Estimation of light extraction efficiency in GaN-based light emitting diodes via ray-tracing modeling

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***Abstract*—Simple ray-tracing model was created to estimate the dependence of light extraction efficiency (LEE) on the shape of the light emitting diodes (LEDs). It is shown that triangularly shaped LEDs have a much greater LEE than standard rectangular devices. Furtheremore, the model is used to determine the internal quantum efficiency of InGaN LEDs grown by plasma-assisted molecular beam epitaxy.**

***Index Terms*—LED, tri-LED, numerical simulation, ray-tracing, InGaN.**

I. Introduction

Efficient light extraction from LEDs is a heavily researched topic, because external quantum efficiency (EQE), which is measurement of how efficient a LED is, strongly depends on the portion of photons emitted from the device. There are many ways to increase light extraction efficiency (LEE), for example: encapsulation in medium with light refraction index (n) value in between that of the LED and air, structurization of external surface of the device or simply using different than usual geometry of the device. This paper discuss the last approach, due to its less post-processing effort in comparison to other methods.

II. Theoretical background

A. Reflectance

Photons generated inside a LED are moving freely, until they come across one of the borders of the LED. At the air-LED interface they have a chance of escaping, determined by angle of incidence - Θ_i, refractive indices, n_1 - for the device and n_2 - for surrounding medium, to pass through or reflect back inside the crystal. Reflectance, depends on polarization and for s-polarized light (often named TE), and equals [1]:

$$R_s = \left| \frac{n_1 \cos\Theta_i - n_2\sqrt{1-(\frac{n_1}{n_2}\sin\Theta_i)^2}}{n_1 \cos\Theta_i + n_2\sqrt{1-(\frac{n_1}{n_2}\sin\Theta_i)^2}} \right|^2 . \qquad (1)$$

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Similarly, for p-polarized (TM) light reflectance equals:

$$R_p = \left| \frac{n_1\sqrt{1-(\frac{n_1}{n_2}\sin\Theta_i)^2} - n_2 \cos\Theta_i}{n_1\sqrt{1-(\frac{n_1}{n_2}\sin\Theta_i)^2} + n_2 \cos\Theta_i} \right|^2 . \qquad (2)$$

For non-polarized light reflectance equals to the average of these two values.

B. Importance of the device geometry

Since most LEDs are made from materials with a high refractive index, photons with an incidence angle above the critical angle are totally reflected back inside the LED. This means that only part of the light generated inside the LED is able to exit the crystal on the first contact with the air-LED interface. External quantum efficiency, defined as:

$$EQE = \eta \cdot LEE \cdot IQE, \qquad (3)$$

where: η - carrier injection efficiency and IQE- internal quantum efficiency, is limited with LEE, and in order to increase EQE one need to maximize both LEE and IQE.

To better understand how LEE changes with different LED base geometries, polar graphs of transmittance were made. Few simplifications were made, such as: all photons are emitted from the geometric center of base figure, sides are perfectly smooth, and there is no light absorption. For InGaN LED, emitting light of wavelength 430 (nm), transmittance graphs are shown on Fig. 1. Transmittance for photons on the first and the second contact with the interface is plotted.

From Fig. 1 one can say that triangular base shape provides better light extraction efficiency than the square shape. This is because after reflection from one side of the triangle the incident angle of the second contact increases by $\frac{\pi}{3}$.

With square geometry, incidence angle after reflection is increased by $\frac{\pi}{2}$. This specific value changes nothing in the calculated reflectance since the existence of the reduction formulas. One can see this effect as totally overlapped patterned and colored sections on the bottom of Fig. 1. Reference [2] was the first to come up with a design utilizing a triangular shape and flip-chip mounting, and named it tri-LED.

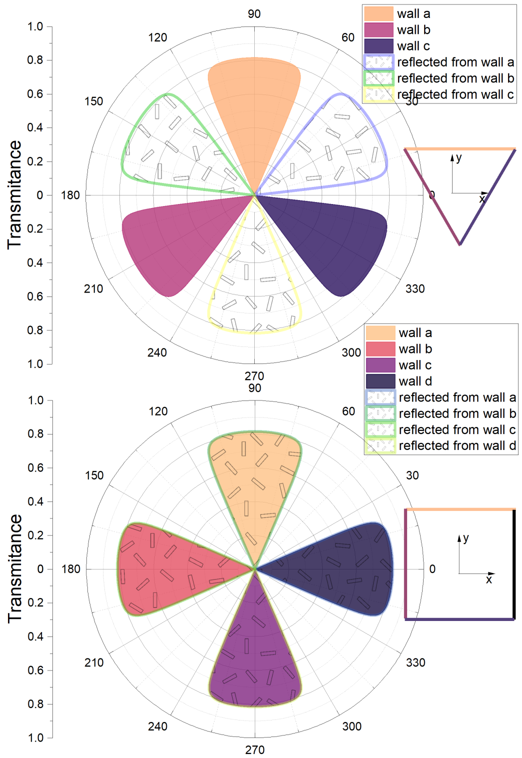

Fig. 1. Polar plots of transmittance made for two different base geometries: equilateral triangle and square. On the right from graph are color-coded sides of the base shapes.

III. Numerical Model

Three dimensional numerical model of photons moving inside the LED was created to better approximate the real behavior. Basic assumptions made to simplify simulation were: no volumetric absorption or scattering, perfectly smooth external surface of the LED, and metallization with a reflectance of 0.9 on the bottom surface of the devices. Inside the simulated LED, photon packets were ray traced from their origin, set in 3 (nm) high bottom layer, until they reached maximum number of collisions, ranging from 0 (no internal reflections) to 250. With each collision, the angle of incidence was used to calculate how much of the packet intensity was able to escape and how much was reflected. Finally these values were used to calculate LEEs, which are shown on Fig. 2.

IV. Device measurements

To confirm that in fact triangular shaped devices have greater LEE than square shaped, electroluminescence measurements of LEDs grown by us using plasma-assisted MBE were conducted. The LEDs were mounted in flip-chip manner, with Ni/Ag/Ni/Au metallization on the bottom. EQE values obtained from these measurements are shown on Fig. 3. It is important to mention that usually MBE-grown LEDs have EQE reaching nearly 1.7% [3], and by using only tri-LED design ours LEDs reached EQE of 22%.

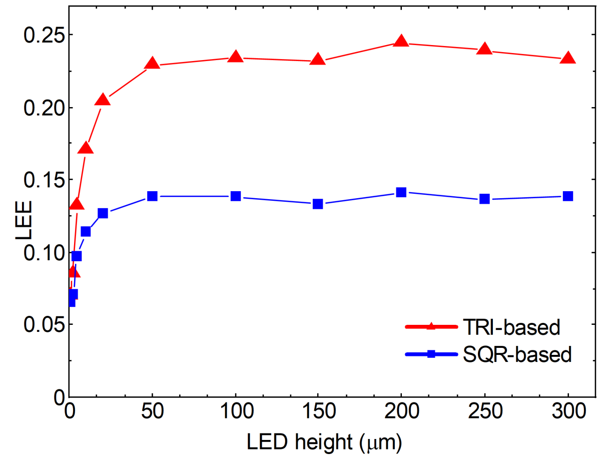

Fig. 2. Obtained from the numerical simulation LEE values for two base geometries: square and equilateral triangle.

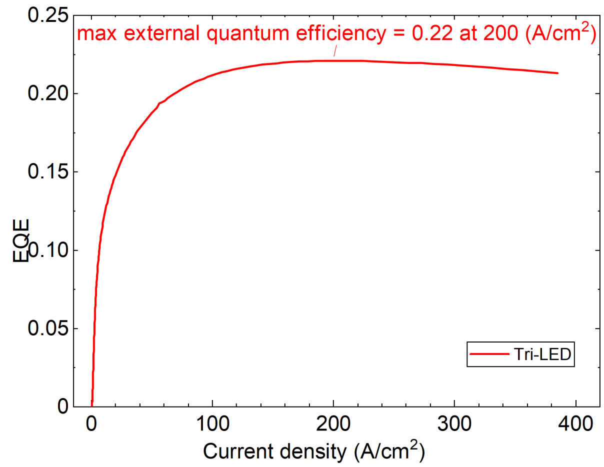

Fig. 3. EQE of InGaN tri-LED, grown by plasma-assisted MBE.

V. Conclusion

Such high EQE is a direct effect of utilizing tri-LED design, as well as very high IQE of measured device. Further improvements to simulation model, inter alia implementation of surface scattering, refraction between layers and volumetric absorption are planned to better fit model behavior to experimental data. The main reason behind creating this model was to numerically confirm that devices with a triangular base shape would have higher light extraction efficiency than square-based ones, which was confirmed.

References

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