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Bulk Degradation of High Power InAlGaAs-AlGaAs Strained Quantum Well Lasers

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Electroluminescence imaging technique was employed to investigate *in situ* the bulk degradation mechanism of high power InAlGaAs-AlGaAs strained quantum well lasers. Two bulk degradation modes were identified as catastrophic degradation mode and gradual degradation mode due to different type of original defects. Catastrophic degradation was observed to result from small dark spots generated randomly in the emission strip. In contrast, parallel dark line defects appeared near the front facets led to gradual degradation and the output power decreased only 6% after 3000 hours aging test. To the best of our knowledge, this is the first report of such type dark line defects, which is ascribed to dislocations in the AlGaAs cladding layers at the crystal planes (1 $\overline{17}$ 12) due to the high local temperature.

Keywords: High Power Laser Diodes, Electroluminescence, Dark Spot Defect, Dark Line Defect, Catastrophic, Gradual Degradation.

1. INTRODUCTION

High power broad-area laser diodes with emission wavelengths at 915–980 nm are used to optically pump various fiber lasers and solid-state lasers. Both the output optical power and reliability of high power laser diodes have been significantly improved during the last decades. However, the degradation mechanism was not fully understood.

Generally speaking, there are three degradation modes: rapid degradation mode, gradual degradation mode and catastrophic degradation mode.[1] For the rapid degradation mode, the output optical power declines quickly during the first hundred hours of operation; for the gradual degradation mode, the optical power decreases gradually and the laser may last for several thousand hours; and for catastrophic degradation mode, the optical power drops suddenly and it can happen at any time during the operation. The catastrophic degradation mode is mainly caused by catastrophic optical damage (COD). When the COD process is associated with the facets, it calls catastrophic optical mirror damage (COMD). By facet passivation and coating, the non-injection regions in the vicinity of the facets and the quantum well intermixing techniques, the catastrophic damage threshold at the facets is increased significantly. The COMD process has been studied for decades by many groups.[2–7] However, due to the pre-existing defects in the substrates and defects or strains introduced during the epitaxial growth, together with high current injection and optical power, the catastrophic damage threshold in the bulk may be lower than that for the facets, so the COD may happen in the bulk, namely catastrophic optical bulk damage (COBD); but there are few investigations about the COBD process.[8,9] The COD process usually associates with spot and line defects. By means of electron beam induced current (EBIC),[3,10] cathode luminescence (CL)[11,12] and electroluminescence (EL)[9] measurements, such defects appear dark since these defects are full of non-radiative recombination centers and no current or luminescence can be observed. However, EBIC and CL measurements are destructive to samples thus make it difficult to observe the evolution of defects *in situ*. In this work, we employed non-destructive EL imaging technique to track the developments of the dark

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defects during the whole operation of the laser diodes to figure out how the defects affect the performances of the laser diodes. Through the EL imaging measurements, we observed some dark spot defects in the epitaxial materials, and captured the whole COBD process occurred in one of our windowed laser diodes based on the same epitaxial materials. Moreover, the EL images revealed a series of parallel dark lines near the front facets of the laser diodes, which caused degradation of the laser output power by 6% after 3000 hours of aging test. According to our preliminary analysis, the parallel dark lines may be in the AlGaAs cladding layers at crystal planes $(1\ \overline{17}\ 12)$.

2. EXPERIMENTAL DETAILS

The InAlGaAs-AlGaAs single quantum well (QW) materials were grown by metal organic chemical vapor deposition (MOCVD), consisting of an InAlGaAs-AlGaAs graded index separated confinement heterostructure sandwiched between AlGaAs cladding layers, and the lasing wavelength is about 975 nm. The laser diodes we studied were made from the same materials and had window regions formed in the backside (n-side) metal contact layers during device fabrication. Through the window region, we can directly observe the spontaneous emission from the entire emitting stripe, as shown in Figure 1. The front facets were coated with anti-reflective coatings and the rear facets were coated with high-reflective coatings. The broad-area windowed laser diodes were bonded in p-side down configuration. The cavity length is 3 mm and the width of the emitting stripe is 100 μm. Under continuous wave operation at 55 °C, the typical threshold current is about 0.84 A and the slope efficiency is about 1.10 W/A.

3. RESULTS AND DISCUSSION

3.1. Experimental Results

At first, we measured directly the InAlGaAs-AlGaAs single QW epitaxial materials by EL imaging technique and observed some dark spot defects. Figure 2 presents a typical dark spot defect with size of few microns under magnification of 200 times. The dark spots are full of non-radiative recombination centers which will definitely degrade the performance of the laser diodes made from the same epitaxial materials. This measurement on epitaxial wafers may also help to pick out those poor quality wafers with dark spots before the whole fabrication process.

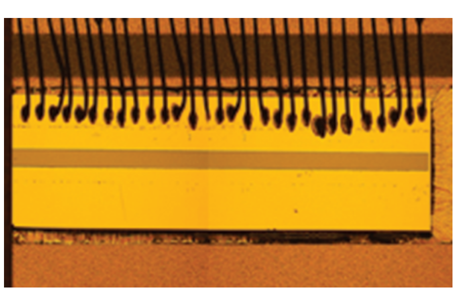

Figure 1. Top-down view of a windowed laser diode used for life-test.

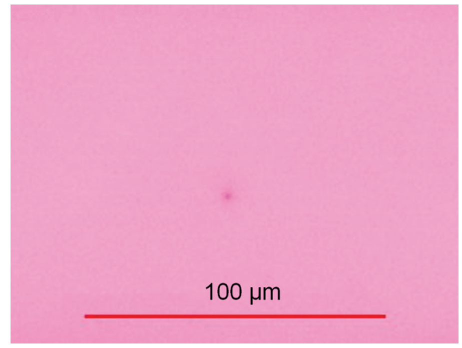

Figure 2. Typical EL image of a dark spot defect in the epitaxial materials under magnification of 200 times.

In order to verify the relationship between material defects observed in Figure 2 and the laser degradation, twenty windowed laser diodes were fabricated using the same epitaxial materials to investigate how dark spots affect the laser diodes. All the laser diodes were put into a commercial laser diode life-tester to perform life-tests under automatic current control mode at $I = 10$ A and $T_c =$ 55 °C, where T_c is the heat-sink temperature. According to the EL imaging measurements from the windows on laser diodes, two bulk degradation modes were distinguished as catastrophic degradation and gradual degradation.

Figures 3 and 4 show the sequential EL images of a typical laser diode sample I obtained at several aging times from the beginning of the test to 3008 hours under different magnifications, clearly demonstrating the whole process COBD occurred.

The EL images in Figure 3 were taken with low magnification of 50 times. We can see that in the whole emitting strip, the dark spot defects generated randomly and became larger with the aging time. The large dark spots in Figure 3(b) turned to short dark lines when the laser diode was aging test for 1204 hours as shown in Figure 3(c).

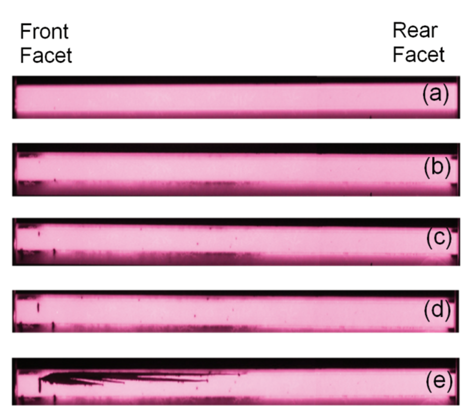

Figure 3. Sequential EL images captured from sample I with the magnification of 50 times at different aging times: (a) 0 h, (b) 100 h, (c) 1204 h, (d) 2404 h, and (e) 3008 h.

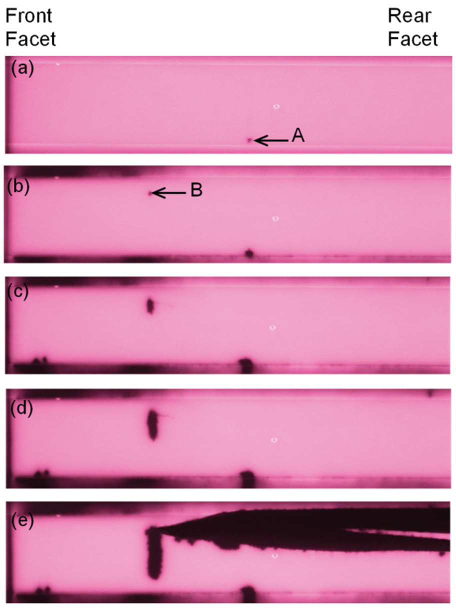

Figure 4. Sequential EL images captured from sample I near the front facet with a high magnification of 200 times at different aging times: (a) 0 h, (b) 100 h, (c) 1204 h, (d) 2404 h, and (e) 3008 h.

Eventually, in Figure 3(e), the laser diode suffered COBD with bulk defects extending along the cavity length. The EL images in Figure 4 were taken near the front facet under higher magnification of 200 times, clearly showing the evolution of dark spot defect during the aging test. Figure 4(a) was captured just after the test was started and there was a small visible dark spot defect A. The image shown in Figure 4(b) was captured at $t = 100$ h. Compared to Figure 4(a), dark spot defect A became bigger, and dark spot defect B appeared. When the aging time came to $t = 1204$ h, both dark spot defect A and B became bigger and darker, as shown in Figure 4(c). Then at $t = 2404$ h, dark spot defect B developed into a dark line defect, as shown in Figure 4(d). Finally, at $t = 3008$ h, COBD occurred initially from the dark line defect, as shown in Figure 4(e). From the sequential images, we have witnessed the appearance of dark spot defect B, prolongation and eventually lead to COBD.

Among our measurements, ten laser diodes showed a series of parallel dark lines near the front facets and the typical EL images of the dark line defects from one of the device denoted as sample II were taken with a high magnification of 200 times at different aging times: (a) 0 h, (b) 400 h, (c) 800 h, (d) 1200 h, (e) 1600 h, (f) 2000 h, and (g) 3024 h. The images shown in Figure 5 clearly show the emergence and development of the dark lines. Figure 5(a) was captured just after the test was started, and there was no dark line defect at first. When the aging time came to 400 h, a dark line defect appeared, as indicated by Figure 5(b). Then more and more dark lines appeared randomly with the aging time. On the whole, they gradually extended towards the inner bulk of the laser diode

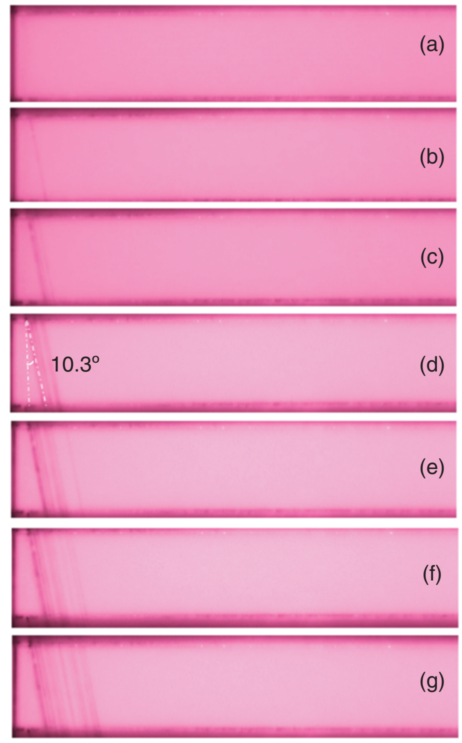

Figure 5. Sequential EL images captured from sample II near the front facet with a high magnification of 200 times at different aging times: (a) 0 h, (b) 400 h, (c) 800 h, (d) 1200 h, (e) 1600 h, (f) 2000 h, and (g) 3024 h.

as presented from Figures 5(c) to (g). After aging test for 3024 hours the dark lines occupied about 200 μm cavity length near the front facet of the laser diode. We measured the angle between the dark lines and the front facet, which is about 10.3° as marked by the white dashed lines in Figure 5(d). Obviously, in contrast to sample I with original dark spot defects sample II with parallel dark lines is gradually aging and no COBD occurred during the 3024 hours test.

Figure 6 shows the light-output power versus operating time characteristics of the two samples exhibiting catastrophic degradation and gradual degradation, which were

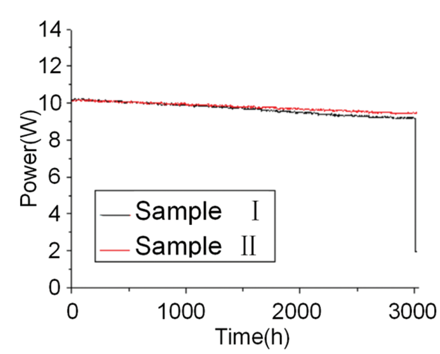

Figure 6. Variation of the output powers from sample I and II during long-term life-test.

measured under continuous wave operation at 55 °C. The preliminary powers of both samples were about 10 W at $I = 10$ A. For sample I showing catastrophic degradation mode, before the occurrence of COBD the optical output power was reduced by 10%, and dropped to about 2 W at $I = 10$ A when COBD occurred, that is to say, the final optical output power was abruptly reduced by about 70% due to the COBD process. For sample II showing gradual degradation mode with parallel dark line defects, the optical output power was reduced only by 6% up to the aging time of 3024 hours.

3.2. Degradation Analysis

Based on our experimental results, we investigated both bulk degradation modes. Figure 7 illustrates the COBD process schematically. During the laser operation, the pre-existing point defects behave as non-radiative recombination centers, which will significantly absorb lasing photons and form the local heat sources. The dark spot defects tend to appear at the place where the point defects are dense due to high local temperature, as shown in Figures 7(a) and (b), which usually happens as the current injection or during the laser operation. If the point defects are sparse, it will take some time to develop into dark spot defects as shown in Figure 7(c). The temperature in the active quantum wells is much more higher than the guiding layers and cladding layers,[13] so the dark spots probably generate and evolve in the quantum wells at first and may extend to the guiding layers and even cladding layers, as shown in Figure 7(d). The dark spots become larger and larger and turn into dark lines with aging, meaning that the non-radiative recombination process is enhanced. It has been shown that non-radiative recombination processes can significantly increase the concentration of non-radiative recombination centers during device operation and form dislocations via recombination enhanced defect reaction (REDR);[14, 15] thus, more heat is generated. When the critical temperature is reached, the thermal runaway process will be triggered and COBD occurs as shown in Figure 7(e). Our experimental result is consistent with the model proposed by Sin et al.[9] Through deep level transient spectroscopy measurements, they suggested that the EL2 traps are actively involved in the REDR process and the pre-existing point defects in the active layer result in the early stage of bulk degradation, then dark line defects are formed initially by optically induced heating followed by the REDR process via non-radiative recombination.

As for the gradual degradation mode, we suggest that the parallel dark lines are located in a series of crystal planes with the same Miller index according to our experimental results. And we attempt to figure out the certain crystal planes and at which epitaxial layer may the parallel dark lines locate.

As shown in Figure 8, the front facets of our devices are (Al)GaAs crystal planes $(0\,\bar{1}\,1)$, and the angle between

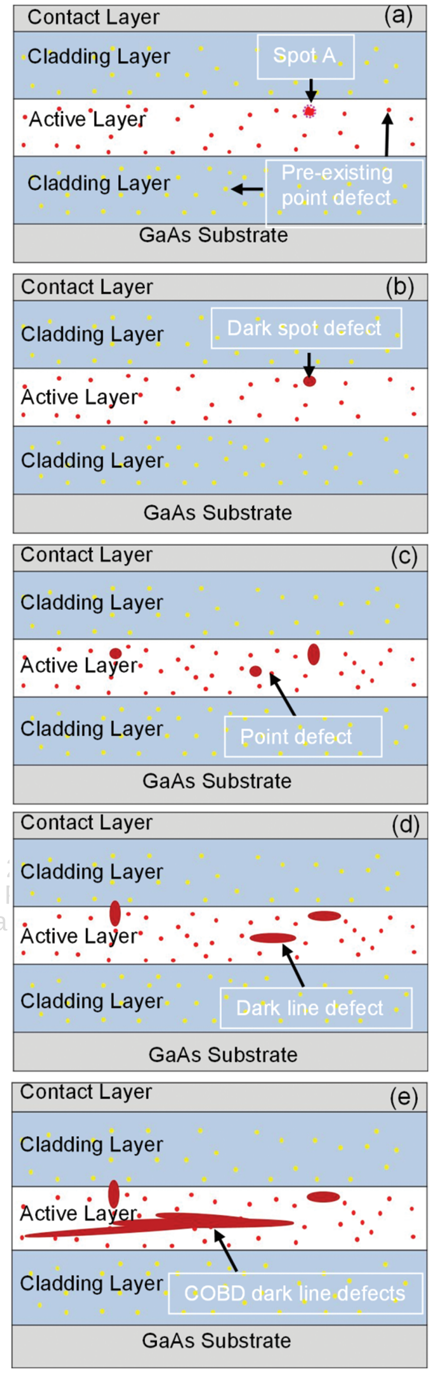

Figure 7. Schematic illustration of the COBD process: (a) Pre-existing point defects, (b) and (c) dark spot defects formation, (d) formation of dark lines from dark spots, and (e) occurrence of catastrophic degradation.

(Al)GaAs crystal plane $(0\,\bar{1}\,1)$ and $(1\,\overline{17}\,12)$ is about 10.2°. Considering the measured angle of 10.3° between the parallel dark lines and the front facet, we preliminarily made a deduction that the parallel dark lines are located in the (Al)GaAs crystal planes $(1\,\overline{17}\,12)$. Here comes another question: which epitaxial layer in the whole laser structure do the dark lines locate in? Obviously, the formation

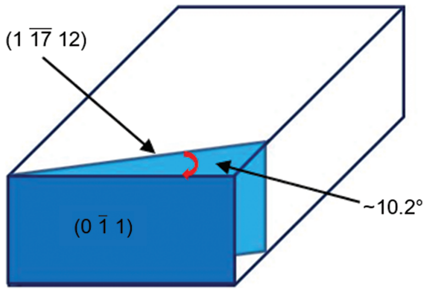

Figure 8. Schematic illustration of a crystal plane (1 $\overline{17}$ 12).

mechanism of the parallel dark lines is different from the dark spots in the active region, as the parallel dark lines are just slightly dark and no COBD occurred from these parallel dark lines. We suggest that the parallel dark lines are confined in the cladding layers. As the parallel dark lines appeared closely to the front facet where the light absorption is usually strong, it is suggested that the high temperature due to high absorption of light contributes to the generation of the parallel dark lines. It is possible that the atom distribution in the (Al)GaAs crystal planes (1 $\overline{17}$ 12) in the cladding layers is sensitive to the high local temperature near the front facet and redistribution of the atoms results in dislocations which are dark lines during the EL imaging measurements. So far, there are no other reports on AlGaAs crystal planes (1 $\overline{17}$ 12), and our experimental results may be helpful in understanding the properties of this particular crystal plane.

4. CONCLUSION

By EL imaging technique, we investigated the bulk degradation mechanism of high power InAlGaAs-AlGaAs strained quantum well lasers. We identified some dark defects in the epitaxial materials. Based on the epitaxial materials, we fabricated 20 windowed laser diodes to observe the whole emitting stripe. During the laser operation, we captured the whole process of the catastrophic bulk degradation of the laser diodes, i.e., dark spots appeared at the beginning, then evolved into dark lines, and eventually led to COBD. Meanwhile, a new gradual bulk degradation phenomenon was captured. Ten laser diodes degraded gradually with a series of parallel dark line defects generating near the front facets. According to the distribution and direction of the dark lines, we made a preliminary deduction that the parallel dark lines are located in the AlGaAs cladding layers at the crystal planes (1 $\overline{17}$ 12). To the best of our knowledge, this is the first report of such type dark lines. The detailed generation mechanism and the effect on the laser performances are under investigation.

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