High-Density Matrix-Addressable AlInGaN-Based 368-nm Microarray Light-Emitting Diodes

Chan-Wook Jeon, Hoi Wai Choi, Erdan Gu, and Martin D. Dawson, *Senior Member, IEEE*

***Abstract*—We report on the fabrication of ultraviolet (UV) microarray light-emitting diodes, toward applications including mask-free photolithographic exposure. Devices with 64×64 elements have been fabricated in matrix-addressed format, generating directed output powers of up to 1 μW per 20-μm-diameter element at less than 1.0-mA drive current. The resistance of each elemental device was found to depend strongly on the n-GaN stripe length. The center wavelength of the emission was measured to be 368 nm, which is very close to that of an i-line (365 nm) UV light source. To our knowledge, this is the first report detailing the fabrication and performance of such devices operating in the UV.**

***Index Terms*—GaN, microarray light-emitting diodes (micro-LEDs), photolithography, ultraviolet light-emitting diode (UV-LED).**

I. INTRODUCTION

THE III-nitride-based light-emitting devices have been successfully developed over the amber-to-violet spectral regions and commercialized over a wide span of these wavelengths. Recently, several groups have reported on high-performance broad-area (0.1–1.0 mm^2) *ultraviolet* light-emitting diodes (UV-LEDs) in the 260–370-nm range [1]–[7], including milliwatt-level continuous-wave performance at selected wavelengths and more than 100-mW pulsed output at high injection current [4]. Such devices are opening up improvements in white LEDs for solid-state lighting applications, and are also expected to offer wide applicability in areas including high-density data storage, chemical and biological sensing devices, in sterilizers and as exposure tools for photolithography. In a commercial photolithographic exposure system, to take one example, both the UV light source, which is currently typically a mercury lamp or a laser, and a mask for each pattern in a semiconductor device, are essential to the microfabrication. Since the light source and the mask are independent, it is not possible to correct any device failure due to a design error without making a new mask. By contrast, integration both of the light source and the masking functions will enable microfabrication with no need for a set of masks, offering the prospect of reduced-cost and improved throughput in selected lithographic applications. Hence, for this and a range of other applications, array-format microemitters will have advantages.

We have been working recently on a series of matrix-addressable two-dimensional microarray-format LEDs for green and blue emission [8]–[10], where the individual device elements are ~20 μm in diameter, in densities of ~1000 elements per square millimeter. These devices were designed to be able to generate a programmable emission pattern by a matrix-driver circuit. In this work, we extend our device fabrication to produce UV micro-LED arrays. The devices are of 64×64 elements, operating in matrix-addressed format and giving top-emission output powers of about 1 μW per element at 368 nm at less than 1 mA of drive current. The individual elements in the array are of diameter 20 μm and have center-to-center spacing of 30 μm, giving an overall emission area of 2.3×2.3 mm^2. We report in detail on the fabrication and performance characteristics of these first-generation UV micro-LED arrays, and propose extensions of the technology toward applications in areas including photolithographic exposure with high resolution.

II. DEVICE FABRICATION

The devices are fabricated from a 370-nm LED wafer structure grown on the c-plane sapphire substrate, which is supplied by Nitride Semiconductors Co. [11]. They have reported that an output power of 2.5 mW at 20 mA has been readily achieved from a bare chip with a size of 350×350 μm^2. The device structure consists of a 25-nm GaN buffer layer over the substrate, followed by 2.3 μm of undoped GaN and 1.4 μm of n-doped GaN, over which was a 200-nm cladding layer and a multiple quantum well (MQW), capped with 100 nm of Mg-doped AlGaN cladding and a 20-nm Mg-doped GaN contact layer. The MQW was of seven periods, of 2-nm InGaN (In ~ 0.05) wells and 10-nm AlGaN (Al ~ 0.2) barriers. Activation of the Mg dopant was carried out by furnace annealing at 950 °C for 20 s in a N$_2$ ambient.

Our fabrication approach (illustrated in Fig. 1) is for the elements within each column to be isolated from the elements of other columns through the etching of rectangular mesa structures. Hence, elements of the same column share a common n-electrode. Combined with horizontal p-metal lines running across the mesas, a matrix-addressing scheme is enabled. Parallel-mesa structures for isolation were formed by photolithographic patterning and inductively coupled plasma (ICP) etching. The etch depth used was 4.2 μm and the plasma comprised 30 sccm of Cl$_2$ and 10 sccm of Ar. The pillar structure of each individual micro-LED element (0.8-μm etch depth and pillar diameter 20 μm) was formed subsequently by the same etching process. Prior to the metallization, 0.1-μm-thick SiO$_2$ was deposited on the etched structure using plasma-enhanced chemical vapor deposition. For the ohmic-contact formation to p-GaN, the SiO$_2$ on top of pillar was partially removed by 7 : 1 buffered oxide agent using photolithographic patterning and then a thin Ni–Au (7/7 nm) bilayer was evaporated on the patterned substrate. A premetallization HCl treatment was applied, and the contacts were alloyed by rapid thermal annealing in air for 4 min at 480 °C. The interconnection of each pillar

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Manuscript received May 7, 2004; revised July 12, 2004.

The authors are with the Institute of Photonics, University of Strathclyde, Glasgow G4 0NW, U.K. (e-mail chanwook.jeon@strath.ac.uk; anthoy.choi@strath.ac.uk; erdan.gu@strath.ac.uk; m.dawson@strath.ac.uk).

Digital Object Identifier 10.1109/LPT.2004.835626

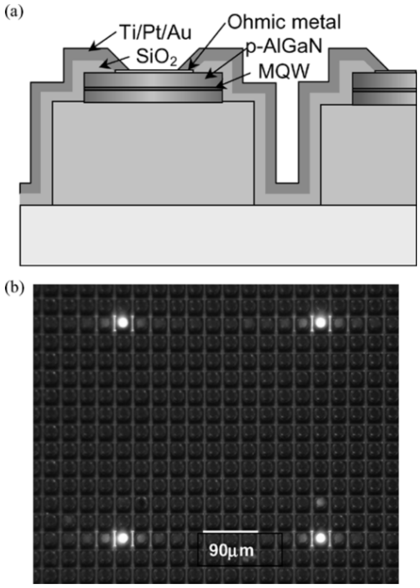

Fig. 1. (a) Cross-sectional schematic of the device structure, and (b) microscope image of the operating device showing four pixels turned on at 6 V.

was done by Ti–Pt–Au (20/100/100 nm) metal lines using a sputtering process. Although the profile of the pillar and mesa structure, which were etched using a sacrificial photoresist mask and ICP process, was confirmed to have sufficient slope to allow conformal metal deposition, the sputtering process was adopted to secure the metal interconnection across the deep trench. As the actual contact on p-GaN is formed by the thin Ni–Au alloy, which was formed before integrating the metal lines, we can exclude any plasma damage during the sputtering.

The current–voltage (I–V) characteristics of the devices were measured with an HP4155B parametric analyzer. Room-temperature electroluminescence data were collected with a cooled charge coupled device spectrometer detection system (0.2-nm spectral resolution), and output power measurements were performed using a power meter, with the calibrated Si photodetector (10 × 10 mm active area) placed in close proximity (2 mm) above the device to collect directed forward emission only. As will be reported elsewhere [12], the forward emission from each device element was largely confined to a cone, assuring collection of most of the forward emission on the detector.

III. RESULTS AND DISCUSSION

Fig. 1 shows a schematic diagram of the device structure and an optical microscope image of the operating device, which, for illustration, shows four pixels turned on at the same time at 6 V. Although there is some degree of optical crosstalk, which is believed to be due to the reflection from the interface of sapphire and air, the light emission from each micro-LED shows a well-defined circular pattern, whose beam characteristics will be reported in detail elsewhere. According to these emission measurements, performed using a confocal microscope, the UV light propagates into the air from each element with a 32.33° emission cone half-angle [12].

Fig. 2(a) shows I–V and light output–current (L–I) characteristics, respectively, of a representative single element of the array device, taken with a UV-calibrated power meter. The micro-LEDs have a turn-on voltage of 5.3 V and a very low reverse-leakage current of less than 0.1 μA at -5 V. In a previous report on a 16×16 array device for blue (470 nm) emission [9], we had a high turn-on voltage of about 6 V from the same geometry micro-LED, which was attributed to the configuration of the metal line [10]. In this work, we applied a thin current spreading metal so that we could reduce the turn-on voltage down to 5.3 V (for the UV device). The differential resistance of each micro-LED taken from the linear section of I–V curves, which was measured across the diagonal of the device, varies from about 2 to 9 k · Ω, as shown in Fig. 2(b). The minimum value is 1917 Ω from the corner pixel. Although this resistance appears very high at first sight, it is comparable to that of the conventional broad-area LED when the few-hundred-times smaller active area (20-μm diameter) is taken into account. Also, the resistance variation was found to be strongly dependent on the length of n-GaN stripe. Using the transmission line method characterization, from the inserted test pattern within the device area, the sheet resistance of the n-GaN was measured to be about 88 Ω/sq. Therefore, the resistance of each micro-LED having a range of 30–1830-μm n-GaN length will have a varying contribution of 110–6718 Ω originating from the different n-GaN length. The constant discrepancy of about 1300 Ω in average between the measured device resistance (R_T) and the calculated resistance of n-GaN

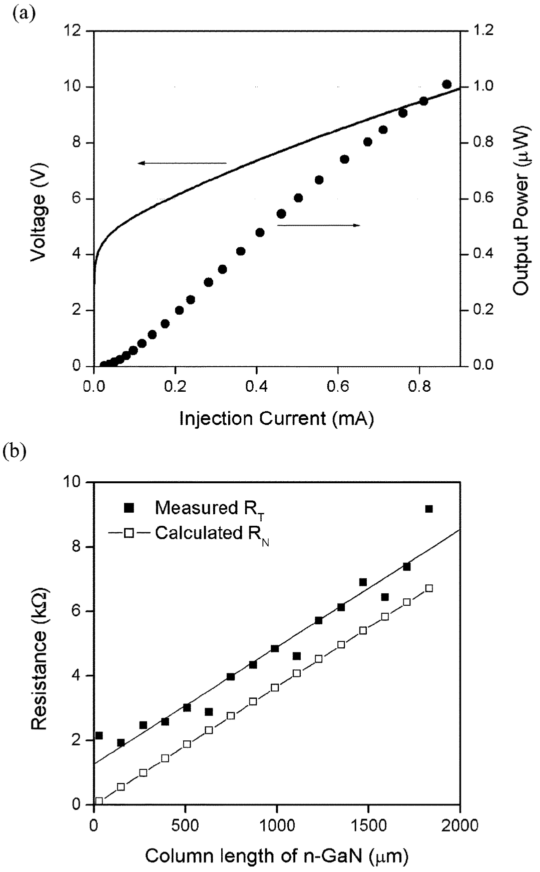

Fig. 2. (a) I–V and L–I characteristics of a representative single element of the 64×64 array device. The light was collected from the top side with 2-mm distance from the Si detector. (b) Measured device resistance (R_T, closed symbol) and the calculated n-GaN column resistance (R_N, open symbol) as a function of the length of n-GaN column.

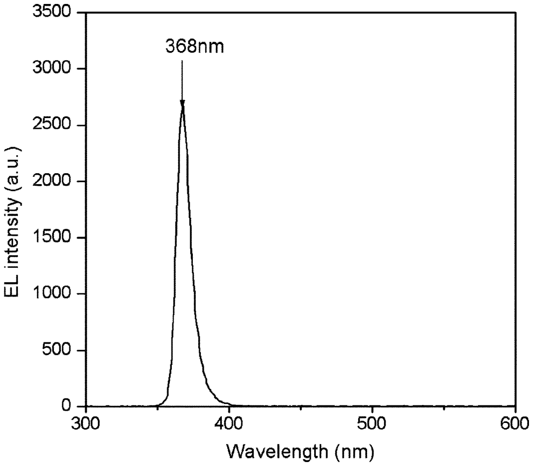

Fig. 3. Emission spectrum of a representative single element driven at 0.5 mA.

is mainly due to the contribution of the p-ohmic contact and the QW structure. These results indicate that the resistance of n-GaN stripe should be taken into account for designing an array device having a narrow n-GaN stripe as an electrode, otherwise the operating voltage will vary with pixel position and the light intensity accordingly. Considering the limitation on increasing the conductivity of n-GaN, we are developing an integration method to put a metal line on the sidewall of n-GaN column so that the overall design rules are maintained.

We have obtained measured light output power of more than 1 μW per element under a dc current of 0.9 mA in top (into air) emission. By contrast, bottom-emission power measurement through the sapphire substrate, by directly locating the device on the detector window (which is 4 mm apart from the actual detector) showed an output power of several microwatts at the same drive current. Although an exact comparison is difficult to make, because of geometrical and light-collection constraints, this indicates that a large amount of light cannot escape through the spreading metal contact layer in top-emission format. Therefore, adopting a thinner spreading metal layer would be beneficial for operating the device at higher output power. Fig. 3 shows the emission spectrum of a single emitter driven at 0.5 mA. The center wavelength is 368 nm, which is very close to that of the i-line (365 nm) UV light source standard for the semiconductor industry.

Preliminary tests of the device for application in mask-less photolithography have been undertaken. Individual elements from the 64 × 64 array device successfully proximity-exposed an i-line photoresist (Shipley S1800 series). The exposure time was 20 s and the resist thickness 0.3 μm. Although the actual exposed area from adjacent elements was found to overlap due to the divergence of the light emission, this points the way to improved devices of higher resolution, where the beam divergence of each element is controlled by microoptics. We are now working on integrating microlenses into the device, for such a purpose, using a UV transparent glue material which has various advantages including easy height control for focal plane adjustment and focal length control of the microlens.

IV. CONCLUSION

Matrix-addressable 64 × 64-element micro-LED arrays with 368-nm emission wavelength have been successfully fabricated and tested, and the fabrication and performance details are reported for the first time to our knowledge for such a device in the UV. Top-emission output power was measured to be 1.1 μW per element at drive currents below 1 mA. The device resistance showed a strong dependence on the n-GaN stripe length and we propose that an additional conductor should be integrated into the array device for better uniformity. Using appropriately integrated microoptics, the microarray device has a high potential as a mask-less photolithographic exposure tool, amongst a wide range of other uses.

ACKNOWLEDGMENT

The authors express their thanks to Dr. C. Bryce of Glasgow University for support on metal deposition.

REFERENCES

[1] D. Morita, M. Sano, M. Yamamoto, T. Murayama, S. Nagahama, and T. Mukai, "High output power 365 nm ultraviolet light emitting diode of GaN-free structure," *Jpn. J. Appl. Phys.*, vol. 41, pp. L1434–L1436, 2002.

[2] T. Wang, Y. H. Liu, Y. B. Lee, J. P. Ao, J. Bai, and S. Sakai, "1 mW AlInGaN-based ultraviolet light-emitting diode with an emission wavelength of 348 nm grown on sapphire substrate," *Appl. Phys. Lett.*, vol. 81, pp. 2508–2510, 2002.

[3] M. Iwaya, S. Takanami, A. Miyazaki, Y. Watanabe, S. Kamiyama, H. Amano, and I. Akasaki, "High-power UV-light-emitting diode on sapphire," *Jpn. J. Appl. Phys.*, vol. 42, pp. 400–403, 2003.

[4] M. Yamada, T. Mitani, Y. Narukawa, S. Shioji, I. Niki, S. Sonobe, K. Deguchi, M. Sano, and T. Mukai, "InGaN-based near-ultraviolet and blue-light-emitting diodes with high external quantum efficiency using a patterned sapphire substrate and a mesh electrode," *Jpn. J. Appl. Phys.*, vol. 41, pp. L1431–L1433, 2002.

[5] J. P. Zhang, S. Wu, S. Rai, V. Mandavilli, V. Adivarahan, A. Chitnis, M. Shatalov, and M. A. Khan, "AlGaN multiple-quantum-well based, deep ultraviolet light-emitting diodes with significantly reduced long-wavelength emission," *Appl. Phys. Lett.*, vol. 83, pp. 3456–3458, 2003.

[6] K. Mayes, A. Yasan, R. McClintock, D. Shiell, S. R. Darvish, P. Kung, and M. Razeghi, "High-power 280 nm AlGaN light-emitting diodes based on an asymmetric single-quantum well," *Appl. Phys. Lett.*, vol. 84, pp. 1046–1048, 2004.

[7] A. J. Fischer, A. A. Allerman, M. H. Crawford, K. H. A. Bogart, S. R. Lee, R. J. Kaplar, W. W. Chow, S. R. Kurtz, K. W. Fullmer, and J. J. Figiel, "Room temperature direct current operation of 290 nm light-emitting diodes with milliwatt power levels," *Appl. Phys. Lett.*, vol. 84, pp. 3394–3396, 2004.

[8] 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, pp. 1516–1518, Nov. 2003.

[9] ——, "A novel fabrication method for a 64 × 64 matrix-addressable GaN-based micro-LED array," *Phys. Stat. Sol. (a)*, vol. 200, no. 1, pp. 79–82, 2003.

[10] C. W. Jeon, K.-S. Kim, and M. D. Dawson, "Fabrication of 2-dimensional InGaN-based micro-LED arrays," *Phys. Stat. Sol. (a)*, vol. 192, no. 2, pp. 325–328, 2002.

[11] H. X. Wang, H. D. Li, Y. B. Lee, H. Sato, K. Yamashita, T. Sugahara, and S. Sakai, "Fabrication of high-performance 370 nm ultraviolet light-emitting diodes," *J. Cryst. Growth*, vol. 264, pp. 48–52, 2004.

[12] C. Griffin, E. Gu, H. W. Choi, C. W. Jeon, G. McConnell, J. M. Girkin, and M. D. Dawson, "Beam divergence measurements of InGaN/GaN micro-array light-emitting diodes using confocal microscopy," *Appl. Phys. Lett.*, submitted for publication.

[13] P. Gueret, P. Buchmann, K. Daetwyler, and P. Vettiger, "Resistance of very small area ohmic contacts on GaAs," *Appl. Phys. Lett.*, vol. 55, pp. 1735–1737, 1989.