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Transient Analysis of InGaN/GaN Light-emitting Diode with Varied Quantum Well Number

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Abstract: A rate equation model for static and dynamic behavior of InGaN/GaN light-emitting diode (LED) has been developed, and the model has been implemented on a SPICE circuit emulator. The model′s parameters have been achieved by fitting simulated results with reported experimental data. The transient response of InGaN LEDs has been comparatively investigated by varying the number of quantum wells in their active region. The simulations show that the rise time of optical outpower increases with the number of wells, and the active region composed of three quantum wells is the optimized structure.

Key words: InGaN; LED; circuit model; rise time
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量子阱数变化对 InGaN/GaN 发光二极管瞬态响应的影响

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摘要: 理论上研究了当 InGaN 发光二极管(LED)有源区的量子阱数变化时,LED 的大信号瞬态响应特性与这种变化的关系。结果来自于 LED 等效电路模型的 SPICE 模拟,模型参数的确定通过拟合已测量的 LED 的实验数据及模拟结果来实现。结果表明,LED 光脉冲的上升时间随量子阱数的增加而增加,由 3 个量子阱构成的有源区是 LED 的优化结构。

关　键　词: InGaN; LED; 电路模型; 上升时间

1　Introduction

The visible Ⅲ-nitride light-emitting diodes (LEDs) have received much attention due to their wide applications in full-color display, liquid crystal display back-lighting, mobile platforms, and illumination[1-4]. High-luminescence and high-efficiency blue/green InGaN LEDs, especially, are of foremost importance for application in illumination market such as outdoor display and solid-state lighting. Up to now, most investigations focus on improving their static illuminant performance including the light

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extraction efficiency, however, few theoretical and experimental investigations have been reported on the dynamic response of InGaN LEDs, except that Shi and his co-workers have made an experimental study about the modulation properties of single LED and three cascade LEDs for the application in plastic optical fiber communication[5-6].

In this paper, a set of rate equations, which describe the dynamics of carriers and photons in InGaN LED respectively, are casted in a circuit simulator SPICE by making use of standard circuit elements. The equivalent circuit model based on the rate equations is versatile in that it can be used to simulate the large-signal transient response. The performance of outpower versus current (*P-I*) is simulated to accord with the reported experimental *P-I* data by adjusting the parameters of rate equations. On the basis of the correct parameters, the transient response is simulated *via* the square current driving the equivalent circuit model. Furthermore, the rise time of optical output, derived from the transient response, is discussed by changing the number of quantum wells.

2　Rate Equations and Circuit Model

A green GaN-based LED with a 518 nm radiative wavelength, denoted as sample B in Ref. [5], is considered here. The quantum wells in active region are composed of 13.5 nm GaN barriers and 2.5 nm InGaN wells. Thus the dynamics of carriers and photons is described in terms of the following two nonlinear differential equations mentioned below[7], which form the basis of circuit model:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \frac{I}{qV_{\mathrm{act}}} - (An + Bn^2 + Cn^3), \qquad (1)$$

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \beta B n^2 - \frac{s}{\tau_{\mathrm{p}}}, \qquad (2)$$

where n denotes the electron density (cm^{-3}) in the active region; I is the injected current; q is the electronic charge; V_{act} is the volume of the active region; s is the photon density; β is spontaneous emission factor; τ_{p} is the lifetime of photon; A, B, and C are the non-radiative coefficient, radiative coefficient, Auger coefficient, respectively. The detailed expressions of V_{act} and β are given below[8]:

$$\beta = \frac{\Gamma \lambda_{\mathrm{S}}^4}{4\pi^2 n_{\mathrm{eff}}^3 V_{\mathrm{act}} \Delta\lambda_{\mathrm{S}}}, \qquad (3)$$

$$V_{\mathrm{act}} = NA_{\mathrm{c}}(L_{\mathrm{w}} + L_{\mathrm{b}}), \qquad (4)$$

where Γ is the confinement factor, n_{eff} is the effective refractivity, λ_{S} and $\Delta\lambda_{\mathrm{S}}$ are peak wavelength and half-peak width, N is the number of quantum well, A_{c} is the area of the cross section, L_{w} and L_{b} are the width of well and barrier, respectively.

In order to derive the equivalent-circuit representation from the rate equations (1) ~ (2), the standard circuit elements are brought to transform the rate equations into the specific type which suits the formation of circuit model. The non-radiative coefficient A is considered to be equal to $1/\tau_{\mathrm{nr}}$, where τ_{nr} is denoted as the non-radiative lifetime of carriers. Therefore the non-radiative recombination current I_{n} is equal to $qV_{\mathrm{act}}n/\tau_{\mathrm{nr}}$, and the radiative recombination current and Auger recombination current are expressed as bI_{n}^2 and cI_{n}^3 respectively, where $b = B/(AqV_{\mathrm{act}})^2$, $c = C/(AqV_{\mathrm{act}})^3$. The carrier population in the active region is also defined as:

$$n = n_0 \exp\left(\frac{qV_{\mathrm{j}}}{\eta kT}\right), \qquad (5)$$

where n_0 is the equilibrium carrier density, V_{j} is the voltage across the active region, η is the corresponding diode ideality factor, typically set equaling to 2, T is the absolute temperature. The differential term $qV_{\mathrm{act}}\mathrm{d}n/\mathrm{d}t$ of rate equation (1) can be denoted as a product of C_{j} and $\mathrm{d}V_{\mathrm{j}}/\mathrm{d}t$, with C_{j} expressed as

$$C_{\mathrm{j}} = \frac{q^2 V_{\mathrm{act}} n_0}{\eta kT} \exp\left(\frac{qV_{\mathrm{j}}}{\eta kT}\right), \qquad (6)$$

where C_{j} is a capacitance representing the charge storage effect in the active region. However, the type of equation (2) is not effective to form corresponding circuit model and improvements must be adopted to satisfy this requirement. The optical output power P_{out}[9] can be represented by a nodal voltage, namely:

$$V_{\mathrm{out}}(V) = P_{\mathrm{out}}(W) = \frac{\eta_0 A_{\mathrm{c}} hc^2}{6\lambda_{\mathrm{s}}} s = \alpha s, \qquad (7)$$

where η_0 is extracted light efficiency, the definition of A_{c} and λ_{s} is referred to equations (3) ~ (4). With these modification, the rate equations (1) ~

(2) are transformed into the following type:

$$I = I_n + bI_n^2 + cI_n^3 + C_j \frac{dV_j}{dt}, \qquad (8)$$

$$\beta b I_n^2 = \frac{V_{out}}{R_s} + C_s \frac{dV_{out}}{dt}, \qquad (9)$$

where $R_s = \alpha \tau_p$, $C_s = 1/\alpha$. The circuit model based on the equations (8) ~ (9) is formed in Fig. 1.

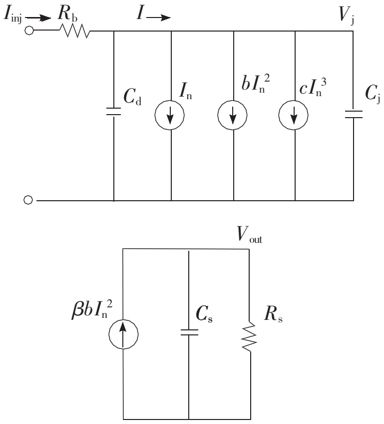

Fig. 1 The equivalent circuit model of LED derived from rate equations

I_{inj} is the total injected current of LED with the parasitic elements R_b and C_d, where R_b is considered to be equal to the differential resistance derived from the Shi's measured *V-I* curve[5], and C_d is a diffusion capacitance, which is added into the circuit model aiming to generalize the equation (8). $C_d = C_0(1 - V_j/V_d)^{-1/2}$, where C_0 is the zero-bias diffusion capacitance, V_d is the diode built-in potential. In our simulations, C_0 is considered to be constant, but R_b is linearly changed with varied wells.

3 Simulation Results and Discussion

The equivalent circuit model of LED is a large-signal model, which is compatible with general purpose circuit simulators SPICE, and SPICE allows a circuit to contain resistors, capacitors, inductors, current dependent current/voltage sources, *etc.* The DC and transient analysis can be done based on the SPICE simulations. The values of the parameters used in our simulations are listed in Table 1[5,10-11].

Fig. 2 shows the light-current characteristics of the sample B in Ref. [5]. The squares represent the Shi's measured experimental data, and the curve is derived from the DC SPICE simulation of our circuit model. By adjusting the value of the model parameters A, B, C, and τ_p, our simulation results are very coincide with Shi's measured data. As shown in Fig. 2, the simulated curve dips when the injected current is greater than 80 mA, which is due to the dominant Auger radiation with the large current injected into LED.

Table 1 Model parameters used in the simulation

Symbol	Description	Value
A	Non-radiative coefficient	7.2×10^{9} s^{-1}
B	Radiative coefficient	2.3×10^{-11} s^{-1}
C	Auger coefficient	1.2×10^{-34} s^{-1}
τ_p	Lifetime of photo	2.5 ps
Γ	Confinement factor	0.02
n_{eff}	Effective refractivity	2.45
λ_S	Peak wavelength	518 nm
$\Delta\lambda_S$	Half-peak width	40 nm
T	Absolute temperature	300 K
η_0	Extracted light efficiency	0.04
A_c	Area of cross section	14 000 μm^2
C_0	Zero-bias diffusion capacitance	85 pF
V_d	Built-in potential	4.2 V

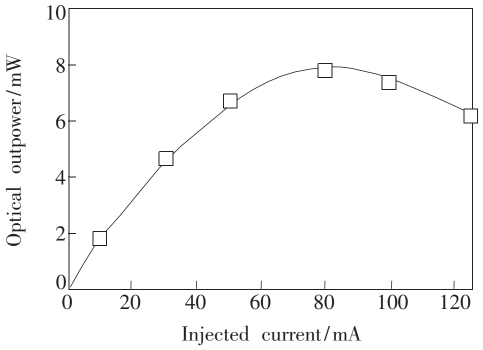

Fig. 2 Output optical power *vs.* the injected current of sample B. Squares represent the Shi's measured experimental data.

Fig. 3 shows the pulse response of InGaN LEDs with 2, 4, and 6 wells in the active region, while a 50 mA-height square current is applicated at the time $t = 0$ ns. The rise time t_r is determined as the time between 10% and 90% points of the light pulse. The rise time of Shi's sample B with 6 wells is calculated to be 7.8 ns, from the equation t_r =

$0.35/f_{-3\text{dB}}$, where its −3 dB bandwidth is equal to 45 MHz. By adjusting the parameter C_0, the rise time derived from transient simulation of SPICE model can be consistent with the calculated results mentioned above.

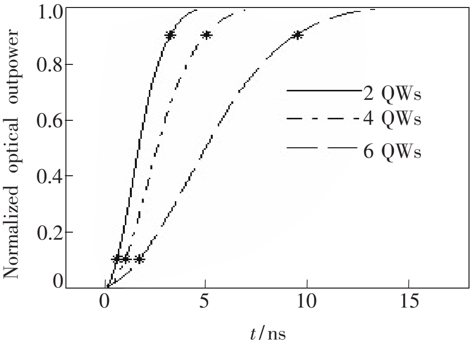

Fig. 3 Transient response of GaN-based LED with 2, 4, and 6 wells.

Fig. 4 shows the relation between our simulated results of the rise time and the number of quantum wells. Two facts can explain why the rise time of light pulse increases with the number of wells. The rise time is governed by the injected carrier lifetime and the stored charge effect[12]. Firstly, the increased volume of the active region will decrease the injected carrier density, which can affect the injected carrier lifetime. Secondly, from the equation (6), the charge stored capacitance C_j increases with the volume, and then this will increase R_bC_j constant of LED.

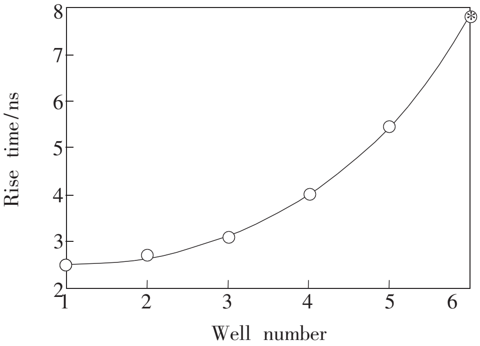

Fig. 4 The simulated rise time *vs.* number of wells. Asterisk represents Shi's measured experimental result.

4 Conclusion

We have investigated the transient response of InGaN green LED with varied quantum wells on the basis of SPICE model. We find that the rise time increases with the number of quantum wells, which is also explained with two facts. Owing to the output power of LED enhanced with the number of wells, we propose that the optimized structure will be three wells in the active region, considering both the luminous power and the dynamic response.

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