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Modeling and simulation of efficiency droop in GaN-based blue light-emitting diodes incorporating the effect of reduced active volume of InGaN quantum wells

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ABSTRACT

The efficiency droop of InGaN-based blue light-emitting diodes (LEDs) is analyzed using numerical simulations with a modified *ABC* carrier recombination model. The *ABC* model is modified to include the effect of reduced effective active volume of InGaN quantum wells (QWs) and incorporated into the numerical simulation program. It is found that the droop of internal quantum efficiency (IQE) can be well explained by the effect of reduced light-emitting active volume without assuming a large Auger recombination coefficient. A simulated IQE curve with the modified *ABC* model is found to fit quite well with a measured efficiency curve of an InGaN LED sample when the effective active volume takes only 2.5% of the physical volume of QWs. The proposed numerical simulation model incorporating the reduced effective active volume can be advantageous for use in the modeling and simulation of InGaN LEDs for higher efficiency.

1. Introduction

The efficiency of a GaN-based blue LED has been improved to a level that allows solid-state lighting to rapidly replace conventional light bulbs [1–3]. However, the emission efficiency of GaN-based LEDs having InGaN quantum-well (QW) active layers decreases significantly as the injection current increases. This “efficiency droop” phenomenon results in limited efficiency at the high current density, and has been a big obstacle in developing high-power and high-efficiency LEDs for future solid-state lighting [4,5]. Over the last decade, extensive works have been devoted to reveal the origin of the efficiency droop in GaN-based LEDs. Auger recombination [6], electron leakage [7], and carrier delocalization [8,9] have been proposed as the droop-causing mechanisms in InGaN LEDs. In addition, internal polarization fields have been regarded to increase the efficiency droop [7,10–12]. However, true origin of the efficiency droop has not yet been clearly identified. Recently, experiments of electron emission spectroscopy demonstrated a correlation between droop onset and hot electron emission at the cesiated p-GaN surface [13]. Although this result may indicate the Auger signature in GaN LEDs, additional experimental and simulation works seem to be necessary [14].

Auger recombination has been a central issue in the debate of the efficiency droop. In the droop model based on the Auger recombination, the efficiency curve of an LED is usually fit to the simple *ABC* carrier rate equation model. The Auger recombination coefficient, C obtained by the fit of efficiency curves have been typically reported to be in the range of 10^{-31}–10^{-29} cm^6/s [4,5]. Although the Auger recombination has been able to explain most of efficiency droop phenomena in InGaN LEDs, there is no consensus on the true value of the coefficient C [15,16]. Theoretically calculated C values in InGaN have been reported to be below 10^{-32} cm^6/s for the direct band-to-band Auger processes [17] and ~2×10^{-31} cm^6/s for the indirect Auger recombination processes mediated by electron-photon coupling or alloy scattering [18]. In some experimental results, however, this theoretical maximum C is still not sufficiently large to model the experimental efficiency curve, and the C value larger than 1×10^{-30} cm^6/s has been required [4].

Several years ago, one of the authors modified the *ABC* rate equation model including the influence of the reduced effective active volume to explain the discrepancy between the theoretical and experimental C values [19]. The effective active volume of

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InGaN QWs can be greatly reduced as a result of carrier localization in In-rich region and inhomogeneous carrier distribution [20–23]. It was found that the efficiency droop could be modeled well with the C value of ~10^{-31} cm^6/s, by assuming that only a small portion of QWs is effectively used as active region [19].

A numerical device simulation can be advantageous to understand the efficiency droop phenomena of InGaN LEDs. Numerical simulations have been frequently employed to interpret experimentally measured LED efficiency and to design LED structures for reducing the droop of internal quantum efficiency (IQE). For the simulation of LED device characteristics, a semiconductor device simulation software, APSYS has been widely employed [24]. The APSYS program self-consistently solves QW band structures, radiative and nonradiative carrier recombination, and the drift and diffusion equation of carriers. In this paper, a model of reduced effective active volume is incorporated into the APSYS simulation and its effect on the efficiency droop is investigated. In Section 2, a simulation model with the modified *ABC* rate equation is introduced. In Section 3, simulation results of the IQE droop are presented based on the proposed simulation model. In Section 4, the simulation model is applied to the measured efficiency curve of an InGaN blue LED sample.

2. Numerical modeling

In the ABC rate equation model, current, I, injected in the effective active region is expressed as

$$I = qV_{\rm eff}(R_{\rm SRH} + R_{\rm rad} + R_{\rm Auger}), \tag{1}$$

where q is the elementary charge and $V_{\rm eff}$ is the effective active volume of MQW layers. $R_{\rm SRH}$, $R_{\rm rad}$, and $R_{\rm Auger}$ are the Shockley-Read-Hall (SRH) recombination rate, the bimolecular radiative recombination rate, and the Auger recombination rate, respectively. The mathematical model for the SRH recombination is expressed as [25,26]

$$R_{\rm SRH} = \frac{np - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)}, \tag{2}$$

where n and p are the electron and hole concentration, n_i is the intrinsic carrier concentration, and τ_n and τ_p are the electron and hole carrier lifetime. In Eq. (2), n_1 and p_1 correspond to electron and hole concentrations calculated when the quasi-Fermi energy is equal to the trap energy. The radiative and the Auger recombination rates are expressed as [26]

$$R_{\rm rad} = B\left(np - n_i^2\right) \tag{3}$$

$$R_{\rm Auger} = C_n n^2 p + C_p np^2, \tag{4}$$

where B is the bimolecular recombination coefficient, and C_n and C_p are the Auger recombination coefficients for electrons and holes, respectively.

Under a typical LED operation condition, n_i, n_1, and p_1 can be neglected compared with n or p. For simplicity, we set $\tau_n = \tau_p = \tau_{\rm SRH}$. Then, the SRH recombination is simplified as

$$R_{\rm SRH} = \frac{np}{\tau_{\rm SRH}(n+p)}. \tag{5}$$

When it is further assumed that $C_n = C_p = C$, the rate equation in Eq. (1) is written as

$$I = qV_{\rm eff}\left[\frac{np}{\tau_{\rm SRH}(n+p)} + Bnp + C\left(n^2p + np^2\right)\right], \tag{6}$$

With $n = p = N$, one can obtain the following widely used simple *ABC* rate equation:

$$I = qV_{\rm eff}\left(AN + BN^2 + CN^3\right), \tag{7}$$

where the SRH recombination coefficient A is equal to $1/(2\tau_{\rm SRH})$.

In the APSYS program, the concept of the effective active volume is not included and the simulated active volume is the same as the physical volume of MQW active layers. So, $V_{\rm eff}$ in Eq. (6) cannot be used as an input parameter in the simulation. In order to incorporate the effect of reduced active volume into the APSYS program, we modify the rate equation model of Eq. (6) as in the following. First, a volume scaling parameter k, which represents the ratio of the effective active volume ($V_{\rm eff}$) to the physical active volume (V_0), is defined as

$$k \equiv V_{\rm eff}\big/V_0. \tag{8}$$

Second, effective recombination coefficients, A', B', and C' are introduced as below.

$$A' = kA, \quad B' = kB, \quad C' = kC \tag{9}$$

Then, we obtain the following modified rate equation from Eqs. (6), (8) and (9).

$$I = qV_0\left[\frac{2A'np}{(n+p)} + B'np + C'np(n+p)\right] \tag{10}$$

Equation (10) implies that the effect of the reduced active volume can be incorporated in the APSYS simulation program by employing the effective recombination coefficients, A', B', and C' in the recombination model instead of the original *ABC* coefficients.

In the simulation, built-in polarization fields at the InGaN/GaN interfaces of MQWs are also considered using the model of Ref. [27] and assuming 50% compensation of polarization fields [28–30]. Then, the strength of polarization fields at the interfaces of the $In_{0.15}Ga_{0.85}N$ QW and the GaN barrier is approximately 1 MeV/cm. The conduction band offset of the AlGaN EBL is set at 0.7. In this EBL height and band offset, no electron leakage from MQWs to p-GaN layer was observed in all simulations of this work.

3. Simulation results

The proposed numerical model is applied to the simulation of efficiency droop for a typical InGaN blue LED sample. The LED layer structure consist of a 3-μm-thick n-type Si-doped GaN layer, a multiple-quantum-well (MQW) active region, a 15-nm-thick p-type Mg-doped $Al_{0.15}Ga_{0.85}N$ electron-blocking layer (EBL) and a 15-nm-thick Mg-doped GaN cap layer. The MQW active region consists of five 2.5-nm-thick $In_{0.15}Ga_{0.85}N$ well layers interleaved by six 8-nm-thick GaN barriers. The concentration of Si donors in n-GaN is 5×10^{18} cm^{-3} and that of Mg acceptors in both the EBL and the p-GaN cap layer is 1×10^{19} cm^{-3}. In the APSYS simulation, incomplete ionization of Mg acceptors and the field ionization model are included, and the AlGaN acceptor energy is linearly scaled from 170 meV in p-GaN to 470 meV in p-AlN [30]. The dimension of the simulated LED chip is 1×1 mm^2. For simplicity, current is assumed to inject vertically through all area of the LED chip without lateral current spreading.

First, IQE curves of the LED sample are simulated using the conventional rate equation model where the effective active