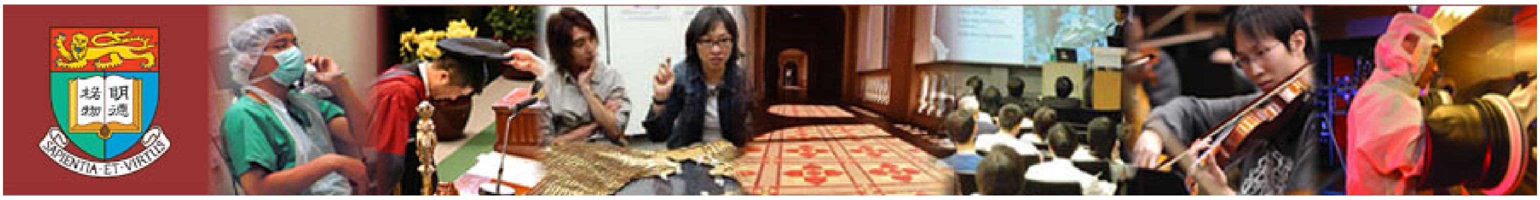

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Citation	**Optics Express, 2009, v. 17 n. 12, p. 9873-9878**
Issued Date	**2009**
URL	**http://hdl.handle.net/10722/58780**
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Design of vertically-stacked polychromatic light-emitting diodes

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Abstract: A new design for a polychromatic light-emitting diode (LED) is proposed and demonstrated. LED chips of the primary colors are physically stacked on top of each other. Light emitted from each layer of the stack passes through each other, and thus is mixed naturally without additional optics. As a color-tunable device, a wide range of colors can be generated, making it suitable for display purposes. As a phosphor-free white light LED, luminous efficacy of 30 lm/watt was achieved.

OCIS codes: (220.0220) Optical design and fabrication; (230.2670) Light-emitting diodes

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1. Introduction

Color down-conversion and color-mixing are the two mainstream methods of producing white light from light-emitting diodes (LEDs) [1]. Using phosphors as a conversion agent is widely adopted in commercial products. Nevertheless, the limited conversion efficiency from shorter wavelengths (typically blue at around 470 nm) to longer wavelengths means the benefits of LEDs can never be fully reaped. Placing three LEDs of red, green and blue into a single package (the RGB approach) resolves this deficiency, but introduces severe issues with color uniformity and homogeneity. From the perspective of energy efficiency, the RGB approach appears to be more attractive; thus a solution to improve color mixing can bring about a much superior white light device, and possibly offer a faster route towards widespread adaptation of LEDs for general lighting.

In this paper we report on the design and development of optically-mixed RGB devices for the generation of polychromatic light, particularly white. The use of Fresnel lenses for this purpose has previously been reported [2]; results are not entirely satisfactory due to the exceedingly low efficiency of diffractive optics. Our proposed approach is based on

#110478 - $15.00 USD Received 23 Apr 2009; revised 9 May 2009; accepted 16 May 2009; published 27 May 2009

optimizing the optical pathways of the emission profiles. Optical mixing requires that the radiation patterns from the discrete LEDs overlap with each other. Instead of attempting to mix the beams using external optics, the RGB devices are physically placed such that their optical paths are aligned. In this way, the emissions from the three LEDs are *naturally* mixed without the need for additional optics.

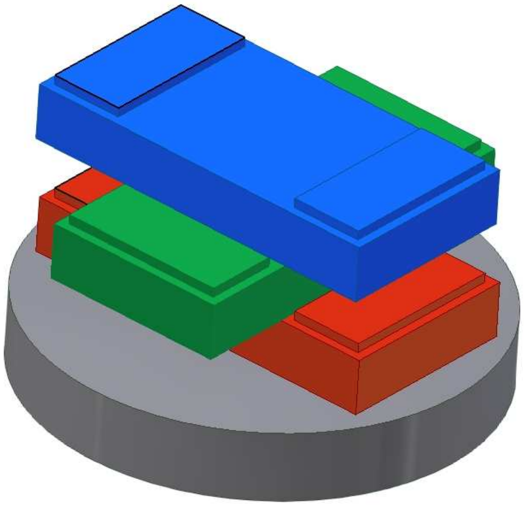

Fig. 1. Schematic diagram illustrating the idea of LED chip stacking.

Implementation of this idea can be realized by stacking the RGB chips on top of each other, in a stacking topography. This is possible by virtue of the fact that GaN LED chips are grown on transparent sapphire substrates; light can transmit through the chip without absorption or significant attenuation. The AlInGaP red LED, with a non-transparent (to visible light) GaAs substrate, must be placed at the bottom of the stack (which happens to be the required sequence as explained shortly). An InGaN green LED is placed on top of the red LED, and a blue InGaN LED is subsequently placed at the top of the stack. Such a stacking strategy *ensures* optimal color mixing. Adopting this stacking sequence also ensures that light emitted from lower devices (with narrower bandap) will transmit through upper devices (with wider bandgaps). The sapphire substrates of the InGaN LEDs are also transparent to visible light. A schematic diagram of the proposed device is illustrated in Fig. 1. The three devices are either connected in parallel or are individually controllable electrically. With the parallel connection method, the cathodes and anodes are interconnected, with the insertion of appropriate resistors for adjusting the required bias voltages of each device (depending on the required proportions of red, green and blue spectral components). Such a two-terminal device acts as an all-semiconductor white light LED.

Another implementation gives user-access to the individual cathodes, while interconnecting their anodes, resulting in a four-terminal device. When all three devices are illuminated, the optically-mixed output results in polychromatic light with three spectral peaks, or white light with the right proportions of red, green and blue. Varying the proportions of the primary colors also offer white light of different color temperatures. On the other hand, monochromatic light can be obtained by turning on a single device only. Other colors can be tuned by lighting up two or three devices simultaneously and adjusting appropriate bias voltages. This proposed stacked design involves no color conversion in generating polychromatic light and is thus conversion-loss-free.

2. Experimental Details

The blue and green LED chips are fabricated from metal-organic chemical-vapor-deposition (MOCVD) grown wafers on c-plane substrates with InGaN/GaN multi-quantum-wells

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(MQWs) with center wavelengths of 440 nm and 550 nm respectively. Deep green LEDs at 550 nm are used as this is the wavelength at which the human eye is most sensitive, thus boosting the luminous efficacy of the device. Details of the growth of this deep green structure with high In mole fraction will be described elsewhere. Devices, with emission area of 500 x 500 μm^2, were fabricated using standard procedures [3], 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 640 nm 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. A dielectric distributed Bragg reflector (DBR) was integrated beneath the MQWs to prevent absorption of emitted light by the GaAs substrate. The chips were diced by laser micromachining with a diode-pumped solid-state (DPSS) ultraviolet (UV) laser at 349 nm.

3. Results and Discussion

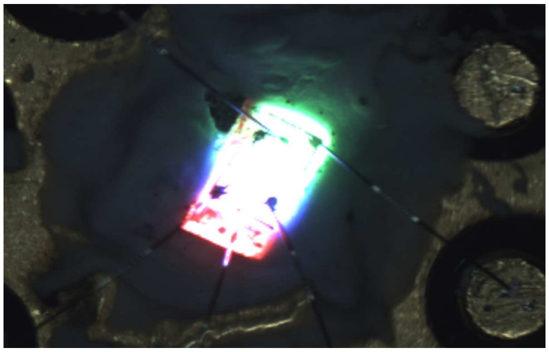

Fig. 2. The first version of an LED stack; sidewall emissions contribute to inhomogeneous color-mixing.

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 green LED chip was mounted on top using a manual die bonder. The bonding pads must not be covered by the epoxy. The blue LED chip was mounted on its top in the same manner. Once the chips were aligned in place, the stack was exposed to UV light under a Deuterium lamp. The adhesive hardens and the stack was fixed in place. Finally, the pads were wire-bonded to the package. To test 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. While the LEDs light up as expected, the optical output was not as homogenous as expected, as shown in Fig. 2. As observed, the contribution of light emission from the sidewalls of the chips was neglected in the design.

A simple solution to this problem was to block sidewall emission; however this would significantly reduce light extraction, defeating the motivation of our stack design (of maximizing efficiency). A solution was needed to channel laterally-propagating light into the vertical direction for emission through the top window; this can be provided for by an LED of inverted pyramid geometry, with mirror coating on its inclined sidewalls. In the paper by M.R. Krames et al, AlInGaP devices of such geometry were prepared by beveled dicing technique [4]. This would be difficult for GaN chips with hard sapphire substrates. Instead, a single-step laser-micromachining approach was adopted for the formation of the angled facets. In traditional laser-micromachining, a focused beam was directed to the wafer orthogonally. Using a modified set-up which involves the insertion of a laser-turning mirror between the focusing objective and the wafer, the beam was re-directed to strike the wafer at an oblique angle. This oblique incident beam was used for the dicing of green and blue GaN LED chips, which shapes the chips into inverted pyramids as it cuts. Details of the laser

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micromachining process can be found in reference [5]. A layer of Ag was selectively coated onto the angled sidewall by electron beam evaporation (by covering the top face with photoresist), serving as a mirror to redirect light into the vertical direction. Devices with inverted pyramidal geometry have been proven to offer as much as 60% enhancement in light output [6].

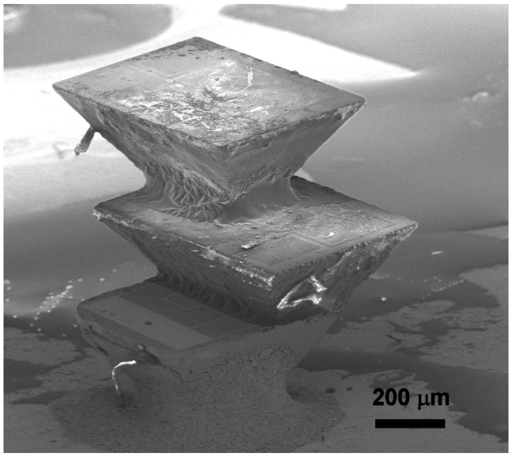

Fig. 3. SEM image showing an LED stack assembled with LED chips of inverted-pyramidal geometry.

Another stack was assembled using these modified chips following an identical procedure. Figure 3 shows a scanning electron microscope (SEM) image of the assembled device, showing the tri-layer topology. The contact pads of each chip are exposed for wire-bonding. The optical characteristics of this device are compared with a commercially-available RGB device, containing similar red, green and blue LED chips with center wavelengths of 652 nm, 526 nm and 468 nm respectively. This time round, the stacked device performs as designed, offering optically-mixed output through its top output aperture. 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 Fig. 4. 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.

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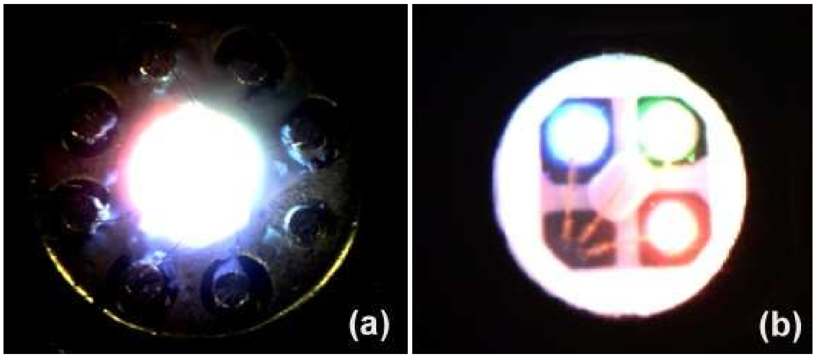

Fig. 4. Optical microphotographs captured from the top of (a) a stacked LED and (b) a conventional RGB LED. Boths LEDs are biased for white light emission, at a total current of 10 mA.

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 Figs. 5(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.

Table 1. Bias voltages (currents) for generating the optical spectrum (a) to (d) in Fig. 5.

Curve	*Red LED*	*Green LED*	*Blue LED*	*CIE (x,y)*
(a)		2.57 V (2 mA)	2.73 V (11 mA)	(0.18, 0.32)
(b)	2.60 V (2 mA)		2.55 V (2 mA)	(0.21, 0.09)
(c)	2.97 V (5 mA)	2.58 V (2 mA)		(0.54, 0.45)
(d)	3.69 V (13 mA)	2.68 V (4 mA)	2.53 V (2 mA)	(0.30, 0.30)

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. In principle, a device based on the RGB approach can offer luminous efficacies exceeding 300 lm/W if the three primary color emission bands are adequately chosen according to theoretical predictions [7]. Obviously, our first attempt in demonstrating a stacked device falls short of this target. While the performance of the individual chips needs to be further improved, several strategies relating to the assembly process have been identified. One of the deficiencies is associated with the laser micromachining process, which introduces surface roughness onto the processed inclined sidewall of chips, and a slight degradation to the electrical characteristics. The imperfect interface between sidewall and the Ag coating reduces the reflectance of Ag mirror. As a result, a lower fraction of light is successfully redirected into the normal direction of the devices. Another issue lies with the thickness and uniformity of the epoxy layer which was used to secure the chips together as a stack, introducing excessive absorption in the lossy epoxy layer. A more precise dispensing and coating technique, such as spin-coating might be adopted for this step.

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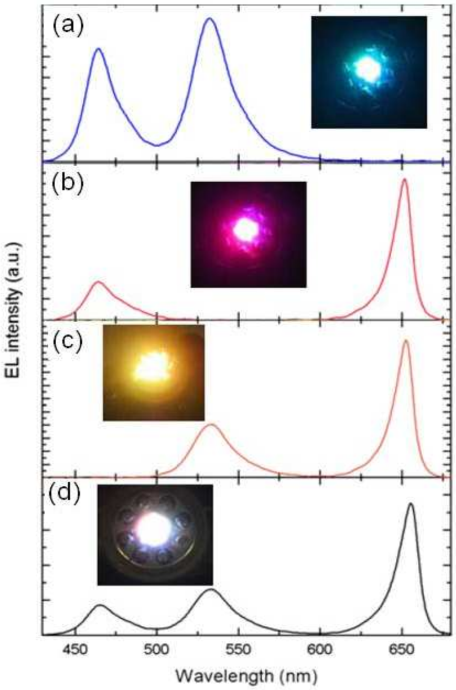

Fig. 5(a)-(d) Optical spectrum of the various colors emitted by the LED stack. Optical microphotographs of the LED are shown in the insets of the corresponding spectrum.

As a final note, this stacking approach bears similarities with the method of monolithically integrating MQWs of different wavelengths into a single wafer. Wafers with blue and green emission bands have been successfully grown [8] [9]. At the same time, polychromatic devices based on quantum dots have also been demonstrated recently [10]. Despite being elegant solutions, these are still at preliminary stages of development. Performances of devices fabricated from such wafers are still sub-standard to the best of our knowledge. Our proposed stacking strategy offers a practical solution available based on today's technology.

4. Conclusion

In summary, polychromatic and color-tunable LEDs have been demonstrated making use of a chip stacking strategy. LED chips of the primary colors are physically adhered on top of each other so that their emission pathways are aligned. On top of this, the chips are shaped as truncated pyramids (with sidewall mirror-coated) to prevent sideway emissions. As such, light from all devices emit through the same top aperture, resulting in optically mixed optical output. Emissions of different colors, including white, can be achieved with this device. As a white light LED, this prototype offers a luminous efficacy of 30 lm/watt.

Acknowledgments

This work was jointly supported by a CERG grant of the Research Grant Council of Hong Kong (project HKU 7121/06E) and the University Development Fund of the University of Hong Kong (Nanotechnology Research Institute, 00600009).

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