High-Performance Laser Diodes With Emission Wavelengths Above 1100 nm and Very Small Vertical Divergence of the Far Field

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***Abstract*—The effect of variations in the vertical structure on the performance of AlGaAs–GaAs laser diodes with an InGaAs quantum well (QW) emitting around 1120 nm was investigated. With very thick waveguide layers, more than 95% of the output power is enclosed in an angle smaller than 35°. This allows the use of fast axis collimators with a small numerical aperture. Broad area laser diodes with 100-μm stripe width, an optimized doping profile, and a double QW emit more than 12 W and show reliable operation at 5 W.**

***Index Terms*—Epitaxial growth, laser reliability, quantum well (QW) lasers, semiconductor lasers.**

I. INTRODUCTION

DUE TO their high output power potential, GaAs-based laser diodes in the wavelength range at and beyond 1100 nm are interesting as pump sources for Raman amplifiers in telecommunication systems, for pumping up-conversion fiber lasers or direct material processing without transfer of optical power to fiber or solid state lasers [1], [2].

For several applications, it is necessary to adjust the emission wavelength exactly to obtain high efficiencies of the whole system; for other applications, additionally, a high output power or a low vertical beam divergence is required. Such a low vertical beam divergence allows the use of fast axis collimators with a numerical aperture of only 0.5 and, thus, relatively large adjustment tolerances. For high optical output power structures with a high differential efficiency η_D and a large equivalent vertical spot size d/Γ (d is the quantum-well (QW) thickness, Γ the confinement factor) are necessary [3].

Laser diodes emitting beyond 1100 nm need a high indium content in the InGaAs QW. Such highly strained layers are grown favorably at low temperatures to avoid strain relaxation or three-dimensional growth. Contrary, Al containing layers are grown typically at higher temperatures for better layer properties, especially a low oxygen contamination [4]. On the other hand, at these long wavelengths, GaAs already forms sufficient barriers for the carriers so that GaAs can be used as waveguide layer (WL) around the QW. The lower affinity of GaAs to oxygen and point defect incorporation allows the use of lower growth temperatures. An additional advantage of GaAs compared to AlGaAs is its higher thermal and electrical conductivity. GaAs WLs will reduce resistive heating and facilitate the removal of heat from the active region. Therefore, such structures have the potential for a very high optical output power [5].

This letter deals with the effect of different vertical layer designs on the performance of laser diodes with emission wavelengths λ between 1120 and 1150 nm. Based on these investigations, high output powers of more than 10 W are demonstrated.

II. GROWTH AND FABRICATION

Growth by metal–organic vapor phase epitaxy was carried out in an Aixtron 200/4 reactor on exactly oriented (001) GaAs substrates. Precursors were pure arsine, phosphine, and the trimethyl compounds of gallium (TMGa), indium (TMIn), and aluminum (TMAl). For p-type doping dimethyl zinc or carbon and for n-type doping disilane diluted in hydrogen were used.

The laser structure consists of a single or double InGaAs QW embedded in thick GaAs WLs and $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ $(x = 0.25)$ cladding layers (CLs). On top of the p-CL is a highly p-doped GaAs contact layer. The structure is designed for a small vertical far field by using very thick WLs. The target specification is to include more than 95% of the output power in an angle smaller than 35°. Higher order vertical modes are suppressed by loss discrimination due to radiation into the substrate. The thickness of the n-CL is optimized in order to achieve low losses only for the fundamental mode. The broad GaAs WLs are undoped in the inner part and lowly doped $(< 5 \cdot 10^{17}\ \mathrm{cm}^{-3})$ toward the CLs. This results in reduced free carrier absorption and low internal optical losses α_i. Therefore, the use of very long cavity lengths is possible, which again improves the heat removal.

In all cases, the InGaAs QWs were grown at 530 °C, while the (Al)GaAs WLs and CLs were grown at temperatures between 570 °C and 770 °C. To adjust the necessary growth temperature, the growth was interrupted between the spacer layers surrounding the QW and the WLs. The growth process is described more in detail in [6].

Although the QW thickness of 6 nm at an In content of 35% in the QW is near the critical thickness of about 8 nm for the single QW (SQW) and exceeds the critical thickness for the double QW (DQW), cathodoluminescence images show no hints for the formation of defects. Also high resolution X-ray investigations show no indications for strain relaxation in the QWs.

The structures were processed into broad-area laser diodes with 60-, 100-, and 200-μm stripe width and cavity lengths L from 1 to 4 mm. The transparency current density j_{tr} and other

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Manuscript received November 29, 2004; revised February 8, 2005.

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Digital Object Identifier 10.1109/LPT.2005.846927

TABLE I

PROPERTIES OF UNMOUNTED AND UNCOATED BROAD-AREA LASER DIODES WITH 100-μm STRIPE WIDTH FOR DIFFERENT STRUCTURES IN PULSED OPERATION. FOR STRUCTURES A–C, EMISSION WAVELENGTH (λ), THRESHOLD CURRENT DENSITY (j_{th}), AND SLOPE EFFICIENCY (η_D) WERE DETERMINED FOR 2 mm LONG; FOR STRUCTURES C1–C3 FOR 1-mm-LONG DEVICES. (j_{tr}: TRANSPARENCY CURRENT DENSITY. ΓG_0: MODAL GAIN COEFFICIENT. η_i: INTERNAL EFFICIENCY. α_i: INTERNAL OPTICAL LOSS. d_{WL}: WL THICKNESS OF ONE SIDE. $d_{\mathrm{WL\text{-}und}}$: UNDOPED PART OF WL)

type	d_{WL} (µm)	λ (nm)	j_{th} (A/cm^2)	η_D (%)	j_{tr} (A/cm^2)	ΓG_0 (cm^{-1})	η_i (%)	α_i (cm^{-1})	T_0 (K)	remarks
A	1.0	1126	173	39	43	9.9	89	8.0	56	SQW
B	1.7	1114	177	42	64	7.2	58	2.0	66	SQW
C	1.7	1139	203	72	128	13.8	77	0.4	81	DQW
C1	1.7	1118	320	82	131	12.7	85	0.9	76	$d_{WL\text{-}und.}$ = 1 µm
C2	1.7	1120	341	81	117	11.6	92	1.4	76	$d_{WL\text{-}und.}$ = 0.4 µm
C3	1.7	1116	363	78	116	12.3	97	3.2	71	$d_{WL\text{-}und.}$ = 0.1 µm

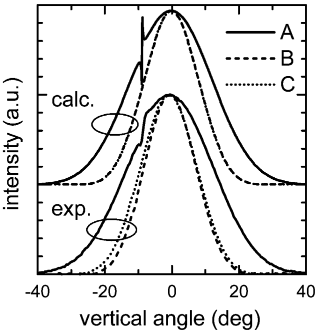

Fig. 1. Calculated and experimentally obtained vertical far-field distribution for structures with different thicknesses of the WL (see Table I).

figures of merit were determined from the cavity length dependence of threshold current density j_{th} and differential efficiency η_d under pulse conditions with a pulsewidth of 400 ns and a duty cycle of 1 : 400, assuming a logarithmic dependence of the gain on current density. For testing under continuous-wave (CW) conditions, the output facet of 4-mm-long laser diodes was antireflection coated to 7% reflectivity and the back facet to values larger than 95%, respectively, after a passivation process [7]. The chips were mounted p-side down on CuW submounts with AuSn solder and on C-mounts.

III. RESULTS AND DISCUSSION

Large optical cavity structures with 1-μm broad GaAs WLs on both sides of the QW have a half-width of the vertical far field (FWHM) of 30° (Table I, Structure A). The distortion of the far-field profile is related to the leakage of the laser light into the substrate, because its effective index is smaller than the refractive index of highly doped GaAs. Increasing the waveguide (WG) thickness to 1.7-μm shifts the effective index above the refractive index of the substrate, the leakage effect vanishes, and the FWHM angle reduces to 18° (Structure B in Fig. 1 and Table I) at the cost of an only slightly increased threshold current density at cavity lengths above 2 mm. The increased WG thickness allows to reduce the thickness of the AlGaAs CLs on both sides from 900 to 450 nm. Fig. 1 shows also the good correspondence between calculated and experimental far fields.

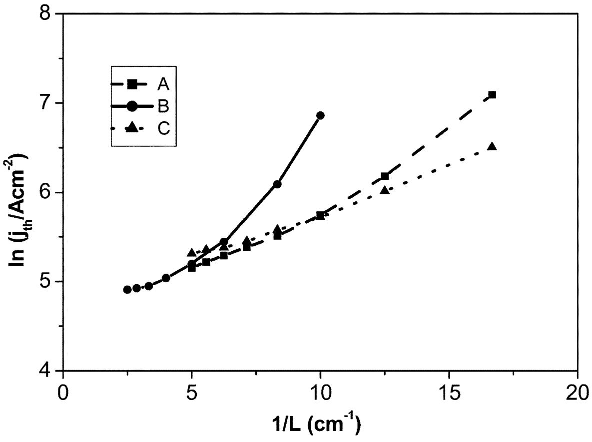

Fig. 2. Threshold current density versus the inverse cavity length for devices with 100-μm stripe width from different structures.

To additionally reduce the relatively high internal optical loss of Structure A only the thickness of the undoped part of the WL was increased. Mainly, the light is guided in undoped GaAs, which results in a reduction of α_i from 8 to 2 cm^{-1}. Due to the decrease of the filling factor Γ from 0.49% to 0.35%, the modal gain coefficient ΓG_0 decreases from 10 to 7.2 cm^{-1}. Fig. 2 shows the dependence of the threshold current density on the inverse cavity length for different structures. From the slope of the tangents and their points of intersection with the ordinate, the modal gain can be estimated. Due to the broad undoped WG in Structure B and the resulting low modal gain coefficient, the threshold current increases drastically at resonator length below 2 mm in accordance with

$$\ln \frac{j_{\mathrm{th}}}{j_{\mathrm{tr}}} = \frac{\alpha_i}{\Gamma G_0} + \frac{\ln \frac{1}{R}}{\Gamma G_0} \cdot \frac{1}{L} \tag{1}$$

where R is the reflectivity of the uncoated facets ($R \approx 0.3$).

From the dependence of the differential efficiency η_D on cavity length, the internal efficiency η_i can be obtained in accordance to

$$\frac{1}{\eta_D} = \frac{1}{\eta_i} \cdot \left(1 + \frac{\alpha_i \cdot L}{-\ln R}\right). \tag{2}$$

The higher thickness of the undoped WL additionally leads to a reduced internal efficiency.

For a better performance of these laser diodes, the thickness of the undoped part of the WGs can be reduced [8] or the SQW has to be substituted by a multiple QW. When the SQW of Structure B is replaced by a DQW (Structure C) with a 140-nm GaAs barrier between the two QWs, the transparency current density and the modal gain coefficient is doubled as expected. The threshold current density is only increased by about 10% by the second QW, while the internal efficiencies η_i increase from 58% to 77% and the internal losses α_i decrease from 2 to below 1 cm^{-1}.

A severe problem of these structures is the small effective electron barrier of about 160 meV between the InGaAs QW and the GaAs WG which leads to a correspondingly large excess electron density in the WG at and above threshold. An increase of the number of QWs decreases the excess electron density in the WG due to the reduced threshold carrier density in the QWs. Therefore, the absorption by excess carriers and the recombination rate of electrons and holes in the WG is diminished which

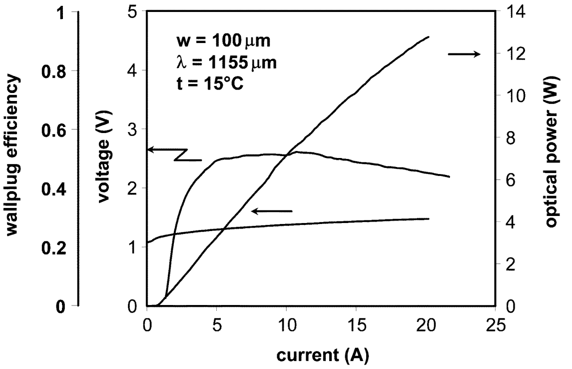

Fig. 3. CW optical output power, forward voltage, and wall plug efficiency versus current for a laser diode with emission wavelength of 1155 nm.

results in a decreased value of α_i and an increased value of η_i. The additional QW drastically improves the laser performance at the expense of a slightly broader width of the vertical far field. The FWHM increases from 18° to 20° (Fig. 1), but 95% of the output power are included in an angle of 35°.

The effect of different doping profiles on the internal efficiency was investigated by varying the thickness of the undoped part of the WL (Table I, Structures C1-C3). All three structures were grown with a DQW using 100-nm GaAs barrier between the QWs. Reducing the undoped region in the WL from 1 to 0.1 μm at a constant thickness of the entire WL of 3.4 μm, the internal efficiency increases from 85% to 97% again caused by a reduction of the electron leakage current. But in this case, α_i also increases from 0.9 to 3.2 cm^{-1} due to an increased absorption by free carriers stemming from the doping. For the use of longer cavity lengths and, therefore, a better heat dissipation at high power, a low value of α_i is more favorable. The effect of broader undoped WGs on the operating voltage is rather low and in the range of 0.1 V at a current of 2 A.

To investigate the potential of these laser diodes, a structure of Type C was processed for CW characterization. The resonator length was chosen to 4 mm. The facets were antireflection and high-reflection coated. The chips were mounted p-side down on copper–tungsten submounts with AuSn solder and on C-mounts finally. In Fig. 3, the optical power and wall plug efficiency are plotted versus the operating current. Despite the relatively low differential efficiency, the wall plug efficiency rises to more than 50%. Due to the low series resistance, the wall plug efficiency drops at a current of 20 A only slightly below 50%. The maximum output power was more than 12 W from a 100-μm-wide broad area laser which was limited by thermal rollover. No indication of catastrophic optical mirror damage was found. To the best of our knowledge, this is amongst the highest CW powers ever published for 100-μm-wide lasers with such a small far field. This very small FWHM of 20° makes this structure especially suitable for a nonsophisticated beam collimation and fiber coupling.

Lifetime tests were performed for 4-mm-long laser diodes emitting at 1150 nm with 60- and 100-μm stripe width at 3- and 5-W optical output power (Fig. 4). After more than 5000 h, there was no noticeable degradation, indicating the excellent crystallographic perfection of the highly strained InGaAs QWs used in these devices.

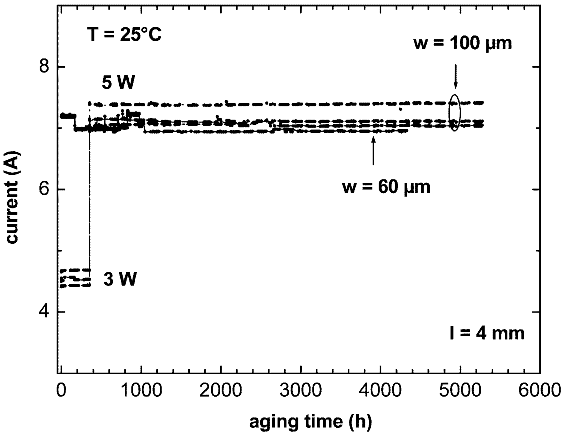

Fig. 4. Aging behavior of laser diodes with emission wavelength of 1155 nm at a constant optical output power of 5 W at 25 °C.

IV. CONCLUSION

The effect of variations of the layer thickness and doping on the performance of laser diodes with emission wavelengths between 1120 and 1150 nm has been investigated. Increasing the WG thickness and reducing the carrier concentration in the WG, laser diodes can be fabricated with resonator length of 4 mm and a very small far field. The low internal efficiency of such structures can be compensated by introducing an additional QW. From such structures, very high output powers of more than 12 W can be obtained for 100 μm× 4 mm laser diodes. Despite the high indium content in the QW, the laser diodes with 60-μm stripe width show a negligible degradation rate at 5-W output power.

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