Improving the -3dB bandwidth of medium power GaN-based LEDs through periodic micro via-holes for visible light communications

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Abstract— Medium power GaN-based light emitting diode (LED) chips with periodic micro via-holes are designed and fabricated. The active area of each chip is $200\mu\text{m}\times 800\mu\text{m}$ and the diameter of each micro via-hole is $50\mu\text{m}$. For comparison, an LED chip with only one big via-hole (Diameter = $86.6\mu\text{m}$) is also fabricated under the same conditions as the control partner. Both kinds of LED chips have an equal effective PN junction area. Experimentally, the LED with periodic via-holes exhibits higher output optical power and the -3dB modulation bandwidth by about 33% and 48%, respectively, than the LED with only one bigger via-hole. The method of concurrently improving modulation and optical performances of power-type LED chips through periodic micro via-holes take the advantages of easy fabrication, suitable for mass-production.

Keywords: LED with periodic micro via-holes, blue LED, Visible-light Communication (VLC), -3dB modulation bandwidth.

1. Introduction

Gallium Nitride (GaN) based light emitting diodes (LEDs) have been considered as the next generation lighting source due to its high efficiency, long lifetime, and high brightness. Thanks to the rapid success of commercial white LEDs, visible light communication (VLC) based on LEDs is expected to be a strong competitor of next generation high speed wireless communications. VLC has many advantages: a license-free of THz bandwidth, no electromagnetic interference, good safety, etc. [1]. However, the commercially available medium and high power LEDs (e.g. OSRAM™) only have very narrow bandwidth, about several MHz, hindering the development of high speed VLC systems.

Significant research efforts are being directed towards the development of high speed power-type LEDs. Many methods, such as blue filtering, equalization (e.g. pre-equalization [2-3] and post-equalization [4-5]), and other special methods, had been proposed to improve the -3dB modulation bandwidth. H. L. Li *et al.* showed the phosphor-based white LED had ~132MHz -3dB bandwidth with optimized analog equalizers [6]. Tian P *et al.* designed GaN-based 10×10 micro-pixelated LED (μLED) arrays and the μLED with a diameter of 45 μm demonstrated a high electrical-to-optical modulation bandwidth of up to ~270 MHz [7]. Such μLED arrays exhibited great potentials for high speed optical interconnects. D. H. Kwon *et al.* proposed an equalization design with pre-equalization and blue filtering, which extended the -3dB modulation bandwidth to ~180MHz [8]. C. H. Yeh *et al.* demonstrated an optimal analogue front end circuit to increase the modulation bandwidth of phosphor-LED. Without using blue filter and post equalization, ~32MHz modulation bandwidth was achieved [9]. Y. C. Lee *et al.* designed a white light LED driver which combined with the pre-equalizer technology. The optical modulation bandwidth could be increased to 10.9MHz [10]. However, these methods had characteristics of high-cost, complex, low-yield, etc. Improving the -3dB bandwidth at the LED chip level is desired.

For power-type LEDs, the poor current spreading and the resulted severe current-crowding always damaged their optical-electrical performances. Optimizing the LED chip design through special n-contact electrodes had been reported to improve the current spreading [11-14]. Lv. J. J et al. reported that the LED chip with distributed via-holes exhibited great impact on the current spreading and the subsequent optoelectronic characteristics. Based on the thermal and parasitic resistance analysis, Yin L.Q. et al. indicated that better performances of LED with through-via structure was attributed to the lower chip thermal resistance (i.e. lower heat-flux generation) and lower extra parasitic series resistance (i.e. lower voltage parameters) compared with conventional LED chips. The series resistance was caused by the current-spreading structure and the gold wire connection. In ref [15], a current-confined aperture was proved to broaden the -3dB modulation bandwidth of a micro-LED chip effectively.

In this paper, we intend to increase both the optoelectronic performances and -3dB modulation bandwidth of a medium power GaN-based blue LEDs through periodic via-holes. Experimentally, the luminous efficiency and -3dB modulation bandwidth of the LEDs with periodic via-holes are increased by ratios of 33% and 48%, respectively, compared with the control LEDs without periodic via-holes.

2. Experiments

Commercially available GaN-based LED epitaxy wafers are used here. The GaN-based epi-stacks are grown on the c-plane patterned sapphire substrate and consist of a 30nm-thick GaN nucleation layer, a 1.5 μm -thick undoped GaN layer, and a 5 μm -thick Si-doped n-GaN layer, an active region with five periods of InGa N /GaN multi-quantum wells (MQWs), 50nm-thick Mg-doped AlGa N and a 101nm thick Mg-doped p-GaN layer.

The device fabrication begins at immersing the wafer into boiling gaquaregia ($\text{HCl}:\text{HNO}_3=3:1$) for 10minutes, and rinsing it in running deionized (DI)water. Prior to lithography, the wafer is ultrasonically degreased by acetone, methanol, and DI

water for 5 minutes at each step, followed by N_2 blowing. After the cleaning process, mesa structures are defined by inductively coupled plasma (ICP) etching. The ICP is also used to etch away the p-GaN, MQWs, and part of n-GaN to form periodic via-holes. The Ni/Au (5nm/7nm) conductive layers are evaporated on the p-GaN surface by electron beam and are treated to form ohmic contacts by rapid thermal annealing (RTA) at 550°C for 15 min in N_2 ambient. Then, all surfaces of the chip are passivated by SiO_2 through plasma-enhanced chemical vapor deposition (PECVD). After removing the parts of the SiO_2 layer to expose the bottom of the via-holes and the p-ohmic contact, Cr/Pd/Au (20/40/200nm) multilayers are deposited to form n-pad and p-pad. Finally, the sapphire substrate is lapped and polished down to $80\mu\text{m}$; LED chips are cut into separate pieces and packaged by standard technique. The active area of each chip is $200\mu\text{m} \times 800\mu\text{m}$ and the diameter of the via-hole is designed as $50\mu\text{m}$. For comparison, an LED chip with only one big via-hole (Diameter = $86.6\mu\text{m}$), which has the same active area as the fabricated sample LEDs with periodic via-holes, is also fabricated under the same conditions, denoted as “the control LED” in the following. In other words, these two kinds of LED chips have an equal effective PN junction area, as shown in Fig.1 [16]. The fabricated LED chips are bonded onto the leadframe packages and encapsulated by standard procedures. The optical microscope images of all LEDs fabricated in this paper are shown in Fig.2. In order to exclude the effect of lower extra parasitic parameters on the improvement of -3dB bandwidth, wire bonding is used for electrode connections.

Fig.1. Fabrication processes for the two kinds of LED chips: (a) the LED chip with periodic micro via-holes, denoted as “the sample LED”; (b) the LED chip without periodic micro via-holes, denoted as “the control LED”.

Fig.2. Optical microscope images of LEDs: (a)LED with 3 periodic micro via-holes and (b)its control sample: LED without periodic micro via-holes(i.e. only one big via-hole); (c) LED with 6 periodic micro via-holes and (d)its control sample: LED without periodic micro via-holes; (e) LED with 10 periodic micro via-holes and (f)its control sample: LED without periodic micro via-holes. (g) The packaged LED. (h) The LED chip with 6 periodic micro via-holes operating at $I=10\text{mA}$.

The electroluminescence (EL) spectra and current-voltage characteristics are measured by Agilent B1500A Semiconductor Parameter Analyzer. The output power of the LEDs is measured by integrated sphere (HAAS 2000). The capacitance-voltage measurement is carried out on Agilent B1505A. The frequency responses of two LEDs are characterized by a network analyzer (Agilent 5071C) and the block diagram of the measurement setup is shown in Fig.3.

The -3dB modulation bandwidth measurement system is comprised of a network analyzer (Agilent 5071C), an amplifier, a bias-tee (mini-circuits ZX85-12G+), a DC

supply, an LED under test, and a PIN photo-detector (New port 818-BB-21A). The network analyzer provides a small-signal sine wave that is amplified to increase the LED modulation depth. The amplified signal is then coupled with the bias direct current through a bias-tee. Lights from the LED are transmitted through free space and detected by the photo-detector. Finally, the output electric signal of the photo-detector is sent to the network analyzer for generating electrical-to-optical (E-O) response curves, from which the -3dB modulation bandwidths can be evaluated.

Fig.3. Block diagram of the setup for measuring the frequency responses of LEDs.

3. Results and discussions

Electrical and optical performances of the blue LEDs with periodic via-holes and without periodic via-holes are characterized. The two kinds of LED chips are designed to have an equal effective PN junction area. Their EL spectra are compared in Fig. 4. Obviously, the LED with periodic via-holes exhibits a 4nm red shift (450nm to 454nm), a larger full-width-at-half-maximum (FWHM) and a higher light intensity compared with the control LED. The reason shall lie in the different stress states in these two kinds of LEDs. One big hole in the LED might release more growth stresses inside the epitaxy layers than periodic small via-holes, thus the blue shift may partly

be resulted from the quantum-confined stark effect (QCSE)[17,18]. But the periodic small via-holes will generate more uniform stress and current distributions in the active region than only one big hole, it is expected that the internal quantum efficiency of the LED can be improved by periodic small via-holes [11-14]. In

addition, when the

the hole/holes

perimeters

$1/\sqrt{N}$. The

total

periodic

larger

generate more

inside the LED, which can explain

wider FWHM than the control LED. A larger perimeter also means a larger sidewall area, which will benefit light extraction efficiency.

total plane area of

are equal, their

take a ratio of

N denotes the

number of the

small via-holes. A

perimeter will

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Fig.4. Electroluminescence (EL) spectra of LEDs with and without periodic micro via-holes.

Fig.5 show the I-V characteristics of the two kinds of LEDs. The turn-on voltages of the LEDs both are around 2.7V. The series resistances, which are extracted from

the above I-V curves, were about 22.98Ω and 23.8Ω , respectively. Since the series resistances have relations with current spreading, the smaller series resistance proves that the sample LED with periodic via-holes has better current spreading uniformity over the active region [11, 19].

The optical powers of LEDs with periodic via-holes and the control LED are measured and plotted as a function of the driving current from 50 mA to 350 mA, as shown in Fig.6. The LED with periodic via-holes not only exhibits higher optical powers at the same input current, but also has a larger “roll over” current value. These can safely lead to the conclusions that the periodic via-holes lead to the better uniformity of current spreading, better heat dissipation and improved the light extraction efficiency [19-21].

Fig.5. The I-V characteristics of the LEDs with and without periodic via-holes.

Fig.6. Curves showing the output power as a function of injection current for the two kinds of LEDs.

Fig.7 plot the normalized frequency responses of two kinds of LEDs at different currents. It can be seen that as the applied current increases, the -3dB modulation bandwidth also increases. The phenomenon was thought to be caused by the possible lower carrier lifetime at high current densities [7, 22]. Fig.8 further clarifies the dependence of the -3dB bandwidth on the injected current. As the forward current increases, the LED with periodic via-holes always presents a larger -3dB bandwidth.

current of 250mA, the -3dB bandwidths of the two LEDs with and without periodic via-holes are 18.4MHz and 12.5MHz, respectively. In order to verify this result, we design additional two groups (group I and group II) of medium power LED chips. The group I has a PN junction area $300\mu\text{m} \times 600\mu\text{m}$ and 6 periodic via-holes. The group II has a PN junction area $300\mu\text{m} \times 900\mu\text{m}$ and 10 periodic via-holes. The diameter of each hole is fixed at $50\mu\text{m}$.

Fig.7. The normalized frequency responses of LEDs at different currents: (a) LED with periodic micro via-holes, (b) LED without periodic via-holes.

Fig.8. The dependence of the -3dB bandwidth on the injected current for LEDs with and without periodic micro via-holes.

The dependences of the -3dB bandwidths on the injected currents for these two groups of LEDs are plotted in Fig.9. Again, the LEDs with periodic via-holes exhibit higher -3dB modulation bandwidths than their control partners for the two groups. These results demonstrated that the periodic via-holes can improve -3dB modulation bandwidth of LEDs effectively.

Fig.9. The dependence of the -3dB bandwidth on the injected current for additional two groups of LEDs with and without periodic via-holes: (a) Group I. (b) Group II.

There are two major factors limiting the modulation bandwidth, one is the minority carrier lifetime and the other is RC time constant [23-27]. The two factors have different effects on the modulation bandwidth under different current densities. The RC delay time seems to be a limiting factor only at the low current density

(<1.6KA/cm²) and the carrier lifetime plays the role at the higher current density (>1.6KA/cm²) [28]. In present experiments, the fabricated medium power LED chips work under relatively low bias current density (<1.6KA/cm²), the RC time constant shall play the major role on -3dB modulation bandwidth. Thus, the -3dB modulation bandwidth can be estimated by [29]:

$$f = \frac{1}{2\pi RC} \quad (1)$$

Where R is the series resistance and C is the diode capacitance.

The capacitances of the two LEDs are measured as a function of the applied voltage, as drawn in Fig.10. The frequency of the input electrical signals is set as 1MHz during the measurement. Combing the measurement results shown in Fig. 5 and Fig. 10, values of R and C of LEDs can be extracted. The sample LED with periodic via-holes has a smaller R value and a larger C value than the control LED, i.e. 22.98Ω versus 23.8Ω, and 403pF versus 327pF. Based on R and C values, the estimated -3dB bandwidth values of LEDs with and without periodic via-holes are 17MHz and 19MHz, respectively. Obviously, the estimated -3dB bandwidth values of LEDs with and without periodic via-holes are different from those measured. A possible explanation is R and C values may vary with the frequency of applied electrical signals. Another explanation is related with the periodic via-holes, which work just like micro-cavities. The “cavity effect” will increase the current densities of regions around the via-holes, which promotes carriers’ recombination rates locally. In other words, the periodic via-holes increase the -3dB modulation bandwidth through reducing the carrier lifetime [30]. Undoubtedly, the periodic micro-via-holes in LEDs can effectively enhance their -3dB modulation bandwidth and luminous efficiency.

Fig.10. The C-V characteristics of two LEDs with and without periodic via-holes
($f=1\text{MHz}$)

4. Conclusions

In summary, through fabricating periodic micro via-holes in LED chip, the medium power LED chip exhibits higher output optical power and the -3dB modulation bandwidth by about 33% and 48%, respectively, compared with the LED without periodic micro via-holes. The mechanism shall be due to that periodic micro via-holes improve the current spreading, heat dissipation and carriers' recombination rates. The method of concurrently improving modulation and optical performances of power-type LED chips through periodic micro via-holes take the advantages of easy fabrication, suitable for mass-production. The power-type LED with periodic micro via-holes pave a way for the application in illumination and high speed communication dual-usage VLC system.

Acknowledgments

The authors acknowledge support by the grants from Natural National Science Foundation of China (NSFC) (U1201254); Program 863 (2015AA03A101); Guangzhou Technical Plan (201510010280); Guangdong Technical Plan (2014B010119003, 2014B010122005, 2015B010113002, 2016B010111002);

Natural Science Foundation of Guangdong (2016A030313336, 2015A030312011).

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