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# Increase in the optical damage threshold of a ZnSe-passivated front mirror of a laser diode

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*Abstract*. **The operation of single-mode diode lasers with a front mirror passivated by ZnSe films of different thicknesses is studied in the pulsed regime (pulse duration $\tau = 0.2 - 10$ μs). It is found that in the case of short (0.2 μs) pulses, the catastrophic optical damage threshold grows almost linearly as the film thickness on the front mirror increases from 0.1 to 0.5 μm. It is shown that lasers with mirrors passivated by 'thick' (0.4 – 0.6 μm) ZnSe films can operate stably in the case of 'long' (2 – 10 μs) pulses. It is assumed that in this pulsed regime the ZnSe film provides an additional heat removal from the hot zone of the front mirror, and consequently increases the optical damage threshold.**

***Keywords***: *catastrophic optical damage, diode laser, passivation.*

## 1. Introduction

Despite the large number of publications devoted to improving the radiation tolerance of diode laser mirrors, the problem still persists. From a practical point of view, of greatest interest is the technological option of cleaving the stripes in air with subsequent cleaning and passivation of the surface in a vacuum. The biggest challenge is the removal of oxygen from the mirror surface, particularly in the case of structures containing Al. It is in this direction that the main efforts of developers are concentrated, who propose to use the methods of ion and gas chemical treatment [1 – 5]. All the authors of these works are unanimous in saying that after passivation of mirror facets they should be protected by a film made of a suitable material.

In this paper, we do not consider these problems. Using a previously developed technology of ZnSe passivation [6], we investigated an alternative way of raising the catastrophic optical damage (COD) threshold by increasing the thickness of the ZnSe film, having a good thermal conductivity ($\sim 0.2$ W cm$^{-1}$ K$^{-1}$). It was expected that this film will be able to remove heat from the hottest region on the mirror surface.

## 2. Experimental, results and their discussion

We performed three series of experiments using MOCVD-grown double quantum well structures emitting at $\lambda = 0.97 - 0.98$ μm. The manufacturing techniques of ridge waveguide laser diodes (LDs) with the stripe width $w = 2.5 - 4.0$ μm and passivated ZnSe-mirrors are described in [6]. Laser chips were mounted p-side up and p-side down on copper heatsinks using indium solder. To measure the electrical and optical characteristics, the heatsinks with chips were installed in a special holder with pressure contacts.

In the first series of experiments we studied the effect of the ZnSe-film thickness on the COD threshold in the pulsed regime (pulse repetition rate, $f = 2$ kHz; pulse duration, $\tau = 0.2$ μs). Given sufficiently large internal losses ($\alpha = 3 - 4$ cm$^{-1}$) in the used epitaxial structures, the length $L$ of the LD cavity with $\lambda = 0.97 - 0.98$ μm was chosen equal to 600 μm.

ZnSe films, produced on the front mirror with an optical thickness $\lambda/4$, $3\lambda/4$, $5\lambda/4$ and $7\lambda/4$, served also as antireflection coatings with reflectivity $R_{\rm a} = 8\,\% - 10\,\%$. The high-reflectivity coatings with $R_{\rm h} \geqslant 97\,\%$ on stripes passivated with ZnSe films of varying thickness on the front mirror were deposited on the rear facet by electron-beam evaporation in one vacuum cycle. Before the pulse tests of LDs, we measured in the cw regime their light – current characteristics and angular divergence diagrams in the plane of the p – n junction.

Figure 1 shows a series of light – current characteristics measured for LDs made of Zh-109 structure ($w = 3$ μm). One can see almost a linear increase in the COD threshold from $\sim 0.4$ W (for the film thickness $\lambda/4$) to $\sim 1.2$ W ($7\lambda/4$). Similar results were obtained for 0.97-μm LDs made of other structures; in this case, the COD threshold increased with increasing stripe width $w$ from 2.5 to 4.0 μm and maximum power $P_{\rm sm}$ in the single-mode regime. These results created prerequisites for subsequent experiments.

In the second series of experiments we studied the behaviour of LDs passivated by 'thick' [$(\lambda - 1.5)\lambda$] ZnSe films at longer pulses (0.2 to 10 μs). To increase the LD power, we used high-quality epitaxial structures with $\alpha = 1.5 - 2$ cm$^{-1}$, the cavity length was increased to 1000 μm, and an additional antireflection $\mathrm{Al_2O_3}$ coating of thickness $\lambda/4$ ($R_{\rm a} = 3\,\%$) was deposited by electron-beam evaporation on the passivated front mirror surface. As in the first series of experiments, only high-reflectivity coatings with $R_{\rm h} \geqslant 97\,\%$ were deposited on the rear facets. The same structures were used to fabricate control LDs (without

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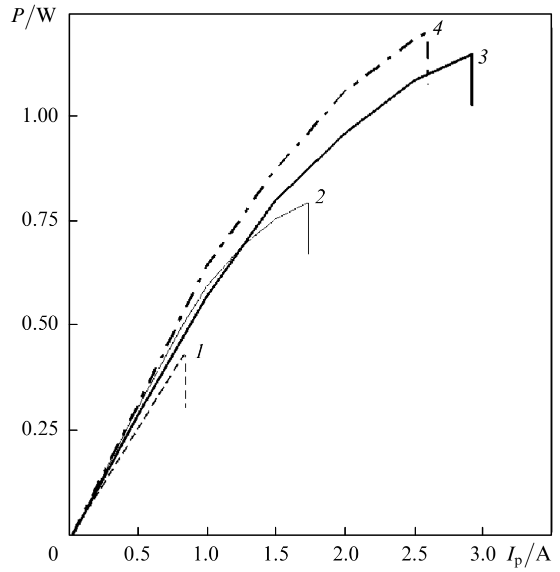


**Figure 1.** Dependence of the COD threshold on the epitaxial ZnSe film thickness by the example of testing the LDs made of Zh-109 structure ($w = 3$ μm) at $\tau = 0.2$ μs, $f = 2$ kHz: (*1*) $\lambda/4$, $R_a = 9\,\%$; (*2*) $3\lambda/4$, $R_a = 8\,\%$; (*3*) $5\lambda/4$, $R_a = 9\,\%$; (*4*) $7\lambda/4$, $R_a = 10\,\%$.

passivation) with the same values of $R_a$ and $R_h$. Before the pulse tests, the assembled LDs were tested in the cw regime. The results of the measurements of their parameters, along with design features of the epitaxial structures and laser elements are shown in Table 1. As can be seen from Table 1, three of the four selected epitaxial structures had the same design. The fourth structure, A-20, used for comparison, had a smaller angular divergence of radiation in the plane perpendicular to the p–n junction (full width at half maximum, $\theta_\perp = 20°–21°$), and hence the larger size of the laser spot. Pulse tests were performed by measuring sequentially the light–current characteristics when the LD was pumped by the current from 0 to 4.5 A and $\tau = 0.2 - 10$ μs at $f = 2$ kHz. The pump current increased in steps of 0.32 A and pulse duration – in steps of 0.4 μs (up to $\tau = 2.0$ μs) and 1.0 μs (from 2.0 to 10.0 μs). The average output power $\langle P \rangle$ in the pulsed regime was recorded 10–15 s after the increase in the pump current. This technique, unlike that used in [7], made it impossible to determine the moment of optical damage inside the long pulse but firmly fixed the level of the power prior to the COD.

Figures 2, 3 and 4 present the series of light–current characteristics for passivated LDs made of A-20, H-67 and A-101 structures (the light–current characteristics of B-31 structure with $L = 1000$ μm are not shown because of their similarity with those obtained for H-67 structure). Despite a slight difference in the output powers at a maximum pump current $I_p = 4.5$ A, the dependences of $\langle P \rangle_{\max}$ on the pulse duration $\tau$ are very similar for all three structures. A noticeable distortion of the light–current characteristic shape and a decrease in $\langle P \rangle_{\max}$ is observed already at $\tau = 0.4$ μs and increases with increasing $\tau$. Moreover, $\langle P \rangle_{\max}$ in the figures is shifted with increasing $\tau$ towards lower pump currents. This effect is more pronounced in the LD made of A-101 structure having the highest series resistance $R_{\text{series}} = 4.4 - 4.7\ \Omega$ (Fig. 4). This character of the curves and the reduction of $\langle P \rangle_{\max}$ are, most likely, due to adiabatic heating of the generation region during the pulse action, because according to estimates, heat removal from the heating zone through the substrate is negligible up to $\tau = 10$ μs [8]. The polarity of assembly, as well as growth of $f$ from 1 to 8 kHz during the measurements had almost no effect on the value of $\langle P \rangle_{\max}$. This interpretation (well known for the cw regime) of a decrease in the quantum efficiency $\eta_{\text{eff}}$ as the mirror is heated by its own heat suggests that, in our case, we observe a kind of thermal pulse roll-over (transition of the light–current characteristic through a maximum).

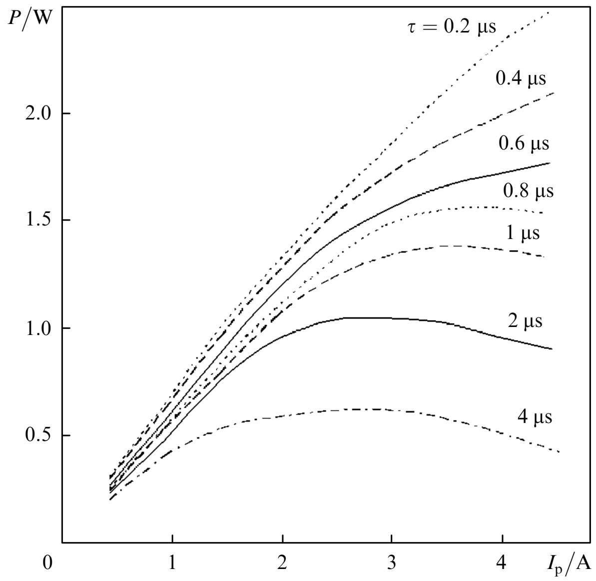


**Figure 2.** A series of light–current characteristics for a typical LD made of A-20 structure passivated by a ZnSe film of thickness $\lambda/2$ ($R_a = 3\,\%$, $R_h \geqslant 97\,\%$).

The advantage of front mirror passivation with 'thick' ZnSe films becomes noticeable by comparing the presented light–current characteristics with the results for unpassivated LDs. This affects primarily the dependence of the COD threshold on $\tau$. The strongest differences are observed in LDs made of A-20 structure. If in passivated LDs the

**Table 1.** Specific features and main parameters of the LDs during their operation in the cw regime.

| Structure | $\lambda$/μm | $d_{\text{wave}}$/μm | $w$/μm | $L$/μm | $d_{\text{ZnSe}}$ ($\lambda$) | $R_a$ (%) | $R_{\text{series}}$/Ω | $\theta_\perp$/deg | $\theta_\parallel$/deg | $P_{\text{sm}}$/mW |
|---|---|---|---|---|---|---|---|---|---|---|
| H-67 | 0.96 | 0.3 | 3.0 | 1000 | 1.5 | 4 | 3.6 | 30–32 | 8.5 | 180 |
| A-20 | 0.85 | 0.12 | 4.6 | 1000 | 0.5 | 3 | 2.2 | 20–21 | 6.5 | 190 |
| A-101 | 0.98 | 0.3 | 3.3 | 1000 | 1.0 | 4 | 4.7 | 27–29 | 9.0 | 200 |
| B-31 | 0.97 | 0.3 | 4.3 | 1000 | 1.0 | 3 | 2.2 | 28–30 | 8 | 240 |
| B-31 | 0.97 | 0.3 | 4.3 | 2000 | 1.0 | 4 | 1.2 | 28–30 | 8 | 260 |

Note: $d_{\text{wave}}$ is the waveguide thickness; molar fractions of aluminium in the waveguide layers of the LDs under study accounted for 27 %–31 %.

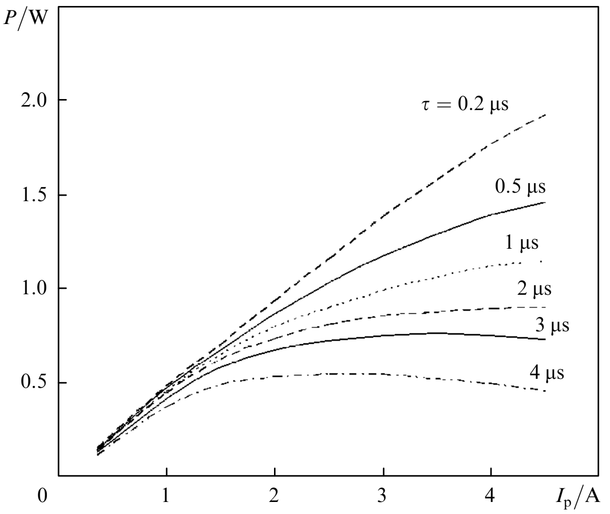


**Figure 3.** A series of light–current characteristics for a typical LD made of H-67 structure passivated by a ZnSe film of thickness $3\lambda/2$ ($R_a = 4\,\%$, $R_h \geqslant 97\,\%$).

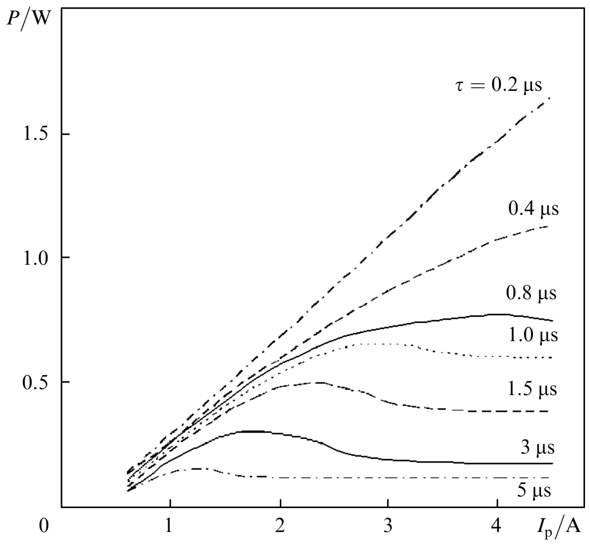
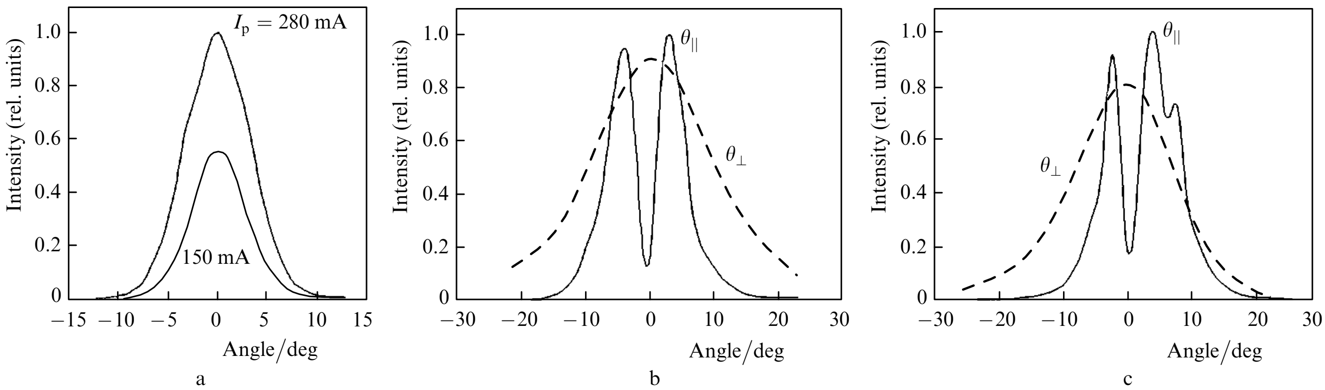


**Figure 4.** A series of light–current characteristics for a typical LD made of A-101 structure passivated by a ZnSe film of thickness $\lambda$ ($R_a = 4\,\%$, $R_h \geqslant 97\,\%$).

power drastically decreased in the range $\tau = 3.0 - 6.0$ μs, the unpassivated mirrors exploded already at $\tau = 0.4 - 0.6$ μs. A similar pattern was observed for the LD made of B-31 structure ($L = 1000$ μm): explosion of unpassivated mirrors occurred in the range 0.8–1.6 μs, while some passivated LDs 'survived' at $\tau = 5 - 7$ μs. In LDs made of H-67 and A-101 structures, the time intervals when the power for passivated and unpassivated LDs sharply decreased partially overlapped. This was particularly noticeable in the case of A-101 structure: $\tau = 0.6 - 2.4$ μs for unpassivated LDs and 1.6–5.0 μs for passivated LDs. In our opinion, the stabilising role of 'thick' (0.4–0.6 μm) ZnSe films consists in the fact that they are perform extra heat removal from the hottest zone, thereby reducing the temperature of the output mirror.

If the unpassivated mirror surface is covered only by a thin ($\lambda/4$) $Al_2O_3$ film, the heat is removed from the hot zone to the structure (in accordance with the two-dimensional model [9]) through a waveguide, and in the presence of the ZnSe film whose thermal conductivity is approximately twice the thermal conductivity of $Al_{0.3}Ga_{0.7}As$, it is necessary to take into account the spreading of heat through the ZnSe film. To this end, the most important is the heat dissipation from the hottest central zone in the direction perpendicular to the mirror plane. As a result, in the presence of 'thick' ZnSe films the temperature at the centre of the hot zone is below the dangerous level, triggering the COD. Similar conclusions were made by the authors of [7]. Additionally, we note that the LDs made of ZnSe-coated ($3\lambda/2$) H-67 structure and of A-20 structure with a thinner ($\lambda/2$) ZnSe coating but a broader laser spot, showed almost identical results.

In the third series of experiments, we analysed the reasons for a sharp decrease in the power of tested LDs in the regime of generation of microsecond pulses, which is usually explained by the explosion of mirrors. However, it turned out that, as a rule, this is true only for unpassivated mirror. Experiments with 'thick' ZnSe films revealed competition between the waveguide and the mirror. The optical control of the LDs made of B-31 and A-20 structures showed that the COD was often accompanied not by the destruction of the front mirror but by the processes inside the laser element. In less effective structures (H-67 and especially A-101), characterised by an increased value of $R_{series}$ (see Table 1,) a stepwise power reduction by



a b c

**Figure 5.** Diagrams of angular divergence for the LDs ($L = 2000$ μm) made of B-31 structure in the cw regime before pulse testing at $I_p = 150$ and 280 mA, $\theta_{||}$ ($I_{th} = 37$ mA, $\eta_{eff} = 0.64$ W A$^{-1}$) (a), after the 'burnout' of the zero mode at $I_p = 150$ mA (b) and $I_p = 280$ mA (c) ($I_{th} = 68$ mA, $\eta_{eff} = 0.29$ W A$^{-1}$).

30 % – 40 % was often observed. The measured angular divergence of radiation $\theta_{||}$ of some LDs in the cw regime showed that after the first drop in power instead of the original single-lobe diagram (Fig. 5a) there appeared a two-lobe diagram typical of the first mode (Figs 5b, c). The burnout of the fundamental mode was accompanied by a reduction of $\eta_{\text{eff}}$ and an increase in the threshold by 1.5 – 2 times. Figures 5b, c show the change of $\theta_{||}$ in the cw regime with increasing $I_{\text{p}}$ from 150 to 280 mA. Further pumping resulted in complete destruction of the waveguide. It should be emphasised that the control of the mode composition (in the case of single-mode lasers) proved to be an effective means of 'sorting' of both types of CODs – mirror and waveguide.

To test the hypothesis that in passivation by 'thick' ZnSe films the waveguide may be a weak point, we reduced the heat load inside the waveguide. To this end, we additionally fabricated LDs with the same ZnSe-passivated coating of thickness $\lambda$ from B-31 structures but increased the cavity length to 2000 μm. Ten LDs with $L = 2000$ μm were tested under the same conditions as LDs with $L = 1000$ μm, i.e. in the range of pulse durations 0.2 – 10 μs. Figure 6 shows the light – current characteristics, averaged over data for seven LDs, which have stood the test without failure (three LDs were damaged at $\tau = 8$ μs). The achieved results are strikingly different from those for the LDs with $L = 1000$ μm, when only one LD collapsed at $\tau = 7$ μs, and the others – in the range of 4 – 6 μs. Note also that the light – current characteristics have no maxima, and $\langle P \rangle$ in the pulsed regime increases with $I_{\text{p}}$ in the entire range of pulse durations, up to $\tau = 10$ μs.

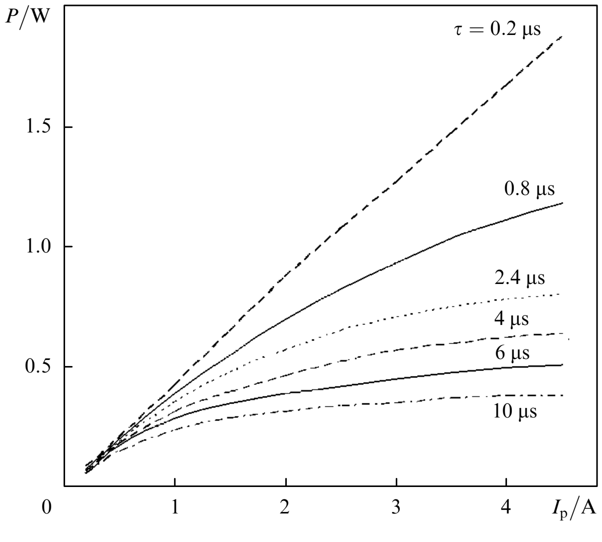


**Figure 6.** A series of light – current characteristics for a typical LD made of B-31 structure ($L = 2000$ μm) passivated by a ZnSe film of thickness $\lambda$ ($R_{\text{a}} = 4\,\%$, $R_{\text{h}} \geqslant 97\,\%$).

The achieved results are due to a decrease in the heat release inside the waveguide (per 1 μm of the cavity length) and, consequently, to an increase in $\eta_{\text{eff}}$ and its thermal stability. This also means that in the studied regimes of long (up to 10 μs) pulses, the front mirror passivated with a ZnSe coating of thickness $\lambda$, as a rule, is not responsible for the LD damage.

## 3. Conclusions

(i) We have studied the operation of diode lasers with the front mirror passivated by ZnSe films of different thicknesses. During the tests in the pulsed regime ($\tau = 0.2$ μs, $f = 2$ kHz), we have found an almost linear increase in the COD threshold with increasing the ZnSe-film thickness from 0.1 to 0.5 μm.

(ii) We have demonstrated the advantages of lasers with coatings passivated by 'thick' (0.4 – 0.6 μm) ZnSe films for operation in the pulsed regime ($\tau = 1 - 10$ μs).

(iii) We suggest that these effects are associated with a decrease in temperature on the mirror due to the additional heat removal from the hot zone in the centre of the laser spot through the ZnSe film.

(iv) We have shown that as the level of the catastrophic optical mirror damage threshold increases, the 'responsibility' for the sudden decrease in the LD power 'moves' from the mirror to the laser active elements.

(v) Tests of the LDs in the microsecond regime make it possible to perform express evaluation of the quality of both mirrors and active elements.

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