High continuous wave power, 0.8 μm-band, Al-free active-region diode lasers

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Efficient, high-power, Al-free active-region diode lasers emitting at $\lambda=0.83$ μm have been grown by low-pressure metalorganic chemical vapor deposition. Threshold-current densities as low as 220 A/cm^2, maximum continuous wave (cw) power of 4.6 W, and a maximum cw wallplug efficiency of 45% are achieved from 1 mm long, uncoated devices with $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layers. Further improvement is obtained by replacing the p-$In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layer with thin (0.1 μm) electron-blocking layers of $Al_{0.85}Ga_{0.15}As$ and $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$, and a p-$In_{0.5}(Ga_{0.9}Al_{0.1})_{0.5}P$ cladding layer. Such devices provide a record-high T_0 of 160 K and reach catastrophic optical mirror damage (COMD) at a record-high cw power of 4.7 W (both facets). The corresponding COMD power-density level (8.7 MW/cm^2)is ~2 times the COMD power-density level for uncoated, 0.81-μm-emitting AlGaAs-active devices. Therefore, 0.81-μm-emitting, Al-free active-region devices are expected to operate reliably at roughly twice the power of AlGaAs-active region devices. © *1997 American Institute of Physics.* [S0003-6951(97)04302-7]

High-power diode lasers emitting in the wavelength range $\lambda=0.8$–0.87 μm are of interest because of important applications such as pump sources for Nd:YAG lasers. Such lasers conventionally use AlGaAs in the active region for $\lambda \leqslant 0.84$ μm, and thus suffer from short lifetimes and limited output powers by comparison to GaAs-active-region devices. The quaternary alloys InGa(As)P, lattice matched to GaAs, offer an attractive alternative to the AlGaAs/GaAs material system because: (1) the potential for better reliability, due to their inherent resistance to the formation of dark-line defects[1] and lower surface recombination velocity of InGaAsP compared to AlGaAs;[2] (2) a smaller increase in facet temperature[1] with drive current, and (3) the potential for growing reliable diode lasers on Si substrates.[3] However, the InGaAsP/GaAs material system has small conduction-band offsets, which cause diode lasers made of such material to suffer from massive carrier leakage. As a result, one obtains a relatively high threshold-current density, $J_{\rm th}$;[1,4,5] low internal efficiency, η_i;[5,6] and low threshold-current characteristic temperature, T_0.[5,7]

A recent attempt to solve the problem of carrier leakage[8] has been the use of high-band-gap material ($Al_{0.7}Ga_{0.3}As$) for the cladding layers which delivered high T_0, promising reliability data, but also relatively high J_{th}. We have designed and fabricated high-power, efficient, Al-free active-region devices by employing two features: (high-band gap) cladding layers of $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ and the ''broad-waveguide'' concept.[9,10] The former significantly reduces carrier leakage, while the latter insures both a low internal loss coefficient, α_i (~2 cm^{-1}), since a large fraction of the optical energy is contained within the not intentionally doped (i.e., low loss) waveguide,[10] as well as a large transverse spot size (0.5 μm full-width at half-maximum). As a result, we report the lowest $J_{\rm th}$ (220 A/cm^2 for 1-mm-long devices) for 0.8 μm band, Al-free diode lasers as well as a record-high T_0(160 K). Furthermore, we have obtained from uncoated, 100-μm-stripe devices record-high continuous wave (cw) output power (4.7 W) allowing the determination of the catastrophic-optical-mirror damage (COMD) power-density level for uncoated InGaAsP-active-layer devices in the 0.8 μm band.

The structures are grown by low-pressure (50 mbar) metalorganic vapor phase epitaxy (LP-MOVPE) at a temperature of 700 °C (except for the p^+-GaAs contact layer, which is grown at 650 °C to increase the Zn incorporation) on exactly oriented (100) n^+-GaAs substrates. The source materials are trimethylgallium, trimethylindium, arsine, phosphine, and diethylzinc and silane for the p- and n-type dopants. The structures are evaluated by characterizing 100-μm-wide stripe lasers formed by chemically etching through the p^+-GaAs contact layer and defining metal-contact openings with a SiO_2 mask. Devices of various lengths are tested under pulsed-current operation (2 kHz, 5 μs pulse width) to extract $J_{\rm th}$, α_i, η_i, and T_0. For cw measurements, devices are mounted junction-side down on diamond or Cu submounts and tested in a fixture employing thermoelectric cooling.

The first laser structure is shown in Fig. 1. The active region consists of a 150 Å $In_{0.04}Ga_{0.96}Al_{0.89}P_{0.11}$ quantum well surrounded by partially ordered 0.4 μm $In_{0.5}Ga_{0.5}P$ optical confinement layers and 1.25 μm $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layers. A typical cw $L-I$ curve is shown in Fig. 2 for a laser emitting at $\lambda=0.83$ μm with uncoated facets, 100-μm-wide stripe, and 1-mm-long cavity. The maximum output power is 4.6 W (both facets). The differential quantum efficiency, η_d, is 77% reflecting the low α_i (2 cm^{-1}) and high η_i(84%). Also shown in Fig. 2 is the wallplug efficiency, η_p, which reaches a maximum value of 45% at an output power of 1.23 W. This record-high η_p for Al-free 0.8-μm-band diode lasers reflects low $J_{\rm th}$, high η_d, small temperature sensitivity for $J_{\rm th}$ and η_d, and a relatively low

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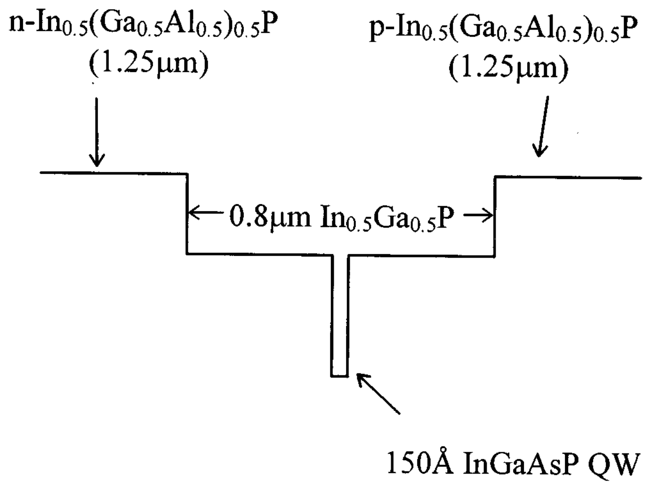

FIG. 1. Conduction-band edge of an Al-free active-region laser structure with 0.8-μm-wide $In_{0.5}Ga_{0.5}P$ waveguide layer and $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layers.

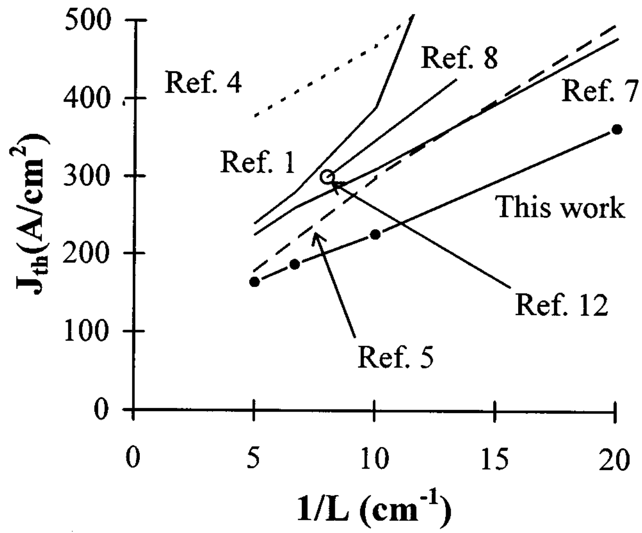

FIG. 3. Comparison between J_{th} vs inverse cavity length curves for the laser structure in Fig. 1 and other Al-free lasers in the 0.8 μm-band ($\lambda=0.81$ μm for Refs. 1, 4, 7, and 8; $\lambda=0.83$ μm for Ref. 12; and $\lambda=0.875$ μm for Ref. 5).

series resistance (0.2 Ω). Specifically, the characteristic temperature coefficients for J_{th} and η_d, T_0 and T_1,[11] are 120 and 1220 K over the 20–60 °C temperature range. By comparison, the highest T_0 values reported for completely Al-free and 2-mm-long devices is 75 K for $\lambda=0.875$ μm[5] and 102 K for $\lambda=0.805$ μm.[7] Therefore, $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layers are highly effective at reducing carrier leakage with little penalty in electrical resistance.

For comparison, J_{th}vs inverse cavity length curves are shown for various Al-free 0.8-μm-band devices in Fig. 3. As can be seen, the J_{th} values obtained for the structure in Fig. 1 are the lowest reported. Due to superior carrier confinement, J_{th} is only 365 A/cm ^{2} for 0.5-mm-long devices. The devices from Refs. 1 and 4 at $\lambda=0.81$ μm, and Ref. 5 at 0.875 μm are completely Al-free with correspondingly small conduction-band offsets (i.e., large carrier leakage) and subsequent high J_{th} values. As expected, the effect is particularly noticeable for devices operating at shorter wavelengths ($\lambda=0.81$ μm)[1,4] with the notable exception of tensile-strained active-layer devices.[7] At $\lambda=0.83$ μm and for 1.25-mm-long devices, J_{th} for the structure in Fig. 1 is 65% of the lowest value reported for completely Al-free devices.[12] With the addition of AlGaAs cladding layers [i.e., Ref. 8 ($\lambda=0.81$ μm)], devices show lower J_{th} and higher T_0 (~150 K for 1-mm-long devices) compared to Al-free 0.81 μm devices. However, their J_{th}values are significantly higher than those for InGaAlP-clad devices.

To further lessen electron leakage, we studied the structure shown in Fig. 4, where the upper cladding layer of p-$In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ has been replaced by thin (0.1 μm) p-$In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ and p-$Al_{0.85}Ga_{0.15}As$ layers, and a p-$In_{0.5}(Ga_{0.9}Al_{0.1})_{0.5}P$ layer for low thermal and electrical resistance. The results look promising as shown in Figs. 5(a) and 5(b) for 1.5-mm-long devices: T_0 has increased to 160 K

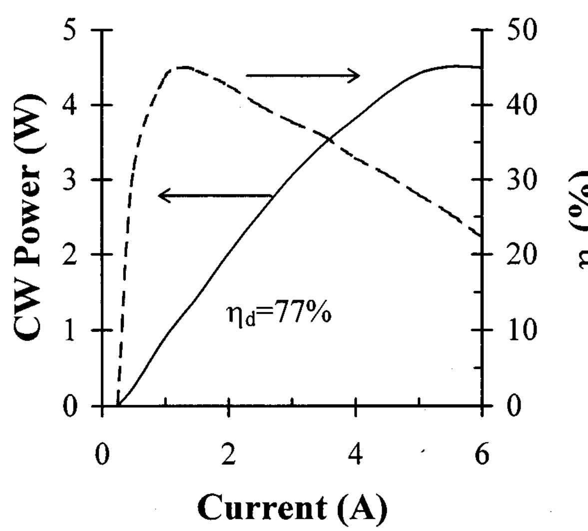

FIG. 2. cw $L-I$ characteristics (both facets) and wallplug efficiency for a 1-mm-long laser with uncoated facets at 20 °C heatsink temperature using the structure shown in Fig. 1.

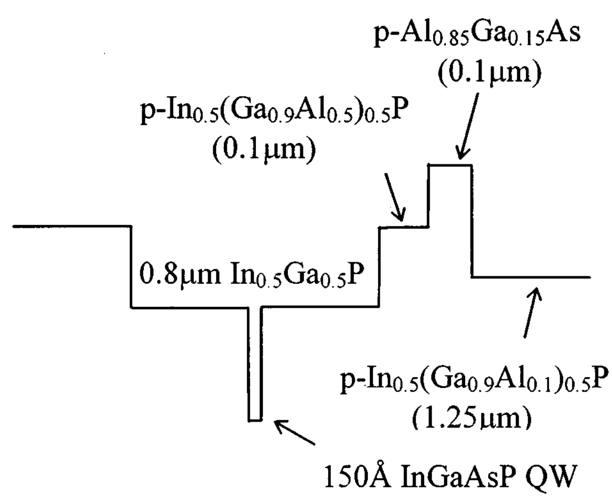

FIG. 4. Conduction-band edge of an Al-free active-layer laser structure with p-side $Al_{0.85}Ga_{0.15}As/In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ carrier-blocking structure.

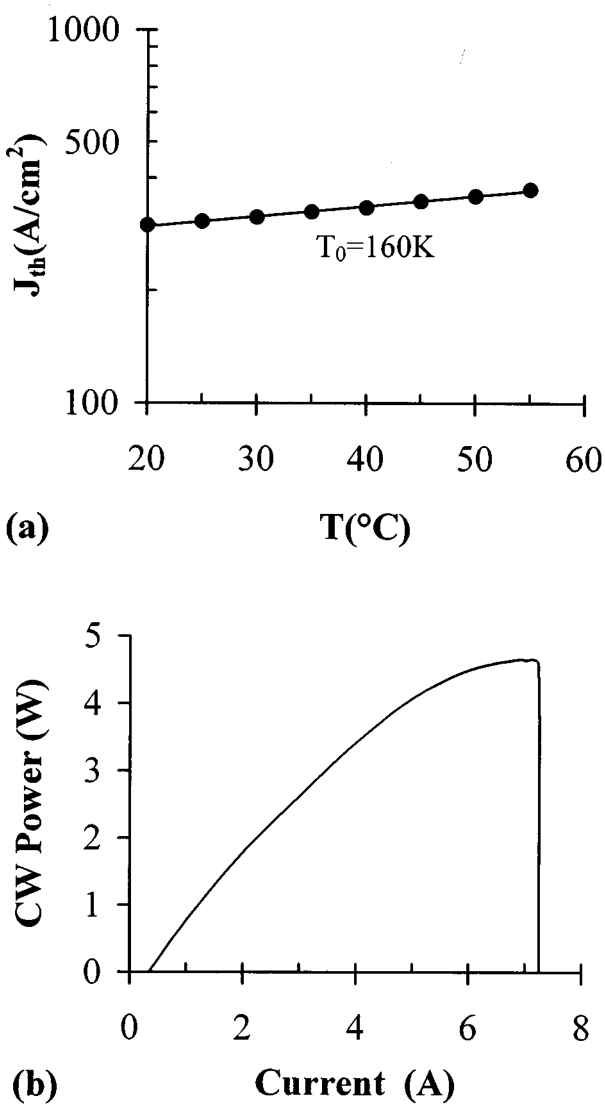

FIG. 5. (a) J_{th}vs temperature and (b) cw L–I characteristics (both facets) for a 1.5-mm-long laser with uncoated facets at 20 °C heatsink temperature made from the structure shown in Fig. 4.

and the maximum cw power achieved is 4.7 W (both facets). It would appear that $Al_{0.85}Ga_{0.15}As$ could not be an effective electron barrier because its band gap is less than that of $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ (i.e., 2.11 eV vs 2.21 eV). However, the conduction-band offset[13] determines the electron-blocking capability. Recent studies[14] have shown that the conduction-band offset of $Al_{0.3}Ga_{0.7}As/In_{0.5}Ga_{0.5}P$ is the same as that for $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P/In_{0.5}Ga_{0.5}P$ and increases with the Al content of $Al_xGa_{1-x}As$. That is, $Al_xGa_{1-x}As$ with $x>0.3$ will block electrons better than $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding-layer materials. This explains why the use of $Al_{0.7}Ga_{0.3}As$ as a cladding layer[8] and $Al_{0.85}Ga_{0.15}As$ as an electron blocking layer (this work) result in higher T_0 values than for $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$-clad devices. The idea of using materials with advantageous conduction-band offsets for electron blockage is not new: It has been proposed[13] and implemented[15] at long wavelengths ($\lambda=1.55$ μm).

At 2.35 W per facet, the power is limited by COMD [Fig. 5(b)] at an internal power density of 8.7 MW/cm^2; that is, 1.7 times that for GaAs-active-layer devices[5] confirming that the surface recombination velocity of InGaAsP ($\lambda=0.83$ μm) is lower than that of GaAs. AlGaAs used for 0.81 μm emission has an even lower COMD than GaAs,[16] so that at $\lambda=0.81$ μm InGaAsP-active layer devices are expected to have at least twice the COMD of AlGaAs devices and thus operate reliably at power levels twice as high.

In conclusion, 0.8-μm-band Al-free active-region diode lasers with novel cladding layers have provided record-high cw output powers. Two laser structures were studied. The first used $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ cladding layers and provided 1-mm-long, uncoated devices with $J_{th}=220$A/cm^2, 4.6 W maximum cw output power and $\eta_{p,\max}=45\%$. The second used on the p-side 0.1-μm-thick carrier-blocking layers of $Al_{0.85}Ga_{0.15}As$ and $In_{0.5}(Ga_{0.5}Al_{0.5})_{0.5}P$ followed by an $In_{0.5}(Ga_{0.9}Al_{0.1})_{0.5}P$ cladding layer, and thus provided 4.7 W cw power and a COMD power density twice that of AlGaAs-active-layer devices. Therefore, these newly developed Al-free devices have the potential to be significantly more reliable than AlGaAs-based 0.81 μm devices.

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