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Novel Stacked Polychromatic Light-emitting Diodes

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1. Introduction

So far, there are numerous spectral conversion schemes commonly adopted for white light emission, such as phosphors, polymer dyes, CdSe/CdS quantum dot and the recently demonstrated usage of fluorescent microspheres by our group for color down-conversion. These schemes, however, suffer inevitably from energy loss due to Stokes shift in the down-conversion processes [1], and scattering losses associated with the particles. Alternative conversion-loss-free approach involves the combination of three or more discrete LED chips of the primary colors red (R), green (G), blue (B) arranged side-by-side on the same plane to generate white light. However, such approach cannot solve the inherent challenges of uniform color mixing, such as color inhomogeneity and colored edge effects in the beam. Also, the overall dimensions are not well optimized due to the sources are far apart. Therefore, lateral RGB mixing method limits its usefulness in high-definition LED display applications.

In this paper, we propose alternative solution to these problems. We demonstrate first use of angled sidewalls LED (AS-LED) produced by laser micro-machining, details will be reported elsewhere [2], to fabricate mirror-coated vertically-stacked LEDs. Our approach involves the use of a focused UV laser beam, tilted at an oblique angle, to produced chips with angled sidewalls. The stack consists of an InGaN/GaN blue LED (440 nm) stacked onto an InGaN/GaN green LED (550 nm), which is subsequently stacked onto an AlGaInP/GaAs red LED (650 nm). Thus multi-quantum-wells (MQWs) in the upper devices are transparent to the lower devices due to their bandgaps (larger bandgap energy materials on top, which will allow longer wavelength photons to penetrate). Therefore, such a stacking strategy ensures optimal color mixing and minimal absorption losses.

2. Experimental Details

In this work, the proposed stacked LEDs are assembled with red AlGaInP/GaAs LED and green/ blue InGaN/GaN based LEDs, all in angled sidewall structures. Note that the emission peak wavelengths of the red, green and blue LEDs are intentionally chosen as 650 nm, 550 nm, and 440 nm, respectively. There are two reasons for that. Firstly, 550 nm deep green LED gives the highest luminous efficacy according to the human eye sensitivity function at (555 nm). Secondly, with regard to luminous efficacy of a white light source, it is shown that the highest possible efficacy is the one contains two monochromatic emission peaks at ~ 448 nm and 569 nm [3]. The 550 nm deep green LED wafer is from LumeiOpto Company. The devices are fabricated using standard photolithography, dry etching and electron beam metal evaporation. Devices, with emission area of 500 x 500 μm^2, were fabricated using standard procedures [4], employing a Ni/ Au (5 nm/ 5 nm) current spreading layer, Ni/ Au (20 nm/200 nm) as p-pads and Ti/Al (20 nm/200 nm) as n-pads. The completed wafers were thinned down to about 150 μm in successive steps by mechanical polishing, leaving a smooth finish to the sapphire face. The red LED was fabricated from an MOCVD-grown AlInGaP wafer on GaAs substrate, with Zn/Au (25 nm/200 nm) top p-pads and AuGe/Ni/Au (50 nm/40 nm/200 nm) n-pads on the backside of the wafer. The chips were diced by laser micromachining with a diode-pumped solid-state (DPSS) ultraviolet (UV) laser at 349 nm. Figure 1 shows the optical micrograph image of mirro-coated angled sidewall LED, and SEM image of stacked LEDs.

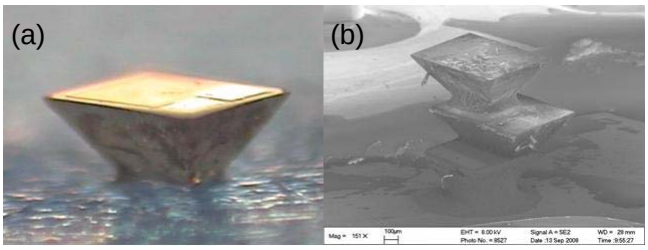

Fig. 1 Optical micrograph of (a) mirror-coated angled sidewall LED, (b) SEM image of vertically-stacked LEDs.

3. Results and Discussion

Assembly of the stack begins with attaching a red LED die to a TO-can using electrically-conductive adhesive. A small volume of UV-curing optical adhesive (Norland 63) was dispensed onto the surface of the red LED chip, just enough to cover the emissive region, before the blue LED chip is mounted on top using a manual die bonder. The bonding pads must not be covered by the epoxy. The green LED chip was mounted on its top in the same manner. Once the chips are aligned in place, the stack was exposed to UV light under a Deuterium lamp. The adhesive

hardens and the stack is fixed in place. Finally, the pads were wire-bonded to the package.

To characterize the device, bias voltages of 3.64 V, 2.60 V and 2.52 V were applied to the red, green and blue LEDs respectively. The optical characteristics of this device is compared with a commercially-available RGB device [5], containing similar red, green and blue LED chips with center wavelengths of 652 nm, 526 nm and 468 nm respectively. For a fair and objective comparison, both the stacked LED and the RGB LED are biased to emit with identical CIE coordinates of (0.31, 0.31) at a total current of 20 mA. Due to slight dissimilarities of the component chips, the bias voltages are slightly different. Optical micrographs of both devices operated under such conditions are shown in Figure 2. It is immediately apparent that color homogeneity is significantly improved, with single spot color-mixed emission, in stark contrast to the three spots of spatially-separated light from the RGB device. The superior light mixing properties are mainly attributed to two factors: firstly, alignment of emission profiles from the individual chips into a single path and secondly, preventing lateral emission from sidewalls, so that the stack behaves as a single point source.

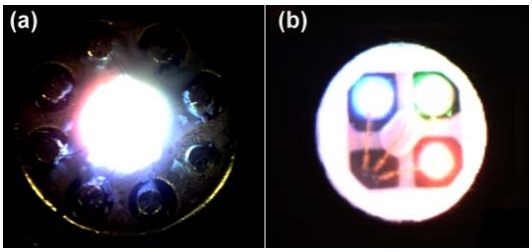

Fig. 2 Optical micrograph captured from top view of (a) a stacked LED and (b) a conventional RGB LED.

As with conventional RGB devices, it is possible to tune the color of emission through control of the individual bias voltages. With the stacked-chip design, it functions even better, with color homogeneity at any viewing distance. To test the color-tuning function, individual chips of the stacked device are biased at various conditions by adjusting the relative intensity of the three emission bands. The combinations of applied bias voltages for generating various colors are summarized in Table 1, where Figures 3(a) to (d) show the electroluminescence (EL) spectral data and optical emission images of the stacked LEDs device driven at these voltage combinations. A wide range of colors can be obtained; the range of which depends on the choice of LEDs (wavelengths and spectral bandwidth) used for the stack, making it suitable for assembly high-resolution large LED panel displays.

Apart from being a color-tunable light source, it is a highly efficient conversion-loss-free white light source, as it initially was designed for. Thus, the performance of the LED stack as a white light LED is evaluated. The packaged device was measured in a calibrated 12-inch integrating sphere, whereby the optical signal was channeled by fiber to an optical spectrometer. At a total driving current of 20 mA, the stacked LED produced a luminous efficacy of 30 lm/W at the corresponding CIE coordinate, CRI and CCT values of (0.32, 0.33), 69, and 6300 K respectively, which is a promising result for a prototype device.

Table I biased voltages for optical spectra (a) to (d) in Fig. 3.

Curve	Red LED	Green LED	Blue LED	CIE (x, y)
a		2.57 V	2.73 V	(0.18, 0.32)
b	2.60 V		2.55 V	(0.21, 0.09)
c	2.97 V	2.58 V		(0.54, 0.45)
d	3.69 V	2.68 V	2.53 V	(0.30, 0.30)

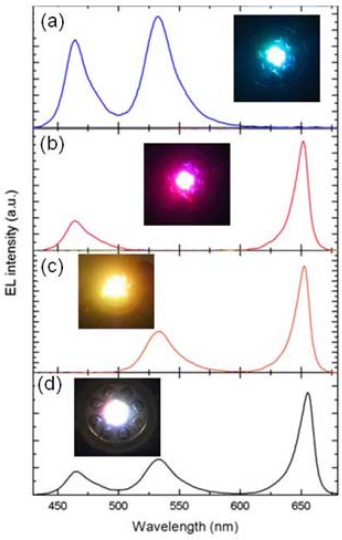

Fig. 3 (a)-(d) Optical spectra of various colors emitted by stacked LED. Insets show EL images of the corresponding spectrum.

Conclusions

In summary, we introduced a fabrication method of angled sidewall by laser micro-machining. Color-tunable LEDs have been demonstrated by stacking LEDs in the vertical arrangement, offering significant color mixing and minimal absorption losses. This prototype LED gives a luminous efficacy of 30 lm/watt.

References

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