High-current Electro-optical Degradation of InGaN/GaN Light-emitting Diodes Fabricated with Ag-based Reflectors

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We have investigated the degradation of the optical power and the operating voltage of InGaN/GaN light-emitting diodes (LEDs) fabricated with Ag-based reflectors during electrical and thermal stress. As the electrical stress increased from 50 mA to 200 mA at a thermal stress of 100 °C, the optical power was significantly reduced. The decrease in optical power was closely correlated to a rapid increase in operating voltage due to an increase in the parasitic series resistance during the accelerated current aging test.

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I. INTRODUCTION

During the last few years, important efforts have been made to improve the performance of high-brightness GaN-based light-emitting diodes (LEDs) emitting in the visible and the ultraviolet wavelength ranges [1,2]. Long-term reliability is a necessity for LEDs. Therefore, a detailed understanding of diode lifetime characteristics and degradation mechanisms is a very important step in improving the performance of LEDs [3–5]. In early reliability studies, failure mechanisms related to direct current (DC) aging tests were extensively studied for their influence on device lifetime and reliability [6,7]. Meneghesso et al. [6] observed a degradation of LEDs due to the generation of deep-level states associated with Mg-H complexes in the active region under high electrical stress. M. Osinski et al. [7] observed degradation due to contact metal migration.

For this paper, we conducted a study of the lifetime of GaN/InGaN blue flip-chip LEDs under different electrical stresses at a constant temperature (100 °C). This work presents the effects of aging in terms of the operation characteristics for the devices. Aging-induced changes in electrical I-V diode characteristics and optical power are considered to be measures of degradation. An increase in the operating voltage of an aged device is believed to be responsible for the degradation of GaN LEDs.

II. EXPERIMENTAL DETAILS

For this study, we used commercial InGaN/GaN blue flip-chip LEDs. The device chip size was 1 × 1 mm², and the chip was fabricated using a flip-chip LED manufacturing process. An Ag-based reflector was deposited as a p-type electrode. A Cr/Au scheme was adopted to form an n-type electrode. GaN LEDs were subjected to accelerate testing at forward currents of 50, 75, 100, and 200 mA at 100 °C for 600 minutes to search for electrical degradation at different current levels.

All devices were electrically and optically characterized by means of current-voltage-light (I-V-L) measurements. The I-V-L characteristics of GaN LEDs were measured periodically during the electrical and thermal stress by using a Keithley 238 unit and a Keithley 2000 unit. At different current levels, the I-V-L measurement was repeated every 5 minutes, and an I-V curve characterization was done hourly to obtain a detailed description of the electrical and the optical parameters during aging. After the electrical and thermal stress, the aged devices were characterized using capacitance-frequency (C-f) measurements.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the variation of optical power as a function of stress time for the flipchip LEDs during the electrical and thermal stress. The LEDs were aged at different current levels and at a constant temperature of 100 °C. All devices aged at different current levels...
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Fig. 1. (a) Optical power decrease (at 100 °C) measured during aging tests at different current levels ranging from 50 mA to 200 mA, (b) Photodiode (PD) current and operating voltage variation during the 100 mA, 100 °C stress.

showed the same behavior with different kinetics in the modification of the optical power. Electrical and thermal stresses were found to induce an optical power decrease on all the analyzed devices. In particular, high electrical stress induced a strong optical power reduction. The optical power of the flipchip LEDs stressed at 75, 100 and 200 mA decreased rapidly in the early stages (within 120 min) of the stress test, and devices lost 20 – 30% of their initial optical power. The optical power changed slowly after 120 min. Fig. 1(b) shows the changes in the photodiode (PD) current and the operating voltage measured for a device aged at 100 mA and 100 °C. It is worth noting that during the initial part of the stress test (t < 120 min), the operating voltage increased significantly and the optical power decreased, as shown in Fig. 1(a). This result suggests that the rapid deterioration of the optical power may be attributed to a significant increase in the electrical properties of the LEDs.

The typical current-voltage (I-V) characteristics of a GaN LED, before and after aging, are shown in Fig. 2. The I-V characteristics can be analyzed by using four characteristic regions in the curve: (I) an increase in the reverse leakage current due to tunneling current related to defect formation in the active layer; (II) at low forward bias, <2.2 V, an increase in the generation-recombination current; (III) an increase in the devices ideality factor; and, (IV) an increase in the parasitic series resistance $R_S$, which can be attributed either to the degradation of contact metal or to an increase in the doping density of the p-layer due to the accelerated current aging test [8].

Figure 3 shows a change in the generation-recombination current at 1.5 V during the aging test.

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Figure 3 shows a change in the generation-recombination current at 1.5 V during the aging test with electrical and thermal stress. A slight increase in generation-recombination current is only seen in the devices after high electrical stresses of 200 mA at 100 °C. The high electrical stress induced the generation of deep-level states in the spacecharge region, which involved non-radiative recombination, as reported in a previous work [6]. The deep-level states can play the role of a re-
combination centers to increase the recombination rate. Nevertheless, in this study, none of the aged devices showed the significant changes exhibited by the degradation of electrical characteristics.

Figure 4 shows that the reverse leakage current \( I_R \) measured at \(-5\) V in the flipchip LEDs appeared in the aging tests at different current levels. During stress, the reverse leakage current of the device aged at 200 mA increased from 1 to 3.5 \( \mu \)A. The \( I_R \) did not show a significant change for the devices aged at 50 and 100 mA. Fig. 5 shows the variation in ideality factor as determined by the slopes of region (III) during the aging tests. These changes in the I-V characteristics induced by electrical and thermal stress obviously are not consistent with the data reported in the literature [9]. The tunneling current is the main component of the reverse current and of the ideality factor. Cao et al. [10] attributed the increase in tunneling current to the generation of point defects, which were induced by the high junction temperature in the active region under high stress current. These defects, which are directly related to an LED’s degradation and failure, may be linked to the growth of non-radiative recombination centers leading to a decrease in optical power. However, in our experiments on aging, the ideality factor and the reverse leakage current of the diodes presented no significant change as a consequence of stress.

Figure 6 shows the forward bias I-V characteristics of the device aged at 100 mA and 100 \( ^\circ \)C. Electrical and thermal stress induced a shift of the forward I-V curve toward higher voltage with strong change in its slope: operating voltage was found to increase during stress, indicating an increase in the parasitic series resistance \( R_S \), which is attributed to a degradation of p-GaN and/or
contact properties [11, 12]. As a consequence of stress, the parasitic series resistance increased from 4.85 Ω to 7.48 Ω within 300 min of testing and increased to 8.65 Ω after 300 min. In the highbias region, these results indicate that severe degradation of the electrical characteristics may occur near the metal/semiconductor interface, suggesting a possible role for parasitic series resistance in the degradation process.

To understand the rapid increase in the parasitic series resistance, we measured the change in the frequency distribution of the C-f spectra by using a HP4284A LCR meter, as shown in Fig. 7. The aging test induced a modification in the C-f spectrum only for the stressed devices with the growth of a new peak for low-frequency values (for frequencies of less than 1 kHz). These results suggest that the stressing of flipchip LEDs induces a degradation of the properties of p-GaN, rather than a worsening of the characteristics of the p-type electrodes Rossi et al. [13] observed a possible role in the effective doping of the p-layer, with a consequential increase in the series resistance and a degradation of the Ohmic contact of p-GaN. These observations have, therefore, led to the measured forward I-V modifications. In this study, the increase in the series resistance of LEDs being closely correlated to the degradation of the p-layer may possibly be linked to the generation of Mg-H complexes [14] and to the increase in the operating voltage, which leads to a decrease in the optical power.

IV. CONCLUSION

We have investigated the degradation of GaN/InGaN flip-chip LEDs subjected to electrical and thermal stress. Early reliability studies recorded a rapid loss of optical power related to the formation of non-radiative generation recombination centers associated with deep-level states and to an increase in the tunneling current due to point defects in the active region. In our study, however, for the aged devices, the strong decrease in the optical power at an early stage was shown to be closely correlated to an increase in the operating voltage due to an increase in the parasitic series resistance during the accelerated current-aging test. The increase in the parasitic series resistance could be attributed to a degradation of the p-side Ohmic contact and of p-type GaN.

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REFERENCES