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Low-Loss Low-Confinement GaAs–AlGaAs DQW Laser Diode with Optical Trap Layer for High-Power Operation

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***Abstract*— A low-confinement asymmetric GaAs–AlGaAs double-quantum-well molecular-beam-epitaxy grown laser diode structure with optical trap layer is characterized. The value of the internal absorption coefficient is as low as 1.4 cm^{-1}, while keeping the series resistance at values comparable with symmetrical quantum-well gradient index structures in the same material system. Uncoated devices show COD values of 35 mW/μm. If coated, this should scale to about 90 mW/μm. The threshold current density is about 1000 A/cm^2 for 2-mm-long devices and a considerable part of it is probably due to recombination in the optical trap layer. Fundamental mode operation is limited to 120–180 mW for 6.5-μm-wide ridge waveguide uncoated devices and to 200–300 mW for 13.5-μm-wide ones, because of thermal waveguiding effects. These values are measured under pulsed conditions, 10 μs/1 ms.**

***Index Terms*—Charge injection, current density, leakage currents, ridge waveguides, semiconductor lasers.**

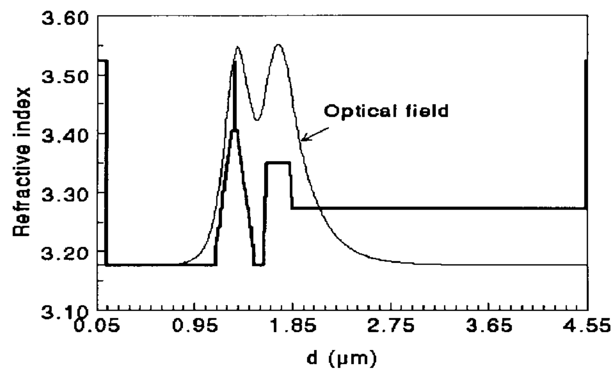

Fig. 1. Refractive index and optical field ($|E|^2$) profile along the growth direction of the asymmetric structure with optical trap layer. The optical trap layer on the n-side of the structure shifts the maximum of the field distribution.

I. Introduction

For quantum-well (QW) semiconductor laser structures, optimization for high-power operation at current densities of 2000–3000 A/cm^2 can be realized with lower values of the confinement factor in the active region, if the threshold current density is below about 500 A/cm^2 [3]–[5]. The optimum value of the confinement factor should be about three times smaller than in usual gradient index (GRIN) symmetrical structures. This can hardly be accomplished using a symmetrical design due to practical limitations related to the thickness of the confinement layers. From the optical point of view, a more flexible approach would employ an asymmetric transversal layer design. The aim of this paper is to report results on devices using a new transversal design with an "optical trap" layer, which shifts the maximum of the optical field away from the active region.

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II. The Structure

Unlike the approach used in [3], that is a 1-μm large optical waveguide, we use here an 0.17-μm-thick $Al_{0.20}Ga_{0.80}As$ "optical trap" on the n-side of the active region, as shown in Fig. 1.

Table I presents the transversal sequence of layers grown by MBE. The optical field extension is restricted in the p-side of the structure and is extended toward the n-side. Thus, the series resistance and free-carrier losses are minimized. As described in [3]–[5], the achievement of structures with absorption coefficient values around 1 cm^{-1} is an important requirement for low-confinement laser diodes, in order to operate at the same material gain as usual GRIN devices with a reasonable differential efficiency. The confinement factor is $\Gamma = 7.5 \times 10^{-3}$ per QW and the corresponding spotsize is 1.07 μm, larger than around 0.55 μm for symmetric structures with increased spot size [1], [2].

III. Experimental Results: Threshold Current Densitiy and Differential Efficiency

Fig. 2(a) and (b) presents the threshold current density and the inverse of the differential efficiency respectively, both as a function of device length in pulsed conditions, 10-μs

TABLE I

layer type	Al composition index	thickness (μm)	type	doping (cm^{-3})
p^{++} contact	0.00	0.10	p^{++}	> 2 x 10^{18}
p confinement	0.50	1.00	p	5 x 10^{17}
grading	0.50-0.20	0.10	-	undoped
QW	0.00	0.008	-	undoped
barrier	0.20	0.100	-	undoped
QW	0.00	0.008	-	undoped
grading	0.20-0.50	0.10	-	undoped
n confinement	0.50	0.05	-	undoped
optical trap	0.20	0.17	n	5 x 10^{16}
n confinement	0.37	0.20	n	1 x 10^{17}
n confinement	0.37	2.30	n	5 x 10^{17}
n^{++} substrate	0.00		n	2 x 10^{18}

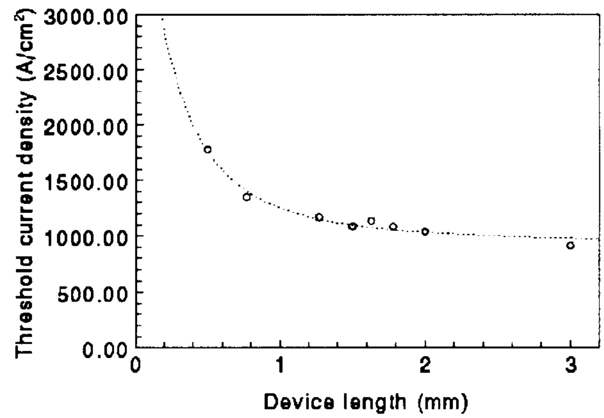
pulsewidth, duty factor $F = 1/100$. The internal absorption coefficient is as low as 1.4 cm^{-1} and the internal efficiency is as high as 90%. The low value of the internal absorption is due to lower doping levels and to the limited extension of the field in the p-type layer. The value of the series resistance of our devices is about 2.0×10^{-4} $\Omega \cdot cm^2$ and is comparable to the values reported for usual GaAs–AlGaAs QW GRIN symmetric structures.

These data refer to two types of weakly index-guided ridge devices. For the first, the ridge is defined by repeated anodic oxidation and the ridge is strongly underetched, the ridge width increasing from 5.5 μm at the top to 13.5 μm at the bottom, the etch depth being 0.94 μm. Nevertheless, the etch is quite uniform and the etch depth is very precisely controlled. In the second case, a wet etch based on citric acid and H_2O_2 mixture was used to define the ridge having the width of about 6.5 μm at the bottom.

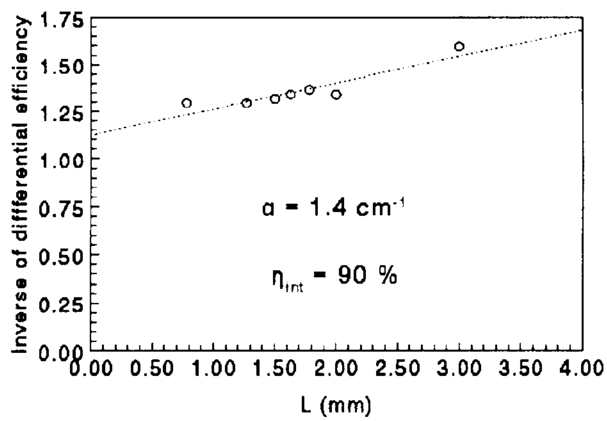
The obtained threshold current density of about 1000 A/cm^2 for 2–3-mm-long laser diodes is larger than expected. The target of our design is around 500 A/cm^2. Still, it is a considerable improvement if we compare with values larger than 2500 A/cm^2 reported in [3] using a different asymmetric design.

This relatively high value of the threshold current density may be due to imperfections of the QW themselves but it might also be related to nonradiative recombination outside the QW including the optical trap layer. In the experimental spectra below and above threshold no contribution of radiative recombination in the optical trap layer was observed. If we use a similar aymmetric structure, but having InGaAs QW's and an optical trap layer with Al content $x = 0.30$ (to be published), the threshold current density significantly decreases down to about 250 A/cm^2. This improvement may be due to decreased nonradiative recombination in the optical trap layer.

If we examine the dependence of the threshold current density as a function of temperature shown in Fig. 3(a), we observe at low temperatures a nonlinear behavior having a maximum around 140 K and different shapes of light output versus current (L–I) curves when decreasing the temperature



(a)



(b)

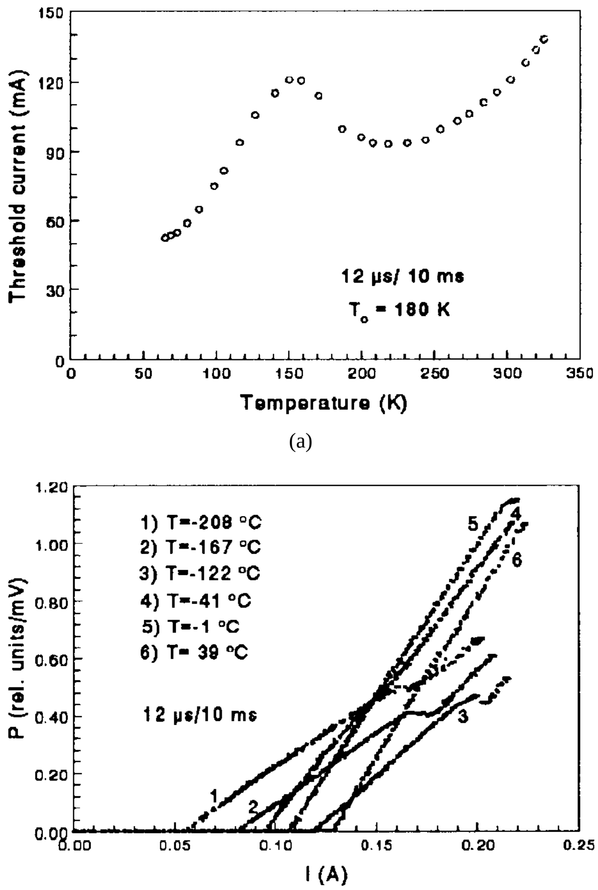
Fig. 2. (a) Plot of the threshold current density as a function of device length under pulsed conditions (10-μs pulselength/1 ms repetition time). (b) The inverse of the differential efficiency as a function of device length under the same conditions.

toward 77 K, as in Fig. 3(b). A possible explanation is that the Shockley–Read–Hall lifetime shows a substantial reduction with decreasing temperature [7] so that the nonradiative recombination in the optical trap layer, which is already large at room temperature, becomes dominant at low temperatures. Concerning the behavior of the differential efficiency, a possible explanation is that carriers get "hot" as a consequence of increasing the barrier to carrier transport in the vicinity of the active region as T is reduced [11].

IV. COD Degradation and Fundamental Mode Operation

The devices were mounted p-side down with AuSn alloy on Si submounts. Measurements were made in pulsed conditions, 10-μs pulsewidth and 1 ms between pulses. As reported in [8], for uncoated devices the COD level for pulses larger than 10 μs should be about the same as for CW operation. The lasing wavelength is 850–855 nm, depending on device length and pulsewidth.

Fundamental mode operation for weakly index guided devices ($\Delta n_{\text{eff}} = 1 \times 10^{-3}$) is mainly limited by thermal effects and depends on p-down or p-up mounting. For p-down mount, the stable regime is found to be up to 120–180 mW/facet for 6.5-μm-wide ridge waveguide laser diodes and 200–300 mW



(a)

(b)

Fig. 3. (a) Threshold current for the asymmetric structure with optical trap layer as a function of temperature. (b) L–I curves for different temperatures ($T = 65$–312 K) for a $L = 0.78$-mm-long device having the ridge width $w = 13.5$ μm, under pulsed conditions (10-μs pulselength/10-ms repetition time).

for 13.5-μm ridge width. These values will be lower for p-up mount. These values are expected to be further improved for devices with coated mirrors [9]. Above this range of output power, kinks are observed in the L–I curves, associated with significant distortions of both far-field and temporal shape of the optical pulse and with broadening of the spectrum. This is attributed to temperature-gradient induced waveguiding in the lateral direction and will be reported in a separate work.

Nevertheless, the maximum output power before COD is as high as 250 mW for 6.5-μm-wide ridge waveguide devices and 460 mW for 13.5-μm ones, which means about 35 mW/μm mean value for uncoated devices and 6.4-MW/cm^2 internal power density at the facet. These values are 2.7–3 times higher than those reported for symmetric GRIN structures not optimized for high-power operation [10]. For coated mirrors, these values should scale with a factor of 2.5 [8] or even 4–5 [12] and would correspond to at least about 88 mW/μm, which would be a factor of 2.7–3 times higher than for symmetric GRINSCH devices optimized for low threshold.

Other authors reached higher output powers by using Al free InGaAs based laser structures [13]. Optimization of spotsize in symmetric structures was reported in wide stripe lasers in [1], [2].

V. Conclusion

This letter describes a new semiconductor GaAs–AlGaAs DQW laser structure for high-power operation, which uses a separate "optical trap" layer on the n-side of the active region to lower the confinement factor, down to 7.5×10^{-3} per QW. The structure shows very low values for the absorption coefficient, i.e., $\alpha \approx 1.4$ cm^{-1} and high COD output power levels, i.e., 35 mW/μm for uncoated devices, which represents a factor of 2.7–3 times improvement if compared with common GaAs–AlGaAs GRIN structures optimized for low threshold. The threshold current density is about 1000 A/cm^2 for 3-mm-long laser diodes. Operation in the fundamental lateral mode is thermally limited to 120–180 mW for 6.5-μm-wide ridge waveguide devices and to 200–300 mW for 13.5-μm-wide ones.

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