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Research on efficiency droop mechanism and improvement in AlGaInP Ultra-High-Brightness LEDs using the transient measurement method ☆

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ABSTRACT

This study proposes a transient measurement method (TMM) for minimizing self-heating in AlGaInP Ultra-High-Brightness LEDs (UHB-LEDs) under low-to-high bias current. The TMM was validated by the wavelength shift method. The luminous intensity ratio measured by the TMM was similar to that in the ideal device under low-to-high current. The contribution of internal quantum efficiency loss to self-heating temperature and electrical efficiency loss affecting the efficiency droop of AlGaInP UHB-LEDs were determined by TMM because of the temperature dependence of injection efficiency and internal quantum efficiency. The analytical results showed 2.4% difference in wall-plug efficiency (WPE) droop at 1.6 A was contributed by internal quantum efficiency and injection efficiency loss. The remaining 10.1% difference was contributed by electrical efficiency loss. This study also discussed the main mechanism, the high contact and sheet resistance resulting in current crowding, that affects electrical efficiency loss, and a qualitative analysis and recommendations for AlGaInP UHB-LEDs design were demonstrated to eliminate efficiency droop.

1. Introduction

The AlGaInP Ultra-High-Brightness LEDs (UHB-LEDs) have recently attracted considerable attention because they can replace conventional lamps used as light sources for various applications, such as indicators, keypads, liquid crystal displays, outdoor displays, and electronic devices. The rapid development of luminous efficiency enabled the combination of AlGaInP red and AlGaInN blue chips to become a promising solution for solid-state lighting (SSL) applications [1]. However, commercial use requires high current to provide the high light-output power needed to satisfy the cost requirements of the market. Thus, a limitation of AlGaInP UHB-LEDs is their reduced external quantum efficiency or wall-plug efficiency with increasing forward current called efficiency droop, which is one of the most challenging issues in SSL applications.

The effect of efficiency droop has been studied extensively in AlGaInN using blue and green LEDs. However, the nature of efficiency droop remains unclear, and no satisfactory solutions have been proposed. Hypothesized causes of the droop effect include electron leakage mediated by an asymmetrical pn junction [2], limited carrier injection efficiency (IE) [3], polarization field [4], Auger recombination [5], junction heating [6], and current crowding [7]. The efficiency droop mechanism in AlGaInP UHB-LEDs, which serves the important function in generating a visible white-light spectrum with a high color-rendering index, is rarely discussed [8]. Given that wall-plug efficiency comprises internal quantum efficiency, electrical efficiency, injection efficiency, and light extraction efficiency. Thus, saturation of defect/spontaneous recombination [8], current crowding effect [7], and electron-drift-induced reduction in injection efficiency [9] remain as the three different perspectives on efficiency droop in UHB-LEDs and high-brightness LEDs (HB-LEDs) resulting from reduced internal quantum efficiency, electrical efficiency, and injection efficiency, respectively. In AlGaInP LEDs, temperature is the most relevant physical parameter and the best explanation for efficiency droop. Approaches for directly predicting junction temperature in the chip under a driving voltage include duty-cycle [10] and voltage method [11,12]. Here, TMM was used to minimize self-heating temperature in AlGaInP UHB-LEDs operated at low-to-high current. After validating TMM by wavelength shift method [10,11],

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the luminous intensity ratio of TMM was compared with that of the commercial measurement method (CMM) and the ideal case. The droop behavior contributed by internal quantum efficiency, electrical efficiency, and injection efficiency was investigated because of the temperature dependence of internal quantum efficiency and injection efficiency. The qualitative analysis results and recommended AlGaInP UHB-LEDs design for eliminating efficiency droop are based on the main mechanism that affects electrical efficiency loss and the high contact and sheet resistance that facilitate current crowding.

2. Device structure and experimental details

2.1. Device structure

The AlGaInP HB-LEDs were deposited on a thick n-GaAs substrate through metal organic chemical vapor deposition (MOCVD). The active region is composed of 12 pairs of $Ga_{0.5}In_{0.5}P/(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ multi-quantum-well (MQW) structures with barrier and well thicknesses of 70 and 40 Å, respectively. To spread the current, two thick *p*-doped GaP and *n*-doped AlGaInP window layers were deposited on the top and bottom of the MQW. A 500 Å ohmic GaAs layer was deposited on an n-GaAs substrate before MQW. Fig. 1 shows a schematic diagram of the AlGaInP HB-LEDs with top and bottom Au electrodes. Wafer bonding, reflective mirror, and texturing techniques were applied on the UHB-LEDs from HB-LEDs to reduce absorption of the GaAs substrate and to increase light extraction. Various UHB-LEDs with wall-plug efficiencies more than 5 times higher than those of HB-LEDs have been developed recently SSL applications. The active area of the chip in this study approximated $1 \times 1\ mm^2$. Temporary substrate and HB-LEDs were initially bonded with the adhesive layer to remove the n-GaAs substrate and to pattern the ohmic GaAs layer and GeAu metal. A soldering layer was formed after depositing the high reflective mirror layer to adhere to the LEDs and silicon substrate. The GaP layer was treated with natural chemical roughing to improve light extraction after removing the temporary substrate and to establish ohmic contact with the BeAu metal. Details of the fabrication techniques and parameters are disclosed in other articles investigated by the authors [13].

2.2. Measurement techniques

The commercial system comprises a Keitheley 2400 power system, an integrating sphere, a spectrometer, a carrier and software. The light converted from the electrical power input is also scattered in the integrating sphere. The spectrometer includes back illuminated CCD sensor and grating inside. The luminous intensities at each wavelength were measured with a commercial spectrometer and associated software. The limitation of the commercial system is its long response time (9 ms) resulting from the filtering signal used by the spectrometer. A chip with a TO-18 carrier is freely attached to the carrier. Fig. 2 shows how this measurement system receives an optical signal generated from the synchronized chip.

Compared with other LEDs, AlGaInP is more sensitive to temperature when driven at a typical current such as 0.35 A for a $1 \times 1\ mm^2$ chip. This material also has lower external quantum efficiency and higher heat accumulation when driven at a high current. Thus, heat is one of the most important factors that affect luminous intensity, especially in AlGaInP LEDs [8–12]. The integration time for this measurement system is at least 9 ms when using CMM, which is the system constraint for capturing a suitable optical signal. This system rapidly accumulates heat on a TO-18 carrier because of poor thermal conductivity. Pulse time should be longer than the integration time for filtering the side signal of a chip. Thus, package carrier, pulse time, and current condition are the main CMM issues that affect the luminous intensity correlated to wall-plug efficiency. Fig. 3 shows the roll-off wall-plug efficiency obtained by CMM in the AlGaInP UHB-LEDs discussed in this study.

For an accurate measurement of wall-plug efficiency droop behavior in an AlGaInP UHB-LED chip, the measurement method should minimize heat accumulation by pulse time. Second, the TO-18 package is inappropriate for heat dissipation under high current drive. Therefore, a new package system with good heat dissipation should also be provided.

Fig. 4 shows the TMM constructions, including the control system, the test vehicle, and the analysis system. The control system is based on the LABVIEW software, and the PCB controlled by DAQ USB-6251 is a digital-to-analog signal processor. The control system PCB has a pulse time limitation approximating 1 ms. The test vehicle was an Si detector with a chip directly mounted on a MCPCB with silver paste. The MCPCB was also attached to a bulk heat sink with radiation paste. The MCPCB is 2 mm thick and made of copper. The material of the bulk heat sink is aluminum with dimensions of 20 cm × 10 cm × 15 cm, which is large enough to let heat spread out. The analysis system is constructed on an SR830 analog signal processor. The working principle is described as follows. The signal triggered from LABVIEW, which has a tunable duty cycle from 5% to 90% within 1 ms, drives the DAQ system and PCB board on the test vehicle by an electrical wire. The analog signal is simultaneously transformed into an optical signal through the LED device. The Si detector receives and delivers the optical

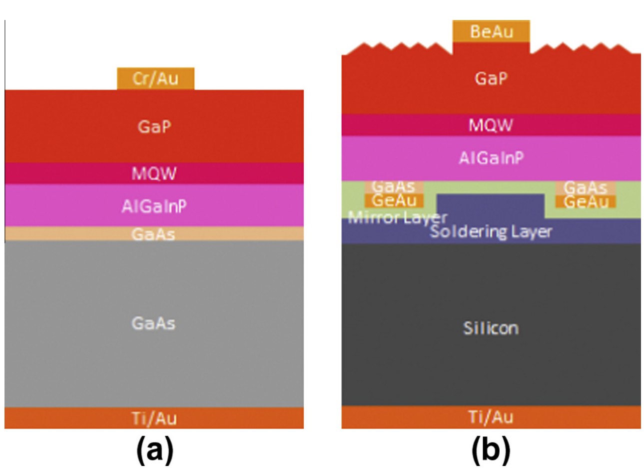

Fig. 1. Schematic diagram of (a) high-brightness-LEDs and (b) Ultra-High-Brightness-LEDs.

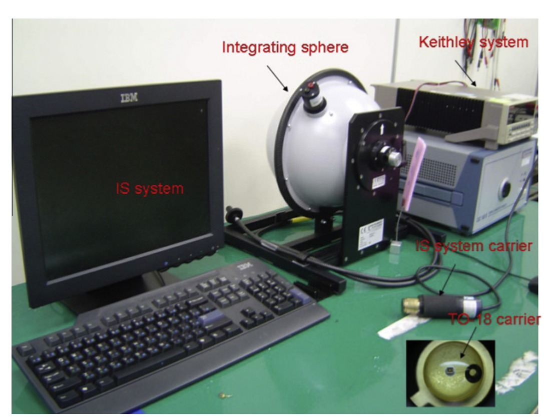

Fig. 2. Test vehicle of Current Measurement Method (CMM).