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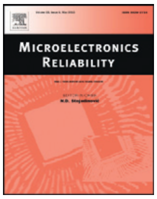

Pump chip and phosphor reliability of broadband light-emitting diodes

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ABSTRACT

We present a study of the degradation of phosphor-based broadband (~90 nm spectral peak width) colour and white LEDs. Specifically, our study looked at the reliability of the blue-emitting GaN/InGaN pump chip and the overlying phosphor in these LEDs. We have investigated thermal degradation arising from heat generation in both the pump chip and the colour-converting phosphor. The robustness of the pump chip in 1 W broadband power LEDs was examined by driving them with various dc and pulsed waveforms at different temperatures. Both catastrophic and long term degradation of pump chips was investigated. Long term degradation behaviour of phosphors was studied by both ex situ and in situ heating of phosphors for hundreds of hours while their total light output was monitored. Optical energy storage in phosphors and its bearing on phosphor degradation is also discussed.

1. Introduction

Solid-state lighting driven by phosphor-converted LEDs has been making great strides in recent years. On the one hand new application areas are opening up new markets for LEDs while on the other hand novel materials and device structures continue to energise LED offerings [1,2]. From bright, high-power LEDs to devices generating high quality illumination, many different types of LEDs are now commercially available. Due to the higher initial cost of LED-based luminaires, compared to, fundamentally different, incandescent and fluorescent lamps, it is very important to ensure long enough lifetimes for LEDs so that they pay for themselves over their lifetime. Thus LED reliability assumes great importance and there have been numerous studies looking at various aspects of their performance, ageing effects and degradation [3,4]. While most present-day commercial LEDs are narrowband devices with spectral output concentrated within a few narrow bands of wavelengths [5,6], broadband phosphor-based LEDs with wide spectral distributions are now also becoming available. These devices use ordinary blue or UV pump LED chips with special phosphors and phosphor blends to produce wider spectral outputs [7]. Their light is suitable for use in high quality, high colour rendering index (CRI) red, green, blue (RGB) and white illumination systems [8,9]. In this paper, certain reliability issues related to broadband LEDs are reported. This study is limited to the two core components of phosphor-converted broadband LEDs i.e. the pump chip and the wavelength conversion phosphor. Other package components, such as the lead frame and the mounting slug pose little, if any, reliability concerns. Thus it is logical to concentrate on those elements that are more prone to degradation. The know-how we gained through this work and described in this paper can be a very valuable guide for engineers designing LED-based lighting systems, especially those using broadband LEDs.

There are three distinct components of any phosphor-converted LED. These are the pump LED chip (including its bond wires), the phosphor (including its binder component) and the packaging material which includes everything else (lead frame, housing, heat sink, thermal interface material and lens material). In this paper we look at certain endurance and reliability issues associated with the first two components i.e. the pump LED chip and the phosphor. Specifically, we study these in the context of broadband colour and white light-emitting devices. Broadband colour LEDs produce light, through phosphor-based down-conversion, that appears to human eyes as having a single colour but has a wide spectral width of 60 to 9 m nm. Broadband white LEDs are simply full-spectrum LEDs that, again through phosphor-based down-conversion, produce light that more-or-less fills the entire visible band (400 to 700 nm) with no pronounced dips in spectral coverage within this range. The behaviour of LED packaging materials, as far as LED reliability is concerned, has been described in several publications [10–13]. That aspect, not discussed here, is also independent of the type of LED i.e. phosphor-based or phosphor-less and narrowband or broadband light-emitting device.

The pump chip and the phosphor constitute the principal optical parts of all phosphor-based LEDs. These two constituents control much of the optical characteristics of such LEDs and thus their operational behaviour, limits of operation and long term ageing trends are crucial to understanding the longevity of phosphor-converted LEDs [14]. High reliability pump chip and robust phosphors go a long way towards ensuring long life for LEDs whereas any pronounced degradation tendency in either or both of them can severely limit the device's performance envelop and shorten its useful lifetime. This is especially

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important at present because high power and high brightness full-spectrum broadband LEDs are now increasingly being used as replacements for traditional incandescent lamps. In order to understand the performance and longevity limits of broadband phosphor converted LEDs we investigated both colour and white LEDs for the robustness of their pump chip and wavelength-converting phosphor material. We constructed our 1 W-rated power LEDs following standard industrial techniques using only reduction of hazardous substances (ROHS) certified materials. Commercial, blue-emitting GaN/InGaN LED chips with 5 quantum wells were used as pump chips whereas commercially available phosphors and binder materials were used as the luminescent component of the LEDs.

2. Materials used

The pump LED chips used in this work were blue-emitting GaN/InGaN LED dies manufactured by Bridgelux Corporation and rated for a maximum forward current of 350 mA. These chips were 2 mm × 2 mm in size – considerably larger than the 0.5 mm × 0.5 mm chips that are used in low power LEDs. These larger chips, rated at 1 W maximum power dissipation, have an emitting area which is 16 times larger than the area of smaller chips that are rated for 125 mW maximum power dissipation. Each chip contained five pairs of GaN/InGaN quantum wells and had the usual III-nitride LED structure with a bottom *Si*-doped n-type GaN layer and a top Mg-doped *p*-type GaN layer sandwiching the active multiple quantum well (MQW) region (GaN: barriers, InGaN: wells) from where light was emitted. These chips also contained a few nanometres thick p-doped AlGaN electron blocking layer between the MQW region and the top p-GaN layer. Gold-topped anode and cathode contact pads formed an integral part of these devices. GaN/InGaN LEDs have excellent characteristics in general [15] and have been used as pump sources for phosphor-converted LEDs since the emergence of these devices in the early 1990s.

We used three rare-earth-doped phosphors in this work to produce broadband LEDs. These included a red phosphor, a green phosphor and a yellow phosphor (for making white-emitting LEDs). The properties of these phosphors are listed in Table 1. The phosphors were obtained from Phosphor Technology Ltd. in England. Phosphors were mixed with a UV-curable polycarbonate resin at a loading of 20% (w/w) and the resulting slurry was applied onto pump chips already mounted and bonded inside their packages. Phosphor + polycarbonate binder slurry was dispensed onto chips with controlled metering, using a GPD-global automatic fluid dispenser. The assembly was allowed to cure for a few hours before a polycarbonate lens was moulded onto the assembly.

A commercial lead frame and plastic package was used for making LEDs. This type of power LED package is commonly used for producing LEDs rated for 1 W to 3 W power dissipation. Further details of this package and its thermal characteristics can be obtained from the published work of Jau-Sheng Wang and colleagues [16].

3. Pump chip endurance

The maximum current, power and output optical intensity of phosphor-converted LEDs are mainly determined by the operational characteristics of the blue or ultraviolet (UV) LED chip that excites the down-conversion phosphor. We tested the operational endurance of the pump LED chips by current stressing them. A series of different forward currents were established in the chips at different temperatures and the currents that resulted in chip failure were determined. Plots of the data that were thus obtained are shown in Fig. 1 here. The ambient temperature and humidity level at the test site was 24 °C and 62% relative humidity, respectively. The different temperatures were obtained with the use of a Peltier module. The LEDs were directly mounted on the cold surface of a Peltier module with no thermal interface material between the backside of the LED and the surface of the Peltier module's cold plate. This was done because the undersides of the LEDs are highly polished and so is the top surface of the Peltier cooler. In this case use of a thermal interface material can hamper rather than improve heat transfer from the LED to the Peltier cooler. Adhesive thermally conducting tape was used around the LED to keep it positioned and in good contact with the cold plate at all times. This arrangement ensured the lowest thermal resistance from the LED package to the Peltier cooler module. Fig. 1 shows the failure currents for continuous wave (CW) operation of the blue LED pump chip as a function of device temperature. Also shown are the failure currents if the LEDs were operated for only 3 s at a time and then turned off to allow the device to cool down completely. This type of low duty cycle pulsing ensured that no excessive heat built up within the LED package, allowing for operation at higher current levels. For CW operation at room temperature, without the use of any heat sink, a maximum continuous current of 250 mA could be sustained by the device. The data-sheet rated maximum current of 350 mA could only be sustained at room temperature with a good heat sink connected to the rear metal slug of the package. This current dropped to only 150 mA when the packaged temperature was raised to 40 °C. On the other hand, with active cooling to −5 °C, the device was able to sustain up to 800 mA of continuous current without thermal failure. If the LED was driven intermittently for only 3 s at a time and allowed to cool for typically 10 s in between the 3 s long current pulses then it was able to sustain up to 2.5 A at −5 °C, 600 mA at room temperature (25 °C) and 350 mA at 40 °C. This method of operation gives much higher brightness than operation at lower currents but the brightness can only be sustained for a few seconds before the LED requires a cooling off period. The light output versus drive current relation is usually linear in the low and medium drive current regimes so that the optical output power increases in proportion to the drive current. At higher currents, the light output does not increase proportionately due to the 'droop' effect. This clearly showed that very large current pulses at low duty cycles can be used with typical commercial LED pump chips without catastrophic failure. This feature allows LEDs to operate as camera flash devices where large currents are discharged from a capacitor through a phosphor-converted white LED for only a brief period of time (typically a few milliseconds).

Examination of failed LEDs showed that the failure was caused by excessive heat generation at one of the two contact pads or associated bond wires. This conclusion was reached both through post-failure visual inspections of LEDs and by monitoring of LEDs, without phosphor coating, during operation using a thermal imaging infrared camera system. Evidently, the devices failed at currents at which so much heat was generated that it could not be effectively dissipated to the metal base on which the LED chip was mounted. This caused excess heat to

Table 1
Properties of phosphors used in this work. All three of them consisted of powders containing crystalline particles of average size around 2 μm across.

Phosphor colour	Phosphor composition	Phosphor density (g/ml)	Peak wavelength (nm)	Spectral width (nm)	CIE coordinates
Red	CaS:Eu	2.5	650	80	$x = 0.70$ $y = 0.30$
Green	$Lu_3Al_5O_{12}$: Ce	3.9	515	90	$x = 0.31$ $y = 0.58$
Yellow	$(Y,Gd)_3Al_5O_{12}$: Ce	4.4	570	120	$x = 0.48$ $y = 0.51$