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Color-Tunable and Phosphor-Free White-Light Multilayered Light-Emitting Diodes

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Abstract—A tightly integrated 3-D RGB light-emitting diode (LED) stack is demonstrated. Chips of identical dimensions are stacked on top of each other, with wire bonds embedded within. This is achieved by integrating laser-micromachined channels onto the sapphire face of InGaN LEDs, serving to accommodate wire bonds from the chip beneath. The resultant structure eliminates leakage of monochromatic light from individual chips, producing optimally mixed emission through the top aperture. The device can emit a wide range of colors and is an efficient phosphor-free white-light LED as well. When emitting at correlated color temperatures (CCTs) of 2362 K, 5999 K, and 7332 K, the device generates \( \sim 20 \, \text{lm/W} \), exhibiting performance invariant of CCT. Thermal characteristics of this multilayered device are investigated via infrared thermometry.

Index Terms—Color tuning, light-emitting diode (LED).

I. INTRODUCTION

A N INCANDESCENT lamp’s color temperature changes with the temperature of the tungsten element, although the emission remains broadband throughout. Fluorescent lighting emits with fixed spectral characteristics. To generate different colors from such light sources, filters are used to remove the unwanted spectral components, incurring energy losses. Light-emitting diodes (LEDs), on the other hand, produce monochromatic radiation by nature; by mixing the emissions from multiple LEDs, a wide range of colors across the visible spectrum can be obtained. Solutions based on this concept, in the form of RGB LEDs whereby chips emitting the primary colors are bonded onto the same package adjacent to each other, are now available and have been adopted on LED panel displays [1]. The technological progresses of blue-light-emitting InGaN quantum well (QW) and red-light-emitting AlInGaP QW LEDs have resulted in promising device characteristics [2]. However, the strong charge separation in InGaN QWs results in low internal quantum efficiencies at longer wavelengths (high In concentration); fortunately, several methods have been pursued to suppress this effect [3]–[6]. Apart from relying on AlInGaP, several recent approaches have been proposed to achieve red-light-emitting LEDs based on III-nitride technology [7]–[9]. Such developments make RGB emitters more promising than ever. Nevertheless, a major drawback of this approach is the spatial color variations giving rise to nonideal color mixing as emission cones from the discrete devices do not overlap with each other completely [10]. Consequently, the dimensions of chips in RGB LEDs are typically kept small (< 500 \( \mu \text{m} \)), which also set limitations on the overall output power that can be delivered. Additionally, diffusers are often used to overcome this problem, although optical losses of \( \sim 20\% \) are inevitable [11], together with a loss of color sharpness and richness. In view of such limitations, the stacked LED architecture has been proposed, whereby RGB LED chips are physically stacked on top of each other. The light paths of the three devices become aligned to each other, producing broad-band emission that is naturally mixed without additional optics. The rationale for adopting this design has been explained in [12] and [13].

A major challenge with this design is the accommodation of wire bonds to the LED chips. The original design makes use of chips of truncated pyramidal geometry [14] so that, when stacked together, the bonding pad regions remain exposed, as shown in Fig. 1(a). In reality, despite significant improvements to color homogeneity, leakage of monochromatic light around the pad regions remains severe. It is apparent that, in order to solve the problem completely, chips in a stack have to be of identical dimensions to overlap with each other completely. In this paper, a new chip stacking architecture is demonstrated, overcoming the limitations described before. The RGB chips are of identical dimensions, eliminating possibilities of optical leakage. This is achieved by forming channels onto the sapphire substrates by laser micromachining [15], designed to snug fit the wire bonds. When assembled, the bond wires would appear to protrude from the stacked chip tower, while the tower maintains a planar facet. Fig. 1(b) shows a schematic diagram of the updated design.

Fig. 1. Schematic diagrams depicting the (a) originally proposed stacked LED with truncated pyramidal chips and (b) the present version with embedded wire bonds.
II. EXPERIMENTAL DETAILS

The red, green, and blue LED chips used in this study emit with center wavelengths of 640, 510, and 470 nm, respectively, fabricated from metal–organic chemical vapor deposition (MOCVD)-grown AlInGaP on GaAs and InGaN on sapphire wafers. The sapphire substrates of the nitride wafers have been thinned down to ∼150 μm, followed by the fabrication of devices via standard microfabrication processes, subsequently diced into 1-mm² chips by laser micromachining using a nanosecond diode-pumped solid-state ultraviolet (349 nm) laser source. Channels are formed at the locations of wire bonds of the chip beneath; they are micromachined with the same laser as used for dicing. The chips to be machined are placed on an x-y motorized platform with the sapphire surface facing up. The laser beam, expanded and collimated by a beam expander, trepans across the surface to form a 2-D channel of desired dimensions. Fig. 2(a) shows a SEM image of one such channel formed on the backside sapphire face of a LED chip.

The stack assembly begins with adhering the bottom n-contact of a red AlInGaP vertical LED chip onto a TO-can using electrically conductive epoxy; the top p-electrode is wire bonded to a lead on the TO-can. The green InGaN LED chip with laser-micromachined bottom channel is aligned to cover the red LED in its entirety and so that the wire bonds of the red LED fit snugly into the trench; in fact, this snap-in action automatically aligns the chips. Between chips, optical epoxy is applied to secure them in position. The p-electrodes on the green LED are then wire bonded to the package. Similarly, the blue InGaN LED chip is piled on top of the green LED, forming a trilayer tower structure, as illustrated in the optical microphotograph of Fig. 2(b). The optical measurements are performed by mounting the packaged LEDs onto the input port of a 2-in integrating sphere, fiber coupled to a radiometrically calibrated optical spectrometer. The junction temperatures of the LED chips are determined from infrared thermometry, imaged with a calibrated long-wave infrared (LWIR) camera (FLIR SC645) with a resolution of 640 × 480.

III. RESULTS AND DISCUSSIONS

The color homogeneity of the stacked device is evaluated, being the primary goal of this design. The red, green, and blue chips in a stack are biased at currents of 79, 109, and 38 mA in order to emit white light with CIE coordinates of (0.3, 0.3) when measured in the normal direction. The measurement of angular emission profiles is one of the methodologies for assessing color homogeneity. For comparison, the same set of measurements is performed on a commercial RGB LED (Avago ASMT-QTC0-0AA02). An optical fiber, coupled to a spectrometer, is rotated about the central axis of the device being tested. The blue, green, and red chips in the stack tower are turned on sequentially, with the optical intensity at each angle between 0° and 180° in steps of 1° recorded (90° being the normal direction). The data collected from the stacked LED are plotted onto the left hemisphere of the polar graph, as shown in Fig. 3(a), while the right hemisphere shows the data from the conventional RGB LED. The shapes of the angular plots are self-explanatory: The emission graphs of the stacked tower overlap with each other, as if they are emitted from the same chip. On the other hand, the emission from individual chips in the conventional RGB LED exhibits distinct directionality, giving rise to an overall nonhomogeneous appearance. To investigate the variation of CIE coordinates with respect to viewing angles between 0° and 180° (90° being the normal direction), all three chips in the stacked tower are turned on simultaneously.
under the same testing conditions as before. The CIE $x, y$ coordinates at each angle are plotted against the angle at which the measurement was conducted, as shown in Fig. 3(b). The set of data measured from the conventional RGB LED is plotted onto the same graph.

The CIE coordinates remain relatively unchanged with fluctuations of less than 20% for the stacked tower except for angles below 2° and beyond 160°. Conversely, the CIE coordinates for the conventional RGB LED fluctuate by over 80% across the same angular range. For both types of devices, the CIE coordinates deviate significantly below 20° and above 160°; this is attributed to the geometries of the packages. The headers on the TO-can block light at wider angles. For the RGB package, the chips are mounted into a recessed cavity so that light is not emitted at wider angles.

While the quantitative measurements presented should be convincing enough, the visual appearances of emission from the devices paint an even clearer picture. Fig. 4(a) and (b) shows the optical photographs of the stacked LED and the conventional RGB LED, respectively, captured in the normal direction using a color CCD camera. Both devices are biased to emit a range of different polychromatic colors by mixing appropriate proportions of red, green, and blue light. Emission from the stacked tower always appears as a single color, a visual proof of satisfactory internal color mixing. On the other hand, red, green, and blue spots of light remain clearly visible from the RGB LED. Note that the linear dimensions of chips in the commercial RGB LED are approximately half of those in the stack. If larger chips are used, the nonhomogeneity would be even more pronounced.

To understand the consequences of stacking to optical performances, $L–I$ characteristics of the chips on different layers of the stack are measured. For the LED chips in the stack, only one of the three chips is turned on for each set of measurements. For
a fair comparison, identical RGB chips are mounted side by side onto an identical package, equivalent to the conventional planar RGB LED configuration; the corresponding chip is turned on and measured. The measured $L-I$ data for the blue, green, and red devices are plotted in Fig. 5(a)–(c); the curves formed by square symbols represent data points for the planar RGB devices, while those with circular symbols represent the stacked devices.

At all measured currents, the emitted light intensity by LED chips mounted in a planar configuration is higher than that of the chips integrated into the stacked structure, although to varying extents, due to a combination of thermal, absorption, and reflection effects. For the red LED at the lowest layer of the stack structure, the emitted power drops by $\sim24\%$ at 300 mA; this is mainly attributed to interface reflections with minimal thermal effects. Fig. 6(a) shows an LWIR image of an intentionally misaligned RGB stack so that a small portion of the red and green chips are exposed for thermometric measurements. Since the junction is in close proximity to the top surface, the temperature readings obtained from the LWIR image accurately represent junction temperatures. In this figure, the green chip is biased at 60 mA, and the surface temperature reading taken near the edge of the protruded chip is $\sim90^\circ$C. Following the same methodology, the surface temperatures of the red, green, and blue chips in the stack at bias currents of 30–300 mA are obtained and plotted in Fig. 6(b), except when the temperature exceeds $\sim350$ °C. As expected, thermal effects on the red LED are minimal since the chip is attached directly to the package with the junction, staying below 60 °C even at 150 mA, signifying sufficient conductive heat sinking. The remaining optical drops are due to optical losses along the red light optical path, mainly in the form of interface reflection losses. Red light, the longest wavelength of the three, will pass through the green and blue QWs, together with the sapphire substrates, with minimal absorption. For the green LED sandwiched between the red and blue LED chips, reduction in optical power is most severe of the three at $\sim34\%$ (at 300 mA); thermal effects are more severe as the generated heat has to be channeled away through the red LED chip. The LWIR data indicate that the junction temperature rises to $\sim188$ °C at 150 mA. Optically, light emitted downward from the green chip is almost entirely absorbed by the red QWs, while upward emitting light encounters interface reflection losses. This is exacerbated by the partial absorption of the green light by the blue QWs from the chip above, due to spectral overlap between the blue and green QWs. This evident from the sharp absorption edge of the EL spectrum measured from the green-in-stack device shown in the inset of Fig. 5(b), compared to the EL spectrum of the green-in-planar device. Fortunately, such losses can easily be avoided by picking blue and green LED chips with a larger separation of central wavelengths. The blue LED, being at the top, suffers an optical drop of $\sim27\%$ (at 300 mA). Being at the top of the stack, there are no reflection losses in the upward optical path, but heat sinking is a major issue with this chip. Heat has to be conducted through the green and red chips to the package, accounting for the high junction temperature attained of $\sim291$ °C (at 150 mA). At such elevated temperatures, device reliability and efficiency (due to droop effect) would be compromised. A suitable heatsinking strategy must be in place before the devices can be driven at higher currents.

Fig. 7. Optical microphotographs of the stacked LED functioning as a phosphor-free white LED emitting at (a) cool, (b) neutral, and (c) warm white. The corresponding spectra are plotted in (d–f).
The thermal and optical analyses provide insight on the major optical loss and heat conduction mechanisms so that suitable remedies to the design can be applied. In particular, a dedicated package allowing direct heat sinking from individual chips (via the facets perhaps) should be designed and implemented to suit the thermal characteristics of the stack. Additionally, the absorption of downward propagated light from the blue and green chips may be eliminated by the coating of a wavelength-selective distributed Bragg reflector on the bottoms of the chips, enabling selective reflection and transmission of light.

The stacked tower also functions as a conversion-free white-light LED and, in fact, a correlated color temperature (CCT)-variable white-light LED. Previously, the use of multilateral QWs [16] and multifacet QWs [17] has also been pursued for realizing phosphor-free white LEDs. Fig. 7(a)–(c) shows the stacked LED operated as cool white (CCT of 7332 K, driven at currents of 79, 120, and 45 mA in the order of RGB), neutral white (5999 K at 79, 110, and 38 mA), and warm white (2362 K at 150, 121, and 29 mA) light sources, respectively, while their corresponding optical spectra are plotted in Fig. 7(d)–(f), respectively. The luminous efficacies of the device operated at the three stated CCTs are 19.23, 20.19, and 20.70 lm/W, respectively, being respectable figures for a prototypic device. For comparison, the planar RGB LED assembled using identical chips performs as follows: 32.02, 32.78, and 37.22 lm/W at currents of 79, 120, and 45 mA in the order of RGB. The stacked tower also functions as a conversion-free white-light LED and, in fact, a correlated color temperature (CCT)-variable white-light LED. Previously, the use of multilateral QWs [16] and multifacet QWs [17] has also been pursued for realizing phosphor-free white LEDs. The RGB stacked LED architecture has been further optimized to eliminate leakage of monochromatic light from individual chips from each layer, therefore creating a device that functions as both a phosphor-free white-light LED with CCT tuning capabilities and a widely tunable color LED. Through $L – I$ measurements and LWIR thermometry, thermal and optical effects arising from chip stacking have been analyzed, prompting the need for the design of a dedicated package to improve heat dissipation from the chips. The luminous efficacies of the device as a CCT-variable white-light LED are approximately 20 lm/W at CCTs of 7332 K, 5999 K, and 2362 K. With diverse functionalities, the device is suitable for both display and illumination purposes.

IV. CONCLUSION

The RGB stacked LED architecture has been further optimized to eliminate leakage of monochromatic light from individual chips from each layer, therefore creating a device that functions as both a phosphor-free white-light LED with CCT tuning capabilities and a widely tunable color LED. Through $L – I$ measurements and LWIR thermometry, thermal and optical effects arising from chip stacking have been analyzed, prompting the need for the design of a dedicated package to improve heat dissipation from the chips. The luminous efficacies of the device as a CCT-variable white-light LED are approximately 20 lm/W at CCTs of 7332 K, 5999 K, and 2362 K. With diverse functionalities, the device is suitable for both display and illumination purposes.

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