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76% Maximum Wall Plug Efficiency of 940 nm Laser Diode with Step Graded Index Structure

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Abstract In order to improve the output power and wall plug efficiency (WPE) of the broad area 940 nm semiconductor laser diode (LD), we design and fabricate a new type quantum well LD with a step graded index (GRIN) structure. By using a two-dimensional self-consistent software, the energy band structures of step GRIN structure laser and traditional separate confinement heterojunction (SCH) laser are simulated and compared. The result shows the significant elimination of band offset between heterojunctions in step GRIN structure. High quality laser materials are obtained by using low-pressure metal organic chemical vapor deposition (LP-MOCVD) method. Broad area laser devices with 100 μm wide stripe and 2000 μm long cavity are fabricated and tested under 25 ℃ continuous wave (CW) operation condition. The new step GRIN structure laser diode shows a drop down voltage of 0.07 V at 10 A operation current than the SCH structure laser. By optimizing the design and growth method, the internal loss of step GRIN structure laser is reduced from 0.52 cm^{-1} to 0.43 cm^{-1} and the wall plug efficiency is increased from 69% to 76%. The LD chip yields a slope efficiency of 1.24 W/A and 10.0 W at 10 A operation current at 25 ℃ room temperature.

Key words lasers; laser diode; step graded index structure; high power; high wall plug efficiency
OCIS codes 140.2020; 140.3070; 140.5960; 160.3380

76%光电转换效率梯度渐变折射率结构 940 nm 半导体激光器

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摘要 为改善宽面 940 nm 半导体激光二极管(LD)的输出功率及光电转换效率(WPE)，设计并制作了一种包含梯度渐变折射率(GRIN)结构的新型量子阱激光器。通过二维自洽软件模拟计算了新结构激光器与传统分别限制结构(SCH)激光器的能带结构，结果表明新的激光器结构能够显著消除各异质结间的过渡势垒。通过低压金属有机物化学气相沉积(LP-MOCVD)的方法生长了高质量激光器外延材料。制成后的 100 μm 条宽、2000 μm 腔长的激光器器件在室温 25 ℃下经过连续(CW)电流测试发现，梯度渐变折射率结构激光器较分别限制结构激光器在 10 A 电流下电压约低 0.07 V。通过结构与生长优化，激光器内吸收系数从 0.52 cm^{-1}降至 0.43 cm^{-1}，最大光电转换效率由 69%提升至 76%。最终制成的 940 nm 半导体激光器器件室温 25 ℃下输出功率 10.0 W(10 A 电流时)，斜率效率高达 1.24 W/A。

关键词 激光器；激光二极管；梯度渐变折射率结构；高功率；高光电转换效率
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1 Introduction

Semiconductor laser diodes (LDs) are widely used in many fields. For lasers emitting at 940 nm, they were mainly used in the biomedical research, surgical treatment, material processing and infrared night-vision of security[1-3]. In recent years, many important improvements of high power lasers around 940 nm have been achieved and the laser can meet the requirement of high power output and high efficiency in which a super-large optical cavity, Al-free material and asymmetric structure are used[4-7]. In this paper, the analysis and approach for improving the power conversion efficiency are introduced. By optimizing the interfaces of the heterojunction in laser diode, the operation voltage and the internal loss are successfully lowered. The laser diode chips are packaged on C-mounts and yield a maximum wall plug efficiency of 76% and a maximum output power of 10.0 W at 10 A operation current.

2 Design and diode laser structure

One of the most important advantages of laser diode is the high conversion efficiency of the electric to optic power, i.e., the wall plug efficiency (WPE), η_{plug}. It can be expressed as[8]

$$\eta_{plug}=\frac{P_{optic}}{I_{op}V_{op}}=\frac{\eta_d(I_{op}-I_{th})}{I_{op}V_{op}}\cdot\frac{h\nu}{e}, \qquad (1)$$

where P_{optic} is the output light power at operation current I_{op} and operation voltage V_{op}, η_d is the external differential quantum efficiency, I_{th} is the threshold current, e is the electron charge, and $h\nu$ is the photon energy at the emitting wavelength. From the equation above, one can find that there are two ways to improve the wall plug efficiency, i.e., lowering the operation voltage V_{op} or raising the output power P_{optic}.

Based on the analysis above, two different structures of broad area laser diodes (BALDs) were designed, as shown in Fig.1. Figure 1(a) is the traditional separate confinement heterostructure (SCH) laser with sharp interfaces of heterojunction. Figure 1(b) is different from Fig.1(a) at two aspects: 1) a step graded index (GRIN) structure contains a 100 nm $Al_{0.05}Ga_{0.95}As$ to $Al_{0.25}Ga_{0.75}$ graded layer, a 100 nm $Al_{0.25}Ga_{0.75}$ layer and a 100 nm $Al_{0.25}Ga_{0.75}As$ to $Al_{0.35}Ga_{0.65}$ graded layer from top 150 nm GaAs to 1.1 μm $Al_{0.35}Ga_{0.65}As$ layer, and there is the same structure from bottom 200 nm GaAs to 1.1 μm $Al_{0.35}Ga_{0.65}As$ layer; 2) a 50 nm $Al_{0.15}Ga_{0.85}As$ to $Al_{0.35}Ga_{0.65}$ graded layer from 450 nm $Al_{0.15}Ga_{0.85}As$ to 1.1 μm $Al_{0.35}Ga_{0.65}As$ layer. The simulation and experiments were carried out simultaneously.

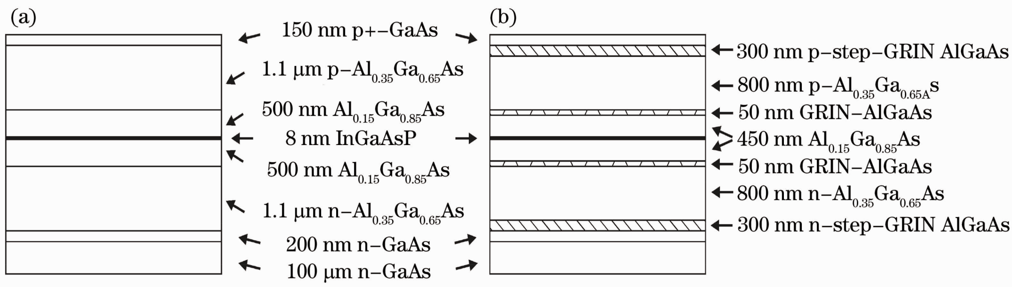

Fig.1 Schematic diagram of broad area laser diode structure. (a) SCH structure; (b) step GRIN structure

The two kinds of laser structures have been evaluated using self-consistent numerical simulation. Figure 2 shows the energy band diagrams of laser structures from the simulation. This figure exhibits the clear view of band offset at each heterojunction because of the discontinuous composition at the interface. By using step GRIN structure, the band offsets at heterojunction are totally eliminated, as shown in Fig. 2 (b). Furthermore, the step GRIN structure at between the large band gap material $Al_{0.35}Ga_{0.65}As$ and small band gap

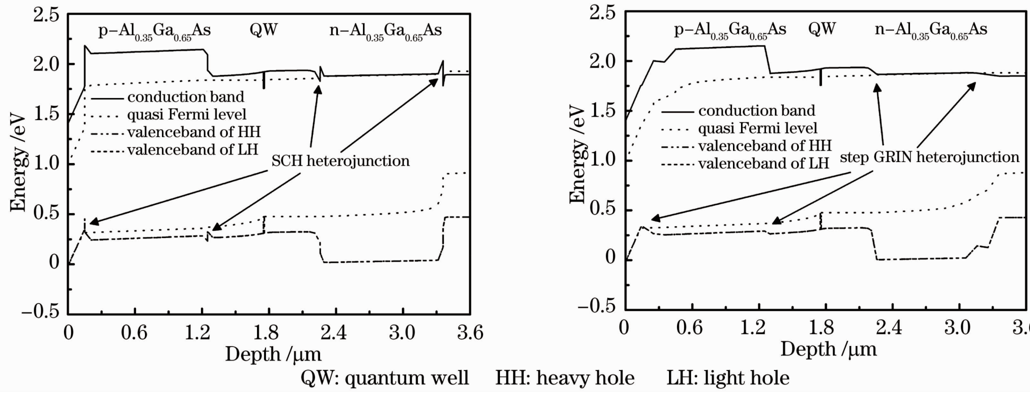

Fig.2 Schematic diagram of semiconductor laser diode band. (a) SCH structure; (b) step GRIN structure

material GaAs will enhance carrier injection on both sides which are influenced by large energy differences of those two materials. This is in principle similar to earlier research in which using GaInP at between AlInP and GaAs can lower operation voltage for red laser diode[9].

3 Epitaxial growth

Epitaxial growth was carried out on Si-doped (100) GaAs substrate with 2° misorientation towards the 〈111〉 direction by low-pressure metal organic chemical vapor deposition (MOCVD) method. Trimethylgallium (TMGa), trimethylindium (TMIn), and trimethylaluminium (TMAl) were used as group III source. AsH_3 and PH_3 were used as group V sources. Diethyelzinc (DEZn) and disilane (Si_2H_6) were used as p-type and n-type dopants, respectively. The growth pressure was 1×10^4 Pa and the growth temperature was 730 ℃.

After epitaxial growth, the two wafers were processed and fabricated into BALDs with 100 μm aperture.

4 Experimental results

In Fig. 3, operation voltages from experiment for two kinds of laser structures are compared. The result shows a clear difference of 0.07 V at 10 A operation current between two structures.

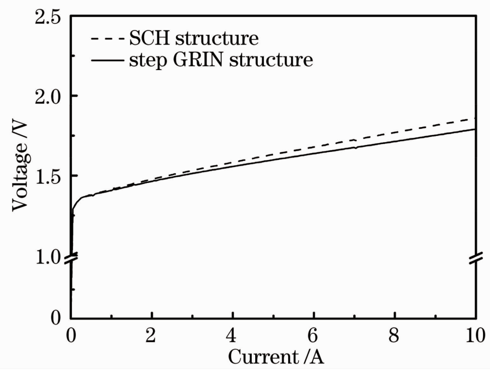

Fig. 3 Comparison of voltage-current profiles from experiment

The internal loss α_i of laser is calculated by using the cavity length and the differential quantum efficiency as

$$\frac{1}{\eta_d}=\frac{1}{\eta_i}\left[1+\alpha_i\Big/\left(\frac{1}{2L}\ln\frac{1}{R_1R_2}\right)\right], \qquad (2)$$

where η_i is the internal quantum efficiency, L is the cavity length, R_1 and R_2 are the reflectivities of the front and rear facets, respectively. The power-current characteristics of uncoated devices from two structures with vary cavity lengths L are measured under pulse condition in Fig. 4. The internal losses α_i of SCH and step GRIN structures are 0.52 cm^{-1} and 0.43 cm^{-1}, and the internal quantum efficiencies are 89.3% and 90.9%, respectively. We believe that the differences are mainly caused by the realistic growth qualities of heterojunction interfaces. For the SCH structure growth, the switch of the source gases may introduce turbulence and increase the roughness of the interfaces.

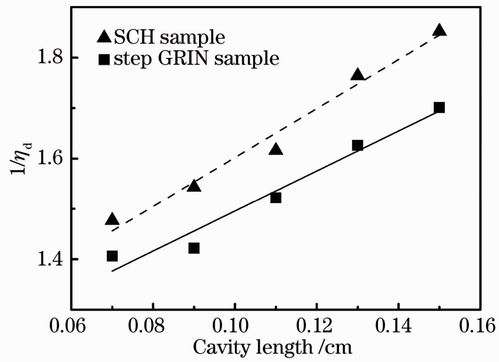

Fig. 4 Reciprocal external quantum efficiency as a function of cavity length

In the last stage, the power-current and efficiency-current characteristics of 2 mm long lasers with 100 μm aperture are measured under continuous wave (CW) condition at 25 ℃ heat sink temperature. The results are shown in Fig. 5. Compared with the traditional laser with SCH structure possessing 9.0 W (at 10 A operation current) and 69% WPE at maximum, the lasers with step GRIN structure show a better performance of 10.0 W and 76% WPE at maximum. The threshold current and slope efficiency of lasers with step GRIN structure are 209 mA and 1.24 W/A, respectively. The laser diode with the best WPE results of 76% in our research is much higher than that of 62% reported by Schmidt *et al*.[10], which means that the device has converted over 10% of wasted heat into optical power by optimizing the structure. However, at the highest WPE point of 3 A, there is still 24% of input energy changed into heat. And this thermal generation accelerates as the injection current increases, which is caused by series resistance in chips and other thermal resistance during packaging. On the contrary, the output power is limited and starts thermal rollover at higher injection current over 8 A. This phenomenon is mainly caused by the saturated gain which shows a nonlinear effect as the carrier concentration

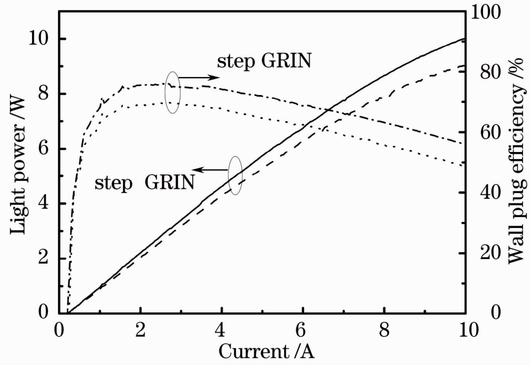

Fig. 5 CW output power and wall plug efficiency at room temperature of BALDs

increases and the higher carrier leakage which is influenced by the rising junction temperature. Finally, all these factors lead to a dropdown of WPE into 56% of the step GRIN sample at 10 A in our experiment.

5 Conclusion

In conclusion, the interfaces of heterojunction have great influence on high power BALDs performance. By applying step GRIN structure, the operation voltage and internal loss are decreased. With the optimized structure, the LDs are fabricated and tested under pulse and CW condition at 25 ℃ heat sink temperature. The experiment demonstrates 10.0 W CW optical power at an injection current of 10 A. Meanwhile, a threshold current of 209 mA, a high slope efficiency of 1.24 W/A and a maximum wall plug efficiency of 76% are obtained from the 100 μm aperture and 2000 μm long cavity device.

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