Catastrophic optical damage of high power InGaAs/AlGaAs laser diodes

J.Souto[a], J.L.Pura[a], A.Torres[a], J.Jiménez[a,*], M. Bettiati[b], F.J. Laruelle[b]

[a] *GdS Optronlab, Ed. i+d, Paseo de Belén, 1, Universidad de Valladolid, 47011 Valladolid, Spain*
[b] *3SP Technologies, Route de Villejust, 91625 Nozay, France*

Abstract

The defects generated by the catastrophic optical degradation (COD) of high power laser diodes have been examined using cathodoluminescence (CL). Discontinuous dark lines that correspond to different levels of damage have been observed along the ridge. Finite element methods have been applied to solve a physical model for the degradation of the diodes that explicitly considers the thermal and mechanical properties of the laser structure. According to this model, the COD is triggered by a local temperature enhancement that gives rise to thermal stresses leading to the generation of dislocations. Damage is initially localized in the QW, and when it propagates to the waveguide layers the laser ends its life.

Key words: cathodoluminescence (CL), high power laser diodes, dark line defects (DLDs), Catastrophic degradation, thermomechanical modeling

Corresponding author.
jimenez@fmc.uva.es
Tel: +34 983423191

1. Introduction

The mechanisms driving the catastrophic degradation of high power laser diodes must be understood in order to increase their power and lifetime [1-3]. The defect signatures responsible for the laser damage have to be identified, and models that allow to the set-up of a degradation scenario related to the evolution of the materials forming the laser structure need to be settled up. Electron beam excited techniques, e.g. cathodoluminescence (CL), and electron beam induced current (EBIC), are powerful tools suitable to observe the main defects generated during the degradation process [4,5]. This is a “post mortem” analysis; however, it permits to establish degradation hypotheses, which would allow to set up a physical model providing the main steps leading to the laser degradation [6].

We present herein a spectrally resolved CL study of the defects generated during the catastrophic degradation of single mode InGaAs/AlGaAs quantum well (QW) 980nm laser diodes. A physical model for the temperature and mechanical stress distribution in the active zone of the laser, when a local heat source is generated during the laser operation, is proposed to rationalize the experimental evidence [7,8].

2. Experimental

High power single ridge waveguide InGaAs/AlGaAs QW (980 nm, ≈10% In) edge emitter pump lasers were studied. The barriers are formed by AlGaAs with ≈ 30% Al, therefore, the InGaAs QW is strained. The lasers underwent aging processes carried out under the typical parameters used for these tests. The laser structures were planarised by removing the metal overlayers and the ridge in order to have access to the laser cavity with the e-beam of the scanning electron microscope (SEM) where the CL experiments were performed.

The CL measurements were carried out with a Gatan mono-CL2 system attached to a field emission scanning electron microscope (FESEM) (LEO 1530). The CL detection was done in single channel mode using an InGaAs detector for the acquisition of the panchromatic CL images. For the spectrum analysis, a Peltier cooled Si CCD camera (200-1100 nm spectral range) was used. The probe depth of the e-beam depends on the acceleration voltage of the electrons. The typical acceleration voltages in our measurements range from 5 to 30 KV. All the CL experiments were carried out at 80 K in order to improve the signal to noise ratio.

Finite element methods (FEM) were used for defining a thermomechanical model of the laser degradation using the commercial software COMSOL.

3. Defects in the laser structure

The sudden degradation occurs when the laser diode abruptly ends lasing after many hours of operation [9]. The degradation mode is achieved by the destruction of the active region of the laser following a thermal runaway process. In order to raise a scenario of the sudden degradation one needs to identify the defects produced during the degradation, and then to establish the physical mechanisms responsible for the formation of those defects, and their subsequent propagation forming the characteristic dark line defects (DLDs) associated with the catastrophic degradation [4,9].

The degradation takes part in the active region of the laser, concerning the QW and the guide layers. Therefore, electron beam excitation techniques are very suitable for studying those layers because of the control of the e-beam probe depth by varying the electron energy. First, one proceeds by means of panchromatic CL images to localize the degraded regions of the laser. These images are taken in top view, therefore, one access to the full laser cavity. The panchromatic CL images of catastrophically degraded devices permit to see the existence of regions with dark CL contrast along the ridge and covering a certain length of the laser cavity. These regions with dark contrast are associated with the defects generated during the laser degradation process and behave as non -radiative recombination centers. As observed in the CL images these degraded areas adopt the form of dark lines. Generally, these DLDs are guided along the laser cavity by the optical field, instead of being aligned along a crystal axis. This is better seen in broad emitter lasers, where one can appreciate DLDs deviating from the cavity axis, being guided by ring modes [4].

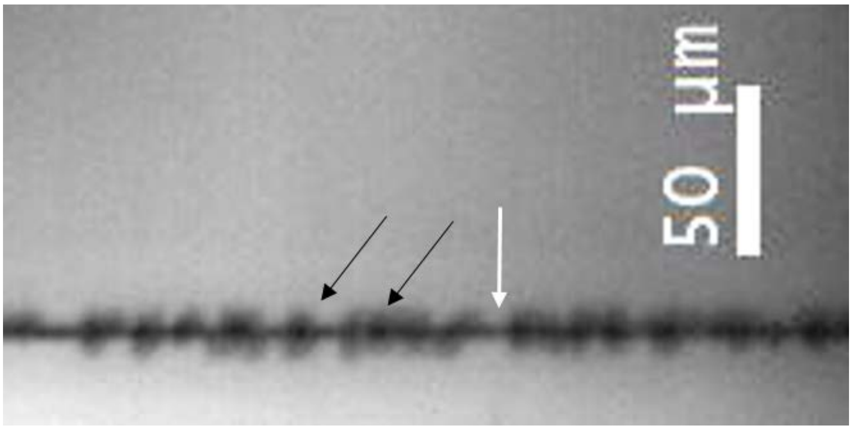

Fig.1. Panchromatic CL image of a DLD aligned along the ridge, showing discontinuous contrast and lateral DLDs (see the black arrows), and regions without those DLDs (white arrow)

Another interesting feature of the DLDs revealed by CL in these lasers is that they seem to propagate in a discontinuous sequence. In fact, the DLDs along the laser cavity seem to have different levels of degradation, Fig.1. Furthermore, some regions of the DLD appear as a sequence of dark spots separated by dark straight segments aligned with the ridge. If one looks in detail to the dark spots one observes that dark clouds extend at both sides of the laser ridge, while the dark segments connecting the dark spots are constrained to the ridge without lateral expansion.

The dark clouds surrounding the dark spots are formed by subtle arrays of DLDs oriented along crystallographic directions, either parallel or perpendicular to the laser cavity (<110> and <1-10>), or aligned along the <100> crystal axis forming 45º with the cavity axis (see Fig.1). These DLDs, which are only observed around the more heavily damaged regions of the ridge, are constituted by networks of dislocations, which propagate during the laser operation by either glide (<1-10>)or climb (<100>) mechanisms [10,11]. Contrarily to the DLD oriented along the laser cavity, the CL emission of these arrays of DLDs spreading at both sides of the ridge is not fully quenched.

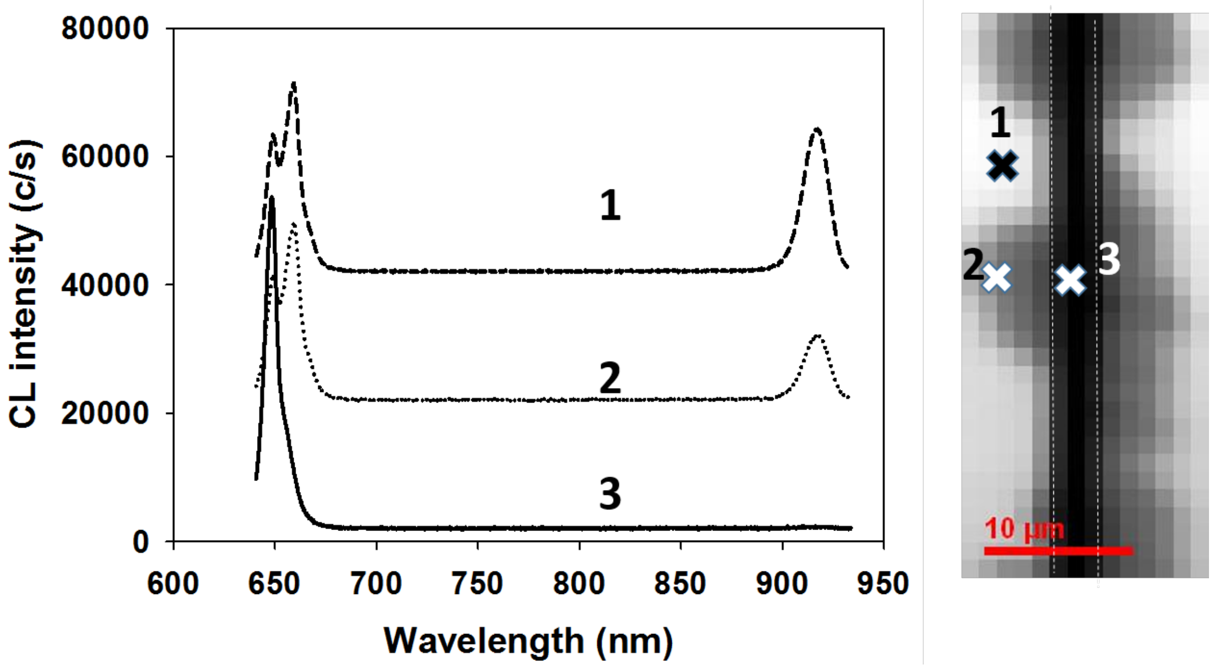

Fig.2. CL spectra taken at the points indicated in the CL image

The next step consists of the localization of these defects inside the laser structure. For this we appeal to the spectrally resolved CL images. These images permit to image the emission of the different layers forming the laser structure. Typical CL spectra acquired at different points across a DLD are shown in Fig.2; one observes the QW emission at 920 nm (instead of 980 nm because of the measurement at 80K), the p-guide (emission at 648 nm) and the n-guide (emission at 658 nm). The spectrum images reveal the spatial distribution of the three emissions, which permits to localize the damage, Fig.3. One can observe that the dark lines extending at both sides of the ridge are not observed all along the cavity, which certainly accounts for different stages of degradation in the main DLD. The subtle DLDs spreading around the ridge mainly concern the QW emission. The two guide layers do not show it, but the guide layers are only damaged along the ridge, Fig.3. This suggests that the dislocations forming these DLDs are inhibited to propagate towards the adjacent layers, which might be associated with the endurance of the strained QW, which would behave as a filter for the propagation of the dislocations [12].

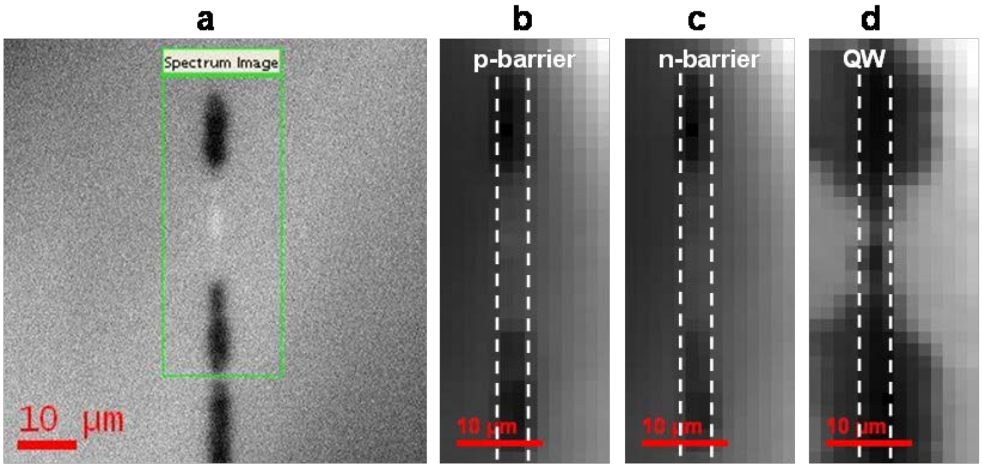

Fig.3. Panchromatic CL image showing a discontinuous DLD along the ridge(a), monochromatic image of the p-barrier emission (b), monochromatic image of the n-barrier emission (c), monochromatic image of the QW emission (d). The parallel dashed lines represent the ridge position. The DLDs spreading at both sides of the ridge are observed in the QW image, while they not appreciable in the two images corresponding to the barriers. The two barriers are damaged at ridge positions where the QW is more heavily damaged.

The morphology of the DLDs aligned along the laser cavity suggests different stages of degradation along it. When the QW appears fully dark, without CL emission, one can infer that it contains a high concentration of dislocations; generally, these fully dark QW areas are the result of melting and subsequent recrystallization, which points to very high local temperatures reached during the laser operation. The progression of the DLDs along the cavity is driven by laser self-absorption due to the temperature increase in local zones of the laser cavity, which reduce the local band–gap of the QW, losing the transparency. The subtle DLDs oriented along the crystallographic directions normally extend out of the ridge, therefore they are extending to regions without optical loading. This suggests that they are generated by thermal stresses because of the local heating of the QW.

A very relevant point concerns the end of lasing, is it the consequence of the destruction of the QW?, or is the waveguide that is destroyed?. The CL images clearly state that the waveguides are only damaged in the regions where the QW is more degraded, while regions with lower degradation do not seem to affect the guide layers. This points to the QW as the origin of the damage, being the propagation to the guide layers the consequence of the heavy damage of the QW. Note that the mere increase of the temperature does not account for the laser light absorption by the guides, which even at very high temperature remain still transparent. However, the propagation of dislocations to the guide layers can render these layers active absorbers of the laser light.

These considerations permit to establish a scenario of degradation:

a. A tiny region of the QW is heated by non-radiative recombination due to the accumulation of point defects generated during the normal operation of the laser. This slightly reduces the band gap, and the optical absorption increases the e-h generation and subsequent non radiative recombination. This must be a very slow process.
b. The optical absorption of the QW and the guide layers depends on the temperature distribution in the presence of a local heat source. In a recent paper we have shown that in this kind of structures the low dimensionality affects its thermal conductivity, resulting in large temperature gradients at the submicrometer scale [13].
3. These temperature gradients raise relevant thermal stresses, which can generate dislocations, which will be the main cause of the sudden failure, once a critical size of damaged material extending to the guide layers is reached.

This scenario can be set up by means of a thermomechanical model accounting for the experimental observations.

4. Thermomechanical model

The above results evidence that temperature and stress play a paramount role in the COD. In fact, one reaches local high temperature and atom bonds can be broken due to the large stresses produced by the local heating and the different thermal expansions of the layers forming the active part of the laser. Heat dissipation from this local heat source is limited due to the reduced dimension of the QW thickness and the presence of interfaces, which result in a substantially reduced thermal conductivity [13]. Our model estimates a very inhomogeneous temperature distribution across the laser structure, Fig.4, with a peak temperature at the QW substantially higher than the temperature of the surrounding layers [14].

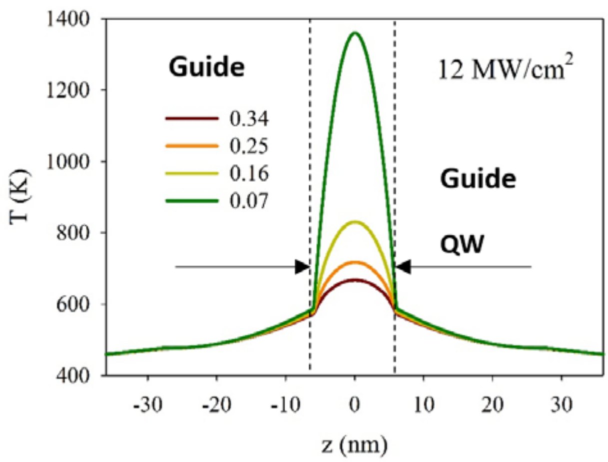

Fig.4. Temperature profile across the laser active zone for a heat source of 12 MW/cm^2 and different thermal conductivities of the structure; the values are normalized to the bulk thermal conductivity

By solving the thermomechanical equation, the amount of thermally induced local shear stress that would trigger the dislocation generation can be estimated. There is a nearly linear relation between the QW temperature and the shear stress, Fig.5. The plastic limit can be reached at different points of this line depending on the strength of the laser structure. Dislocations are generated when the shear stress is higher than the yield stress [7]. They can be created at the QW, but they are not transmitted to the barrier layers below a threshold stress value, which should depend on the laser structure. Once the extended defects (dislocations) penetrate the barrier layers extrinsic laser absorption at the barrier layers becomes relevant, the barrier temperature increases and eventually launches a thermal runaway process that results in the destruction of the waveguide. This seems to occur in the areas surrounding the most degraded QW zones where the laterally spread out dislocations account for large thermal stresses. Note that the calculated stresses show a maximum induced stress along the z axis, perpendicular to the epitaxial plane, which should account for the guide damage just below the ridge.

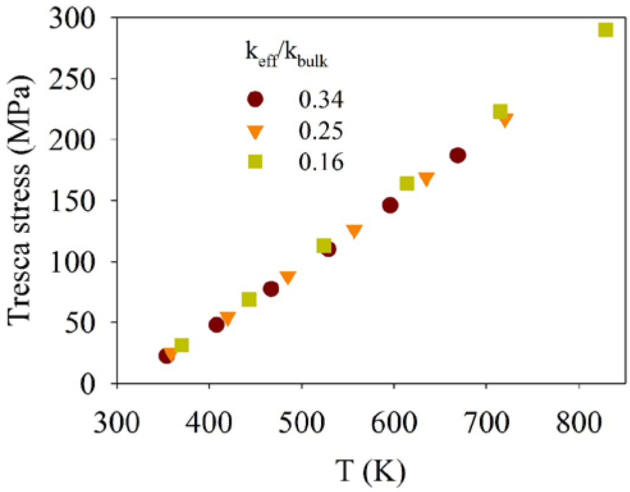

Fig.5. Shear stress (Tresca) vs the local QW temperature, calculated for different heat source powers and different thermal conductivities of the active laser region. The points are organized in a nearly linear dependence. The plastic deformation occurs somewhere along this line depending on the laser structure, and the residual stresses

Conclusion

In conclusion, CL inspection of the degraded lasers permits to raise a fear scenario of the defects generated during the catastrophic degradation of the laser diodes. The mechanism leading to the degradation can be simulated by a thermomechanical model. These results evidence that the properties, optical, mechanical and thermal of the laser structure play a paramount role in the occurrence and evolution of the thermal runaway process leading to the laser degradation.

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