Degradation Characteristics of Blue Light-Emitting Diodes under Accelerated DC Aging Process

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***Abstract*-Blue light-emitting diodes (LEDs) have been subject to high-current DC aging process at room temperature in order to study its degradation characteristics by electrical and optical characterizations. Electrical measurements show that after each cycle of aging, the diode's ideality factor increases at all forward bias levels. The reverse saturation current also increases after each aging process. Optical measurements show that although the peak wavelength of the diode remains almost constant at 468nm, its full-width-at-half-maximum (FWHM) value broadens from 27nm to 34nm after 24-hr of aging, and nearly saturate at 39nm after 48 hours. The peak wavelength intensity also decreases steadily with time. We attribute the LED's degradation to the creation (or activation) of defect levels inside the band gap. These levels provide pathways for non-radiative recombination, resulting in dimmed LEDs under forward bias. They also contribute to generation current under reverse bias.**

I. INTRODUCTION

Blue light-emitting diodes (LEDs) are widely used in general electrical appliances and electronic devices such as function panels in cars and keypads light in mobile phones. In general, LEDs are finding more lighting and signaling applications as they are more efficient than other light sources. Because of growing usage, LED characteristics must be fully understood. When used in commercial applications, warranties are usually given against LED malfunction. For manufacturers or system designers to be confident of the warranty period, it is important to subject blue LEDs of interest to accelerated DC aging and study the electrical and optical properties of the LEDs before and after aging.

The blue LED under test is a commercially available, InGaN-based high-brightness blue LED. The LED is well encapsulated under blue cover and its rated nominal working parameters are 20mA of forward injection current, and 3.2-3.9V of forward voltage under the ambient temperature at 25^{o}C. For the reverse bias region, the maximum bias should not exceed -5V in order to avoid damage to the LED. At normal forward bias operation, the peak wavelength is 464nm and the full-width-at-half-maximum (FWHM) is 23nm.

It is generally known that long-term operation of diodes degrades their electrical and optical characteristics: LEDs become dimmer and consume more power with time. It usually takes a long time for such degradation to be noticeable. In order to simulate the aging process in a controlled environment, all the LEDs used in this study are subjected to accelerated DC aging where power larger than the rated value is intentionally supplied to the LEDs. Since the power supplied is larger than the amount that the packaging can dissipate, the heat builds up inside the device and accelerates the degradation mechanisms. With proper DC bias and power supplied, it is possible to subject the LEDs to one day under test which has a theoretical equivalence of one year of continuous operation at the rated conditions. Care must be taken, however, for LEDs can easily be damaged in the event of sudden change of device temperature. By studying the LED characteristics before and after accelerated DC tests, it is possible to estimate the LED's lifetime which has important implications for warranty periods.

The LED's characteristics of interest are optical and electrical performances before and after the aging process. What follows in the remaining of the paper will show how the electrical and optical characteristics are degraded, and what are the causes and consequences of the degradation. The structure of the paper is as follows: the experimental procedures including the electrical and optical measurement set-ups will be given next in Section II. This is followed by Section III where the results are shown and discussions are given, followed by the conclusion in Section IV.

II. EXPERIMENT

The structure of the blue LED under test is shown in Fig. 1. The device is grown on a sapphire substrate starting from n-type contact layer (n-GaN), InGaN active layer, p-AlGaN emitter and p-GaN as the top contact layer. The device is subjected to the accelerated DC aging process shown in Fig. 2. For each cycle of the process, the LED's electrical and optical characteristics are measured using the set-ups shown in Figs. 3 and 4, respectively.

The schematic flow diagram in Fig. 2 describes how the LED is subjected to tests and measurements. The LED is measured before (0 hour) and after each of the three 24-hour aging cycles (24, 48 and 72 hours). A computer program has been written to control a power supply (Advantest TR6143) in such a way that only dissipated power needs be input. The program will automatically adjust the current and voltage to match the power required. The program has a ramp-up and down features to prevent sudden temperature change of the device. The program is set to supply the required power (500mW) for 24 hours before being terminated. Afterwards, the LED's electrical and optical characteristics are measured and the LED is further subjected to the same aging process until it is aged by 72 hours, which corresponds to approximately 3 years of operation at the nominally rated conditions.

The electrical measurement set-up shown in Fig. 3 consists of a control personal computer (PC) which is connected to a power supply via a general-purpose interface bus (GPIB). The power supply is either a HP 4140 or Advantest TR6143, depending on the required current/power used in measurement or for aging process. In either case, the power supply outputs a current (*I*) and measures the voltage (*V*), or vice versa. Each data point (*I*,*V*) can be subsequently read back by the PC via GPIB.

The optical measurement set-up shown in Fig. 4 consists of a monochromator, a photomultiplier and a digital multimeter (DMM). The PC is used to adjust the grating of the manochromator so that only selected wavelength can go through it. The filtered light is subsequently detected at the other end by a photomultiplier whose output is measured by the DMM and read back by the PC. The control value (λ required) and the result read back (volt, corresponding to light intensity) are then used to plot the optical characteristic.

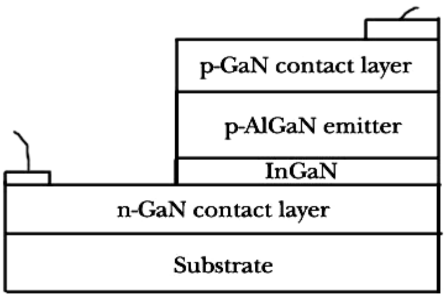

Fig. 1. Structure of the device.

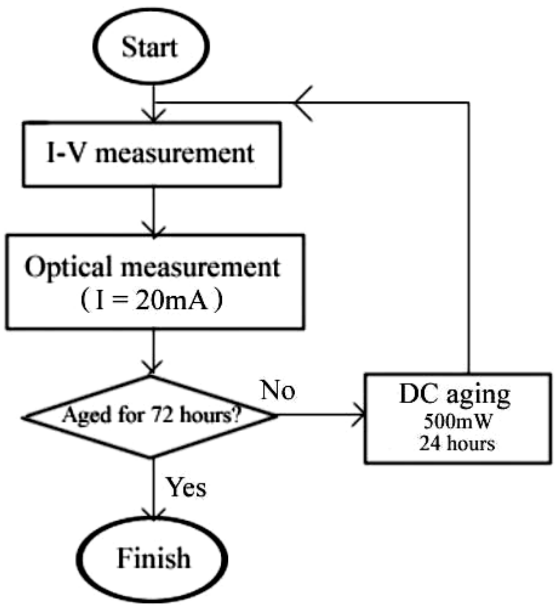

Fig. 2. Flow diagram of the accelerated DC aging process.

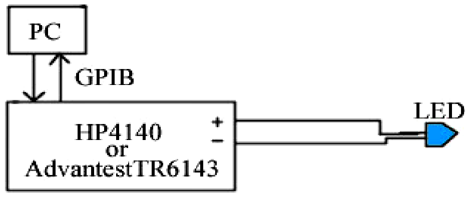

Fig. 3. The electrical measurement set-up.

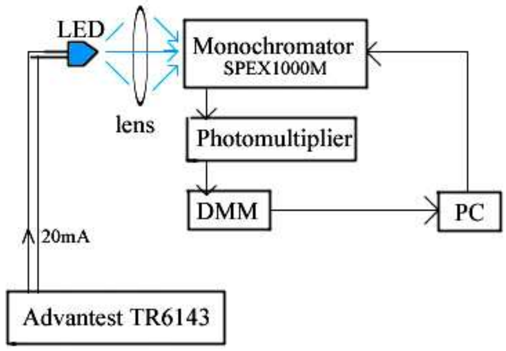

Fig. 4. The optical measurement set-up.

III. RESULTS AND DISCUSSIONS

The electrical characteristic of the LED in Fig. 5 shows the current-voltage (*I-V*) of the diode before and after being aged at 500mW for 24, 48 and 72 hours. The semi-logarithmic plot shows that the electrical characteristics of the diode's forward and reverse biases are significantly affected, most notably after the first 24 hours of aging. The inset of Fig. 5 shows that the reverse saturation current of the LED increases with the aging time, indicating that there may be physical changes in the active area of the LED.

The reverse saturation current is associated with generation centres in the semiconductor band gap. The centres may be inactive as grown, but become active after prolonged usage.

These mid-gap centers can also become active at forward bias conditions where they are effective as recombination centers. This is evident in Fig. 6 which shows the plot of ideality factor as a function of forward bias for two conditions: new and 24-hour aged LEDs. The ideality factor η can be determined from the relationship [3]:

$$I = I_0(\exp(qV/\eta\, k_B\, T)-1) \qquad (1)$$

where I is the current, V is the voltage, I_0 is the reverse saturation current, q is the electronic charge, k_B is the Boltzmann constant, and T is the temperature.

The ideality factor depends on relative contribution of diffusion and recombination currents. The value of η approaches 1 if all current components are diffusion currents, and reaches 2 when recombination current dominates [2,3]. Fig. 6 shows that the ideality factor η increases for all bias levels [1]. Ideality factor even greater than 2 is possible if the quasi-Fermi levels splitting is less than bias voltage and the recombination spreads out over a wide region [5].

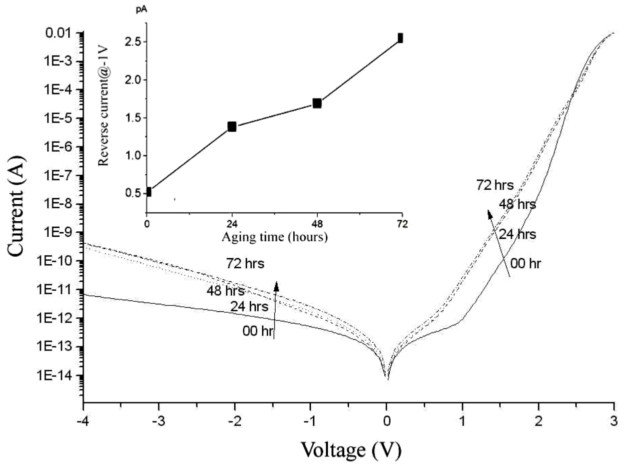

Fig. 5. The current-voltage (I-V) characteristics of the blue LED before and after being aged at 500mW for 24, 48 and 72 hours.

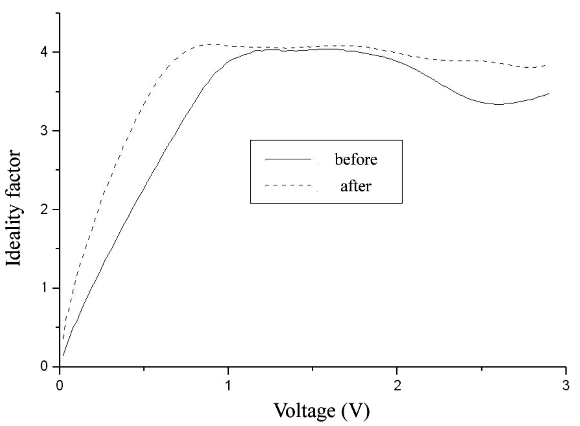

Fig. 6. Ideality factor of the LED before and after being aged at 500mW for 24 hours.

The optical characteristic of the LED is shown in Fig. 7. The intensity of light output from the LED when it is forward biased at the rated current (20mA) is shown before and after being aged at 500mW for 24, 48 and 72 hours. The inset shows the relative peak intensity and FWHM values of each aged cycle.

The optical results show that the peak wavelengths stay almost constant at the rated value of 465 nm while the intensity at the peak wavelength reduces significantly, most notably between the first and the second aged cycles (i.e between 24 and 48 hours). The FWHM values which indicate the "purity" of the color that the eyes perceive also degrade after each aging cycle. The reduced intensity results in dimmer LEDs after long-term operation while the broadened FWHM contributes to the change in color that human eyes perceive.

The fact that the electrical characteristic undergo a critical change after 24 hours of aging while the optical characteristic undergo a critical change between 24 and 48 hours of aging is indicative that different mechanisms may be responsible for electrical and optical degradations However, it has been suggested that defects in recombination region may be responsible for both types of degradations [4].

In order to explain our results, and in agreement with the mechanism suggested by Cao [4], we propose a simple model to illustrate why the reverse current increases and the emission efficiency decreases after each aged cycle.

Fig. 8 shows a plot of (upper) energy-wave vector (*E-k*) diagram and (lower) energy-distance diagrams across a p-n junction in the case of (left panels) new and (right) aged LEDs. A mid-gap energy level (E_r) is shown only for the aged LEDs. The existence of E_r in the *E-k* diagram means that carrier recombination can occur via indirect recombination, which results in heat or phonons. E_r in the energy-distance diagram shows that it can function as an effective generation center under reverse bias conditions [3], resulting in increased reverse current as shown by the comparatively larger arrow in Fig. 8.

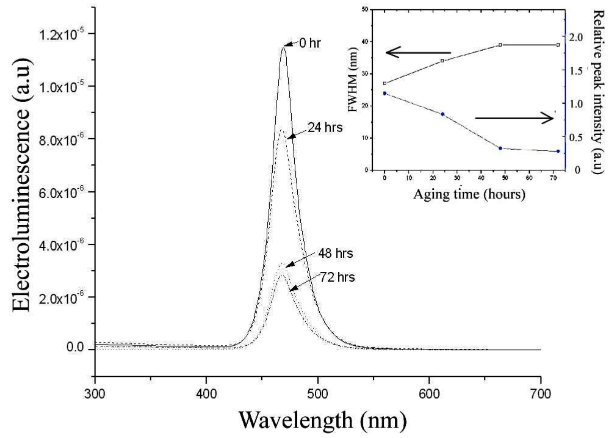

Fig. 7. Optical emission from the LED before and after being aged at 500mW for 24, 48 and 72 hours. The inset shows the peak wavelength and FWHM of each cycle.

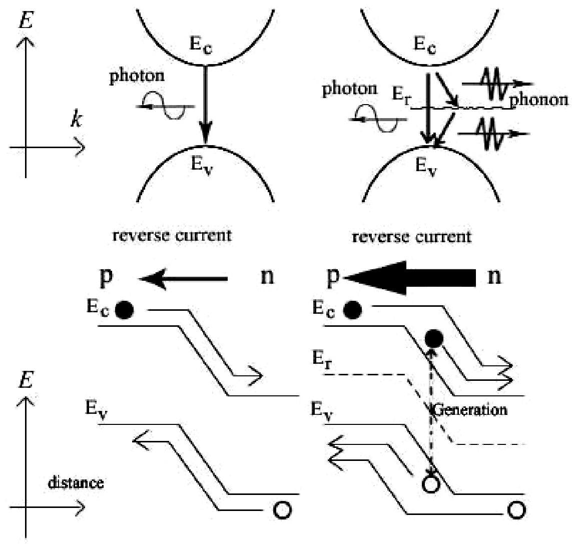

Fig 8. Energy-wave vector (upper) and energy-distance across a p-n junction (lower) of new (left) and aged (right) LEDs.

IV. CONCLUSION

In conclusion, commercially available blue LEDs have been subject to accelerated DC aging process and their electrical and optical characteristics are measured. It is found that both characteristics are degraded after each aging cycle: the ideality factor and the reverse saturation current in *I-V* characteristics increase while the peak wavelength intensity in the electroluminescence characteristic decreases. We attribute the degraded characteristics to the formation (or activation) of mid-gap energy levels which can effectively function as non-radiative recombination centres in the forward-biased mode, and generation centres in the reverse-biased mode.

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