Fabrication of High-Performance InGaAsN Ridge Waveguide Lasers With Pulsed Anodic Oxidation

C. Y. Liu, S. F. Yoon, S. Z. Wang, W. J. Fan, Y. Qu, and S. Yuan

***Abstract*—We have demonstrated high-performance InGaAsN triple-quantum-well ridge waveguide (RWG) lasers fabricated using pulsed anodic oxidation. The lowest threshold current density of 675 A/cm^2 was obtained from a P-side-down bonded InGaAsN laser, with cavity length of 1600 μm and contact ridge width of 10 μm. The emission wavelength is 1295.1 nm. The transparency current density from a batch of unbonded InGaAsN RWG lasers was 397 A/cm^2 (equivalent to 132 A/cm^2 per well). High characteristic temperature of 138 K was also achieved from the bonded 10×1600-μm^2 InGaAsN laser.**

***Index Terms*—InGaAsN, laser diode, pulsed anodic oxidation (PAO), ridge waveguide (RWG).**

I. Introduction

RECENTLY, there has been considerable interest in InGaAsN quantum wells (QWs) grown on GaAs substrate, which is a promising alternative to conventional InP-based technology, for realizing low-cost, high-performance, and high-temperature laser diodes in the 1.3-μm wavelength regime [1]–[8]. High-performance InGaAsN lasers have been fabricated from structures grown by molecular beam epitaxy (MBE) [1]–[6] and metal–organic chemical vapor deposition (MOCVD) [7], [8]. For MBE-grown InGaAsN lasers in the 1.3-μm wavelength region, low threshold current density ($J_{\rm th}$) of 546 A/cm^2 at room temperature (RT) [1], high continuous-wave (CW) output power of 8 W at 10°C [2] and high characteristic temperature (T_o) of 122 K [3] have been reported. For MOCVD-grown InGaAsN lasers in the 1.3-μm wavelength region, Sato *et al.* [7] have reported the highest T_o of 205 K and Tansu *et al.* [8] have reported the lowest $J_{\rm th}$ of 210 A/cm^2. With regards to InGaAsN edge-emitting lasers, so far most results have been focused on broad area (BA) lasers, while there have been relatively few reports on high-performance InGaAsN ridge waveguide (RWG) lasers [4]–[6], whose application has been practical due to their better electrical and optical confinement properties.

In fabricating laser diodes, a uniform and high-quality current blocking layer is of crucial importance. This layer is conventionally formed by depositing SiO_2 or Si_3N_4 using plasma-enhanced chemical vapor deposition (PECVD). Dallesasse [9] has applied wet thermal oxidation in the fabrication of AlGaAs lasers for the first time. However, the oxidation process is carried out at a typically high temperature of ~400 °C. Furthermore, this method was limited to high Al content, and the oxidation rate of $Al_xGa_{1-x}As$ is highly dependent on the Al composition. Pulsed anodic oxidation (PAO) has been proposed and investigated [10]–[12] to produce high-quality native oxide on compound semiconductor for laser diode fabrication. Compared to PECVD and wet thermal oxidation, the advantage of PAO lies in its low cost, RT, and self-aligned processing nature. Furthermore, photoresist can be used as the mask during oxidation. Therefore, RWGs defined by wet chemical etching and subsequent PAO involves only one photolithography step. In this letter, we report the fabrication of high-performance strain-compensated InGaAsN triple QW (TQW) RWG lasers in the 1.3-μm wavelength regime using PAO for the first time.

II. Experimental Details

InGaAsN–GaAs–GaAsP TQW laser structures used in this work were grown by MOCVD. The active region consists of three $In_{0.35}Ga_{0.65}As_{0.985}N_{0.015}$ (6.4 nm)/GaAs (7 nm)/$GaAs_{0.82}P_{0.18}$ (8 nm) QWs, which are embedded in two 12-nm-thick $GaAs_{0.82}P_{0.18}$ tensile-strained barrier layers. The active region is then symmetrically sandwiched between two 35-nm-thick undoped GaAs waveguide layers. A 1.2-μm-thick Si-doped (6.4×10^{17} cm^{-3}) n-type $Al_{0.5}Ga_{0.5}As$ lower cladding layer was grown on the 200-nm-thick n^+-GaAs buffer layer, which was grown on the n-GaAs substrate. A 1.2-μm-thick C-doped (5×10^{17} cm^{-3}) p-type $Al_{0.5}Ga_{0.5}As$ upper cladding layer was grown above the active region, and followed by a 200-nm-thick P^+ (1.4×10^{19} cm^{-3}) GaAs cap layer. Following the standard photolithography process, wet chemical etching was carried out using $H_3PO_4 : H_2O_2 : H_2O$ (1 : 1 : 5, by volume) to form the ridge. Photoresist was used as a mask during the etching. The ridge height was ~1.23 μm, for both contact ridge widths of 4 and 10 μm, respectively. With photoresist still present on top of the ridge, a ~200-nm-thick oxide layer was formed using PAO. The experimental setup for PAO was previously reported in [11]. After oxidation and photoresist removal, P-type ohmic contact layers (Ti–Au, 50/250 nm) were deposited by electron beam evaporation. The substrates were then lapped down to ~100 μm. N-type ohmic contact layers (AuGe–Ni–Au, 150/30/150 nm) were deposited on the backside of the substrates. The samples were alloyed at 410 °C for 3 min in N_2 ambient. Individual InGaAsN RWG lasers were then cleaved at different cavity lengths for measurement of laser output power versus injection current (P–I) characteristics under CW operation without facet coating.

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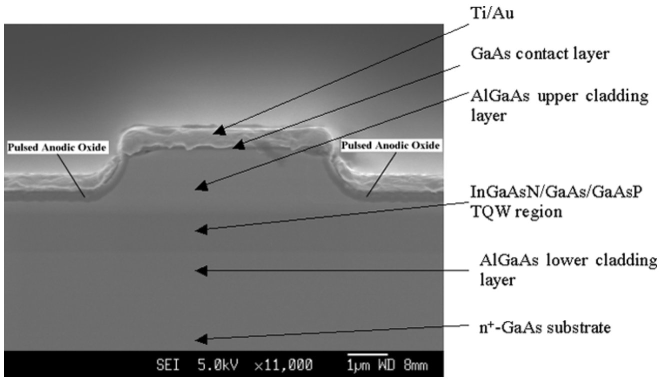


Fig. 1. Cross-sectional SEM image of an InGaAsN RWG laser diode fabricated using PAO, with indicated respective layer structure.

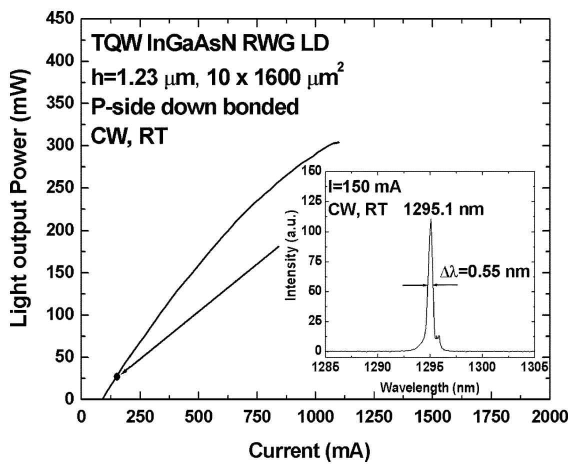


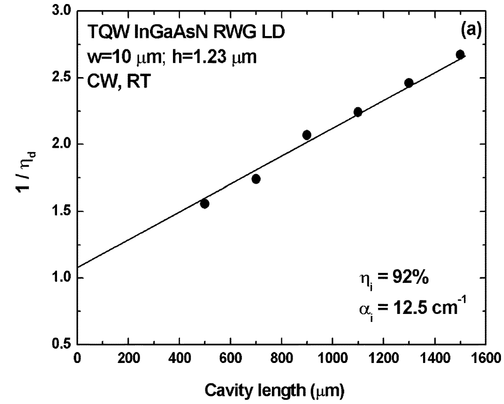
Fig. 2. P–I characteristic of a bonded 10×1600-μm^2 InGaAsN laser diode with 1.23-μm ridge height. Inset shows the emission spectrum of the laser at injection current of 150 mA.

III. Results and Discussion

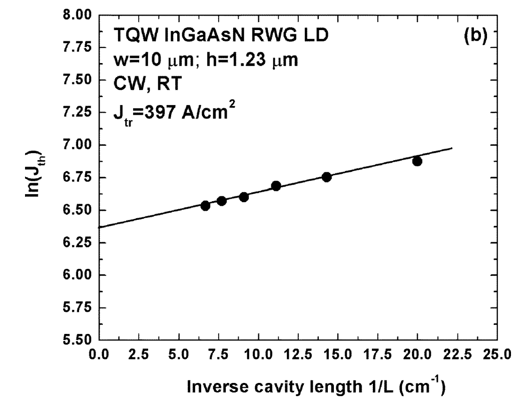
Fig. 1 shows a scanning electron microscope (SEM) cross-sectional image of an InGaAsN RWG laser fabricated using PAO, with indicated respective layer structure. For observation convenience, the chosen device has a ridge width of 4 μm for favorable aspect ratio. The dark region seen in Fig. 1 is the oxidized AlGaAs layer above the active region with thickness of ~200 nm. No obvious undercutting of the GaAs cap layer was observed in the oxidation process. This is an important aspect for contact metal coverage.

Fig. 2 shows the P–I characteristics of the InGaAsN TQW RWG laser, with contact ridge width of 10 μm and cavity length of 1600 μm (10×1600 μm^2), under CW RT operation. The laser was P-side-down bonded onto a copper heat sink with indium. The laser exhibits threshold current $I_{\rm th}$ of 108 mA, corresponding to $J_{\rm th}$ of 675 A/cm^2. The inset shows the emission spectrum of the same laser at injection current of 150 mA. A primary mode centered at 1295.1 nm was observed.

Fig. 3(a) shows the relationship between the reciprocal of external quantum efficiency (η_d) and cavity length (L) measured from a batch of unbonded InGaAsN TQW RWG lasers with contact ridge width of 10 μm. The cavity length ranges from



(a)



(b)

Fig. 3. (a) Plot of inverse external quantum efficiency ($1/\eta_d$) as function of laser cavity length (L). The internal quantum efficiency (η_i) and internal optical loss (α_i) were determined to be 92% and 12.5 cm^{-1}, respectively. (b) Plot of threshold current density, $\ln(J_{\rm th})$ as function of inverse laser cavity length ($1/L$). The transparency current density ($J_{\rm tr}$) was determined to be 397 A/cm^2.

500 to 1500 μm. The internal quantum efficiency (η_i) and internal optical loss coefficient (α_i) were determined to be 92% and 12.5 cm^{-1}, respectively. $\ln(J_{\rm th})$ as a function of inverse cavity length ($1/L$) from the same batch of InGaAsN lasers was plotted in Fig. 3(b). The transparency current density ($J_{\rm tr}$) of the lasers was derived to be 397 A/cm^2 (equivalent to 132 A/cm^2 per well) from Fig. 3(b) using the following [13]:

$$\ln J_{\rm th} = \ln\left(\frac{J_0}{\eta_i}\right) + \frac{\alpha_i}{\Gamma g_0} + \frac{L_{\rm opt}}{L} - 1 \tag{1}$$

where α_i, η_i, Γ, g_0 are the internal optical loss, internal quantum efficiency, optical confinement factor, and material gain, respectively. The optimum cavity length is defined as $L_{\rm opt} = (1/2\Gamma g_0)\ln(1/R_1 R_2)$, and $J_0 = eJ_{\rm tr}$. $R_1 = R_2 = 0.32$ are the optical power reflection coefficients at both facets.

The temperature-dependent P–I characteristics of a P-side-down bonded 10×1600-μm^2 InGaAsN RWG laser are shown in Fig. 4. The inset shows the logarithm of the threshold current $\ln(I_{\rm th})$ as function of heat sink temperature in the range of 20 °C–100 °C. T_o was estimated to be 138 K using the following:

$$I_{\rm th} = I_o \exp\left(\frac{T}{T_o}\right). \tag{2}$$

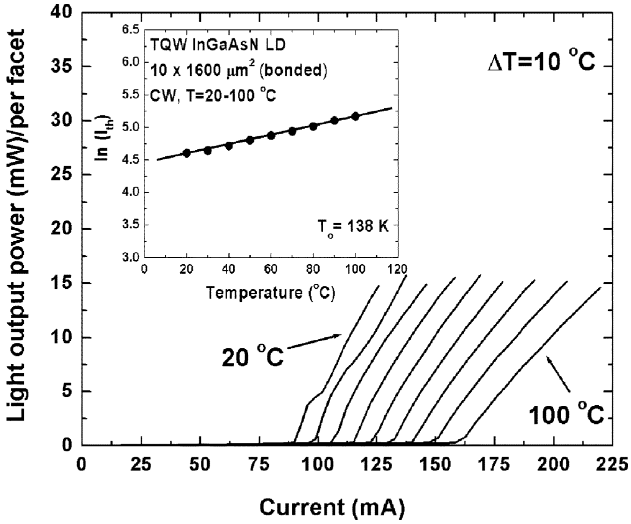


Fig. 4. Temperature-dependent (20 °C–100 °C) P–I characteristics of a junction-down bonded 10×1600-μm^2 RWG InGaAsN laser. Inset shows a plot of $\ln(I_{\rm th})$ as function of temperature. The characteristic temperature T_o was determined to be 138 K.

In a QW laser, comparison of $J_{\rm th}$ and T_o is important, as these parameters are typically of practical interest for such devices. Here, we compare the $J_{\rm th}$ and T_o of our devices with similar works, and devices fabricated using conventional method on the same wafer as ours. Borchert *et al.* [4] have reported pulsed operation of an InGaAsN RWG [$3.5 \times 350 \mu$m^2, double QW (DQW)] laser emitting at 1.29 μm with $J_{\rm th}$ of 1.31 kA/cm^2 and CW operation of an InGaAsN RWG (4×700 μm^2, DQW) laser with T_o of 110 K. Fischer *et al.* [5] have reported CW operation of an InGaAsN RWG (4×600 μm^2, SQW) laser emitting at 1.29 μm with $J_{\rm th}$ of 875 A/cm^2 and T_o of 160 K, while Ha *et al.* [6] have reported pulsed operation of an InGaAsN RWG (20×770 μm^2, TQW) laser emitting at 1.315 μm with $J_{\rm th}$ of 1.31 kA/cm^2 and T_o of $\sim$65 K.

Using the same wafer as ours as presented in this work, InGaAsN RWG lasers with contact ridge width of 2 μm and BA lasers with contact ridge width of 50 μm were fabricated with conventional SiO_2 confinement deposited by PECVD [14], [15]. For a P-side-up bonded uncoated 2×400-μm^2 SiO_2-confined RWG InGaAsN laser, $J_{\rm th}$ of $\sim$1.875 kA/cm^2 at RT, and T_o of 135 K were obtained [14]. For a 50×1200-μm^2 SiO_2-confined BA laser, $J_{\rm th}$ of $\sim$ 1.1 kA/cm^2 was obtained [15]. Compared with the above-mentioned published data [4]–[6], and results from devices fabricated using conventional SiO_2 confinement on the same wafer as ours [14], [15], we have shown that InGaAsN TQW RWG lasers fabricated using the simple PAO technique showed better, or comparable performance with the lowest $J_{\rm th}$ of 675 A/cm^2, $J_{\rm tr}$ of 397 A/cm^2 (equivalent to 132 A/cm^2 per well), and high T_o of 138 K. Overall, in terms of $J_{\rm th}$ and T_o, these results are among the best for InGaAsN RWG lasers in the $1.29 \sim 1.30$ μm wavelength regime ever reported.

It can be seen that devices fabricated using the PAO process exhibit high performance. Since the native oxide was formed by consuming a part of the semiconductor material, better passivation of the sidewalls after wet etching can be expected. Furthermore, the laser fabrication process with PAO is much simpler than that of conventional method using SiO_2 confinement, which could have also contributed to the high performance of the device by minimizing the possibility of process variations.

IV. Conclusion

High-performance InGaAsN strain-compensated TQW RWG lasers have been fabricated using the PAO technique, which is relatively simple, cost-effective, and reliable. The lowest $J_{\rm th}$ of 675 A/cm^2 was obtained from a P-side-down bonded as-cleaved 10×1600-μm^2 InGaAsN laser with emission wavelength of 1295.1 nm. The $J_{\rm tr}$ from a batch of unbonded as-cleaved InGaAsN RWG lasers was 397 A/cm^2 (equivalent to 132 A/cm^2 per well). The P-side-down bonded 10×1600-μm^2 InGaAsN RWG laser also exhibited high T_o of 138 K.

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