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Laser diode reliability: crystal defects and degradation modes

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Abstract

Degradation analysis is a crucial issue for the improvement of high power laser diodes. Degradation occurs in three different modes: rapid, gradual and catastrophic. It can be located inside the cavity or at the facet mirrors. Each type of degradation presents its own signature and different crystal defects appear associated with them. The main physical mechanisms responsible for laser degradation are analysed showing the relation between the main degradation modes and the different materials properties of the laser structures. ***To cite this article: J. Jiménez, C. R. Physique 4 (2003).***

Résumé

Fiabilité des diodes laser : défauts cristallins et modes de dégradation. L'analyse de la dégradation est fondamentale pour l'optimisation des diodes lasers de puissance. La dégradation des lasers se présente sous trois modes : rapide, graduelle et catastrophique. Elle peut se produire à l'intérieur de la cavité ou au voisinage des facettes. Chaque mode de dégradation présente sa propre signature et des défauts cristallins différents sont associés à chacun de ces modes. Les principaux mécanismes de dégradation sont analysés en montrant les relations entre les modes de dégradation, les propriétés des matériaux et la structure des lasers. ***Pour citer cet article : J. Jiménez, C. R. Physique 4 (2003).***

Keywords: Degradation; Catastrophic degradation; Dark line defects; Dark spot defects; Recombination enhanced defect reaction; Dislocation climb; Dislocation glide

Mots-clés : Dégradation ; Dégradation catastrophique ; Défauts lignes noires ; Défauts points noirs ; Recombinaison ; Montée de dislocations ; Glissement de dislocations

1. Introduction

High power laser diodes cover a broad spectrum of applications from erbium doped fiber amplifiers (EDFA) to pumped solid state lasers, a brief history of high-power semiconductor lasers is presented in [1]. These applications need long lifetime devices, and therefore, reliability is a very crucial issue of high power laser diode technology. A great effort is devoted to understanding the main causes of laser failure, in view to improving their lifetime and to extending the range of their applications.

The degradation of the laser diodes occurs in different modes, which have their own signature depending on the architecture and composition of the laser. The most common lasers are based on lattice matched AlGaAs/GaAs, InGaAsP/InP and strained InGaAs/GaAs heterostructures. These lasers have been the object of an extensive literature, in spite of which a full understanding of the degradation is not yet available. A major problem to achieve such an understanding is the complexity of the laser structures and the diversity of factors that can induce degradation. Amongst others, one can consider the perfection of the

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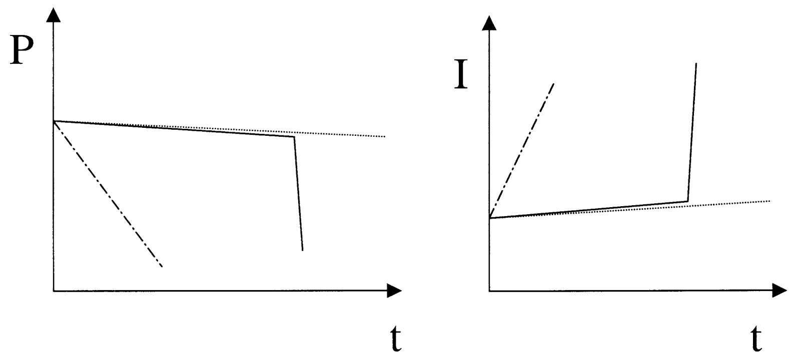

Fig. 1. Degradation modes in constant current (left) and constant power modes (right). Rapid degradation (-·-·), gradual degradation (- - -), catastrophic degradation (—).

substrates, layers and interfaces that constitute the material support of the laser, the architecture of the lasers that can induce defects and strain, the processing steps, like metallisation and facet coatings, and the packaging step. These factors, inherent to the structure of the laser, interact among themselves and with external factors as temperature, current injection, optical power and ambient atmosphere, leading to complex degradation mechanisms. One presents here an overview of the main degradation modes affecting the material properties forming the active parts of lasers and the description of the main defects involved in the degradation. For additional information, the monographs and review articles about the subject, [2–8], are suggested to the reader.

2. Degradation modes

The degradation of laser diodes is measured as the evolution with time of either the light output power at constant injection current or the threshold current at constant light output power. The constant output power mode implies a progressive increase of the injection current as the device performance degrades, which gives an additional enhancement of the junction temperature, contrarily to what happens for constant current mode [9]. Constant output power is the operation mode of lasers for telecommunications, while constant current mode is used for other applications. If one examines the plots P versus t and I versus t, degradation occurs in three different time scales and can be classified as rapid, gradual and catastrophic degradation, Fig. 1.

Rapid degradation is normally observed in the first hundred hours of operation. It appears as a quick decrease in the optical output power or a quick increase in the threshold current. Gradual degradation is the usual failure mode of a device operating over its service life, which can extend to several thousand hours, and manifests itself as a gradual decrease in the quantum efficiency. This is the expected degradation mode for a device free of crystal defects in the active region, or operating at low power. Catastrophic damage appears as a sudden failure after a regular operation life of the laser, which represents the end of life for the device [5]. Catastrophic degradation can occur at the facet mirror or inside the cavity. One should refer to facet degradation as Catastrophic optical mirror damage (COMD). Catastrophic degradation is a very hazardous degradation mode, since it is silent and appears suddenly without a previous sign that such a failure could arrive; therefore, it is very difficult to screen, and constitutes one of the main challenges regarding the reliability of laser diodes. Though catastrophic damage is the main cause of laser failure, the long lifetime demanded for lasers in submarine telecommunications (over 200 000 hours) is a challenge for long term gradual degradation analysis.

The degradation phenomena are closely related to the existence, generation and motion of defects in the laser structure. Basically, the different degradation modes listed above can be associated with different types of defects. This means that defects must be avoided to allow good quality heterostructures, free of dislocations and point defects. Other factors proper to the processing and packaging steps have to be optimised in order to increase the life of the device. These technological steps can introduce defects, strain, electrical resistances, ... which are important degradation agents. Inadequate handling drastically reduces laser lifetime.

3. Rapid degradation

Rapid degradation is associated with the presence of extended defects that destroy the active region of the laser (QW and cladding layers) and quench the optical emission. The study of these dark regions reveals two main defect structures: Dark Line

Defects (DLDs) and Dark Spot Defects (DSDs). These defects appear as regions of very low luminescence efficiency. Some of them are fully dark, without any luminescence emission for heavily degraded devices. The DLDs look like oriented dark structures in Cathodoluminescence (CL) and Electroluminescence (EL) top view images; Fig. 2 shows a CL monochromatic image at 980 nm of a degraded InGaAs/GaAs laser showing DLDs [10].

The structure of the DLDs has been the object of many studies [1,2,5,11–13]. Transmission Electron Microscopy (TEM) analyses of DLDs present them as dense three-dimensional networks of dislocation loops and dipoles. These clusters of crystal defects develop around a threading or a misfit dislocation crossing the active layer, and are primarily found at the QW and the neighbouring cladding layers. The growth of the DLDs is a typical process of dislocation elongation as a consequence of the interaction between the dislocation, point defects and the minority carriers introduced in the active region by electric injection and optical generation due to self-absorption of the laser light inside the optical cavity.

The rapid degradation of the optical power occurs as a consequence of the formation and quick growth of large DLDs or DSDs. The threading dislocations can be present in the heterostructure as a consequence of the crystal growth process. Most of the threading dislocations emerge from the substrate and thread through the epitaxial multilayer structure. Misfit dislocations arise from internal stresses associated with the differences between the lattice parameters of the layers forming the multilayer structure. They can also be introduced by handling and mounting processes.

The generation of dark defects is closely related to solid state reactions involving the generation, diffusion and motion of defects. These processes are thermally activated and, at temperatures inside the laser cavity, are normally very slow, which could not account for the reported times of laser degradation. However, the energy necessary for a significant acceleration of these processes can be supplied by non-radiative recombination of the injected carriers. Defect formation and motion are rendered possible at such low temperatures (20–30 °C) when the vibrational energy released by the non-radiative recombination is concentrated at the recombination centre in an excited vibrational state. In such a state the released energy is supplied to the defect that can undergo simple solid state reactions, such as diffusion, dissociation and annihilation. The defect reactions undergo an effective reduction of the activation energy in the presence of non-radiative recombination [14]. This mechanism is called Recombination Enhanced Defect Reaction (REDR).

The dislocation motion leading to the formation of the DLDs proceeds by two different mechanisms:

- Recombination Enhanced Dislocation Climb (REDC);
- Recombination Enhanced Dislocation Glide (REDG).

Dislocation climb consists of the increase in the dislocation length mediated by either the absorption or emission of point defects. Dislocation climb is not constrained to the glide plane of the dislocation. This mechanism leads to the formation of ⟨100⟩ DLDs, which are basically networks of dislocation loops and helical dipoles elongated along the ⟨100⟩ crystal direction. The dark pattern of ⟨100⟩ DLDs forms an angle of 45° with the laser cavity. They are observed in the waveguide region around the contact stripe, see Fig. 2. Plan view TEM shows the structure of these DLDs in Fig. 3, where helical dipoles and loops are observed. The nature of the DLDs observed in degraded devices is a matter of controversy; Waters et al. [15] showed that DLDs grew predominantly in unstrained AlGaAs QW lasers, while strained InGaAs QW lasers showed endurance to these

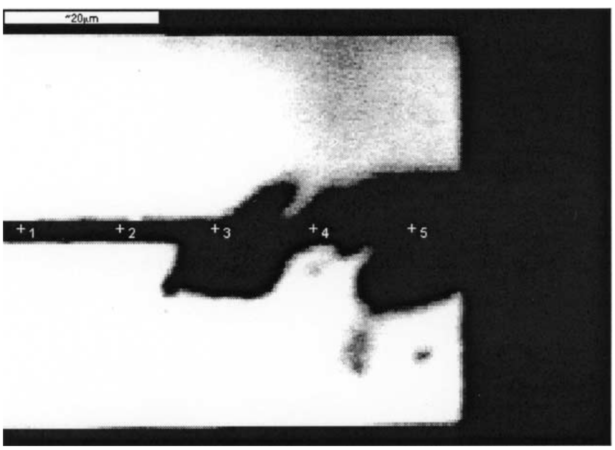

Fig. 2. Monochromatic CL image of the QW emission in an InGaAs/GaAs laser showing DLDs. (From [10], with permission of Wiley-VCH Verlag GmBH.)

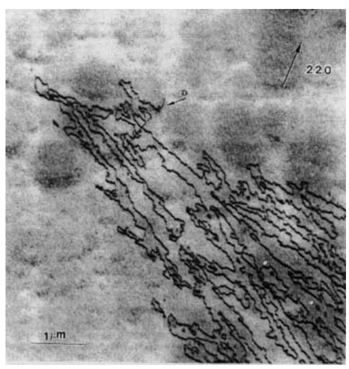

Fig. 3. Dislocation microloops and dislocation network in an AlGaAs/GaAs laser. The microloops are indicated by arrows. (From [2], with permission of Academic Press.)

DLDs, which was associated with the lattice hardening due to In. The presence of strain relievers (such as As vacancies) was also claimed to contribute to the higher stability of strained InGaAs/AlGaAs lasers [13]. Dislocation motion by climb can be achieved by two different mechanisms, that have been used to describe the formation of ⟨100⟩ DLDs in AlGaAs lasers:

- absorption of extrinsic defects, e.g., interstitials, at the dislocation and emission of vacancies and antisites forming dislocation loops intrinsic in nature [12];
- emission of point defects, e.g., interstitials, by absorbing intrinsic defects, vacancies, forming dislocation loops extrinsic in nature [11,13].

Both mechanisms demand the presence of a significant concentration of point defects, mostly stoichiometric defects. Fine TEM analyses are necessary to identify the nature of the ⟨100⟩ DLDs.

The ⟨110⟩ DLDs grow much slower than ⟨100⟩ DLDs and the dislocation motion is done by glide on the (111) planes under the action of stresses. The presence of ⟨110⟩ DLDs in AlGaAs/GaAs DH lasers has also been reported [16]. The ⟨110⟩ DLDs are associated with 60° dislocations oriented along the ⟨110⟩ axis. These dislocations elongate in the glide plane as a consequence of increased local stress. The energy necessary for the dislocation to surmount the energy barrier in between two equilibrium positions is supplied by non-radiative recombination (REDG). It is dominant against climb in InGaAsP/InP DH lasers [17,18], contrary to AlGaAs lasers that present mostly a signature of ⟨100⟩ DLDs. Strained InGaAs/AlGaAs lasers show slower climb dislocation motion than AlGaAs/GaAs lasers and similar glide motion. The smaller band-gap energy of InGaAsP with respect to AlGaAs and InGaAs supplies less energy to the lattice in non-radiative recombination.

Dark spot defects (DSDs) are observed as dark spot-like regions in the EL images of the active region. They are common in degraded InGaAsP/InP lasers and were also observed in AlGaAs/GaAs [4], although they are more common in quaternary compounds where alloy clustering becomes more important in relation to ternary alloys.

It was proved that the generation rate of DSDs increases with injection current [4], which accounts for the relevant role played by non-radiative recombination in the formation of DSDs. Large DSDs become dark and are efficient light absorbers, inducing a local increase in the cavity temperature around the DSDs [19]. DSDs seem to be related to segregated host atoms forming precipitates or droplets. Indium, gallium and arsenic to a minor extent are the main elements forming the microprecipitates or droplets that can be considered as the precursors of the large DSDs [4].

4. Gradual degradation

Gradual degradation corresponds to a slow and progressive decay of the optical output power throughout the device lifetime. The EL image shows a homogeneous darkening of the active region. This effect is due to the formation of point defects by REDR. Deep levels are observed by DLTS (Deep level transient spectroscopy) in operated AlGaAs/GaAs, the concentration of these levels increases with operation time [20]. One can describe the gradual degradation as the following sequence: non-radiative recombination at existing point defects produces new point defects assisted by REDR; these point defects act as non-radiative recombination centres, reducing the light generation efficiency and assisting the formation of new point defects by REDR. This feedback mechanism leads to migration and condensation of point defects, forming precipitates or small dislocation loops, which also contribute to lower the quantum efficiency of the device. The rate of the gradual degradation depends on:

- the concentration of point defects. Stoichiometric defects are inherent to III-V compounds and alloys, which can also present clustering; these failures of the materials' quality have strong consequences for the device lifetime;
- the stress distribution around the stripe;
- the quality of the interfaces; heterostructures are inherently unstable with respect to the atomic interdiffusion across interfaces. This instability is enhanced by the stresses and is an important source of point defects.

The gradual degradation is a thermally activated process, for which the lifetime of the laser can be expressed by an Arrhenius term:

$$\tau = \tau_0 \exp(\Delta E/kT)$$

with ΔE the activation energy. The activation energy measured for the degradation of lasers lies between 0.4 and 0.9 eV [21], which is significantly lower than that required for defect formation and diffusion, which take values around 2.6 eV. This supports the role played by non-radiative recombination in the gradual degradation.

5. Catastrophic degradation

This degradation is usually associated in the literature with the COD (Catastrophic optical damage) of the mirror facets; however, catastrophic degradation can occur at the inner part of the cavity. Vanzi et al. reported the observation by top view EBIC of dark defects inside the cavity of strained InGaAs/GaAs lasers, without any connection to mirror damage [22]. We will refer to that degradation as catastrophic degradation as opposed to COMD (Catastrophic optical mirror damage) that is exclusively associated with the degradation of the mirror facets.

This degradation was described by Vanzi et al. [22] in two steps: first a power reduction before any detectable degradation of the optical cavity was observed; this was followed by a very fast degradation. When observed by EBIC in top view, extended dark regions inside the waveguide region were reported; these dark defects were inside the cavity, independent of the mirror facet region, that was not degraded. TEM analysis demonstrated the presence of a dense network of dislocations located inside the QW, but propagating towards the adjacent AlGaAs confinement layers, as previously reported by Ueda [6]. TEM contrast revealed the presence of misfit dislocations [22].

The degradation pattern observed by EL mapping, CL or EBIC is similar to that observed in rapid degradation, i.e., DLDs, which shows that the physical mechanisms leading to both degradations are similar with two phenomenological differences:

- the time scale is very different. Rapid degradation is observed within the first 100 hours of operation, while catastrophic degradation appears after many hours of normal operation, Fig. 1;
- the rapid degradation shows a fast but monotonic decay of the output power, while the catastrophic degradation appears as a sharp output power decrease, Fig. 1.

Taking into account these considerations, one can assume that both degradation modes are caused by the formation of dense networks of dislocations. However, the growth rate of the dark defects for catastrophic degradation is much faster than it was for rapid degradation. This is the main clue regarding catastrophic degradation. The second one is why it appears suddenly without any previous signature.

Vanzi et al. [22] suggested that dislocations inside the depletion layer, but outside the active region, could be responsible for the sudden degradation. These dislocations should move slowly, assisted by non-radiative recombination, and progressively approach the active region. When the dislocation enters the active region a very fast elongation of the dislocation takes place, which is the cause of the sudden degradation. The last step could occur so rapidly because of the high concentration of point defects in lasers after long operation times as a consequence of the gradual degradation process that basically consists of the generation of point defects. DLDs grow by a combined glide and climb mechanism [23,24]; therefore, a high concentration of point defects should activate the propagation of DLDs. This is one of the main differences with lasers that degrade in the first hundred hours. In such lasers the dislocations grew slowly (in a few hours) because the sources of point defects were reduced at such an stage of the laser lifetime. Another hypothesis is that the initiating factor is a dislocation cloud produced by microprecipitates and defects created during the laser operation, probably at the interfaces [25]. In any of these cases the very fast dark defect propagation by climb, leading to sudden degradation, demands a large concentration of point defects, which is only available by a prolonged laser operation.

The active parts of the laser are destroyed, intermixing between the different layers was reported by different authors, Chu et al. [26] showed that In outdiffusion was the main reason for degradation in strained InGaAs/GaAs lasers. Misfit stress was found to not contribute to the compositional instability in strained InGaAs/GaAs systems [27]; in these cases inter-diffusion can take place by the concentration difference between each side of the interface; a similar consideration can be made for AlGaAs/GaAs systems. The role of impurities in the intermixing must also be considered; impurity diffusion has been demonstrated to produce disorder in heterostructures [28]. This suggests that the compositional instability induced by impurity diffusion after prolonged gradual degradation could be one of the causes of sudden degradation. In this way, the p–n junction of AlGaAs/GaAs lasers was displaced under operation, suggesting an active p-type impurity (beryllium in this case) outdiffusion [29]. Other laser structures were also shown to intermix at the late stages of degradation, see for example [30], where GaAs based AlGaAs/GaInP/GaInAs ridge waveguide lasers showed local composition changes. Frigeri et al. [23] observed that the destruction of the active region of InGaAlAs/AlGaAs lasers was due to the outdiffusion of Al into the confinement layers. They assumed that the Al outdiffusion was driven by the temperature gradient caused by localized overheating in the active region.

6. Facet degradation

While the lifetime of low power laser diodes is limited by gradual degradation, the maximum optical power of high power laser diodes is mostly limited by the catastrophic optical mirror damage (COMD). This failure consists in the destruction of the mirror facets. The study of this degradation mode has received a great deal of attention, since it is one of the main factors, if not the main factor, limiting the lifetime of high power laser diodes.

Classical models describing the COMD mechanism include the following sequential steps: non-radiative recombination at the facet mirror releases thermal energy to the lattice, increasing the local temperature. This induces a band gap narrowing in the region close to the mirrors that enhances the self-absorption at the facets, generating additional free carriers, which recombine non-radiatively, increasing further the temperature of the facet region. This feedback mechanism can increase the temperature of the facet, which can eventually melt locally [31,32].

The main cause of facet degradation is, therefore, the anomalously high temperature, which is the result of the non-radiative recombination. According to this, the key parameters controlling the COMD are:

(i) the Surface Recombination Velocity (SRV);
(ii) the density of defects at the facet;
(iii) the facet treatment and coating, which partially determine the previous parameters;
(iv) the temperature dependence of the band gap of materials forming the active region;
(v) the optical power and the current injection;
(vi) the thermal conductivities of the different layers forming the laser structure.

The many factors contributing to the heat generation at the facets give an idea of the complexity of the physical mechanisms involved in the COMD process.

According to the previous discussion, the assessment of the local temperature at the facets is of prime interest in understanding the COMD mechanism. Experimental investigations about the local temperature are usually carried out by micro-Raman spectroscopy [33–36]. Reflectance modulation [7] and micro-photoluminescence (μ-PL) [37]. These data are confronted to theoretical calculations about the temperature enhancement at the facets [31,32,38,39]. They show clear evidence for thermal runaway initiated for a critical temperature between 120 and 140 °C in GaAs/AlGaAs lasers [31].

The facet temperatures were found to depend on the surface recombination velocity showing the importance of the facet treatment for COMD [38]. It was also shown that the temperature increase penetrates about 1 μm inside the laser cavity, beyond this distance a significant cooling is observed, which allows one to assert that the cavity is basically cold as compared to the facets [38].

Compositional changes are observed at the facet during the life of the device. Uncoated mirror facets undergo a fast oxidation process that lead to COMD. Oxidation is enhanced by temperature and the laser output light density; the oxidation rate at the facets is proportional to the light output density; an excitation enhanced oxidation model was proposed [40]. The nature of the semiconductors forming the active regions and the cladding layers is determinant for the oxidation of the facets; the Al based compounds are easily oxidized, while Al-free lasers have shown much better facet stability.

The interface between the oxide and the semiconductor can be also viewed as a sink for either III or V elements, leaving behind defects in the active region, which can be vacancies, clusters or stoichiometric defects. The presence of solid As and clustering presented under the form of alloy disorder has been observed by microRaman spectroscopy of facets with clear symptoms of COMD [34]. These defects can be at the origin of the dislocation loops observed in COMD facets. It should be noted that COMD can occur without the melting of the facet. The point defects also act as non-radiative recombination centres, which feedback the process by increasing the temperature and creating new defects assisted by REDR.

The lifetime of the device is significantly improved when the mirror facets are coated; this coating aims to suppress the facet oxidation. COMD is also related to the type of laser structure. In particular, both the thickness of the active region and the cavity length have influence on the COMD level. Fig. 4 shows the normalized temperature rise at the facet as a function of the active region thickness [32]. This suggests differences between the COMD levels of DH and QW lasers. The temperature increase in QW is more confined to the facet, in relation to the DH lasers for which it extends beyond inside the cavity, even if the peak temperature can be higher at the QW facet. This should mean that the light absorption region has a much smaller volume in QW lasers, reducing the carrier photogeneration and improving the transparency of the QW facet [5,32]. The active region thickness is about 20 times smaller in QW lasers compared to DH lasers. The different dimensionality of the carrier confinement (2D versus 3D) also has important consequences in the facet transparency and heating. The photon flux was shown to have more importance on the facet heating of DH lasers than in QW lasers. When one represents the facet temperature versus the injection current, a sharp increase is observed for DH lasers at the threshold current when photons start to be absorbed by the facet, showing the importance of output light power on the heat generation of DH lasers. Such an increase was not observed for QW lasers at the onset of photon emission, Fig. 5 [41]. The facet heating of QW lasers is primarily due to the current injection density [33]. It was demonstrated that the facet temperature of QW lasers can be lowered, reducing the surface current [42].

The chemical changes at the facets were studied by Houle et al. [43]. They showed that the facets can be quite variable in composition before operation and that they undergo pronounced changes from the very early stages of operation.

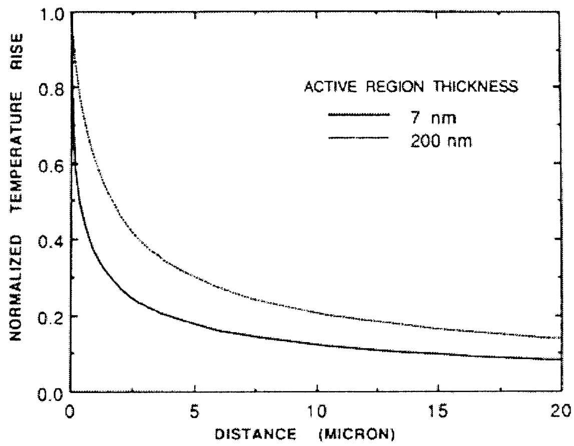

Fig. 4. Normalized temperature rise along the cavity in the active region for two different active region thicknesses. (From [32], with permission of American Institute of Physics.)

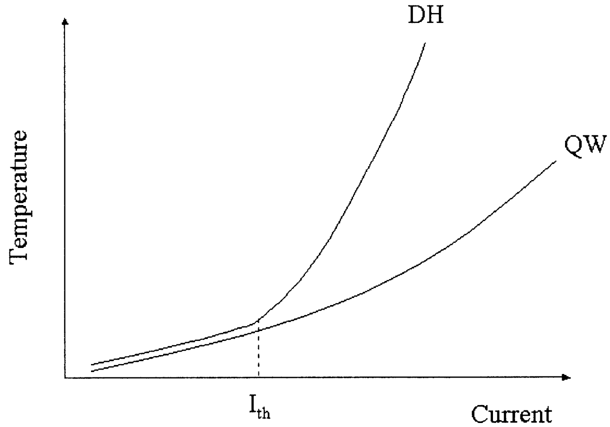

Fig. 5. Facet temperature versus injection current for a DH laser and a QW laser. Note the increase of temperature at the threshold current for the DH laser. (Data from [41].)

Chemical changes observed in AlGaAs/GaAs QW lasers [43] were evaluated as:

(i) Stoichiometric changes, which appear as cation segregation and alloy disorder (clustering);
(ii) at long times the facets appear mostly enriched with group III elements;
(iii) QW laser facets are more oxidized than the facets of DH lasers;
(iv) coated lasers that have suffered COMD are not necessarily more oxidized than lasers which have not undergone COMD;
(v) melting after COMD did not occur for all the lasers.

The stoichiometric deviation near the facets is assumed to produce a concomitant increase in the density of non-radiative recombination centres, which should account for the time dependent facet heating. A monochromatic CL image of a damaged facet of an AlGaAs based laser (808 nm) is shown in Fig. 6. The luminescence peak of the damaged region is shifted to the blue with respect to the non-damaged region, which suggests that intermixing took place at the QW.

Commercial Al-free high power laser bars emitting in the 780–840 nm spectral range are now available. Generally, these devices consist of InGaAsP QW, an aluminium free waveguide (InGaP) and an InGaAlP cladding layer. These lasers are relevant for comparison with AlGaAs lasers because both emit in the same spectral window. Al free lasers were shown to have more resistance to COMD. The InGaAsP/InGaP lasers showed a lower facet temperature during operation than the corresponding AlGaAs/GaAs laser emitting in the same spectral range. This lower temperature can be attributed to several factors [40]:

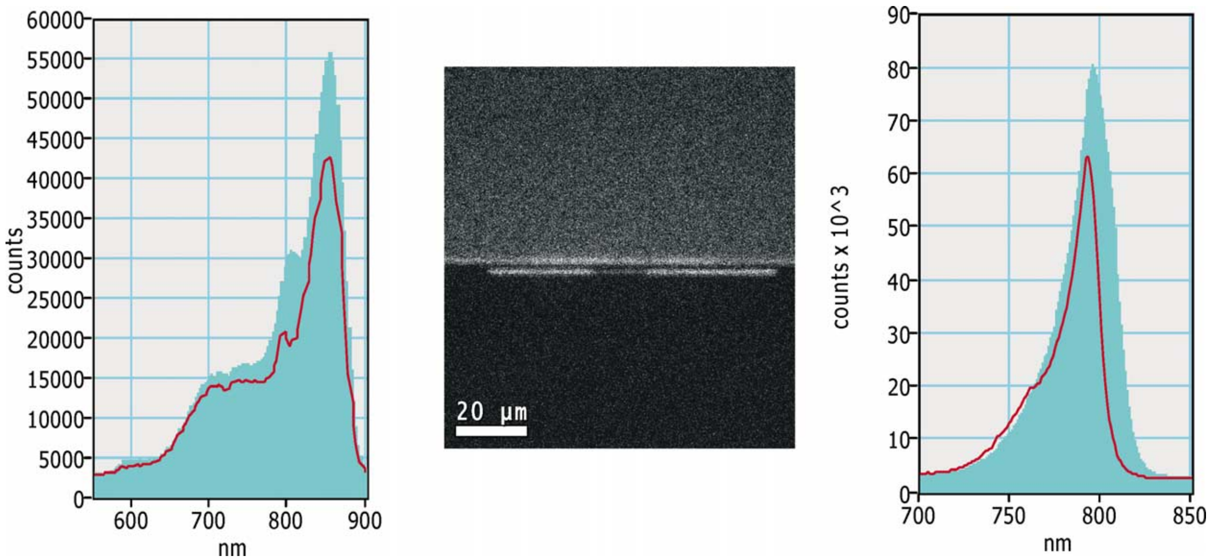

Fig. 6. CL monochromatic (800 nm) of a laser facet showing a defect (dark region in the middle of the QW (centre). CL global spectra at the dark region (full line) and the non-damaged region (left), and QW spectra at the non-damaged region and the damaged region (full line), note the blue shift of the luminescence peak in the damaged region (right).

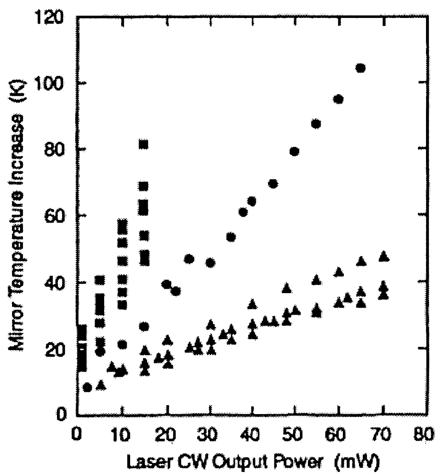

Fig. 7. Temperature increase ΔT at uncoated mirror facets of 5-μm wide (Al)GaInP (squares), (Al)GaAs (circles), InGaAs/AlGaAs (triangles) SQW ridge lasers vs optical power. (From [7], with permission of SPIE.)

(i) Lower SRV of InGaAsP/InGaP;
(ii) lower reactivity to oxygen of Al-free materials;
(iii) smaller band gap variation with T in these materials.

In spite of the low facet temperature of these lasers the existence of COMD has been demonstrated [44] in single mode InGaAsP/InGaP QW buried heterostructure lasers. However, the COMD level was significantly enhanced in relation to the Al-containing lasers.

Strained single QW InGaAs/GaAs 980 nm pumping lasers show also a much higher COMD level than equivalent AlGaAs/GaAs lasers [45]. The aging data obtained on GaAs SQW and InGaAs SQW lasers without facet coating were compared in [39], showing much better stability of the InGaAs laser. However, the facets of these lasers were heavily oxidized. One can expect that oxidized facets should have a marked tendency to develop COMD at relative low power density. This seems to be true for lattice matched systems, but fails for strained systems, for which the high oxidation rate at the facets is mediated by uniaxial stress parallel to the cleaved facet [39]. The temperature of the mirror facet increases with the injection current

Table 1
COMD level and emission wavelength for various active region compositions (Data from [50].)

Active region compound	Emission wavelength (nm)	COMD level (MW/cm^2)
InGaAs	920–980	18–19
InGaAsP	810	18–19
InAlGaAs	810	13
GaAs	810–870	11–12
GaAsP	810	11
AlGaAs ([A1] = 0.07)	810	8
AlGaAs ([A1] = 0.13)	780	5

and the output power; however, this increase depends on the type of laser. In particular T_{mirror} versus I shows a superlinear behaviour for Al based lasers instead of the linear or sublinear behaviour of strained InGaAs/GaAs lasers [46]. The influence of the output power on the temperature for different lasers emitting at different wavelengths is shown in Fig. 7. InGaAlP/InGaP shows higher temperature than AlGaAs/GaAs and AlGaAs/InGaAs. The oxidation of the facet creates point defects in the active layer near the facet. These defects could saturate and generate DLDs assisted by REDR (recombination enhanced defect reactions). Catastrophic degradation is probably associated with the generation of these DLDs close to the facet. However, there was not a specific facet state that could be associated with COMD [43]. An empiric relation between the time to COMD and the facet temperature was presented under the form of an Arrhenius law. The analysis of time to COMD in Al-based lasers with different coating treatments suggests that a common defect generation process was responsible for COMD [47]. This suggests that the resistance to COMD of the oxidized facet of the InGaAs laser is probably related to the inhibition of the specific defect generation mechanism leading to COMD. This will be the consequence of the lattice hardening by In alloying, which enhances the energy necessary for dislocation formation [48].

The photo-oxidation rates of different binary and alloy compounds were studied in [49] with the conclusion that P containing semiconductors are more stable than those containing As. This must be added to the high reactivity to oxygen of Al containing compounds.

One can define the COMD level as the maximum output power density allowed without COMD. Table 1 provides the COMD level values estimated for lasers with different active and cladding layers [50]. The COMD level is increased with In content of the active region and decreases with Al content.

7. Conclusions

Laser diode degradation is the result of the interaction between different intrinsic (material properties, crystal defects, quality of the interfaces, ...) and external factors (packaging, bonding, temperature, injection current, facet coating, ...), which introduce profound changes in the materials forming the active parts of the devices, with the result of a decrease in the quantum efficiency. The many inputs that contribute to the degradation render difficult a full understanding of the physical processes governing degradation. High quality heterostructures, free of defects with sharp interfaces and reduced stresses, and facets with optimal coatings are required to guarantee long lifetime devices. The main degradation modes present specific defect signatures for each type of laser.

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