High-Power InAlGaAs/GaAs and AlGaAs/GaAs Semiconductor Laser Arrays Emitting at 808 nm

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***Abstract*—Molecular beam epitaxy (MBE) growth, device fabrication, and reliable operation of high-power InAlGaAs/GaAs and GaAlAs/GaAs laser arrays are described. Both InAlGaAs/GaAs and AlGaAs/GaAs laser arrays reached maximum continuous wave output powers of 40 W at room temperature. The external quantum efficiency was 50% and 45% for the InAlGaAs/GaAs and AlGaAs/GaAs laser arrays, respectively. Threshold current density for InAlGaAs/GaAs and AlGaAs/GaAs lasers was 303 A/cm^2 and 379 A/cm^2, respectively. While the current of AlGaAs laser arrays went up significantly after 1000 h of operation at a constant power of 40 W, InAlGaAs laser arrays had an increase in the injection current of less than 4% after 3000 h at 40 W.**

***Index Terms*—High power, laser array, lasers, reliability.**

I. Introduction

HIGH-POWER laser diodes and laser arrays have found applications in pumping solid-state layers, in the photodynamic therapy, in materials processing, etc. [1]–[3]. Laser diodes emitting light at 808 nm are used mainly as pump source for Nd: YAG lasers. Main parameters for these lasers include output power, lifetime (reliability), efficiency, etc. [4]. The active region of 808 nm lasers is usually an AlGaAs or InGaAsP quantum well structure. InAlGaAs quantum well is also used, because the addition of In into AlGaAs improves the reliability of the laser. Emanuel *et al.* [3] fabricated InAlGaAs/GaAs lasers emitting at 731 nm for photodynamic, high-power (up to 2.2 W) operation was achieved. Yellen *et al.* [5] reported reliability studies of InAlGaAs lasers emitting at 810 nm, and obtained catastrophic optical damage limits of 1.87 MW/cm^2, the same as similar AlGaAs lasers. The maximum power of such InAlGaAs lasers was $\sim$ 1.15 W, slightly better than the AlGaAs counterpart ($\sim$ 1.1 W). Waters *et al.* [4] tested 823 nm InAlGaAs lasers at 100 mW/facet and observed a significant reliability advantages over AlGaAs lasers emitting at 800 nm, and demonstrated resistant to $\langle 100 \rangle$ dark-line propagation in InAlGaAs lasers. Moore *et al.* [6] have compared low indium composition (2–4.5%) InAlGaAs lasers with InGaAs lasers, and constant-power (10 mW) tests showed no sudden death of the lasers. Differential quantum efficiencies of 68–70% were obtained in InAlGaAs lasers. Frigeri *et al.* [7] studied the failure mechanism of InAlGaAs lasers which were subjected to high currents beyond rollover, and found that original quantum wells were destroyed by Al outdiffusion into the confinement layers.

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TABLE I
Wafer Structure for InAlGaAs and AlGaAs Lasers

Layer	Thickness (nm)	Doping ($1/cm^3$)	Growth temperature (C)
GaAs	20	Be, 1.0×10^{19}	600
$Al_{0.45}Ga_{0.55}As$	1500	Be, 5×10^{17}	720
$Al_{0.2}Ga_{0.8}As$	450	undoped	720
$In_{0.1}Ga_{0.73}Al_{0.17}As$ Or $Al_{0.07}Ga_{0.93}As$	7 7	undoped quantum well	680 700
$Al_{0.2}Ga_{0.8}As$	450	undoped	720
$Al_{0.45}Ga_{0.55}As$	1500	Si, 5×10^{17}	720
$Al_{0\text{-}0.45}GaAs$	500	Si, 1×10^{18}	600 - 720
GaAs	500	Si, 1×10^{18}	600
(100) GaAs substrate	400 micron	Si, 1×10^{18}	

Recently, Kreutz *et al.* [8] have studied packaged-related reliability and degradation of InAlGaAs high power lasers mounted on copper microchannel heat sinks. They tested the laser arrays at constant currents of 40 A for 40 h (burn-in test), the output power dropped about 1.5% after the burn-in test. None of them described the lifetime test of high power ($>$ 30 W) operation of InAlGaAs laser arrays. In this work, we report the growth, fabrication, and lifetime testing of InAlGaAs high power ($\sim$ 40 W) laser arrays and compare the results with AlGaAs laser arrays. While most lasers in [3]–[8] were made of wafers grown by metal organic chemical vapor deposition (MOCVD), both types of lasers in this work were grown by molecular beam epitaxy (MBE). Chyi *et al.* [9] reported InAlGaAs lasers grown by MBE, and obtained output powers in the range of 150 mW and a threshold current density of 190 A/cm^2.

II. Experiment

Both InAlGaAs and AlGaAs laser structures were grown by molecular beam epitaxy. The growth conditions were almost the same for both type of laser structures, except for the quantum well layers. The structures are listed in Table I.The growth was carried out in a VG V80H MBE system. The substrate temperature was held at 600 °C for GaAs buffer layer, while the InAlGaAs quantum well layers were grown at 680 °C, the AlGaAs quantum wells were grown at 700 °C. After the quantum well was grown, the growth temperature was raised to 720 °C for subsequent layers, except the top contact layer which was grown at 600 °C to ensure the quality of the GaAs layer.

Both InAlGaAs and AlGaAs broad area lasers were fabricated together in the same batch. After cleaning, 150-μm wide photoresist stripes with a pitch of 300 μm were first made on the surface, and the top contact GaAs between the photoresist stripes were etched by standard selective wet etching (i.e., the depth was 20 nm). A 200-nm thick SiO_2 film was deposited on the wafer by electron beam evaporation. Then the photoresist was removed by resist stripping solvent, together with the SiO_2 on top of the photoresist. Ti/Pt/Au layers (20/20/200 nm) were subsequently deposited on the p-GaAs contact layer by electron beam evaporation. The wafer was thinned to about 100 μm thick to facilitate laser bar cleaving. N-type Ohmic contact AuGe alloy (Au 88% by weight) and Ni/Au multiple layers (30/30/250 nm) were deposited by electron beam evaporation on the thinned and polished n-GaAs substrate. The wafers were annealed at 420 °C for 30 s in H_2 gas ambient to alloy both the p-type and n-type Ohmic contact. The wafers were finally cleaved into 800-μm wide and 10 mm long bars, each bar (laser array) contains 33 individual lasers. The laser bars were coated with high reflection (95%) and antireflection (5%) layers on the facets by electron beam evaporation. For the high reflection coating, three pairs of Si/SiO_2 layers were evaporated. For the antireflection, a single SiO_2 layer was evaporated. The laser bars were p-side-down bonded onto copper heat sinks. Before bonding, copper blocks were polished and a gold layer was plated onto it. Indium was then deposited on the copper heat sink by thermal evaporation. During the bonding, mechanical force was applied to the laser bar, and the heatsink and laser bar were heated together to 220 °C for a short time in N_2 ambient to prevent indium from oxidation.

III. Results and Discussion

Output power (L) versus injection current (I) characterization of the laser arrays was carried out in continuous wave (CW) mode at 20 °C. Fig. 1 shows typical L-I curves for InAlGaAs and AlGaAs lasers. Both laser arrays reached relatively high powers of 40 W, No testing was carried out beyond 40 W, so 40 W was not the limit for these lasers. Thermal rollover was not observed up to this power. The threshold current was 12.0 A and 15.0 A for InAlGaAs and AlGaAs laser arrays, respectively. The average threshold current density was 303 A/cm^2 and 379 A/cm^2 for the InAlGaAs and AlGaAs laser arrays, respectively. The slope efficiency was 1.1 W/A and 1.0 W/A, for the InAlGaAs and AlGaAs lasers, respectively, and is comparable to the slope efficiency (0.98 W/A) of Kreutz *et al.* [8]. Fig. 1 also shows the differential quantum efficiency as a function of injection current for both the InAlGaAs and AlGaAs laser arrays. The maximum efficiency was higher for the InAlGaAs lasers ($\sim$ 50%) than for the AlGaAs lasers ($\sim$ 45%). Therefore, the InAlGaAs laser arrays in general showed slightly better performance than the AlGaAs counterpart. These indium-related performance improvements are mainly due to the strain effects introduced by the strained InAlGaAs laser, since strain has been well known to improve InAlGaAs strained layer quantum well

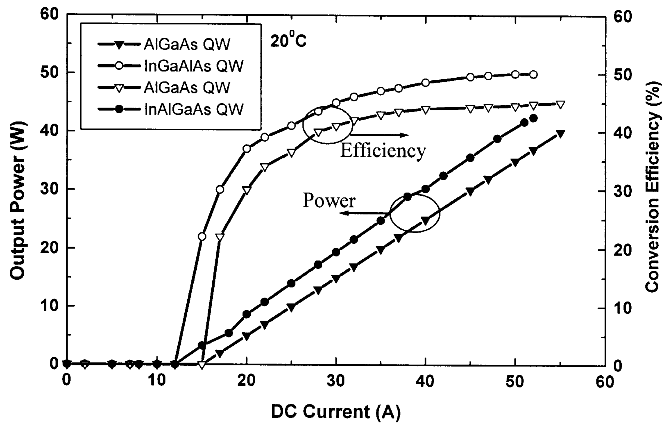
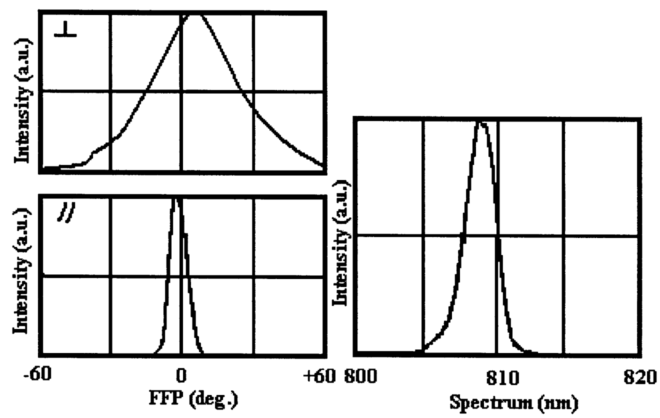
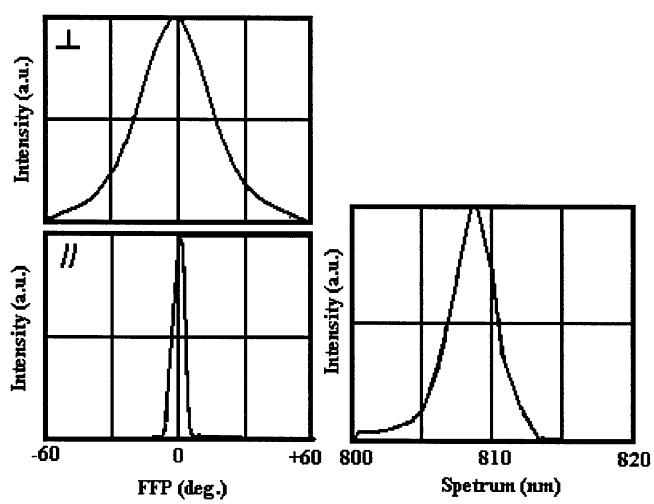


Fig. 1. CW output power and external quantum efficiency of the laser arrays versus injection current characteristics for both InAlGaAs (solid circles) and AlGaAs (open squares) laser arrays at 20 °C. The measurements were not carried out beyond 40 W due to equipment limit. The laser arrays were laser bars of 10 mm length and 800 μm wide, each bar containing 33 individual lasers. The lasers are 150 μm wide (contact stripe) and 800 μm long. The maximum value was 50% and 45% for the InAlGaAs and AlGaAs laser arrays, respectively.



(a)



(b)

Fig. 2. Typical emission spectra and far field patterns in the vertical and horizontal directions of the laser arrays at 40 W at room temperature. (a) InAlGaAs laser arrays and (b) AlGaAs laser arrays.

lasers [10]. Fig. 2(a) shows a typical emission spectrum and typical far field patterns of the InAlGaAs laser arrays at 40 W. Similar results for the AlGaAs laser arrays are given in Fig. 2(b).

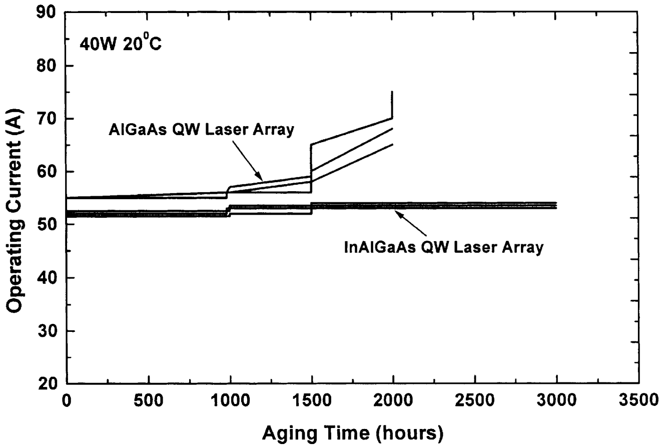


Fig. 3. Injection current as a function of time at a constant power of 40 W for both AlGaAs and InAlGaAs layer arrays.

No obvious difference in the wavelength was observed between these two types of laser arrays. Also no obvious differences in the far field patterns in the vertical and horizontal directions were observed, indicating the incorporation of indium into the active region does not affect application of the laser arrays as pumping source for diode-pumped lasers.

We tested the laser arrays at constant power of 40 W and measured the injection current as a function of time, the results are shown in Fig. 3. After 3000 h, the injection current of InAlGaAs laser arrays only increased by less than 4%, while the AlGaAs laser arrays deteriorated noticeably after about 1000 h, as the injection current went up significantly, and the current increased by about 18% after 2000 h of operation. The addition of indium into the quantum well significantly increased the reliability of the high power laser arrays, this can be attributed to the fact that indium effectively pinned the dislocation in the laser active region. [4] Al oxidation has usually caused reliability problems in AlGaAs lasers. In this work, the Al content in the AlGaAs laser was nominally 7%, much lower than the 17% (nominal value) Al in the InAlGaAs lasers, but the Al oxidation problem seems to not have caused significantly problems. For high power lasers and laser arrays, there are generally three types of failure mechanism [8], namely, gradual degradation, rapid degradation, and catastrophic degradation. In this work, gradual degradation was observed in the InAlGaAs laser arrays, while rapid degradation was observed in the AlGaAs laser arrays, no catastrophic degradation was observed in both types of laser arrays in the power range ($\sim$ 40 W). The rapid degradation observed in the AlGaAs laser arrays could be attributed to the well-known dark-line defect (DLD) which was introduced during device fabrication. [4] With the incorporation of indium into to active region, the movement of the DLD was suppressed, resulting in the gradual degradation in the InAlGaAs laser arrays.

IV. Conclusion

In conclusion, InAlGaAs and AlGaAs laser structures were grown by molecular beam epitaxy, and broad area laser arrays were fabricated and bonded to copper heat sinks. High power operation ($\sim$ 40 W) in continuous wave mode was achieved. Comparisons of optical properties between these two types of lasers show that InAlGaAs laser arrays had lower threshold current densities, higher slope efficiency/higher external quantum efficiency, and more importantly much better reliability. While AlGaAs laser arrays degraded significantly after 1000 h of operation at a constant power of 40 W, InAlGaAs laser arrays had less than 4% increase in current after 3000 h, indicating that the InAlGaAs lasers can be operated at such high power levels for a long time. The improved optical properties were attributed to the strain effects of the InAlGaAs strained-layer in the quantum well, and the improved reliability was attributed to the pinning dislocations by indium atoms in the quantum well.

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