Mg-Si Doped Barriers For Polarization Field Screening in High-Power InGaN/GaN Green LEDs

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***Abstract*— We present numerical simulations demonstrating that polarization-induced electric fields in c-plane InGaN/GaN quantum wells (QWs) can be effectively neutralized by introducing asymmetrically doped barrier layers sandwiching a 3 nm-thick $In_{0.3}Ga_{0.7}N$ QW. Specifically, a 6 nm-thick n-GaN layer doped with Si (1×10^{19} cm^{-3}) and a 1 nm-thick p-GaN layer doped with Mg (2×10^{19} cm^{-3}) are employed as barriers to form the sandwich structure named Mg–QW–Si. Based on this design, we propose a green LED that achieves a peak internal quantum efficiency of 87%, exhibits only 32% droop at 500 A/cm², and a 32% reduction in operating voltages. These results demonstrate a viable pathway for realizing high-efficiency in long-wavelength III-nitride LEDs for high-power applications.**

Keywords—III-Nitride, efficiency droop, green-gap, polarization field screening.

I. Introduction

InGaN-based light-emitting diodes (LEDs) have achieved widespread adoption, but their efficiency at high injection currents is limited by a phenomenon known as efficiency droop, a non-thermal decline in internal quantum efficiency (IQE) at elevated current densities [1]. This phenomenon restricts high-power LEDs to operate at lower current densities, where peak efficiency is typically achieved. In conventional c-plane LEDs, strong polarization-induced electric fields in strained InGaN/GaN quantum wells (QWs) aggravate this issue by spatially separating the electron and hole wavefunctions, thereby reducing their overlap and the associated oscillator strength. The suppressed radiative recombination rate leads to an elevated carrier concentration (n) in the active region at a given injection current density (J), which in turn accelerates the onset of droop, primarily due to Auger recombination that dominates at high n [2]. Furthermore, these polarization fields give rise to the quantum-confined Stark effect (QCSE), a well-known phenomenon responsible for the green-gap, which refers to the significant efficiency degradation observed in long-wavelength III-nitride QWs [3]. Consequently, neutralizing the internal electric field within QWs presents a promising strategy to mitigate both efficiency droop and green-gap.

While non-polar and semipolar orientations help reduce internal electric fields and suppress the QCSE, their dependence on expensive substrates limits widespread adoption. Alternatively, reducing polarization fields in c-plane structures through QW design and polarization screening methods such as doping offers a scalable and cost-effective solution. In this work, we explore such doping-based strategies to enable high-efficiency, low-droop LEDs on large-area c-plane substrates.

II. Device Structure

The reference structure of the Ga-polar c-plane InGaN/GaN LED with p-side-up geometry is shown in Fig. 1.

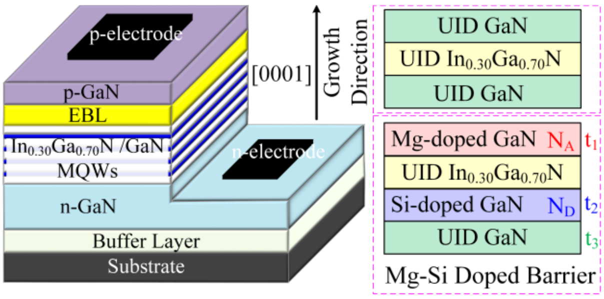

Fig. 1. Schematic of reference device structure with UID GaN barriers and engineered Mg–QW–Si architecture.

It consists of a 200 nm-thick n-GaN layer (Si:5×10^{18} cm^{-3}) followed by a multi-quantum-well (MQW) active region, a 15 nm-thick p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer (EBL), and a 180 nm-thick p-GaN layer (Mg: 2×10^{19} cm^{-3}). The active region comprises five unintentionally doped (UID) 3 nm-thick $In_{0.3}Ga_{0.7}N$ QW, each separated by 18 nm UID GaN barriers with a background doping of 1×10^{16} cm^{-3}. Numerical simulations were performed using a one-dimensional drift-diffusion charge control solver that self-consistently resolves energy band diagrams and current density–voltage (J–V) characteristics. Further details on the simulation methodology with experimental validation are provided in [4].

III. Results And Discussion

In c-plane InGaN/GaN QWs, the polarization-induced internal electric field (E_{pol}), resulting from spontaneous and piezoelectric polarization, can reach several MV/cm and typically points toward the $[000\bar{1}]$ substrate direction. Its magnitude is inherently linked to the In-content in the InGaN QWs, making independent tuning difficult without affecting the emission wavelength. To counteract E_{pol} and suppress the QCSE, we introduce an asymmetric doping scheme within the GaN barriers, specifically using Si-donors (N_D) on the n-side and Mg-acceptors (N_D) on the p-side, as illustrated in Fig. 2. This configuration establishes a built-in electric field (E_{pn}) oriented opposite to E_{pol}, effectively reducing the net electric field in the QW (E_{QW}). Unlike the fixed nature of E_{pol}, the compensating field E_{pn} is tunable by adjusting the dopant concentrations (N_A, N_D) and the spatial widths of the doped regions (t_1, t_2), along with an UID intermediate layer (t_3).

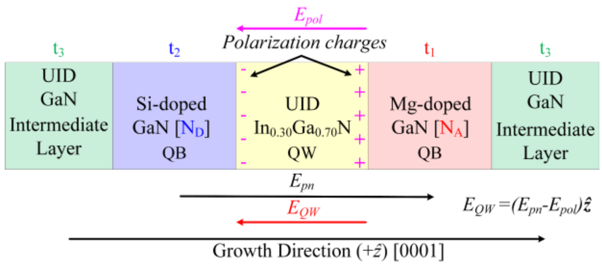

Fig. 2. Conceptual illustration of polarization field cancellation.

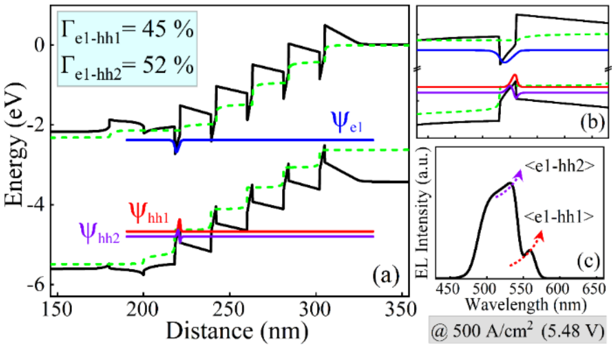

Fig. 3. (a) Energy band diagram with localized wavefunctions, (b) magnified last QW, and (c) EL spectrum with dual peaks at 532 nm and 560 nm for the LED with UID-QWs structure.

Moreover, E_{pn} aligns co-directionally with the forward bias-induced electric field (E_{FB}), enhancing polarization field screening and facilitating more efficient carrier injection. To identify the optimal doping profiles and layer thicknesses for the Mg–Si sandwich QW architecture, a series of numerical simulations were performed. The final structure comprises 3 nm-thick $In_{0.3}Ga_{0.7}N$ QW asymmetrically enclosed by a 1 nm thick (t_1) p-GaN ($N_A = 2\times10^{19}$ cm^{-3}) and a 6 nm thick (t_2) n-GaN ($N_D=1\times10^{19}$ cm^{-3}), forming the Mg–QW–Si configuration. To prevent the formation of a direct p–n junction, which could introduce abrupt band bending and localized electric field discontinuities, a 4 nm thick (t_3) UID GaN intermediate layer is inserted between the doped barriers. This design ensures a smooth potential profile and uniform electric field distribution across the active region.

As illustrated in Fig. 3 (a), the energy band diagram and corresponding localized wavefunctions are plotted for the last QW of the LED structure employing undoped sandwich QWs (UID-QWs) under an injection current density of 500 A/cm². As expected, the UID-QW structure exhibits a substantial E_{pol}, resulting in strong band bending across the QW region. This effect is clearly depicted in the magnified view in Fig. 3 (b), where the internal field reduces the spatial overlap between the ground-state electron (e1) and heavy-hole (hh1 and hh2) wavefunctions. The close proximity of these overlap values indicates that both transitions contribute notably to radiative recombination. As a result, the electroluminescence (EL) spectrum, as shown in Fig. 3 (c), exhibits a characteristic head-and-shoulder profile, with two peaks located at 532 nm and 560 nm. This spectral broadening reflects reduced color selectivity, attributed to the simultaneous contribution of multiple recombination pathways within the MQWs induced by the strong QCSE.

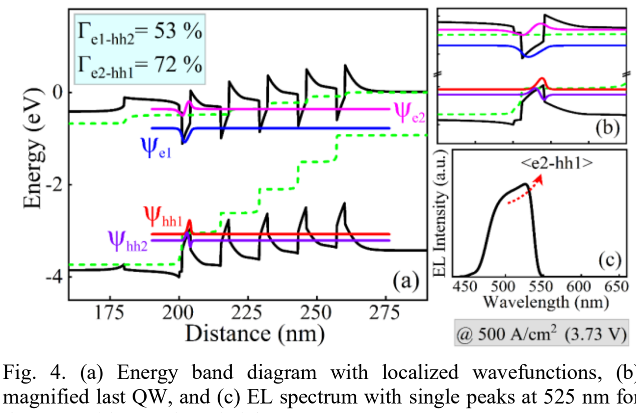

Fig. 4. (a) Energy band diagram with localized wavefunctions, (b) magnified last QW, and (c) EL spectrum with single peaks at 525 nm for the LED with Mg-Si sandwich QW.

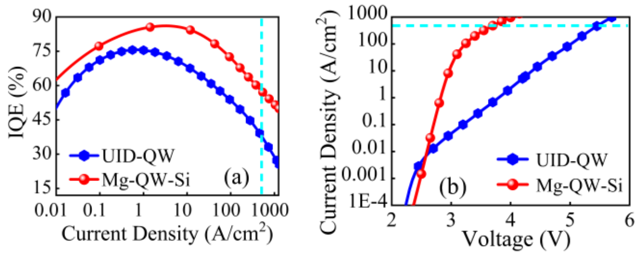

Fig. 5. (a) IQE-J, and (b) J-V characteristics for injection currents density ranging from 0 to 1000 A/cm².

In contrast, the Mg–QW–Si structure exhibits distinctly improved electrostatic and optical behaviour. Optimised asymmetrically doped GaN barriers generates a compensating field E_{pn} that neutralizes E_{pol}, resulting in a flattened band profile across the QW at 500 A/cm^2, as shown in Fig. 4 (a) and (b), confirming effective field compensation. This enhances the wavefunction overlaps to 53% for the <e1–hh2> transition and a significantly higher 72% for the <e2–hh1> transition. This significant difference in the improved overlap leads to a single dominant EL peak at 525 nm, as illustrated in Fig. 4 (c). The observed blue shift of the emission peak relative to the 532 nm peak in the undoped structure further validates the suppression of QCSE. The enhanced spatial overlap directly improves radiative recombination efficiency. As a result, the Mg–QW–Si structure achieves a peak IQE of 87% at low injection levels (<20 A/cm²), outperforming the UID-QW structure, which reaches a maximum of 75%, as shown in Fig. 5 (a). More importantly, the Mg–Si design maintains superior performance at high injection levels, sustaining an IQE of 58% at 500 A/cm², compared to only 35% for the UID-QW. Furthermore, as shown in Fig. 5 (b), the Mg–QW–Si LED yields a 32% reduction in forward operating voltage at 500 A/cm², which directly contributes to improved wall-plug efficiency and enhanced overall performance under high-power operating conditions.

IV. Conclusion

The proposed Mg–QW–Si architecture offers an effective and scalable approach for polarization field compensation in high-power c-plane InGaN/GaN LEDs. The design enables significant improvement in wavefunction overlap, spectral purity, and voltage performance, achieving 72% overlap, 32% lower operating voltage, and 58% IQE at 500 A/cm². These findings confirm the effectiveness of field-neutralization in high-In-content QWs for overcoming efficiency droop and the green-gap problem in long-wavelength III-nitride optoelectronic devices.

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