ABOUT THE CRITICAL TEMPERATURE FOR CATASTROPHIC OPTICAL DAMAGE IN HIGH POWER LASER DIODES

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ABSTRACT

Degradation of laser diodes during operation constitutes a serious drawback for both laser manufacturers and end users. The catastrophic optical damage (COD) of laser diodes consists of the sudden drop off of the optical power. COD involves a thermal runaway mechanism in which the active zone of the laser is molten. Degraded devices present dark line defects (DLDs) produced during the laser operation; these DLDs are regions of the active zone of the laser without emission. These dark lines are locally generated, either at the front facet, or inside the cavity, and then propagate along the cavity driven by the optical field. The physical mechanism leading to the formation of such lines and the associated loss of output optical power is described in the literature, but there is not consensus about the origin of the COD. Usually, the COD is described in a sequence of different phases, in the first phase the process is incubated, this phase ends when a critical temperature is reached; then, it is followed by a sharp increase of the optical absorption with the corresponding sharp temperature increase which leads to melting and the failure of the device. Here we will focus on the first phase, we will discuss about the critical temperature, and the physical mechanisms involved in this phase; in particular, we will describe the conditions under which such critical temperature can be reached. For this we will analyze the conditions for reaching the critical temperature and the influence of the laser structure on the laser strength. We compare the critical temperature estimated by our thermomechanical model with the values experimentally reported, which range between 130ºC and 180ºC.

INTRODUCTION

Because of the demand of increasing optical power from laser diodes, reliability remains to be a strong challenge for the use of these devices in many applications. The understanding of the degradation mechanisms of high power laser diodes is critical to improve their power and lifetime. The failure of the laser diodes is due to the generation of extended defects in the active parts of the laser structure during the laser operation [1,2]; in high power laser diodes the thermal management is a critical issue because of the important amounts of wasted power. Degradation of laser diodes during operation constitutes a serious drawback for both laser manufacturers and end users. The catastrophic optical damage (COD) is a harmful degradation event, since it takes place without previous warning. The COD consists of the sudden drop off of the optical power. COD involves a thermal runaway mechanism in which the active zone of the laser can reach very high temperatures, ending by melting [3].

Degraded devices present dark line defects (DLDs) generated during the laser operation; these DLDs are regions of the active zone of the laser with very low or null light emission. These dark lines are locally generated, either at the front facet, or inside the cavity, and then propagate along the cavity driven by the optical field [4,5]. The physical mechanism leading to the formation of such lines and the associated loss of output optical power is described in the literature [5], but there is not consensus about the origin of the COD, and about the technological factors that can strengthen the laser diodes. Usually, the COD is described in a sequence of different phases, in the first step the process is incubated, this step is certainly related to the long term degradation [1,6], in which point defects are generated in a slow process. The local accumulation of these defects will form “weak” zones in the active region. These “weak” zones react to the laser field leading to the COD process. In fact, the “weak” zones are defect rich zones, which when interacting with the electric current and/or laser light can trigger the catastrophic degradation. In the presence of defects an initial temperature increase can occur, obeying to different physical mechanisms, e.g. non radiative recombination at defects, or local Joule heating due to local resistance changes; note that the presence of defects can contribute to both mechanisms. When the “weak” region accumulates sufficient energy it reaches a critical temperature, for which a sudden increase of the optical absorption takes place, resulting in the thermal flash observed by means of a thermocamera in lasers operating in pulsed mode [5,7]. This COD triggering has been reported to occur between 120ºC and 200ºC, depending on the laser structure and the nature of the active region, this is the so-called critical temperature for COD [4,7,8,9].

One needs to understand why such a temperature is reached at certain regions of the laser active zone, and why the critical temperature constitutes a turning point for the optical absorption of the laser light. Once the critical temperature is reached the DLDs propagate very fast (microseconds scale); on the other hand, the propagation is driven by the laser field as it propagates along the waveguide, for both broad and narrow emitters. Furthermore, the damage is mainly concentrated in the QW, which is destroyed, but it can also touch the guide layers. We present here an analysis of the critical temperature in QW laser diodes using finite element methods for solving the heat transport equation in a multilayer structure as a laser diode.

THERMOMECHANICAL MODELING

The lasers studied are AlGaAs based (808 nm) broad emitters, or 980 nm (InGaAs QW), both multimode and single mode. The main parameters used for the calculations were taken from the literature [10 and references therein]. A description of the laser structures is given in [10,11].
The COD process can be subdivided in two consecutive steps, first a critical temperature is reached; once this situation is reached, a sharp temperature increase is produced in a process fed by the thermal bandgap shrinkage with the concomitant laser light absorption, leading to temperatures close to the melting point. During this step the defects grow very quickly forming extended motifs, with the corresponding laser output power drop. These defects are revealed by CL and normally they give a true dark contrast [11], which permits to distinguish them from other defects which though giving dark contrast are still able to emit light, Fig.1.
In recent works, we have developed a thermo-mechanical model for studying the role of local heating on high power lasers [10,12,13]; the model can be applied to different laser structures. In this model, the origin of the degradation is a local accumulation of energy constituting a very local heat source; it can be the consequence of an enhanced non radiative recombination contribution associated with the accumulation of point defects during the laser operation in a reduced region of the active region, e.g. in the facet this results in the increase of the surface recombination; alternatively, one can consider that the point defects might induce local resistance

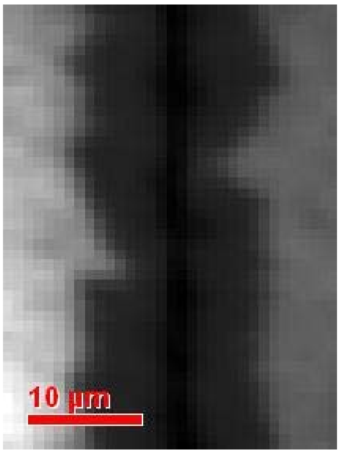

Fig.1. CL image of the QW emission showing the fully dark line along the ridge, and defects propagating at both sides of the ridge.

changes, which would enhance the temperature by local Joule heating. The origin of the local temperature increase is out of the present scope, though it is a very relevant point to consider in forthcoming analyses. In our model one solves by finite element methods (fem) the heat transport equation. Thereafter, one resolves the thermo-mechanical equation resulting from the local stresses induced by the local heat source in a structure formed by layers with different properties, both thermal and mechanical.
An important issue revealed by the solution of the heat transport equation is the large inhomogeneity of the temperature distribution across the laser structure, the temperature profile across the laser structure is shown in Fig.2 for different thermal conductivity scenarios, showing that the QW temperature is much higher than the temperature of the surrounding layers (guides and claddings). This temperature inhomogeneity is the consequence of the differences in the thermal conductivity of the different layers constituting the laser structure, the thermal barriers at the interfaces, and the thermal conductivity suppression associated with the nanoscale

dimension of the QW [14,15]. The peak temperature is reached in the QW, while much lower temperatures are reached in the guides and claddings. In this calculation the dependence with T of the thermal conductivity and other physical parameters was entailed.

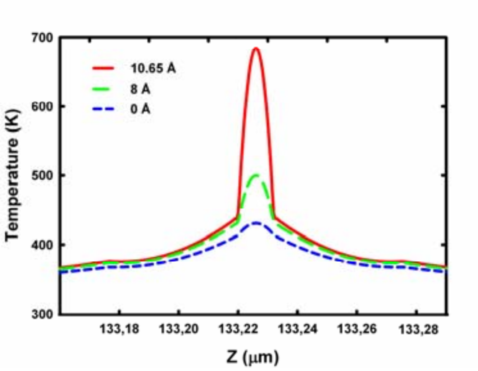

Fig.2. Temperature profile across the laser structure for a heat source of 6 MW in the mirror facet, for three different interface roughness (0, 8 Å, 10.65 Å), showing the peak temperature in the QW, and the lower temperature in the adjacent layers.

What does the critical temperature mean?. In the frame of our thermo-mechanical model the critical temperature is the temperature at which the QW generates dislocations due to the thermal stresses induced by the local heating. This has been discussed in previous articles [10,12,13], and the results are summarized in Fig. 3, where one represents the shear stresses vs local T (temperature of the heat source in the QW), for different heat powers and different properties of the laser structures. The results are roughly aligned along an imaginary line crossing the yield strength vs T plot for bulk GaAs; the crosshatch occurs around 500 K (see the dashed circle in Fig.3), which suggests that under the thermal stresses induced by the local heating the dislocations start to form around this temperature, at which the yield strength is reached; therefore, in a first approach this can be considered the critical temperature.

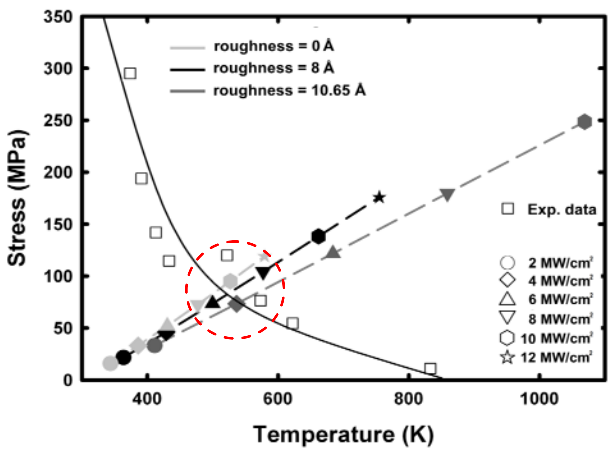

Fig.3. Shear stress vs QW temperature for different laser power densities and different interface roughness. The open square represent the yield strength of bulk GaAs. The dashed highlights the intersection between the shear stress (T) and the yield strength of bulk GaAs, representing the onset of plasticity, which occurs at about 500K for the different scenarios represented.

DISCUSSION

The critical temperature has been measured by different procedures, microRaman spectroscopy, thermo-reflectance, micro-photoluminescence, thermal imaging directly using a thermocamera… Because the methods of measuring the temperature in a laser under operation use large probes (∅≥1μm), the estimated temperature should be an average over a region at least two orders of magnitude larger than the QW, where the highest temperature is reached; therefore, one can argue that those measurements are severely underestimating the peak temperature reached in the QW. For example in micro-Raman measurements the Raman signal arising from the QW is not observed, because of the very small volume, therefore the temperature measurement in the front facet of the laser corresponds to the temperature of the guides and claddings averaged over the probe beam [16]. Similar arguments can be applied to other measurement techniques. In general, the measured temperature is an average over the different layers simultaneously probed, but always with a very low contribution of the QW. Fig.4a shows the average temperature over the probe size, e.g. Gaussian laser beam, calculated from the temperature distributions obtained by solving the heat transport equation. One observes temperatures substantially lower than the peak temperatures, Fig.4b. The measurements with the thermocamera give higher temperature than the spectroscopic techniques [17,18], because of the T^4 dependence of the radiation, which enhances the weight of the emission from the hottest region, the QW, with respect to the other layers. Fig. 4c shows the temperature averaged over the thermocamera pixel size making use of the T^4 emission law and the temperature distribution derived from our model. In any case, the experimentally measured critical temperature is not the peak temperature in the laser, which is significantly higher. This has consequences on the interpretation of the COD mechanisms, and the critical temperature.

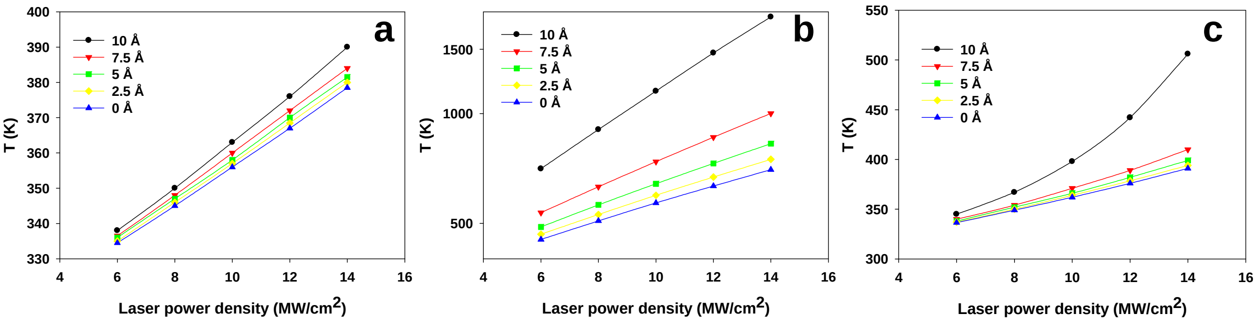

Fig.4. a) Average temperature estimated from the calculated temperature distribution, when an optical probe (e.g.Raman) is used for temperature measurements. b) peak temperature calculated at the QW. c) The same as (a) but using the T^4 law, which reproduces with more fidelity the thermocamera measurements. The data are obtained for different interface roughness, for increasing the interface roughness the thermal conductivity across the laser structure is decreased. Note the important discrepancies between the three for the same laser power density and the same interface roughness.

The thermal stresses calculated for different scenarios in an AlGaAs based QW laser are shown in Fig.3 together with the yield strength of bulk GaAs; when the shear thermal stresses overcome the yield strength one assumes that the COD has started. According to Fig.3 this occurs for a temperature of ≈500K, which is not to far from the critical temperatures reported in the literature; however, in our calculations this is the peak temperature (QW temperature), while the measured temperatures correspond to the adjacent guides. Assuming peak temperatures of 500K, the temperature of the adjacent layers is too low to match the experimental data. This suggests the need to revise the criteria followed to define the critical temperature. In previous papers we have estimated the starting of the COD when the shear thermal stresses overpass the yield strength of bulk GaAs. However, our approach is probably not fully correct, if one considers the hardening due to the reduced thickness of the QW [, which will displace the onset of plasticity to significantly higher stresses. Furthermore, this criterion could still be too conservative, if one considers that a strong optical absorption is necessary to increase the local temperature at the QW to values that would correlate to those experimentally measured. Therefore, a sufficient volume of dislocations would be required to absorb that substantial part of the optical power. As the number of dislocations grows, the laser absorption would increase accordingly, and so would the temperature at the QW. This suggests that the critical temperature would be reached well after the mechanical flow regime starts.

CONCLUSION

We have presented a study of the critical temperature for COD based on the thermomechanical model developed in previous articles [10-13]. A very inhomogeneous temperature distribution across the laser structure is estimated. In contrast to this, the experimental measurements of the critical temperature are underestimating the peak temperature, since they are mainly measuring the temperature of the adjacent layers (guides and claddings), whicc are substantially lower than the QW temperature. In this frame, the critical temperature is the one necessary for the onset of plasticity in the QW. This onset is enhanced with respect to the bulk GaAs because of the reduced thickness of the QW.

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