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Fabrication and Characterization of Monolithic GaN Blue Light-Emitting Diode in Wheatstone Bridge Configuration for High-Voltage Operation

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***Abstract*— In this study, we report fabrication and characterization of monolithic GaN-based alternating current (AC) blue light-emitting diode with 6 numbers of microchips connected in Wheatstone bridge configuration. The 4 numbers of microchips out of six were illuminated in each bias direction. The size of each micro-LED chip is 500 µm x 500 µm and the total size of AC-LED chip is ~ 1.7 mm x 1.2 mm. Reactive ion etching was used for isolation of each micro-LED chip. Ti/Au (10/300 nm) metal layers were used for interconnection of each micro-LED chip. The measured output power by integrating sphere on wafer level under 20 V dc is ~ 30 mW. The blue shift of peak wavelength (477.38 nm to 466.48 nm) was observed under injected current between 5 mA to 30 mA.**

Keyword- GaN, quantum wells, light-emitting diode, Wheatstone bridge, alternate current, high voltage.

I. INTRODUCTION

Last few years, conventional direct current (DC) operated GaN based light emitting diodes (LEDs) [1-2] have attracted great attention for various applications such as, traffic signals, backlight for phones, full color display, automotive, lighting applications etc. LED based lightings have various advantages such as high efficiency, low cost, environmentally friendly and long life time over traditional light sources such as incandescent bulb as well as compact florescent lamp (CFL). The conventional LEDs are designed to operate direct current (DC) power only. The conversion of AC to DC requires various electronic components like rectifier, transformer and other electronic components, which make its hefty, shorter lifetime and less energy efficient (20-30% energy loss during conversion). All these limitations make obstacles to LEDs for lighting applications. Therefore, a new approach or design is needed to operate LED chip directly on AC power. The AC-LED chip is composed of numerous micro-LED chips that are internally connected in different ways such as in series, antiparallel, or Wheatstone bridge (WB) configurations [3-6]. The AC-LED chip design based on Wheatstone bridge configuration has one major advantage i.e. more light emitting area compared to series or antiparallel design e.g. in series connected design only half amount of micro-LED chips are ON for first half positive cycle of AC source and rest half amount of micro-LED chips are OFF, while for first negative half cycle, the rest half amount of micro-LED chips are in ON and half amount of micro-LED chips are OFF, but in Wheatstone bridge design, the micro-LED chips are arranged in 4 rectifying branches and a group of micro-LED chips are to output branch. The micro-LED chips connected to output branch are always ON for both cycles (positive and negative) of AC source, because they are always forward bias condition. The micro-LED chips in output branch increase more utilization area compare to series or antiparallel design of AC LED chip.

In this paper, we present fabrication and characterization of a monolithic blue LED in Wheatstone bridge configuration that can be operated directly under ac voltage.

II. DEVICE FABRICATION

The GaN epitaxial material used in this study was grown on c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD) system. Fig. 1 shows the schematic of the InGaN/GaN MQWs AC blue LED structure. The structure consists of a low temperature (500 ^{0}C) grown ~ 25 nm thick GaN nucleation layer, ~ 1 µm thick buffer GaN, ~ 2 µm thick n-GaN layer (Si-doped), five InGaN/GaN multiple quantum wells (MQWs), a 20 nm thick $Al_{0.2}Ga_{0.8}N$ electron blocking layer (Mg doped) and a Mg-doped p-type GaN contact layer. To activate Mg, sample was annealed in rapid thermal annealing (RTA) system in nitrogen ambient. To fabricate GaN AC-blue LED, BCl_3 and Cl_2 based chemistry was used to isolate micro-LED chips using Sentech (model; SI 590) reactive ion etching (RIE). For complete isolation of each micro-LED chip from each other, an isolation trench (30 µm wide) was etched up to sapphire through n-GaN layer using RIE. The mask for deep etching process consisted of e beam deposited Ni (270 nm) and double coated photoresist (Shipley 1818) layers (~ 3.6 µm thick) above. After isolation, GaN epilayers were etched until exposed of n-GaN for formation of n-contact. A transparent current spreading layer of Ni/Au (5/5 nm) was evaporated by electron beam system on p-GaN. This current spreading layer is also served as p-electrode. The p-contact was annealed in rapid thermal anneal (RTA) system at 550 ^{0}C for 5 min in N_2+O_2 ambient to reduce contact resistance. Cr/Au (30/50 nm) was evaporated by e-beam system on exposed n type GaN surface and served as n-contact. A low temperature (300 ^{0}C) plasma enhanced chemical vapor deposition (PECVD) deposited SiO_2 (500 nm) was deposited on samples for passivation. The SiO_2 was etched from p-and n-electrodes by reactive ion etching for metal interconnection between micro-LED chips. The Ti/Au (30/300 nm) multilayer metals were evaporated on samples by electron beam system and followed by lift-off process. These metal layers works as electrical connection between micro-LED chips and pads for probe tips. Figs. 3 and 4 show the SEM and photomicrographs of fabricated GaN AC-LED. The white regions in SEM photographs are due charging effect because of SiO_2.

In this study, the fabricated WB AC-LED was composed of total 6 micro-LED chips. The four micro-LEDs chips (LED1, LED2, LED3 and LED4) were arranged in four rectifying branches and 2 micro-LEDs (LED5 and LED6) were in output branch as shown in Fig. 2. The micro-LED chips (LED1, LED2, LED3 and LED4) are served as rectifiers in transforming the input AC signal into DC and LED5 and LED6 always under forward bias condition. The dimension of each micro-LED chip was 500 µm x 500 µm and total dimension of AC-LED chip was ~ 1.7 mm x 1.2 mm. The current-voltage (I-V), output power versus injection current (L-I) were measured by probe station system along with integrating sphere and LED tester at room temperature and shown in Fig. 6a and Fig. 6b. The electroluminescence (EL) spectra of blue AC-LED chip was also measured at different current from 5 mA to 30 mA and shown in Fig. 8.

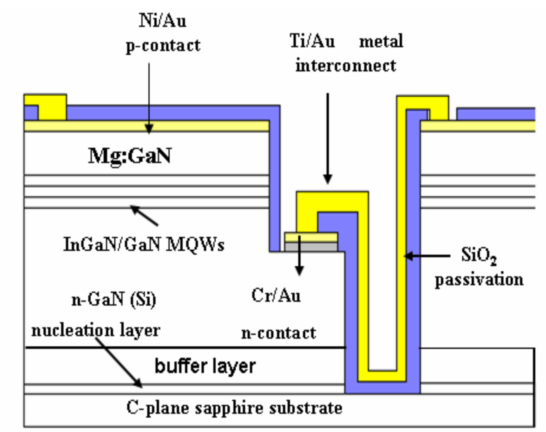

Fig. 1 Schematic structure of the GaN blue alternating-current (AC) light-emitting diode.

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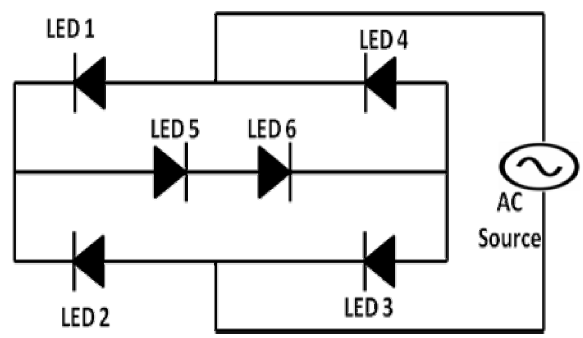


Fig. 2 Circuit diagram of Wheatstone Bridge AC-LED

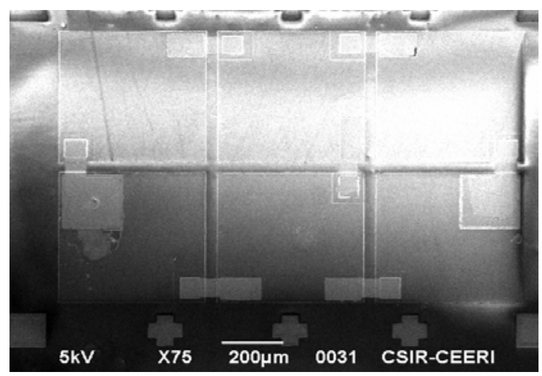


Fig. 3 SEM picture of the fabricated GaN blue alternating-current (AC) light-emitting diode.

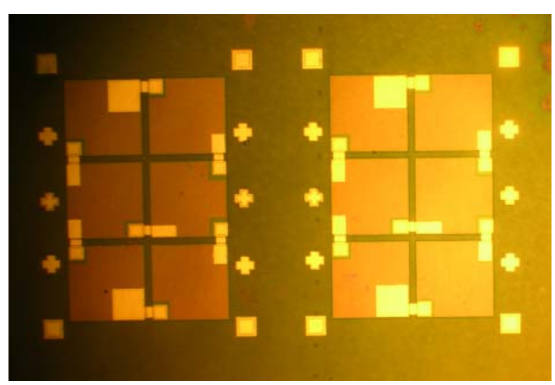


Fig. 4 Photograph of fabricated high voltage GaN AC blue LED in Wheatstone bridge configuration

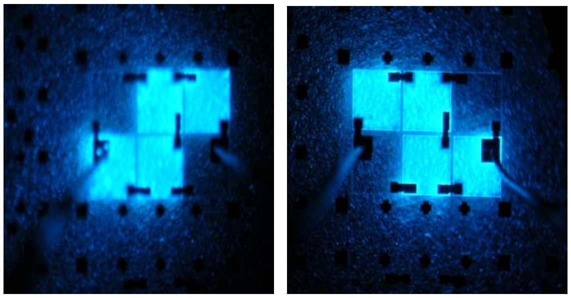


Fig. 5 Top view photographs of the AC blue LED illumination under (a) positive and (b) negative dc voltage (13V).

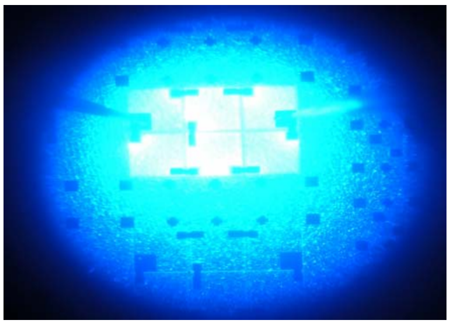
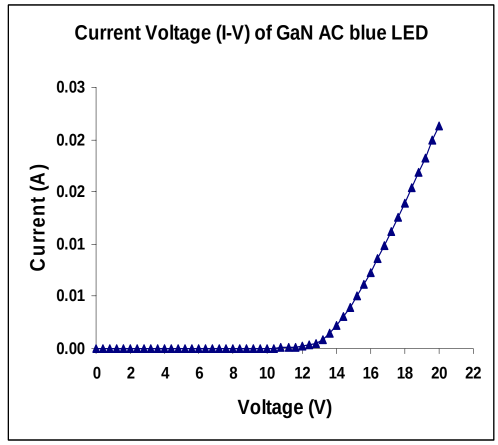


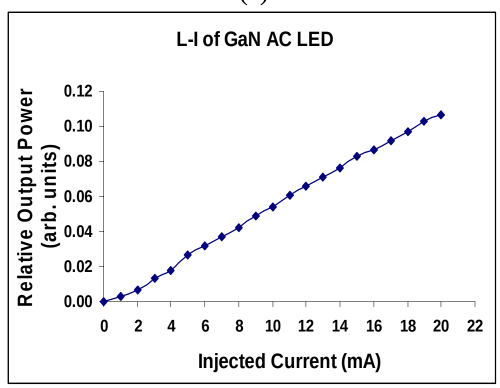
Fig. 6 Top view photographs of the AC blue LED driven by 24V AC.

III. RESULTS AND DISCUSSIONS

The fabricated AC blue LED with Wheatstone bridge configuration was characterized on wafer under dc and ac voltages. When a device array was positively biased (13 V DC), first group of 4 LEDs (Fig. 5 (a)) turned on and two were OFF and when polarity was changed the second group of 4 LEDs (Fig. 5 (b)) turned on and two were OFF. Figure 6 shows the photomicrograph of 24 V AC operated AC blue LED. The relative output power of AC-LED chip as a function of injection current is shown in Fig. 7(b). The total voltage drop @ 20 mA was 19.6 V. The voltage drop each micro-LED chip was ~ 4.9 V. The high forward voltage across each micro-LED may be due to large series resistance. Figs. 7 (a)) and (b) shows the current-voltage (I-V) and output power-current (L-I) characteristics of fabricated AC-LED under DC. The output power versus injection current (Fig. 7 (b)) nearly increases linearly. In order to measure output power of AC LED chip at wafer level, the sample was put directly on chuck of probe station attached with LED tester with 4 inch diameter integrating sphere for measurement of optical power without sapphire substrate thinning and packaging. Two probe tips were contacted to p- and n-electrode of chip to apply dc voltage. The measured output power of about 30 mW was obtained under 20V (dc) by calibrated integrating sphere. The measured output power should be much higher after thinning of sapphire substrate (~ 80 µm) and suitable packaging because light coming out from sapphire substrate side was not collected by integrating sphere. Moreover, thermal management is also big issue because sapphire has low thermal conductivity (~ 35 W/m.K). Also, the thinning of sapphire substrate may reduce the residual compressive stress in GaN layers and due to which there may be a reduction of the piezoelectric fields in QWs and which results the reduction in quantum confinement stark effect in InGaN/GaN MQWs active region [7] i.e. increase in internal quantum efficiency. The electroluminescence (EL) spectra blue AC-LED chip was measured at different current from 5 mA to 30 mA and shown in Fig. 8. The peak wavelength shifts from 478.39 nm to 466.48 nm with injection current from 5 to 30 mA. The shift in peak wavelength should be attributed due to band filling effect [8-9].



(a)



(b)

Fig. 7 (a) Current-voltage (I-V) characteristics (b) light output power versus injected current (L-I) of fabricated GaN AC blue LED.

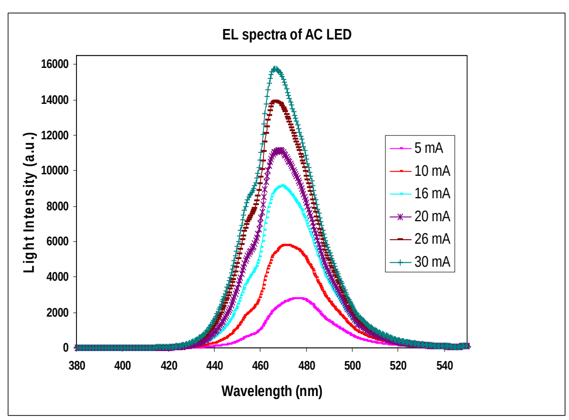


Fig. 8 Room temperature EL spectra of InGaN/GaN MQWs AC- LED at different injection current (dc).

IV. CONCLUSION

In this paper, we have demonstrated fabrication and operation of monolithic GaN based-AC blue LED under high voltage. Six micro-LEDs chips were connected in Wheatstone bridge configuration for better active layer utilization compared to series connected to meet ac operation. Reactive ion etching was performed for deep trenches on GaN material for micro-LED chip isolation. Two metal layer (Ti/Au) interconnects were used to connect micro-LED chips. The monolithic GaN AC blue LED was operated under dc and ac source. The on wafer measurement shows the output power was ~ 30 mW @ 20 mA (dc).

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REFERENCES

[1] S. Nakamura, T. Mukai, and M. Senoh, "Candela-class high brightness InGaN/AlGaN double heterostructure blue-light-diodes," Applied Physics Letter, vol. 64, pp. 1687-1689 (1994).

[2] M. Koike, N. Shibata, H. Kato and Y. Takahashi, "Development of high efficiency GaN-based multi-quantum- well LEDs and their applications," IEEE Journal of Selected Topics in Quantum Electronics, vol. 8, pp. 271-277 (2002).

[3] Jin-Ping Ao, Hisao Sato, Takashi Mizobuchi, Kenji, Shunshuke Kawano, Yoshihiko Muramoto, Youn. Bae Lee, Daisuke Sato, Yasuo Ohno and Shiro Sakai, "Monolithic blue LED series for high-voltage AC operation," Phys Stat. Sol. (a) vol. 194, pp. 376-379 (2002).

[4] Hsi-Hsuan Yen, Wen-Yung Yeh and Hao-Chung Kuo,"GaN alternating current light-emitting device," Phys. Stat. Sol. (a) vol. 204, pp. 2077-2081 (2007).

[5] Giuseppe Y. Mak, Edmund Y. Lam and H. W. Choi, "Interconnected alternating light-emitting diode arrays isolated by laser micromachining," J. Vac. Sci. Technol. B vol. 29, pp. 011025-1-1-011025-4 (2011).

[6] Zhan Teng, Zhang Yang, Li Jing, Ma Jun, Liu Zhiqiang, Yi Xiaoyan, Wang Guohong, and Li Jinmin, "The design and fabrication of a GaN-based monolithic light-emitting diode array," Journal of semiconductors vol. 34, pp. 094010-1-094010-4 (2013).

[7] www.semiconductortoday.com/news_items/2014/JAN/CNU_020114.shtml

[8] Y. K. Su, G. C. Chi, J. K. Sheu, "Optical properties in InGaN/GaN multiple quantum wells and blue LEDs," Optical Materials vol. 14, pp. 205-209 (2000).

[9] S. J. Chang, W. C. Lai, Y. K. Su, J. F. Chen, C. H. Liu and U. H. Liaw, "InGaN-GaN multiquantum-well blue and green light-emitting diodes," IEEE Journal of Selected Topics in Quantum Electronics, vol. 8, pp. 278-283 (2002).

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