Ray Tracing Simulation of a GaN-based integrated LED-Photodetector System

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***Abstract*— An optical sensor system consisting of a pair of GaN LED and Photodetector (PD) is simulated using COMSOL Multiphysics, and the possibility of using this system as absorption coefficient sensor is studied. By locating both LED and PD on a same substrate and measuring transmitted power to the PD, it would be possible to sense changes in the optical parameters of the transmission path. In the present work, the gap between LED-PD pair is filled with an ink, and the optical extinction coefficient of the ink is monitored by measuring transmitted power from the LED to the PD.**

Keywords—sensor, refractive index, LED, PD

I. Introduction

GaN Light Emitting Diodes (LED) can be operated as Photodetectors (PD) just by measuring the short circuit current instead of applying a voltage. Employing this effect and by pattering the layers of an LED substrate it would be possible to integrate an LED and PD in a single device [1]. Emitted light from the LED will travel through the patterned gap on the substrate and reach the PD, and the transmitted power will depend on the optical parameters of the gap, which is filled by an ink that changes its optical properties depending on ambient conditions like presence of certain gases. By measuring PD current, we can monitor changes in optical parameters of the optical path.

Ray Tracing has been used to simulate light extraction from LEDs [2], optical microscopy [3] and sensors [4]. In this paper, the Ray Tracing module of COMSOL Multiphysics [5] has been used to model a GaN integrated LED-PD sensor, and the possibility of using this system as an absorption coefficient sensor has been studied. In the following sections the modelling process is described and the results are presented and discussed.

II. Design and Modelling

A schematic representation of the studied structure is shown in Fig 1. It consists of a pair of LED (left) and PD (right). The p-GaN and active multi-quantum well (MQW) layers between these two diodes has been etched to form a trench for the ink. On the two sides of this trench layers of SU-8 have been added to increase interaction of the light with ink, and to isolate the semiconductor layers. Thicknesses and widths of layers are given in the Table 1. At a wavelength of 450 nm, the refractive index of the GaN, Sapphire, Ink and SU-8 are 2.5, 1.7, 1.4 and 1.8, respectively.

The Ray Tracing module of COMSOL Multiphysics has been used to study propagation of the Rays from the LED to the PD. Initially, a 2D geometry has been created using the data in the Table 1. Several light sources inside the MQW layer have been added to represent the LED. We assumed these sources to emit uniformly in all directions. On the PD's side, ray detector boundary conditions have been applied, which absorb all the rays reaching PD.

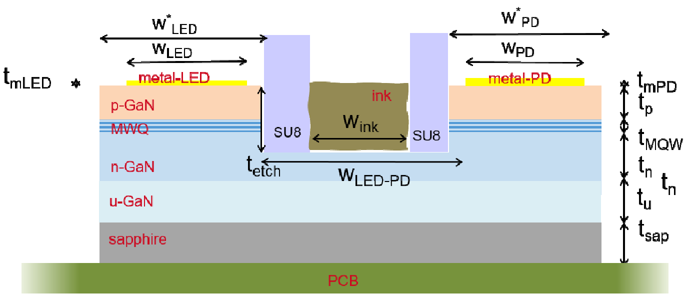

Fig. 1. Cross-section of the LED-PD optical sensor which consist of a pair of LED and PD from the same InGaN/GaN epilayer structure.

TABLE I. Thickness and Length of the Layers

Parameter	Value(μm)	Parameter	Value(μm)
W_{LED}	200	t_p	0.3
W_{PD}	200	t_{MQW}	0.6
W_{gap}	1000	t_n	3.64
W_{Ink}	500	t_u	3.2
t_{etch}	1.2	$t_{sapphire}$	430
t_{metal}	0.013		

III. Results

As shown in Fig 2, emitted rays can reach the PD through two paths. One is direct transmission of the rays through the SU-8 and and the ink, and one is through the GaN layer underneath the ink. Due to higher refractive index of GaN compared to ink and sapphire, rays will be trapped inside the GaN layer and propagate until they are absorbed by the PD or scattered into the air or sapphire. It should be noted that only rays that travel inside the ink are affected by the ink's absorption coefficient. In Fig 3 the power transmission from LED to the PD is plotted. In the case of ideal absorber boundary condition for printed circuit board (PCB) layer, approximately 20% of the emitted power will reach the PD. The remaining optical power is either extracted to the air or sapphire, or absorbed in the carrier PCB. However, when PCB boundary condition is assumed as an ideal mirror, rays will be reflected and directed to the PD, and as it can be seen in Fig 3 more power will reach the PD.

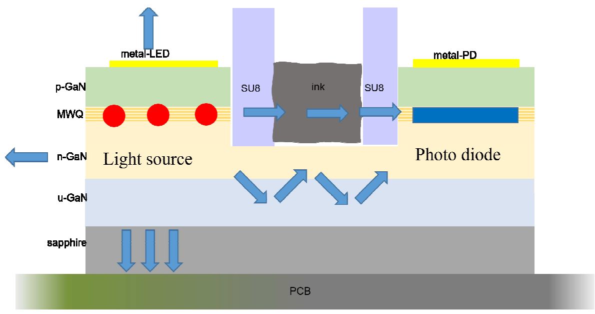

Fig. 2. Optical paths of the emitted rays from the LED

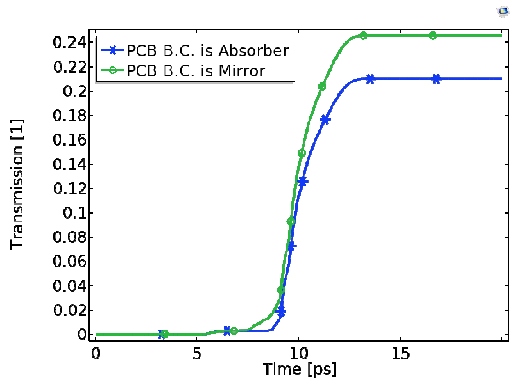

Fig. 3. Optical Transmission of the light from LED to PD, for two cases of ideal absorber and ideal mirror boundary condition for Sapphire-PCB interface.

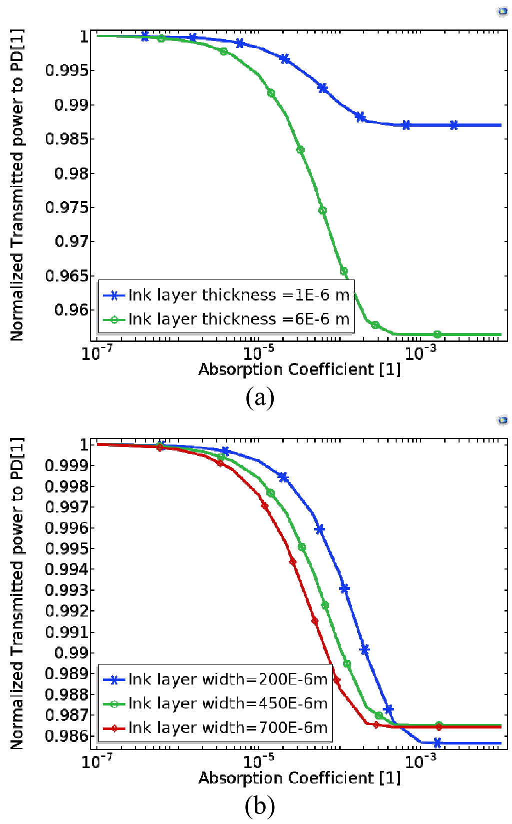

Fig. 4. Normalized transmitted power to the PD with respect to absorption coefficient of the ink (a) for ink layer thickness of 1 µm and 6 µm. (b) and ink layer's length of 200, 450 and 700 µm.

In order to study the sensitivity of the system, the absorption coefficient of the ink has been varied over several orders of magnitude. Normalized transmitted power has been plotted against ink absorption coefficient in Fig 4 (a). As the absorption coefficient increases, more power will be lost and less will reach the PD. Thickness of the ink layer also has been increased from 1 µm to 6 µm. This would allow rays to have more interaction with the ink, which leads to an increase of the sensitivity from 1.1% to 4.4%. Transmitted power is sensitive to changes of the optical extinction factor in the range of 10^{-5} to $2x10^{-4}$. One key element in modifying this range is the length of the ink-filled gap between the LED and the PD. In Fig 4 (b) the length of the ink layer has been swept from 200 µm to 700 µm, while maintaining SU-8 length constant, and normalized transmitted power has been calculated. As the length of ink layer increases, the transmission curve shifts toward lower absorption coefficients, indicating that longer interaction length of rays with ink will enable us to monitoring even smaller values of absorption coefficients.

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IV. References

[1] Wasisto, Hutomo Suryo; Prades, Joan Daniel; Gülink, Jan; Waag, Andreas, "Beyond solid-state lighting: Miniaturization, hybrid integration, and applications of GaN nano-and micro-LEDs," *Applied Physics Reviews,* vol. 6, no. 4, p. 41315, 2019.

[2] Lee, Jong Won; Kim, Dong Yeong; Park, Jun Hyuk; Schubert, E Fred; Kim, Jungsub; Lee, Jinsub; Kim, Yong-Il; Park, Youngsoo; Kim, Jong Kyu, "An elegant route to overcome fundamentally-limited light extraction in AlGaN deep-ultraviolet light-emitting diodes: Preferential outcoupling of strong in-plane emission," *Scientific reports,* vol. 6, no. 1, 2016.

[3] Moreno, Sergio; Canals, Joan; Moro, Victor; Franch, Nil; Vilà, Anna; Romano-Rodriguez, Albert; Prades, Joan Daniel; Bezshlyakh, Daria D; Waag, Andreas; Kluczyk-Korch, Katarzyna;, "Pursuing the diffraction limit with nano-led scanning transmission optical microscopy," *Sensors,* vol. 21, no. 10, p. 3305, 2021.

[4] Chataignier, Guillaume; Vandame, Benoit; Vaillant, Jérôme;, "Joint electromagnetic and ray-tracing simulations for quad-pixel sensor and computational imaging," *Optics Express,* vol. 27, no. 21, p. 30486, 2019.

[5] "COMSOL," 2022. [Online]. Available: WWW.COMSOL.COM.