Failure mechanisms in blue InGaN/GaN LEDs for high power operation

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1. Introduction

The solid state lighting programs based on blue power InGaN/GaN LEDs with package/phosphor system are developing in many countries. One of common fundamental problem which obstacle to cutting of production costs (1 lm/W) is the unriability of white LEDs related with unpredictable failure after a comparatively short operation time of some part of LEDs with the same initial parameters as LEDs having long lifetime. Several reasons of this phenomenon such as the degradation of the package/phosphor system and the failure of GaN-based LEDs submitted to electrostatic discharge events were found out and removed \cite{1,2}. However the most important physical mechanisms that responsible for unriability of GaN-based LEDs in solid-state lighting origin not clarified until now, despite nearly 20 years of efforts made by research groups in the industrial countries \cite{1,2}. It is clear now that degradation of power InGaN/GaN LEDs is a multi-faceted problem that involves change of defect population, catastrophic optical destruction, metal diffusion and electrode delamination \cite{3,4}. The increase in the radiative recombination in the active junction of the LEDs due to the propagation of defects and the migration of the indium and impurities in the multiple quantum well (MQW) region is observed \cite{4}. It is important to note the difficulties in identifying a specific degradation mechanism in different types of LEDs. In fact, different causes may dominate even in a single type of diode, and different degradation mechanisms can be observed simultaneously \cite{4}. One can believe that the difficulties are related with numerous forms of nanostructural arrangement (NA) in the GaN-based LEDs. These forms are governed by coalescence crystallites of near 3D growth mode to near 2D one with the extended defects system (EDS) formation and nanoscale phase separation in InGaN.

The aim of this paper is to clarify the mechanisms of unpredictable failure in blue power InGaN/GaN LEDs and to discuss methods which make in possible to reveal unreliable LEDs on early stage of aging tests.

In order to solve these problems, the approach taking into account numerous forms of NA of LED structures has been used \cite{5}. NA determines the properties of EDS, including a high density of threading dislocations, screw, their accumulations, dilatation and dislocation boundaries \cite{5,6}. NA becomes apparent in surface and in surface morphology of LED structures. The different NA forms can be characterized quantitatively using such multifractal parameters as degree of order (or degree of disorder) \cite{5}. Correlation between values of degree of disorder values and properties of EDS such as leakage current values at biases \(U < 2 \; \text{V}\) had been clarified earlier \cite{7}. It had been shown in particular that the degradation processes develop quicker the greater is the degree of disorder. It was noted also the leakage current values at biases \(U < 2 \; \text{V}\) is higher in LED with great values of degree of disorder \cite{7}. These observations make it possible to select for aging tests LED with appropriate degree of disorder.

2. Experimental

LEDs under study from several leading manufactures had maximum values of external quantum efficiency (\(\eta\)) in the range 40–45%. Radiation emission maximum was observed at wavelength 450–460 nm. To except the processes related to the package/phosphors /lens system on reliability of LEDs, the LEDs were mounted in metallic TO packages using flip-chip technique. The main aging mode chosen for studying the degradation processes was to pass metal TO packages using flip-chip technique. The main aging mode chosen for studying the degradation processes was to pass metal TO packages using flip-chip technique.
and low-frequency current noise spectra were measured; low-frequency spectral noise density was studied in diapason 1 Hz – 10 kHz.

3. Experimental results and discussion

Typical the current–voltage characteristics and external quantum efficiency dependences on current densities of selected LEDs before and after aging are shown at Fig. 1.

No considerable changes in η and I–V characteristics were observed for majority of LEDs under the study even after several thousand hours of aging. However, about 1–10% of total number of LEDs from different sets demonstrated the increase in forward current values (curve 3 in Fig. 1), which was not followed by a simultaneous growth in reverse current values (curve 1 in Fig. 1 corresponds to both case of unstressed and stressed LEDs as no changes in current has been observed), even after 10 h of aging. The dependences of external quantum efficiency η on current density for such LEDs are presented in Fig. 2. As seen, the η increases slightly in these diodes after 10 h of aging (Fig. 2, curve 2). However, after 60 h of aging the external quantum efficiency in these structures decreases sharply.

The dependences of the current spectral noise density on the forward current density $S_j(j)$ (Fig. 3, curve 2) demonstrate complicated behaviour. The increase on several order of $S_j$ (Fig. 3, curve 2) in comparison with initial value (Fig. 3 curve 1) to current densities $\sim 10^{-2}$ A/cm$^2$ ($j$ value correspond to the onset of radiative recombination) is observed. The increase of $j$ to $\sim 1$ A/cm$^2$ is accompanied by the decrease of $S_j$ (Fig. 3, curve 2). The minimal $S_j$ value and weak dependence on the current are observed within the range $1 \leq j < 10$ A/cm$^2$, where η reaches maximum. Thus the mechanism of non-radiative recombination rate suppression under injection current and reabsorption takes place. It should be noted that the shape of the decreasing part of $S_j(j)$ differs noticeably from $S_j(j) \sim 1/j^2$ being typical for local trap filling mechanism. This allows one to assume that the mechanism is related to filling traps created by EDS [5–7].

The increase in aging time to 60 h results in the quantum efficiency values drop by a factor of 1.5–2 (curve 3, Fig. 2) as well as both reverse and forward currents dramatic increase (Fig. 1, curves 4 and 5). It is seen from Fig. 3 that such a behaviour is accompanied by an $S_j(j)$ increase by several orders of magnitude (Fig. 3, curve 3) at $j < 10^{-2}$ A/cm$^2$. In this case the shape of $S_j(j)$ dependence is similar to one at Fig. 3, curve 2, however, the noise level is the highest on the all current range. The behaviour of the LEDs with the fast degradation process development is non-linear at the time over 100 h with unpredictable failure for different LEDs at diverse aging time.

The simultaneous increase in both the reverse and forward current at bias $U < 2$ V during aging tests is characteristic for all LEDs. However, this increase differs for LEDs with different aging time. It is known that the increase in reverse current values at $U < 2$ V reflects the change of properties quasi–ohmic paths related with EDS [7]. At high level of degradation, the diffusion of In along dislocations had been observed after aging by transmission microscopy [3].

The change in I–V characteristic at forward current reflects the decrease of active region resistance on several orders at $U < 2$ V. According to [8] the shape of $I–V$ characteristic at forward current at this voltage range reflects the non uniform composition of solid solution and presence of local regions with smaller $E_g$ and the common area at many times smaller than LED area.

To check correlation between change in the shape of forward I–V characteristics and the presence of local regions with smaller values of $E_g$ electroluminescence (EL) spectra of LEDs at 300 K were studied (Fig. 4). Curve 1 shows EL spectrum of initial LEDs. It has a conventional form with a maximum at 460 nm. EL spectra of LEDs after aging contain the wide long-wave band (curves 2 and 3). It is
noteworthy that long-wave band is absent in EL spectra of LEDs with long lifetime even after several hundreds hours of aging test. The band is observed with confidence at forward bias $\leq 2.5$ V, with its intensity increasing both with the increase in injection current and growth of aging time. Some blue shift of the band can be observed with the increase of bias. At $U > 2.5$ V the intensity of peak at 460 nm increases more quickly than that of long-wave band (Fig. 5). It should be noted that the further increase of stressing time lead to a rise in the long-wave band intensity. Appearance of the band could be related to conditions of InGaN growth. Non optimal growth condition can result in formation of local nano-scale regions with random non-equilibrium InGaN composition. This assumption agrees well with data on fast degradation of LEDs based on InGaN grown with rate which differs from optimal one [3]. As a result of non-optimal growth rate, non-uniform distribution of In and non uniform distribution of forward current can appear. In its turn, local heating caused by non-uniform current density distribution makes it possible migration of In [3]. This effect might lead to annihilation some defects, which may result in an efficiency rise at initial stages of aging process (see curve 1 at Fig. 2). However, the further increase in the aging time lead this process is followed by defect generation resulting in efficiency decrease.

Conclusions on non uniform distribution of current and on presence of local heating could be made also from noise spectra presented in Fig. 3. An extremely characteristic feature of the noise spectra in Fig. 3 is the presence of parts in which the noise density grows as $S_i \sim j^2$ (curve 2) and even $S_i \sim j^4$ (curve 3) (after aging...
tests) at very small average current density of \( \sim 10^{-3} - 10^{-2} \text{ A/cm}^2 \). It is noteworthy that \( S_i \sim j^m \) dependences appear also in LEDs with long lifetime, however only after several thousand hours of aging and at average current density \( \geq 10 \text{ A/cm}^2 \) (Fig. 6, curve 2).

According to Ref. [9], the increase in noise density with current stated by the law \( S_i \sim j^n \), where \( n > 2 \) indicates that the flowing current generates new defects. Defect generation, generally, occurs under conditions of rather high current density and resultant overheating [9]. Meanwhile, the average current density in the parts in which the dependences \( S_i \sim j^3 \) and \( S_i \sim j^4 \) are observed is exceedingly low. In our opinion, this fact provides one with the conclusive evidence that charge transport in blue InGaN/GaN LEDs is extremely non-uniform, especially during degradation.

Non-uniform current distribution becomes especially apparent on the spectral density \( \text{voltage fluctuations} \) dependences on current density (Fig. 7). It is well known that at the uniform current distribution, the spectral density of voltage fluctuations, \( S_v \), depends on \( j \) as \( S_v \sim 1/j \) in forward biased \( p-n \) junctions and Schottky diodes. The law \( S_v \sim 1/j \) is valid at low currents when virtually whole voltage applied to the structure drops on the barrier [10]. As seen in Fig. 7, the \( S_v(j) \) dependence follows more or less this law for innocent LEDs (curve 1). With increasing in aging time, deviation from this law increases monotonically (Fig. 7, curves 2 and 3). Similar behaviour is observed also in LEDs with long lifetime, but only after several thousand hours of aging test.

Thus we may conclude that, irrespective of the degradation scenario, defects causing degradation of the LEDs under study are generated extremely non-uniformly, with non-uniformity increasing during the degradation process. The gradual non-uniform accumulation of defects results in formation of current leakage paths and local hot spots which had been observed in many studies [1,3,11].

This assumption is confirmed by the fact that ohmic portions shunting the heterobarrier appears in the LEDs at high levels of degradation Fig. 8, with the resistance of this channel decreasing rapidly with further aging.

It should be noted that, for further LED degradation, local overheating regions (channels) that appear in the diodes were observed by IR imaging microscopy [11]. Increasing non-uniform current distribution causing local overheating enables the migration of gallium and indium metal impurity ions along the system of extended defects penetrating through the LED active region. Effects of this kind were observed, e.g., in [1,3].

4. Conclusion

The results obtained suggest that several mechanisms of the degradation processes take place in the blue power InGaN/GaN LEDs. The most general mechanism for all LEDs is local overheating along extended defect system. This overheating is accompanied by migration of In along EDS and increase in conductivity of leakage paths. The study of degradation processes in LEDs with small values of degree of disorder (the values of leakage current less than \( 10^{-10} \text{ A} \) at \( U < 1 \text{ V} \)) allows one to reveal another mechanism at early stage of aging tests. It is related to redistribution of In between nano-scale regions of InGaN alloy with non-equilibrium composition. This mechanism is characteristic for LEDs with unpredictable fast failure. One can believe that both mechanisms can make contribution in degradation process at long aging tests. Unreliable LEDs can be recognized by increase in forward current values at \( U < 2 \text{ V} \) which is not accompanied by simultaneous reversed current growth during short aging test (less than 100 h).

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References