PACS numbers: 42.55.Px; 42.60.Jf; 42.60.Lh
DOI: 10.1070/QE2004v034n09ABEH002742

Single-mode ridge lasers fabricated in an inductively coupled plasma source

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***Abstract*. The parameters of 0.98-μm laser diodes with a narrow ridge waveguide fabricated by low-energy ion – chemical etching using an inductively coupled plasma source are studied. It is shown statistically that, when the geometrical parameters of ridge waveguides correspond to the results of calculations, the production of acceptable 150 – 200-mW diodes can achieve 78%. It is found that the optical properties of a waveguide in the perpendicular direction substantially affect the percent of production of diodes with a specified output power. When conventional $SiO_2 - ZrO_2$ optical coatings were used, the maximum single-mode power (220 – 230 mW) was limited by the degradation of mirror faces.**

Keywords: *laser diodes, active element, ridge waveguide, inductively coupled plasma source.*

1. Introduction

The increasing requirements to the power and lasting quality of single-mode lasers stimulate the improvement of their design and manufacturing technology. One of the most important stages of fabrication of widely used ridge-waveguide lasers is ion – chemical etching (ICE) of the ridge. This process determines the shape and width of the ridge and also the etching depth of the upper emitter layer required for the efficient side optical confinement. It is also important to minimise radiative effects produced in surface layers upon ion etching. The authors of papers [1, 2] described the formation of narrow ICE ridges with the help of an inductively coupled plasma (ICP) source [3] emitting ~ 150-eV particles. A low level of defect formation observed in Ref. [2] gives promise that the ICE process can be excluded from the factors restricting the service life of these lasers. At the same time, the ridge shape differs somewhat from the shape produced upon etching by 350-eV particles in an HF diode system, which was used to obtain 200-mW cw lasing with a good quality laser beam [4].

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Received 16 April 2004
Kvantovaya Elektronika **34** (9) 805 – 808 (2004)
Translated by M.N. Sapozhnikov

In this connection it is interesting to verify the coincidence of the energy and optical parameters of ridge lasers with the 'low-energy' ridge shape by using the calculated ridge width W and the residual width Δh of the emitter layer within the framework of model [4].

2. Experimental results

Laser diodes were fabricated using three epitaxial structures with two quantum-well layers prepared by MOS hydride epitaxy, which had somewhat different compositions of emitter and waveguide layers (Table 1). All the laser diodes emitted at ~ 0.98 μm. The design of a ridge laser is shown in Fig. 1.

Ridges were fabricated in a modified ERA-2M ICE unit with an ICP source. An active element with a ridge waveguide was made using calculations [4] performed for

Table 1. Parameters of epitaxial structures (d is the layer thickness, x_{Al} is the Al content in $Al_xGa_{1-x}As$).

Structure number	Epitaxial structure			
	Waveguide layer		p-emitter layer	
	$d/\mu m$	x_{Al} (%)	$d/\mu m$	x_{Al} (%)
I	0.3	26	1.5	32
	0.3	26	1.5	32
II	0.3	30	1.5	40
	0.3	30	1.5	40
III	0.3	30	1.67	38
	0.3	30	1.67	38

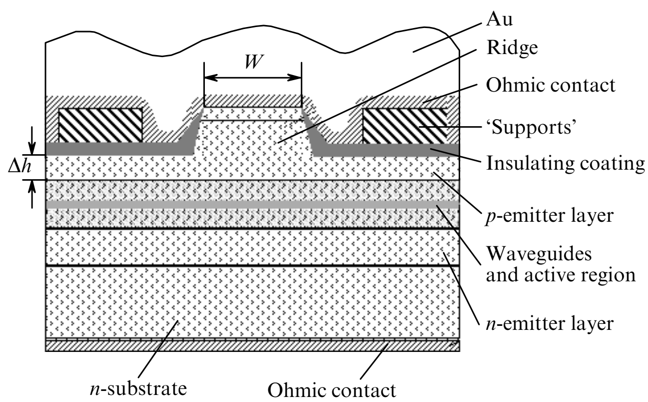

Figure 1. Scheme of a laser with a ridge waveguide (W is the ridge width; Δh is the residual thickness of the emitter).

an epitaxial structure, whose parameters were close to those for structure I (Table 1). It follows from the calculations that, to obtain the effective refractive index $\Delta n \approx 6 \times 10^{-3}$ recommended in [5], the residual thickness Δh of the emitter layer should be ~ 0.4 μm.

It was pointed out in the analysis of the data presented that, despite a somewhat greater amplification of the zero mode with increasing W, the probability of excitation of the first mode increases even at slightest deviations from the specified parameters Δh and W of laser elements being fabricated (Table 2).

Table 2. Parameters of laser diodes.

Plate number	Laser			
	W/μm	Δh/μm	L_{cav}/μm	R_1/R_2
Ia	4	0.4	800	3/97
Ib	4	0.4	800	5/97
IIa	4	0.4	800	8/97
IIb	3	0.4	1000	3/97
IIIa	3	0.4	1000	1/97
IIIb	3	0.3	1000	1/97

In accordance with the effect of compensation of mechanical stresses [1], the total width of the insulating ZnSe coating, the p contact, and the galvanic gold layer were adjusted to minimise these stresses. The structure was thinned on the n-substrate side down to ~ 100 μm, and an ohmic n contact film was deposited on the substrate.

Plates with active elements prepared in this way were divided into strips with the cavity length $L_{cav} = 800$ and 1000 μm, and then reflecting coatings were deposited on their ends.

We selected the reflectivities R_1 and R_2 of optical coatings based on the data [6] according to which the use of the output mirror with the antireflection coating providing $R_1 = 3\,\% - 5\,\%$ enhances the maximum output single-mode power of the laser. Lasers with other values of R_1 were also studied (reflectivities are presented in Table 2).

After the division of the strips into laser elements, they were soldered on a copper heat sink by means of indium solder. Unlike [4], we compared the experimental results with calculations by a statistical method. Thirty lasers were fabricated from each of the three epitaxial structures, which were selected from different strips and different assembling lots. The statistical method allowed us to estimate the technology level taking into account the accuracy of measurements and different thicknesses of etched layers, as well as different etching rates in the region being processed.

The emission properties were measured in test housings with clamp electric contacts. After a preliminary selection of acceptable samples (without soldering and assembling defects, etc.), a 100 % control of watt – ampere and volt – ampere characteristics of lasers was performed. Also, the diagrams of angular divergence $\Theta_{||}$ were measured in the plane parallel to the $p-n$ junction in the power range between 30 and 200 mW. The angular divergence $\Theta_{\perp}$ in the plane perpendicular to the $p-n$ junction was controlled selectively for 20 % – 25 % of lasers assembled from each epitaxial structure. The laser parameters were measured for pump currents from zero to 250 mA.

The tested lasers were considered single-mode if their radiation satisfied the following conditions:

(i) the far-field radiation pattern corresponds either to the refractive confinement regime (a strong waveguide is mainly formed due to a step in the effective refractive index) [Fig. 2, curve (*2*)] or to the dissipative confinement regime determined by amplification (here, amplification occurs at the central part, and absorption is observed at the edges) [Fig. 2, curve (*3*)]. It is in this region, where the regime of optical confinement due to the refractive index is only approached, laser diodes operate most efficiently [7];

(ii) the maximum of the radiation pattern does not deviate from the vertical axis over the entire range of measurements;

(iii) the increase in the radiation divergence $\Theta_{||}^{0.5}$ at the 0.5 level does not exceed 2 – 30° over the entire range of measurements.

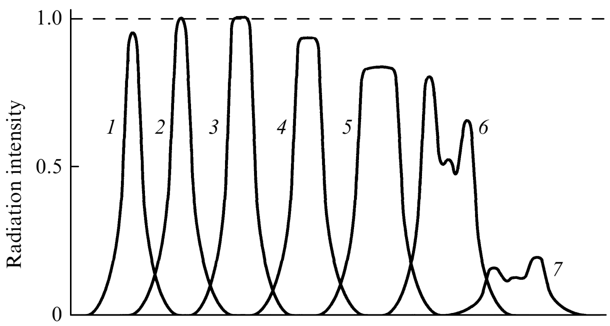

Figure 2. Change in the far-field angular divergence diagram due the degradation of the output mirror of the laser upon repeated measurements. The pump current is $I = 215$ mA (*1*), 230 mA ($P \sim 200$ mW) (*2*), 240 mA (one measurement cycle) (*3*), 240 mA (three cycles) (*4*), 240 mA (five cycles) (*5*), 240 mA (six cycles) (*6*), 240 mA (eight cycles, $P \sim 30 - 40$ mW) (*7*).

The maximum output power (200 mW) of lasers was limited, as a rule, by the degradation of mirrors (more that 10 laser diodes were damaged at powers 210 – 230 mW used in the study of their parameters).

Unlike tests in a pulsed regime, when a sudden thermal explosion occurs [4], we managed to observe a gradual, from cycle to cycle, variation in the diagram of angular divergence $\Theta_{||}$ (Fig. 2).

Figure 2 shows that first the diagram amplitude ceases to increase with increasing pump current I [curve (*2*)], then the diagram broadens [curve (*4*)], its top becomes flat [curve (*5*)] and, finally, the suppression of the zero mode occurs and higher-order modes are excited [curve (*6*)]. The degradation process is accompanied by a drastic decrease in the output power.

Table 3 presents a fraction of lasers (in %) emitting 100, 150, and 200 mW in the single-mode regime, the angular divergence of radiation in the $p-n$ junction plane for the single-mode power 150 – 200 mW, and some other parameters of epitaxial structures and lasers.

The results presented in Table 3 demonstrate that the technological complex used by us provides the acceptable productivity of fabrication of laser diodes capable of emitting the 150 – 200-mW single-mode radiation. Despite the difference in assembling variants (ridge upwards or downwards) and some scatter in the values of Δh (0.3 – 0.4 μm), W (3 – 4 μm), and R_1 (1 % – 8 %), a dominating influence of the initial epitaxial structure is distinctly manifested.

Table 3. Parameters of lasers fabricated from structures presented in Table 1.

Structure number	Fraction of single-mode lasers (%) with the output power $P = 100$ mW	$P = 150$ mW	$P = 200$ mW	$\langle\eta_d\rangle$/W A^{-1*}	$\langle R_{ser}\rangle/\Omega$	$\Theta_{\parallel}^{0.5}$/deg.**	$\Theta_{\perp}^{0.5}$/deg.
I	92.8	78.5	35.7	1.0	2.3	6 – 8.5	28 – 30
II	84.4	52	12	0.96	2.9	7.5 – 12.5	31 – 32
III	62.5	41.7	8	1.08	3.3	9 – 13	33 – 34

Note: $^*\langle\eta_d\rangle$ measured in the power range from 10 to 200 mW; $^{**}\Theta_{\parallel}^{0.5}$ measured in the power range from 150 to 200 mW.

The best results were obtained for lasers made of structure I (35 % of samples exhibited stable single-mode 200-mW lasing), whereas only 12 % and 8 % of lasers made of structures II and III, respectively, could operate in this regime (Fig. 3). This circumstance can be explained first of all by the fact that the design and the composition of layers in structure I are most close those of the calculated structure. The angular divergence $\Theta_{\perp}^{0.5}$ of radiation for this structure is also lower (28 – 30°) than that for other structures. On the one hand, this suggests the radiation region broadens in the perpendicular direction, thereby increasing the catastrophic degradation threshold. On the other hand, this provides a better side optical confinement due to a deeper penetration of the field into the *p*-emitter layer. In addition, the real alloying profile is probably close to the optimal one because it provides both the minimal series resistance $\langle R_{ser}\rangle = 2.3\ \Omega$) and a weak decrease in the slope quantum efficiency η_d in the power range from 150 to 200 mW. This provides a high quality of radiation emitted by laser diodes of the first group fabricated from structure I.

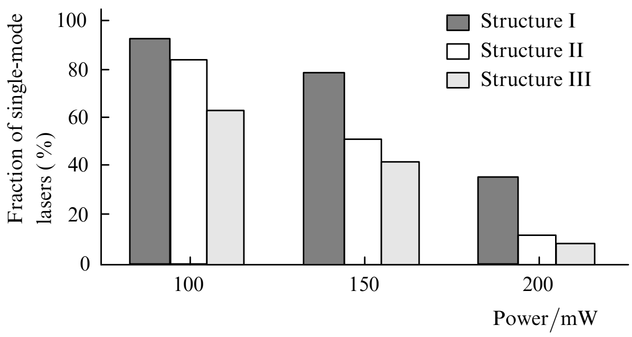

Figure 3. Fractions of single-mode lasers made of different structures emitting 100, 150, and 200-mW radiation.

Figure 4a shows the radiation pattern in the $p - n$ junction plane for a typical 200-mW laser. The angular divergence of the radiation pattern is $\Theta_{\parallel}^{0.5} = 7°$. The type of radiation of this laser shows the presence of side optical confinement, which corresponds to the refractive type in the calculation model. The optical waveguide is mainly formed by a step in the effective refractive index, while the compression of side modes results in some reduction in the slope quantum efficiency. In this case, the $\sim$ 200-mW output power was achieved at the pump current of 230 mA. We emphasise that single-mode lasing was retained in the power range from 1 to 200 mW.

Lasers of the second group had the same single-mode radiation pattern up to the output power 150 – 200 mW. As the output power was further increased, the divergence angle $\Theta_{\parallel}^{0.5}$ increased up to 9 – 11.5° or the pattern axis displaced, which typically characterises the deviation from single-mode lasing with increasing output power. This deviation was

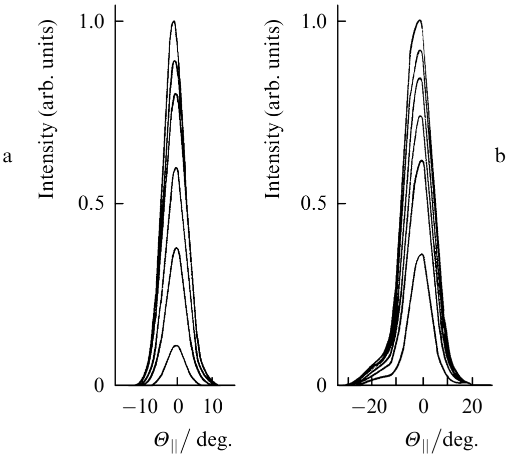

Figure 4. Far-field angular radiation distribution in the $p - n$ junction plane for laser diodes at different pump current in the side optical confinement regime corresponding to the refractive type (a) and in the regime of dissipative confinement of side optical confinement for the output power exceeding 100 mW (b); the maximum amplitude corresponds to the 200-mW output power.

observed in some lasers beginning from $P \geqslant 100-$ 120 mW.

The results of measurements for lasers assembled from structure II and especially III substantially differ from the above results, being inferior from the point of view of single-mode lasing. A fraction of 200-mW single-mode lasers made of these structures is smaller and the divergence angle $\Theta_{\parallel}^{0.5}$ increases up to 8.5 – 13°.

As a rule, the radiation patterns of lasers of these groups correspond to the refractive type of optical confinement gradually transforming to the dissipative type. Examples of such radiation patterns are presented in Fig. 4b. A change in the pattern shape can be explained by a decrease in the side step of the refractive index compared to the profile of *n* for lasers made of structure I with decreasing the depth of penetration of the optical field into the upper emitter layer. We managed to improve the radiation pattern to some extent by increasing side optical confinement ($\Delta h = 0.3$ μm) and decreasing the gain of the first-order mode ($W = 3$ μm). The main fraction of single-mode lasers emitting >150 mW with the radiation divergence in the vertical plane $\Theta_{\perp}^{0.5} = 33 - 34°$ corresponds namely to this plate (IIIb in Table 2), A few lasers of this group produced the 200-mW output power. However, as a whole, the results for lasers made of plate IIIb are noticeably worse than those for lasers fabricated from plates I.

3. Conclusions

We have shown that low-energy (150 eV) ion – chemical etching in a ICP source can be used to fabricate 150 – 200-mW cw single-mode lasers on a table of diameter $D > 150$ mm (provided the epitaxial structure and the values of W

and Δh have been appropriately chosen). The production of acceptable lasers corresponds to their batch production.

The applicability of the model of a ridge waveguide with a rectangular profile to the calculation of a trapezoid ridge (85°) formed upon low-energy ICE is confirmed. It is shown that, for the same emitter-layer thickness $\Delta h \approx 0.3 - 0.4$ μm, structures with a lower angular divergence in the perpendicular direction provide a noticeably higher single-mode output power.

It seems that a single-mode output power of 200 – 220 W achieved for structure I is maximal for the angular divergence of radiation $\Theta_{\perp}^{0.5} \geqslant 28°$ and non-passivated mirrors.

It is obvious that actual results depend to a great extent on the heat-sink efficiency provided in laser assembling, the quality of optical coatings of mirrors, the series electrical resistance of the diode, and other factors.

Acknowledgements. The authors thank E.V. Berlin (Tirs Research and Production Association, Zelenograd) for his help in mastering the ICP source.

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