Low-Divergence Single-Mode Ridge Waveguide Diode Lasers

C. M. Harding, Y. C. Chen, R. J. Dalby, and R. G. Waters

Abstract—**Ridge waveguide laser diodes of a GaAs-AlGaAs separate-confinement graded-index monolithically stacked triple quantum-well structure have been fabricated. Results for 4-μm-wide by 600-μm-long optically coated devices are presented. Single-longitudinal mode, CW output power in excess of 90 mW, and a far-field divergence of 21° × 3.5° is demonstrated.**

INTRODUCTION

RESEARCHERS have, in recent years, striven to increase the overall output power and beam quality of single-mode GaAs-AlGaAs laser diodes. Pursuant to this goal, the major device configurations have been distributed feedback (DFB) lasers [1], distributed Bragg reflector (DBR) lasers [2], buried stripe lasers [3], and ridge waveguide lasers [4] (RWGL's). In addition, others have incorporated nonabsorbing mirrors [5] (NAM's) in their devices in order to increase output power and reliability. With the exception of RWGL's, the fabrication of these different architectures is quite complex. In this letter, we present results on optically coated 4-μm-wide RWGL's fabricated from a GaAs-AlGaAs separate-confinement graded-index monolithically-stacked triple quantum-well (TQW) structure [6], [7] which have a lateral divergence (parallel to the junction) of 3.5° and a transverse divergence (perpendicular to the junction) of 21°. To our knowledge, this is the lowest divergence for a single element device ever reported. In addition, we have obtained over 90 mW CW of single longitudinal mode output power.

STRUCTURE AND DEVICE FABRICATION

This new TQW structure was grown via metalorganic chemical vapor deposition (MOCVD) in a vertical chamber reactor. The group III sources were trimethylaluminum and trimethylgallium. The group V source was arsine and the dopant gases were diethylzinc and hydrogen selenide. The structure was grown on 2° off (100) Si-doped (2×10^{18} cm^{-3}) GaAs substrate. The epilayers are as follows: n-GaAs buffer, 0.5 μm (1×10^{18} cm^{-3}); n-Al$_{0.15}$Ga$_{0.85}$As buffer, 1.0 μm (1×10^{18} cm^{-3}); n-Al$_{0.60}$Ga$_{0.40}$As confinement layer, 1.1 μm (5×10^{17} cm^{-3}). The next eleven layers are the monolithically stacked graded-index, quantum well layers. There are three undoped GaAs quantum wells, each surrounded by AlGaAs graded layers with a AlGaAs ($x = 0.60$) spacer layer separating the three graded index (GRIN)/QW regions. The structure was grown so that the junction was coincident with the central well. The central QW thickness is 100 Å and both the satellite wells are 50 Å thick. The graded layers for all three wells are 0.2 μm thick and the aluminum concentration was linearly graded from 60% down to 30% prior to the growth of each well and graded from 30% up to 60% after the QW was grown. The two spacer layers are both 0.6 μm thick. The spacer in the p-type region was nominally undoped, as were the graded regions in the p-type region. The spacer and the graded regions in the n-type region were doped to 1×10^{17} cm^{-3}. The following epilayers finish the structure: p-Al$_{0.60}$Ga$_{0.40}$As confinement layer, 1.1 μm (5×10^{17} cm^{-3}); and a p-GaAs cap layer, 0.1 μm (1.5×10^{19} cm^{-3}). The growth was carried out at 800°C and at atmospheric pressure. Fig. 1 shows the aluminum composition as a function of depth in the TQW structure. Although we have referred to the complete structure as a triple quantum well (TQW), it should not be confused with a multiquantum well structure. The spacing between wells in our structure is 1 μm.

The devices were fabricated as follows. Chemically assisted ion beam etching (CAIBE) was used to etch a 4-μm-wide mesa which serves as the waveguide for the device. The structure was etched to a depth of 0.62 μm which resulted in a quantum well (uppermost) to etched surface distance of 0.50 μm. Silicon dioxide was then deposited on the p-side of the wafer and 2-μm-wide stripes were opened on top of the etched mesas. Subsequently, titanium-platinum-gold and gold-germanium-nickel metallizations were deposited on the p and n sides of the wafer, respectively. The devices were then annealed and a titanium-tungsten-gold bonding metallization was deposited on the n-side. Next, the wafer was cleaved into bars which were optically coated. The back facet was coated with a high reflecting (HR) film which consists of a six-layer stack of alternating quarter-wave-thick layers of silicon and aluminum oxide. A quarter-wave-thick layer of zirconium oxide was deposited on the emitting facet to form an anti-reflecting (AR) coating. The reflectivity of the HR and AR are 98 and 0.5%, respectively. The coated bars were subsequently cleaved into individual devices and bounded junction side up to a copper heat sink. Greater detail of the RWGL fabrication process can be found elsewhere [8].

RESULTS AND DISCUSSION

As would be expected from a device which has such a low reflectivity AR coating, the threshold current density of the coated RWGL was increased significantly compared to an uncoated device. At 30°C the CW threshold current density of the former was 2671 A/cm^2 and that of the latter was 1354 A/cm^2. The CW differential external quantum efficiency of the coated devices was 78% (82% uncoated). Fig. 2 is a plot of intensity versus wavelength for one of the coated triple quantum well (TQW) RWGL diodes operating with approximately 100 mW output power. As can be seen from this figure, this laser is operating in a single longitudinal mode. Fig. 3 is a superposition

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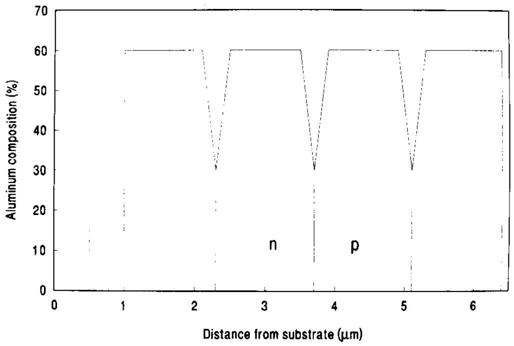

Fig. 1. Aluminum composition versus thickness for the TQW structure.

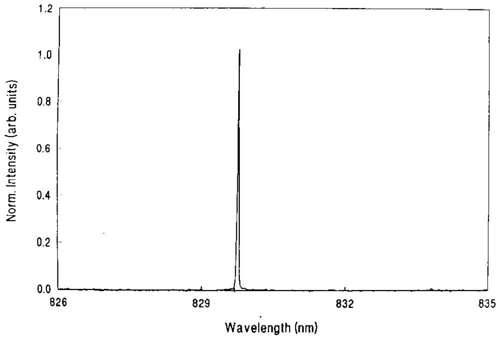

Fig. 2. Intensity versus wavelength for a 4 × 600 μm TQW-RWGL operating with 100 mW output power.

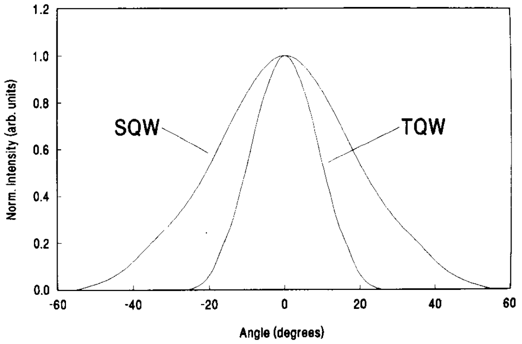

Fig. 3. Intensity versus transverse far-field divergence angle for a 4 × 600 μm TQW-RWGL (FWHM = 21°) and a 5 × 600 μm SQW-RWGL (FWHM = 42°). Output power = 100 mW.

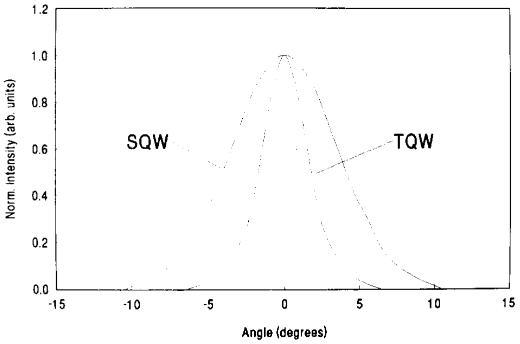

Fig. 4. Intensity versus lateral far-field divergence angle for a 4 × 600 μm TQW-RWGL (FWHM = 3.5°) and a 5 × 600 μm SQW-RWGL (FWHM = 8°). Outpower = 100 mW.

of intensity versus angle for the transverse far-fields of a 5-μm-wide RWGL fabricated from a single-quantum well (SQW) structure and a 4-μm-wide RWGL fabricated from the triple quantum well structure. This figure shows that the full width half maximum (FWHM) divergence of the transverse far-field has been reduced by a factor of two from approximately 42° for the SQW to 21° for the TQW. A comparable reduction in the divergence of the lateral far-field has also been achieved. Fig. 4 compares lateral far-fields for the same SQW and TQW-RWGL. The FWHM divergence of the SQW and TQW devices are 8° and 3.5°, respectivley. As was the case in Fig. 2, the far-fields in Figs. 3 and 4 were recorded when the output power for both the TQW and SQW-RWGL's was approximately 100 mW (2.2 × I_{th} for the TQW device). At drive currents greater than this, the operation of the TQW devices becomes multimode in the lateral direction. The transverse far-field remains single lobed over all current ranges.

The divergence of the transverse far-field is controlled by varying the width and spacing between each of the three quantum wells. When varying these two parameters it is necessary to meet two conditions. The three wells must be spaced so that sufficient optical coupling results and the effective source size is increased resulting in a narrowing of the divergence. Additionally, the well width and spacing must be tailored to force the operation of the fundamental transverse mode while suppressing higher order modes. This was done empirically on broad-area devices. A high resolution near field measurement of the TQW-RWGL's reveals three distinct lobes with the central lobe having the greater intensity. The outermost lobes have reduced, but equal, intensities. A similar structure described by Chen *et al.* [9] incorporates three GRIN regions but contains only one QW sandwiched between the centermost graded layers. The near field measurement obtained by Chen is very similar to what we have found for the TQW structure, in that case because it is an allowed waveguide mode. Consequently, the occurrence of satellite lobes does not necessarily imply recombination in all wells. Device measurements [6], [7] however, suggest that all wells are inverted in which case in-phase coupling will be favored when the satellite (slave) quantum wells depend partially on photon pumping from the central (master) well to achieve lasing.

The reduction in the lateral far-field divergence is due to an increase in current spreading which increases the emitting width in the TQW-RWGL as compared to a SQW device. The distance from the etched surface to the pn junction has been increased from ~ 0.5 μm in a SQW-RWGL to ~ 1.0 μm. As a result, the width of the near-field of the TQW-RWGL was measured to be 8 μm (FWHM), whereas the width of the near-field of a RWGL fabricated from SQW material is typically 4 μm. Regarding the modal properties, the greater embedment of the near-field centroid weakens the guiding sufficiently to insure modal discrimination despite the large (8 μm) effective source size. Our calculations indicate that the resulting effective index steps is $\sim 10^{-4}$. Hence, the TQW-RWGL's are not strongly index guided devices.

SUMMARY

In summary, single longitudinal mode ridge waveguide diode lasers have been fabricated from a new triple GRIN/QW structure which results in a reduction of the beam divergence in both directions by more than a factor of two as compared to the same device architecture fabricated from a standard GRINSCH-SQW structure.

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REFERENCES

[1] Y. Luo, Y. Nakano, K. Tada, T. Ionue, H. Hosomatsu, and H. Iwaoka, "Purely gain-coupled distributed feedback semiconductor lasers," *Appl. Phys. Lett.*, vol. 56, pp. 1620-1622, 1990.

[2] O. Ishida, H. Toba, Y. Tohmori, K. Oe, "Multielectrode DBR laser diode for wide bandwidth and flat FM response," *Electron. Lett.*, vol. 25, pp. 703-704, 1989.

[3] L. J. Mawst, G. Costrini, C. A. Zmudzinski, M. E. Givens, M. A. Emanuel, and J. J. Coleman, "Complementary self-aligned laser by metalorganic chemical vapour deposition," *Electron. Lett.*, vol. 21, pp. 903-905, 1985.

[4] F. R. Gfeller and D. J. Webb, "Degradation and lifetime studies of high-power single-quantum-well AlGaAs ridge lasers," *J. Appl. Phys.*, vol. 68, pp. 14-20, 1990.

[5] H. Shimizu, "Long-life GaAlAs high-power lasers with nonabsorbing mirrors," in *Proc. SPIE*, Los Angeles, CA, 1989, vol. 1043, pp. 76-80.

[6] R. G. Waters, M. A. Emanuel, and R. J. Dalby, "Integrated quantum-well manifold laser," *Appl. Phys. Lett.*, vol. 66, pp. 961-963, 1989.

[7] R. G. Waters, Y. C. Chen, and R. J. Dalby, "Monolithically stacked quantum well lasers," in *Proc. SPIE*, Los Angeles, CA, 1990, vol. 1219, pp. 69-78.

[8] C. M. Harding and R. G. Waters, "Long-lived dry-etched AlGaAs-GaAs ridge waveguide laser diodes," *Appl. Phys. Lett.*, vol. 56, pp. 2175-2176, 1990.

[9] Y. C. Chen, R. G. Waters, and R. J. Dalby, "Single quantum well laser with vertically integrated passive waveguides," *Appl. Phys. Lett.*, vol. 56, pp. 1409-1411, 1990.