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# Efficiency enhancement of InGaN/GaN light-emitting diodes with pin-doped GaN quantum barrier

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**Abstract**

Blue InGaN/GaN light-emitting diodes with undoped, heavily Si-doped, Si delta-doped, heavily Mg-doped, Mg delta-doped, and Mg–Si pin-doped GaN barrier are investigated numerically. The simulation results demonstrate that the Mg–Si pin-doping in the GaN barrier effectively reduces the polarization-induced electric field between the InGaN well and the GaN barrier in the multiple quantum well, suppresses the quantum-confined Stark effect, and enhances the hole injection and electron confinement in the active region. For this light-emitting diode (LED) device structure, we found that the turn-on voltage is 2.8 V, peak light emission is at 415.3 nm, and internal quantum efficiency is 85.9% at 100 A $cm^{-2}$. It is established that the LED device with Mg–Si pin-doping in the GaN barrier has significantly improved efficiency and optical output power performance, and lower efficiency droop up to 400 A $cm^{-2}$ compared with LED device structures with undoped or Si(Mg)-doped GaN barrier.

Keywords: light-emitting diode, gallium nitride, indium nitride, silicon doping, magnesium doping, pin-doping, internal quantum efficiency

(Some figures may appear in colour only in the online journal)

## 1. Introduction

In the past decade, the InGaN/GaN-based light-emitting diode (LED) has attracted the attention of most researchers as a promising candidate to replace conventional lamps in lighting applications, including general illumination, liquid crystal display backlighting, and automobile lighting [1–4]. However, the efficiency of LEDs is significantly reduced at high current density, which is known as the 'efficiency droop' phenomenon [5]. To explain the efficiency droop phenomenon, several mechanisms and models have been proposed such as Auger recombination [6], electron overflow [7], the quantum-confined Stark effect (QCSE) [8, 9], the junction heating effect [10], poor hole injection efficiency [11, 12], and polarization effects [13].

In order to improve the efficiency and the light output power of the InGaN/GaN-based LED, several approaches and modifications to LED structures were suggested. Xiong *et al* [14] improved the efficiency of LED devices by using AlGaN barriers with increasing Al concentration. Piprek [15] proposed the use of tunnel-junction-cascaded active regions to significantly enhance the internal quantum efficiency (IQE) and wall-plug efficiency (WPE) of LED devices. It is well known that the GaN-based materials have large piezoelectric and spontaneous polarization that lead to reducing the radiative recombination probability of LEDs due to the spatial separation of the electron–hole wave functions within the InGaN/GaN multiple quantum wells (MQWs). To reduce the piezoelectric field and spatial separation of electron–hole wave functions, the Si-doping [16–19], Si step-doping [20, 21], and Si delta-doping [22, 23] of GaN barriers were suggested and these structures were investigated experimentally. It was also experimentally demonstrated that inserting prelayer Si-doped GaN or InGaN layers led to enhanced crystalline structure and reduced the strain dislocations, and thus enhanced the efficiency of GaN-based LED devices [24, 25]. However, the Si-doping in the GaN barrier also modifies the band structure and increases the energy barrier height for holes, resulting in hole-injection deficiency. Therefore, several approaches have been proposed to improve the hole injection and hole transport within InGaN/GaN MQWs and to enhance the LED device efficiency. This includes Mg-doping- [26], two-step Mg doping- [27], Mg-delta-doping in the GaN barriers [28], and the insertion of a hole modulator [29] or a hole accelerator layer [30].

In this work, we study numerically the effect of Mg–Si pin-doping in the GaN barriers within InGaN/GaN MQWs on the LED efficiency in comparison with LED devices with undoped Si(Mg)-doped or Si(Mg) delta-doped GaN barriers. It is found that Mg–Si pin-doping in the GaN barrier could improve carrier injection in the active region and its confinement significantly, as well as effectively screening the piezoelectric field and reducing the QCSE effect. These improvements enhance the IQE and WPE as well as the optical output power of the InGaN/GaN LED devices.

## 2. Model, methods and LED device structures

The transport and optical properties of the InGaN/GaN LEDs with different structures are investigated numerically using the 1D Schrödinger–Poisson solver software 1D-DDCC [31]. This software is based on the ABC model and computes the Schrödinger–Poisson and drift-diffusion equations self-consistently using a finite difference scheme with a uniform mesh. The ABC model used takes into account the radiative bimolecular recombination [32], Shockley–Read–Hall (SRH) recombination [33], Auger non-radiative recombination [34], carrier leakage [35], and polarization effects [13]. Herein, the interface charge density is assumed to be 50% of the value calculated by the methods proposed by Fiorentini *et al* [36]. The band structure and radiative recombination rate are calculated based on a self-consistent $\mathbf{k}\cdot\mathbf{p}$ method [37]. The ionization energy of Si donors in GaN is assumed to be 20 meV, and the ionization energy of Mg acceptors in AlGaN is scaled linearly from 170 meV (GaN) to 470 meV (AlN) [15]. The GaN, InGaN, and AlGaN material parameters were taken from [38, 39]. For all LED simulations the bimolecular recombination coefficient, SRH recombination lifetimes, and Auger coefficients are assumed to be $2 \times 10^{-11}$ cm$^3$ s$^{-1}$, 100 ns, and $1 \times 10^{-31}$ cm$^6$ s$^{-1}$, respectively. All simulations were performed for room temperature (300 K). The size of all LED devices is fixed to 350 × 350 $\mu$m.

In the ABC model, the total recombination rate $R$ accounts the main three parts of recombination mechanisms which occur in the active region of LED devices, namely: non-radiative defect-related — SRH recombination $R^{\text{SRH}}$ ($A$), radiative bimolecular recombination $R^{\text{rad}}$ ($B$), and non-radiative Auger recombination $R^{\text{Auger}}$ ($C$), and also the non-radiative recombination caused by electron leakage from the active region $R^{\text{leakage}}$:

$$R^{\text{SRH}} = A \cdot n(x); \quad (1)$$

$$R^{\text{rad}} = B \cdot n^2(x); \quad (2)$$

$$R^{\text{Auger}} = C \cdot n^3(x); \quad (3)$$

$$R = R^{\text{SRH}} + R^{\text{rad}} + R^{\text{Auger}} + R^{\text{leakage}} = A \cdot n + B \cdot n^2 + C \cdot n^3 + R^{\text{leakage}}. \quad (4)$$

Here, $A$, $B$, $C$ are the — SRH constant, bimolecular recombination constant, and Auger constant, respectively, and $n(x)$ is the concentration of free electrons. Therefore, this model is called the ABC model, because it accounts for the three main material parameters $A$, $B$, $C$. The IQE is the ratio of the radiative recombination rate to the total recombination rate integrated over all regions and can be calculated as follows:

$$\text{IQE} = \int \frac{R^{\text{rad}}}{R^{\text{SRH}} + R^{\text{rad}} + R^{\text{Auger}} + R^{\text{leakage}}} \text{d}x, \quad (5)$$

where $R^{\text{rad}}$ is the radiative recombination rate, $R^{\text{SRH}}$ is the non-radiative crystal-defect related—SRH recombination rate, $R^{\text{Auger}}$ is the non-radiative Auger recombination rate, and $R^{\text{leakage}}$ is the non-radiative recombination caused by electron leakage from the active region. The 1D-DDCC software used is already employed as the solver of coupled Schrödinger–Poisson equations, as well as all terms of the total recombination rates including the leakage of carriers and IQE.

The investigated LED devices were characterized by performance parameters such as the IQE, described above, as well as the external quantum efficiency (EQE), WPE, and power efficiency (PE), defined by the following relations [39, 40]:

$$\text{EQE} = \text{IQE} \cdot \text{LEE}, \quad (6)$$

$$\text{EE} = \frac{\hbar\omega}{q \cdot \text{V}}, \quad (7)$$

$$\text{WPE} = \frac{P^{\text{opt}}}{P^{\text{in}}} = \frac{P^{\text{opt}}}{I \cdot \text{V}} = \text{EQE} \cdot \frac{\hbar\omega}{q \cdot \text{V}} = \text{EQE} \cdot \text{EE}, \quad (8)$$