

GEOMETRICAL ANALYSIS OF LIGHT-EMITTING DIODE FOR ENHANCING EXTRACTION EFFICIENCY

ADAM SHAARI*¹, AHMAD FAKHRURRAZI AHMAD NOORDEN¹, SAIFUL NAJMEE MOHAMAD² AND SUZAIRI DAUD³

¹International Islamic University Malaysia, Kuantan 25200 Pahang, Malaysia. ²Universiti Sains Malaysia, Penang, 11800 Malaysia. ³Universiti Teknologi Malaysia, Skudai 81310 Johor, Malaysia.

*Corresponding author: adamshaari123123@gmail.com

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Abstract: A non-uniform current spreading in the current spreader can greatly reduce the efficiency of the light-emitting diode (LED). The effects of the electrode contact area to the spreading layer towards extraction efficiency of LED chips is analysed in analytical simulations. Length of current spreading and light extraction efficiency is analysed for variation of contact area. The contact area value is varied by changing the shape of the electrode and the value of width of contact area. The increase in contact area decreases light extraction efficiency as more light are absorbed by the bottom electrode surface. The effective current spreading length for Indium Tin Oxide (ITO) of thickness 300nm is 36.44 μ m. The 6 strips 'fork' design is the most optimum. The design has the most area for photons produced in active region to escape without reducing the area cover with current density. This enables the chip to have more extraction efficiency with more uniform current spreading.

Keywords: Light-emitting diode, spreading pad, indium tin oxide, extraction efficiency.

Introduction

Light-emitting diode (LED) has become a preferred research area for its contribution in producing highly efficient and environment friendly light source (Ryu *et al.*, 2011). Increasing the efficiency of LED has been the main concern in the lighting technologies and industries (Hao *et al.*, 2016). The main factor for the reduction of efficiency of LED is a non-uniform current spreading in the LED (Wang *et al.*, 2010; Zhou *et al.*, 2017). This is highly dependent on the pattern and configuration of epitaxial-layer of the LED. This research focused on improving current uniformity in ITO and providing design with high extraction efficiency.

Gallium-Nitride-based (GaN-based) LED can have vertical design that stacks every layer on top of another to form epitaxial-layer. The design does improve LED performance significantly as larger vertical current gives lower device resistance. However, the light output was lowered as light emitted was absorbed by the n-electrode (Kim *et al.*, 2007). Electrode

pattern improvement was made by Yun *et al.* in 2009 that improves the current uniformity in mesa-structured GaN/InGaN blue light-emitting diodes (LEDs). Comparisons between an LED with a new electrode pattern taking the proposed methodology and an LED with a commercially used electrode were made by comparing both current and luminance distributions. They verified the effect of the proposed methodology by both simulations and experiments (Yun *et al.*, 2009). Another advancement was made on lateral GaN-based LEDs. The lateral current spreading (CS) effect on the efficiency droop in GaN-based LEDs was studied in terms of the CS distance. The research found a trend of improvement in the efficiency droop of LEDs with shorter CS distances. However, the effect of CS performance on ideality factors, n_{ideal} of LEDs is not significant (Huang *et al.*, 2013). Zhou *et al.* has analysed LED with discontinuous n-electrode and reflective p-electrode design on lateral LED. The effect of opaque p-electrode towards light absorption is reduced in this research as the p-electrode was made reflective

by double Cr/Pt/Au layers (Zhou *et al.*, 2013). Besides, GaN-based flip-chip LED by inserting a silver (Ag) reflector covered with diffusion barrier of tungsten-titanium (TiW) is analysed with a strip-shaped SiO₂ current blocking layer design to reduce the effect of current crowding in ITO layer. The fabricated design shows the improvements on current uniformity in ITO layer, light output power and maximum output power of the LED. The Ag reflector increases the optical reflectance while the current blocking improved the current spreading of the LE (Zhou *et al.*, 2017). Silicon Dioxide (SiO₂) blocking layer is also used to provide better extraction efficiency of the LED by blocking the concentration of current in the area right below the p-electrode and reducing the amount of light absorbed in the p-electrode (Huh *et al.*, 2002 and Zhuo *et al.*, 2015). Later in 2019, Zhuo and his team made an advancement by inserting a high reflectance of Ag film of 95.0%. The research found that the Ag-based reflector increased the light extraction efficiency (LEE) of the LED and improved the current spreading (Zhuo *et al.*, 2019). However, low current uniformity in the epitaxial layer causes low recombination rate in which reduces the chip efficiency. Big electrode increases the current uniformity but decreases the light extraction efficiency.

In this work, the research simulated improved current spreading across indium tin oxide (ITO) layer while having the design of electrode that does not reduce the extraction efficiency of a vertical LED. The research focused on analytical formulation for design of electrode with the most exposed area for photon escape from the epitaxial-layer for enhanced extraction efficiency.

Materials and Methods

Indium Tin Oxide

The experiment considered growing the layer of current spreading pad ITO on p-GaN layer for better current spreading to the p-GaN layer. The p-type GaN has low conductivity. The resistivity is bigger than 1 Ω.cm as the hole mobility in III-V nitrides is 1~20 cm²/(V s) and the concentration of hole is in the range of 10¹⁷ cm⁻³, resulting in resistivity to be bigger than 1 Ω cm (Schubert, 2018). The chosen thickness of ITO used in this research was 300nm (Li *et al.*, 2012).

Extraction Efficiency

Photons produced in the active layer must be transmitted to escape into free space from the LED chip. Extraction efficiency can be described as:

$$\eta_{\text{extraction}} = \frac{\text{number of photon emitted into free space per second}}{\text{number of photon emitted from active region per second}} \quad (1)$$

$$\eta_{\text{extraction}} = \frac{P/(h\nu)}{P_{\text{int}}/(h\nu)} \quad (2)$$

where P is the optical power emitted into free space and P_{int} is the optical power emitted from the active layer. Not every photon produced in the active layer manage to escape LED chip. This

is caused by few factors such as light absorption in the substrate of the LED, absorption by metal electrode and total internal reflection (Schubert, 2018).

Current Spreading Length

In conventional vertical LED design, the current is injected directly from the top electrode into the active region through p-type material. This will introduce more current crowding in the p-type material and resulting in low efficiency of the LED. To prevent this from happening, current spreading layer is introduced to spread the current in the p-type material, ensuring a more uniform current across the active region. The absence of the current spreading layer can result in the current-injected area in the active region to be only slightly bigger than the electrode contact area (Schubert, 2018). Current spreading layer used in this experiment is ITO. Equation (3) shows how current density, J , is related to distance from the electrode contact area

$$J(x) = \frac{2J_0}{[\frac{x-r_c}{L_s} + \sqrt{2}]^2} \quad (x \geq r_c) \quad (3)$$

where L_s is the effective current spreading length, r_c is the diameter of the electrode and x the distance in measurement relative to the center of electrode. L_s is defined by equation (4) as

$$L_s = \sqrt{\frac{tn_{ideal}kT}{\rho J_0 e}} \quad (4)$$

where ρ is the resistivity of the ITO, n_{ideal} is the ideality factor of the chip and t is the thickness of the ITO (Schubert, 2018). Table 1 shows the parameters used in this research to obtain the value of L_s .

Table 1: Parameters for spreading length calculation

Variable / Parameter	Value
t	300nm
	1.2
kT/e	25.9 mV
J0	2000000
ρ	3.51x10 ⁻⁶ Ω.m

The model used in this research assumes a constant potential and current density (J) in the area under the metal ($x < r_c$). Figure 1 illustrates how current spreading layer can affect the current flow and current density below and electrode.

Equation (3) states that the value of current density decreases with increasing value of distance to the edge of strip. To verify the pattern and compatibility of the equation with the research, an analytical formulation has been made to obtain the pattern of the graph. Equation (4) and the pattern of the graph gives the value of L_s . Figure 1 shows the pattern of current density extending away from the edge of electrode contact. L_s is the value of distance from the edge of electrode where the tangent line to the curve when x is equals to r_c intercepts the base of the ITO layer (Schubert *et al.*, 2018). Equation (4) was used to find the L_s in ITO based on the size and pattern of electrode on the ITO layer. The L_s of the ITO determined the size of electrode to effectively spread the current across the whole surface of epitaxial-layer.

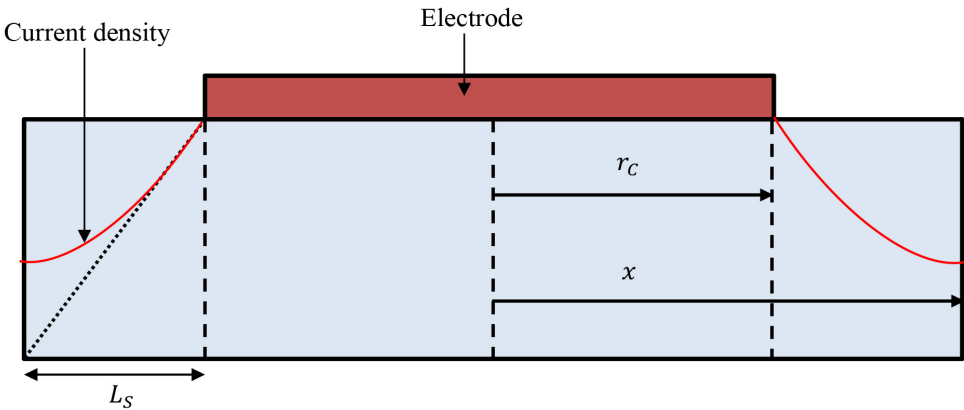


Figure 1: Schematic illustration on how current is spread inside ITO layer

Electrode

The pattern electrode is designed to have a shape that can provide sufficient current density across active region without reducing the extraction efficiency of the chip. That was done by having a maximum distance of from the edge of electrode to the edge of epitaxial-layer. Figure 2 explains the pattern of electrode for most uniform current density across active region.

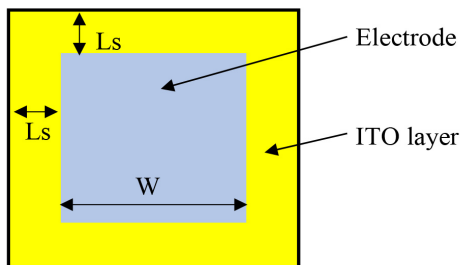


Figure 2: Top view of LED chip for design with uniform current spreading area

The design will give good current uniformity, but will allow low extraction efficiency. To increase the extraction efficiency of the LED, a fork design was proposed. The design will allow current uniformity with less area of electrode in contact with ITO. Figure 3 below explains the fork design with two strips.

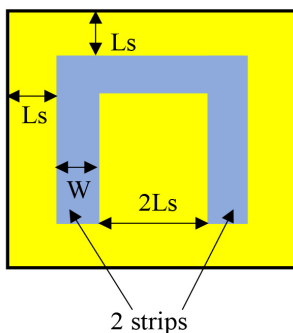


Figure 3: Top view of LED chip with fork design to maximize extraction efficiency

The research focuses on the variation of number of strips of electrode for the fork design. The area of ITO layer not covered by electrode for every variation was analyzed. The design with the biggest area not covered

by the electrode is the design with the highest extraction efficiency as it has the most area available for the generated photon in the active region to escape the chip.

Results and Discussion

Effective Current Spreading Length

The research focused on finding the effective current spreading length and also the most suitable 'fork' design for maximum exposed area for photon escape. The research found that the value of for ITO of thickness 300nm is $36.44\mu\text{m}$. The value was used to find the area of p-electrode on top of ITO. The value of provided the information needed for width, W , of electrode for every variation of number of stripes. The value of W gives the area of electrode in contact with the ITO. The area exposed is found by the difference from the total ITO area to the electrode contact area.

Electrode Design

Table 2 shows the values of area of electrode and the exposed area for photon to escape for designs with different number of strip.

Table 2 shows that the highest value of exposed area is acquired when the number of electrodes is 6 at width $10.44\mu\text{m}$. This allows for maximum extraction efficiency and uniform current spreading across the ITO. The lowest value of exposed area is acquired when the number of electrodes is 1 at width of $427.11\mu\text{m}$. This is because, for single strip electrode, the width has to be at $427.11\mu\text{m}$ for the current to be uniformly spread across ITO. Figure 5 shows the graph of comparison for value of W , area of electrode in contact and exposed area for photon escape for all 6 variants of number of stripes.

The graphs in Figure 4 show the relation of number of strips to the value of exposed area for light emission. The graphs show that the value of exposed area increases as the number of strips increases. The design with least area of contact of electrode to ITO have the least number of photons produced in the active region absorbed

Table 2: W, Area of electrode and area exposed for photon escape for every variation of number of stripes in each fork design.

Number of strip	Width of strip, W (μm)	Area of electrode in contact with ITO(m^2)	Area exposed for photon escape (m^2)
1	427.11	1.8242×10^{-7}	6.7577×10^{-8}
2	177.11	1.5144×10^{-7}	9.8563×10^{-8}
3	93.77	1.2044×10^{-7}	1.2956×10^{-7}
4	52.11	8.9464×10^{-8}	1.6054×10^{-7}
5	27.11	5.8478×10^{-8}	1.9152×10^{-7}
6	10.44	2.7483×10^{-8}	2.2252×10^{-7}

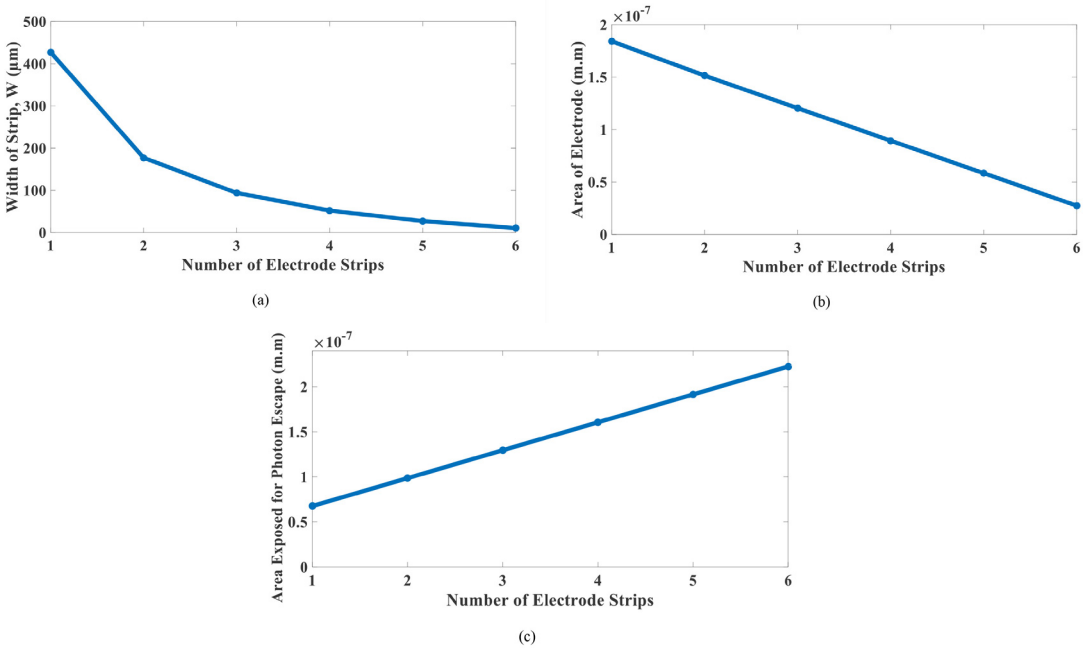


Figure 4: Comparison for (a) width of strip for each number of strips in the fork design, (b) area of electrode for every number of stripe and (c) area exposed for photon escape

by the electrode. The design with biggest area exposed for photon to escape enables more photon to escape LED chip to free region. This increases the extraction efficiency of the LED.

In summary, 6 strips design is the most optimum. The design has the most area for photons produced in active region to escape without reducing the area of effective current density spreading. Uniform current density in ITO leads to a more uniform current density in active region.

This research provide theoretical proof on how the extraction efficiency can be increased to be more than 50%. However, to further validate the calculation, ray tracing optical simulation could be done in the future to simulate a large number of photons generated in the active region to escape the chip. The bottom layer of the LED can be coated with thin layer of silver as it has 99% reflectivity thus can reflect rays generated towards the bottom to be reflected upwards. Enhancing the extraction efficiency would be a huge contribution in this field where LED is desired to have high extraction efficiency.

Conclusion

Effective current spreading length, for Indium Tin Oxide (ITO) of thickness 300nm is known, which is at 36.44 μ m. The value of is then used to find the most suitable electrode pattern using the ‘fork’ design. value is used to find the distance between electrode ‘fingers’ and distance between electrode and edge of LED dice. The most suitable design is fork design with 6 fingers. The design gives minimum electrode contact area with ITO and maximum area exposed for photon to escape, making the design has least number of photon produced in active region to be absorbed by the electrode. This research provided an analysis on the design of electrode and how to optimize the design to provide better extraction efficiency. This theoretical work will provide solutions to improve the design of LED with sufficient amount of data.

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