Simulation of InGaN/GaN light-emitting diodes with a non-local quantum well transport model

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***Abstract*-Blue InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) are simulated by the APSYS software with a non-local quantum well transport model. The simulation results are in good agreement with experiment and indicate the non-local quantum well transport model has a significant influence on the radiative recombination, the carrier transport and the current crowding of the InGaN/GaN MQW LEDs.**

I. INTRODUCTION

InGaN-based multiple quantum well (MQW) light-emitting diodes (LEDs) are receiving tremendous attention due to their potential applications in energy saving solid-state lighting [1]. Although significant improvements in material quality and device fabrication have been achieved during the past decade, there are still some problems such as electron leakage [2], poor hole injection efficiency [3], junction heating [4] and current crowding [5], which could largely degrade the optical and electrical performances of these devices. So it is imperative to resolve these issues by optimization of device structure.

Numerical simulation is an effective method to promote this process with low cost [6][7][8]. However, it is usually difficult to get good agreement between simulated results and experimental data for InGaN-based MQW LEDs by using traditional Drift-Diffusion model since this model is not adequate to describe the case where carriers directly fly over the quantum well (QW) without scattering. Recently, a non-local QW transport model has been implemented in our APSYS simulation software [9] to explain this effect. In this paper, we will carry out a 2D simulation for blue InGaN/GaN MQW LED with the APSYS software and show the importance of the non-local QW transport model to the LED simulation.

II. THEORETICAL MODELS AND PARAMETERS

The APSYS simulation software is a finite-element based device simulator which self-consistently solves Poisson-Schrödinger equations, current continuity equations, heat transfer equations and hydrodynamic equations, including K·P models for MQW band structure, quantum tunneling model for heterojunction, heat flow model for self-heating, ray-tracing model for photon extraction, spontaneous and piezoelectric polarization models for built-in electric field, as well as Shockley-Read-Hall (SRH) recombination and Auger recombination of carriers. The non-local QW transport model in APSYS is a modified version of Drift-Diffusion equation where QWs are treated as carrier traps with trapping rates determined by phonon scattering. The trapping rate is usually expressed as:

$$R_{qw} = (n - n_0)/\tau \quad (1)$$

where τ is capture time constant. n is carrier concentration and n_0 is that at equilibrium. High value of τ means that more carriers can directly flow over the QWs.

In this simulation, the SRH lifetime within QWs is estimated to be 100 ns. The built-in interface charges due to spontaneous and piezoelectric polarization are calculated by the methods developed by Fiorentini *et al*. [10], 50% of the theoretical value is used to account for the compensation by fixed defects and other interface charges. The AlGaN band offset ratio is assumed to be 50:50, according to the results of Piprek *et al*. [11] The Auger recombination coefficient is set to be 1.0×10^{-34} cm^6s^{-1} [12] which has a negligible influence on the emission efficiency of the LEDs.

III. LED DEVICE STRUCTURE

The simulated structure in this paper is similar to that in [13], which consists of a 1-μm-thick n-type GaN:Si (5×10^{18} cm^{-3}), a 30 period GaN(4nm)/InGaN(4nm) superlattice:Si (5×10^{18} cm^{-3}), and six or nine periods of $In_{0.18}Ga_{0.82}N$(4nm)/GaN(20nm) MQW active regions, ending in a 16-nm-thick GaN barrier, followed by a 10-nm-thick undoped $Al_{0.15}Ga_{0.85}N$ electron blocking layer and a 0.2-μm-thick p-type GaN:Mg (1×10^{18} cm^{-3}) cap layer. The device geometry is 526 × 315 μm^2.

IV. RESULTS AND DISCUSSIONS

Fig.1 shows the calculated and experimental [13] output power for the 6-QW and 9-QW LEDs. As shown in Fig. 1(a), there is small difference in output power for both of the 6-QW and 9-QW LEDs calculated by using the traditional Drift-Diffusion model. However, when the non-local QW transport model is employed, the output power for both of them

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is decreased, but the difference between them is increased gradually with the increase of τ as indicated in Fig. 1(b)-1(d). Moreover, good agreement between experimental data and simulated results is demonstrated when $\tau = 1.0\times10^{-6}$ s.

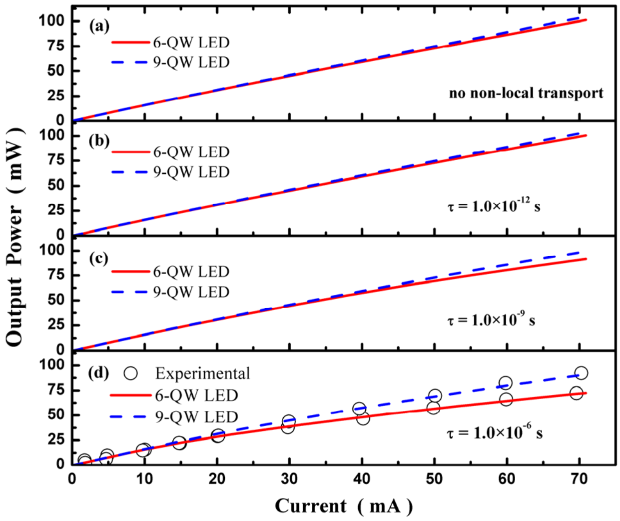

Fig. 1 Experimental and simulated output power for the 6-QW and 9-QW LEDs with and without the non-local QW transport model

The simulated current-voltage (I-V) curves for the 6-QW and 9-QW LEDs are plotted in Fig. 2. It is apparent that the I-V characteristics of these two LED devices are both improved markedly by using the non-local QW model with a higher value of τ compared to those based on the traditional Drift-Diffusion model. As shown in Fig. 2(d), the forward voltages of the 6-QW and 9-QW LED at 20 mA are similar to those that have been reported in experiment [13]. These results indicate that there are more carriers that can directly fly over the QWs to take part in the transport process other than being captured by the QWs in the realistic LED devices.

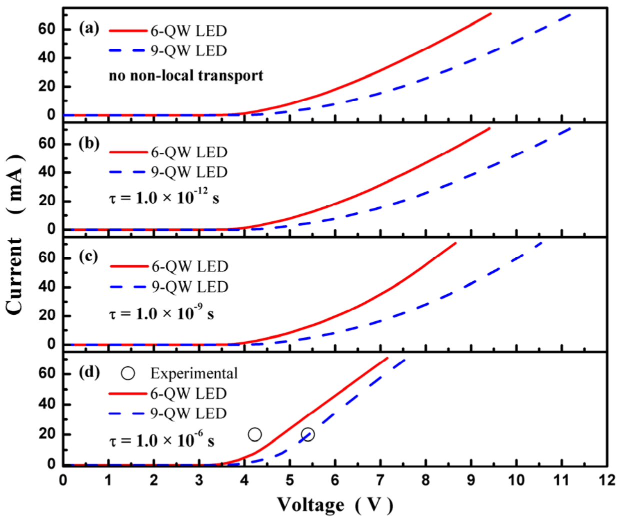

Fig. 2 Simulated I-V curves for the 6-QW and 9-QW LEDs with and without the non-local QW transport model.

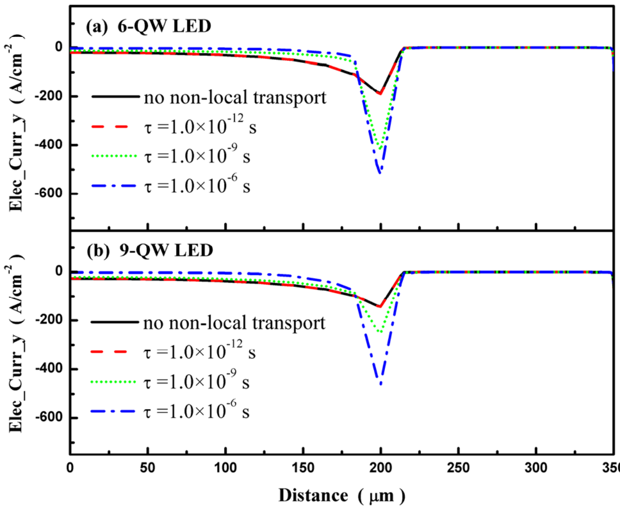

Fig. 3 Local electron current density in the horizontal direction at the middle of n-GaN layer for the 6-QW and 9-QW LEDs with and without the non-local QW transport model.

The horizontal profiles of the local electron current density at the middle of n-GaN layer for both of the LEDs are shown in Fig. 3 and they reveal that the non-local QW transport model with a higher value of τ leads to stronger current crowding due to the increasing number of transportable carriers. Furthermore, the stronger current crowding in the 6-QW LED as compared to that in the 9-QW LED may result in the lower output power for the 6-QW LED as indicated in Fig. 1.

V. CONCLUSIONS

We have simulated the electrical and optical characteristics of blue InGaN/GaN MQW LEDs with a non-local QW transport model. The simulation results are in good agreement with experimental data. We found that the non-local transport model can explain the experimental phenomena well and has a significant influence on the radiative recombination, the carrier transport and the current crowding of the InGaN/GaN MQW LEDs.

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