Deep-Etched Native-Oxide-Confined High-Index-Contrast AlGaAs Heterostructure Lasers With 1.3 μm Dilute-Nitride Quantum Wells  

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Abstract—Using a modified, O₂-enhanced non-selective wet thermal oxidation process, deep-etched ridge waveguides in AlGaAs heterostructures containing λ=808 nm InAlGaAs single quantum well or aluminum-free λ=1.3 μm GaAsP/InGaAsN dilute nitride multi-quantum-well active regions have been directly oxidized to effectively provide simultaneous electrical isolation, interface state passivation, and sidewall roughness reduction. The resulting high-index-contrast (HIC) ridge waveguide (RWG) diode lasers showed improved performance relative to conventional shallow-etched devices owing to both strong optical confinement and the complete elimination of current spreading, with 5 μm stripe width dilute-nitride devices showing up to a 2.3 times threshold reduction and strong index guiding for kink-free operation. Oxidation of an AlGaAs graded-index separate confinement heterostructure (GRINSCH) is studied for varying O₂ concentrations, and the interface passivation effectiveness of the native oxide is studied through comparison with deposited SiO₂ and via a study of the stripe-width dependence of internal quantum efficiency and modal loss. The HIC RWG structure is shown to enable the operation of half-racetrack-ring-resonator lasers with a bend radius as small as r=6 μm.

Index Terms—Semiconductor lasers, materials processing, semiconductor waveguides, integrated optoelectronics.

I. INTRODUCTION

The emission wavelength of GaAs-based diode lasers may be extended to the 1.3 μm and 1.55 μm fiber-optic telecommunications bands through the use of quantum-dot active regions [1, 2] or through the incorporation of dilute amounts of nitrogen into the active region (yielding “dilute nitride” alloys) [3-7]. In each of these cases, the lower gains available relative to conventional quantum-well lasers make having a low-loss index guiding structure with a high lateral optical confinement factor, Γ₁ (i.e., strong lateral overlap of the in-plane optical field and gain) of paramount importance for achieving good laser performance. To realize a high Γ₁ requires both a large lateral refractive index step and minimization of lateral current spreading. Index-guided laser structures are conventionally realized through etching into the upper cladding layer, or through a more complex etching and selective area regrowth process. Low-threshold-current InGaAsN quantum well ridge waveguide (RWG) lasers have also been fabricated by pulsed anodic oxidation of an Al₀.₆₅Gaₐ.₃₅As upper cladding layer [8]. Conceptually, improved optical and electrical confinement could be provided by a deeply-etched ridge waveguide (i.e., etched to below the active region/heterostructure waveguide core), but in practice the device performance with such a process is often degraded by non-radiative recombination due to etch defects and surface states at the exposed active region sidewall, and passivating these defects has proven to be difficult.

Although wet thermal oxidation has conventionally been limited to high Al-content III-V alloys [9, 10], we have elsewhere demonstrated a non-selective, O₂-enhanced wet thermal oxidation process for forming a native oxide directly on the deep-etch-exposed low-Al-content active region/waveguide core of an AlGaAs quantum-well heterostructure [11]. The oxide is of sufficiently high quality to effectively passivate the sidewall surface in a deep-etched high-index contrast (HIC) RWG which, through both strong optical confinement and the complete elimination of current spreading, has enabled high-efficiency single-mode lasers to be fabricated from an AlGaAs graded-index separate confinement heterostructure (GRINSCH) [12]. Because the scattering loss in HIC waveguides is much more strongly affected by sidewall roughness [13], another important benefit of the AlGaAs sidewall oxidation process is the significant smoothing of surface roughness (down to ≤ 5 nm) attained with O₂-enhanced wet oxidation [14].

In Section II below, we review the details of our HIC RWG laser fabrication process. Then in Section III, we show in this work that a device-quality thermal oxide can be grown on a deep-etched dilute nitride laser heterostructure on not only the Al₀.₆₅Gaₐ.₃₅As cladding layers, but also on the Al-free GaAs waveguide and GaAsP/InGaAsN active region layers. With the high Γ₁ provided by the resulting HIC RWG, enhanced laser performance with stable spatial-mode behavior is achieved. Relative to conventional shallow-etched index-guided RWG lasers fabricated out of the same material, HIC RWG narrow-stripe lasers show ~2 times lower lasing threshold current densities with kink-free operation. In Section IV, we report additional studies of the non-selective ox-
HIC RWG LASER FABRICATION PROCESS

Laser fabrication typically starts with a ~200 nm plasma-enhanced chemical vapor deposition (PECVD) SiOxNy deposition to protect the p-GaAs cap layer from later oxidation. The waveguide stripe is then patterned through conventional photolithography followed by two successive reactive ion etching (RIE) steps in CFx/Ox and BCl3/Cl2/Ar plasma to translate the photoresist pattern to the SiNx layer and semiconductor epilayers, forming a ridge as shown in Fig. 1(a). Unlike conventional dry etching which is stopped above the active layer so that defects introduced by etching are kept away from the active region, dry etching in this case reaches the lower cladding layer to form a waveguide with lateral dimension close to that of the photoresist mask. Nonradiative recombination centers formed during this initial etching process are largely reduced during the following thermal oxidation process, typically at 450 °C. The O2-enhanced nonselective wet thermal oxidation [11] of the waveguide sidewalls (and base) [Fig. 1(b)] under conditions given below provides a high-quality native oxide to serve as an insulating dielectric while simultaneously providing lateral optical confinement via the HIC (Δn~1.7) semiconductor/oxide interface, enabling the realization of a HIC RWG capable of supporting very sharp bending [15, 16].

Instead of depositing PECVD SiO2 or SiNx for electrical confinement and surface passivation, the use of the native oxide as the dielectric layer also results in a self-aligned process which eliminates the potential alignment errors and the narrowing of the top contact area unavoidably resulting from a second lithography step to open a current window in a conventional RWG fabrication process. A final dry etching procedure in RIE with a CFx/Ox plasma then selectively removes the dielectric stripe mask, using special care to prevent etch damage to the p-GaAs cap layer. After standard lapping (to ~100 µm thickness) and polishing, and the wafer is then metallized and cleaved into laser bars. In this work, the total p-side metallization (Ti/Au) thickness is ~320 nm, and the device facets are uncoated. For ease of characterization, unbonded devices are probe tested (junction-side up) under both pulsed (2 µs pulse, 1% duty cycle) and continuous wave (cw) conditions at 300 K using a Keithley Model 2520 pulsed laser diode test system.

To further highlight the advantages of this fabrication process, we note that the conventional ridge structure formed by removing or oxidizing the upper cladding layer can yield only a small lateral effective index step (Δn~0.1), providing relatively weak optical mode confinement in the horizontal direction and leading to two undesirable effects: current spreading and output beam asymmetry. The significant current spreading (tens of microns) which plagues conventional RWG laser designs is prevented in our new process as current flow is effectively restrained to a vertical channel defined by the insulating oxide. Strong optical mode confinement from the vertical oxide walls also offers a potential means for overcoming the asymmetry in the optical mode profile and output beam in-plane vs. out-of-plane far-field divergence in edge-emitting lasers [17]. The oxidation can also provide scaling from an optical lithography defined ridge dimension (≥1 µm) to the submicron dimensions required for both HIC waveguide single-mode operation and to realize a symmetric output beam laser device. However, we have observed in practice that multimode HIC RWG devices with widths of even 7 µm exhibit kink-free operation to high output powers in a stable single-mode due to the excellent optical confinement, lack of current spreading and apparent preference for lasing in the lowest-loss fundamental mode [12].

III. DILUTE NITRIDE HIC RWG LASERS

Both deeply-etched HIC-type and conventional (shallow-etched) index-guided RWG laser diodes are fabricated in a λ~1250-1270 nm large optical cavity, multiple quantum well (MQW) heterostructure grown by metal-organic chemical vapor deposition. Three 8 nm InGaAsN (In=40%, N=0.5%) quantum wells are alternately embedded in four 10 nm GaAs0.35P0.65 barriers, which are sandwiched in a 300 nm GaAs separate confinement heterostructure (SCH) formed with 1.1 µm Al0.3Ga0.7As cladding layers [3]. Prior to RWG laser fabrication, wet-etched stripes are used to study the nonselective oxidation of the GaAsP/InGaAsN MQW active region. Fig. 2 shows a scanning electron microscope (SEM) image of a 7 µm wide stripe-masked ridge wet etched in a H2PO4:H2O2:H2O solution for 90 sec and then wet oxidized for 30 min at 450 °C with the addition of 7000 ppm O2 (relative to the N2 carrier gas bubbled through 95°C H2O). The higher magnification SEM image inset clearly demonstrates ≥40 nm of oxide growth in the Al-free active region with 115 nm of oxide formed in the GaAs waveguide core layer. While there is a possibility that the InGaAsN layers may contain trace amounts of Al due to the interaction of the nitrogen source (DMHy) and Al in the MOCVD reactor, we believe this effect is very small. We note that the Al-free GaAs layer does not have this potential issue, nor does InGaAs quantum wells for which we have observed oxide growth (data not shown). We have shown elsewhere that the addition of O2 significantly enhances the oxidation rates of an undoped AlGaAs waveguide core containing a single 10 nm GaAs
quantum well. Fig. 2 demonstrates that substantially thicker GaAs layers and even a dilute-nitride MQW structure can also be non-selectively oxidized.

For HIC RWG laser fabrication, devices are deeply etched via RIE with a BCl3/Cl2/Ar plasma for 12 min to form a 1.8 µm high ridge. A 2 hour non-selective oxidation at 450 °C with the addition of 7000 ppm O2 is then used to grow ~2.5 µm of oxide (measured at the etch-exposed GaAsP/InGaAsN MQW active region), resulting in an effective laser aperture on all devices 5 µm smaller than the optically patterned laser stripe width. For comparison, conventional index-guided RWG lasers are fabricated with a shallow etch for 8 min under the same dry etch conditions to a 0.75 µm depth, followed by a short 30 min nonselective oxidation at 450 °C with 7000 ppm O2 to convert part of the Al0.65Ga0.35As upper cladding layer to a 200 nm native oxide for device isolation.

Fig. 3 shows the pulsed (1% duty cycle) light output power vs. current (LI) characteristic of a L=307 µm cavity length, w=85 µm (effective laser aperture dimension) broad-area device having a low threshold current of 169.6 mA and a high slope efficiency of 0.51 W/A, corresponding to a threshold current density of 650 A/cm². Extrapolation of threshold current density vs. inverse cavity length data (not shown) to 1/L=0 gives 416.1 A/cm² at infinite cavity length, a low value indicative of the high quantum efficiency of 50.8% (at λpeak=1.234 µm), respectively. Extraploation of threshold current density vs. inverse cavity length data (not shown) to 1/L=0 gives 416.1 A/cm² at infinite cavity length, a low value indicative of the high quantum efficiency of 50.8% (at λpeak=1.234 µm), respectively. For L=1 mm devices, a 16% threshold current density reduction is obtained for HIC broad-area lasers (Jth=502 A/cm², w=85 µm) relative to shallow-etch broad-area devices (Jth=598 A/cm², w=90 µm), demonstrating a benefit due to the elimination of current spreading even in wide emitter devices. The inset in Fig. 3 shows a SEM cross-sectional image of the etch-exposed RWG sidewall oxidized under the same conditions but for a shorter time period of 1 hour, resulting in about 430-1220 nm of oxide growth in the MQW active region. An apparent superlinear lateral oxidation rate at the GaAsP/InGaAsN MQW active region observed from three samples oxidized for 30 min, 1 and 2 hours to thicknesses of 40 nm, 1220 nm and 2500 nm, respectively, can be attributed to the additional effect of inward oxidation of this more slowly oxidizing region from the surrounding faster-oxidizing GaAs and AlGaAs layers. The non-uniform oxidation observed in the AlGaAs cladding layers and GaAs waveguide p-n junction layer may be attributed to doping-related effects [18] and interface-enhanced oxidation [19] observed in other heterostructures. The spectrum in Fig. 3, measured at 300 mA (~1.7x Jth) with 1% duty cycle pulses, shows a peak wavelength of 1.234 µm. We have shown elsewhere that growth modifications not incorporated in the structures used in this work can extend the wavelength to close to 1300 nm [4,5].

In narrow-stripe lasers, where optical and current confinement become more critical, a much more significant performance advantage is achieved by employing the HIC RWG structure of Fig. 1 (b). Fig. 4 shows typical output power vs. current characteristics for (a) HIC and (b) conventional RWG...
lasers with a w~10 μm laser effective active stripe width. It is well known that both poor optical confinement and carrier leakage via current spreading [20] can lead to mode hopping in weakly-guided narrow-stripe lasers which in turn causes kinks in the LI characteristics. Such behavior is observed for the device of Fig. 4 (b), and is typical in most of our conventional devices. In contrast, the HIC RWG laser of Fig. 4 (a) shows kink-free operation suggesting stable spatial-mode behavior. As observed for AlGaAs GRINSCH lasers [12], the vertical channel formed after non-selective oxidation both completely eliminates current spreading and provides strong index-guiding. As shown in Fig. 4(a), low-threshold (Ith=45.7 mA) and high slope efficiency (Rc=0.45 W/A) operation is obtained without visible mode-hopping induced LI kinks. The inset spectrum is measured at a pulsed injection current of 100 mA (~2.2× Ith), showing a similar peak wavelength of 1.23 μm as the broad-area device of Fig. 3.

To further study current spreading effects, Fig. 5 plots the threshold current density vs. laser stripe width for comparable cavity length (a) HIC and (b) conventional, shallow-etched RWG devices. The shallow-etched devices especially show dramatically increasing threshold current density with decreasing stripe width, with a highest value of Jth=2587 A/cm² for the w=5 μm conventional device which is more than 2.3x higher than that (1103.3 A/cm²) of a HIC RWG device with the same effective active stripe width. Notably, the threshold current density of the w=5 μm HIC structure laser is merely 2x higher than that of broad-area (w>90 μm) HIC devices, indicating not only excellent optical and electrical confinement, but also negligible sidewall non-radiative recombination even though the native oxide is grown in direct contact with the active layer. As conventional lasers fabricated from similar material and bonded to heatsinks operate cw at temperatures up to 100 °C [5], we believe these improved performance HIC RWG lasers will also operate cw when soldered to heat sinks.

Finally, we note that oxide growth on the GaAsP/InGaAsN active region has also recently been observed with conventional (non O₂-enhanced) wet thermal oxidation, although to a lesser extent (e.g., 50-130 nm in 1 hour at 450°C, i.e., 8-9X slower oxidation rate; data not shown). Preliminary analysis of HIC RWG lasers made with such non-O₂ enhanced oxidation appear to have comparable performance to those reported above. It is known that relative to conventional wet oxidation, O₂-enhanced wet oxidation of Al0.3Ga0.7As produces a denser oxide with much higher refractive index [11] and greater etch resistance [14]. However, further study is required for dilute nitride material systems to understand the role and benefit of adding O₂ during wet thermal oxidation.

IV. OXIDATION OF ALGaAS GRINSCH

Our studies of HIC RWG laser diodes) [12, 15-17] have mostly focused on devices fabricated in a λ~808 nm high-power, large optical cavity, single strained InAlGaAs quantum well GRINSCH with Al0.65Ga0.35As waveguide cladding layers, grown via metal-organic chemical vapor deposition by EpiWorks, Inc. to closely match the design in Ref. [21]. Since the Al-ratio of the AlGaAs waveguide core region is not constant but graded towards the InAlGaAs single quantum well as shown by the schematic conduction band (Ec) inset in Fig. 6(a), the oxidation rate selectivity which mainly depends on Al-ratio is likely to result in variations in the depth of the oxidation front. Here we further explore the oxidation profile of a GRINSCH waveguide to...
optimize oxidation conditions for the best control the dimensions for electrical and optical confinement.

Fig. 6 shows the SEM cross-section images for samples wet oxidized with (a) ultra-high purity (UHP) $\text{N}_2$ carrier gas at 450 °C for 100 min, (b) with mixed 2000 ppm $\text{O}_2$+$\text{N}_2$ at 450 °C for 45 min, (c) with mixed 4000 ppm $\text{O}_2$+$\text{N}_2$ at 450 °C for 40 min and (d) with mixed 7000 ppm $\text{O}_2$+$\text{N}_2$ at 450 °C for 35 min, respectively. All samples are etch-stained for 5 sec in 1:1:10 HCl:$\text{HClO}_4$:H$_2$O for enhancing SEM image contrast. To provide the best comparison, oxidation times were adjusted for each case to obtain a native oxide of approximately 400 nm thickness in the upper and lower AlGaAs cladding layers. A noticeable difference clearly exhibited in the SEM images is that the oxide growth in the GRINSCH waveguide region is “catching up” to that in the upper and lower cladding layers as the $\text{O}_2$ content in the reaction gases is increased. For the case (a) of the conventional wet oxidation, a fairly long oxidation time (100 min) is required to achieve the same thickness cladding layer oxide as the non-selective ($\text{O}_2$-added) oxidation achieves in 35-45 min. The oxidation rate selectivity for different Al-ratio AlGaAs is also shown by the “protruded” oxidation front in the waveguide region for case (a). Here, the minimum thickness oxide (~160 nm) is grown at the center of the waveguide region where the InAlGaAs QW is located, making it the region of weakest lateral carrier and optical confinement. The oxide is also formed directly beneath the p+GaAs cap layer in case (a) due to enhanced lateral oxidant diffusion along the GaAs/AlGaAs interface [19], which for narrower stripes could block the path for current injection needed for laser operation.

In contrast, the oxidation front in the waveguide region becomes progressively more uniform with increasing $\text{O}_2$ content due to the enhancement of the oxidation rate for low Al-ratio AlGaAs [11] and the lateral diffusion of oxidant through the oxide in the cladding layers [Fig. 6 (b-d)]. A similar thickness of oxides in the waveguide core and cladding regions is observed when 4000-7000 ppm $\text{O}_2$ is added into the oxidation stream, giving optimum lateral dimension control and electrical confinement. Based on this study, 4000 ppm $\text{O}_2$ was chosen as the optimal content for the laser diodes fabricated in this work.

The HIC RWG achieved through this process enables very tight waveguide bends with low loss. This has been demonstrated through the fabrication of half-racetrack-ring resonator lasers with a bend radius as low as $r=6 \, \mu\text{m}$, as shown here in Fig. 7 [16]. In addition to lasing for e-beam lithography defined devices with $r=25$, 10 and 8 $\mu\text{m}$ reported in [16], Fig. 7 (d) shows lasing with comparable performance for an $r=6 \, \mu\text{m}$, $w=10 \, \mu\text{m}$ ridge width device. The slightly improved threshold current and efficiency is due to the $r=6 \, \mu\text{m}$ device’s shorter cavity length (636 $\mu\text{m}$ vs. 1 mm for the others).

V. INTERFACE PASSIVATION STUDY

Interface passivation is a critical factor affecting semiconductor device performance, particularly for GaAs-based devices which can have high surface recombination velocities [22]. As the dimension of devices shrinks, the increasing surface-to-volume ratio may further degrade the device performance. For HIC RWG lasers in this work, the direct contact of the oxide with the active region could be quite problematic if it does not form a high quality, low-defect interface with the semiconductor [23]. In order to compare the passivation capacity of a thermally-grown native oxide with conventionally used deposited dielectric films, deep-etched lasers passivated by similar thicknesses (~150 nm) of PECVD SiO$_2$ vs. a grown non-selective wet thermal native oxide are compared. The index of the PECVD SiO$_2$ for the recipe used was measured to be ~1.456 at 808 nm indicating good stoichiometry.

Fig. 8 shows that the typical LI characteristics of narrow stripe (effective aperture width $w=7.7 \, \mu\text{m}$) lasers passivated by the native oxide are much better than PECVD SiO$_2$-passivated devices. Due to its shorter cavity length of 335 $\mu\text{m}$, the PECVD SiO$_2$-confined laser should have a higher slope efficiency and a lower threshold current than the 590 $\mu\text{m}$ native oxide-confined laser if it had provided better or compara-

Fig. 7. Total output power vs. current characteristics for $w=10 \, \mu\text{m}$ wide HIC RWG lasers in half-racetrack-ring geometry with bend radii of (a) $r=25 \, \mu\text{m}$, (b) $r=10 \, \mu\text{m}$, (c) $r=8 \, \mu\text{m}$ and (d) $r=6 \, \mu\text{m}$. Total resonator cavity lengths are ~1 mm for (a)-(c) and 636 $\mu\text{m}$ for (d).

Fig. 8. Total output power vs. current in (a) pulsed, (b) quasi-cw and (c) true cw modes for a native oxide-confined laser ($w=7.7 \, \mu\text{m}$, $L=590 \, \mu\text{m}$) and a PECVD SiO$_2$-confined laser ($w=7 \, \mu\text{m}$, $L=335 \, \mu\text{m}$) in (d) pulsed and (e) quasi-cw modes. Inset: spectrum of the native oxide-confined laser operating at 85 mA cw current, showing a peak wavelength of 816.7 nm.
ble passivation relative to the native oxide. This, however, is clearly not the case; compared with a threshold current of 24 mA and a slope efficiency of 1.1 W/A achieved on a native-oxide-confined laser under pulsed operation (1% duty cycle), the PECVD SiO$_2$-confined laser needs a higher current to reach threshold ($I_{th}$=40 mA) and exhibits a much lower slope efficiency ($R_s$:0.65 W/A), indicating that the PECVD SiO$_2$ is not nearly as good as the non-selective native oxide in passivating surface states.

Without any heat sink, under a fast-cw condition (a fast dc current sweep time of ~0.34 sec), Fig. 8 (b) shows that the native-oxide-confined laser has a comparably low threshold current and follows the pulsed LI curve without rolling over until $I$=160 mA. In contrast, under fast-cw operation the PECVD SiO$_2$-confined laser (Fig. 8 (e)) experiences a higher threshold and lower efficiency with a “rollover” of output beginning at $I$=120 mA. The earlier onset of rollover, usually associated with heating, may suggest a poorer thermal performance of PECVD SiO$_2$-confined devices. Surprisingly, the native oxide-confined laser tested p-side up without a heat sink shows a true cw (steady state dc) threshold of only $I_{th}$=26 mA, just 2 mA higher than the pulsed threshold current, with no LI curve roll over until $I$=125 mA. A linear spectrum with a peak lasing wavelength at 816.7 nm is obtained for a dc injection current of 85 mA. No data was taken above 125 mA to prevent possible thermal damage to the device.

In addition to interface passivation differences, the oxidation smoothing discussed in Ref. [14] should result in a lower scattering loss than that of the PECVD SiO$_2$-confined devices, contributing to improved laser performance. The reduction of defects associated with etching during the oxidation process (both through thermal annealing and via conversion of etch-damaged semiconductor near the surface to amorphous oxide) is an additional benefit of the oxide-confined lasers not afforded by the deposited oxide-confined devices.

To further compare the efficacy of deposited vs. native oxides while eliminating the impact of the distributed mirror loss, inversely proportional to laser cavity length, further analysis is conducted by selecting laser bars of both PECVD SiO$_2$ and native-oxide-confined HIC RWG lasers of almost identical cavity length containing devices with varying stripe width. Results of this stripe width-dependent study are shown in Fig. 9 where the threshold current densities of (a) native oxide-confined and (b) PECVD SiO$_2$-confined lasers with nearly identical structure dimensions are plotted as a function of the laser stripe width. As the laser stripe width decreases, the lasing threshold current densities increase rapidly but at different rates for both laser types. Native oxide-confined lasers clearly demonstrate a smaller increase, especially in the narrow stripe range (w<15 µm). For a native oxide-confined laser, the threshold current density at w=5 µm is 978 A/cm$^2$, 3.4x higher than that of a laser with w=40 µm. For a w=5 µm PECVD SiO$_2$-confined device, the value of 1590 A/cm$^2$ is 3.8x higher than at w=40 µm. At w=15 µm, the SiO$_2$-insulated devices have 1.96x higher threshold current densities than the native-oxide devices, and narrower native-oxide devices all maintain more than 1.5x lower threshold current density than their SiO$_2$-insulated counterparts because the non-radiative recombination becomes the dominant electrical loss in narrow stripe devices. An overall lower threshold current density of native-oxide-confined lasers further proves the superior interface passivation of the native oxide relative to a deposited dielectric.

Low non-radiative recombination can also be reflected by a high internal quantum efficiency, $\eta$, defined as the ratio of radiative electron-hole recombination rate to total (radiative+non-radiative) recombination rate. From the relationship of $I/\eta_s$ vs. $2L/\ln(1/R_l)R_2$, where $\eta_s$, $R_l$, $R_2$ respectively represent the external differential quantum efficiency, front and rear facet reflectivity (defined as $R_f$=0.32 in this work), the internal quantum efficiency $\eta_i$ and can be obtained by extrapolating the external differential quantum efficiency to the point of zero cavity length ($L=0$) and the internal modal loss $\alpha_l$ can be found from the slope for the data shown in Fig. 10 for 3 different cavity lengths of each of 5 different width native-oxide-confined HIC RWG lasers (w=5, 7, 10, 40 and 90 µm (BA)). Fig. 11, which plots the resulting internal quantum efficiency $\eta_i$ and internal loss $\alpha_l$ vs. laser stripe width w resulting from the linear fits in Fig. 10, shows that all of the devices achieve an internal quantum efficiency higher than 80%. This indicates that the non-radiative recom-
bent waveguides required for integrated ring resonator lasers and routing waveguides. Several desirable features including self-aligned processing and effective optical and carrier confinement have been found to result from the application of non-selective oxidation to AlGaAs/GaAs heterostructures containing both 808 nm InAlGaAs single quantum well and 1.23 μm GaAsP/InGaAsN multi-quantum well (MQW) active regions. Compared with conventional index-guided lasers, HIC RWG dilute nitride lasers exhibit desirable kink-free operation due to the uniform carrier distribution in the active region and up to 2.3X reduction of threshold current density for narrow-stripe devices primarily owing to the elimination of current spreading.

Both HIC AlGaAs native oxide-confined and plasma-enhanced chemical vapor deposition (PECVD) SiO₂-confined RWG lasers have been successfully fabricated from a graded-index separate confinement heterostructure (GRINSCH) diode laser wafer and characterized, with low threshold current, high efficiency HIC RWG laser operation observed. Non-radiative interface recombination has been studied by comparing native oxide-confined and PECVD SiO₂-confined straight lasers of varying stripe width, with an up to 1.95X reduction of threshold current density demonstrated on narrow-stripe native oxide-confined diode lasers. The lower threshold current density and higher efficiency of native-oxide-confined lasers proves that the high-quality non-selective thermal native oxide provides better surface state passivation than a deposited PECVD dielectric.

VI. CONCLUSION

Motivated by the desirable enhancements in photonic integrated circuit (PIC) design flexibility and chip functional density that a high-index-contrast (HIC) waveguide structure can provide, we have implemented a new deep-etch plus non-selective, roughness-smoothing oxidation process to achieve a HIC ridge waveguide (RWG) structure with a simplified fabrication process which significantly improves the performance of laser devices and enables the formation of sharply-bent waveguides required for integrated ring resonator lasers and routing waveguides. Several desirable features including self-aligned processing and effective optical and carrier confinement have been found to result from the application of non-selective oxidation to AlGaAs/GaAs heterostructures containing both 808 nm InAlGaAs single quantum well and 1.23 μm GaAsP/InGaAsN multi-quantum well (MQW) active regions. Compared with conventional index-guided lasers, HIC RWG dilute nitride lasers exhibit desirable kink-free operation due to the uniform carrier distribution in the active region and up to 2.3X reduction of threshold current density for narrow-stripe devices primarily owing to the elimination of current spreading.

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VI. CONCLUSION

Motivated by the desirable enhancements in photonic integrated circuit (PIC) design flexibility and chip functional density that a high-index-contrast (HIC) waveguide structure can provide, we have implemented a new deep-etch plus non-selective, roughness-smoothing oxidation process to achieve a HIC ridge waveguide (RWG) structure with a simplified fabrication process which significantly improves the performance of laser devices and enables the formation of sharply-bent waveguides required for integrated ring resonator lasers and routing waveguides. Several desirable features including self-aligned processing and effective optical and carrier confinement have been found to result from the application of non-selective oxidation to AlGaAs/GaAs heterostructures containing both 808 nm InAlGaAs single quantum well and 1.23 μm GaAsP/InGaAsN multi-quantum well (MQW) active regions. Compared with conventional index-guided lasers, HIC RWG dilute nitride lasers exhibit desirable kink-free operation due to the uniform carrier distribution in the active region and up to 2.3X reduction of threshold current density for narrow-stripe devices primarily owing to the elimination of current spreading.

Both HIC AlGaAs native oxide-confined and plasma-enhanced chemical vapor deposition (PECVD) SiO₂-confined RWG lasers have been successfully fabricated from a graded-index separate confinement heterostructure (GRINSCH) diode laser wafer and characterized, with low threshold current, high efficiency HIC RWG laser operation observed. Non-radiative interface recombination has been studied by comparing native oxide-confined and PECVD SiO₂-confined straight lasers of varying stripe width, with an up to 1.95X reduction of threshold current density demonstrated on narrow-stripe native oxide-confined diode lasers. The lower threshold current density and higher efficiency of native-oxide-confined lasers proves that the high-quality non-selective thermal native oxide provides better surface state passivation than a deposited PECVD dielectric.
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He is currently a Professor in the Electrical and Computer Engineering Department at the University of Wisconsin-Madison, where he is involved in the development novel III’V compound semiconductor device structures, including vertical cavity surface emitters (VCSELs), active photonic lattice structures, InGaAsN lasers, and high-power AI-free diode lasers. His current research on low temperature MOCVD grown highly strained InGaAs and InGaAsN led to record low threshold current density diode lasers. Prof. Mawst has authored or coauthored more than 140 technical papers and holds 18 patents. He is a senior member of IEEE.

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