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High power, 1060-nm diode laser with an asymmetric hetero-waveguide

T. Li, E. Hao, Y. Zhang

Abstract. **By introducing an asymmetric hetero-waveguide into the epitaxial structure of a diode laser, a 6.21-W output is achieved at a wavelength of 1060 nm. A different design in p- and n-confinement, based on optimisation of energy bands, is used to reduce voltage loss and meet the requirement of high power and high wall-plug efficiency. A 1060-nm diode laser with a single quantum well and asymmetric hetero-structure waveguide is fabricated and analysed. Measurement results show that the asymmetric hetero-structure waveguide can be efficiently used for reducing voltage loss and improving the confinement of injection carriers and wall-plug efficiency.**

Keywords: *high power, diode laser, hetero-waveguide.*

1. Introduction

High-power lasers emitting at 1060 nm find widespread applications in such fields as medicine, defenses, direct frequency-doubling, etc. [1 – 3]. Nowadays, the two main factors to limit the power of diode lasers are catastrophic optical damage (COD) and low electrical-to-optical conversion (wall-plug) efficiency [4 – 5]. Big efforts are underway to solve these problems. An asymmetric broad waveguide [6, 7] made of a homogeneous material is considered to be an ideal choice. Although this kind of epitaxial structure ensures the necessary optical confinement [8 – 10], it also makes the offset of the conduction bands and valence bands to be relatively fixed, which limits optimisation of epitaxial layers. To find out the solution to this problem, we designed and manufactured a 1060-nm diode laser with a heterogeneous waveguide which could decrease the voltage loss arising during the carrier transport.

2. Epitaxial design

The schematic of the epitaxial structure is shown in Fig. 1. The InGaAsP material system is used as waveguide and cladding layers on the n-side, while the AlGaAs material system is used on the p-side. Both of them constitute a hetero-waveguide, which provides restriction for the transportations of electrons and holes. The whole epitaxial structure is as follows: A 2-μm-thick n-GaAs buffer layer is grown on the n-GaAs substrate (the Si concentration is 2×10^{18} cm^{-3}). A 1-μm-thick $In_{0.32}Ga_{0.68}As_{0.4}P_{0.6}$ layer with the n-doped concentration of 1×10^{18} cm^{-3} is used as a lower cladding layer, and an undoped lower waveguide layer is 0.7-μm-thick $In_{0.03}Ga_{0.97}As_{0.95}P_{0.05}$. A 9-nm undoped $In_{0.2}Ga_{0.8}As$ single quantum layer is chosen as an active region. An upper waveguide layer is $Al_{0.2}Ga_{0.8}As$, whose thickness is 0.48 μm; a 0.8-μm-thick upper cladding $Al_{0.45}Ga_{0.55}As$ layer is zinc-doped with the concentration of 2×10^{18} cm^{-3} which is followed by a 0.25-μm-thick GaAs ohmic contact layer.

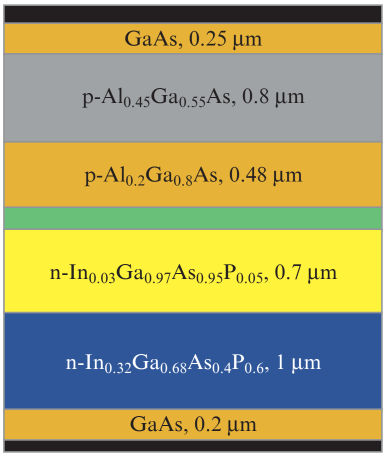

Figure 1. Schematic of the epitaxial structure with hetero-waveguide configuration.

According to the theoretical analysis, one of the most important reasons that result in the electric power loss of laser diodes is voltage consumption which includes the voltage drop of the external circuit and excess voltage drop existing in the material. Figure 2 shows the valence and conduction bands numerically calculated by using the commercial software Lastip. It is evident that the electron energy loss between the n-cladding layer and the waveguide layer decreases because the InGaAsP system has a relative smaller conduction band step compared to that of the AlGaAs system. At the same time, the optimised valence band jump helps to form a barrier for holes, which will reduce the loss of injection holes.

3. Growth and fabrication

The epitaxial structure with a hetero-waveguide layer reported here was grown by MOCVD. $(CH_3)_3In$, $(CH_3)_3Ga$ and $(CH_3)_3Al$

T. Li, Y. Zhang National Key Lab. On High Power Diode Laser, Changchun University of Science and Technology, Changchun, 130033, China; e-mail: ltcust@gmail.com;
E. Hao College of Physics, Jilin University, Changchun, 130021, China

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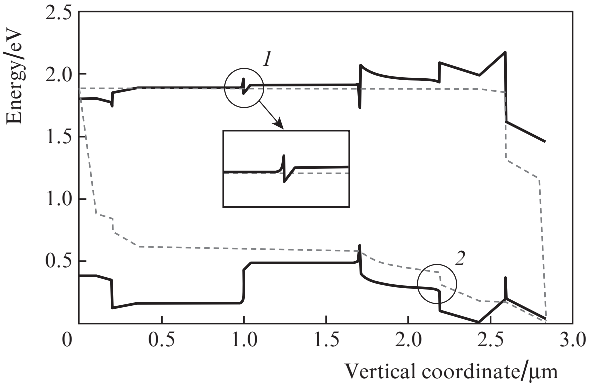

Figure 2. Calculated energy bands of the epitaxial structure at a working voltage of 1.2 V; circles show the voltage losses in (*1*) conduction bands and (*2*) valence bands.

were used as group III sources, while AsH_3 and PH_3 were used as group V sources. DEZn and SiH_4 were used as p- and n-dopants, respectively. The temperature of the MOCVD chamber was carefully controlled since the ideal growth temperatures for InGaAsP and AlGaAs material systems are different. Then, the wafers were fabricated for large-aperture diode laser with a 97-μm stripe width and various cavity lengths by traditional III–V processes. After coating on both ends of laser bars, the bars were cleaved into chips which were mounted on CuW heat sinks with p-side down.

4. Result and discussion

Figure 3 shows the output power versus current characteristics measured in cw mode at room temperature for a typical device with a 2.5-mm-long cavity. The maximum power of 6.12 W is reached at an injection current of 6 A. The slope efficiency is as high as 1.20 W A^{-1}. The threshold voltage is about 1.2 V, only 30 meV larger than quasi-Fermi level separation. The increment of voltage is only 0.18 V when the working current rises from 1 A to 6 A. This indicates that the voltage loss in this epitaxial structure has been controlled appropriately. The maximum wall-plug efficiency is 62.1% and its tendency of a decrease is rather flattened in the whole current range due to high efficiency of electron and hole injection.

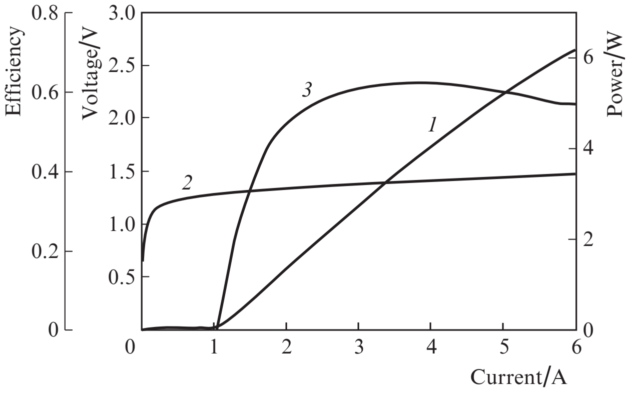

Figure 3. Dependences of (*1*) power, (*2*) voltage and (*3*) electro-optical efficiency of a typical diode laser with a 2.5-mm-long cavity and hetero-waveguide configuration on current.

To estimate the temperature efficiency, threshold currents were measured at different working temperatures (Fig. 4). It is obvious that the threshold currents increase almost linearly with increasing temperature. By fitting the experiments data and calculation results based on empirical equation, we found a characteristic temperature equal to 138.7 K. This indicates that the confinement of carriers in the epitaxial structure is sufficient for the device to operate at a relative high temperature.

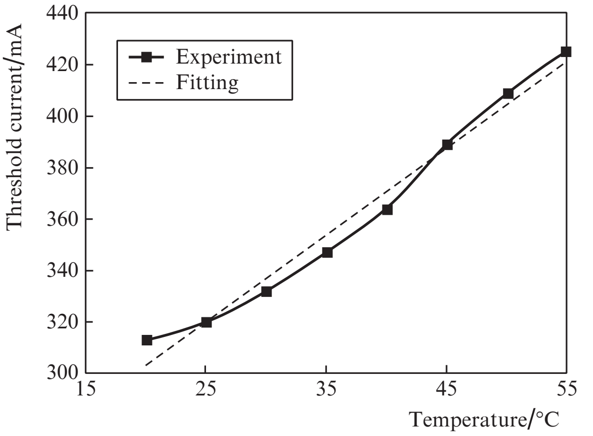

Figure 4. Dependence of the threshold laser current on the working temperature.

In addition, we have investigated the lifetime of the device. To this end, we used an accelerated aging model [11] according to the threshold current variation. In this model, the change in the threshold current is a function of operating time

$$(I_{\text{th}} - I_{\text{th0}})/I_{\text{th0}} = At^n \exp(-E_a/kT), \tag{1}$$

where I_{th0} is the initial threshold current, I_{th} is the threshold current after the lifetime test, A is a constant, n is the time exponent, E_a is the activation energy (here it is 0.43 eV) [12], k is the Boltzmann constant, and T is the absolute temperature.

To simplify equation (1), we intentionally define

$$D = (I_{\text{th}} - I_{\text{th0}})/I_{\text{th0}}, \tag{2}$$

$$D_0 = A \exp(-E_a/kT). \tag{3}$$

Then by applying a logarithmic function in both sides of equation (1), we obtain

$$\lg D = \lg D_0 + n \lg t. \tag{4}$$

In order to statistically estimate the lifetime, the device was kept operating at an injection current of 1.5 A and a heat sink temperature of 40 °C. Then, the dependence of the variation in the current on the operating time was measured. The double-log scale of Fig. 5 shows the relationship between D and t. The solid line represents the experiment data, while the dashed line is the linear-fit result whose fitting equation is also shown

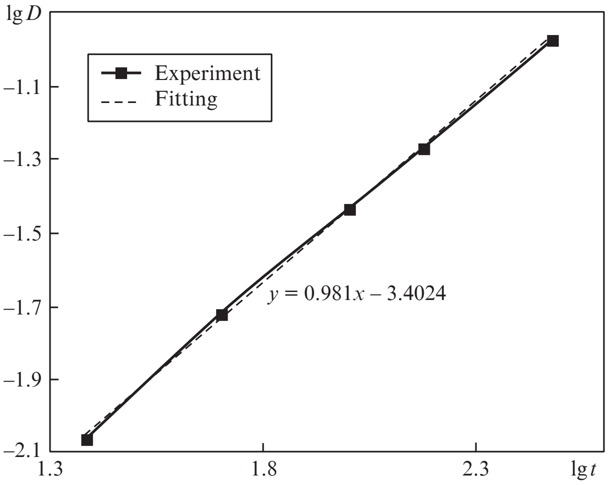

Figure 5. Dependence of the threshold current on the lifetime in the double-log scale.

in the figure. The values of D_0 and n can be extracted from the slope of the linear part of the fitting line. Afterwards, assuming that the device failure criterion is a two-fold increase in the threshold current as compared with I_{th0}, we finally figure out that the lifetime t of the device is about 3000 hours.

5. Conclusions

To improve the efficiency and output power of a 1060-nm diode laser, we have designed an epitaxial structure with hetero-waveguide configuration, which has made it possible to decrease the energy loss in the transportation of carriers. Some devices have been fabricated in order to identify the merit of this kind of structure. The maximum output power and slope efficiency were 6.12 W and 1.2 W A^{-1}, respectively. A characteristic temperature of 138.7 K was achieved, which indicates the capability of confining the carriers of the epitaxial structure. The characteristics of electronics indicate that the voltage loss was decreased compared with that in a conventional diode laser with a homogeneous material system waveguide. The accelerated aging test indicates that the lifetime of the device is about 3000 hours.

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