8 W continuous wave front-facet power from broad-waveguide Al-free 980 nm diode lasers

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Al-free 980 nm InGaAs/InGaAsP/InGaP laser structures grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) have been optimized for high cw output power by incorporating a broad waveguide design. Increasing the optical-confinement layer total thickness from 0.2 to 1.0 μm decreases the internal loss fivefold to 1.0–1.5 cm^{-1}, and doubles the transverse spot size to 0.6 μm (full width half-maximum). Consequently, 4-mm long, 100-μm-aperture devices emit up to 8.1 W front-facet cw power. cw power conversion efficiencies as high as 59% are obtained from 0.5-mm long devices. Catastrophic-optical-mirror-damage (COMD) power-density levels reach 15.0–15.5 MW/cm^2, and are found similar to those for InGaAs/AlGaAs facet-coated diode lasers. © *1996 American Institute of Physics.* [S0003-6951(96)01237-5]

Diode lasers with reliable operation in the 980 nm wavelength range are needed for applications such as pump sources for solid-state lasers or rare-earth-doped fiber amplifiers, and medical therapy. The growth of InGaAsP alloys lattice-matched to a GaAs substrate is very attractive as an aluminum-free alternative to the conventional AlGaAs-based materials. The aluminum-free InGaAs(P)/InGaP/GaAs material system has several advantages over the GaAs/AlGaAs material system for the realization of reliable, high-power diode laser sources: (1) the low reactivity of InGaP to oxygen facilitates regrowth for the fabrication of single-mode index-guided structures,[1,2] (2) higher electrical[3,4] and thermal conductivity[5] compared with AlGaAs, (3) potential for improved reliability,[6] and (4) potential for growth of reliable diode lasers on Si substrates.[7] Here, we report on the optimization of InGaAs/InGaAsP/InGaP strained-layer quantum well laser structures by using the broad-waveguide concept,[8,9] for maximizing the cw output power. As a result, record cw performances (8.1 W front-facet power, cavity length $L=4$ mm; and 59% wallplug efficiency, $L=0.5$ mm) are obtained from broad-area (100-μm wide stripe) devices. Catastrophic optical mirror damage (COMD) values from LR/HR facet-coated devices under cw operation (i.e., ~ 15 MW/cm^2) are found to be similar to those for InGaAs/AlGaAs facet-coated lasers, indicating that the quantum-well material (i.e., strained-layer InGaAs), and not the cladding/confinement layers material, primarily determines the COMD value.

The cw output power of a diode laser is generally limited by either thermal rollover or COMD. Thermally limited power saturation can be eliminated by designing laser structures to have high total power conversion efficiencies, low threshold-current density, and weak temperature sensitivity for both the threshold current and the external differential quantum efficiency (i.e., high T_0 and T_1 values).[4] As previously reported,[4] the use of a double-quantum-well (DQW) InGaAs active region together with high-band-gap InGaAsP ($E_g = 1.62$ eV) optical-confinement layers, leads to 0.98 μm diode lasers with relatively temperature insensitive characteristics. Given a certain COMD power-density value, high cw output powers can be attained by making devices of large transverse spot size. The subsequent decrease in the (transverse) optical confinement factor, Γ, can be offset by increasing the device cavity length, L, in structures of low internal loss, α_i (<2 cm^{-1}).[8,9] Thus, a large optical spot size can be obtained with little penalty in threshold-current density or efficiency.[9]

The Al-free DQW laser structure with a broad waveguide is shown in Fig. 1(a). The structures are grown by low-pressure (50 mbar) MOVPE in an Aixtron A-200 system on nominally exact (100) GaAs substrates.[4] Details of the growth conditions have been previously given.[4] The material is evaluated by fabrication and characterization of wide-stripe (100 μm) devices. The stripe contact is formed by chemically etching through the p^+ GaAs cap layer outside

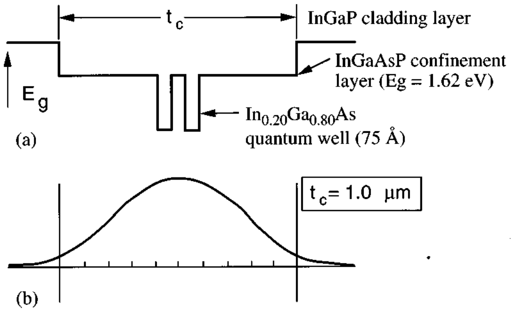

FIG. 1. (a) Schematic diagram of double-quantum well Al-free laser structure with broad-waveguide design; (b) field intensity profile for a waveguide width, t_c, of 1.0 μm.

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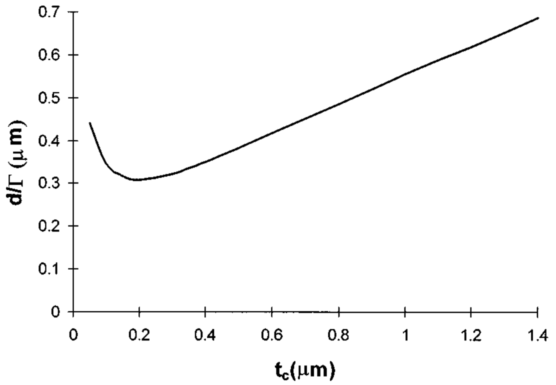

FIG. 2. Calculated equivalent transverse spot size, d/Γ; as a function of the waveguide width, t_c. Γ is the optical confinement factor and d is the quantum well width.

the 100-μm-wide stripe, and defining a metal contact opening using a SiO_2 mask. Devices of various cavity lengths are characterized under low-duty cycle (0.1%) pulsed-current operation to extract material parameters such as the threshold current density, J_{th}, the internal cavity loss, α_i, the internal efficiency, η_i, and the characteristic temperature coefficients[4] for threshold current, T_0, and external differential quantum efficiency, T_l. For cw measurements, devices are mounted junction-side down on either copper or diamond heatsinks operated with a thermoelectric cooler.

We have previously reported[4] on laser structures with 0.2-μm-thick InGaAsP optical cavity width. The calculated equivalent (transverse) spot size, d/Γ, is shown in Fig. 2 for InGaAs/InGaAsP/InGaP structures as a function of the optical cavity width, t_c, where Γ is the (transverse) optical confinement factor and d is the quantum well(s) width. A 0.2-μm-thick optical cavity minimizes d/Γ (see Fig. 2), resulting in the lowest threshold-current density. However, since the equivalent spot size, d/Γ, is minimized, the structure is not optimal for high cw output-power operation. The internal loss for these structures is relatively high (5–7 cm^{-1}), although similar to that reported by others.[10,11] Devices ($L = 1000$ μm, $w = 100$ μm) with uncoated facets mounted junction down on diamond heatsinks, operate cw to an optical power of 3.0 W (both facets), limited by COMD.

Improved performance has been achieved by employing a broad waveguide design with an InGaAsP waveguide region whose width, t_c, is varied from 0.6 to 1.0 μm (see Fig. 1). It should be pointed out that, as t_c increases, the first-order transverse mode will not lase, since it has a null in the active region, and thus very small Γ. We have confirmed from far-field measurements on devices with $t_c = 0.6$ μm that only the fundamental transverse mode lases. For $t_c = 1.0$ μm devices, one is slightly above the cutoff condition for the second-order transverse mode (i.e., $t_{c2} = 0.88$ μm). However, this mode has higher losses and lower Γ than the fundamental transverse mode, and thus is not likely to lase. Structures with confinement layer thickness, $t_c = 0.6$ μm, possess low internal losses, $\alpha_i = 2.5$ cm^{-1}, relatively low optical confinement factor, $\Gamma = 3.4\%$ (compared with 4.6% for the structure with 0.2-μm-wide confinement region), and large effective spot size, $d/\Gamma = 0.42$ μm, as shown in Fig. 2. This combination of low α_i and Γ, results in high differential quantum efficiencies and an increased output power at COMD. The low internal loss in this structure is the result of reduced optical overlap with the heavily doped confinement layers, and possibly from reduced field interaction with the p-side InGaAsP/InGaP interface.[12] However, further studies are required to determine quantitatively the contribution of that interface to the internal loss. HR/AR (3%/95%) coated devices ($L = 1$ mm, $W = 100$ μm) mounted junction down on diamond heatsinks operate to 6.0 W cw output power (Fig. 3) at 18 °C, with a maximum wallplug efficiency, η_p, of 51%. The maximum η_p value occurs at 1.7 W in good agreement with theory.[13] The series resistance is measured to be as low as 0.1 Ω, with the COMD power density at the front facet estimated to be 15 MW/cm^2. The COMD level is calculated for the internal power density at the facet, P_{int}

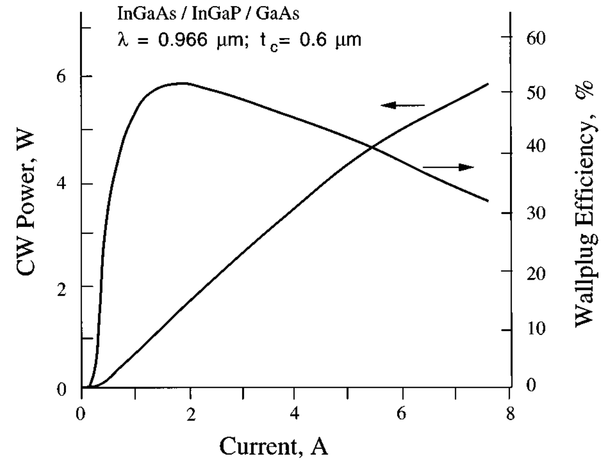

FIG. 3. cw light-current characteristics and wall plug efficiency for a laser structure with $t_c = 0.6$ μm; $L = 1$ mm; LR/HR: 3%/95%.

$$P_{int} = P_{out}[(1-R)/(1+R)], \tag{1}$$

where P_{out} is the density of the power emitted from the facet, and R is the facet (power) reflectivity. The COMD power density for the uncoated devices with 0.2-μm-wide confinement regions[4] is calculated to be 8.6 MW/cm^2. Interestingly, the COMD value (15 MW/cm^2) for the facet-coated devices is only a factor of ~ 2 larger than for the uncoated devices. By contrast, for GaAs/AlGaAs devices, facet-coated devices generally have COMD values a factor of 4–5 higher than for uncoated devices.[14] This is possibly a result of the lower surface recombination velocity[15] of the InGaAsP confinement layer versus AlGaAs confinement layers.

Increasing the optical confinement layer thickness, t_c, to 1.0 μm further decreases Γ to 2.4%, and increases the equivalent spot size, d/Γ, to 0.55 μm. As shown in Fig. 1(b), 94% of the mode energy resides in the undoped InGaAsP optical confinement region, resulting in a low $\alpha_i = 1.0$–1.5 cm^{-1}. Devices with 4 mm cavity lengths and (3%/95%) LR/HR coatings operate up to 8.1 W cw output power at 10 °C (Fig. 4). The external differential quantum efficiency reaches values as high as 72%, and the wallplug efficiency, η_p, is above 44% from 2 to 8.1 W, with a maximum of 47% in the 3.5–4.8 W range. The relative constancy of η_p is due to an extremely low series resistance, R_s, value: 0.05 Ω. The characteristic temperature for the threshold current, T_0, is

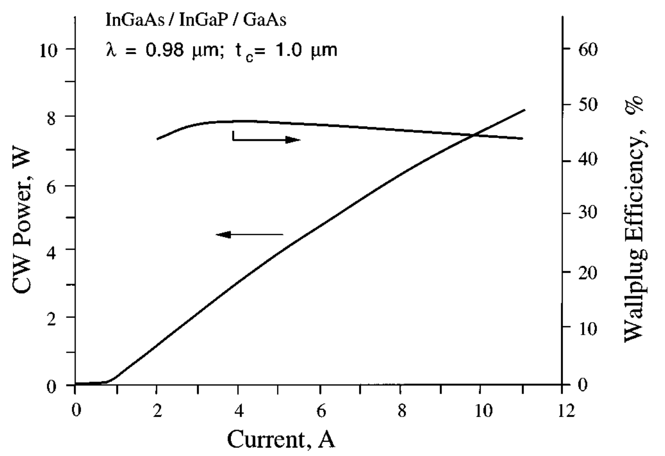

FIG. 4. cw light current and wall plug efficiency characteristics from a laser structure with $t_c = 1.0$ μm; $L = 4$ mm; LR/HR: 3%/95%.

measured to be 250 K. The spectra peak and full width at half-maximum vary from 972.8 to 978.2 nm, and from 1.2 to 3.1 nm, respectively as the drive is varied between 0.8 to 5.8 A. This indicates a junction temperature rise of only ~20 °C between threshold and the 5 W cw power level. Shorter cavity-length devices, LR/HR (20%/95%) coated, operate with wallplug efficiencies as high as 59% at 1.6 W cw output power. To the best of our knowledge the 59% wallplug efficiency is the highest value reported for any type of strained-layer InGaAs-active diode lasers. This high value is in part due to the fact that Al-free diodes have series resistance, R_s, values 2–3 times smaller than Al-containing diodes of similar geometry.[3,4]

The 8.1 W cw result represents the highest cw power reported from 100-μm-aperture diode lasers. It is 2.7 times higher than the best published data[16,17] for 0.96–0.98 μm lasers, and well surpasses the best results from 100-μm-aperture GaAs/AlGaAs devices *with* nonabsorbing mirrors.[18] The measured COMD values for the Al-free broad-waveguide-type lasers are found to be 15–15.5 MW/cm^2, and are shown in Fig. 5 together with those for InGaAs/AlGaAs 100-μm-wide-stripe devices[16,19] as a function of the equivalent spot size, d/Γ. Interestingly, the COMD values do not appear to depend on the type of cladding or confining layer materials. As a result, facet-coated Al-free lasers have COMD values similar to that of conventional InGaAs/AlGaAs-based lasers. Previously reported[9] broad-waveguide-type GaAs/AlGaAs lasers have lower values for COMD (11 MW/cm^2), possibly a result of InGaAs having a lower surface recombination velocity compared to GaAs. Applying nonabsorbing mirrors, such as ZnSe[17] on oxide-free facets should eliminate COMD and allow cw operation well above 10 W.

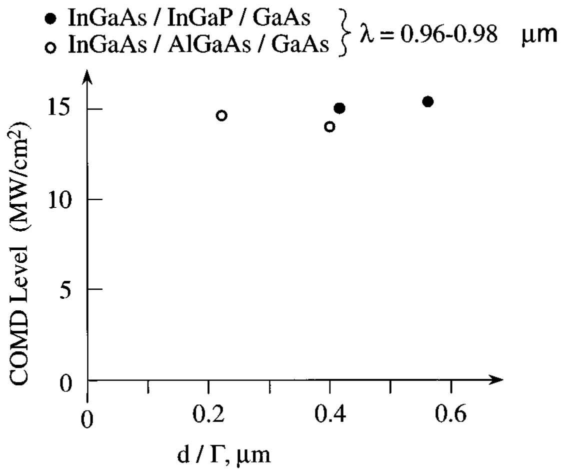

FIG. 5. COMD values for the Al-free lasers shown in Figs. 3 and 4, plotted as a function of equivalent transverse spot size, d/Γ. Also shown are COMD values for InGaAs/AlGaAs-based lasers.

In conclusion, Al-free InGaAs/InGaAsP/InGaP diode laser structures have been grown by MOVPE and have demonstrated record performances. cw front-facet output power as high as 8.1 W is achieved from optimized broad-waveguide double-quantum well lasers with 100-μm-wide stripes and 4-mm-long cavity lengths. Devices with shorter, 0.5-mm cavity lengths, exhibit total power conversion efficiencies as high as 59%. COMD values are found to be similar to InGaAs/AlGaAs facet-coated lasers, indicating that the cladding/confinement layer materials do not affect COMD.

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