 自由载流子吸收

1 Introduction

Recently, with the development of material growth technology and chip fabrication process, the performance of semiconductor lasers has been greatly improved. High power diode lasers at near 9xx nm emission have been widely used for solid-state laser pumping, laser marking, materials processing and medical applications[1-4]. These applications require high output power and high electrical-to-optical power conversion efficiency of the laser diodes. Increase of output power from a single laser diode directly leads to decrease of the number of devices in the system and the component cost. Improved efficiency

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enables to reduce the cooling cost as well as the junction temperature of devices, which relates to the device reliability[5].

A big deal of works have been done to improve the output power and electrical-to-optical power conversion efficiency of semiconductor lasers. In 2017, Kaifuchi *et al*. tuned the vertical layer design and stripe width of single emitter broad stripe 9xx nm laser diodes. As a result, newly designed laser diodes with 4 mm long cavity and 220 μm wide stripe demonstrate maximum continuous work (CW) output power as high as 33 W and power conversion efficiency more than 60% at 27 W output power[6]. The main factor affecting the output power and power conversion efficiency of a semiconductor laser is the internal loss. The internal loss comes mainly from waveguide scattering loss[7-8] and free carrier absorption[9-11]. Adjusting the doping profile of the cladding layer can reduce internal losses[12-13]. But little attention is paid to the influence of adjusting the doping profile of the cladding layer on the performance of 9xx nm high power broad-area (BA) laser diodes.

In this work, the internal loss of 9xx nm high power semiconductor laser is reduced by adjusting the doping profile of n-cladding layer and p-cladding layer. The leakage of carrier in the active region is suppressed by introducing high energy band gap GaAsP layers between the active region and the waveguide layer. A broad area laser with an internal loss of 1.25 cm^{-1} is obtained. The laser diode has a maximum output power of 26.5 W, and the maximum electrical-optical power conversion efficiency is 72.4%. A slop efficiency of 1.16 W/A is obtained.

2 Epitaxy Design and Device Fabrication

In our work, we reduce the internal loss by optimizing doping levels in the cladding layers. Meanwhile, the GaAsP layers with high band gap between linearly graded waveguide layer and active layer provide effective carrier capture into the quantum well, and suppress the carrier leakage. The carrier leakage from an active layer increases with increasing injection current, and results in the thermal rollover of output power at high injection current. The epitaxial structure studied in this paper is schematically shown in Fig. 1. A graded-index separate-confinement single quantum well (GRIN-SCH-SQW) was grown on a (100) n^+ GaAs substrate using metal-organic chemical vapor deposition (MOCVD). Starting from the n^+ (100) GaAs substrate, the epitaxial structure was as follows: 0.42 μm n-gradual AlGaAs buffer; 1.85 μm n-$Al_{0.37}Ga_{0.63}As$ cladding layer; 0.7 μm n-gradual $Al_{0.255}Ga_{0.745}As$ cladding layers; 0.35 μm undoped $Al_xGa_{1-x}As$ linearly graded waveguide layer ($0.255 > x > 0.154$); 1.7 nm GaAsP with high band gap; 8 nm undoped AlGaInAs QW; 1.7 nm GaAsP with high band gap; 0.35 μm undoped $Al_xGa_{1-x}As$ linearly graded waveguide layer ($0.154 < x < 0.255$); 120 nm p-gradual $Al_{0.255}Ga_{0.745}As$ cladding layers; 1.21 μm p-$Al_{0.37}Ga_{0.63}As$ cladding layer; 250 nm p-GaAs Ohmic contact layer. The photoluminescence (PL) was performed to characterize the energy shift of the emission from the active region, using a diode-pumped solid-state frequency doubled green laser at 532 nm for excitation and a cooled InGaAs photo-detector and a monochromator with a slit width of 0.5 μm. The emission wavelength of active region is 955.2 nm. After photolithography, dielectric film growth and other related processes, p-electrodes were formed by sputtering Ti/Pt/Au. The backside Ohmic contact is made by AuGeNi/Au metallization after backside polishing. Laser bars of various cavity lengths ranging from 1 500 μm to 4 500 μm are cleaved. Anti-reflective (AR) and high-reflective

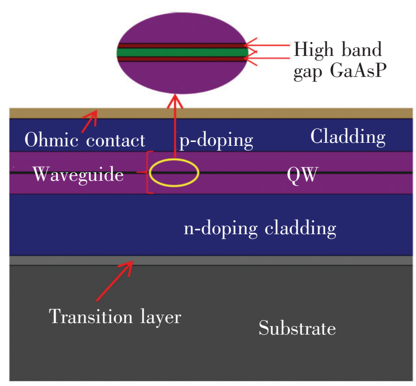

Fig. 1　Schematic of epitaxial structure

(HR) coatings were deposited on the front and rear facets (2.75% and 97.5%, respectively). The devices with 4 mm cavity length and 200 μm strip width were cleavaged from the bar and soldered p-side (epi-side) down on AlN submounts with a AuSn solder.

3 Results and Discussion

In laser diodes, the differential quantum efficiency(η_d), also known as the slope efficiency, is often used to describe the efficiency characteristics of the device. The external differential quantum efficiency of a laser diode (η_d) is given by

$$\eta_d^{-1} = \eta_i^{-1} + L\eta_i^{-1}\alpha_i/\ln(1/R), \qquad (1)$$

where R is the reflectivity of cavity surface without coating, η_i is the internal quantum efficiency, α_i is the internal propagation loss, and L is the length of the laser cavity.

It can be seen from Eq. (1) that the value of internal loss α_i can be derived from the relationship between cavity length and external external differential quantum efficiency. In order to obtain the internal loss α_i and internal quantum efficiency η_i of the device, pulse power current test is performed for BA lasers with various cavity lengths ranging from 1 500 μm to 4 500 μm before coating. The pulse width of 50 μs and repeat frequency 100 Hz are selected to avoid current induced heating of the laser waveguide and active region. Fig. 2 shows the plots of measured inverse differential quantum well efficiency ($1/\eta_d$) as a function of cavity length. In 2015[14], Tan Shao-yang *et al.* studied 1 060 nm InGaAs/AlGaAs high power semiconductor laser, the internal loss of the device with uniform doping profile is 6.6 cm^{-1}. In order to reduce internal loss, they adjust the doping profile of the p-cladding layer, so the internal loss is reduced to 4.3 cm^{-1}. In our work, the internal loss of the device with uniform doping profile and without high energy band gap GaAsP is 3.7 cm^{-1}, by adjusting the doping profile of the p-cladding layer and the n-cladding layer and introducing the high energy band gap GaAsP layers between the active region and the waveguide layer, the internal loss of the device is reduced to 1.25 cm^{-1}. This result is very amazing. There are two reasons for this result, first the high energy band gap GaAsP effectively prevents the carrier leakage in the active region, reduces the probability of non-radiation recombination; second, the p-cladding and n-cladding layer after adjusting the doping profile reduce the carrier absorption, so that the internal loss of the device is greatly reduced.

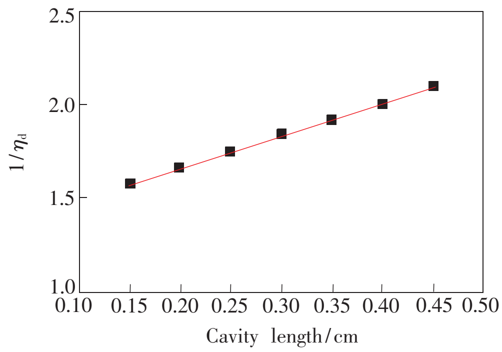

Fig. 2 Picture of inverse external differential quantum efficiency *versus* cavity length

In our experiments, in order to reduce the leakage of carriers in the active region of the device may caused by the adjustment of the p-cladding layer and the n-cladding layer doping profile, a high energy band gap GaAsP was introduced between the active region and the waveguide layer. At the same time, the high energy band gap GaAsP increases the thermal rollover threshold of the semiconductor laser, enabling the device to work reliability for a long time at high power output. The threshold current and threshold current density of the device vary with the cavity length as shown in Fig. 3. As can be seen from the figure, when the cavity length increases, the threshold current increases, while the threshold

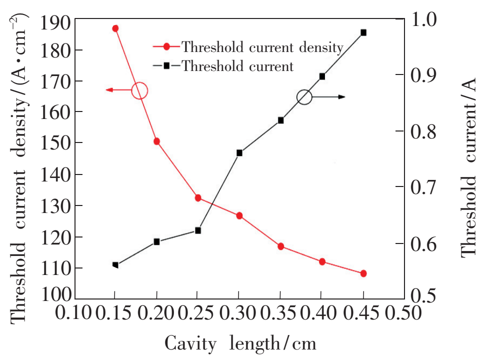

Fig. 3 Threshold current and threshold current density as a function of cavity length

current density of the device decreases. In our experiments, the minimum threshold current density of the device is 108.2 A/cm^2, which is obtained when the cavity length is 0.45 cm. Increasing the cavity length of the device, a smaller threshold current density can be obtained.

Fig. 4 shows the continuous wave (CW) power-current-voltage property high power semiconductor laser with 4 mm cavity length and 200 μm strip width at room temperature. The device is packaged on the AlN secondary heat sink. The threshold current is less than 1 A. The slope efficiency is 1.16 W/A. The maximum output power is more than 26.5 W, the electrical-optical power conversion efficiency is 58.4%. A slight thermal rollover can be observed when the output power is more than 25 W. The maximum electrical-optical power conversion efficiency is 72.4%, which is obtained when the output power is 10.5 W. If the device is mounted on a copper heat sink, a higher output power and electrical-optical power conversion efficiency can be expected.

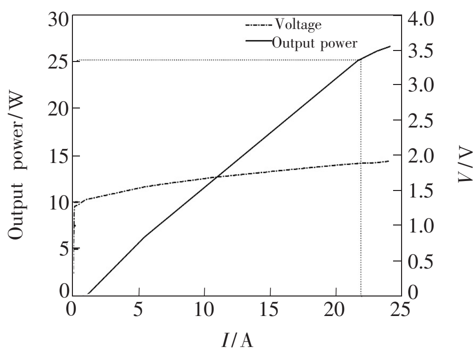

Fig. 4 CW power-current-voltage property of ridge waveguide laser at room temperature

The spectral distribution at output power of 10.5 W is shown in Fig. 5. It can be seen from the figure that the peak of the spectrum is 970.6 nm, and the full width at half maximum (FWHM) is 2.9 nm.

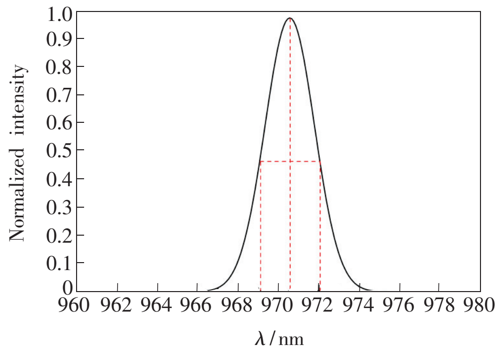

Fig. 5 Spectral distribution at output power of 10.5 W

4 Conclusion

The performance of 9xx nm high power laser diode with a graded-index separate-confinement single quantum well (GRIN-SCH-SQW) is improved in this paper. The internal loss is reduced to 1.25 cm^{-1} by adjusting the doping profile of n-cladding layer and p-cladding layer. In order to suppress carriers leakage in the active region, high energy band gap GaAsP is introduced between the active region and the waveguide layer. Only a slight thermal rollover is observed of the laser diodes packaged with AlN submounts at the output power of 25 W. The maximum electrical-optical power conversion efficiency is 72.4%, which is obtained when the output power is 10.5 W. The performance of the 9xx nm high power laser diode can be further improved by optimizing the epitaxial structure.

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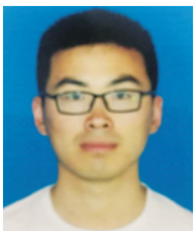

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