Investigating current and temperature dependencies of UV-A light-emitting diodes

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Abstract

UV-A LEDs have achieved efficiencies in par with GaN blue LEDs and reductions in cost over the years. These developments have enabled their use in a variety of applications including industrial curing, 3D printing, and safe germicidal inactivation. These applications demand for the UV-A LED sources to operate at high current densities and elevated operating temperatures. Therefore, it is important to understand how the luminous characteristics of UV-A LEDs depend on such operating conditions. This study focuses on how the emission spectrums of UV-A LEDs behave under different operating temperature conditions and drive currents. It was observed that out of the tested ones, the LED group with shortest wavelength emission showed a higher efficiency drop at high operating currents compared to longer wavelength UV-A LEDs. The peak wavelength shifts of samples tested at varying currents and temperatures was observed to be minimal. The suitability of these UV-A LEDs in different types of applications depends on different factors such as optical conversion efficiency, current and temperature sensitivity of radiated emission.

Keywords: UV-A, Gallium Nitride (GaN) LEDs, UV-A curing, UV-A safe germicidal inactivation, Radiation efficiency.

1. Introduction

1.1 Developments in UV-A LEDs

UV-A is defined by CIE as radiation in the wavelength range between 315 nm and 400 nm [1]. With developments in the past few years, UV-A LEDs can operate with stability at current densities as high as 4 A/mm^2. They have achieved significant efficiencies up to 70% and also gone down in price enabling widespread adoption for different applications[2].

UV-A LEDs have a similar chip construction to that of blue LEDs and are manufactured as fixed bandgap InGaN/GaN multi-quantum well (MQW) structures[3]. In order to shift the emission spectrum to longer wavelengths, the indium (In) content of the active InGaN region should be increased[4]. The Indium content of UV-A LEDs (365 nm – 405 nm) is minimal compared to blue and green GaN based LEDs. Higher indium content in the active layers can lead to more point defect formation due to lower growth temperatures and could also lead to quantum-confined Stark Effect (QCSE). The QCSE can reduce the radiative recombination rate due to electron-hole wave function overlap reduction. Since the efficiency of the LED is dependent on the InGaN layer thickness, in commercial products, it's usually kept at a constant optimum value[4]–[6]. The radiant power output of UV LEDs strongly depends on the LED technologies. The external quantum efficiency (EQE) of UV-A LEDs with emission peak wavelengths higher than 365 nm is in par with those of blue LEDs. The EQE of state of the art UV LED products with peak wavelengths shorter than 365 nm (which marks the transition from InGaN to AlGaN based LED technologies) is still lower than 10% [7]. In this study, we focus on UV-A LEDs of peak wavelengths between 365 nm to 405 nm.

1.2 Applications of UV-A LEDs

Gallium Nitride (GaN) based light-emitting diodes (LEDs) are being used in a variety of applications ranging from white light LEDs when combined with phosphors, outdoor displays, and other solid-state lighting applications[8]. The developments in UV-A LEDs, a subset of GaN-based LEDs, have enabled novel medical applications, germicidal inactivation applications, industrial curing processes, and new manufacturing techniques such as maskless lithography and additive manufacturing.

Some of the claimed advantages of UV-A LEDs compared to conventional UV sources are their lower power consumption, lower heat emission, smaller and compact geometries, higher useful life, and instant turn on/off/dimming capabilities. Also, these UV-A LEDs have narrower emission spectrums compared to conventional UV emitting mercury lamps[2]. This enables providing UV radiation of targeted wavelength ranges to applications without emitting radiation in other unwanted wavelengths.

Industrial curing applications utilize UV-A photons to activate photoinitiators (PI) in inks, coatings and adhesives that initiates curing. The initiation rate is a function of the absorbance of the PI, the quantum yield of initiating species formation, and the light intensity [9]. Photoinitiators typically absorb across a range of wavelengths, not a single narrow band. However, UV formulations developed for UV-LED curing are now being tailored to absorb in 360 – 400 nm UV-A emission band. Also, the level of radiation penetration depends on peak wavelength. As a result, the spectrum of the UV-A LED sources used for UV curing should be consistent and fall between this wavelength band regardless of the drive current or operating temperature for effective curing. In addition, the peak irradiance and the radiation dose (multiple of irradiance and dwell time) is important for the speed of curing [2], [9].

The possibility of UV-A being used as a supplement to standard cleaning is being investigated by the researchers. Livingston et al. showed UV-A radiation was effective in reducing MRSA, E. coli, and bacteriophage MS2 at an intensity level ($3W/m^2$) proposed for use in patient rooms [10]. Another study showed that UV-A radiation at 366 nm reduces burden of hospital acquired infections at doses (maximum dosage, 10 W/m^2 for 8 hours) set to minimize negative health effects for occupants [11]. For such applications, UV-A intensity and exposure time should be controlled for effective disinfection dosage.

1.3 Study Objectives

Previous studies on visible spectrum emitters and UV LEDs have suggested that current density and temperature at the junction can affect the spectral characteristics of the GaN-based LEDs. The blue peak wavelength shift for green LEDs with increasing current is explained by the band filling effect of localized energy states due to Indium composition changes in the active well layer[12]. Also, as described in the previous section, to be successfully utilized in curing applications, within operating current and temperature ranges, the UV-A emission spectrum of LEDs should not shift away from the UV-A range for which curing photoinitiators are tailored for.

However, the authors were unable to find any studies that have characterized the current and temperature dependence of near-UV LEDs in their full-rated operating current and temperature ranges. As UV LEDs become popular in applications, such characterization would be important for understanding changes in emission spectrum and radiation efficiency as functions of input current and practical operating temperature. During this study, the authors characterized UV LEDs under more practically used current levels and mimic operating temperatures that real lighting applications may go through to determine the behavior of maximum emission peak wavelength. Whereas previous studies were conducted under the 100 mA range to understand the mechanisms of GaN LEDs[5], [6].

The objectives of this study are to characterize initial performance of UV-A LEDs across their full range of drive currents and operating temperatures and assess their suitability in applications. UV-A LEDs of four different nominal wavelengths: 365 nm, 385 nm, 395 nm, and 405 nm were selected to study the current and temperature dependence on the radiant flux and peak wavelength shift.

2. Experimental Details

The experiment was performed with commercially available UV LEDs, with nominal peak wavelengths of 365 nm, 385 nm, 395 nm, and 405 nm. During the fall of 2019, the LED samples were procured and three samples from each wavelength group were used for characterization. Each sample had a nominal operating current of 500 mA and the maximum rated current of 1500 mA. The rated operating junction temperature range was given as 25°C - 85°C.

Prior to the electrical, spectral, and power measurements, separate J-type thermocouples were attached to the LED boards using thermal epoxy to measure board temperatures during the experiment. An integrating sphere setup with a thermoelectric cooler was used for characterizing the LEDs at constant temperatures. The power supply to the LEDs was controlled and measured with a YOKOGAWA GS610 source measure unit, and spectral distributions were obtained using a Sensing SL300 Spectroradiometer. Temperature measurements recorded throughout the experiment correspond to the board temperatures of LEDs. Board temperature was measures by J-type thermocouples attached to the locations specified by board manufacturers. Measured LED board temperature can be linearly related to the junction temperature of the LED, assuming thermal resistance between junction and temperature measurement location on the board to be constant for all operating current and temperature conditions. Estimation of junction temperature (T_j) can be obtained by the Eq.1 where $R_{\theta\ J-B}$is thermal resistance between junction and board and T_b is the measured board temperature.

$$T_j = T_b + R_{\theta\ J-B} \times (P_{electrical} - P_{optical}) \quad (1)$$

The first phase of the study was done under constant temperature with different input currents to determine the input current dependence of radiant flux and peak wavelength shift. The LED board temperature was controlled by the thermoelectric cooler at 25°C, while changing the drive current from

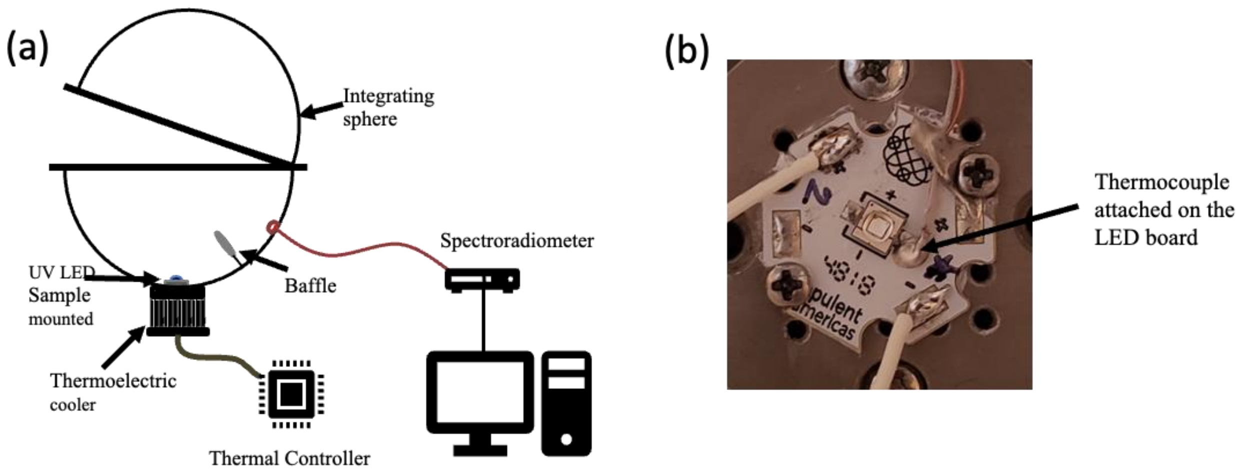

Figure 1. (a) Experimental setup used in the study, (b) Attachment of thermocouple on the LED board

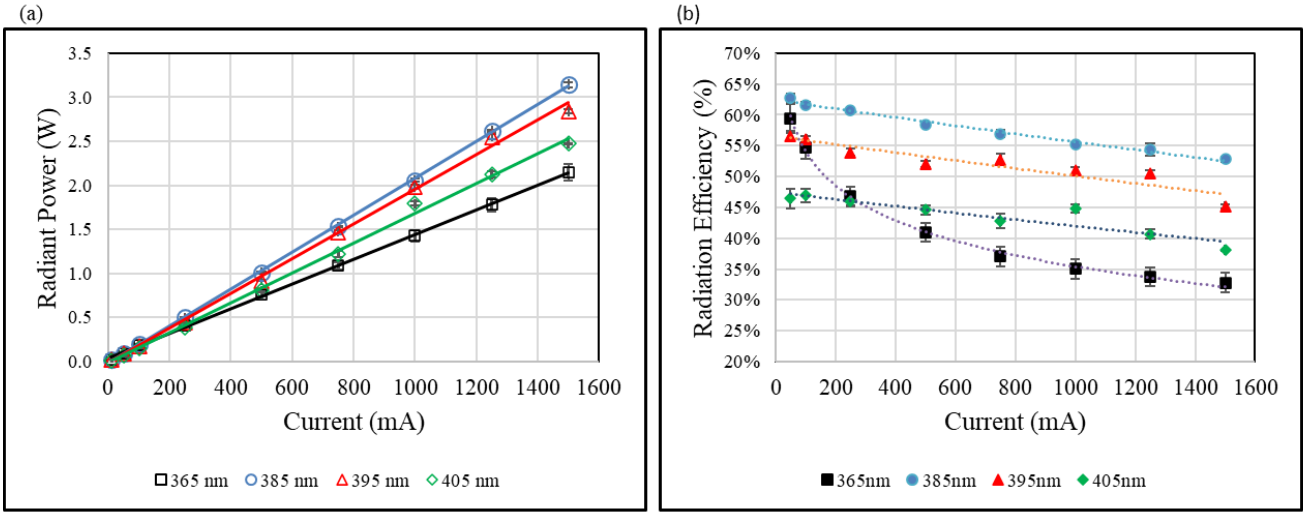

Figure 2. Under constant board temperature of 25ºC, (a) radiant flux Vs. drive current, and (b) radiation efficiency Vs. drive current

10 mA to the rated maximum of 1500 mA in this phase. Next, same current levels were used to drive LEDs under 85°C board temperature on 385 nm and 395 nm UV LEDs for comparison purposes.

In the second phase, to characterize the LED performance under constant current with different operating temperatures, board temperature was changed in the range from 25°C to 85°C while controlling drive current at 500 mA. During all the conditions, electrical parameters, spectral measurements, radiant power, and temperatures were measured and recorded.

3. Results and Discussion

3.1 Radiant flux as a function of input current

To understand the relationship between drive current and radiant flux, the LED forward current was changed from 10 mA to 1500 mA, while maintaining the LED board temperature constant at 25°C. As the board temperature tends to increase with higher currents, a Peltier cooler with a temperature controller was used to maintain the board temperature constant.

As shown in Figure 2, it was observed that compared to 365 nm samples, 385 nm produces 30% more radiant power at rated current. Also, radiation efficiency drop at higher currents is more prominent in shorter wavelength 365 nm samples compared to other UV-A samples tested. For example, the average radiation efficiency change for 385 nm samples when driven at 50 mA and 1500 mA was 63% and 53%. In comparison, the radiation efficiency of 365 nm samples changed from 59% to 33% when driven at 50 mA and 1500 mA respectively. In longer wavelength near-UV LEDs, due to the higher indium content in InGaN active layers, more localized energy states are available. Higher radiation efficiency in longer wavelength UV-A LEDs compared to 365 nm samples may be due to carriers filling into more localized energy states enabling more radiative recombinations [5], [13].

3.2 Peak Wavelength shift with input current

Figure 3. represents the measured peak wavelength of samples under constant 25°C LED board temperature throughout the full range of drive currents. 365nm, 395 nm and 405 nm graphs demonstrate a statistically significant (with 95% confidence interval) downward shift in peak wavelength through the current range. The maximum shifts in emission peak among the samples are between 0.4 nm to 6.7 nm.

The downward trend in peak wavelength shift with the increasing current can be explained by band filling effects. This might have been caused by the availability of localized energy states due to indium composition fluctuations in the active layer. These results confirm the behavior of the experiment conducted by Mukai et al. on 375 nm and 380 nm LEDs[12], where they have compared wavelength shifts with drive current while keeping the ambient temperature constant.

With the observation of 395 nm and 405 nm LEDs having the same trend of peak wavelength shift with increasing current compared to the 385 nm LEDs, a follow-up experiment was conducted at an elevated constant board temperature of 85°C. Figure 4 represents the emission peak wavelength of 385 nm and 395 nm LEDs at 85°C. The peak wavelength shifts at 25°C is also plotted for comparison. Regardless of the higher operating board temperature at 85°C, the peak wavelength shift pattern is similar to a redshift of wavelength due to higher board temperature[14].

3.3 Peak wavelength fluctuation with board temperature

In this section, peak wavelength shift as a function of LED board temperature was investigated. The board temperature was regulated using a Peltier cooler to which the LED starboard was attached while in operation. The drive current of the LED samples was kept constant at 500 mA, and the board

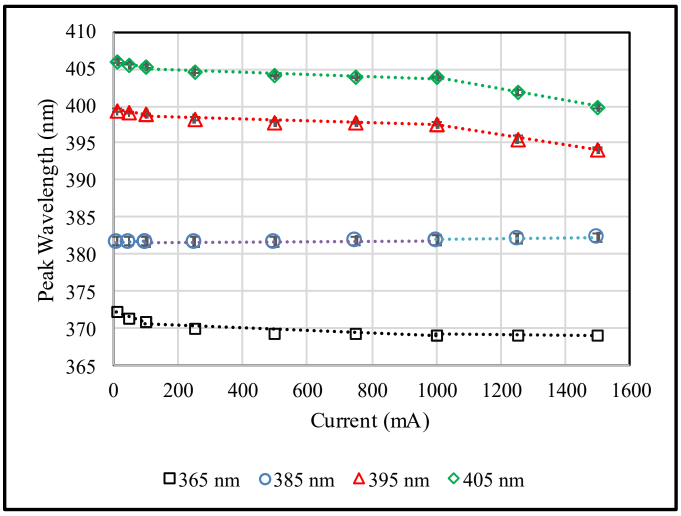

Figure 3. Peak wavelength Vs. drive current under constant board temperature of 25°C

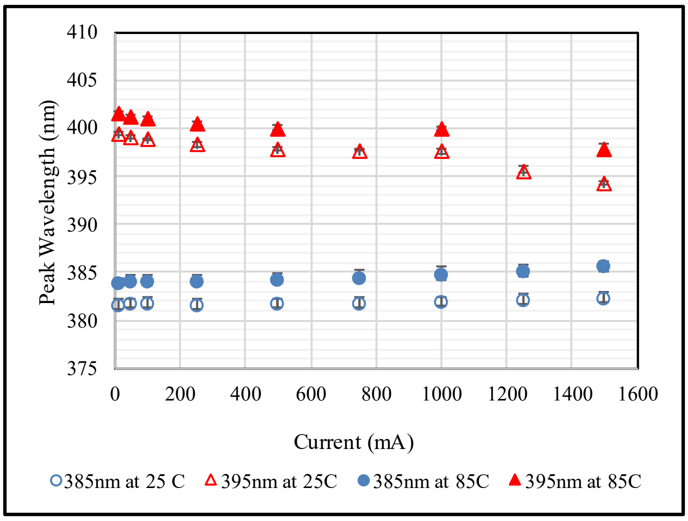

Figure 4. Peak wavelength Vs. drive current under 85°C and 25°C constant board temperatures

temperature was varied from 25°C to 85°C. Figure 3 shows the observed peak wavelengths under four different temperatures . All 365 nm, 385 nm, 395 nm, and 405 nm LED samples demonstrated a statistically significant (with a 95% confidence level) increase in peak wavelength with increasing temperature. The maximum shift in emission peak due to temperature effects is less than 2 nm for each sample.

These observations can be explained by the quantum well structure of the UV LEDs. The bandgap energy of a semiconductor layer in an LED largely determines the emission wavelengths. Higher the bandgap energy, the shorter the peak emission wavelength, and vice versa. When the temperature increases, carriers in these localized energy states move to higher energy states[5], [12]. Therefore, under constant current of 500 mA, when the temperature is increased, bandgap energy of the semiconductor materials becomes lower. This results in emission peak wavelengths become longer (redshift) at higher temperatures[12].

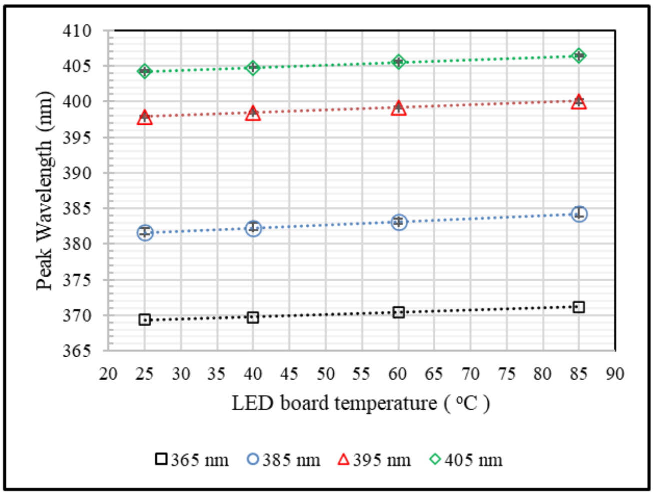

Figure 5. Peak wavelength Vs. board temperature when driven at 500 mA

4. Conclusions

UV-A LEDs (365 nm-405 nm) have very similar chip structures to InGaN Blue LEDs [2]. Technical improvements on blue LEDs have enabled UV-A LEDs to achieve high radiation efficiencies (up to 70%) and high current densities that enables applications such as UV curing, 3D printing.

By considering the four sets of near-UV LEDs tested, it was observed that emission spectrum characteristics (such as peak wavelength shift) are less affected by variations in current density and operating temperature. Applications such as UV curing, and germicidal inactivation are unaffected by these minimal spectral changes since they accept wider action spectrums.

In in longer wavelength UV LEDs, due to the higher indium content in InGaN active layers, more localized energy states are available[5]. This enables higher optical conversion efficiency for longer wavelength InGaN LEDs due to carriers filling into localized energy states enabling more radiative recombinations[13]. Therefore, for shorter wavelength near-UV LEDs (with lower indium content in the active layer), even though the peak wavelength shift would be minimum, the light conversion efficiency would be lower than longer wavelength emitters. Radiant efficiency drop of shorter wavelength UV-LEDs (365 nm) at higher current densities is higher (32% drop) compared to other samples (less than 8% drop). Safe disinfection systems for occupied spaces (such as healthcare facilities) require maintaining UV irradiation (3-10 W/m2) for continuously on applications. Since this involves irradiating large spaces for extended periods of times, emphasis should be paid on energy efficiency. Driving a higher number of UV-A LEDs at low current densities will maintain a higher radiant efficiency (similar approach to mid-power white LEDs).

In practical applications, the junction temperature of the LEDs may rise when driven at higher currents depending on the ambient temperature and heat transfer mechanism. Operating LEDs at higher temperatures will shorten the system's lifetime due to faster lumen depreciation at higher operating temperatures[16]. Therefore, when selecting a UV LED for a white light application, all these factors should be considered to maximize its performance in terms of efficiency and ensure a longer lifetime of the system.

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