Multiple-Quantum-Well GaInNAs–GaNAs Ridge-Waveguide Laser Diodes Operating out to 1.4 μm

Wonill Ha, Vincent Gambin, Mark Wistey, Seth Bank, Seongsin Kim, and James S. Harris, Jr.

***Abstract*—In this letter, results from a ridge waveguide laser diode (LD) structure, with three GaInNAs quantum wells (QWs) and GaNAs barriers, are presented. The sample was grown by solid source molecular beam epitaxy with an RF plasma nitrogen source. These devices differ from previously reported GaInNAs QWs LDs that used GaAs as the barrier material. The introduction of nitrogen into the barriers reduces the spectral blue shift caused by post-growth annealing. Long wavelength emission out to 1.405 μm was observed. The devices exhibited threshold current densities as low as 1.5 kA/cm^2, high differential efficiency of 0.67 W/A, and a maximum output power of 350 mW.**

***Index Terms*—Epitaxial growth, gallium compounds, nitrogen compounds, optical fiber communications, optical fiber lasers, semiconductor lasers.**

I. Introduction

THE MOTIVATION for this work lies in the tremendous need for low-cost 1.33–1.55-μm diode lasers that can operate over a significant temperature range (-10 °C to 85 °C) and deliver moderate power ($>$10 mW). There is also a significant demand for higher power single-mode devices as Raman amplifiers to increase the power budget for wavelength-division-multiplexing (WDM) systems. An ordinary silica-based fiber can be used as the active medium which, when pumped with a high power laser, provides gain to a signal at a longer wavelength through the process of stimulated Raman scattering. The dominant technology, InP-based lasers, have serious limitations to cover the entire 1.3–1.55-μm wavelength range [1], for either low cost vertical-cavity surface-emitting lasers (VCSELs) or high-power Raman pumps. Recent work on GaInNAs quantum wells (QWs) on GaAs has demonstrated considerable improvement in thermal properties. Additionally, being based on a GaAs substrate, one can take advantage of well-established processing techniques and a superior distributed Bragg reflector (DBR) mirror technology [2], [3]. In the past few years, much research has been done showing that GaInNAs, closely lattice-matched to GaAs, has a bandgap energy in the desired range. GaInNAs–GaAs devices have shown the potential for low threshold current density, high temperature continuous-wave operation, and high T_o in the wavelength range of 1.1–1.3 μm [4]–[7]. One challenge in achieving longer wavelength ($>$1.3 μm) GaInNAs is that during the annealing process, which must be done to improve the material quality [8], the emission blue shifts. At high annealing temperatures (700 °C–800 °C), nitrogen out-diffuses from the GaInNAs QWs. As a result, most attempts to achieve laser emission beyond 1.3 μm, while still maintaining low threshold current density, have been unsuccessful.

We present a new structure for maintaining long wavelength emission after anneal. The material grown used for this study was grown by solid source molecular beam epitaxy (MBE) with an RF plasma source. We utilize GaNAs barriers between QWs rather than the conventional GaAs barriers. This design decreases nitrogen out-diffusion from the QW, thus reducing the emission blue shift. Additionally, the tensely strained GaNAs barriers also reduce the overall compressive strain inherent in high indium GaInNAs QWs. Additionally, the decreased carrier confinement of GaNAs supports longer emission wavelength compared to GaAs barrier [3]. We present the results of long wavelength multiple QW (MQW) GaInNAs ridge-waveguide laser diodes (LDs) using GaNAs barriers. These inplane LDs have emission spectra out to 1.405 μm and a threshold current density as low as 1.5 kA/cm^2. Our devices show pulsed operation up to 95 °C. The maximum output power under pulsed operation (1-μs duration and 1% duty cycle) is 350 mW with a differential efficiency of 0.67 W/A.

II. Device Structure and Fabrication

The separate confinement heterostructure (SCH) MQW LD structure, grown on a (100) n-GaAs substrate, is shown schematically in Fig. 1. The active region consists of three QWs, each 7 nm thick, separated by 20-nm GaNAs barriers. The active region is symmetrically embedded in an 80-nm-thick undoped GaAs waveguide. A 1.8-μm Si-doped (5×10^{18} cm^{-3}) n-type AlGaAs cladding layer was grown between the n-substrate and the active layer and a 1.7-μm Be doped (2×10^{18} cm^{-3}) p-type AlGaAs cladding followed the active layer. A 50 nm p$^+$ (1×10^{19} cm^{-3}) GaAs cap layer was grown for contacting. Annealing was performed at 720 °C for 2 min with an rapid thermal annealing (RTA). The ridge waveguide was patterned by a self-aligned mesa etch to the p-cladding layer by reactive ion etching. The contacts to the p-layer were Ti–Pt–Au. The processed sample was lapped and polished down to 100 μm and backside Ni–Ge–Au contacts were evaporated. The n- and p-contacts were then annealed at

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W. Ha, V. Gambin, M. Wistey, S. Bank, and J. S. Harris are with the Solid State and Photonics Laboratory, Stanford University, Stanford, CA 94305 USA.

S. Kim is with the Agilent Technology Inc., San Jose, CA 95131 USA.

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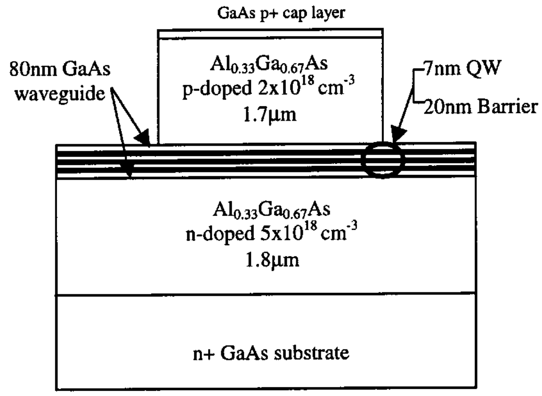

Fig. 1. Schematic diagram of GaInNAs ridge waveguide laser.

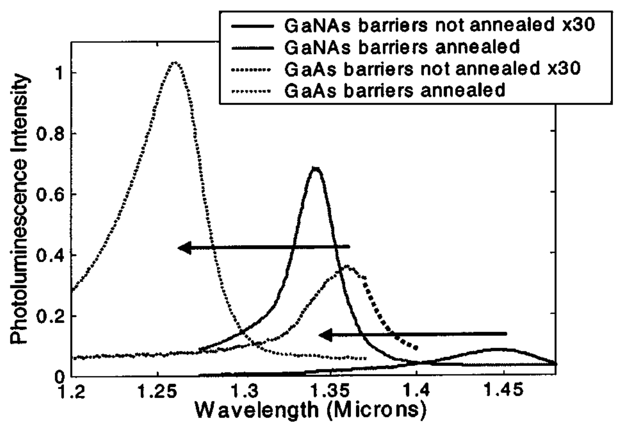

Fig. 2. PL comparison between GaAs barrier and GaNAs barrier structure.

430 °C. The ridge waveguide LDs have stripe widths of 5, 10, and 20 μm and cavity lengths were varied from 400 to 1500 μm. After cleaving, the devices are mounted on a temperature-controlled heat sink for room-temperature measurement as well as T_o measurement. Light output was measured using a calibrated broad area InGaAs photodiode. The optical spectrum was measured by coupling the output into an optical spectrum analyzer via a graded-index lensed multimode fiber.

III. Results

Fig. 2 compares photoluminescence (PL) measurements of GaInNAs–GaAs and GaInNAs–GaNAs samples. Both samples were annealed at 720 °C for 2 min, which has proven to be the optimum annealing temperature from our annealing studies. The sample with GaAs barriers shows a PL peak at 1.26 μm, while the GaNAs barrier sample has a PL peak at 1.34 μm. Additionally, because GaNAs barriers reduce the overall strain it becomes possible to grow many QWs because the critical thickness is effectively increased. This is of particular interest for high power device applications. Fig. 3 shows the PL intensity comparison between samples with a different number of QWs. The PL intensity increases superlinearly with the number of QWs, which will make it possible to use larger gain regions for high-power laser applications. We are able to grow up to nine QWs with a total quantum well thickness of 63 nm in spite of only a predicted 6-nm critical thickness for $Ga_{0.70}In_{0.30}NAs$.

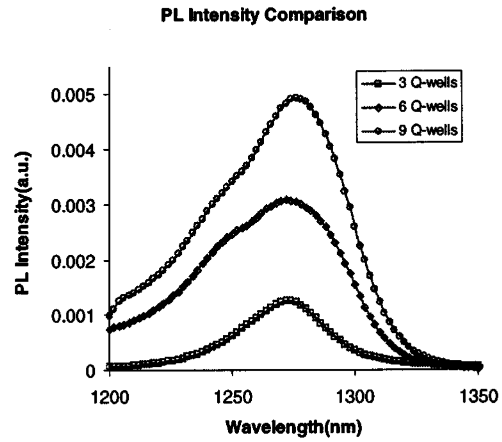

Fig. 3. PL intensity comparison with varying numbers of QWs.

A ridge waveguide LD with 3 $Ga_{0.68}In_{0.32}N_{0.015}As_{0.0985}$ QWs and $GaAs_{0.98}N_{0.02}$ barriers was grown and fabricated. This LD showed emission at 1.315 μm at $I = 1.2I_{\rm th}$ (Fig. 4). The light output versus injection current (L–I) and voltage versus injection current (V–I) are shown in Fig. 4. The turn-on voltage was less than 1 V proving that we have achieved excellent contacts and diode structure. Above threshold, the differential quantum efficiency (DQE) from both facets was 0.45 W/A. Devices were tested under pulsed conditions at various operating temperatures to characterize temperature dependence. The resulting L–I curves are shown in Fig. 5. These devices operate up to 95 °C. The T_o of these devices was around 65 K, relatively low compared to those of previously reported GaInNAs lasers [9]. This low T_o can be attributed to the low carrier confinement between QWs and barriers. The other important factor is the poor contact between our devices and copper block that further reduces T_o. The threshold current density for this sample was 1.5 KA/cm^2, which is approximately 500 A/cm^2 per QW. The maximum pulsed output power, from both facets, and without heat sink or AR/HR coating was 350 mW. This maximum power was reproducible without device failure and, to our knowledge, this is the highest power reported from GaInNAs QW LDs at this wavelength. The epitaxial layer design and device geometry used for our devices were not optimized for high power device application and with proper modification, higher output power can be achieved.

A laser with both higher indium (35%) and nitrogen (1.7%) compositions was grown to demonstrate longer wavelength emission than 1.3 μm. The output power versus injection current for a device with $Ga_{0.65}In_{0.35}N_{0.017}As_{0.0983}$ QWs and $GaAs_{0.978}N_{0.022}$ barriers is shown in Fig. 6. This inplane laser showed room temperature emission at 1.39 μm. The threshold current density for this sample was 2.1 KA/cm^2, which is approximately 700 A/cm^2 per QW. The slope efficiency from both facets was 0.67 W/A above threshold current and the maximum output power under pulsed conditions was 320 mW from both facets without a heat sink or AR/HR coating. This maximum output power was achievable without device failure. The maximum operating temperature was 70 °C without a heat sink. The longest wavelength we have observed to date from our GaInAs QWs LDs was 1.405 μm.

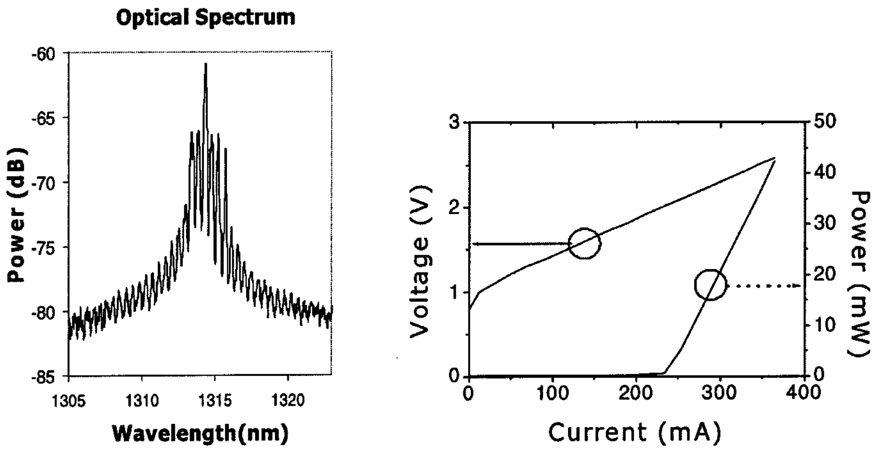

Fig. 4. $Ga_{0.68}In_{0.32}N_{0.015}As_{0.0985}$–$GaAs_{0.98}N_{0.02}$ laser results. Device dimensions are $20\ \mu m \times 770\ \mu m$.

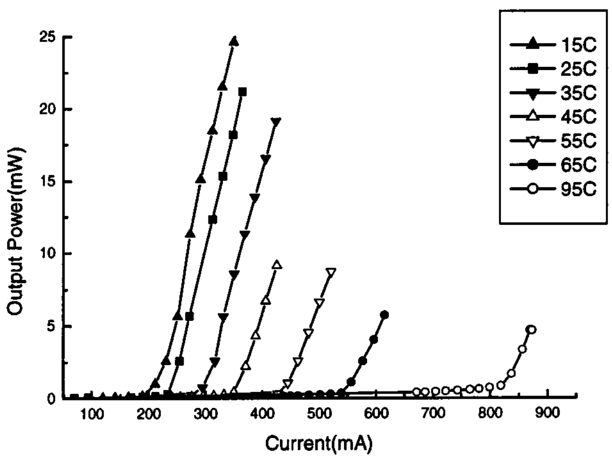

Fig. 5. Temperature-dependent device operation of a $20\ \mu m \times 600\ \mu m$ device.

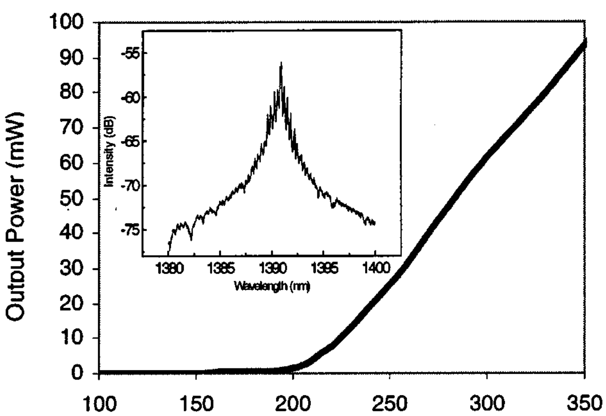

Fig. 6. L–I for the LD operating at room temperature of a $20\ \mu m \times 560\ \mu m$ device. D.Q.E. (from both facets) = 0.67 W/A (74.6%). Inset: Spectrum at 1.39 μm.

IV. Conclusion

We have demonstrated long wavelength GaInNAs MQW lasers with high efficiency (74.6%) and low threshold utilizing GaNAs barriers. Our devices exhibited 1.3–1.405-μm emission, 1.5-kA/cm^2 threshold current density, and maximum pulsed operation up to 350 mW. It is expected that reduced doping in the cladding will increase the maximum output power as well and lower the threshold current density. Optimized indium and nitrogen composition for these wavelengths will make possible even longer wavelength operation, with low threshold currents.

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