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The effects of carrier transport phenomena on the spectral and power characteristics of blue superluminescent light emitting diodes

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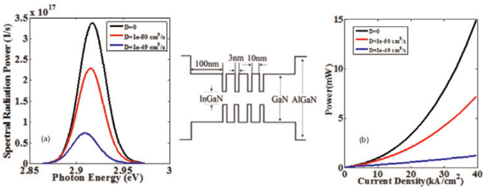
HIGHLIGHTS

- In this article $In_{0.2}Ga_{0.8}N/GaN$-MQW superluminescent light emitting diodes has been investigated.
- The effects of carrier escape, capture, and diffusion rates, and also carrier leakage are calculated.
- The simulation is implemented at 300 K and at a constant current density of 15 kA/cm^2.
- The increasing of the drift leakage coefficient decreases the output power, significantly.
- The escape times do not affect the SLD characteristics.

GRAPHICAL ABSTRACT

The effects of carrier escape, capture, and diffusion rates, and also carrier leakage term on the spectral and power characteristics of $In_{0.2}Ga_{0.8}N/GaN$ multiple quantum well (MQW) superluminescent light emitting diodes (SLDs or SLEDs) has been investigated.

Output spectral radiation power of studied SLD versus photon energy and (b7) output power as a function of current density for different drift leakage coefficients.



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ABSTRACT

In this article, the effects of carrier escape, capture, and diffusion rates, and also carrier leakage term on the spectral and power characteristics of $In_{0.2}Ga_{0.8}N/GaN$ multiple quantum well (MQW) superluminescent light emitting diodes (SLDs or SLEDs) has been investigated. The investigation is done by means of numerical analysis of the rate equations at steady state. In the model, a wide range of escape, capture, and diffusion times and also drift leakage coefficient correspond to the reported values have been examined in modeling procedure. The simulation is implemented at 300 K and at a constant current density of 15 kA/cm^2. Our modeling results show that the escape times do not affect the SLD characteristics, but the variation of capture and diffusion times have moderate effects on output characteristics, while the increasing of the drift leakage coefficient decreases the output power significantly.

1. Introduction

Broadband light sources based on superluminescent light emitting diodes (SLDs or SLEDs) are optoelectronic devices with the characteristics of both a laser diode (LD) and light emitting diode (LED) [1]. They present highly directional LD beam and incoherent light emission of an LED [2]. The beam directionality is caused high efficiency coupling with optical fiber systems. They are used for various applications including optical coherence tomography (OCT) [3], wavelength-division-multiplexing (WDM) testing systems [4], speckle-free illumination [5]. Recent investigations have focused on producing blue SLEDs using GaN-based materials [6]. The first blue SLD have been reported in 2009 by Feltin et al. [7]. Short wavelength optoelectronic devices (UV to visible) can be used in spectroscopy, display lighting, projection systems [8] and medical applications [7].

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SLD devices are fabricated by various crystal growth techniques e.g. metal organic vapor phase epitaxy (MOVPE), molecular beam epitaxy (MBE), liquid phase epitaxy (LPE) and usually for blue emission range they were grown on GaN substrates. InGaN/GaN quantum wells/barriers were embedded in a p–n waveguide consisted of GaN separate confinement heterostructure (SCH) and AlGaN cladding layers. For current injection, ridge waveguide and ohmic contacts are made by several standard fabrication techniques e.g. dry etching to form the ridge and thin-film deposition of metals to form ohmic contacts. Different waveguide geometries are applied to suppression of resonant feedback and lasing of device, for example: tilted waveguide, bent waveguide, obliquely etched facet, antireflection coating on facets and etc.

The carrier escape, capture, and diffusion times are very important parameters that determine the static and the dynamic performance of quantum well (QW) laser diodes (LDs) [9], light emitting diodes (LEDs) and superluminescent light emitting diodes (SLDs). The effects of the carrier transport in a multiple quantum well (MQW) active region and across separate confinement heterostructures (SCH) layer and their influence on the LD operation have been studied variously in III–V compounds [10] and group-III nitride devices by drift-diffusion model [11,12]. On the other hand there is not any research report about influence of drift leakage term in rate equations on the SLD performance. However, in this paper, we investigate the effects of the escape, capture, and diffusion rates and also carrier leakage term on the spectral and power characteristics of a GaN-based SLD, using the rate equations model. We have examined the possible range of the escape, capture, and diffusion times and drift leakage coefficient for our simple typical device and those effects on the output performance of SLD have been analyzed. Our investigation is implemented at 300 K. Our studied structure is a simple edge emitting device consists of four 3 nm $In_{0.2}Ga_{0.8}N$ quantum wells (QWs), three 10 nm GaN barriers confined with two 100 nm SCH GaN layers. We suppose index-guided waveguide were defined by 2 μm wide ridge and 800 μm Cavity length. The reflectivity of the end facets is assumed to be zero.

2. Theoretical model

To model the device, we started with calculation of the band profile of the active layer using finite difference method. Then, using an analytical expression for spectral radiation power of SLD, and solving two level rate equations, corresponding to MQW active region and separate confinement heterostructures (SCH) layer self-consistently with no-*k* selection energy dependent gain, and quasi-Fermi level functions at steady state, the output power can be obtained [13–15]. The rate equations for the carrier density in the MQW region (N), the SCH layer (N_{SCH}) and the spectral density of optical power along the cavity in z direction, ($P^{\pm}_{(z,\, h\nu)}$), at steady state are written as

$$\frac{\eta_{inj}J}{eL_{SCH}} - \frac{N_{SCH}}{\tau_s} + \frac{N}{\tau_e}\frac{L_z}{L_{SCH}} - A_{SCH}N - B_{SCH}N^2 - C_{SCH}N^3 = 0 \tag{1}$$

$$\frac{N_{SCH}}{\tau_s}\frac{L_{SCH}}{L_z} - \frac{N}{\tau_e} - AN - BN^2 - CN^3 - DN^4$$

$$- \int \Gamma g(h\nu)\frac{P^{+}_{(z,\, h\nu)} + P^{-}_{(z,\, h\nu)}}{h\nu s}d(h\nu) = 0 \tag{2}$$

$$\pm\frac{\partial P^{\pm}_{(z,\, h\nu)}}{\partial z} = (\Gamma g - \alpha)P^{\pm}_{(z,\, h\nu)} + \frac{1}{2}\beta\Gamma r_{sp}h\nu s \tag{3}$$

These equations are two level rate equations [13,16–18] for MQW and SCH regions, and spectral density of optical power (s^{-1}) propagating in forward (right) and backward (left) direction along cavity length [14,19,20]. Escape time, τ_e, is the time that carriers escape from the quantum well (2D state) to the SCH layer (3D state) and it is related to thermionic emission over the SCH layers [17]. The carrier thermionic emission/escape time is an important parameter in determining efficiency of QW lasers [17]. Transport time, τ_s, describes the carrier transport from the SCH layer to the QW and is controlled by the transverse carrier diffusion in the SCH layer and the carrier capture of the QW [18]. The carrier transport time in the SCH (τ_s) is the sum of diffusion time in the SCH (τ_d) and the capture time in the QW (τ_c) as: $\tau_s = \tau_d + \tau_c$. J is the current density and A, B, C, A_{SCH}, B_{SCH}, C_{SCH}, are the Shockley–Read–Hall, spontaneous radiative, and Auger recombination coefficients in MQW and SCH regions, respectively [17,21] and D is drift leakage coefficient in MQW region [22–28]. The cross section of the SLD's active medium is $s = wL_a$; w and L_a are its ridge width and the thickness of active medium, respectively [14]. The integral in Eq. (2) accounts for stimulated recombination of carriers due to amplified spontaneous emission [19]. The spontaneous emission rate per unit volume per unit energy interval ($s^{-1}\,cm^{-3}\,eV^{-1}$) is defined as [14,15,21,29,30]

$$r_{sp}(h\nu) = \frac{8\pi n_r^2}{hc^2}\nu^2 g(h\nu)\,\frac{1}{1 - \exp\left[\frac{h\nu - (F_C - F_\upsilon)}{kT}\right]} \tag{4}$$

where F_c, F_υ are quasi-Fermi levels in conduction and valence bands, and we have obtained these levels as following relation by using charge neutrality relation as

$$F_c = kT\,\frac{N_t}{n_w n_c + N_c} + \frac{n_w n_c E_{e1} + N_c E_{CSCH} - kTN_c}{n_w n_c + N_c} \tag{5}$$

$$F_\upsilon = -\,kT\,\frac{N_t}{n_w n_\upsilon + N_V} + \frac{n_w n_\upsilon E_{h1} + N_V E_{VSCH} + kTN_V}{n_w n_\upsilon + N_V} \tag{6}$$

where n_w is the number of the quantum wells and N_t is the total electron density in the SCH-MQW region defined as [10,31,32] $N_t = N + N_{SCH}$. Symbols E_{CSCH}, E_{VSCH}, E_{e1}, E_{h1}, N_c, N_V, n_c, and n_υ are the conduction band edge energy of SCH region, the valence band edge energy of SCH, the first electronic subband energy, the first heavy hole subband energy, band edge effective density of states in the SCH conduction band, band edge effective density of states in SCH valence band, effective density of states in the conduction subbands, and effective density of states in valence subbands, respectively. For $g(h\nu)$ we have used the gain in the model of transitions without the *k*-selection rules for ground state transition in the MQW subbands that is better compatible with SLDs [14]. All of the other parameters and symbols have been introduced in Table 1.

We suppose that the gain function is uniform along cavity length in the z direction and reflectivity of left facet is zero at $z = 0$ in Eq. (3) and then we calculate spectral radiation power of SLD by integration along cavity length at the steady state, $P_s(L, h\nu)$. Therefore, at a certain current, the total radiation power on the right facet is calculated by integration of $P_s(L, h\nu)$ over photon energy range

$$P_{out} = \int P_s(L, h\nu)\; d(h\nu)$$
$$= \int \frac{4\pi\beta s n_r^2}{c^2} n_{sp}\nu^3 \frac{\Gamma g}{\Gamma g - \alpha}\left[e^{(\Gamma g - \alpha)L} - 1\right] d(h\nu) \tag{7}$$

The material parameters of binary InN and GaN in our simulation have been obtained from Refs. [40–44]. All other material parameters and physical constants used in this work have been extracted from published reports and have been collected in Table 1.

For considering of the escape and capture rates, we have taken into account the reasonable range of escape and capture times in the simulation process. In the case of diffusion time, we calculate it for our