APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 20 15 NOVEMBER 2004

Optimization of ridge height for the fabrication of high performance InGaAsN ridge waveguide lasers with pulsed anodic oxidation

C. Y. Liu,[a] Y. Qu, and Shu Yuan
School of Materials Engineering, Nanyang Technological University, Singapore, 639798, Singapore

S. F. Yoon
School of Electrical and Electronic Engineering, Nanyang Technological University,
Singapore, 639798, Singapore

(Received 18 November 2003; accepted 5 October 2004)

The dependence of the ridge height on the performance of the ridge waveguide (RWG) lasers has been systematically studied. It was found that the optimum ridge height corresponds to an etching depth where all the *p*-doped layers above the active region were removed. InGaAsN triple-quantum-well RWG lasers with optimized ridge height were fabricated with pulsed anodic oxidation. The lowest threshold current density (J_{th}) of 711 A/cm^2 was obtained from a $10 \times 1300\ \mu\mathrm{m}^2$ InGaAsN RWG laser. The corresponding transparency current density (J_{tr}) of the fabricated InGaAsN RWG lasers was 438 A/cm^2 (equivalent to 146 A/cm^2 per well). © *2004 American Institute of Physics*. [DOI: 10.1063/1.1824180]

Recently, the growth of InGaAsN quantum well (QW) active region on GaAs substrate has been studied extensively to realize light emitters at 1.3 μm regime for telecommunication applications.[1–8] High performance broad area InGaAsN QW lasers have been fabricated from wafers grown by using both molecular beam epitaxy (MBE)[1–5] and metalorganic chemical vapor deposition (MOCVD).[6–8] Li *et al.*[2] have reported that the lowest threshold current density (J_{th}) of the MBE grown InGaAsN QW lasers is 546 A/cm^2 at wavelength of 1317 nm. For the MOCVD-grown InGaAsN lasers, Tansu *et al.*[8] have reported that the lowest J_{th} is in the range of 210–270 A/cm^2. On the other hand, nearly all the reports on the J_{th} of InGaAsN QW ridge waveguide (RWG) lasers have shown much higher value than that of the broad area lasers.[3–5] Optimization of the ridge height is of crucial importance in achieving the lowest possible J_{th} of an RWG laser.[9,10]

Pulsed anodic oxidation (PAO) has been proposed to produce high quality native oxide on compound semiconductors for laser diode fabrication.[11–13] We have recently shown a significant reduction of J_{th} in AlGaInP/GaInP lasers by using PAO in the laser fabrication.[13]

In this letter, we report the fabrication of high performance strain-compensated InGaAsN triple quantum well (TQW) RWG lasers in the 1.3 μm regime by using PAO method with an optimized ridge height. Since the growth of InGaAs/GaAs laser structure is much more mature, and furthermore, its structure is similar to InGaAsN laser structure except their active regions. Thus, we first optimized the ridge height on InGaAs/GaAs 980 nm, lasers in terms of J_{th} and external quantum efficiency (η_d). Then, the TQW InGaAsN RWG lasers were fabricated with PAO based on the results obtained from the fabricated InGaAs/GaAs lasers.

InGaAsN/TQW laser structures are listed in Table I grown by MOCVD. Following the standard photolithography process, wet chemical etching at RT was carried out with $H_3PO_4/H_2O_2/H_2O$ (1:1:5) as the etchant to form the ridge. InGaAs/GaAs samples with identical size (7×7 mm^2) from the same 2 in. wafer were etched with various time, resulting in the different etch depths of 0.39, 0.80, 1.23, 1.55, and 1.77 μm (below the active region). The etching depth was measured with an Alpha-step stylus profiler. With photoresist still on top of the ridge, oxide film with a thickness of 200 ± 5 nm was formed by means of PAO.[12,13] Laser output power versus injection current ($P-I$) characteristics of the InGaAs/GaAs lasers with different ridge height were measured at RT under cw operation. After optimizing the ridge height using InGaAs/GaAs laser structure, we fabricated InGaAsN RWG lasers based on the obtained information.

Figure 1 shows typical $P-I$ characteristics of three 1100 μm long InGaAs/GaAs 980 nm lasers with ridge heights (h) of 0.39, 1.23, and 1.77 μm, respectively, under cw operation at RT. The corresponding J_{th} (η_d) were found to be 136 (57.8%), 94 (88.5%), and 116 A/cm^2 (77.5%), re-

TABLE I. Strain-compensated InGaAsN/TQW laser structure.

Layer	Thickness (nm)	Doping (cm^{-3})
GaAs	200	C, 1.4×10^{19}
$Al_{0-0.5}GaAs$	100	C, 5.0×10^{17}
$Al_{0.5}Ga_{0.5}As$	900	C, 5.0×10^{17}
$Al_{0-0.5}GaAs$	200	Undoped
GaAs	35	Undoped
$GaAs_{0.82}P$	12	Undoped
$In_{0.35}Ga_{0.65}As_{0.85}N_{0.015}$		Quantum well region
	6.4/7/8	
$/GaAs/GaAs_{0.82}P$		3 period
$GaAs_{0.82}P$	12	Undoped
GaAs	35	Undoped
$Al_{0.5-0}GaAs$	200	Undoped
$Al_{0.5}Ga_{0.5}As$	900	Si, 6.0×10^{17}
$Al_{0.0.5}GaAs$	100	Si, 5.0×10^{17}
GaAs	200	Si, 1.0×10^{18}
(100) GaAs substrate	a.u.	Si, 1.0×10^{18}

---

[a] Author to whom correspondence should be addressed; present address: S1-B2C-20, Clean Room, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, 639798, Singapore; electronic mail: liucy@ntu.edu.sg

0003-6951/2004/85(20)/4594/3/$22.00

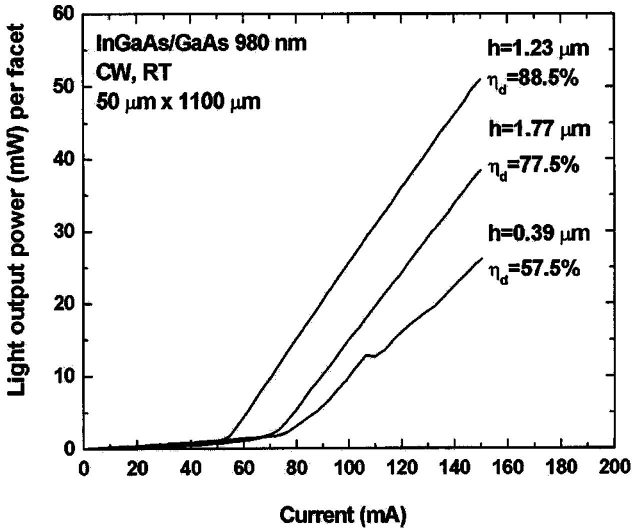

FIG. 1. Light output power (P) vs injection current (I) characteristics of InGaAs/GaAs lasers with different ridge height (h) of 0.39, 1.23, and 1.77 μm, respectively. The cavity length (L) for all the lasers is 1100 μm, with contact ridge width (w) of 50 μm.

spectively. The laser with h of 1.23 μm has shown both the lowest J_{th} and the highest η_d. It is clearly seen that the value of h plays an important role in the device performance. From the relationship between the reciprocal of η_d and the cavity length L for 50 μm stripe width InGaAs/GaAs lasers, an internal optical loss α_i of 3.54 cm^{-1} and average internal quantum efficiency η_i of 95.94% were obtained for the InGaAs/GaAs laser structure used in this work.

Figure 2(a) plots $\ln(J_{\mathrm{th}})$ against the inverse of cavity length (1/L) of the InGaAs/GaAs lasers with different values of h. It is observed that the laser with an $h = 1.23$ μm showed the lowest J_{th} for all the cavity lengths. This is consistent with the finding given in Fig. 1. The transparency current density (J_{tr}) of the lasers can be deduced from Fig. 2(a) using the following equation:[14]

$$\ln J_{\mathrm{th}} = \ln\left(\frac{eJ_{\mathrm{tr}}}{\eta_i}\right) + \frac{\alpha_i}{\Gamma g_0} + \frac{L_{\mathrm{opt}}}{L} - 1, \qquad (1)$$

where α_i is the internal optical loss, η_i is the internal quantum efficiency, Γ is the optical confinement factor, and g_0 is the material gain. The optimum cavity length is defined as $L_{\mathrm{opt}} = (1/2\Gamma g_0)\ln(1/R_1R_2)$. R_1(=0.32) and R_2(=0.32) are the optical power reflection coefficients at the two cleaved facets.

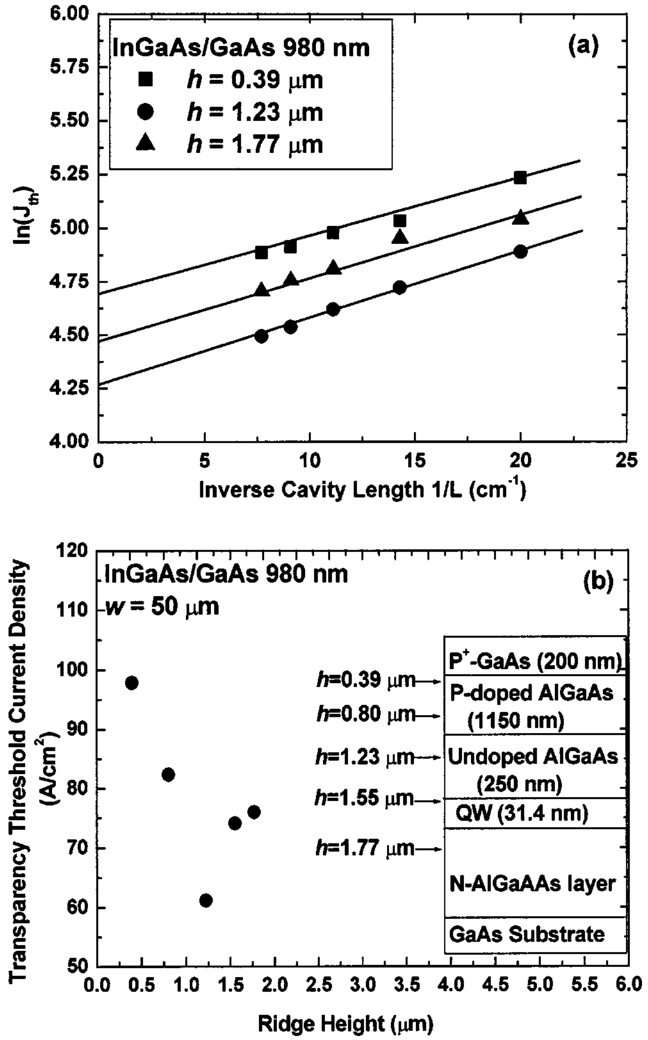

FIG. 2. (a) Logarithm of threshold current density, $\ln(J_{\mathrm{th}})$, vs inverse cavity length $(1/L)$ for InGaAs/GaAs lasers of different ridge height (h) of 0.39, 1.23, and 1.77 μm, respectively, with contact ridge width (w) of 50 μm. For each height, the laser cavity length (L) ranged from 500 to 1300 μm. (b) Transparency current density (J_{tr}) of InGaAs/GaAs lasers with different ridge height (h) of 0.39, 0.80, 1.23, 1.55, and 1.77 μm, respectively.

Figure 2(b) shows the estimated value of J_{tr} as a function of h. It is shown that the lowest J_{tr} (61.2 $\mathrm{A/cm}^2$) is obtained from the laser with h of 1.23 μm, which corresponds to an etching depth where all the p-doped layers above the active region were removed (i.e., p-type contact layer, p-type upper cladding layer). This value of J_{tr} (i.e., 61.2 $\mathrm{A/cm}^2$) is not too far from the theoretically calculated J_{tr} (i.e., 43 $\mathrm{A/cm}^2$) for InGaAs/GaAs lasers emitting at 980 nm.[10] Lasers with the other values of h such as $h = 0.39$ μm (etching off the P^+-GaAs contact layer), $h = 0.80$ μm (etching stopped in the upper cladding layer), $h = 1.55$ μm (right above the quantum well), $h = 1.77$ μm (extended below the active region) showed noticeably higher magnitude of J_{tr}. This is because if lasers with shallower ridges, the injected carriers spread out laterally and the effective carrier density in the active regions was lower, thus a higher J_{tr} was required. However, if lasers with too high ridges (i.e., $h > 1.23$ μm), the sidewall area of the ridge will be large and resulting in a heavy carrier loss due to interface recombination. In addition, when the active region is exposed to air, the light will be confined laterally in the region defined by the high ridge, light scattering at the side wall of the active region might also cause losses to the laser field, contributing to the increase of J_{tr}. Our studies of InGaAs 980 nm lasers have indicated that the optimal ridge height can be obtained if the p-doped layers above the active are completely removed (i.e., including the top contact layer and p-doped cladding layer).

Using the similar approach for the design of the ridge height of the InGaAs/GaAs 980 nm lasers, InGaAsN RWG lasers with ridge height of ~1.2 μm were also fabricated with PAO. Figure 3 shows the P–I characteristics of a 4 μm × 1260 μm TQW InGaAsN RWG laser (without facet coating and intentional heatsink) under RT and cw operation. The inset shows the emission spectrum at 1.2895 μm with an inject current of 150 mA.

Figure 4(a) shows the relationship between the reciprocal of η_d and the cavity length L from a batch of unbonded as-cleaved InGaAsN lasers with a contact ridge width of

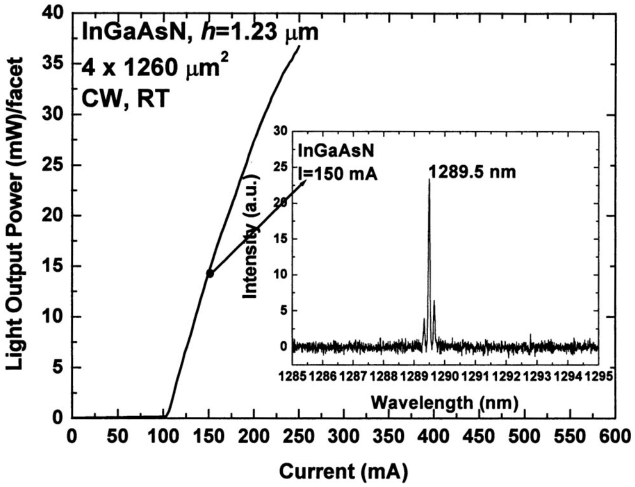

FIG. 3. Light output power (P) vs injection current (I) characteristics for a 4 μm × 1260 μm InGaAsN laser diode with 1.23 μm ridge height (h); the inset shows the emission spectra of the same laser with the injection current of 150 mA.

10 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. Figure 4(b) shows a plot of ln(J_{th}) vs $1/L$ from the same batch InGaAsN lasers presented in Fig. 4(a). Using Eq. (1), a J_{tr} of 438 A/cm^2 was obtained (equivalent to 146 A/cm^2 per well). The lowest J_{th} in this work was obtained from a 10 μm InGaAsN laser with a cavity length of 1300 μm, which was 711 A/cm^2. Riechert *et al.*[3] reported pulsed operation of InGaAsN RWG laser emitting at 1.29 μm with a J_{th} of 1.71 kA/cm^2; Borchert *et al.*[4] reported cw, RT operation of InGaAsN RWG laser in the 1.29 μm with a J_{th} of 1.5 kA/cm^2; recently, Fischer *et al.*[5] reported cw operation of InGaAsN RWG laser in the 1.3 μm with a J_{th} of 875 A/cm^2. These indicated that our InGaAsN RWG lasers emitting at 1.29–1.30 μm regime have the lowest value of J_{th} when compared with the literatures. The high performance of our InGaAsN RWG lasers is attributed to the proper selection of ridge height to achieve minimum scattering and absorption losses. Furthermore, since the native oxide in the PAO process was formed by consuming a part of the semiconductor material, better passivation of the sidewalls after wet etching can be expected.

In conclusion, we have systematically studied the influence of ridge height on the performance of RWG lasers. It is found that the optimum ridge height can be obtained by removing all the p-doped layers of the RWG. The lowest J_{th} and J_{tr} as well as the highest η_d can be obtained from lasers under this optimal condition. High performance InGaAsN TQW RWG lasers were fabricated with PAO using the optimum ridge height. The lowest J_{th} was 711 A/cm^2 obtained from a 10 μm × 1300 μm InGaAsN RWG laser, with a J_{tr} of 438 A/cm^2 (equivalent to 146 A/cm^2 per well) for the InGaAsN RWG laser. PAO has also presented itself again as a cost-effective, reliable method in the fabrication of high performance RWG lasers.

The authors thank S. F. Yu, W. J. Fan, S. M. Wang, and S. Z. Wang for comments on the manuscript and helpful discussions. They also thank J. Ma, F. Boey, G. Chen, K. Pita, and S. C. Tjin for their support of the work.

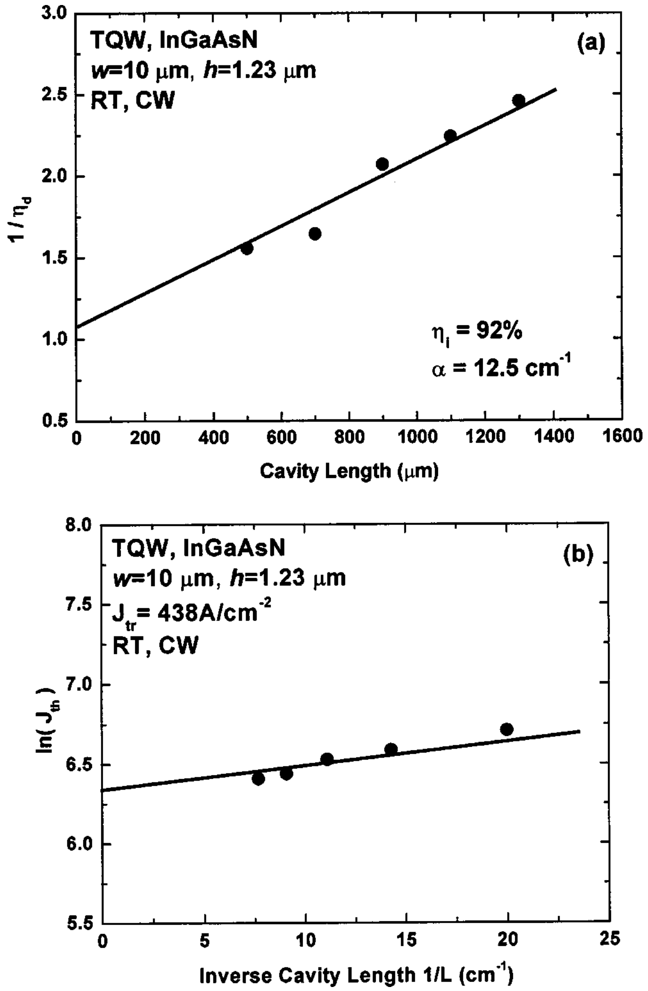

FIG. 4. (a) Inverse external quantum efficiency ($1/\eta_d$) as a function of InGaAsN TQW RWG laser cavity length (L), with contact ridge width (w) of 10 μm, ridge height (h) of 1.23 μm. The internal quantum efficiency (η_i) and internal optical loss (α_i) were determined to be 92% and 12.5 cm^{-1}, respectively. (b) Logarithm of threshold current density, ln(J_{th}), as a function of InGaAsN TQW RWG laser inverse cavity length ($1/L$). The transparency threshold current density (J_{tr}) was determined to be 438 A/cm^2 (equivalent to 146 A/cm^2 per well).

[1] M. Kondow, K. Uomi, A. Niwa, T. Kitatani, S. Watahiki, and Y. Yazawa, Jpn. J. Appl. Phys., Part 1 **35**, 1273 (1996).
[2] W. Li, T. Jouhti, C. S. Peng, J. Konttinen, P. Laukkanen, E.-M. Pavelescu, M. Dumitrescu, and M. Pessa, Appl. Phys. Lett. **79**, 3386 (2001).
[3] H. Riechert, A. Y. Egorov, D. Livshits, B. Borchert, and S. Illek, Nanotechnology **11**, 201 (2000).
[4] B. Borchert, A. Y. Egorov, S. Illek, and H. Riechert, IEEE Photonics Technol. Lett. **12**, 597 (2000).
[5] M. Fischer, D. Gollub, M. Reinhardt, and M. Kamp, J. Cryst. Growth **251**, 353 (2003).
[6] N. Tansu, N. J. Kirsch, and L. J. Mawst, Appl. Phys. Lett. **81**, 2523 (2002).
[7] N. Tansu, A. Quandt, M. Kanskar, and L. J. Mawst, Appl. Phys. Lett. **83**, 18 (2003).
[8] N. Tansu, J.-Y. Yeh, and L. J. Mawst, Appl. Phys. Lett. **83**, 2512 (2003).
[9] C. P. Chao, S. Y. Hu, K-K. Law, B. Young, J. L. Merz, and A. C. Gossard, J. Appl. Phys. **69**, 7892 (1991).
[10] S. Y. Hu, D. B. Young, A. C. Gossard, and L. A. Coldren, IEEE J. Quantum Electron. **30**, 2245 (1994).
[11] M. J. Grove, D. A. Hudson, P. S. Zory, R. J. Dalby, C. M. Harding, and A. Rosenberg, J. Appl. Phys. **76**, 587 (1994).
[12] S. Yuan, C. Y. Liu, and F. Zhao, J. Appl. Phys. **93**, 9823 (2003).
[13] C. Y. Liu, S. Yuan, J. R. Dong, S. J. Chua, M. C. Y. Chan, and S. Z. Wang, J. Appl. Phys. **94**, 2962 (2003).
[14] S. L. Chuang, *Physics of Optoelectronic Devices* (Wiley, New York, 1995).