High-Power Ridge Waveguide InGaAsN Lasers Fabricated With Pulsed Anodic Oxidation

Yi Qu, C. Y. Liu, S. G. Ma, Shu Yuan, Baoxue Bo, Guojun Liu, and Huilin Jiang

***Abstract*—High-power InGaAsN triple-quantum-well strain-compensated lasers grown by metal–organic chemical vapor deposition were fabricated with pulsed anodic oxidation. A maximum light power output of 145 mW was obtained from a 4-μm ridge waveguide uncoated laser diode in continuous-wave (CW) mode at room temperature. The devices operated in CW mode up to 130 °C with a characteristic temperature of 138 K in range of 20 °C–90 °C.**

***Index Terms*—GaInNAs, InGaAsN, lasers, pulsed anodic oxidation (PAO).**

I. Introduction

THE 1.3-μm laser diodes have been widely used for optical access systems and optical interconnection systems [1]. Conventionally, InGaAsP–InP lasers are used in these applications, but such lasers exhibit a relatively low characteristic temperature (T_0) due to poor electron confinement [2]. It has been reported that the incorporation of nitrogen into InGaAs reduces the bandgap energy and allows emission wavelengths as long as 1.5 μm to be reached [3], [4]. High output power operation has been demonstrated in InGaAsN broad area lasers grown both by molecular beam epitaxy (MBE) [$\sim$4.2 W at a heatsink temperature of 10 °C] [5] and metal–organic chemical vapor deposition (MOCVD) [1.8 W at 20 °C] [6].

While most InGaAsN laser reports are based on results from broad area lasers, few results have been reported on narrow stripe ($\leq$4 μm) devices. Caliman *et al.* [7] reported pulsed operation of a 2 $\times$ 400 μm laser and obtained 20-mW output power at the wavelength of 1.22 μm. Fischer *et al.* [8] reported MBE-grown InGaAsN narrow stripe (4 μm) lasers with continuous-wave (CW) output power up to 16 mW at room temperature. Recently, Kovsh *et al.* [9] reported the fundamental-mode operation of a 2.7 $\times$ 1000 μm laser with a CW output power of 210 mW by antireflection–high reflection facet coating. In this work, we report the high-power operation of MOCVD grown narrow stripe (4 μm) InGaAsN uncoated lasers fabricated by a simple methd of pulsed anodic oxidation (PAO) process. A maximum light power output of 145 mW was achieved in CW mode at room temperature, high temperature operations up to 130 °C of the prepared devices were realized.

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In the fabrication process of semiconductor lasers, a uniform current blocking layer with high quality is usually prepared for current confinement within stripes. This layer is often formed by the deposition of oxides by plasma-enhanced chemical vapor deposition (PECVD), which is a relatively costly and complicated process. On the other hand, PAO is a simple and cost-effective method for the fabrication of optoelectronic devices [10], as it reduces process steps, resulting in better reproducibility and higher yield. It is also a self-alignment process in narrow stripe device fabrication. Constant current or pulsed current can be applied to oxidation process, but the oxide film quality by the former method is inferior to that by PAO process. Previously, PAO has been applied to quantum-well (QW) intermixing in GaAs–AlGaAs and InGaAs–GaAs QW and quantum wire structures [11]; we have recently shown a significant reduction of threshold current density in AlGaInP–GaInP lasers by PAO [12].

II. Experiment

The wafer used in this work was grown by MOCVD by IQE (Europe) Ltd. The active region consists of three $In_{0.35}Ga_{0.65}As_{0.985}N_{0.015}$ QWs, each 6.4 nm thick, separated by 7-nm GaAs and 8-nm $GaAs_{0.82}P_{0.18}$ barriers. The active region is symmetrically embedded in a 35-nm-thick undoped GaAs waveguide. A 1.2-μm Si-doped (6×10^{17} cm^{-3}) n-type $Al_xGa_{1-x}As$ $(x = 0–0.5)$ cladding layer was grown between the n-substrate and active layer and 1.2-μm C-doped (5×10^{17} cm^{-3}) p-type $Al_xGa_{1-x}As$ $(x = 0–0.5)$ cladding layer followed the active layer. A 20-nm P^+ (1×10^{19} cm^{-3}) GaAs cap layer was grown for contacting. GaAsP strain-compensated layers were introduced into the GaAs barriers to improve the carrier confinement and material quality of MQW laser structures [13], [14]. After standard photolithography and selective wet etching for 4-μm-wide ridge waveguide stripes, the oxide film was formed on the wafer by PAO process with a thickness of 120 nm $\pm$3 nm [15]. A vacuum tube was used as the vacuum tweezers to hold the sample and conduct current. The electrolyte was made of ethylene glycol : deionized water : phosphoric acid (40 : 20 : 1 by volume). The initial current was set according to the current density at the sample surface, which was fixed at 120 mA/cm^2. The pulsewidth was 1 ms, while the pulse period was 12 ms. The total anodization time was 4 min. The wafer was then thinned and contact metals were deposited by electron beam evaporation and then alloyed. Laser bars were cleaved and individual lasers were sawed from the laser bars. Fig. 1 shows a schematic diagram of the InGaAsN laser fabricated with PAO. The laser chips were not facet coated, and bonded p-side-down onto copper heat sinks with indium. The details

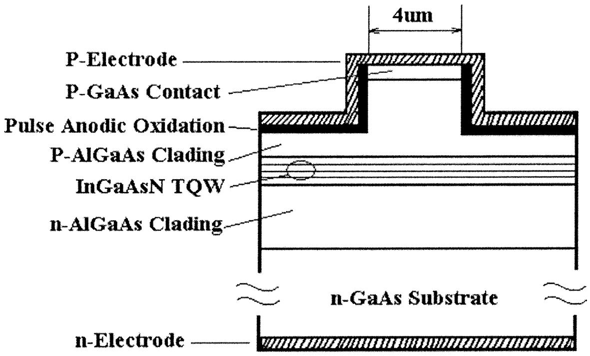

Fig. 1. Schematic diagram of the ridge waveguide laser diodes fabricated with PAO.

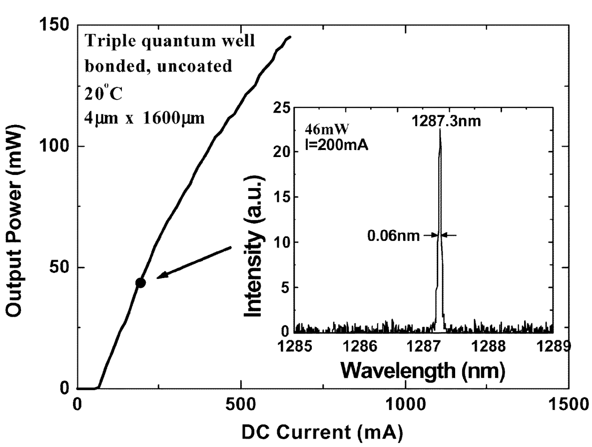

Fig. 2. Room-temperature CW light output power versus injection current for a 4 × 1600 μm ridge waveguide InGaAsN laser diode fabricated with PAO. Single-mode operation was maintained for laser power up to 46 mW. The inset shows the lasing spectrum at an injection current of 200 mA (46 mW). The laser was not facet-coated, but was bonded p-side down on copper heatsinks with indium.

of the bonding were published elsewhere [16]. (Note, lasers used for the determination of wafer materials quality, were not bonded, but simply placed on a home-made spring-loaded jig for easy handling.) The heatsink with the laser chip on it was then mounted on standard TO-3 can. During the characterization of the laser, the cap of the TO-3 can was removed, and the laser was placed in front of the entrance of a Newport integration sphere.

III. Results and Discussion

The room temperature optical power versus current characteristics of a 4 × 1600 μm triple QW uncoated laser in CW mode is shown in Fig. 2. The threshold current was 70 mA, corresponding to a threshold current density $(J_{\rm th})$ of 1.093 kA/cm^2. Single longitudinal mode lasing was observed for output power up to 46 mW in our measurement, which is shown in Fig. 2. The emission wavelength at 200 mA was 1287.3 nm, the slope efficiency was 0.36 W/A in linear output region. A maximum light power output of 145 mW has been achieved under CW condition.

To characterize material properties of the wafer, minimum lateral current spreading effect should be considered. We fabricated 10-μm stripe lasers for this purpose by PAO process. In

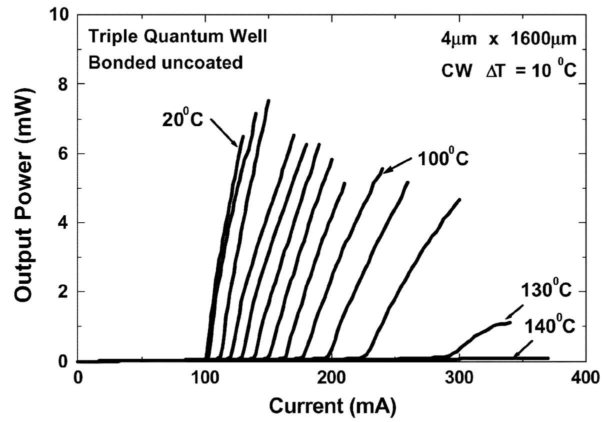

Fig. 3. Temperature-dependent optical power versus current characteristics of the InGaAsN triple-quantum-well laser. It lased up to 130 °C. The characteristic temperature was 138 K in the linear region (20 °C–90 °C).

contrast to the laser shown in Fig. 2, these uncoated lasers were not bonded by indium on TO-3 package, but were placed on a home-made spring-loaded jig during testing. A plot of the relationship between the reciprocal of η_d and the cavity length L of the unbonded lasers. The internal efficiency η_i and internal absorption coefficient α_i were calculated to be 92% and 12 cm^{-1}, respectively, for this wafer. In the literature, reported values for the internal efficiency were between 82% and 93% for MBE-grown InGaAsN wafers, and between 75% and 97% for MOCVD-grown InGaAsN wafers [17]. Reported values for the internal loss were between 4 and 9.8 cm^{-1} for MBE wafers, and between 6 and 15 cm^{-1} for MOCVD wafers [17].

The temperature-dependent light power versus current curves are shown in Fig. 3 for the 4-μm ridge devices. The laser operated up to 130 °C. A plot of $\ln(I_{\rm th})$ versus temperature was linear up to about 90 °C, similar to the result of Fischer *et al.*, [8] and yielded a high characteristic temperature of 138 K.

As a comparison, lasers were fabricated by conventional method, where the current-blocking layer was SiO_2 deposited by PECVD instead of PAO process.[1] The wafer was from the same wafer as used in this work. The ridge width was 2 μm, and laser cavity lengths were 400 μm. The devices were soldered p-side up on to a Si carrier tile and uncoated. The threshold current density was 1.95 kA/cm^2. The maximum CW output power was 18 mW from the laser. Laser fabricated with PAO with ridge width of 4 μm and cavity length of 400 μm showed threshold current density of 1.25 kA/cm^2. These PAO lasers were also unbonded and uncoated, and were tested in CW mode. The maximum power was 40 mW in a 400-μm-long laser. It should be pointed out that ridge waveguide lasers with narrower ridge width usually show higher threshold current density and lower output power, due to high lateral current leakage and smaller active volume [18].

The reasonable device performance of this work might be due to the adoption of PAO process combined with episide-down mounting of the devices. Conventional methods for the fabrication of ridge waveguide lasers usually require the deposition of SiO_2 or Si_3N_4 by PECVD, and may increase the chance of

[1]The lasers were fabricated and the data was provided by the wafer manufacturer, IQE Europe Ltd., private communications.

process-induced damage (e.g., plasma damage) besides more complicated processes. SiO_2 reacts easily with Al in the AlGaAs cladding layer, leaving behind Si atoms as impurities in the p-cladding layer. In addition, both SiO_2 and Si_3N_4 cause considerable stress in the underlying layers due to lattice mismatch [19]. The stress increases interface defect densities. For the fabrication by PAO process, however, such problems are avoided. Since the oxides are native oxides formed at room temperature, it causes little stress damage to the device, and serves as a passivation layer which reduces interface trapping centers. In addition, heat dissipation is critical for laser operation, as the power density in the ridge is very high. Anodic oxides are composed of various oxides of aluminum, arsenic, and gallium and have higher thermal conductivity than SiO_2 [20]. Heat generated during the operation of the lasers is removed more efficiently in PAO lasers.

It was well established [13], [14] that strain-compensated layers can enhance device performance by allowing higher indium concentration and lower nitrogen concentration to be used in the active region. The GaAsP layers used in this work were close to the InGaAsN layers and had higher bandgap than GaAs, thus, the carrier confinement was increased. The tensile strain in the GaAsP also reduced the overall stress of the active region (strain compensation). Therefore, stress-related defects were reduced in the active region. These effects may have contributed to the overall satisfactory performance of the lasers.

IV. Conclusion

A simple PAO process was applied to the fabrication of ridge waveguide InGaAsN triple-quantum-well strain-compensated lasers grown by MOCVD. Laser output power of 145 mW was obtained from 4-μm stripe uncoated lasers in CW mode at room temperature; single longitudinal mode lasing was observed up to 46 mW with a wavelength of 1287.3 nm. The lasers operated up to 130 °C with a high characteristic temperature of 138 K in range of 20 °C–90 °C. The transparency current density was determined to be 438 A/cm^2 and internal quantum efficiency and internal material loss were determined to be 92% and 12 cm^{-1}, respectively. Maximum slope efficiency of the uncoated laser was found to be 0.36 W/A at room temperature.

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