Oxide-Confined High Index Contrast Ridge Waveguide Curved Resonator Laser Diodes

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Abstract—A simple, novel self-aligned deeply-etched plus wet thermally oxidized ridge waveguide fabrication process is demonstrated which enables high-index-contrast, low loss curved resonator GRINSCH lasers with a bend radius as low as 10 µm.

I. INTRODUCTION

We have previously reported that the wet oxidation rate of lower Al content AlxGa1-xAs (x<0.6) can be greatly enhanced (and the rate selectivity to Al content reduced) via the controlled addition of trace amounts of O2 to a conventional wet (N2+H2O) thermal oxidation process [1], [2]. In this work, we show that this modified process (which we call “nonselective” oxidation) allows the direct passivation of the semiconductor laser active region at the sidewall of a deeply-etched ridge waveguide (RWG) structure, enabling the realization of high-index-contrast (HIC, Δn≈1.7) RWG lasers capable of supporting very sharp bending. While such deep etching is typically avoided in laser fabrication to prevent the formation of defects and surface states that can lead to non-radiative interface recombination in the bipolar active region, reducing carrier lifetime, gain and efficiency, the nonselective wet native oxide appears to be of sufficiently high quality to effectively passivate the etched active region surface. Because the oxide also provides electrical isolation from the contact metallization, a self-aligned process results, eliminating the need for a second lithographic alignment step and deposited dielectric. The significant current spreading (tens of microns) which plagues conventional ridge waveguide laser designs is avoided, and the resulting high lateral optical confinement factor (strong overlap of injected carriers with optical field) significantly enhances the laser gain and efficiency. Finally, optical scattering loss due to sidewall roughness may be reduced concurrently through oxidation smoothing [3].

II. EXPERIMENT

Both straight and half-ring HIC RWG laser diodes are fabricated in an λ=808 nm high-power, large optical cavity, single quantum well graded-index separate confinement heterostructure (GRINSCH) with AlxGa1-xAs waveguide cladding layers, grown via MOCVD by Epiworks, Inc. to closely match the design in Ref. [4]. After deposition and patterning of a 200 nm thick PECVD SiNx mask layer, the ridge is dry-etched via RIE into the lower cladding layer and subsequently nonselectively wet oxidized at 450 °C with the addition of 4000 ppm O2 (relative to N2 carrier gas). Using oxidation times of 15 or 30 min, approximately 150 and 340 nm of oxide is grown on the RWG sidewall (and base) for the straight and half-ring geometry lasers, respectively. The scanning electron microscope (SEM) image in Fig. 1 shows the RWG cross section for the half-ring (actually, half-oval racetrack) devices, where the stripe width at the active region was w~3.9 µm (~7.7 µm for straight RWG devices). A bracket marks the approximate position of the GRINSCH active layer. Following oxidation, the SiNx mask is selectively removed by RIE. After standard lapping, polishing, metalization and cleaving, unbonded devices are probe tested, junction side up, under both pulsed (0.5-1 µS pulse, 0.05% duty cycle) and continuous wave (cw) conditions at 300 K using a Keithley Model 2520 laser test system. Device facets are uncoated. The leakage through the oxide layer is negligible (J<5 nA/cm²@2.5 V for an 184 nm oxide).

III. RESULTS

Fig. 1 shows the total (2 facet) output power vs. current characteristic for a straight HIC RWG stripe geometry laser, showing a low 24 mA threshold current and a high differential responsivity of 1.08 W/A (differential quantum efficiency of ηd=71%) in both pulsed and cw mode (sweep time ~ 0.34 sec). The spectra shown in the inset, measured at 40 mA cw (steady on), shows a single longitudinal mode of width 0.08 nm (limited by the optical spectrum analyzer resolution). Fig. 2 shows total output power (now 1 facet due to the wrap-around cavity geometry) for (a) r=150 µm, (b) 40 µm and (c) 10 µm radius half-ring lasers having the HIC RWG cross section shown in the Fig. 1 inset. The inset to Fig. 2 shows an SEM top view image of a 10 µm radius device.

For comparison of straight and curved cavity laser results, data are plotted in Fig. 3 for the threshold current density vs. inverse cavity length of (a) w=100 µm broad area (also fabricated with the same HIC RWG process) and (b) w=7.7 µm narrow stripe straight cavity lasers along with values for the three half-ring lasers of Fig. 2. We note that planar geometry 100 µm broad area lasers fabricated without etching and only a shallow oxidation had higher thresholds than those of Fig. 3(a) due to their current spreading. That our best narrow 7.7 µm wide straight RWG laser (Fig. 1) has Jth=528 A/cm², only ~1.65X higher than for same length broad-area devices (Fig. 3), indicates reasonably low total optical and interface recombination losses due to the etched + oxidized ridge structure.
As shown in Fig. 3, the $r=150 \, \mu$m half-ring laser ($I=16.6 \, \text{mA}$, $L=719 \, \mu$m, $w=4 \, \mu$m) has a comparable threshold current density of $J_{\text{th}}=577 \, \text{A/cm}^2$ to the straight lasers of the same cavity length, demonstrating an extremely low bend loss. To our best knowledge, the smallest radius of curvature previously reported for high-index contrast curved resonator lasers was $r=100 \, \mu$m for half-ring laser fabricated using an impurity-induced layer disordering plus oxidation process [5].

In Fig. 2, we demonstrate lasing at threshold currents of $I=62 \, \text{mA}$ for $r=40 \, \mu$m and $I=65 \, \text{mA}$ for $r=10 \, \mu$m radius of curvature half-ring resonators giving $J_{\text{th}}=1088$ and $1465 \, \text{A/cm}^2$, just 2.8X and 3.3X higher, respectively, than for straight narrow stripe devices, and 4.8X and 6.0X higher, respectively, than for straight broad-area stripe devices of corresponding lengths (Fig. 3).

To summarize, we have demonstrated a novel self-aligned deeply-etched plus directly oxidized high-index-contrast ridge waveguide structure for low-bend loss curved resonator laser diodes which shows excellent laser performance results and lasing for half-ring resonators with a 10 µm bend radius.

REFERENCES


