Microstripe-Array InGaN Light-Emitting Diodes With Individually Addressable Elements

H. X. Zhang, E. Gu, C. W. Jeon, Z. Gong, M. D. Dawson, *Senior Member, IEEE*, M. A. A. Neil, and P. M. W. French

***Abstract*—High-performance InGaN light-emitting diodes consisting of 120 side-by-side and individually addressable microstripe elements have been successfully fabricated. Each stripe in these devices is 24 μm in width and 3600 μm long, with a center-to-center spacing between adjacent stripes of 34 μm. The emission wavelengths demonstrated range from ultraviolet (UV) (370 nm) to blue (470 nm) and green (520 nm). The devices show good uniformity and performance due to finger-pattern n-electrodes running between adjacent stripes. In the case of the UV devices for example, turn-on voltages are around 3.5 V and continuous-wave output powers per stripe $\sim$80 μW at 20 mA. A major feature of these devices is their ability to generate pattern-programmable emission, which offers applications in areas including structured illumination wide-field sectioning optical microscopy.**

***Index Terms*—InGaN, light-emitting diode (LED), micropixellated light-emitting diode (LED).**

I. Introduction

MOST OF the established applications for InGaN light-emitting diodes (LEDs) emphasize their use in illumination and lighting, where output power and electrical-to-optical efficiency are major performance factors and only a general directionality of the light output is required. Recently, however, there has been increasing interest in special forms of these devices for applications in areas requiring a higher degree of spatial, spectral, or temporal control, such as instrumentation and bio- and chemical-sensors. Micropixellated InGaN LEDs have emerged as very promising sources for such purposes [1]–[3]. Here, the emission area is patterned into a high-density array of microemitting elements, which may, for example, be in the form of disks [1]–[3] or rings [4] and can be matrix-addressed. Such devices have been reported at near-ultraviolet (UV), blue, and green wavelengths in arrays of up to 128×96 matrix-addressable elements [5], and extension to the deep-UV is underway [6]. Pulsed operation down to nanosecond durations has been achieved [7], as has integration of microlenses for beam projection [2], [8]. These successes open up a wide range of potential applications, and the search for other suitable forms of microstructured devices continues apace.

In this letter, we report the fabrication of high-performance microstripe device arrays, where 120 side-by-side stripe light-emitting elements, each individually addressable, form the active area of the device. Stripe structure has previously been embodied in broad-area LEDs to aid light extraction via interdigitated contacts or gratings [9], [10]. Our stripe devices are specifically engineered to allow pattern-programmable control for imaging applications in areas such as structured illumination wide-field sectioning microscopy [11]. The stripe array facilitates individual element addressing in continuous-wave (CW) mode.

II. Device Fabrication

The devices were fabricated from "standard" LED wafers which were grown on c-plane sapphire substrates by metal–organic chemical vapor deposition. The wavelengths demonstrated are 370, 470, and 520 nm, depending upon the specific wafers used; full details of the respective wafer structures have been reported previously [3]–[5]. The fabrication requirement for the microstripe LEDs is for each stripe to be electrically and optically isolated from the others; this is facilitated through the etching of rectangular mesa structures down to the n-type GaN. In our approach, each individual microstripe has an n-electrode rail alongside the mesa, running to a common broad-area n-electrode contact pad, and each stripe has an independent p-electrode running along its length.

The first process step defining the rectangular GaN LED mesa for isolation was performed by standard photolithographic patterning and inductively coupled plasma dry etching. The ridge structure of each individual micro-LED bar was formed subsequently by the same etching process. Prior to the metallization, SiO_2 was deposited on the etched structure using plasma-enhanced chemical vapour deposition. For the ohmic contact formation to the p-GaN, the SiO_2 on the top of the ridges was partially removed by buffer oxide enchants using photolithographic patterning. Then a thin Ni–Au transparent contact was evaporated on the patterned area. A premetallization HCl acid treatment was applied and the contacts were alloyed by rapid thermal annealing in air. The connection of each of the stripes was performed by a Ti–Au metal deposition using a sputtering and liftoff process. Finally, the contacts were alloyed by RTA in N_2.

III. Results and Discussion

Fig. 1 shows a schematic cross section of the device structure (a) and a microphotograph of the individual p-finger contact arrangement to each stripe and n-contact metal rail on the

Manuscript received March 1, 2006; revised May 25, 2006. This work was supported by the Research Council's U.K. Basic Technology Research Programme.

H. X. Zhang, E. Gu, Z. Gong, and M. D. Dawson are with the Institute of Photonics, University of Strathclyde, Glasgow G4 0NW, U.K. (e-mail: haoxiang.zhang@strath.ac.uk; zheng.gong@strath.ac.uk; m.dawson@strath.ac.uk).

C. W. Jeon is with the Advanced Display Team, Daegu Gyeongbuk Institute of Science and Technology, Daegu 700-742, South Korea (e-mail: cwjeon@dgist.ac.kr).

M. A. A. Neil and P. M. W. French are with the Department of Physics, Imperial College London, South Kensington Campus, London SW7 2AZ, U.K. (e-mail: mark.neil@imperial.ac.uk; paul.french@imperial.ac.uk).

Digital Object Identifier 10.1109/LPT.2006.879926

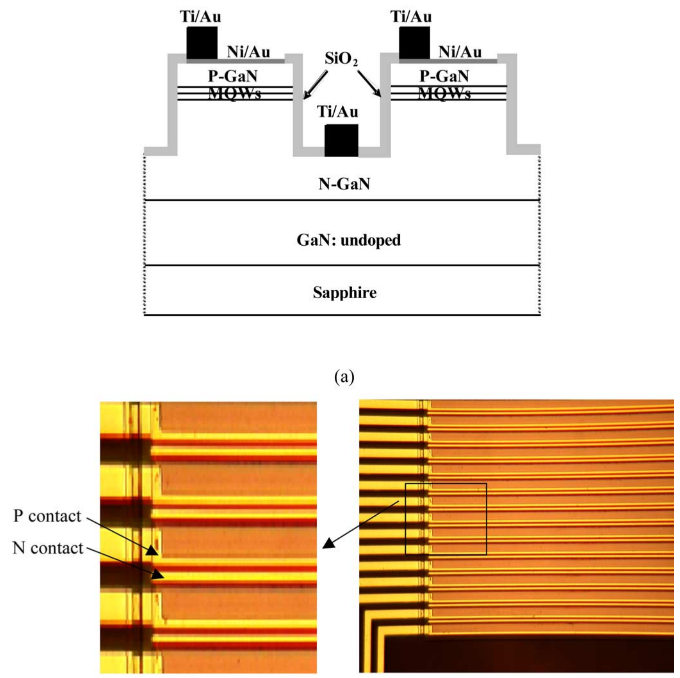

Fig. 1. (a) Cross-sectional schematic of the device structure, (b) optical microphotographs of microstripe-geometry UV LEDs, at the end of the p-electrodes. The center-to-center spacing of adjacent stripes is 34 μm. (Color version available online at http://ieeexplore.ieee.org.)

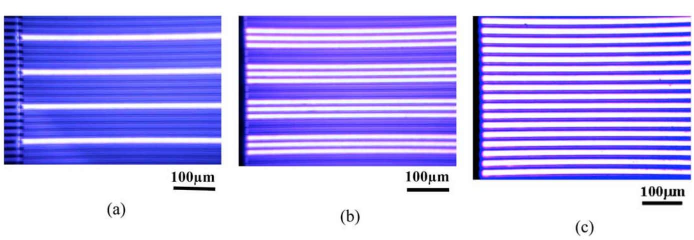

Fig. 2. Operational patterns of the individually addressed blue microstripe-format LEDs, with (a) one element ON, adjacent four elements OFF; (b) three adjacent elements ON, two neighbouring elements OFF; and (c) all elements ON. (Color version available online at http://ieeexplore.ieee.org.)

side of each stripe (b). The exemplar devices reported here have 120 bars, the size of each being 24×3600 μm^2 and the space between two bars being 10 μm (center-to-center spacing 34 μm). Therefore, the whole active area of each device is 4080×3600 μm^2.

Fig. 2 shows representative demonstrations of the pattern-programmable operation of the devices. For illustration, a blue (470 nm) device driven by different control programs is shown in configurations of (a) 1 element ON/4 elements OFF, period = 5 elements; (b) 3 elements ON/2 elements OFF, period = 5 elements; and (c) all elements ON. From these images, we can see that the light emission is quite uniform, not only along the length of the stripes but also from stripe to stripe. We attribute this good uniformity to the 4-μm-wide n-metal line of Ti–Au (20/200 nm) inserted between each adjacent pair of stripes, which facilitates uniform current spreading along the length of each stripe. From the patterns of Fig. 2, several aspects of these stripe format micro LEDs are revealed. First, each bar of the device can be individually addressed; second, required patterns can be obtained by the designed driving program under CW or pulsed operating mode.

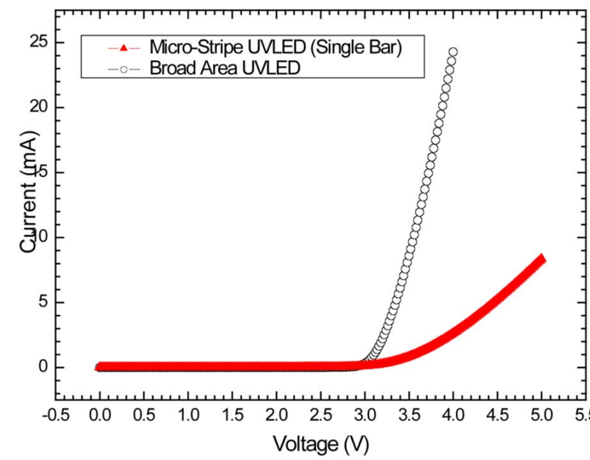

Fig. 3. Typical single-bar *I–V* characteristics of microstripe-geometry UV LED compared to a conventional broad-area reference LED. (Color version available online at http://ieeexplore.ieee.org.)

Fig. 3 shows typical current–voltage (*I–V*) characteristics of a single bar of this microstripe format LED emitting at 370 nm. For comparison purposes, the *I–V* curve of a conventional single-element broad-area LED fabricated from the same wafer and following an identical process flow, is included in the same graph. A feature observed from the graph is the higher differential series resistance of 187 Ω for this stripe device compared to the differential series resistance of the broad-area LED devices of 33.7 Ω, although the turn-on voltages are similar (3.46 V for stripe-geometry LEDs; 3.35 V for the broad-area LED). The p-contact of the broad-area LED has a size of 420×660 μm^2, which is 4.8 times larger than the p-contact area (16×3590 μm^2) of the microstripe LED. The ratio of the p-contact areas of these two devices is close to their series resistance ratio. This result shows that the series resistance is mainly determined by the area of the p-contact although the resistance is also affected by other factors such as the current spreading length. The n-ohmic contact contributed little resistance to the total differential series resistance compared to the p-contact and the QW structure. The whole stripe device shows good uniformity of electrical properties. The differential series resistances and turn-on voltages for all 120 stripes of this device vary only from 170 to 200 Ω and from 3.4 to 3.5 V, respectively.

Representative light output power versus current curves of an individual stripe-LED element is shown in Fig. 4(a). In order to make an accurate comparison to the broad-area LED, the currents and output powers were normalized to the device active areas to obtain the current and output power densities. The relation between these parameters for the two devices is plotted in Fig. 4(b), showing the superior performance of the microstructured devices. The larger sidewall surface area in stripe geometry micro-LEDs is one of the reasons for higher light extraction as explained previously in the case of microring and microdisk structures [4]. However, the larger sidewall surface area in the microstripe LED is not the only factor in improving micro-LED

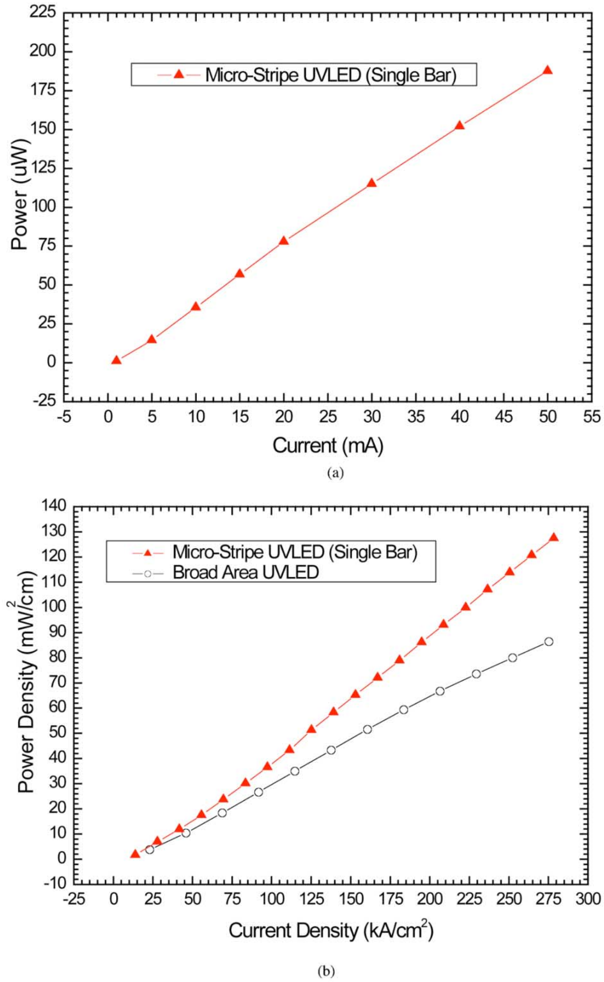

Fig. 4. Plots of (a) power versus current for a single UV bar, (b) power density versus current density for microstripe UV LED (single bar) compared to the reference broad-area LED. (Color version available online at http://ieeexplore.ieee.org.)

external efficiency and other contributions should also be considered. When reducing the LED size down to the microscale, much better current spreading can be achieved. Also, in a microscale LED structure with lateral dimensions close to the absorption length, most of the laterally propagating photons can reach the sidewall and scatter out without suffering absorption. These characteristics associated with the microscale LEDs will enhance the light extraction and conversion efficiency.

It should be pointed out that the power measurement we performed was under the CW mode. In this situation, the output power of the stripe format LEDs (single bar) saturated when the injection current was over 80 mA due to the problem of self-heating. Hence, effective thermal management will reveal the full-power scaling capabilities of these stripe-geometry devices. Flip chip bonding technology, for example, should improve the heat dissipation to get higher output power.

As for the blue and green microstripe format LEDs, they show similar results, which mean the stripe devices have higher forward voltage, series differential resistance, and output power compared to those of broad-area LEDs at the same injection current, respectively. Table I shows the detailed measurement results, performed at 20 mA in CW mode.

TABLE I
MEASUREMENT RESULTS OF THE BLUE AND GREEN LEDs

Wavelength (nm)	Format	Forward voltage (V) @ 20mA	Series resistance (Ohms)	Output power (μW)
Blue (470nm)	Microstripe	5	116	219
	Broad area	3.3	30	156
Green (520)	Microstripe	5.2	123	337
	Broad area	3.3	36	264

IV. CONCLUSION

Individually addressable microstripe-format LEDs have been successfully fabricated at UV, blue, and green wavelengths. A major feature of such devices is that they are pattern-programmable. *I–V* characteristics and output power measurements reveal that the light emission of this stripe geometry device is quite uniform owing to the special design of finger-geometry n-electrodes. The output power is enhanced greatly due to the large sidewall area. The encouraging performance of these microstripe devices opens up a range of possible applications. The stripes can be individually addressed in a wide range of spatially and/or temporally programmed modes. Grating illumination from such a device with three separately phased patterns, for example, would represent a novel approach to structured illumination microscopy [11].

REFERENCES

[1] H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-nitride blue microdisplays," *Appl. Phys. Lett.*, vol. 78, pp. 1303–1305, 2001.
[2] I. Ozden, M. Diagne, A. V. Nurmikko, J. Han, and T. Takeuchi, "A matrix-addressable 1024 element blue light emitting InGaN QW diode array," *Phys. Stat. Sol. (a)*, vol. 188, pp. 139–142, 2001.
[3] C. W. Jeon, H. W. Choi, and M. D. Dawson, "Fabrication of matrix-addressable InGaN-based microdisplays of high array density," *IEEE Photon. Technol. Lett.*, vol. 15, no. 11, pp. 1516–1518, Nov. 2003.
[4] H. W. Choi and M. D. Dawson, "Improved current spreading in 370 nm AlGaN microring light emitting diodes," *Appl. Phys. Lett.*, vol. 86, p. 053504, 2005.
[5] H. W. Choi, C. W. Jeon, and M. D. Dawson, "High-resolution 128 × 96 nitride microdisplay," *IEEE Electron Dev. Lett.*, vol. 25, no. 5, pp. 277–279, May 2004.
[6] V. Adivarahan, S. Wu, W. H. Sun, V. Mandavilli, M. S. Shatalov, G. Simin, J. W. Yang, H. P. Maruska, and M. A. Khan, "High-power deep ultraviolet light-emitting diodes based on a micro-pixel design," *Appl. Phys. Lett.*, vol. 85, pp. 1838–1840, 2004.
[7] S. X. Jin, J. Shakya, J. Y. Lin, and H. X. Jiang, "Size dependence of III-nitride microdisk light-emitting diode characteristics," *Appl. Phys. Lett.*, vol. 78, pp. 3532–3534, 2001.
[8] C. W. Jeon, E. Gu, and M. D. Dawson, "Maskless photolithographic exposure using a matrix-addressable ultraviolet micro-pixel AlInGaN light-emitting diode," *Appl. Phys. Lett.*, vol. 86, p. 221105, 2005.
[9] X. Guo, Y.-L. Li, and E. F. Schubert, "Efficiency of GaN/InGaN light-emitting diodes with interdigitated mesa geometry," *Appl. Phys. Lett.*, vol. 79, pp. 1936–1938, 2001.
[10] Y. J. Lee, H. C. Teng, H. C. Kuo, S. C. Wang, C. W. Chang, T. C. Hsu, Y. L. Yang, M. H. Hsieh, M. J. Jou, and B. J. Lee, "Improvements in light-output efficiency of AlInGaP LEDs fabricated on stripe-patterned epitaxy," *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2532–2534, Dec. 2005.
[11] M. A. A. Neil, R. Justkaitis, and T. Wilson, "Method of obtaining optical sectioning by using structured light in a conventional microscope," *Opt. Lett.*, vol. 22, pp. 1905–1907, 1997.