Effect of Laser Ablation on Light Output in LED

H. Chandran*, P. Poopalan
School of Microelectronic Engineering, University Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.

*haymachandran@yahoo.com

Abstract. Surface roughening is a technique used to modify the light extraction efficiency (LEE) from a LED die. UV laser ablation was used to roughen the backside surface of LED dies by creating pore like structures which would enhance the light output. Measurements of light output before and after laser ablation were taken and modifications of the light output were analysed. The ablating source used was a 248nm pulse focused laser.

1. Introduction
Rapid development in light-emitting diode (LED) has enabled its usage in every possible application. LED is essentially a diode consisting a p-n junction which emits incoherent light when carriers are injected across a forward-biased junction [1]. It has been utilized in many applications including backlight display and illumination [2]. LEDs operate according to the principle of electroluminescence, a phenomenon in which photons are emitted due to the electronic excitation of a semiconductor material. The wavelength of the light emitted corresponds to the energy of the photon released [3].

The main limitation for LED is its inability to emit out the light generated by the die’s active layer. This is due to high refractive index mismatch between the die and the surrounding medium which causes most of the light to undergo total internal reflection (TIR). The light rays will undergo multiple reflections inside the die material which eventually will be lost as heat [4]. It is important to maximize the light extraction of LED so that more light can be given out from the die to the surrounding. The more the light given out, the brighter will be the LED. The brightness of LED directly corresponds to LEE. LEE is the ratio of number of photons emitted from LED to the number of generated photons inside the LED [5].

There are several methods proven to improve LEE which includes surface roughening and die shaping. Surface roughening is a technique of enhancing LEE by roughening the surface of the LED which can scatter the path of light trapping and significantly increase the probability for light striking the escape cone. Die shaping is another way of enhancing LEE by altering the geometrical structure of LED which will result in facet pairs no longer being parallel and possibly alter its propagation direction of reflected light [6].

In this work, surface roughening is chosen as a method to enhance the LEE of a GaN on sapphire LED. Laser ablation was used as a technique to roughen the surface of the die by introducing defect structures to the die sapphire substrate layer.
2. Background Research

2.1. LED Efficiency

LED efficiency can be described as 100% if every generated photons from injected electrons, can be given out from the LED to the surrounding [7]. Light output power (LOP) is the number of photon generated per unit time per unit volume. It is a measure of how bright a LED would be. The higher the LOP, the brighter would be the LED. LOP is directly proportional to external quantum efficiency (EQE). EQE is the ratio of emitted photons from LED to the injected electrons [5]. The equation below describes EQE.

\[ EQE = \frac{I}{\eta_{INJ}} \times LEE \times \eta_{INJ} \quad (1) \]

Internal quantum efficiency (IQE) is the ratio of generated photon inside the LED to the number of electrons injected into LED. Light extraction efficiency (LEE) is the ratio of number of photons emitted from LED to the number of generated photons inside the LED. Since LEE is the ratio of generated photon inside the chip to emitted photon from the chip, therefore LEE can be calculated using the formula below [6].

\[ \eta_{ext} = \frac{P / (hv)}{P_{int} / (hv)} \quad (2) \]

P is the optical power emitted from the active region into free space.

On the other hand, injection efficiency (\(\eta_{INJ}\)) is the ratio of the number of injected electrons to the number of electrons supplied by power source. This research deals with LEE which is related to the device geometry [6].

2.2 UV Laser Ablation

Laser ablation is a process of removing material from a sample by laser irradiation. In order to remove part of a material by laser irradiation, a certain threshold power density is required. The threshold power density to ablate the target material depends on the properties of the material, laser wavelength and pulse duration [8]. When laser beam irradiation occurs, exposed target material surface will be immediately vaporized. Since the absorption depth of UV light is very small, the layer of material affected by the beam is very thin. One laser pulse will vaporize one layer of material a fraction of micron deep [9].

3. Experimental Work

The experimental work was started with laser ablation on c-plane sapphire wafer with a thickness of 884µm in order to study how laser parameters will affect the structure of the defect produced before implementing on a real die. A KrF pulsed laser with a wavelength of 248nm was used as a laser source for the laser ablation process. One of the parameter that was studied was number of laser pulses given impinging onto the wafer. Laser pulses were increased from 10 pulses to 80 pulses while other parameters of the laser source were kept constant. The configuration of the laser source is illustrated in the Figure 1.
Figure 1. Block diagram of the KrF laser source.

Table 1. Parameters setting for laser machine.

| Parameter                           | Value |
|-------------------------------------|-------|
| Laser Energy                        | 15mJ  |
| Rectangular Variable Aperture Size (RVA) | 2mm   |
| Pulsing Time                        | 0.02s |

After completing wafer ablation, light emitted from LED die was measured. The LED die used was GaN on sapphire LED die with a dimension of 600 x 600 x 150µm. The die was probed in order to supply the voltage and complianced at 20mA. Light emitted from each side surface of the die was measured using an integrating sphere. Each side surface was measured thrice and average value was taken. Then, laser ablation on the LED die was carried out followed by measurement of light emitted from each side surface of the die after the ablation. Two sample of die were ablated for each number of laser pulses. The laser pulsing used was from 25 pulses to 150 pulses. The result obtained was plotted in a graph.

4. Result and Discussion

Light generation in LED is a result of photon emission during electron-hole pair recombination process in the multi-quantum well. Since photons are generated inside the LED die, most of the light rays are trapped inside the die due to total internal reflection. The refractive index of die material is much higher than air as for GaN on sapphire LED the refractive index of GaN material is approximately 2.4 and the refractive index of air is approximately 1. According to Snell’s law,

\[ n_{\text{die}} \sin \theta_{\text{die}} = n_{\text{air}} \sin \theta_{\text{air}} \quad (3) \]

\[ (2.4) \sin \theta_{\text{die}} = (1) \sin(90^\circ) \quad (4) \]

\[ \sin \theta_{\text{die}} = \frac{\sin(90^\circ)}{2.4} \quad (5) \]
Based on the calculation, the critical angle of GaN layer to air is 24.6243°. This means that light ray that fall in between 0° to 24.6243° may escape from the GaN layer to the air while the light rays that possesses \( \theta_{die} \) more than 24.6243° will undergo multiple reflection inside the die itself and eventually will be absorbed by the active layer. The light ray which undergoes multi reflections will also enter the substrate layer which is sapphire. The refractive index of sapphire is 1.77. According to Snell’s law,

\[
\theta_{die} = \sin^{-1} \left( \frac{\sin(90°)}{2.4} \right) = 24.6243° \quad (6)
\]

\[
\theta_{die} = \sin^{-1} \left( \frac{\sin(90°)}{1.77} \right) = 34.4° \quad (7)
\]

The critical angle of sapphire substrate to air is 34.4°. Light rays that fall in between 0° to 34.4° may escape from the substrate to the air while the light rays that possesses \( \theta_{die} \) more than 34.4° will undergo multiple reflection inside the die itself and eventually will be absorbed by the active layer. Introduction of defects to the substrate surface might enable the light ray to pass through the sapphire-air interface.

The defect at the sapphire-air interface will alter the normal for the light rays that impinge upon the defect area and will increase the possibilities for the light ray to escape into air as illustrated in Figure 2 and Figure 3. Based on Figure 2, the light ray that impinges on the surface at an angle more than 34.4° will result in TIR. When defects are applied to the surface, the normal to the surface will be altered. By making the light ray impinging at the same point of the surface, this light ray may fall inside the escape cone region which is between 0° to 34.4°. These defects are introduced on sapphire substrate by laser ablation. Laser ablation on sapphire wafer gives a better understanding on the defect structure that can be obtained by manipulating each parameter of the laser source. The most important parameter that gives a deeper defect is the number of laser pulse applied. Figure 4 shows the result of laser ablation on sapphire wafer at different laser pulse.
Based on the results obtained, the higher the number of laser pulse given on the same point, the deeper the defect obtained. The lowest depth value was obtained for 10 laser pulses which was 2.6985 µm and the highest depth value was obtained was for 80 pulses with a value of 18.3281 µm. Beam attenuator was not used for sapphire wafer ablation which results in deeper defect. When LED die was ablated without a beam attenuator the top surface of the die which consist of active layers was heavily damaged. This results in either damaged LED die or severely degraded LED die. In order to avoid these damages, a beam attenuator was used. Beam attenuator is a fused silica window with a nominal reflectance of 50% when mounted at 45° to the incoming beam. It reduces the optical strength of the laser which will result in lesser or no damage on LED die. Higher value in laser pulses, aperture size and laser energy results in deeper defect. Higher value in aperture size value results in both wider and deeper defect. Figure 5 shows laser ablated LED die at 150 pulses, 2mm aperture, and 0.02s pulsing time.

![Graph of Average Depth of Laser Ablation against Number of Laser Pulse](image1)

**Figure 4.** Graph of average depth of laser ablation against number of laser pulse.

![Backside surface of laser ablated die](image2)

**Figure 5.** Backside surface of laser ablated die.
Laser ablation does not give a visible damage to the die’s active layer due to the use of beam attenuator but it does degrade the luminous flux of the die which is the measure of LED brightness. Figure 6 shows degradation value of the die in comparison to its luminous flux before the laser ablation from the four side surfaces against the number of laser pulses given.

![Graph of Degradation of Luminous Flux of LED Die against Number of Laser Pulses](image)

**Figure 6.** Graph of degradation of luminous flux of LED die against number of laser pulses.

Based on the result obtained, increase in number of laser pulse impinging backside surface of a LED die results in degradation in the light output of the die. Lowest degradation value was observed for sample B at 25 laser pulses for all the four surfaces while highest degradation value was observed for sample K at 150 laser pulses. Laser ablation of LED die degraded the quality of light production of the die even when a beam attenuator was used because the irradiation of the laser damaged the active layer of the die. Active layer is the place where generation of light occurs. When laser pulse was given to the backside surface of the die, thermal decomposition of active layer occurs [10]. Cracking and melting of the active layer resulted in lower luminous flux of the LED die. The degradation value is not the same for the dies ablated at same number of pulses because every die has a different value of luminous flux even before ablation. Since average value of dies were not taken, value difference in degradation of luminous flux may occur.
Figure 7 shows graph of LEE degradation after laser ablation against number of laser pulses. Based on the graph, LEE degrades as number of laser pulses given increases. This is due to damage caused by the laser on dies active layer.

5. Conclusion
In short, UV laser ablation on backside surface of LED die degrades the light output since active layer of the die damages which results in lower LEE. Instead of creating defects like pores, creating roughness at the surface level may give a better light output. LED die thickness also would affect the light output as thicker substrate would absorb some of the laser shock rather than thinner substrate which will directly affect the active layer of the die. Laser parameters such as laser energy, aperture size and number of laser pulse can be reduced in order to prevent damages to the active layer.

Acknowledgements
The authors would like to acknowledge the support from the Targeted iGRASP Research Grant under a grant number of CREST/T09C1-17 from CREST and University Malaysia Perlis.

References
[1] Bourget C M 2008 An Introduction to Light-emitting Diodes HortScience 43 1944–6
[2] Jiang Y, Li Y, Li Y, Deng Z, Lu T, Ma Z, Zuo P, Dai L, Wang L, Jia H, Wang W, Zhou J, Liu W and Chen H 2015 Realization of high-luminous-efficiency InGaN light-emitting diodes in the ‘green gap’ range Sci. Rep. 5 1–7
[3] Tuite D 2013 Understanding LED Application Theory and Practice 36–4 https://www.electronicdesign.com/technologies/components/article/21796017/understanding-led-application-theory-and-practice
[4] Zhmakin A I 2011 Enhancement of light extraction from light emitting diodes Phys. Rep. 498 189–24
[5] Shen S C, Huang J and Kuo H C 2018 Nitride Semiconductor Light-Emitting Diodes (LEDs) 2nd
Ed (Cambridge: Woodhead Publishing)

[6] Li K H 2016 Nanostructuring for Nitride Light-Emitting Diodes and Optical Cavities (New York: Springer)

[7] Piprek J 2017 Efficiency droop of nitride-based light-emitting diodes Handb. Solid-State Light. LEDs 2225 99–122

[8] Schneider C W and Lippert T 2010 Laser Ablation and Thin Film Deposition (New York: Springer) vol 139 pp 89–112

[9] Rapidx R 2011 Technical Reference https://www.cateye.com/intl/support/manual/TL-LD700-R.html

[10] Lam H M, Hong M, Yuan S and Chong T C 2003 Laser Ablation of GaN / Sapphire Structure for LED Proc. SPIE Int. Soc. Opt. Eng. 4830 114–8