# 810-nm InGaAlAs/AlGaAs double quantum well semiconductor lasers with asymmetric waveguide structures

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The 810-nm InGaAlAs/AlGaAs double quantum well (QW) semiconductor lasers with asymmetric waveguide structures, grown by molecular beam epitaxy, show high quantum efficiency and high-power conversion efficiency at continuous-wave (CW) power output. The threshold current density and slope efficiency of the device are 180 A/cm$^2$ and 1.3 W/A, respectively. The internal loss and the internal quantum efficiency are 1.7 cm$^{-1}$ and 93%, respectively. The 70% maximum power conversion efficiency is achieved with narrow far-field patterns.

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During the last few years, advances in semiconductor technology have made possible the fabrication of high efficiency quantum well (QW) semiconductor laser. A series of research results have been obtained and some of these have been used for optimal design and the improved output performance and catastrophic optical damage of high-power lasers. Improvements of the laser structures yielded significant results. InGaAs/AlGaAs laser diodes with power conversion efficiency of 63% were reported[1]. Al-free 970-nm emitting InGaAs(P)/InGaP/GaAs laser diodes with power conversion efficiency of 73% were proposed[2]. Using an asymmetric ultra-thick waveguide structures, 1.06-$\mu$m emitting AlGaAs/GaAs/InGaAs QW lasers with 16-W continuous-wave (CW) output optical power, the power conversion efficiency of 74% and low internal optical loss of 0.34 cm$^{-1}$ were presented[3]. High-power laser diodes operating at 808 nm are widely employed due to many applications in the fields of communication, data storage, pumping of solid state lasers, material processes, and medical treatment[4]. However, in the 808-nm wavelength region, the value of power conversion efficiency is still much lower[5].

The efficiencies can be improved mainly by the optimized laser structures to obtain high power, which is relevant to threshold current density, series resistance, internal loss, and external differential quantum efficiency. Internal loss was reduced mainly with decreasing free carrier absorption through lowering the distribution of the optical field in the doped regions. Carrier leakage is controlled through providing carriers with enough energy barriers near the active region[6]. In fact, a semiconductor laser with an asymmetric waveguide can improve the differential quantum efficiency, power output, and far-field profile[7−10]. Such a structure allows the optical loss in the waveguide to be minimized and the optical field penetration into the p-cladding layer to be decreased, thus the internal efficiency increases[8]. Using the asymmetric waveguide structures, the decrease of the cladding losses could be enough to lead the quantum efficiency to increase to 15% − 20%. Appropriately optimized asymmetric structures can offer an advantage in laser efficiency[10]. In this paper, we obtain high efficiency InGaAlAs/AlGaAs double QW semiconductor laser with narrower far-field patterns using an asymmetric waveguide structure.

The epitaxial layers were grown on an n$^+$ GaAs substrate (100) 4° off towards ⟨111⟩A by molecular beam epitaxy. For a double QW laser with an asymmetric waveguide structure, the energy band gap diagram is schematically shown in Fig. 1. The asymmetric waveguide can pull the peak optical intensity away from QW active layer, which will be beneficial for reducing the optical absorption of the injected free carriers in the QW layer. This is because that such a structure allows the optical loss in the waveguide to be minimized, decreasing the optical field penetration into the p-cladding layer, thus the optical mode distribution are shifted away from the center waveguide towards the n-cladding layer[8]. The structure is based on an 8-nm-thick $In_{0.16}Ga_{0.66}Al_{0.18}As$ double QW, with a 10-nm-thick $Al_{0.4}Ga_{0.6}As$ barrier, 400-nm $Al_{0.4}Ga_{0.6}As$ lower waveguide layer and 500-nm $Al_{0.45}Ga_{0.55}As$ upper waveguide layer, 1200-nm-thick Si-doped $Al_{0.55}Ga_{0.45}As$ lower cladding layers, and 1000-nm-thick Be-doped $Al_{0.55}Ga_{0.45}As$ upper cladding layer.

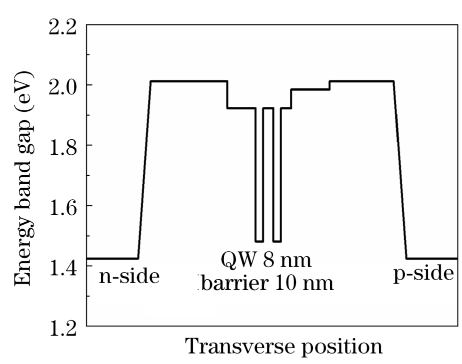


Fig. 1. Schematic diagram of energy band gap of double QW laser with asymmetric waveguide structure.

 

For the antireflection (AR, 0.05) coating a layer of $Al_2O_3$ and for the high reflecting (HR, 0.95) coating a layer stack mode of $Al_2O_3$ and $TiO_2$ were used.

Figure 2 shows the lasing characteristics of InGaAlAs/AlGaAs double QW semiconductor lasers with a cavity length of 1000 $\mu$m, tested at a cooling water temperature of 20 °C. The device has a low threshold current density of 180 A/cm$^2$ and the slope efficiency of 1.3 W/A. This curve also shows that the turn-on voltage of the device $V_0$ and the series resistance $R_s$ are 1.56 V and 0.07 Ω, respectively. The peak wavelength of emitted light at a driving current of 2.2 A is about 810 nm with a full-width at half-maximum (FWHM) of about 1.5 nm. The far-field patterns are shown in Fig. 3, the FWHMs in the vertical and parallel directions are 33.2° and 8.3°, respectively.

To determine the internal loss $\alpha_i$ and the internal quantum efficiency $\eta_i$, the reciprocal external differential quantum efficiency $1/\eta_d$ is plotted as a function of the cavity length. The external differential quantum efficiency as a function of cavity length can be expressed as [11]

$$\frac{1}{\eta_d} = \frac{1}{\eta_i}\left(1+\alpha_i\frac{1}{\frac{1}{2L}\ln\frac{1}{R_f R_r}}\right), \quad (1)$$

where $\alpha_i$, $L$ are internal loss and cavity length, respectively; $R_f$ and $R_r$ are reflectivities of the front and back facets, respectively.

Figure 4 shows the reciprocal external differential quantum efficiency versus cavity length. From the plot,

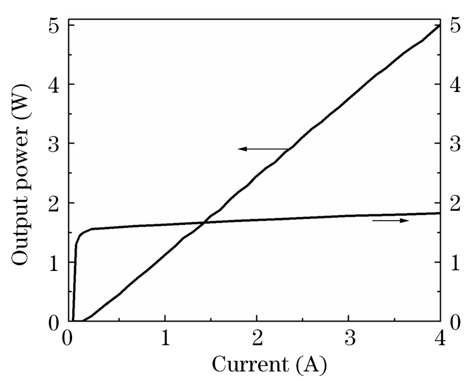


Fig. 2. Lasing characteristics of InGaAlAs/AlGaAs double QW semiconductor lasers.

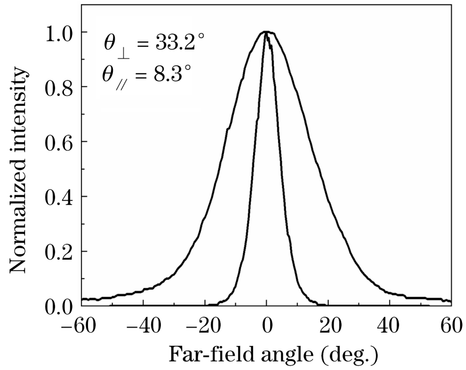


Fig. 3. Far-field patterns of lasers.

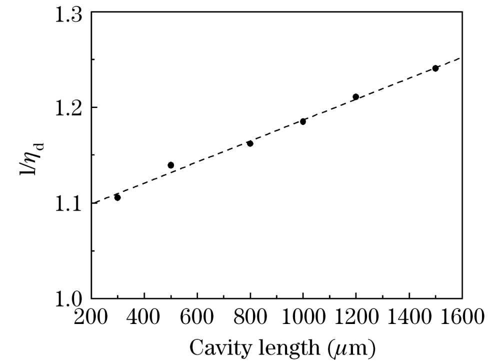


Fig. 4. Reciprocal external differential quantum efficiency ($1/\eta_d$) as a function of cavity length.

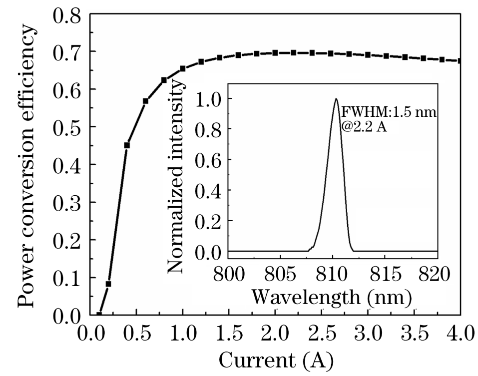


Fig. 5. Power conversion efficiency for a cavity length of 1000 $\mu$m, the inset shows the lasing spectra at a driving current of 2.2 A.

the internal quantum efficiency and the internal loss are calculated to be $\eta_i = 93\%$ and $\alpha_i = 1.7$ cm$^{-1}$, respectively. As shown in Fig. 5, the device has a maximum power conversion efficiency of 70% at a driving current of 2.2 A, and the device produces an output power of 2.7 W. The device holds the power conversion efficiency above 67% at 4.0-A driving current, and the output power increases to 5.0 W.

In conclusion, the InGaAlAs/AlGaAs double QW semiconductor lasers with an asymmetric structure have been successfully fabricated by molecular beam epitaxy. The threshold current density and slope efficiency of the device are 180 A/cm$^2$ and 1.3 W/A, respectively. Such devices not only exhibit the internal quantum efficiency of 93% with the internal loss of 1.7 cm$^{-1}$, but also reach the 70% maximum power conversion efficiency in 810-nm emitting laser diodes with narrow far-field patterns.

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