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Degradation Mechanism in 1.3 μm InGaAsP/InP Buried Crescent Laser Diode

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A degradation mechanism in an InGaAsP/InP buried crescent (BC) laser diode is examined. It is shown that the degradation is attributed to a decrease in the built-in potential of an InP p-n junction formed between an n-InP cladding layer and a p-InP current blocking layer. The degradation characteristics are successfully explained by a theoretical model proposed in this study.

The degradation is eliminated by displacing the InP p-n junction. The improved BC lasers operate quite stably at as high as 80°C in APC mode aging test.

I Introduction

InGaAsP/InP diode lasers are currently at the stage of practical use as light sources for optical communication systems, since their emission wavelength covers the low-loss, low-dispersion region of silica-fused fibers. For the practical use, the InGaAsP/InP diode lasers are required to have a long life time. Many efforts have been devoted to realize a long-lived InGaAsP/InP diode laser.[1)-3)]

We have previously reported on a buried crescent (BC) laser diode (λ=1.3 μm) with a very low threshold current and a fundamental transverse mode oscillation.[4),5)] The life time of the BC laser at a temperature of 50°C was estimated to be about 3 x 10^5 hours.[1)] Some BC lasers, however, exhibited a rather rapid degradation at a higher temperature of 70°C.

In this paper, the degradation mechanism of th BC laser is examined. It is shown that the degradation of the BC laser at a high temperature is due to the degradation of an InP p-n junction adjacent to an active region and the degradation behaviour is successfully explained by a theoretical model proposed in this study. The degradation of the InP p-n junction is found to be eliminated by displacing the junction from an interface which was exposed to a high temperature ambient before the 2nd LPE growth. The improved BC lasers operate stably at as high as 80°C in APC mode aging test.

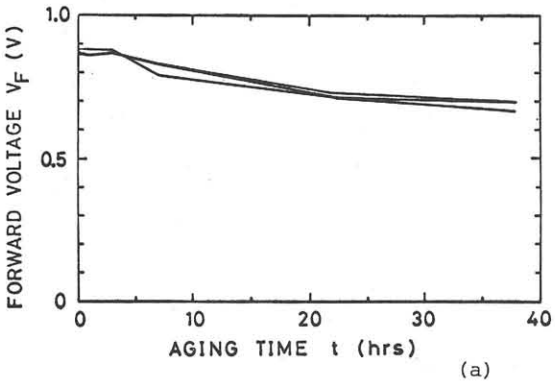
II Degradation behaviour

At a high temperature of 70°C some BC lasers exhibited a rather rapid degradation within a few hundreds of hours. The degradation results in an increase in a threshold current (I_{th}), a decrease in a forward voltage at a current level of 1mA (V_F), and an increase in a differential resistance (dV/dI). Although I_{th} remarkably increases with the degradation, a change of a differential quatum efficiency (η) is little in comparison with that of I_{th}, which is a characteristic of the degradation of the BC laser. The similar degradation behaviour is observed in a few tens of hours when a high level current (~200 mA) is applied to the BC lasers at a high temperature (~100 °C).[6)] (This stress test is referred to as EL mode aging test.[6)]) Typical example of the degradation behaviour by the EL mode aging test is shown in Fig. 1. Since the degradation property by the EL mode aging test is quite similar to that by the APC mode test at 70°C, the EL mode aging test is employed to investigate the degradation mechanism through this study.

III Location of the degradation

The degradation behaviour of the BC laser mentioned above suggests that the active region itself does not degrade, since the active region

degradation, such as the occurrence of dark defects, should result in a large decrease in η.[7] It was confirmed that the dark region was not ob-



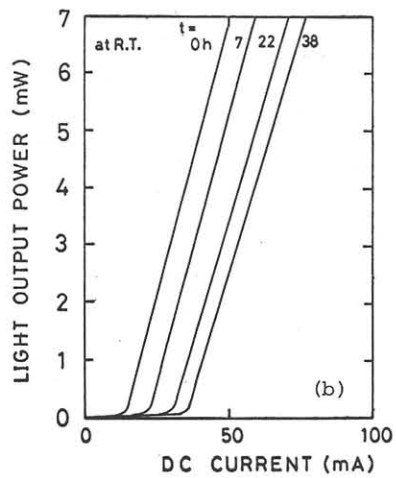


Fig. 1 Typical example of the degradation behaviour by the EL mode aging test. Variation of V_F (a) and P-I curves (b).

served in the electroluminescence topograph of the degraded BC lasers.

Since the effect of light output power on the degradation of InGaAsP/InP laser diodes is estimated to be small,[8] the facet degradation is not the cause of the degradation of the BC laser.

A metal electrode degradation is not responsible for the degradation of the BC laser, since a test sample with the same electrode materials as the BC laser does not degrade through the EL mode aging test as described later.

The possible places responsible for the degradation are schematically shown in Fig. 2, that is, 1) a p-n-p-n current blocking layer, 2) an InP p-n junction grown in the 1st LPE growth, and 3) an InP p-n junction formed at a groove wall.

Figure 3 shows typical I-V characteristics of a p-n-p-n current blocking structure outside of the active region. The size of the structure measured was about 100 x 300 μm^2. Forward and reverse voltages at 10 μA are 4 V and 10 V, respectively. The structure was stressed at 100 °C with a forward-biased voltage of 4 V for about a hundred hours. No appreciable change of I-V characteristics was not observed after the stress test. So the p-n-p-n current blocking layer is not the candidate of the degradation of the BC laser. To investigate the 2nd and 3rd candidates, several test samples were examined by means of the EL mode aging test.

An InP p-n junction with a stripe-geometry was fabricated as follows; an n-InP buffer layer, a p-InP layer, a p^+-InGaAsP cap layer, and an n-InP current blocking layer were successively grown on an n-InP substrate. After the EL mode aging test, the forward voltage of the diode was found almost unchanged. This indicates that the InP p-n junction fabricated in the 1st growth is not responsible for the degradation of the BC laser.

Next, a property of an InP p-n junction formed at a groove wall was examined. It should be noted here that the p-n junction was formed at an interface which was exposed to a high temperature ambient before a melt contact of the 2nd growth and any intentional melt-back is not carried out for preserving the initial shape of the groove.

After a growth of an n-InP buffer layer, the layer was exposed to the growth ambient, then a p-InP layer was grown without any melt-back. The stripe-geometry diode with that p-n junction and a BC laser without an active region were prepared.

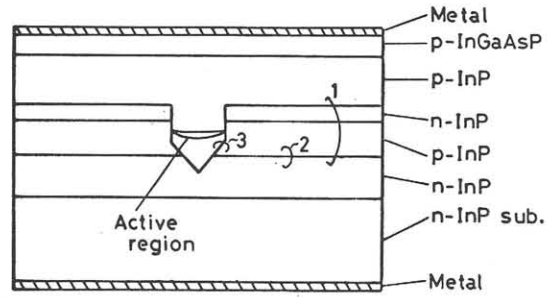


Fig. 2 Schematic drawing of the possible places of the degradation.

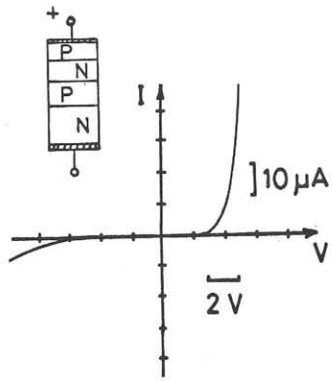


Fig. 3 I-V curve of a p-n-p-n current blocking structure.

The both test samples were stressed by the EL mode aging test. The forward voltages of the both samples were found to decrease remarkably and a tendency of the decrease was similar to that of the BC laser. Therefore it can be concluded that the degradation occurs at the InP p-n junction which is formed at the "exposed" interface.

IV Degradation model

We propose a model, which explains the behaviour of the degradation mentioned above. As shown in Fig. 4, the BC laser diode is assumed to be represented by a two-diode parallel circuit. A diode current, I flows through a resistor, R common to the both diodes (D_1 and D_2), and is divided into two components, I_1 and I_2. Before the degradation, the built-in potential of the InP p-n

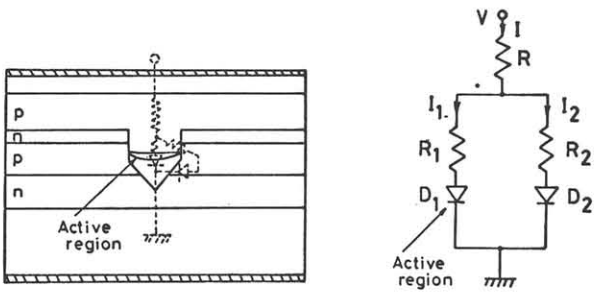


Fig. 4 Schematic drawing of BC laser and its degradation model circuit.

junction at the groove wall is larger than that of the InGaAsP active region, so almost all the diode current is concentrated within the active region. As the degradation proceeds, the built-in potential of the junction at the wall decreases. This increases a leakage current (I_2) flowing the InP p-n junction and increases the threshold current. On the other hand, a quasi-Fermi level may be pinned after lasing, so the increase in η could be small in comparison with the increase in I_{th}.

The current I_1, I_2 and I can be given by eqns. (1)-(3), when $qV/n_i kT \gg 1$ is assumed.

$$I_1 = exp\{q(V - V_{f1} - I_1R_1 - IR)/n_1kT\} \quad (1)$$
$$I_2 = exp\{q(V - V_{f2} - I_2R_2 - IR)/n_2kT\} \quad (2)$$
$$I = I_1 + I_2 \quad (3)$$

where n_i (i=1,2) is a junction parameter, V_{fi} (i=1,2) is forward voltage (at 1 mA) for each diode V, k, q and T are the applied voltage, Boltzmann constant, electronic charge and absolute temperature, respectively. Since the junction voltage of the active region may be clamped at a voltage V_j when I_1 reaches a threshold current I_{tho}, the eqn. (1) is replaced by $V = V_j + I_1R_1 + IR$. V_j is to be determined from the threshold condition, $I_1 = I_{tho}$

Figure 5 shows light output vs. current (P-I) characteristics (a) and differential resistance vs. current (dV/dI-I) chracteristics (b) of a BC laser diode before and after the EL mode aging test (38 hrs). As can be seen in the figure, the theoretical results of both P-I and dV/dI-I characterictics (solid lines) are comparatively in good agreement with the experimental results (open circles)

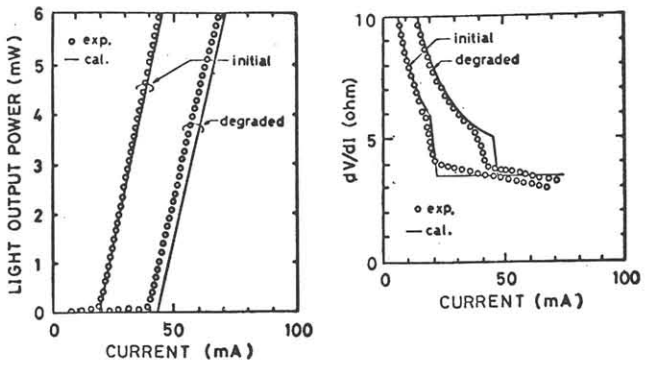


Fig. 5 Calculated (solid lines) and measured (open circles) P-I (a) and dV/dI-I (b) curves of a BC laser before and after degradation by EL mode aging test.

V New BC laser

The degradation is found to be eliminated by displacing the p-n junction from the groove wall by means of Zn out-diffusion during the 2nd LPE growth.[9] The fabrication procedure of a newly developed BC laser is the same as the conventional one. In the new BC laser, a carrier density of the p-InP current blocking layer is designed to be higher than that of the n-InP cladding layer in order to displace the p-n junction from the groove wall. The new BC laser with the "displaced" p-n junction is schematically shown in Fig. 6

The new BC lasers were stressed by the EL mode aging test, and it is clarified that the V_F of the new BC laser is almost constant through the test.

The aging tests of the new BC lasers at 70°C and 80°C with a light output of 5 mW are now carried out. The diodes aged here are mounted p-side up on BeO heat sinks with Au/Sn solder.

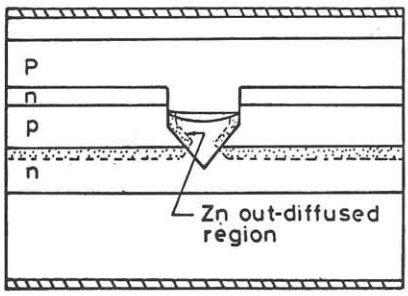


Fig. 6 Schematic drawing of improved BC laser with "displaced" p-n junction.

Figure 7 shows the variation of the operating current with aging time. As can be seen in the figure, the diodes are stably operating in excess of 3500 hours and 2500 hours at 70 °C and 80 °C, respectively.

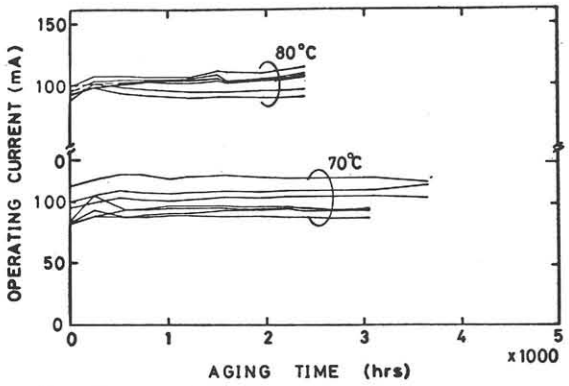


Fig. 7 Operating current variation with the aging time.

VI Conclusion

It is shown that the degradation of the BC laser at a high temperature is attributed to the decrease in the built-in potential of the InP p-n junction formed at the groove wall. The degradation characteristics are successfully explained by the theoretical model developed in this study.

The degradation has been eliminated by displacing the InP p-n junction from the groove wall. The newly developed buried crescent laser diodes operate quite stably at as high as 80 °C in APC mode aging test.

Ackowlegement

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