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Enhancing Bandwidth and Efficiency in GaN LEDs for VLC Systems

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Abstract

Gallium nitride (GaN) light-emitting diodes (LEDs) are essential for visible light communication (VLC), enabling high-speed data transmission and energy-efficient lighting. However, c-plane GaN LEDs face limitations due to polarization fields and the quantumconfined Stark effect (QCSE), restricting bandwidth and data rates. Advances in semi-polar and non-polar GaN structures have enhanced bandwidth, supporting gigabit-per-second VLC performance. Optimizing the active region through quantum well thinning and hybrid quantum dot integration further boosts modulation speeds. Additionally, Europium (Eu^{3+}) doping provides high-color-purity red emission and faster recombination, improving bandwidth and reducing efficiency droop. This review highlights these innovations for high- speed VLC systems.

1. Introduction

Visible light communication (VLC) systems, utilizing light-emitting diodes (LEDs), provide several advantages, including high data rates, security, and energy efficiency. Gallium nitride (GaN)-based LEDs are particularly well-suited for VLC due to their high efficiency, brightness, and long lifespan. However, despite their widespread use in lighting applications, traditional cplane GaN LEDs face significant challenges that limit their performance in high-speed VLC systems. One of the main limitations is the quantum-confined Stark effect (QCSE).

To address these challenges, recent research has focused on alternative GaN crystal orientations, such as semi-polar and non-polar structures, which show improved carrier dynamics and higher modulation bandwidths. Additionally, optimization of the active region through strategies like quantum well (QW) thinning, single QW designs, and quantum dot (QD) integration has enhanced the efficiency and modulation speed of GaN LEDs. Another promising approach is doping GaN with rare-earth (RE) elements, such as Europium (Eu^{3+}), which provides high-color-purity emission and faster recombination dynamics, thereby improving modulation bandwidth and data transmission capabilities. This paper explores the latest advancements in GaN-based LEDs for VLC, focusing on crystal engineering, active region optimization, and RE doping, aiming to enable high-speed VLC systems capable of gigabit-per-second data rates.

2. Advancement of GaN LEDs for VLC Systems

2.1 Crystal Orientation in GaN based LED

GaN typically crystallizes along the polar c-plane (0001) orientation, largely due to substrate availability and successful high-brightness LED fabrication. However, c-plane growth induces strong spontaneous and piezoelectric polarization, generating internal electric fields that cause the QCSE. This effect separates electrons and holes spatially, reducing radiative recombination efficiency and limiting modulation bandwidth. To overcome these issues, researchers have explored semi-polar and non-polar GaN orientations. Semi-polar (20-21) and (11-22) planes have demonstrated higher modulation bandwidths, reaching up to 1.102 GHz and 166 MHz, with data rates exceeding 3.4 Gbps [1]. Non-polar orientations, such as the (10-10) plane, exhibit shorter carrier lifetimes (200 ps) and even higher bandwidths, enabling high-speed VLC applications [2]. Despite these advantages, fabrication of semi-polar and non-polar LEDs remains complex and costly, limiting their widespread adoption. Consequently, most commercial devices still employ c-plane GaN, with ongoing efforts focused on reducing QCSE through substrate engineering and active layer modifications, such as ultra-thin quantum wells that enhance electron-hole overlap and decrease carrier lifetime. However, challenges persist, including reduced light output due to defect-related non-radiative recombination, particularly in high-indium-content structures.

2.2 Crystal Orientation in GaN based LED Optimization of the Active Region for Modulation Bandwidth Enhancement

The modulation bandwidth of GaN-based LEDs is primarily constrained by the RC time constant and carrier lifetime. In micro-LEDs, reduced pixel size minimizes the RC component, making carrier lifetime the dominant factor. The relation of modulation bandwidth, f_{-3dB}, with carrier lifetime, τ, is as follows,

$$f_{-3dB} = \frac{1}{2\pi\tau}$$

[3]. To enhance speed, strategies include thinning QWs and reducing their numbers to promote radiative recombination and shorten carrier lifetimes. Zhu et al. investigated QW thickness, showing that 5 nm wells achieved shorter carrier decay times and a modulation bandwidth of ~700 MHz due to QCSE reduction at higher currents [4]. Conversely, Cai et al. found that multiple 2 nm QWs with 10 nm barriers yielded higher bandwidths due to uniform carrier distribution [5]. Apart from micro-LEDs, nano-LEDs with a size smaller than 1 µm, also show a promising high-speed for optical communication due to the Purcell effect [6]. Emerging approaches, such as hybrid QD structures, aim to balance bandwidth and internal quantum efficiency (IQE), though higher bandwidth often compromises efficiency, necessitating careful active region design [7].

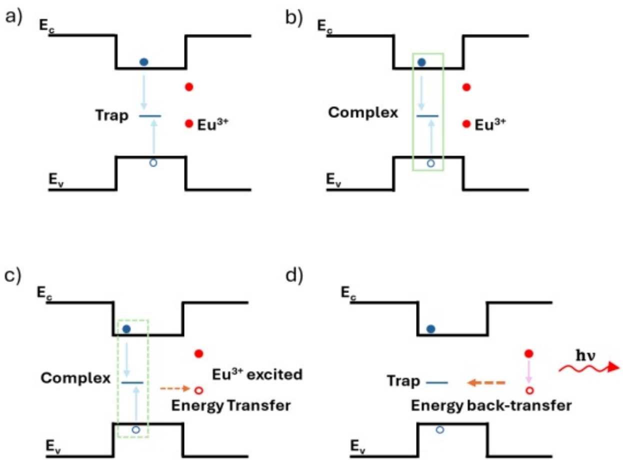

Figure 1. The excitation mechanism of Eu^{3+}.

2.3 Eu^{3+} as Rare Earth (RE) Element in GaN LED

Over the past three decades, RE ion luminescence has advanced considerably, and incorporating RE dopants into GaN LEDs marks a significant step in optoelectronics. RE ions, with shielded 4f electrons, exhibit sharp, well-defined emission lines across various host matrices, supporting high color purity and broad color gamut [8]. RE-doped GaN LEDs exhibit faster recombination dynamics and reduced efficiency droop at high currents, making them well-suited for bandwidth enhancement in VLC systems [9]. Murakami et al. found that dilute doping of Eu in GaN at approximately 0.1% reduces the bandgap energy by about 37 meV [10]. The trap-assisted excitation model by Fragkos et al. [11] outlines how Eu^{3+} ions in GaN are excited through a multi-step process as depicted in Figure 1. In (a), free carriers are captured by traps near Eu^{3+} ions and form an exciton complex as in (b). In (c), the complex may (i) recombine non-radiatively, transferring energy to the lattice, (ii) transfer energy to excite a nearby Eu^{3+} ion, or (iii) dissociate, returning carriers to the GaN host. In (d), the excited Eu^{3+} ion can either recombine radiatively, emitting a photon (red light), or transfer energy back to a trap, reforming the complex. This model highlights the competing radiative and nonradiative pathways influencing Eu^{3+} emission efficiency.

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