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Reliability investigation of light-emitting diodes via low frequency noise characteristics

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Investigation of changes of operation and noise characteristics during aging process of light-emitting diodes (LEDs) has been carried out. Several groups of different design (different optics) LEDs based on different materials (nitride-based blue and white LEDs, phosphide-based red LEDs) have been investigated. It is found that leakage current components appear due to LED's defects and their affect is observed as increase of both the low frequency electrical noise intensity and non-ideality factor of current-leakage characteristic in small current region. No considerable changes of light intensity characteristics during LEDs aging have been observed. Noise modeling, spectral and correlation analysis of optical and electrical fluctuations show on partly correlated optical and electrical fluctuations caused by defects in the active region of the LED. Degradation processes of investigated LEDs foremost occur in the diode chip and lead to the leakage current that has important affect to the electrical fluctuation level, but practically has a weak influence to the light emission properties of LED. Phosphorous layer of white LEDs and additional optical elements have no significant influence to the reliability of investigated LEDs under given aging conditions.

1. Introduction

Nowadays light-emitting diodes (LEDs) not only increasingly penetrate to consumer electronics, but also they are important in scientific, medical, sensor applications as cheap and reliable light sources. The economy, simplicity and high reliability of LEDs make them an attractive choice also for short-distance, moderate speed optical data links [1].

Modern light-emitting devices are characterized as high reliability, fast, small size, power saving and environmental-friendly devices. However reliability issues of light-emitting diodes will always be of major concern [2–9]. Material degradation and structure damage due to electrical, thermal, chemical and mechanical stresses sometimes lead to the light output power degradation, color variation or early death of LED [3,4].

In order to improve LED operation and lifetime one needs to know physical processes that take place during LED aging, worsen the device quality and accelerate the degradation. Highly accelerated stress testing (HAST) methods are proposed to investigate the reliability of LED devices [2,8]. But these methods are destructive and physical processes that took place at HAST conditions could be different from ones at normal operation conditions. Therefore HAST methods do not clear up physical processes that took part during device aging at normal operation conditions.

The noise level undoubtedly is important indicator of LED quality [10–13]. It is shown that noise characteristic investigation is a sensitive and non-destructive method for explaining quality and reliability problems of optoelectronic devices (laser and light-emitting diodes, photodetectors) [14–21]. Investigation of noise characteristics gives valuable information on LED reliability [15,20–23] and is useful for evaluating quality of semiconductor devices and predicting their lifetime [15,19–21,24,25]. Nevertheless there are very few papers where long-lasting aging processes in LEDs are investigated via noise characteristic measurements [10–13,22,26].

Today LEDs cover all visible light spectrum and beyond. Different materials are used for the fabrication of different wavelength light-emitting devices. For the light sources emitting on the short wavelength spectrum side nitride-based materials are used – GaN, InGaN, AlGaN LEDs emitting in blue, green, and ultraviolet spectral region. The nitride-based technology enables fabrication of white light LEDs, too. White LED comprises from nitride-based active region, where blue light is emitted, and phosphorous layer

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that converts the part of the blue radiation into a broad yellow-greenish spectrum. The sum of the blue light emitted by the active region and the luminescence of the phosphorous is perceived as white light.

The nitride-based material systems exhibit high mechanical strength and durability, and have the potential to be used for the high-temperature and power electronics [27,28]. The problem that arises on fabrication of multilayer nitride-based light-emitting devices is the lattice mismatch (of 15%) between nitride layer and sapphire substrate that leads to the large number of structural and point defects ($(10^8–10^{10})$ cm^{-2}) in the devices [29]. Additional strains present due to dislocations generated by lattice mismatch. That led to the non-radiative recombination processes [19,30], and also influences the device quality and reliability, and accelerates the degradation processes [27–31]. In spite of such a large number of dislocations, the efficiency of nitride-based LEDs is high as well as the conventional III–V compound semiconductor-based LEDs.

Defects in the active region are the main source that determines the bad quality and degradation of LEDs. There are many reasons for existence of defects in the LED structure [5,19,31]. The presence of the defects leads to the leakage current, capture and non-radiative recombination of the injected electron–hole pairs, which lower the efficiency of the light-emitting device and accelerate the device aging [6,7,9,11,16,19,24,29–32]. Usually defects affect both optical and electrical properties of LED: it is observed that optical degradation is correlated with the changes in the electrical characteristics of the devices [6].

LEDs consist of multiple components – separate regions can be named as: active region, phosphorous layer (for white LEDs), optics and packaging. All these components of the device perform different function and can differently influence the device reliability during aging process. It is important to separate these different effects of the LED structure – different physical processes take part in different regions and these regions can differently influence to device degradation [11,33]. It is shown that large level of the diode terminal voltage fluctuations (electrical noise) in optoelectronic device does not always indicate on the high defectiveness of the active layer, it can be related with the physical processes outside the active region and only weakly can influence the light emission processes. In order to characterize the defectiveness level of the active region and its interfaces, it is needed to measure both electrical and optical noises and their cross-correlation factor [17,24]. Moreover, it is shown that decomposition of the total low-frequency fluctuation spectrum to $1/f^{\alpha}$- and Lorentzian-type spectrum components is very useful for the noise and reliability analysis [24]. In our previous works it is shown that cross-correlation factor between optical and electrical fluctuations is especially informative characteristic [16,17,24,25].

As pointed above the white light-emitting diodes have additional structural element: phosphorous layer that can be an additional source of the optical spectrum degradation [6,9]. Besides, the secondary optics is used in order to get desirable light radiation diagram. It can influence LED optical properties and could be affected during device aging.

In this paper we present new research data on the comprehensive investigations of reliability of the different design light-emitting diodes through the analysis of their low frequency noise characteristics: electrical and optical fluctuations and their cross-correlation factor, also considering in analysis our earlier investigation results. The aim of the investigation was to clear up the physical processes that accelerate device degradation, to show how different regions of the LED structure are affected during the device degradation process.

The paper is organized as follows: in Sections 2 and 3 there are described the investigated samples and the noise measurement details; in Section 4.1 there are presented the typical noise characteristics of initial (not aged) LEDs; Section 4.2 deals with the degradation mechanisms of the nitride-based light-emitting diodes; Section 4.3 is devoted to the investigation of the influence of the phosphorous layer to the device degradation of the white light-emitting diodes; Section 4.4 describes noise characteristics and degradation of LEDs with different secondary optics; Section 5 presents the noise modeling and decomposition of noise spectrum into different noise components, and correlation analysis; in Section 6 there are presented the comparison of the noise characteristics obtained during aging of different design LEDs and discussion on the degradation mechanisms.

2. Investigated light-emitting diodes

In this research, a set of different modern 1 W power LEDs have been investigated. The investigated devices differ by several features: material and emitting light wavelength, design of lens (Table 1).

LED structures based on different materials have been investigated in order to compare noise characteristics and degradation mechanisms related with the growth defects in materials. As different materials are used to get different light wavelength consequently the LEDs with different color of radiation light were entered. White light LEDs with phosphorous layer (employed for the re-emitting the blue light radiated in the active region to the yellow-greenish) also were investigated. The phosphorous layer can be a source of additional degradation of both the light intensity and spectrum.

Another point of the investigation was to examine, if the secondary optics (additional lenses that form side-emitting LED or device with Lambertian or batwing lens) has any influence to the LEDs degradation. For this purpose the LEDs of the same structure and material but with different type of optics have been investigated (samples LED3, LED4 and LED5 in Table 1).

3. Measurement technique

Low-frequency (10 Hz–20 kHz) noise characteristics (optical noise – the emitted light power fluctuations detected by photodetector; electrical noise – the terminal voltage fluctuations; cross-correlation factor between optical and electrical fluctuations) have been measured at room temperature during accelerated aging. The aging was performed at maximum permissible operation forward current (350 mA) at room temperature (293 K). Initial samples were measured before aging and then the measurements of the current–voltage, light–current and noise characteristics have been periodically done by interrupting the aging procedure at room temperature.

The measurement circuit of the optical and electrical noise signals of light-emitting diodes is presented in Fig. 1. Each noise measurement channel has the low-noise amplifier, the filter system and the analog-to-digital converter (NI PCI6115). Optoelectronic device investigation requires two identical channels that operate simultaneously – this enables to measure the simultaneous

Table 1
Parameters of the investigated LEDs.

Samples	Wavelength (nm)	Material of the active region	Optics
LED1	450	GaN	Side-emitting
LED2	White	GaN	Lambertian
LED3	645	AlInGaP	Side-emitting
LED4	645	AlInGaP	Lambertian
LED5	645	AlInGaP	Batwing
LED6	White	InGaN	Lambertian

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