Analysis of Quantum Well-Stacking Order in Multi-Quantum Well MicroLEDs

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Abstract

This study investigates the influence of quantum well stacking order on the emission characteristics of InGaN-based micro-LEDs using COMSOL Multiphysics simulations. Six configurations of red, green, and blue quantum wells were analyzed under varying current injection conditions. The findings reveal that spatial carrier dynamics and radiative recombination processes are significantly affected by the stacking sequence, with the n-InGaN-blue-green-red-p-InGaN configuration exhibiting the most uniform carrier distribution and highest emission efficiency. These results provide valuable insights for optimizing micro-LED designs to achieve enhanced performance in next-generation optoelectronic devices.

Keywords

Micro-LEDs; Simulation; InGaN; Quantum Well Stacking; Emission Spectra;

1. Introduction

Micro LEDs are emerging as a promising technology for next-generation displays and optoelectronic devices due to their high efficiency, compact size, and excellent brightness. Their potential for applications in augmented reality (AR), virtual reality (VR), and high-resolution displays has driven extensive research into improving their performance. Among various design factors, the structure of multi-quantum wells (MQWs) plays a critical role in determining emission characteristics and carrier dynamics.

The stacking order of quantum wells significantly affects carrier injection efficiency, recombination dynamics, and overall emission performance. For instance, optimized stacking sequences have been shown to reduce carrier overflow and improve the stability of emitted wavelengths, particularly in micro-scale devices where high current densities exacerbate carrier losses [1], [2]. Furthermore, advanced simulations of MQW configurations demonstrate the importance of quantum well energy band alignment in achieving efficient color performance and minimizing blue-shift under operating conditions [3].

Despite these advancements, most existing studies focus on macro-scale LED systems, with limited attention to the unique challenges of micro-LEDs, such as increased surface recombination and carrier losses due to reduced device dimensions. Recent simulations have highlighted that quantum well designs tailored for micro-LEDs can enhance light extraction and carrier recombination, paving the way for efficient full-color applications [4], [5].

This study employs COMSOL Multiphysics to simulate the effect of quantum well stacking order on the emission characteristics of 20 µm InGaN-based micro-LEDs. By analyzing single-color emission under low current conditions, we reveal how carrier injection and recombination dynamics are influenced by the stacking sequence. These findings provide valuable insights into optimizing micro-LED designs for improved efficiency and color performance.

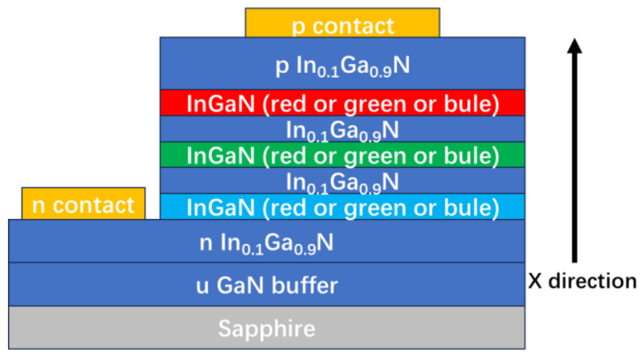

Fig. 1. Schematic of the simulated 20 µm Micro LED structure**.**

Table. 1. Simulation parameters and material properties.

Name	Value	Description
$In_{0.1}Ga_{0.9}N$_bg	3 eV	Bandgap energy of InGaN layer
$In_{0.39}Ga_{0.61}N$_bg	2 eV	Bandgap energy of red-emitting layer
$In_{0.29}Ga_{0.71}N$_bg	2.3 eV	Bandgap energy of green-emitting layer
$In_{0.2}Ga_{0.8}N$_bg	2.63 eV	Bandgap energy of bule-emitting layer
A_cross	4E−10 m^2	Cross sectional area
n $In_{0.1}Ga_{0.9}N$_doping	1E18 cm^{-3}	doping concentration of n InGaN
p $In_{0.1}Ga_{0.9}N$_doping	1E18 cm^{-3}	doping concentration of p InGaN

2. Simulation

Simulations were performed using COMSOL Multiphysics to explore the effects of quantum well stacking order on the emission characteristics of 20 µm InGaN-based micro-LEDs. The simulated device consists of an n-InGaN cladding layer, a multi-quantum well (MQW) region with three wells (red, green, blue), and a p-InGaN cladding layer. Each quantum well is 10 nm thick, separated by 10 nm InGaN barriers. Bandgap energies were set at 2.0 eV (red), 2.3 eV (green), and 2.63 eV (blue) to simulate wavelength emission. Six stacking sequences were simulated to investigate their impact on carrier dynamics and emission efficiency under low and high injection conditions.

As shown in Table. 1, key parameters include an n-type doping concentration of 1E18 cm^{-3} in the n-InGaN layer and

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a p-type doping concentration of 1E18 cm^{-3} in the p-InGaN layer. The applied forward bias is 2.5 V, and the active area of the micro-LED is 4E−10 m^2. Carrier dynamics are governed by charge carrier transport models based on drift-diffusion principles coupled with Poisson's equation, which were solved using COMSOL's semiconductor module. The radiative and non-radiative recombination rates within the quantum wells were analyzed to determine emission efficiency and spectral characteristics for each stacking order.

3. Results and discussion

The simulation results demonstrate the significant influence of quantum well stacking order on the emission characteristics of the micro-LED. Key findings are presented and analyzed below.

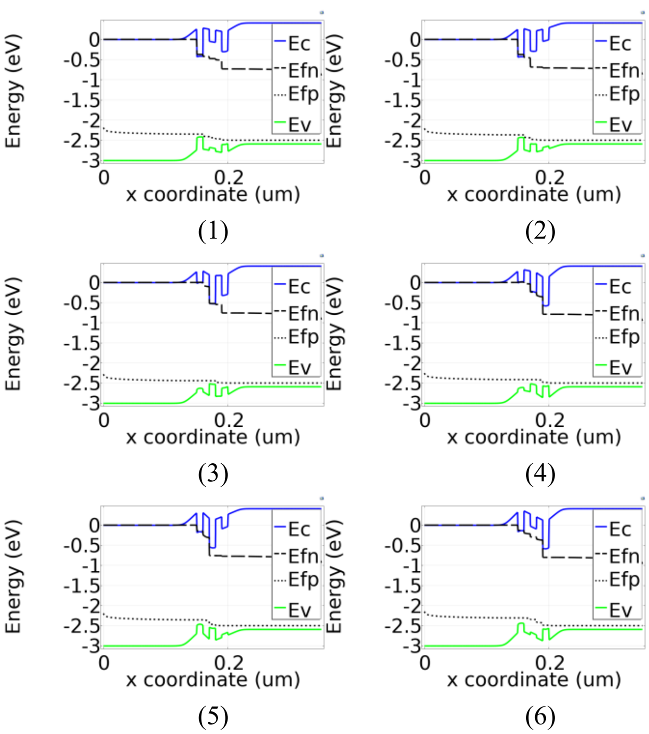

Fig. 2. Energy band diagrams of different stacking configurations under 2.5 V forward bias

(1) n InGaN-red-bule-green-p InGaN
(2) n InGaN-red-green-bule-p InGaN
(3) n InGaN-bule-red-green-p InGaN
(4) n InGaN-bule-green-red-p InGaN
(5) n InGaN-green-red-bule-p InGaN
(6) n InGaN-green-bule-red-p InGaN

Energy Band Diagram Analysis

Under a forward bias of 2.5V, the energy band diagrams for various quantum well stacking configurations are shown in Fig. 2. The electron concentration is primarily dictated by the proximity of the quantum well to the n-InGaN layer—the closer the quantum well is to the n-InGaN, the higher the electron concentration. The conduction band offset between the quantum well and the InGaN quantum barrier further modulates the electron capture efficiency [4]. Similarly, the hole concentration is determined by the relative position of the quantum well to the p-InGaN layer—the closer the quantum well is to the p-InGaN, the higher the hole concentration. The valence band offset between the quantum well and the InGaN quantum barrier also plays a significant role in influencing hole capture efficiency. Among all configurations, the red quantum well, owing to its smaller bandgap width and larger conduction and valence band offsets relative to the quantum barriers, demonstrates the strongest carrier confinement capability. The carrier capture efficiency ranks in the order of red > green > blue. Notably, the n-InGaN-blue-green-red-p-InGaN configuration achieves the most uniform carrier distribution among all stacking sequences, which is critical for enhancing the overall light emission efficiency of the device.

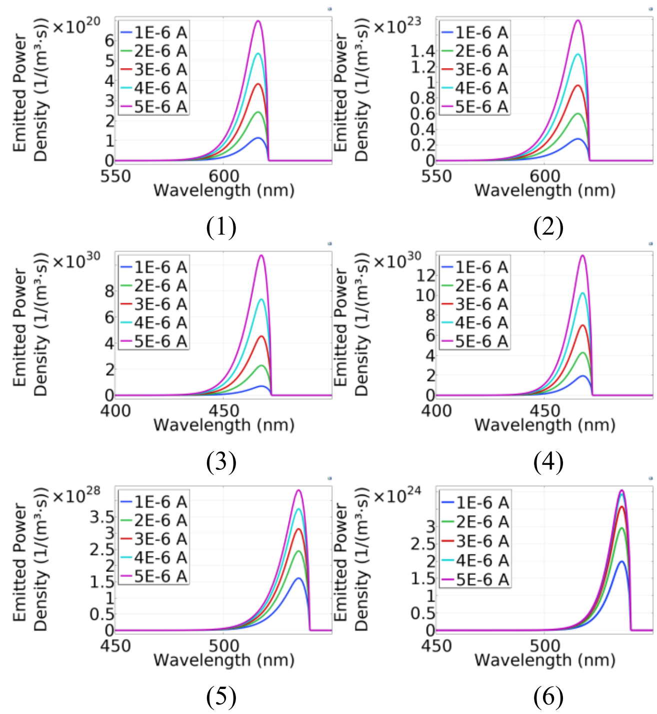

Fig. 3. Energy band diagrams of different stacking configurations under 2.5 V forward bias

(1) n InGaN-red-bule-green-p InGaN
(2) n InGaN-red-green-bule-p InGaN
(3) n InGaN-bule-red-green-p InGaN
(4) n InGaN-bule-green-red-p InGaN
(5) n InGaN-green-red-bule-p InGaN
(6) n InGaN-green-bule-red-p InGaN

Emission Spectra

The emission spectra atsub-threshold current injection levels, shown in Fig. 3, reveal that the stacking order of the quantum wells significantly impacts the carrier distribution and recombination efficiency. The n-InGaN-blue-green-red-p-InGaN structure exhibits the highest emission intensity, primarily because the blue quantum well, located near the n-InGaN region, benefits from enhanced electron population density near the injection interface. Meanwhile, the red quantum well, positioned near the p-InGaN, has a smaller bandgap, which improves carrier confinement efficiency, particularly holes, leading to higher recombination efficiency.

Additionally, the green quantum well in the middle helps balance the electron and hole distribution, resulting in a more uniform carrier distribution and improved overall emission efficiency. In contrast, structures like n-InGaN-red-blue-green-p-InGaN and n-InGaN-red-green-blue-p-InGaN show uneven carrier distributions, resulting in lower recombination efficiency and weaker emission intensity.

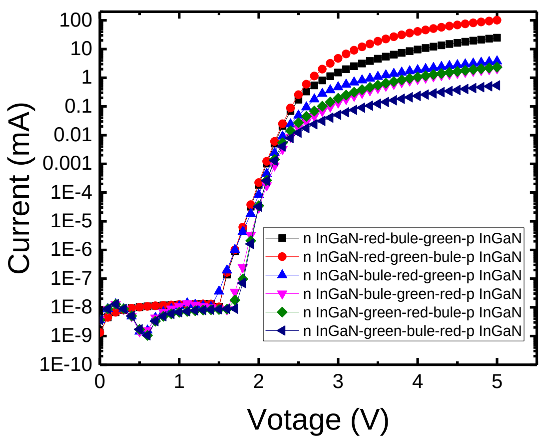

Fig. 4. IV characteristics of the Micro LED with different quantum well stacking orders.

IV Characteristics

The IV curve, shown in Fig. 4, shows distinct variations in current performance under the same bias voltage for different quantum well stacking configurations. The n-InGaN-red-green-blue-p-InGaN configuration exhibits the highest current at 5V, yet its emission efficiency is not the highest. This can be attributed to asymmetric carrier localization in the quantum wells, leading to carrier leakage and diminished radiative recombination rates. In particular, the red quantum well near the n-InGaN region captures a high electron concentration but has limited hole injection, reducing recombination efficiency. Similarly, the green and blue quantum wells near the p-InGaN region have higher hole concentrations but insufficient electron injection, further limiting radiative recombination. These results demonstrate that higher current does not directly translate to improved emission efficiency.

3. Conclusion

This study demonstrates the critical role of quantum well stacking order in influencing the optoelectronic performance of micro-LEDs. Using COMSOL-based simulations, the analysis revealed that the stacking sequence governs carrier injection efficiency, spatial carrier dynamics, and radiative recombination rates. The n-InGaN-blue-green-red-p-InGaN configuration achieved the best balance of electron and hole distribution, minimizing carrier leakage while maximizing recombination efficiency. However, structures such as n-InGaN-red-green-blue-p-InGaN exhibited higher currents at equivalent biases due to increased carrier leakage. These findings underscore the necessity of tailoring quantum well configurations to enhance spatial carrier management and overall emission efficiency.

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