Characteristics and applications of InGaN micro-light emitting diodes on Si substrates

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Abstract **—InGaN micro-light emitting diodes on Si substrates have been fabricated and characterized. Their abilities for micro-display, high modulation bandwidth of 270 MHz and data transmission rate of up to 400 Mbit/s have been demonstrated.**

Index Terms* – *GaN, micro-LEDs, Si, bandwidth.

I. INTRODUCTION

GaN-based individually addressable micro-light emitting diode ('µLEDs') are a novel format of LED that offers spatially-controllable micro-scale light output patterns with individual emitters of sizes ≤ 100 µm. These devices have some advantages over larger conventional LEDs, such as high modulation bandwidths [1], reduced device self-heating [2], and higher optical output power densities [3], and have been demonstrated for applications as diverse as visible-light communication (VLC) [1], [4], [5], micro-displays [6], opto-electronic trapping of cells [7] and mask-free photolithography [8].

Growth of InGaN LED material on Si substrates has the potential to substantially reduce the cost of device fabrication [9], [10], including the cost of µLED fabrication. However, until now there have not been any reports of µLED devices fabricated on Si substrates. Here we report a 10×10 array of individually-addressable 45 µm diameter µLEDs, fabricated from a 6" Si substrate (termed "Si/µLEDs"). These devices are characterized and we show that the Si/µLEDs can sustain high current densities (up to 6.6 kA/cm^2) and has a high electrical-to-optical modulation bandwidth of up to 270 MHz. These properties make them ideal device candidates for the applications listed previously, and offer a potentially lower cost route to fabrication of µLEDs compared to the previously reported µLEDs devices grown on sapphire substrates thus far.

II. EXPERIMENT

The Si/µLEDs were fabricated from InGaN LED wafers grown on 6" substrates by metal-organic vapour phase epitaxy (MOVPE). The detailed LED/Si epitaxial structure and µLED fabrication process used have been reported previously [1], [11]. Also, 250 µm×250 µm broad-area LEDs on Si have been fabricated for comparison. Fig. 1(a) shows a completed 10×10 µLED/Si array with each individually-addressable pixel having a diameter of 45 µm on a 100 µm pitch and the inset demonstrates the uniform light emission from a representative µLED pixel. The peak emission wavelength of the µLED/Si array is ~470nm.

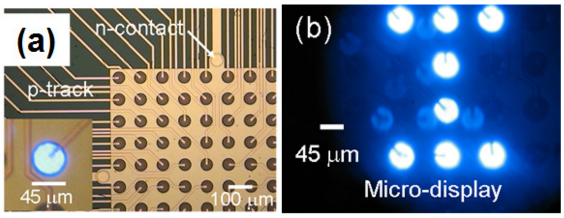

Fig 1. (a) Micrograph of the individually addressable 10 ×10 µLEDs array (inset: light emission through the spreading layer of a representative pixel). (b) Light emission of a micro-display pattern.

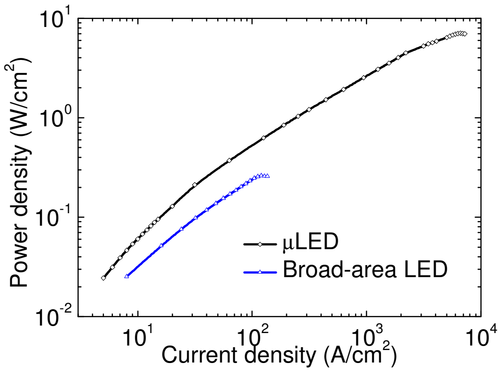

Fig 2. Comparison of power density versus current density characteristics of µLED and broad-area LED.

III. RESULTS AND DISCUSSION

As shown in Fig 2, compared with 250 µm×250 µm broad-area LEDs on Si, our measurements show these µLEDs have higher optical output power density and can sustain a much higher current density, up to 6.6 kA/cm2, before thermal rollover. Additionally, good pixel-to-pixel uniformity of these µLED/Si arrays demonstrates their potential for micro-display applications. As such, Fig. 1(b) shows a light pattern generated by a µLED/Si array through individually controlling each µLED pixel.

We have previously reported that the µLEDs on sapphire substrates exhibit higher electrical-to-optical (E-O) modulation bandwidths than their broad-area counterparts [1]. For VLC, the modulation behaviour of the µLED/Si device was characterised. The E-O modulation bandwidth of a representative Si/µLED pixel was measured from 0.1 mA to 110 mA. As shown in Fig. 3(a), an optical modulation bandwidth of 270 MHz has been achieved. The E-O bandwidth shows a strong dependence on the injected current. At present, we attribute this behavior to a complex interplay between the carrier recombination lifetime and the RC time constant of the device. We note that it is possible to use measurements of this kind to ascertain the recombination coefficients in micro-LEDs [12], and we aim to perform such an analysis on this device in due course. In Fig. 3(b), open eye diagrams at 155 Mbit/s, 200 Mbit/s, and 300 Mbit/s could be obtained at 20 mA, however, an open eye diagram at 400 Mbit/s is only obtained at higher currents, e.g. 80 mA, illustrating the potential for optical data transmission using a single Si/μLED.

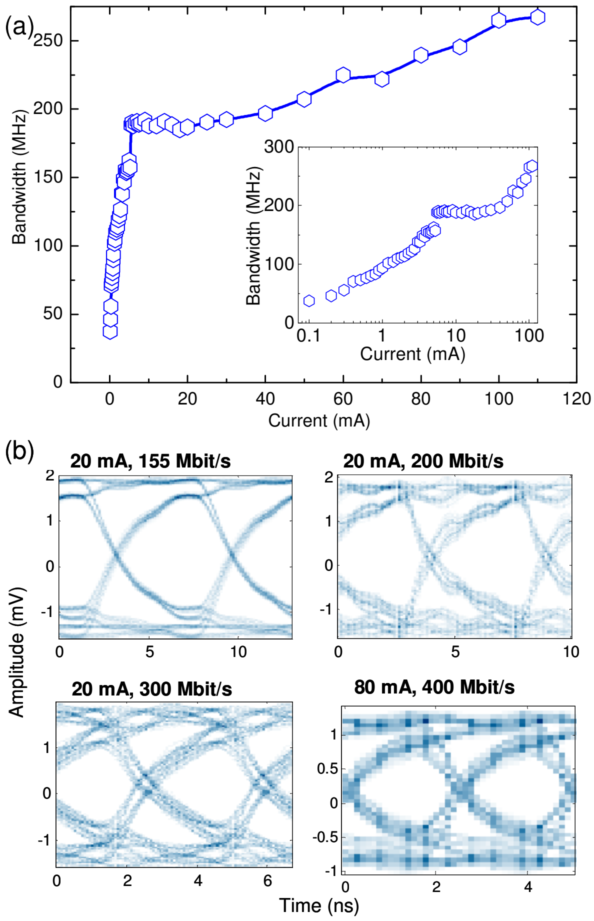

Fig. 3 (a) Bandwidth of one representative μLED versus current. Inset: bandwidth versus log(current). (b) The eye diagrams taken at 155 Mbit/s (at 20mA), 200 Mbit/s (at 20mA), 300 Mbit/s (at 20mA), and 400 Mbit/s (at 80mA).

IV. Conclusion

In summary, individually addressable μLED arrays have been fabricated for the first time on GaN-on-Si material. This offers a possible way to fabricate μLED arrays at a reduced cost compared to using conventional GaN-on-Sapphire material. The μLED/Si devices were characterized and shown to be able to generate high-contrast micro-scale light patterns, with higher optical output power densities than their conventional broad-area counterparts. These Si/μLED devices also have electrical-to-optical modulation bandwidths as high as 270 MHz, demonstrating the potential these devices have for low cost micro-display and VLC applications.

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References

[1] J. J. D. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, A. E. Kelly, and M. D. Dawson, "Visible-Light Communications Using a CMOS-Controlled Micro-Light- Emitting-Diode Array," *Journal of Lightwave Technology*, vol. 30, no. 1, pp. 61–67, Jan. 2012.

[2] Z. Gong, S. Jin, Y. Chen, J. J. D. McKendry, D. Massoubre, I. M. Watson, E. Gu, and M. D. Dawson, "Size-dependent light output, spectral shift, and self-heating of 400 nm InGaN light-emitting diodes," *Journal of Applied Physics*, vol. 107, no. 1, p. 013103, 2010.

[3] H. X. Zhang, D. Massoubre, J. J. D. McKendry, Z. Gong, B. Guilhabert, C. Griffin, E. Gu, P. E. Jessop, J. M. Girkin, and M. D. Dawson, "Indivdually-addressable flip-chip AlInGaN micropixelated light emitting diode arrays with high continuous and nanosecond output power," *Optics Express*, vol. 16, no. 13, pp. 9918–9926, 2008.

[4] J.-M. Wun, C.-W. Lin, W. Chen, J. K. Sheu, C.-L. Lin, Y.-L. Li, J. E. Bowers, J.-W. Shi, J. Vinogradov, R. Kruglov, and O. Ziemann, "GaN Based Miniaturized Cyan Light Emitting Diodes on Patterned Sapphire Substrate with Improved Fiber Coupling for Very-High-Speed Plastic Optical Fiber Communication," *IEEE Photonics Journal*, vol. 4, no. 5, pp. 1520–1529, 2012.

[5] P. P. Maaskant, H. Shams, M. Akhter, W. Henry, M. J. Kappers, D. Zhu, C. J. Humphreys, and B. Corbett, "High-Speed Substrate-Emitting Micro-Light-Emitting Diodes for Applications Requiring High Radiance," *Applied Physics Express*, vol. 6, no. 2, p. 022102, Jan. 2013.

[6] H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-nitride blue microdisplays," *Applied Physics Letters*, vol. 78, no. 9, p. 1303, 2001.

[7] A. Zarowna-Dabrowska, S. L. Neale, J. J. D. McKendry, D. Massoubre, B. R. Rae, R. K. Henderson, M. J. Rose, H. Yin, J. M. Cooper, E. Gu, and M. D. Dawson, "Miniaturized optoelectronic tweezers controlled by GaN micro-pixel light emitting diode arrays," *Optics Express*, vol. 19, no. 3, pp. 1714–1720, 2011.

[8] B. Guilhabert, D. Massoubre, E. Richardson, J. J. D. McKendry, G. Valentine, R. K. Henderson, I. M. Watson, E. Gu, and M. D. Dawson, "Sub-Micron Lithography Using InGaN Micro-LEDs: Mask-Free Fabrication of LED Arrays," *IEEE Photonics Technology Letters*, vol. 24, no. 24, pp. 2221–2224, 2012.

[9] D. Zhu, C. McAleese, K. K. McLaughlin, M. Häberlen, C. O. Salcianu, E. J. Thrush, M. J. Kappers, W. a. Phillips, P. Lane, D. J. Wallis, T. Martin, M. Astles, S. Thomas, A. Pakes, M. Heuken, and C. J. Humphreys, "GaN-based LEDs grown on 6-inch diameter Si (111) substrates by MOVPE," in *Proceedings of SPIE*, 2009, vol. 7231, no. 111, p. 723118.

[10] D. Zhu, C. McAleese, M. Häberlen, C. Salcianu, T. Thrush, M. Kappers, A. Phillips, P. Lane, M. Kane, D. Wallis, T. Martin, M. Astles, N. Hylton, P. Dawson, and C. Humphreys, "Efficiency measurement of GaN-based quantum well and light-emitting diode structures grown on silicon substrates," *Journal of Applied Physics*, vol. 109, no. 1, p. 014502, 2011.

[11] P. Tian, J. J. D. McKendry, Z. Gong, B. Guilhabert, and I. M. Watson, "Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes," *Applied Physics Letters*, vol. 101, p. 231110, 2012.

[12] R. P. Green, J. J. D. McKendry, D. Massoubre, E. Gu, M. D. Dawson, and A. E. Kelly, "Modulation bandwidth studies of recombination processes in blue and green InGaN quantum well micro-light-emitting diodes," *Applied Physics Letters*, vol. 102, no. 9, p. 091103, 2013.