

# On Degradation Studies of III–V Compound Semiconductor Optical Devices over Three Decades: Focusing on Gradual Degradation\*

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This paper describes studies on the reliability of semiconductor optical devices over the course of more than three decades, dating back to the early 1970s. First, a retrospective look is taken at the evolution of optical device development and reliability studies. Second, the three main degradation modes for optical devices (rapid degradation, gradual degradation, and catastrophic failure) are outlined. Third, the results of the classical research into rapid degradation that was carried out in the 1970s and 1980s are presented as an introduction to a systematic discussion of the research that followed—remarkable research into gradual degradation. © 2010 The Japan Society of Applied Physics

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## 1. Introduction

Semiconductor optical devices (hereafter referred to as optical devices), such as semiconductor lasers and light-emitting diodes (LEDs), come in a great variety of materials and structures, and they are used in an extremely wide range of fields. In addition to being used as light sources in medium-to-high capacity fiber-optic communications systems, they are also used as light sources in consumer electronic devices, such as audio and digital systems, and in optical printers, as well as being used in sensing systems and medical equipment. It would thus be no exaggeration to say that improving the reliability of optical devices is essential to the development of high-performance, highly reliable products. That is why vigorous reliability studies have been conducted from the very outset and to the present day.

This paper first outlines the history of the development of optical devices (including non-group III–V devices) and of the reliability studies concurrently conducted on them. This is followed by an outline of the three main degradation modes for optical devices—rapid degradation, gradual degradation, and catastrophic failure. Finally, an introduction to the results of the classical research into rapid degradation that was carried out in the 1970s and 1980s precedes a systematic discussion of the research that followed—remarkable research into gradual degradation.

## 2. Evolution of Semiconductor Optical Device Development and Reliability Studies

This section takes a retrospective look at how optical device reliability has been improved up to the present, detailing the history of optical device development and reliability studies (see Fig. 1).

### 2.1 The evolution of the development of semiconductor optical devices

The first optical device to be developed was the LED. Its development commenced in the 1960s, and in 1969, GaAsP and GaP LEDs were put to practical application in the USA. Subsequently, Stanley Electric commenced mass production of high-brightness red AlGaAs LEDs and green LEDs in

1982. There was also strong demand for a blue LED (the third and last primary color), and in 1993 the first blue LEDs were commercialized by the Nichia Corporation. White LEDs, featuring a combination of the three primary colors (red, blue, and green) have been mass produced since 1996 and are used in many different types of illumination applications.

In the semiconductor laser domain, the continuous-wave properties of AlGaAs/GaAs double-heterostructure (DH) lasers were verified by AT&T's Bell Laboratories and other research groups<sup>1)</sup> in 1970, and these were commercialized in the mid-1970s as light sources for use in 0.8- $\mu\text{m}$ -band communications. The start of the 1980s saw the development of 1.3- $\mu\text{m}$ -band InGaAsP/InP DH lasers. Fortunately, lasers fabricated from these materials exhibit fairly longer lifetimes. Since then, as progressively higher levels of output and performance have been attained with the appearance of such devices as multi-quantum-well structure lasers and distributed feedback lasers, semiconductor lasers have come to be used in a wide variety of communications systems.

In terms of lasers in the visible wavelength range, AlGaAs DH lasers in the up-to-760 nm-wavelength region (red) were commercialized in the mid-1980s, to meet the requirement for light sources in printers and audio equipment. However, shorter wavelengths entailed reduced lifetimes, and since then, InGaP/InAlGaP lasers, which have comparatively long lifetimes, have come to be used exclusively in high-output devices operating in shorter wavelength regions. In the 1990s, the development of blue lasers gathered momentum. Initially there was progress in the development of the ZnSe-based DH laser; however, its practical application was hampered by problems of degradation caused by specific crystal defects.<sup>2)</sup> The mid-1990s produced a replacement with the emergence and rapid development of the InGaN/GaN DH laser,<sup>3)</sup> which (despite the high density of such defects as dislocation in the active layer) yielded devices with long lifetimes. By the beginning of the 2000s, various types of blue and blue/green lasers were finding practical application.

### 2.2 The evolution of semiconductor optical device reliability studies

In Japan, joint research projects that commenced in 1974 and lasted more than a decade were actively conducted by two groups, with a view to extending the lifetimes of semi-

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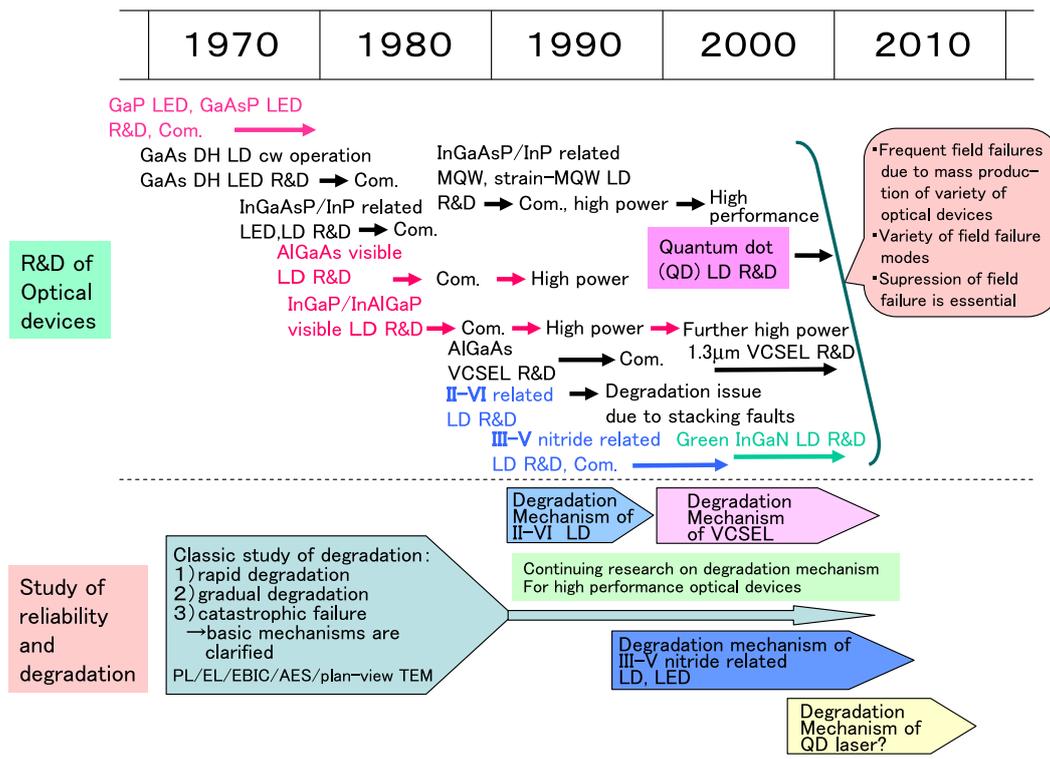


Fig. 1. (Color online) Development of semiconductor optical devices and evolution of reliability studies. Com.: Commercialization.

conductor lasers for use in optical communications. One group was comprised of Nippon Telegraph and Telephone (the present-day NTT Group) and Fujitsu (the author was also involved in these studies), and the other consisted of Nippon Telegraph and Telephone and NEC. Research into the degradation mechanism progressed remarkably through the analysis of degraded devices.

Numerous conference papers were presented—principally by device manufacturers—and vigorous debate was conducted. As a result, the basic mechanisms behind various types of degradation were elucidated, countermeasures were devised on the basis of these mechanisms, and the lifetimes of such lasers as InGaAsP/InP DH lasers were extended. At the time, however, the technology for analyzing such problems was limited, and these phenomena were not fully understood at the atomic level. In this sense, the degradation studies of this period (1970–1985) could be called as “classical degradation studies”.<sup>4-6)</sup>

Although degradation studies on optical devices constructed using III–V compound semiconductor materials subsequently lapsed into general stagnation, some work has continued up to the present. Meanwhile, in the first half of the 1990s, serious reliability problems were encountered with II–VI ZnSe-based blue lasers, as has previously been noted, and active research was conducted in which other materials were compared with III–V compound materials.<sup>2)</sup> In addition, AlGaAs vertical-cavity surface-emitting lasers (VCSELs), which had been the subject of research since the 1980s, finally found practical application at the beginning of the 2000s. However, the material used in their fabrication (AlGaAs/GaAs) frequently exhibited degradation problems due to the uniqueness of the laser’s characteristic structure (such as its having a vertical optical waveguide and optical aperture). Degradation studies have continued to advance,

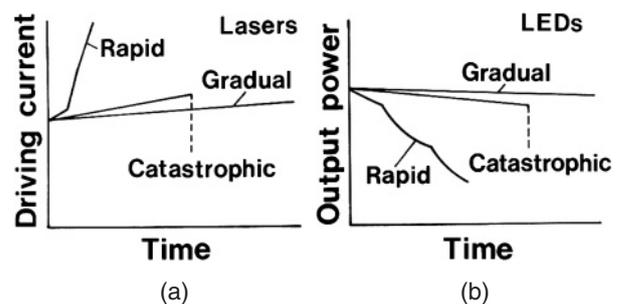


Fig. 2. Three main degradation modes for semiconductor lasers and light emitting diodes (LEDs).

principally in the USA,<sup>7)</sup> and, though a number of problems still remain, improved reliability has been achieved. InGaN blue lasers also now boast high reliability, the results of a number of degradation analysis studies have been reported, and the degradation mechanisms are gradually being resolved.<sup>8)</sup> In terms of the future, while the day is not far off when such devices as quantum dot lasers will find practical application, there are concerns about their reliability as well.

### 3. Outline of the Three Degradation Modes of Semiconductor Optical Devices

The three main degradation modes in optical devices are rapid degradation, gradual degradation, and catastrophic failure. When a semiconductor laser is operated with a constant output, there are cases in which the operating current will rapidly increase [as marked “Rapid” in Fig. 2(a)]—within 100 h, for example. When an LED is operated at a constant current, this corresponds to a rapid reduction in the optical output [as marked “Rapid” in

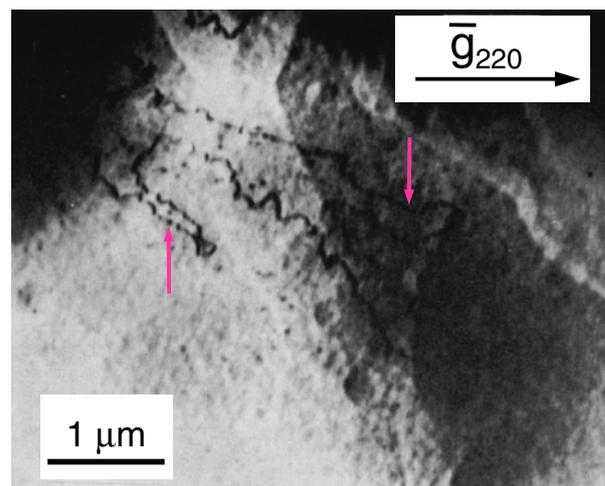
Fig. 2(b)] known as “rapid degradation”. Even if it is suppressed, however, there will still be the other degradation modes to consider. In semiconductor lasers, there is the phenomenon of a gradual increase in the operating current [see the curved line marked “Gradual” in Fig. 2(a)]. In an LED, gradual degradation corresponds to a gradual decrease in the optical output [as shown in Fig. 2(b)]. Both device types can also experience instantaneous degradation, due to a current surge, for example. This is referred to as “catastrophic failure” and is marked in Figs. 2(a) and 2(b) as “Catastrophic”.

The characteristics of rapid degradation are: (1) the optical output decreases rapidly during constant current operations (or, in the case of constant output power operations, there is either a rapid increase in the operating current or a rapid decrease in the internal quantum efficiency) and (2) non-emitting regions are formed within the emitting region (the active region). There are three types of non-emitting regions: i) dark-line defects (DLDs),<sup>9)</sup> ii) dark-spot defects (DSDs),<sup>10)</sup> and iii) dark regions.<sup>11)</sup> Here, the half-life of a component (the time taken for its output to drop to half its initial level) is less than 100 hours at room temperature. This type of degradation is due to either dislocation climb motion enhanced by non-radiative recombination of minority carriers, known as recombination-enhanced dislocation climb (REDC) or a similarly enhanced dislocation glide motion known as recombination-enhanced dislocation glide (REDG).<sup>12)</sup>

In contrast to this, gradual degradation is a slow mode of degradation which remains extant even after the rapid degradation mode has been eliminated and which continues over a long term. Ultimately, it is this mode that determines the lifetime of a component. The characteristics of this degradation are: (1) optical output gradually decreases during constant current operations (or, in the case of constant output power operations, there is a gradual increase in the operating current), (2) there is a uniform darkening in the light emitting region (DSD), and (3) (in the case of AlGaAs/GaAs devices) there is a gradual increase in deep levels.<sup>13)</sup> This degradation mechanism is thought to involve point-defect reactions due to non-radiative recombination during operations, the generation of point defects, and the formation of point defect clusters or micro-dislocation loops due to condensation of the point defects. (This is discussed in detail later in this paper.)

Catastrophic failure is a mode in which degradation occurs extremely fast, or “catastrophically”, due to a current surge during high-output operations. In semiconductor lasers, catastrophic failure occurs due to catastrophic optical damage (COD)<sup>14–16)</sup> at a mirror or in a defect region. In AlGaAs DH LEDs, catastrophic failure occurs due to dislocation glide.<sup>17)</sup> In addition, catastrophic failure due to melting of the crystal can occur in InGaAsP/InP DH LEDs when Joule heating at the contacts causes a rise in temperature (for a detailed explanation of catastrophic failure, see Chap. 12 of ref. 1).<sup>18)</sup>

Recently, with growing customer demand for increased performance (in terms of higher output power), a new degradation mode has appeared: the “sudden-death mode”, which causes serious damage and which is distinct from the modes described so far. It involves the sudden degradation



**Fig. 3.** (Color online) Transmission electron microscopy (TEM) image of dislocation dipoles (U-shaped section indicated by the arrow) corresponding to  $\{100\}$  dark-line defects in an AlGaAs double-heterostructure (DH) LED that has suffered rapid degradation.

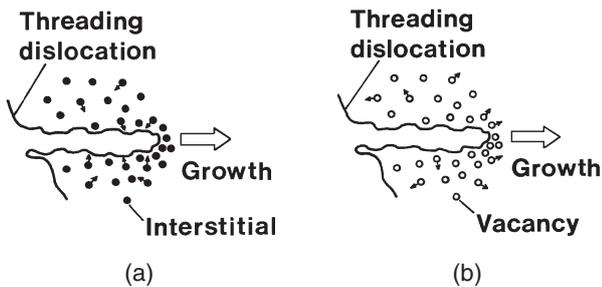
of a device after a certain period of normal operations. The various causes of it are under investigation and countermeasures are required for its prevention.<sup>19)</sup>

The next two sections consist of a discussion of the results of classical research into rapid degradation, followed by a more in-depth treatment of gradual degradation, the study of which has shown recent progress.

#### 4. Rapid Degradation

As previously noted, rapid degradation is caused by REDC or REDG; discussion in this paper, however, is confined to research results relating to REDC, from classical studies of rapid degradation.

Figure 3 is a transmission electron microscopy (TEM) image of dislocation dipoles (the U-shaped section indicated by the arrow) corresponding to a  $\{100\}$  DLD that was observed in an AlGaAs DH LED that had suffered rapid degradation.<sup>20)</sup> Detailed analyses under varying diffraction conditions reveals that these dislocation dipoles have Burgers vectors of  $(a/2)\langle 011 \rangle$  that are inclined at an angle of  $45^\circ$  to the  $(001)$  plane and are of the interstitial type. These defects are believed to originate from threading dislocations that propagate from the substrate into the epitaxial layer when the crystal is growing, and to develop and extend into the active region as a result of REDC. Prior to the above study, the same results had also been obtained for AlGaAs DH lasers that had suffered rapid degradation.<sup>9)</sup> In addition, it was reported that dislocation dipoles were also formed from dislocation clusters<sup>21)</sup> generated by the interface between the substrate and the epitaxial layer, and from dislocation loops that occurred during the growth of the crystal or during the impurity diffusion process.<sup>22,23)</sup> However, rapid degradation due to REDC has not been observed in InGaAsP/InP DH LEDs.<sup>24)</sup> In addition, although degradation due to REDC has been reported in InGaAsP/InP DH lasers, it is clear that this takes place at a much slower rate (at least three orders of magnitude slower) than in AlGaAs lasers.<sup>25)</sup> It has also been revealed that in InGaAsP/InGaP DH lasers in which there is lattice-matching with an active layer of GaAs, rapid degradation also occurs if dislocation,



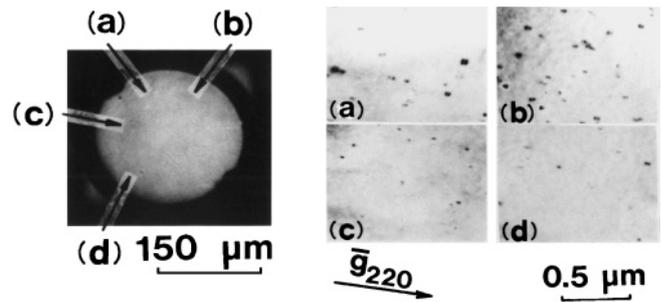
**Fig. 4.** Two proposed models for dislocation climb motion enhanced by non-radiative recombination of minority carriers. (a) Extrinsic defect model; (b) intrinsic defect model.

dislocation clusters, or dislocation loops are present in the active layer.<sup>22)</sup>

As previously noted, the ease with which rapid degradation can occur in an optical device depends on the material used for the active layer. To understand the effects of this, let us consider two typical models of REDC out of the several that have so far been proposed. One is known as the “extrinsic defect model”<sup>26)</sup> and is shown in Fig. 4(a). In it, only a single type of interstitial atom—for example, a Ga interstitial atom—needs be absorbed into the dislocation core in order for dislocation to climb. The second model, known as the “intrinsic defect model”,<sup>27)</sup> is shown in Fig. 4(b). It requires emission of two types of vacancies (those of groups III and V atoms) from the dislocation core—for example, emission of Ga- and As-vacancies in GaAs.

It is currently unclear whether either of these two models is valid, but a number of physical parameters are believed to be candidates as factors contributing to REDC. First, as REDC is thought to involve the non-radiative recombination of minority carriers and to correspond to a local transfer of energy from a multi-phonon mode to a lattice-vibrational mode excited by light absorption at defects in the crystal,<sup>12,28)</sup> REDC is believed to depend essentially on the band gap energy of the material. This provides a good explanation of why, for example, GaAs and GaP materials are prone to suffer from REDC, while InGaAsP materials are not. However, since InP—with its relatively wide band gap—is also prone to REDC, band gap energy alone is not a sufficient explanation. Other dominant factors for REDC are deep-levels, which are related to such defects as dangling-bonds and native-point defects, and non-radiative recombination rates at the deep levels. The cases for these factors are supported by the fact that AlGaAs materials (in which such defects form at deep levels during growth) and InGaAsP materials in which there is lattice-matching with GaAs are also prone to suffer from REDC, and by the fact that InGaAsP materials in which there is lattice-matching with InP (in which such defects do not form at deep levels) are not prone to suffer from REDC. In addition, since REDC is believed to be due to the absorption of interstitial atoms in the dislocation core or to the emission of vacancies, it is thought that the magnitudes of generation energy and migration energy for point defects may also have a major influence on REDC.

As previously noted, rapid degradation due to REDC can essentially be inhibited by reducing such defects as disloca-



**Fig. 5.** Electroluminescence (EL) and TEM images of AlGaAs DH LEDs which have suffered gradual degradation. (a) an EL image; (b) (four photographs arranged in a square): TEM images obtained from regions (a)–(d) in (a) [shown respectively as (a)–(d)].

tion, dislocation clusters, and dislocation loops during the crystal-growth and processing stages. However, even today—in the 2000s—the specific mechanism behind REDC has yet to be fully elucidated, and much of the debate is based on conjecture. This will be the subject of future studies.

## 5. Gradual Degradation

### 5.1 Studies from the 1970s to the mid-1980s

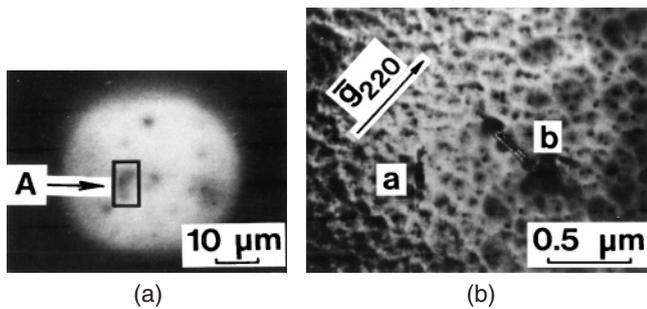
This section will first outline the results of studies conducted at the dawn of the era of research into gradual degradation. Due to the use of the liquid-phase epitaxy (LPE) process in crystal growth, there existed so-called “deep-level” defects that acted as traps for injected carriers in the undoped AlGaAs and GaAs crystals used as the active layers of optical devices. Among five models proposed for gradual degradation were a gradual degradation mechanism due to propagation of these deep-level defects (Model 1), as well as (in the case of InGaAsP materials) a gradual degradation mechanism due to native-point defects (Model 2) and a diffusion or concentration of electrode atoms (Model 3). These are outlined in the sub-sub-sections that follow.

#### 5.1.1 Gradual degradation in AlGaAs/GaAs optical devices (Model 1)

AlGaAs DH LEDs, which do not suffer from rapid degradation, were subjected to high-temperature acceleration testing (at ambient temperatures of 90, 169, and 230 °C, and with a current density of 556 A/cm<sup>2</sup>). Devices that suffered gradual degradation were analyzed using deep-level transient spectroscopy (DLTS) and TEM.<sup>13)</sup> Two hole traps (A and B) were formed in GaAs and AlGaAs crystals grown using liquid-phase epitaxy (LPE).<sup>29)</sup> (These were situated, respectively, at 0.43 and 0.87 eV from the valence band.) It was ascertained that the density of, and flow of current in, these traps gradually increased.

In contrast to this, no dark defects were seen in the active regions of diodes that exhibited gradual degradation—the active regions were uniformly dark over their entireties. Figure 5(a) shows a typical electroluminescence (EL) image of an active region. TEM images corresponding to a–d of the active region are shown in Fig. 5(b). Interstitial type microdislocation loops and point defect clusters were uniformly observed in each region.

On the basis of these results, the following model was proposed for the gradual degradation mechanism in AlGaAs



**Fig. 6.** EL and TEM images of InGaAsP/InP double-heterostructure optical diodes that have suffered gradual degradation. (a) EL image of light emitting region; (b) TEM image corresponding to a single dark-spot defect observed in region A in (a). (Bar-shaped defects are observed at a and b.)

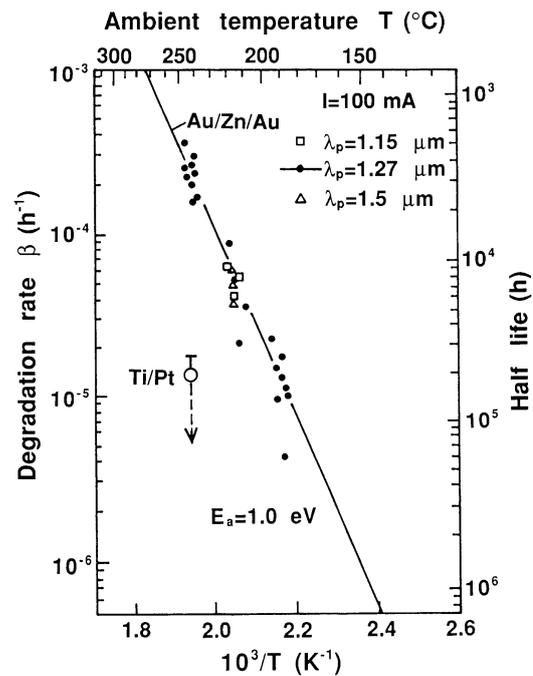
DH LEDs. First, non-radiative recombination occurs in some kind of defect (for example, in an existing point-defect or in point-defect complex consisting of several existing point defects in an as-grown crystal), and new distinct point-defect complexes are formed due to point-defect reactions. Possible defect complexes in this context could be  $Ga_i-V_{Ga}$ ,  $V_{As}-Ga_{As}$ , or  $V_{As}-Ga_{As}-V_{Ga}$ , since growth is carried out under Ga- or Al-rich conditions in order to promote LPE growth. These point-defect complexes also act as non-radiative recombination centers. Accordingly, reactions generate positive feedback. As a result, point-defects that are generated as byproducts (individual interstitial atoms, such as  $Ga_i$  and  $Al_i$ ) migrate and concentrate into some kind of product nucleus (for example, residual impurities such as O and C). Finally, point defect clusters and micro-dislocation loops are formed.

### 5.1.2 Gradual degradation in InGaAsP/InP optical devices (Models 2 and 3)

This section discusses the decline in the uniform optical output of InGaAsP/InP DH LEDs during high-temperature acceleration testing—that is, the results of an investigation of gradual degradation in the device.<sup>30)</sup> In a temperature acceleration test, ten diodes were linked together in a nitrogen atmosphere and operated at a constant current of 100 mA (DC). The optical output, cut-off frequency, and EL image of the diodes were then evaluated at 20 °C at fixed time intervals. Although DSDs frequently appeared in the active regions during high-temperature operations, above 170 °C, no rapid degradation occurred. It was also observed that, even when up to several tens of DSDs appeared in the active regions, optical output remained essentially unchanged.

Figure 6(a) shows an EL image of DSDs that appear in high-temperature operations in an InGaAsP/InP DH LED.<sup>30)</sup> The number of DSDs is less than 30, and is on average around 10. DSD diameters are 2–3 μm, and contrast levels among them vary.

Figure 6(b) shows a TEM image of a defect that corresponds to one of the DSDs observed in the region shown in A in Fig. 6(a).<sup>30)</sup> Comparing these two images reveals that several bar-shaped defects can be related to a single DSD. Moreover, since the contrast did not disappear under any diffraction conditions, and since no abnormal spots were seen in the electron diffraction patterns obtained



**Fig. 7.** Results of high-temperature acceleration testing on InGaAsP/InP DH LEDs. In the diagram,  $\lambda_p$  and  $\beta$  (“degradation rate”) represent, respectively, the peak emission wavelength and the degradation rate for the LEDs in a constant current operation test. (For more details, please refer to the main text.)

from these defects, it was assumed that the defects were precipitates.

Based on the above results, the following mechanism was suggested as being a factor in the formation of the bar-shaped precipitates (Model 2):

- i) The interstitial atoms of the constituent elements of the matrix crystal are formed by a defect reaction caused by the non-radiative recombination of injected carriers at high temperature.
- ii) These interstitial atoms are somehow absorbed into a product nucleus, and bar-shaped precipitates are formed.

Although this model was also suggested for semiconductor lasers, no supporting experimental evidence was obtained.

Separately, though interstitial atoms could not be detected from the precipitates using EDX, another mechanism that was regarded as a possible candidate, as discussed below, was the formation of precipitates due to diffusion of metal atoms from the electrodes (such as Au) penetrating into the active layer and concentrating there.

Figure 7 shows an Arrhenius plot obtained in a high-temperature acceleration testing of InGaAsP/InP DH LEDs.<sup>31)</sup> In the diagram,  $\lambda_p$  and  $\beta$  (“degradation rate”) represent, respectively, the peak emission wavelength and the degradation rate for LEDs in a constant-current operation test.

The degradation rate,  $\beta$ , is shown in the following equation:

$$P = P_0 \exp(-\beta t),$$

where  $P$  represents the optical output and  $P_0$  the initial optical output.

The data set connected by straight lines in the figure was obtained from LEDs that use an Au/Zn/Au alloy electrode

as the p-electrode. The figure also shows one data point for an LED using a Ti/Pt/Au non-alloy electrode. These results can be summarized as follows:

- The degradation mechanism is independent of the wavelength of the active layer—that is, of the composition of the four-element mixed crystal.
- The activation energy is 1.0 eV, which is higher than the 0.5–0.7 eV in AlGaAs DH LEDs.
- When Ti/Pt/Au non-alloy electrodes (which have strong barrier properties) are used, the lifetime of the device is an order of magnitude greater than when alloy electrodes are used.

The above results suggest that the degradation mechanism might be thought of as a process whereby Au atoms from the p-electrode diffuse into, and concentrate in, the active layer during the operation, due to non-radiative recombination or carrier overflow (Model 3).<sup>30–33</sup>

## 5.2 Advances in research since the mid-1980s

As the capabilities of InGaAsP/InP long-wavelength lasers grew ever greater, defects in the light emitting region caused by gradual degradation during high-temperature, high-output operations could clearly be seen using EL (or EBIC) and TEM, and the degradation mechanism became fairly clear. In this section, two extensive studies on gradual degradation mechanisms are introduced.

### 5.2.1 Gradual degradation in InGaAsP/InP DH lasers 1: Formation of (prismatic-type) micro-dislocation loops (Model 4)

The first of the two studies was by Chu *et al.*<sup>34</sup> This group analyzed degradation in channeled-substrate buried heterostructure (CSBH) lasers during acceleration testing in which the operating current was 200 mA and the ambient temperature was 100 °C. Dark regions along both sides of the stripe can be seen in the EL image of the degraded diode.  $\langle 100 \rangle$  DLDs were also frequently observed in components, although these were short. Using plan-view TEM observation, the group first found that high-density interstitial type micro-dislocation loops had formed on both sides of the stripe. From cross-sectional TEM observation, they also ascertained that the dislocation loops were not in the active layer but just below the active layer, and that they were formed in the vicinity of the n-InP buffer layer just above the p-InP current-restriction layer [see ② in Figs. 8 and 9(b)]. As these loops are only present in laser diodes in which both edges of the active layer are in contact with the p-InP current-restriction layer, the group also proposed a model for the formation of these loops in which carriers (positively charged holes, in this case) that flow to the region outside the active layer become trapped in this region [in the vicinity of the boundary between the n-InP buffer layer and the p-InP current constriction layer—the region shown in pink in Fig. 9(a)] by point defects formed during crystal growth, with the interstitial atoms which form as a result of the non-radiative recombination of minority carriers concentrating to form dislocation loops [see ① and ② in Fig. 8, and Figs. 9(a) and 9(b)].

The group also verified that dislocation dipoles can grow from the dislocation loops in the  $\langle 100 \rangle$  direction, although this is rare. The conjecture is that this is probably the

result of rapid degradation that occurs because part of the dislocation loop grows, expanding to make contact with, and penetrate, the active layer [see ③ and ④ in Fig. 8, and Figs. 9(c) and 9(d)]. These results indicate that care is required here because, even in InGaAsP/InP lasers, under severe current flow conditions gradual degradation may develop into rapid degradation due to the growth of dislocation dipoles, and this may lead to sudden death.

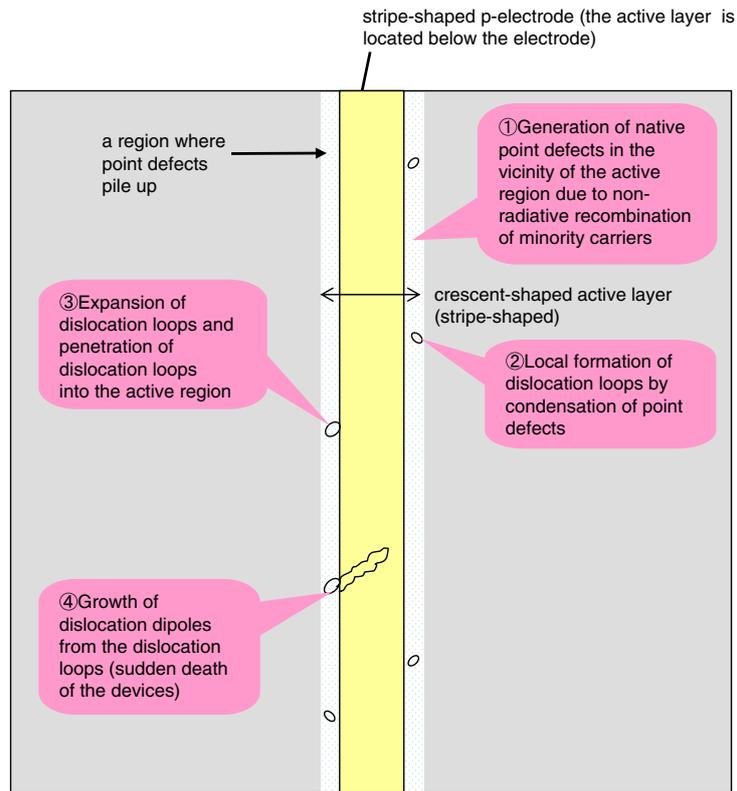
### 5.2.2 Gradual degradation in InGaAsP/InP DH lasers 2: Formation of (Frank-type) micro-dislocation loops (Model 5)

This section introduces the model proposed by de Cooman *et al.*, which is currently regarded as the most influential model.<sup>35</sup> The group subjected so-called DCPBH (double-channel planar buried heterostructure) lasers—embedded-type 1.3- $\mu\text{m}$ -band InGaAsP/InP lasers<sup>36</sup>—to high-temperature (70 °C) acceleration testing and analyzed components that suffered degradation. First, from the cross-sectional electron beam induced current (EBIC) observation of degraded diodes, areas with dark contrast were observed in the regions just outside—and on both sides of—the active layer stripe. Plan-view TEM observations showed that multiple interstitial type dislocation loops [Frank loops on the (111) plane] were generated which corresponded to these dark regions. Cross-sectional TEM observation has shown that the loops were generated in the p-InP layer just outside the normal mesa sidewall region of the active layer.

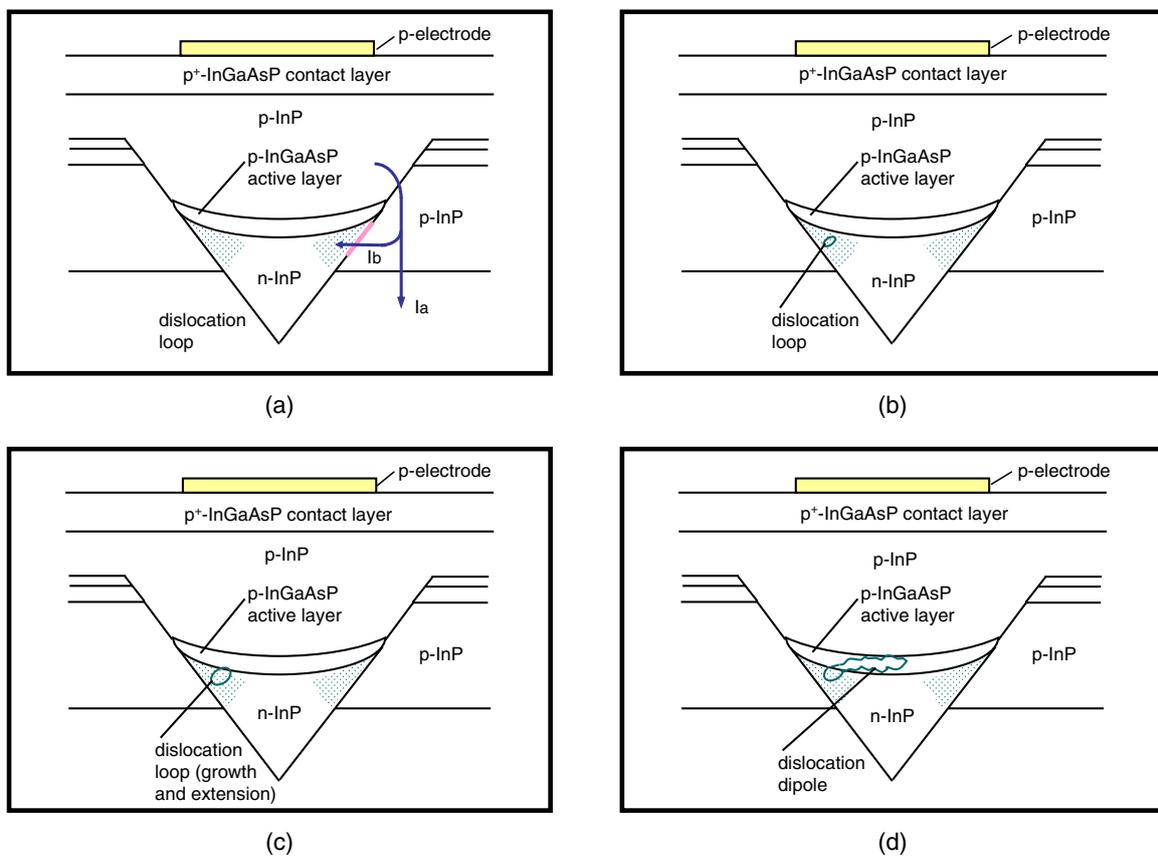
Thus, despite the fact that the de Cooman group obtained the similar observational results to the Chu group (although the type of loops identified are different to each other), the degradation mechanism that it proposed was based on an entirely different view. That is, although, in the case of this structure, p-type dopant of Zn atoms (the carrier concentration is only around  $1 \times 10^{17} \text{ cm}^{-3}$ ) are doped just beside the active layer, the de Cooman group focused on the behavior of these p-type dopant atoms. Their work also explained to some extent the physics behind the ready diffusion of Zn in compound semiconductor crystals subjected to high-temperature heat treatment. For example, if Zn is intentionally diffused into an AlAs/GaAs superlattice structure, Ga and Al atoms are discharged due to the injection of the Zn, and the super-lattice is destroyed as a result. This phenomenon was initially discussed in relation to interstitial Si atoms in Si crystals, and has subsequently been called as “kick-out mechanism”, in reference to the diffusion of Zn in GaAs.<sup>37</sup> The model proposed by the group is as follows.

In Step 1, the Zn interstitial dopant atoms are energized by some kind of injected-carrier non-radiative recombination process, as shown below, and they diffuse. At this point, group III atoms (such as In atoms) that are those of the constituent element of the matrix crystal are discharged from their position in the lattice.

It is believed that, if this process occurs at a certain frequency, it excites the Step 2 reaction, so as to reduce the free energy in the system. Under these conditions, intrinsic-point defects proliferate in the vicinity of the active layer. These somehow concentrate in the nuclei and a dislocation loop is formed.



**Fig. 8.** (Color online) Schematic diagram of the mechanism for transition from gradual degradation to sudden death in an embedded-type semiconductor laser.



**Fig. 9.** (Color online) Cross-sectional diagrams of the mechanism for transition from gradual degradation to sudden death in an embedded-type semiconductor laser. The cross-sectional diagrams (a)–(d) shown in this figure correspond to (1)–(4) in Fig. 8. In this model, positively charged holes are first injected via the current pathway lb, as shown in (a), and these become trapped in the point defects in the region shown in pink. Interstitial atoms are then formed by the non-radiative recombination energy that this generates. There is then a progression from the formation of a dislocation loop to the growth of dislocation dipoles, as shown in (b)–(d) below. (For more details, please refer to the main text.)

Step 1:  $\text{Zn}_i^+ \rightarrow \text{Zn}_s^- + \text{In}_i$  (or  $\text{Ga}_i$ ) +  $2h^+$

Step 2:  $\text{P} \rightarrow \text{P}_i + \text{V}_\text{P}$

Of all the models proposed so far, this model seems to offer the clearest physical picture and to be best able to explain the phenomenon of degradation.

There is a report by Endo *et al.*, with reference to this model, about lasers which have an active layer of strongly ordered InGaP and which suffer degradation due to disordering of their ordered structure during operation.<sup>38)</sup> They proposed a similar model (degradation caused by diffusion of Zn) based on the rate of increase in the threshold current, which is dependent on  $\sqrt{t}$ . Of major interest, too, is the assumption by Tomiya *et al.* that in GaN lasers the rate of degradation also depends on  $\sqrt{t}$  and that degradation is due to the diffusion into the active layer of defects related to Mg.<sup>8)</sup>

## 6. Conclusions

This paper has offered a brief introductory glimpse of the progress in reliability studies conducted over the course of the development of semiconductor optical devices since the early 1970s, with a focus on classical research into rapid degradation and on advances in research into gradual degradation. It is anticipated that demand for semiconductor optical devices—including VCSELs—will increase even further in the future, making their long-term reliability increasingly important.

To this end, it is vital that device manufacturers and equipment manufacturers cooperate in the development of new devices and systems, elucidate degradation mechanisms, and attempt to prevent field failure.

Meanwhile, although the efforts of numerous researchers have already yielded a certain degree of understanding of the physics of the phenomenon of degradation, many unanswered questions still remain. It is hoped that research into degradation mechanisms will progress further in the future—to include resolution of the phenomenon at the atomic level.

- 1) I. Hayashi, M. B. Panish, P. W. Foy, and S. Sumski: *Appl. Phys. Lett.* **17** (1970) 109.
- 2) S. Guha, J. M. DePuydt, M. A. Haase, J. Qui, and H. Cheng: *Appl. Phys. Lett.* **63** (1993) 3107.
- 3) S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto: *Jpn. J. Appl. Phys.* **35** (1996) L74.
- 4) O. Ueda: *J. Electrochem. Soc.* **135** (1988) 11C.
- 5) O. Ueda: *Reliability and Degradation of III-V Optical Devices* (Artech House, Norwood, MA, 1996).
- 6) M. Fukuda: *Reliability and Degradation of LEDs and Semiconductor Lasers* (Artech House, Norwood, MA, 1991).
- 7) J. Guenter, D. Mathes, B. Hawkins, and J. Tatum: *Proc. SPIE* **6908** (2008) 690805.
- 8) S. Tomiya, T. Hino, S. Goto, M. Takeya, and M. Ikeda: *IEEE Sel. Top. Quantum Electron.* **10** (2004) 1277.
- 9) P. M. Petroff and R. L. Hartman: *Appl. Phys. Lett.* **23** (1973) 469.

- 10) S. Kishino, H. Nakashima, R. Ito, and O. Nakada: *Appl. Phys. Lett.* **27** (1975) 207.
- 11) O. Ueda, H. Imai, T. Fujiwara, S. Yamakoshi, T. Sugawara, and T. Yamaoka: *J. Appl. Phys.* **51** (1980) 5316.
- 12) P. M. Petroff: *Semicond. Insul.* **5** (1983) 307.
- 13) K. Kondo, O. Ueda, S. Isozumi, S. Yamakoshi, K. Akita, and T. Kotani: *IEEE Trans. Electron Devices* **30** (1983) 321.
- 14) C. H. Henry, P. M. Petroff, R. A. Logan, and F. R. Meritt: *J. Appl. Phys.* **50** (1979) 3721.
- 15) O. Ueda, H. Imai, T. Kotani, K. Wakita, and H. Saito: *J. Appl. Phys.* **50** (1979) 6643.
- 16) O. Ueda, K. Wakao, A. Yamaguchi, S. Komiya, S. Isozumi, and I. Umebu: *J. Appl. Phys.* **58** (1985) 3996.
- 17) O. Ueda, S. Yamakoshi, T. Sanada, I. Umebu, T. Kotani, and O. Hasegawa: *J. Appl. Phys.* **53** (1982) 9170.
- 18) O. Ueda, S. Yamakoshi, I. Umebu, T. Sanada, and T. Kotani: *J. Appl. Phys.* **54** (1983) 6732.
- 19) O. Ueda: *Nikkei Electronics* **5** (2008) No. 5, 152 [in Japanese].
- 20) O. Ueda, S. Isozumi, T. Kotani, and T. Yamaoka: *J. Appl. Phys.* **48** (1977) 3950.
- 21) K. Ishida and T. Kamejima: *J. Electron. Mater.* **8** (1979) 57.
- 22) O. Ueda, K. Wakao, A. Yamaguchi, S. Isozumi, and S. Komiya: *J. Appl. Phys.* **57** (1985) 1523.
- 23) H. Saito and T. Kawakami: *IEEE J. Quantum Electron.* **13** (1977) 564.
- 24) O. Ueda, I. Umebu, S. Yamakoshi, and T. Kotani: *J. Appl. Phys.* **53** (1982) 2991.
- 25) K. Ishida, T. Kamejima, Y. Matsumoto, and K. Endo: *Appl. Phys. Lett.* **40** (1982) 16.
- 26) P. M. Petroff and L. C. Kimerling: *Appl. Phys. Lett.* **29** (1976) 461.
- 27) S. O'Hara, P. W. Hutchinson, and P. S. Dobson: *Appl. Phys. Lett.* **30** (1977) 368.
- 28) R. D. Gold and L. R. Weisberg: *Solid-State Electron.* **7** (1964) 811.
- 29) D. V. Lang and R. A. Logan: *J. Electron. Mater.* **4** (1975) 1053.
- 30) O. Ueda, S. Yamakoshi, S. Komiya, K. Akita, and T. Yamaoka: *Appl. Phys. Lett.* **36** (1980) 300.
- 31) S. Yamakoshi, M. Abe, O. Wada, S. Komiya, and T. Sakurai: *IEEE J. Quantum Electron.* **17** (1981) 167.
- 32) A. K. Chin, C. L. Ziepfel, S. Mahajan, F. Ermanis, and M. A. DiGiseppe: *Appl. Phys. Lett.* **41** (1982) 555.
- 33) S. Mahajan, A. K. Chin, C. L. Ziepfel, D. Brasen, B. H. Chin, R. T. Tung, and S. Nakahara: *Mater. Lett.* **2** (1984) 184.
- 34) S. N. G. Chu, S. Nakahara, M. E. Twigg, L. A. Koszi, E. J. Flynn, A. K. Chin, B. P. Segner, and W. D. Johnston, Jr.: *J. Appl. Phys.* **63** (1988) 611.
- 35) B. C. de Cooman, C. W. T. Bulle-Lieuwma, J. A. de Poorter, and W. Nijman: *J. Appl. Phys.* **67** (1990) 3919.
- 36) I. Mito, M. Kitamura, K. Kobayashi, S. Murata, M. Seki, Y. Odagiri, H. Nishimoto, M. Yamaguchi, and K. Kobayashi: *J. Lightwave Technol.* **1** (1983) 195.
- 37) U. Goesele and F. Morehead: *J. Appl. Phys.* **52** (1981) 4617.
- 38) K. Endo, K. Kobayashi, H. Fujii, and Y. Ueno: *Appl. Phys. Lett.* **64** (1994) 146.



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