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Numerical simulation of UV LED single quantum well based on AlGaN/GaN/AlGaN

***Abstract**. Optical sources such as light-emitting diodes (LEDs) are good solutions for creating more robust luminaires, with better conversion efficiency and more environmentally friendly. The objective of this work is to study and to simulate ultraviolet light-emitting diode with a single GaN quantum well sandwiched between two layers; respectively p-doped and n-doped AlGaN, using the SILVACO software. This simulation allowed us to extract different characteristics of the LED, such as the current-voltage (I-V) characteristic, the emitted light power, the spontaneous emission rate, radiative recombination, Auger recombination, Shockley-Read-Hall recombination, optical gain, luminous flux, spectral power density, overall efficiency. These simulations allowed us to extract the electrical and optical characteristics of the ultraviolet light-emitting diode with a single quantum well* based on p-AlGaN/GaN/n-AlGaN *and examine their performance.*

Streszczenie** Źródła optyczne, takie jak diody elektroluminescencyjne (LED), są dobrym rozwiązaniem do tworzenia bardziej wytrzymałych opraw oświetleniowych o lepszej wydajności konwersji i bardziej przyjaznych dla środowiska. Celem tej pracy jest zbadanie i symulacja diody elektroluminescencyjnej ultrafioletowej z pojedynczą studnią kwantową GaN umieszczoną pomiędzy dwiema warstwami; odpowiednio p-doped i n-doped AlGaN, przy użyciu oprogramowania SILVACO. Ta symulacja pozwoliła nam wyodrębnić różne charakterystyki diody LED, takie jak charakterystyka prądowo-napięciowa (I-V), moc emitowanego światła, szybkość emisji spontanicznej, rekombinacja radiacyjna, rekombinacja Augera, rekombinacja Shockleya-Readа-Halla, wzmocnienie optyczne, strumień świetlny, gęstość widmowa mocy, ogólna wydajność. Te symulacje pozwoliły nam wyodrębnić charakterystyki elektryczne i optyczne diody elektroluminescencyjnej ultrafioletowej z pojedynczą studnią kwantową opartą na p-AlGaN/GaN/n-AlGaN i zbadać ich wydajność.* (Numeryczna symulacja pojedynczej studni kwantowej diody UV LED na bazie AlGaN/GaN/AlGaN)***

Keywords: *GaN, AlGaN, UV light emitting diode, silvaco Tcad.*
Słowa kluczowe: GaN, AlGaN, dioda emitująca światło UV, silvaco Tcad.

Introduction

Gallium nitride (GaN) based solid state lighting technology has revolutionized the semiconductor industry.

The GaN technology has played a crucial role in reducing world energy demand as well as reducing the carbon footprint. As per the reports, the global demand for lighting has reduced around 13% of total energy consumption in 2018. The Department of Energy (USA) has estimated that bright white LED source could reduce their energy consumption for lighting by 29% by 2025. The last decade researchers round the globe working on III-N material to improve the existing technology and to push the limit of III-V domain. Now, With the recent development, the GaN is not only limited to lighting, but latest innovations also led the development of micro-LEDs, lasers projection and point source. These developments have pushed GaN into the realm of display technology. The miniaturization of the GaN-based micro-LED and integration of GaN on silicon driving the application into fast response photonic integrated circuits (ICs). Most of the recent advancements in GaN LED field would be discussed in detail [1]

Group III-nitrides (GaN, AlN, and InN) and their alloys have been considered the most promising semiconductor materials for various optoelectronic applications due to their excellent physical properties and stability in harsh environmental conditions [2, 3, 4]. Today, III-nitrides-based light-emitting diodes (LEDs) are widely used for solid-state lighting (SSL) applications all over the world because of their high efficiency, low power consumption, and longer lifetime than fluorescent and incandescent bulbs [5, 6]. LEDs are a more promising low-power light resource to replace conventional fluorescent. Along with LEDs, III-nitride-based laser diodes (LDs), high-power electronics, photodetectors, etc., are other extended optoelectronic applications that are also demonstrated [7, 8].

This work consists of the study and simulation of a single quantum well ultraviolet LED based on Galium nitride GaN, in this manuscript we present the results of simulations of the LED studied as well as presenting their electrical and optical characteristics.

Recent advancements in GaN LED (gallium nitride light-emitting diode) technology

Recent advancements in GaN LED (gallium nitride light-emitting diode) technology have significantly improved the efficiency, brightness, and reliability of LED lighting. GaN LEDs are known for their high energy efficiency, longer lifespan, and potential for various applications. Here are some key advancements in GaN LED technology:

1. Increased efficiency: Researchers have made significant progress in improving the efficiency of GaN LEDs. By enhancing the crystal structure and optimizing the manufacturing processes, the efficiency of GaN LEDs has increased, leading to reduced energy consumption and lower operating costs.
2. Higher brightness: Advancements in GaN LED technology have resulted in higher luminous efficacy and increased brightness levels. This improvement allows for better illumination in various applications, including general lighting, automotive lighting, and displays.
3. Enhanced color rendering: GaN LEDs have also undergone advancements in terms of color rendering index (CRI), which measures the accuracy of color reproduction. With improved phosphor materials and LED chip designs, higher CRI values are now achievable, enabling more accurate and vibrant color representation.
4. Miniaturization and design flexibility: GaN LEDs have become smaller in size, allowing for compact lighting fixtures and versatile design possibilities. This miniaturization has expanded the range of applications for GaN LEDs, including wearable devices, automotive lighting, and architectural lighting.
5. Improved thermal management: Effective heat dissipation is crucial for LED performance and longevity. Recent advancements in thermal management techniques, such as advanced packaging materials and heat sink designs, have improved the heat dissipation capabilities of GaN LEDs, leading to better reliability and longer lifespan.
6. Integration with smart lighting systems: GaN LEDs are compatible with smart lighting systems, enabling advanced control features such as dimming, color temperature

adjustment, and remote operation. This integration enhances energy efficiency and allows for personalized lighting experiences.
7. Emerging applications: GaN LED technology is enabling new applications and innovations. For example, micro-LED displays, which utilize arrays of microscopic GaN LEDs, offer high-resolution, energy-efficient displays for various devices, including smartphones, televisions, and augmented reality/virtual reality (AR/VR) headsets.
Overall, the recent advancements in GaN LED technology have paved the way for more energy-efficient, reliable, and versatile lighting solutions, with potential applications ranging from general lighting to specialized sectors like automotive, displays, and beyond.

Structure description

Figure 1 shows the studied structure of single quantum well LED.

The GaN-LED structure consists of sapphire substrate , 5 nm AlN buffer layer, 500 nm n-doped GaN cladding layer with a concentration of 1×10^{18} cm^{-3}, 60 nm n-doped $Al_{0.2}$- $Ga_{0.8}N$ cladding layer with a concentration of 1×10^{19} cm^{-3}, undoped GaN QW, 60 nm p-doped $Al_{0.2}$- $Ga_{0.8}N$ cladding layer with a concentration of 1×10^{18} cm^{-3}, and 120 nm p-doped GaN contact layer with a concentration of 1×10^{18} cm^{-3}.

The electrodes have a thickness of 15nm ; the band gaps of GaN and AlGaN are 3.4 eV and 3.8 eV respectively.

Simulation parameters of the LED

In order to simulate a device, it is necessary to determine the parameters of the materials used in the conception of the device, such as gap energy (eV), electron affinity (eV), electron and hole mobility (cm^2/Vs), lifetime of electrons and holes τn_0 and τp_0 (ns) and auger recombination $augn$And $augp$ of both materials AlGaN and GaN. These parameters are recorded in the following table 1.

Table 1. Parameters used in simulation of of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

Parameters	GaN	AlGaN
Bande gab Eg (eV)	3.4	3.8
Electronic affinity (eV)	4.23	3.98
Mobility (cm^2/Vs)	mun_0=100 and mup_0=10	mun_0=100 and mup_0=10
Life time of electrons and holes τn_0 and τp_0 (ns)	10^{-9} 10^{-9}	10^{-9} 10^{-9}
Auger Recombination $augn$ and $augp$($cm^{-3}s^{-1}$)	10^{-34} 10^{-34}	10^{-34} 10^{-34}

Mesh

Mesh has an important role in getting a good simulation. Therefore, the utmost care must be taken to ensure reliable and accurate results. The elements that define the unit cell that the emulator uses are posts. To get good and accurate results, so the network resolution must be determined according to the changes of physical quantities. The network must be dense in the AlGaN layers. It's also very good on top and bottom. Thus, the grid designed for our structure is shown in the figure below (Figure 2).

Results and discussion

Energy band diagram

Figure 3 illustrates the energy band diagram of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

The energy band diagram of the LED shows the matching of a quantum well in the GaN region which is located between the two AlGaN regions with a bandgap larger than that of GaN.

Electrons and holes concentrations

Figure 4 illustrates the electrons and holes concentrations of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

The electrons and holes concentrations in the quantum well is of the order of 10^{19} cm^{-3} which represents the highest concentration compared to adjacent regions, this will produce a higher recombination rate in the quantum well.

Electric field

Figure 5 illustrates the electric field in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

As shown in Figure III.5, the electric field in the quantum well is of the order of 8.2×10^5 V/cm.

Electrical characteristics

I-V characteristic

The I-V characteristic of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN is shown in Figure 6.

The voltage from which our LED is conducting is 3.4V, this voltage is called threshold voltage (V_{TH}).

Luminous power

Figure 7 illustrates luminous power emitted as a function of the current applied to the anode of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

We obtain a luminous power emitted of approximately 0.62mW for a current of 0.47mA corresponding to a voltage of 5V.

Optical characteristics

Spontaneous emission rate

Figure 8 illustrates the characteristic spontaneous emission rate, as a function of energy for the LED for an anode voltage of 3.5V.

The maximum value of the spontaneous emission rate of the LED is 1.15×10^{28} s^{-1} $cm^{-3}eV^{-1}$ corresponding to an energy of 3.44eV (λ= 360nm).

Radiative recombination

Figure 9 shows radiative recombination for LED, at a bias voltage of 3.5 V.
The radiative recombination rate in the quantum well is of the order of $1.8\times10^{27}cm^{-3}s^{-1}$.

Auger recombination

Figure 10 illustrates the Auger recombination rate for a bias voltage of 3.5V.
The Auger recombination rate in the quantum well is of the order of 8.7×10^{21} $cm^{-3}s^{-1}$.

Shockley-Read-Hall recombination

Figure 11 illustrates the Shockley-Read-Hall recombination in the p-AlGaN/GaN/n-AlGaN single quantum well LED for a bias voltage of 3.5V.

The recombination rate (SRH) in the quantum well is of the order of 1.75 10^9 $cm^{-3}s^{-1}$.

TE gain

Figure 12 illustrates the TE gain (TE: transverse electric field) as a function in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN at 3.5V.

From an energy of 3.43 eV (λ = 361.4 nm), we notice that the gain decreases slowly until reaching the energy of 3.58 eV (λ = 346.4 nm) from this value it decreases rapidly.

Luminous flow

The flux density spectral as a function of energy for single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN is shown in Figure 13.

As shown in figure 13, the luminous flux reaches a value of 3.5 × 10^{18} s^{-1} cm^{-1} eV^{-1} corresponding to an energy of 3.45eV.

Power spectral density

The emission spectrum of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN is shown in figure 14.

The simulation result shows that the maximum value of power spectral density reaches 1.93W/cm. eV corresponds to a wavelength λ= 359.5nm.

Wall Plug Efficiency (WPE)

The Wall Plug Efficiency (WPE) of the LED is given by the following relationship:

$$\eta_{WP} = \frac{P_{opt}}{P_{elec}}$$

With:

P_{opt}: is the optical power; P_{elec}: is the electrical power.

The Wall Plug Efficiency (WPE) of the single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN. is shown in Figure 15.

At the beginning, the Wall Plug Efficiency reaches a maximum rate of 76% which corresponds to a current of 0.002mA, from this value it decreases until reaching a rate of 26% which corresponds to a current of 0.47mA.

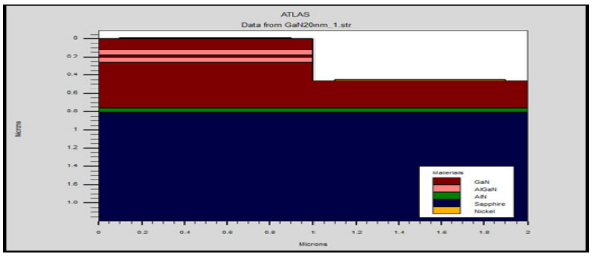

Fig.1. Schematic structure of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

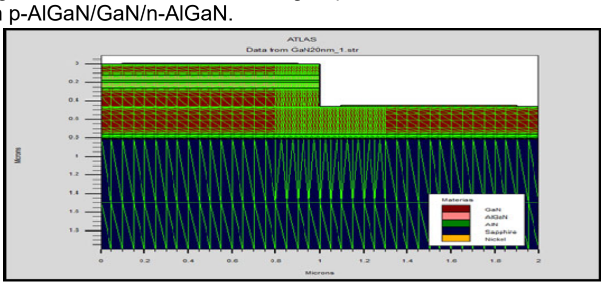

Fig.2. Mesh structure of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

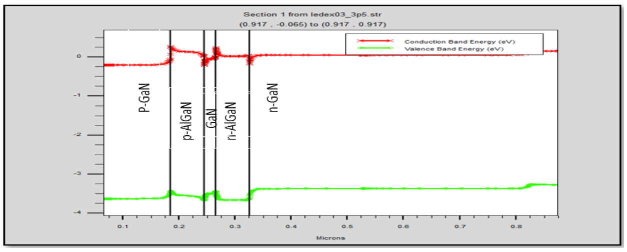

Fig.3. Energy band diagram of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

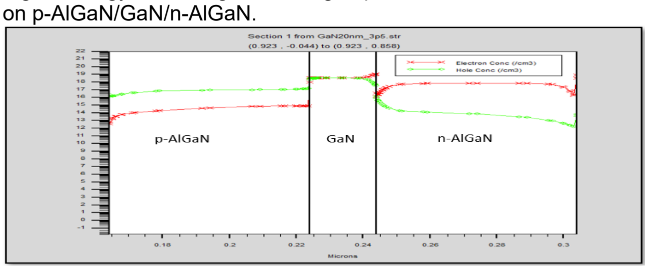

Fig.4. Electrons and holes concentrations of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

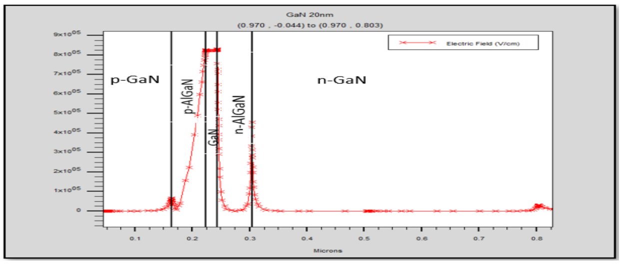

Fig. 5. Electric field in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

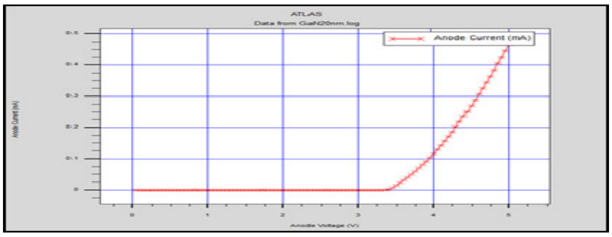

Fig. 6. I-V characteristic of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

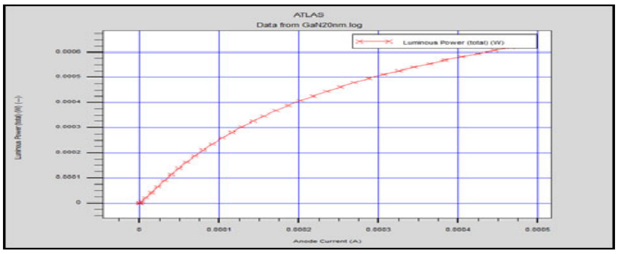

Fig. 7. luminous power emitted of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

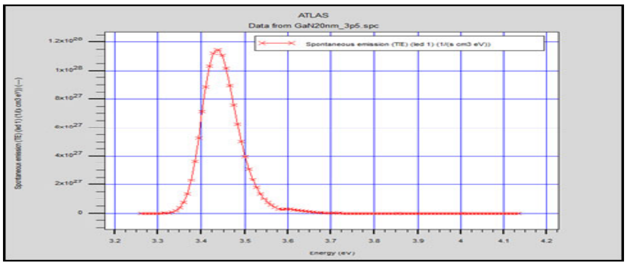

Fig.8. Spontaneous emission as a function of energy of single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

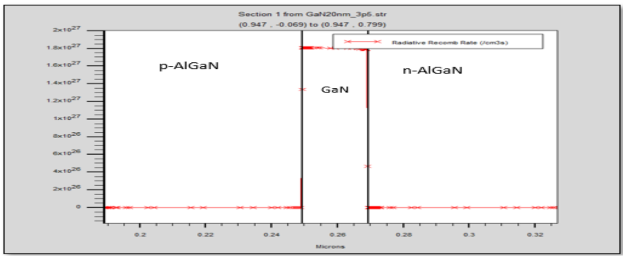

Fig.9. Radiative recombination in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

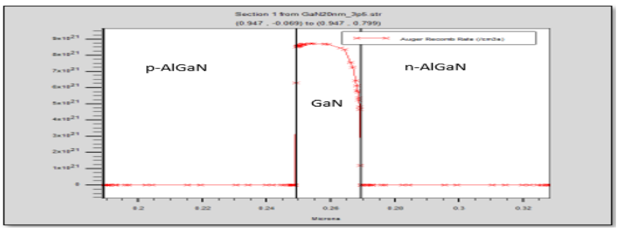

Fig. 10. Auger recombination in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

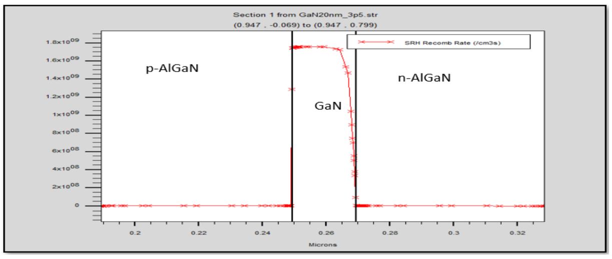

Fig. 11. Shockley-Read-Hall recombination in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

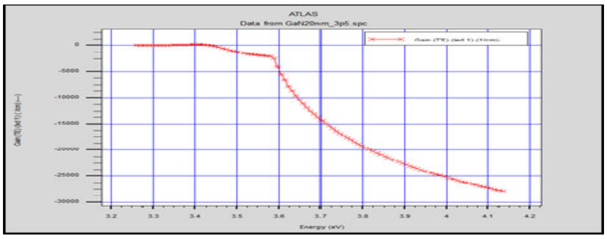
Fig. 12. The TE gain in single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

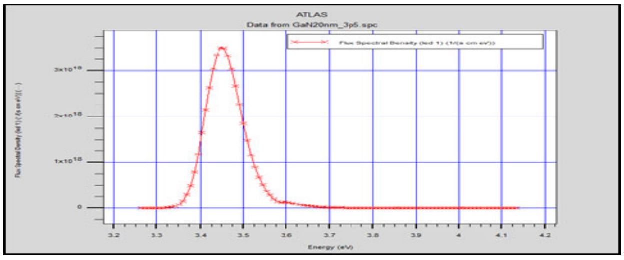
Fig. 13. flux density spectral for single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

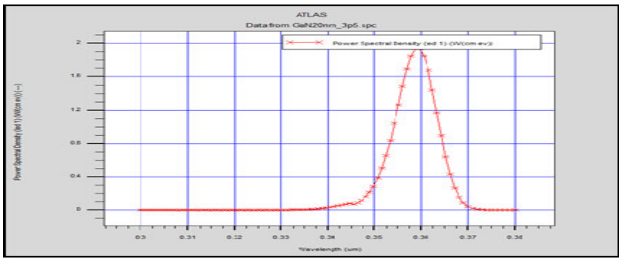
Fig. 14. Power spectral density for single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

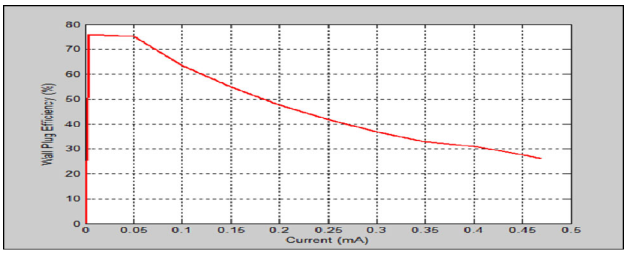

Fig. 15. Wall Plug Efficiency for single quantum well UV LED based on p-AlGaN/GaN/n-AlGaN.

Conclusion

Light-emitting diodes (LEDs) produce light (or infrared radiation) by the recombination of electrons and electron holes in a semiconductor, a process called "electroluminescence",

light emitting diode (LED) has many advantages: greater energy savings, longer LED life span, reduced environmental impact, low heat emissions, enhanced safety, flexible design, directional lighting, frequent switching, dimming capability, low voltage operation, operation in versatile temperatures, excellent color rendering index…

In this work, I simulated UV LEDs single quantum well based on AlGaN/GaN/AlGaN, my objective was to simulate the electrical and optical properties of this diode.

I simulated different characteristics of the LED such as the (I-V) characteristic, emitted light power, spontaneous emission rate, radiative recombination, Auger recombination, Shockley-Read-Hall recombination, optical gain, luminous flux, power spectral density…

Through these simulations, I was able to extract the electrical and optical characteristics of the LED studied and examine their performance.

Indeed, this work gave me a good understanding and explanation of the electrical and optical physical mechanisms in the world of UV LEDs single quantum well based on AlGaN/GaN/AlGaN.

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