406 MHz Modulation Bandwidth of GaN-Based Light-Emitting Diodes with Improved Transparent p-Contact Design

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Abstract

In this report, the optical frequency responses of GaN-based LEDs with different p-contact designs are presented. The higher modulation bandwidth is owing to better current spreading with embedded transparency contact layer (TCL). The f_{-3dB}-J curve of the LEDs with TCL exhibits higher injection current density and optical modulation bandwidth. The highest f_{-3dB} up to 406 MHz is achieved.

Introduction

The wireless network will be the fastest-growing category which is caused by the rise of the mobile devices equipped Wi-Fi and Bluetooth. Visible light communication (VLC) will be the next generation green and smart technology, and a great potential market owing to several advantages such as license-free spectrum range, high security, and electromagnetic interference (EMI) free [1-3]. Gallium Nitride (GaN) based light-emitting diode is one of today's most rapidly-developing lighting technologies due to its high efficiency. In addition to lighting application, GaN-based LEDs as VLC sources is also available and promising as a solution for dramatically increasing wireless data traffic in radio frequency (RF) [4-10]. However, different design kits for high frequency modulation such as transparency contact layer (TCL), mesa size and shape still not be discussed. In this letter, we demonstrated how different designed p-contact layer affect the DC and RF characteristics of high speed LEDs. The designed LEDs with TCL (W/ TCL) owns higher current density, which is the main reason of higher optical modulation bandwidth.

Device Fabrication

The device fabrication process of the designed LEDs (W/ TCL) starts with Ni/Au transparency p-contact layer deposition followed by mesa etching in a inductively coupled plasma (ICP) etching system. The Ti/Au based metal stacks are used for forming n-contacts. All contacts are annealed with RTA 600°C. Deposition of a polyimide layer and the reactive-ion etching (RIE) were used for via hole open. A GSG (ground-signal-ground) RF contact pad (Ti/Au) was deposited for the characterization of frequency response. The schematic side view and the OM image of the LEDs (W/ TCL) are shown in Fig. 1(a) and Fig. 1(b). The LEDs (W/O TCL) were also fabricated using the same procedure as the LEDs (W/ TCL) except for using lift-off process to form p-contact layer (Pd/Au). The light-emitting area is defined by the p-mesa square shape with five kinds of length L (10, 20 ,30 ,40, and 50 μm).

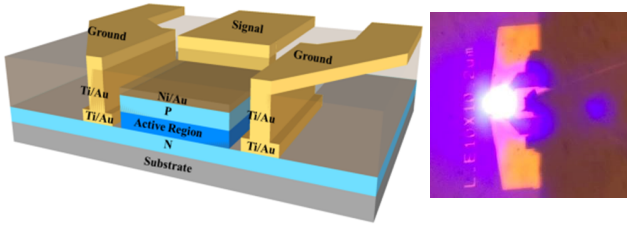
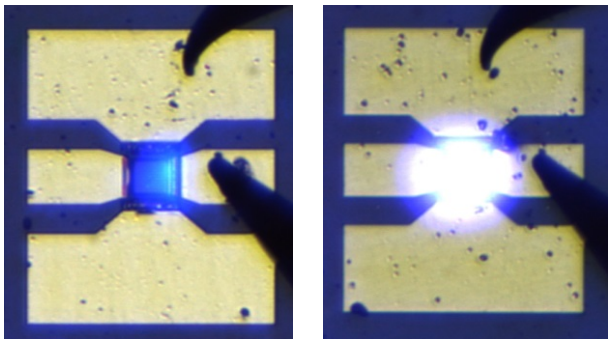


Fig. 1. (a) Schematic of the designed LED (W/ TCL); (b) The OM image of the designed LED (W/ TCL) under the injected current of 5 mA.

Experimental Results and Discussions

The OM images of the two designed LEDs with mesa size of 50x50 μm^2 under the injected current of 0.5mA are shown in Fig. 2(a) and Fig. 2(b). The designed LEDs (W/O TCL) shows weaker light output and less light transmission area.



(a) W/O TCL (b) W/ TCL

Fig. 2. (a) The OM image of the designed LEDs (W/O TCL); (b) The OM image of the designed LEDs (W/ TCL).

The L-I-V curves of the two designed LEDs are shown in Fig. 3(a) and Fig. 3(b). The LEDs (W/ TCL) exhibit the lower turn-on voltages (~5-6V) due to the lower contact resistance (larger contact area). Owing to the embedded transparent p-contact, the magnitude of penetrating light can be much stronger than the LEDs (W/O TCL). The spontaneous optical frequency responses for the LEDs (W/ TCL) with mesa size of 10x10 μm^2 are shown in Fig. 4. The optical modulation bandwidth (f_{-3dB}) increases with increasing injected current from 10mA to 50mA. The highest f_{-3dB} of 406 MHz is obtained under the injected current of 50 mA. Fig. 5 shows the f_{-3dB}-J curve with the two designed LEDs. The f_{-3dB} is proportional to $(J)^{0.233}$ and $(J)^{0.215}$ for the LEDs (W/ TCL) and (W/O TCL). Moreover, the LEDs (W/ TCL) show higher injection current density (J) and f_{-3dB}. Table I summarize the two designed LEDs of DC and RF performance. With the embedded transparent contact layer, current crowding effect dramatically decreased under the same injected current. Therefore, more light output, current injection, and optical bandwidth is obtained with the LEDs (W/ TCL).

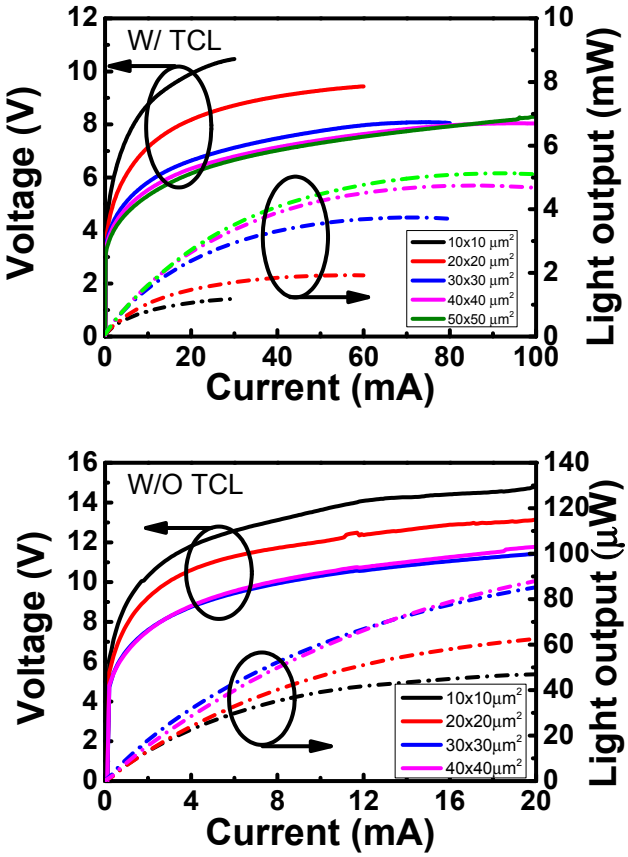


Fig. 3. (a) LIV curve of the designed LEDs (W/ TCL); (b) LIV curve of the designed LEDs (W/O TCL).

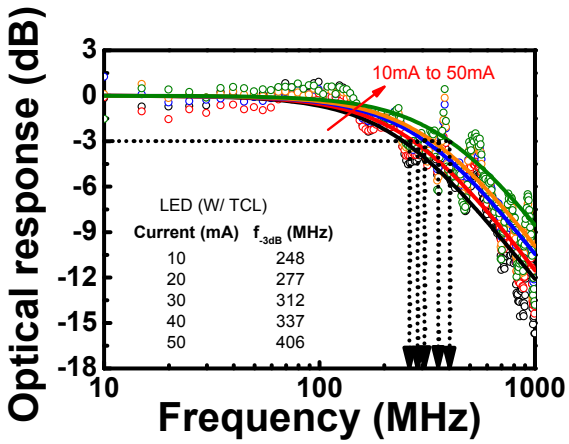


Fig. 4. Optical frequency response of the design LEDs (W/ TCL).

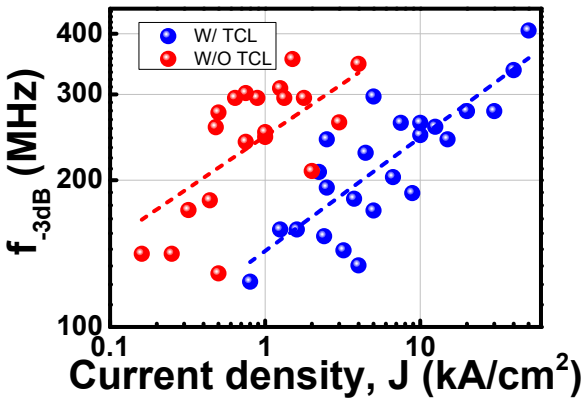


Fig. 5. The f_{-3dB}-J curve of the two design LEDs.

TABLE I.
COMPARISON OF THE TWO DESIGN LEDS

Sample	Current Density	Light Output	Highest f_{-3dB}
W/ TCL	50 kA/cm^2	5.1 mW	406 MHz
W/O TCL	4 kA/cm^2	0.09 mW	355 MHz
Improvement	12.5 times	56.7 times	1.14 times

CONCLUSIONS

In conclusion, the L-I-V curve and the optical frequency response of the two designed LEDs with TCL and without TCL are demonstrated. With embedded TCL, 14% high-speed performance improvement and ~50 times the light output power with ~2.5 times the injection current are obtained. The highest optical modulation bandwidth of 406 MHz is achieved. In the application of VLC, our report shows the great potential of the GaN-based LEDs for high speed communication.

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REFERENCES

[1] T. Komine, et al., "Fundamental Analysis for Visible-Light Communication System using LED Lights," IEEE Transactions on Consumer Electronics, vol. 50, no. 1, February 2004.

[2] H. Elgala, et al., "Indoor Optical Wireless Communication: Potential and State-of-the-Art," IEEE Communications Magazine, September 2011.

[3] S. Rajbhandari, et al., "A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications," Semicond. Sci. Technol., January 2011.

[4] J. J. D. McKendry, et al., "High-speed visible light communications using individual pixels in a micro light-emitting diode array," IEEE Photon. Technol. Lett., vol. 22, no. 18, pp. 1346–1348, Sep. 15, 2010.

[5] J. J. D. McKendry, et al., "Visible light communications using a CMOS-controlled micro-light-emitting-diode array," J. Lightw. Technol., vol. 30, no. 1, pp. 61–67, 2012.

[6] D. Tsonev, et al., "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μ LED," IEEE Photon. Technol. Lett., vol. 26, no. 7, pp. 637–640, Apr. 1, 2014.

[7] C. L. Liao, et al., "High-speed GaN-based blue light-emitting diodes with gallium-doped ZnO current spreading layer," IEEE Electron Device Lett., vol. 34, no. 5, pp. 611–613, May 2013.

[8] C. L. Liao, et al., "High-speed light-emitting diodes emitting at 500 nm with 463-MHz modulation bandwidth," IEEE Electron Device Lett., vol. 35, no. 5, pp. 563–565, May 2014.

[9] Y.-F. Yin, et al., "High-speed modulation from the fast mode extraction of a photonic crystal light-emitting diode," Appl. Phys., vol. 119, no. 1, p. 013103, Jan. 2016.

[10] C. H. Lin, et al., High modulation bandwidth of a light-emitting diode with surface plasmon coupling," IEEE Transactions on Consumer Electronics, vol. 63, no. 10, October 2016.

ACRONYMS

LED: Light Emitting Diode
VLC: Visible Light Communication
TCL: Transparency Contact Layer
ICP: Inductively Coupled Plasma