CONFOCAL MICROSCOPIC ANALYSIS OF OPTICAL CROSSTALK FROM MICRO-PIXEL LIGHT-EMITTING DIODES

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Self-illuminating displays comprising two-dimensional arrays of micro-emitters are superior over conventional backlight-illuminated liquid-crystal displays (LCD) in many aspects, including lower power consumptions, thinner profiles, higher image contrasts, wider viewing angles, and broader operating temperatures. There still are several technical challenges prevent self-illuminating organic light-emitting diodes (OLEDs) from becoming a dominant commercial product in the field of image display devices, such as limited lifespans, susceptibility to water damages and poor performance under high ambient lighting. In particular, blue OLEDs have lifetimes of only few thousand hours, which is much lower than those of LCDs or plasma displays. Self-illuminating displays based on III-nitride semiconductor materials are potentially an alternative solution, owing to their intrinsic advantages of stabilities, efficiencies and reliabilities.

The performances of displays can be greatly influenced by the extents of optical crosstalk, whereby areas beyond the defined emissive pixels also appear to emit light, as illustrated in Figs. 1(b) and 1(d) for LCD and OLED displays respectively. As light cannot be turned off, true black cannot be achieved on an LCD display, while light emitted from OLEDs unavoidably channels along the glass/polymer substrate. Similarly, GaN-based μ-LED arrays fabricated on GaN-sapphire wafers suffer from severe optical crosstalk [1]. Several methods, such as adopting the flip-chip configuration [2] and geometrical sapphire shaping [3], have been proposed to enhance the light output and alter the emission divergence of individual μ-LEDs. Nevertheless the crosstalk problem has not yet been addressed, which is a critical factor determining image quality and visual comfort. In this study, confocal microscopy is employed to investigate the crosstalk performances from μ-LEDs of three different architectures.

In confocal microscopy, signals from out-of focus planes can be suppressed by using a pinhole in front of the detector. Employing this technique, a clear view of intensity distributions from specific planes of the emissive μ-LED arrays can be obtained. The crosstalk phenomenon associated with typical GaN-on-sapphire μ-LEDs is highlighted in Fig. 2(a)-(c); light emission from the μ-LED pixels is surrounded by intense background noise. Detected noise levels (defined as the ratio of noise intensity to maximum signal intensity) can be as high as 0.38 when multiple μ-LEDs pixels are illuminated simultaneously. By removing the sapphire substrate via laser lift-off (LLO), thin-film μ-LED devices are formed in an attempt to minimize the crosstalk. As shown in Fig. 3(b)ii, the crosstalk noise is highly diminished, but not eliminated due to lateral light channeling along the remaining GaN layer. Apparently, zero optical crosstalk between the μ-pixels can only be achieved by complete optical isolation of the pixels. The fabrication of such crosstalk-free μ-LED begins with the preparation of LED thin-films. The sapphire of p-side bonded wafer is removed by LLO and the GaN layer is thinned down to 2 μm by dry etching. The pixelated structure is then fabricated by standard microfabrication techniques and the unmasked region is completely etched through the entire GaN layers terminating on the metal layer. The confocal image shown in Fig. 3(b)iii clearly illustrate that optical crosstalk is eliminated from such devices. Ray-tracing simulation results shown in Fig. 3(c)i-iii suggest that the underlying transparent GaN/sapphire substrate beneath the μ-LEDs determine the extent of crosstalk. The calculated intensity maps shown in Fig. 3(d) are well-correlated to the measured data. The crosstalk-free performance is also apparent from the intensity plots shown in Figs. 4(a)-(b) whereby the intensities detected beyond the emission mesa drop sharply. By minimizing optical leakage, light emitted from the active region can be fully extracted, thus maximizing the light output power as evident from Fig. 4(c).

[1] H. W. Choi et al., “High-resolution 128 x 96 nitride microdisplay”, IEEE Electron Device Letters, Vol. 25, pp 277-279, 2004.

[2] H. X. Zhang et al., “Individually-addressable flip-chip AlInGaN micropixelated light emitting diode arrays with high continuous and nanosecond output power”, Optics Express, Vol. 16, pp 9918, 2008.

[3] P. P. Maaskant et al., “High-Speed Substrate-Emitting Micro-Light-Emitting Diodes for Applications Requiring High Radiance”, Applied Physics Express, Vol. 6, pp 022102, 2013.

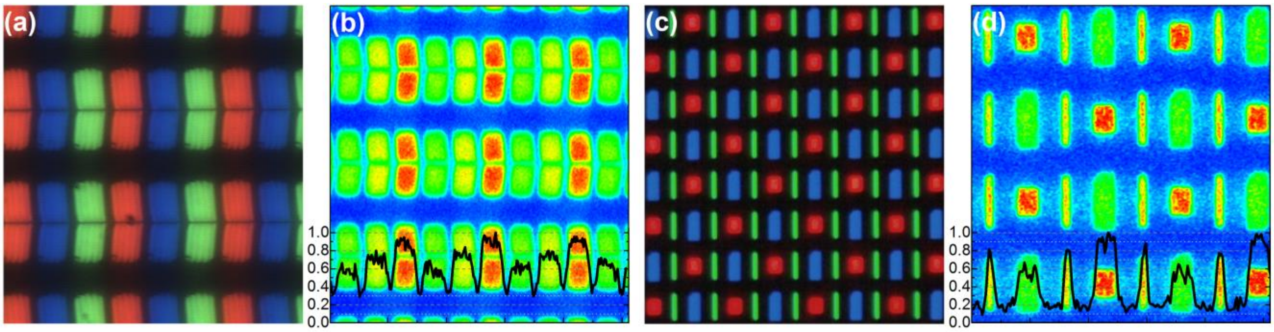

Figure 1 Microphotographs of (a) LCD and (c) OLED displays. Intensity maps of (b) LCD and (d) LED displays captured by confocal microscopy.

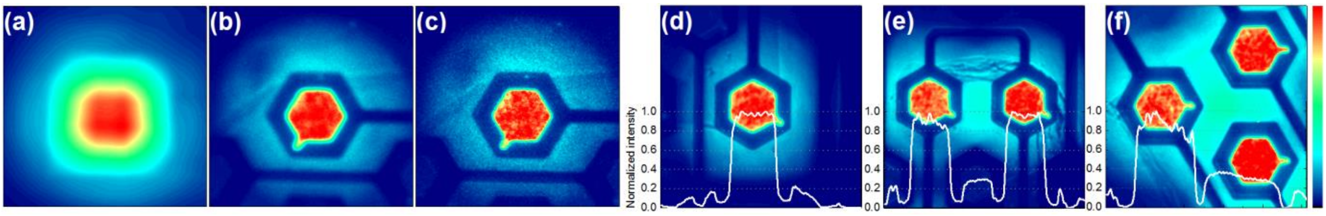

Figure 2 Intensity maps of GaN-on-sapphire μ-LEDs captured by confocal microcopy (a) without and with (b) 1 au and (c) 0.3 au pinhole. Confocal images of (d) single, (e) double and (f) triple emitting μ-LED pixels.

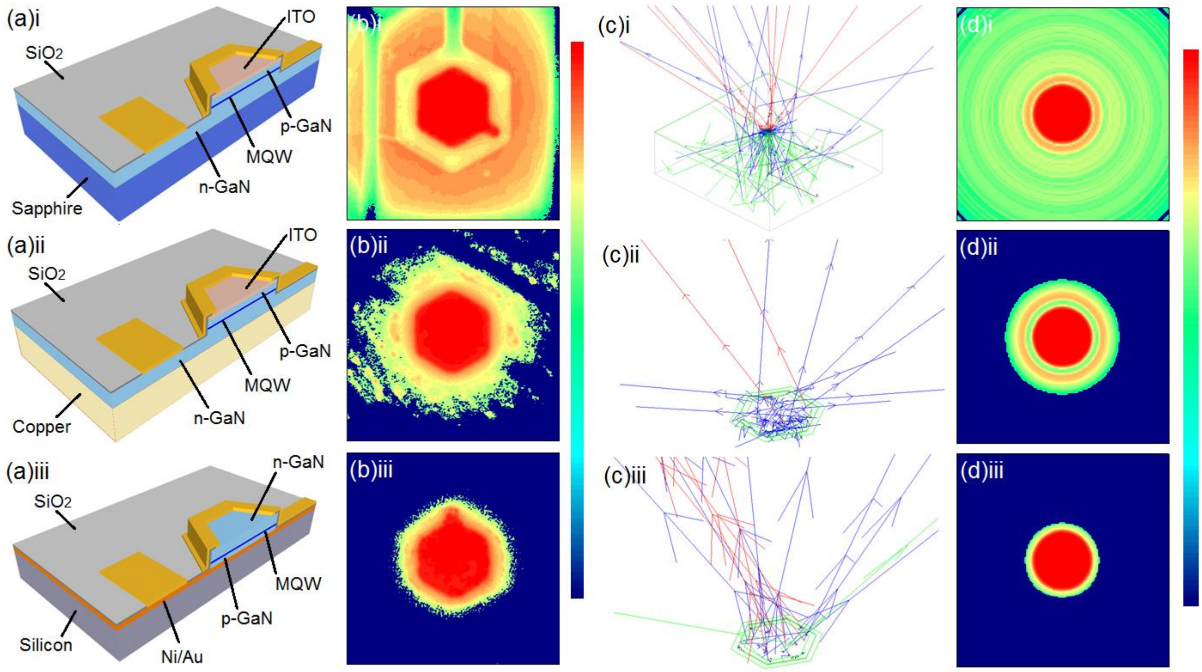

Figure 3 (a) Schematic diagrams depicting architectures of μ-LEDs; (b) confocal images along the x-y plane captured at the devices surfaces; (c) Ray-tracing diagrams; (d) calculated intensity maps. ((i) GaN-on-sapphire μ-LED, (ii) thin-film μ-LED and (iii) crosstalk-free μ-LED)

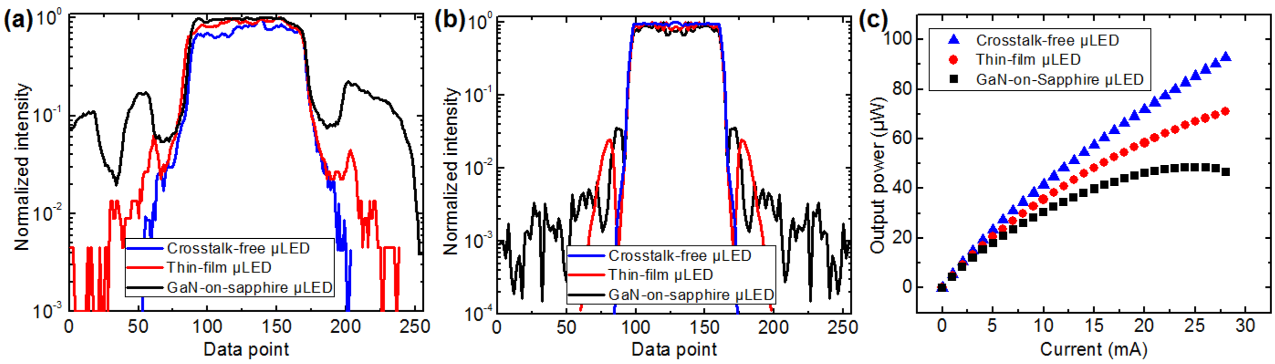

Figure 4 (a) Measured and (b) calculated intensity distributions plotted in log-scale. (c) Intensity-current (L-I) characteristics of μ-LEDs.