Role of Thermal Stresses in Degradation of High Power Laser Diodes

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Abstract: Catastrophic degradation of high power laser diodes is due to the generation of extended defects inside the active parts of the laser structure during the laser operation. The mechanism driving the degradation is strongly related to the existence of localized thermal stresses generated during the laser operation. These thermal stresses can overcome the yield strength of the materials forming the active part of the laser diode. Different factors contribute to reduce the laser power threshold for degradation. Among them the thermal transport across the laser structure constitutes a critical issue for the reliability of the device.

Key words: high power laser diodes; thermal stresses; laser degradation; extended defects

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1 Introduction

Rapid progress has been achieved in the last years in the reliability improvement of high power laser diodes. However, as the demands of higher optical powers are increasing for many applications, reliability remains a strong challenge for the continuum development of applications of these devices. Therefore, the understanding of the degradation mechanisms of high power laser diodes is critical to improve their power and reliability. The degradation of high power laser diodes is due to the generation of extended defects in the active parts of the laser structure during the laser operation[1-2].

The presence of dislocations in the active zone of the laser leads to irreversible damage, usually described by a thermal run away process[3]. Extended defects in the active parts, quantum well (QW), waveguide and claddings, generated during the laser fabrication process are responsible for infant mortality, which is known as the rapid degradation mode; the lasers with defects in the active parts are screened during the burn-in tests. However, extended defects generated during the normal operation of the laser are hazardous, because of the difficulty to screen them; therefore, the understanding of the mechanisms contributing to the formation of such defects during the normal operation of the laser is crucial to the improvement of the laser device fabrication and the operation conditions. Catastrophic degradation is unambiguously associated with the formation of extended defects in contraposition to the point defect generation characteristic of the wear out aging.

The extended defects are formed because of the atomic bond breaking, which evidences that the yield strength of the active materials is reached during the laser operation. Therefore, stresses have to be generated during the laser operation, which should be responsible for the generation and subsequent propagation of dislocations. We present herein a thermo-mechanical analysis of the laser diode structure, where we demonstrate that the conditions for dislocation generation in the active part of the laser can be achieved under standard laser operation conditions.

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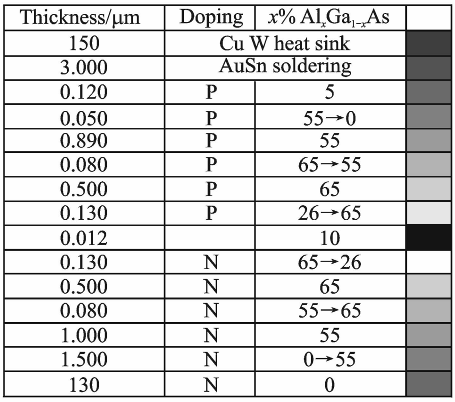
Once the dislocations are formed, it will further evolve to the thermal runaway process leading to catastrophic optical damage (COD)[3]. We present herein the calculation based on finite element methods (FEM); where we demonstrate that the critical shear stress can be reached at relatively low power density threshold, pointing to the reasons for the different vulnerability of devices made with similar technologies, as well as the relevance of the technological steps. We pay special attention to the suppression of the thermal conductivity across the laser structure, which drastically lowers the laser power threshold for catastrophic degradation[4]; also, the residual stresses (packaging, bonding wiring …) are shown to contribute to lowering the COD threshold[5].

2 Laser Structures

A laser diode is a multilayer structure, in which dissimilar materials, in terms of mechanical and thermal properties, are stacked. We use here the example of laser bars, composed of 25 broad area AlGaAs/GaAs graded-index separate confinement heterostructure individual emitters (808 nm) with optical output powers up to a few tens of watts. The emitters are separated by optically and electrically isolated channels, with a period between emitters of 400 μm. The bars are 130 μm thick, 1 cm wide, and the cavity length is 1 200 μm. The p-type dopant is C while the n-type dopant is Si. The active part of each single emitter has a width of 200 μm, and is divided into 20 injection channels separated by dielectric stripes with a period of 10 μm. The laser bars are soldered p-side down on a CuW heat sink using AuSn as a solder. The multilayer structure is schematically shown in Fig. 1.

The active parts of the laser are the QW, the waveguide, and the cladding layers. Under normal operation conditions the cavity works at a temperature circa 25 °C, at which the thermal stresses and the residual stresses, associated with the structure and processing of the laser, are far from the yield strength.



Thickness/μm	Doping	x% Al$_x$Ga$_{1-x}$As	
150	Cu W heat sink		■
3.000	AuSn soldering		■
0.120	P	5	▨
0.050	P	55→0	▨
0.890	P	55	▨
0.080	P	65→55	▨
0.500	P	65	▨
0.130	P	26→65	▨
0.012		10	■
0.130	N	65→26	□
0.500	N	65	▨
0.080	N	55→65	▨
1.000	N	55	▨
1.500	N	0→55	▨
130	N	0	▨

Fig. 1 Laser diode structure

3 Thermomechanical Model of Degradation

Typical defects observed in degraded devices are the dark line defects (DLDs)[1,6]. Usually, the DLDs appear oriented along crystallographic directions, either parallel or perpendicular to the cavity (⟨110⟩ and (⟨1-10⟩), or forming 45° with the cavity (⟨100⟩), depending on the type of laser. These DLDs are networks of dislocations, formed and propagated during the laser operation.

The catastrophic degradation in broad area emitters has been described by a local ignition, which corresponds to a local temperature increase, followed by a fast propagation across the laser waveguide[7]. Often, the active parts, QW and the waveguide are destroyed, showing evidence of melting. However, the laser degradation is a dynamical phenomenon, the melting of the QW indicates the end of the process, rather than the beginning. In fact, the temperature at which the degradation has been estimated to start is in the range of 150—200 °C[3,8], which is significantly lower than the melting temperature. In order to build up a model of the laser degradation, one can assume a degradation scenario where a very local temperature increase in the active part of the laser shrinks the bandgap with the concomitant laser self-absorption. It will form a tiny absorbing volume in which the temperature is enhanced; the local temperature increase will be determined by the fraction of the laser power locally absorbed, which is not a constant quantity, but is increasing as far as the temperature grows. This means that the energy deposited on that region is progressively increasing. The local temperature enhancement in a multilayer structure, formed by materials with different thermal expansions, and different thermal conductivities, shall generate thermal stresses. Now the question is: can these thermal stresses be responsible for the formation of the extended defects and their subsequent propagation along the laser structure?

The following degradation sequence can be proposed: it would be initiated by non-radiative recombination at facet defects, or at clusters of point defects inside the cavity; these defects might be generated during the normal wear out aging of the laser. Non-radiative recombination at these defects can transfer heat to the lattice, increasing the local temperature, producing band gap shrinkage with the corresponding laser light self-absorption; besides, the energy can be transferred to the surrounding lattice allowing defect formation and motion by the mechanism of recombination enhanced defect reactions (REDR)[9]. The self-absorption, and the REDR mechanisms feedback the temperature increase during the laser operation; sharp temperature increases on tiny areas of the QW shall introduce very sharp thermal gradients, with the consequence of the mismatching between the different layers constituting the laser structure.

Assuming a local heat source which is fed by the laser self-absorption, one proceeds to solve the heat transfer equation across the laser structure by FEM [4,5,10]. Once the temperature distribution is resolved, one proceeds to solve the thermoelastic equation, the solution of which provides the thermal stress field generated by the local heat source. All the materials parameters used for the calculation (thermal expansion coefficient, Poisson ratio, heat capacity, thermal conductivity and Young′s modulus) can be found in Refs. [11, 12]. Thermal boundary conditions are of two different types: specified temperature and specified heat flux. The former is of Dirichlet type and prescribes the temperature at a boundary, while the second is of Neumann type and specifies the inward heat flux, for more details see Ref. [5]. In this case example, the heat source representing the zone under the influence of the non-radiative recombination was two-dimensional, and different sizes were used. The boundary conditions for the mechanical model are free displacements in all the external faces, except the bottom surface of the structure that remains fixed.

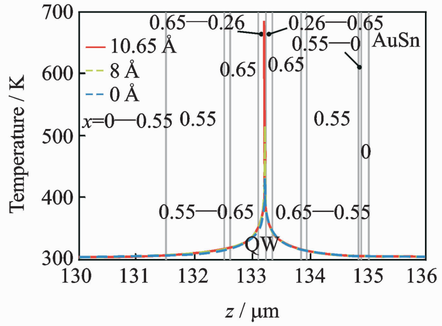
The plastic deformation, which triggers the formation of dislocations and therefore constitutes the beginning of the catastrophic degradation, would occur if the maximum shear stress component (Tresca criterion), or the maximum shear strain energy per unit volume (von Misses criterion) overcomes the yield strength of the active parts of the laser[5].

The heat extraction from the active zone of the laser is crucial to the degradation. In fact, a poor heat extraction should result in sharp temperature gradients, which will enhance the thermal stress. Therefore, the thermal conductivity across the laser structure must be improved as much as possible. It is well known that in semiconductor structures with nanometer dimensions, e. g. the thickness of the QW, and the barrier layers, the thermal conductivity is reduced with respect to the bulk value[13,14]. Furthermore, this suppression is dependent on the quality of the interfaces, being more important for rough interfaces[13]. Rough interfaces enhance the phonon boundary scattering, slowing down the heat evacuation; therefore, the morphology of the interfaces is crucial for the heat transport across the laser structure.

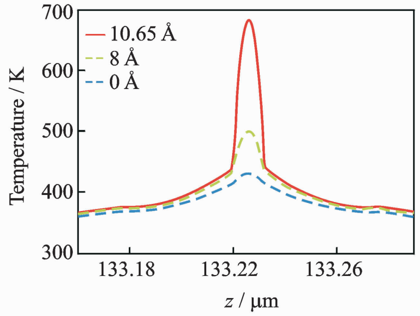
The temperature profiles calculated across the laser structure, for different absorbed laser powers, and different interface roughness are shown in Fig. 2.

The temperature distribution across the laser structure depends on the interface morphology, and on the laser power absorbed; note that only a fraction of the laser power density is absorbed. At the beginning of the absorption process, the fraction of power density absorbed increases during the process. For a laser of these characteristics, the power density under normal operation is around 10 MW/cm^2.

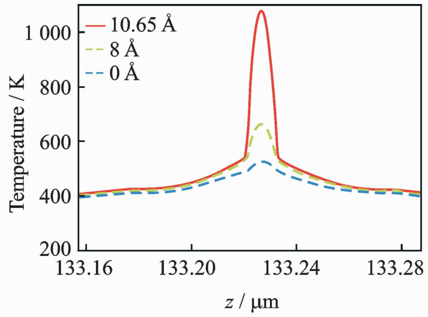
The shear stress fields across the laser struc-



(a) Temperature profile across laser structure

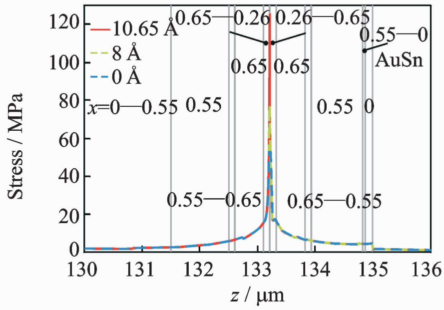


(b) Temperature distribution for 6 MW/cm² power density

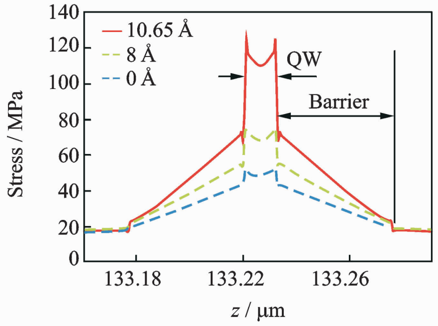


(c) Temperature distribution for 10 MW/cm² power density

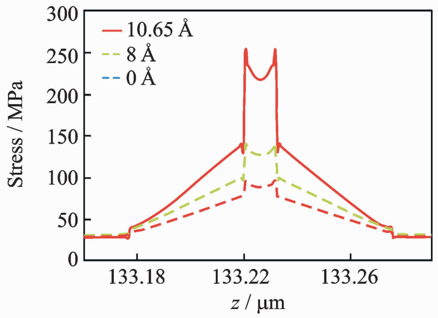
Fig. 2 Temperature distribution across the laser structure for different QW/barrier interfaces roughness, and different power density absorption



(a) Shear stress across laser structure



(b) Shear stress for 6 MW/cm² power density



(c) Shear stress for 10 MW/cm² power density

Fig. 3 Shear stress across the laser structure for three different interface roughness, 0, 8 and 10.65 Å, respectively

ture calculated from the temperature distributions shown in Fig. 2 are represented in Fig. 3. One observes a large shear stress gradient along the QW/barrier interface, and a strong increase of the stress with the interface roughness. The shear stress needs to be compared with the yield strength of the active layers of the laser in order to establish the operation conditions at which dislocations are formed. Fig. 4 shows the maximum shear stress reached in the conditions of Fig. 3, for a heat source of 6 MW/cm^2 power density, and different interface roughness; the line guiding the open symbols marks the yield strength as a function of temperature for bulk GaAs[15,16]; this constitutes a crude approximation, but there are not experimental data for thin layers of different compositions.

The full symbols represent the stress values at the maximum temperature reached in each case. One observes that for flat interfaces with roughness 0 nm, the thermal shear stress cannot generate dislocations, and the stress is below the threshold for plastic deformation. When the interface roughness increases to 8 Å, the shear stress is close to the yield strength. Finally, for 10.6 Å roughness the threshold for dislocation generation is largely surpassed. This evidences the capital role that the quality of the interfaces plays in the reliability of high power laser diodes.

Note that the dislocation generation takes place at the crosshatch between the yield strength and the Tresca stress calculated under different power absorption and interface roughness, see Fig. 4. Increasing the interface roughness should significantly lower the power threshold for degradation. The two lines cross at about 200 °C, which is in the order of the temperature ≈160 °C usually given for starting the catastrophic degradation. Note that 6 MW/cm^2 is a fraction of the laser power density of these devices (≈10 MW/cm^2 for a 30 W laser), therefore, smooth interfaces will warrant reliability, while rough interfaces will accelerate the degradation.

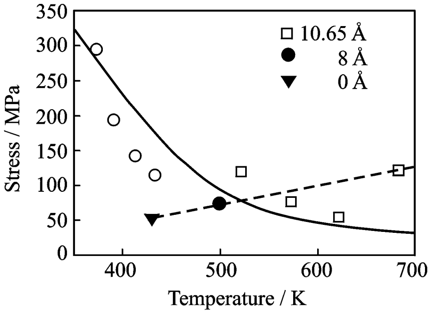


Fig. 4 Shear stress vs. temperature for three interface roughness, and 6 MW/cm^2 laser power, open circles[15], and open squares[16]

It should be noted that one could add other stress terms to the calculation, e. g. the packaging stress, which should reduce the temperature threshold for dislocation generation. For example, assuming a packaging compressive stress of 50 MPa, one estimates a decrease of the threshold temperature ≈50 °C, which approaches the temperature threshold to the experimentally reported one[3,8].

4 Conclusions

A thermomechanical model is developed in order to describe the initial stages of the catastrophic degradation of high power laser diodes. The role of the interface quality is analyzed in terms of the reduced thermal conductivity across such interfaces. The threshold powers for degradation are found to lie within the normal limits of laser operation.

Acknowledgement

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