Investigation of the Effect of Recombination on Superluminescent Light-Emitting Diode Output Power Based on Nitride Pyramid Quantum Dots

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ABSTRACT— In this article, the temperature behavior of output power of superluminescent light-emitting diode (SLED) by considering the effect of non-radiative recombination coefficient, non-radiative spontaneous emission coefficient and Auger recombination coefficients has been investigated. For this aim, GaN pyramidal quantum dots were used as the active region. The numerical method has been used to solve three-dimensional Schrodinger equations and traveling-wave equations. The spectral width of the gain spectrum in each case has been investigated. Eliminating the non-radiative recombination, non-radiative spontaneous emission coefficient and Auger recombination coefficients increased the output power of SLED and in some cases reduced the negative effect of temperature increase on output power.

KEYWORDS: Auger recombination, GaN, gain, non-radiative spontaneous emission, output power, pyramidal quantum dot, ridge bent waveguide, Superluminscent light emitting diode.

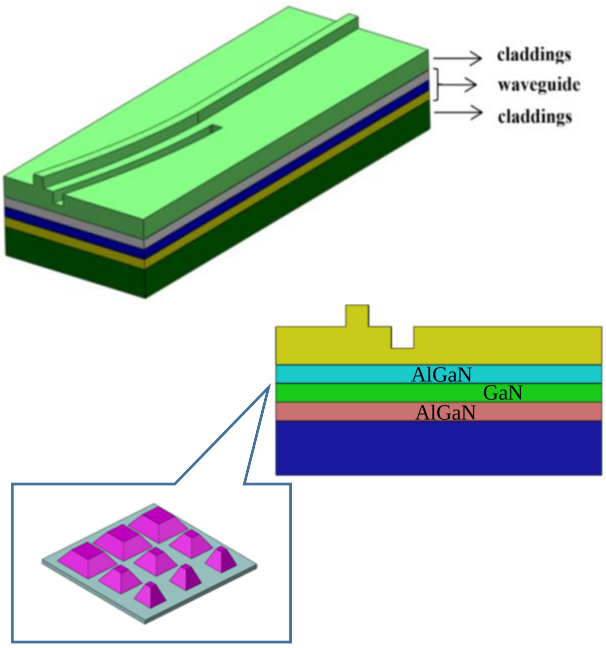
I. INTRODUCTION

The performance of light-emitting semiconductors such as light-emitting diodes (LEDs), laser diodes (LDs) is based on the forward current p-n junction diode. Superluminescent light-emitting diodes (SLEDs) are another type of light-emitting semiconductors which combine the characteristics of both, LEDs and LDs, have a broadband emission spectrum and high output power. These properties enable the device to be an excellent candidate for applications such as Optical Coherence Tomography Systems (OCT), optics devices testing, fiber-optic sensors, and speckle-free illumination [1]-[4].

Many types of research have been done on broadening the bandwidth of the emission spectrum of SLEDs, including multilayer QDs structures, Dot in wells (Dwell) structures, manipulated structures by Strain Reducing Layers (SRLs), annealing, or other processes. Using the post-growth annealing technique, hybrid structures, p-doping in addition to chirped QD multilayer the spectral width has been improved and reported many times [5]-[6]. The special properties of SLEDs based on nitride components, such as a wide range of emission frequencies, high quantum efficiency, and higher luminescence, have given them special attention [7].

Temperature characteristics of SLDs based on InAs/GaAs QDs multilayers have been investigated by M. Rossetti *et al*. [8]. The improvement of the output power by application of p-doping in the active region of QD to increase the modal gain in the presence of temperature changes has been reported [9]. The temperature dependence of L-I characteristics has been surveyed frequently [10]-[12].

In this research, the effect of temperature on the output power of SLED has been surveyed and the role of non-radiative recombination, spontaneous emission, and Auger recombination has been shown. The structure used for this purpose is a GaN-QD based SLED with bent ridge waveguide with a trench section as shown in Fig.1.



QDs active layer in the middle of the waveguide layer

Fig. 1. Schematic view of the bent-waveguide SLED structure.

II. Theoretical Model and Governing Equations

Eigen values (eigen states of energy) and eigen wave functions related to electrons and holes, in the active region, were obtained by solving the three-dimensional Schrodinger equation [13] and the effect of the pyramid shape of quantum dots was considered in Hamiltonian.

The traveling-wave equation in the one-Dimensional model can describe the propagation of optical waves along the cavity. By applying a theoretical model including a ridge waveguide structural model accompanied by QD energy states and position-dependent rate equations for the carrier density, this issue was solved through a numerical method [13].

The used traveling wave equation in the steady-state condition is simplified as follows [14]:

$$\pm\frac{\partial P^{\pm}(z,t,\lambda)}{\partial z} = (\Gamma(\lambda)g(z,t,\lambda) - \alpha_{int})P^{\pm}(z,t,\lambda) + \gamma R_{sp}(z,t,\lambda)\frac{hc\omega d}{\lambda} \qquad (1)$$

where P^{+} and P^{-} are the forward and backward traveling optical power, respectively. Γ is the optical mode confinement factor (the fraction of the propagating field mode confined to the active region), g is the material gain, α_{int} is the optical loss in the cavity, R_{sp} is the spectral density of spontaneous emission, γ is the spontaneous emission coupling coefficient, λ is the wavelength, w and d are the active region cross-sectional width and thickness, respectively. The power equation in the steady-state condition is expressed as follow [14]:

$$\frac{I(z)}{edLw} = [AN(z,t) + BN^2(z,t) + CN^3(z,t)] + \sum\frac{\Gamma g(z,t,\lambda)[P^{+}(z,t,\lambda)+P^{-}(z,t,\lambda)]}{h\upsilon_k wd} \qquad (2)$$

where *I*(z) is the bias current and *dLW* is the volume of the active region. The first term on the right-hand side of Eq. (2) is the recombination rate term, where ‘A’ denotes the non-radiative recombination coefficient, ‘B’ the non-radiative spontaneous emission coefficient, and ‘C’ the Auger recombination coefficient and N is the carrier density. The second term on the right-hand side of the equation is the amplified spontaneous emission (ASE) term.

The traveling-wave Eq. (1) and the carrier density rate Eq. (2) were solved numerically and simultaneously to obtain output power [13].

III. Results and Discussion

A. *The Effect of Non-Radiative, Spontaneous Emission, and Auger Recombination Coefficient*

Processes that affect the output of a light-emitting semiconductor are non-radiative recombination, non-radiative spontaneous emission, and Auger recombination (as seen in Eq. (2)). Non-radiative recombination causes a decrease in semiconductor output power, in the process of spontaneous emission. If one can protect exciton from their defects environment, using methods such as those shown in [15], then photo-excited electrons are kept in the core of QDs and cause to suppression of non-radiative recombination, Auger recombination, and non-radiative spontaneous emission.

Here, we present the effect of eliminating non-radiative recombination, Auger recombination, and the non-radiative spontaneous emission coefficient on the output power (Fig. 2.)

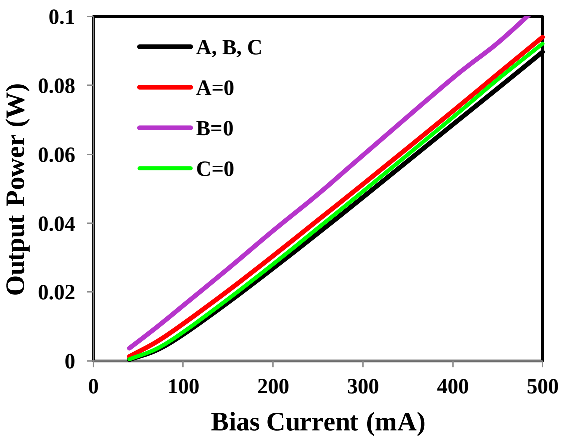


Fig. 2. The output power as a function of bias current by changing the recombination coefficients (these data are in temperature of 300K).

In Fig. 2. letter A represents the non-radiative recombination coefficient, letter B represents the non-radiative spontaneous emission coefficient and C denotes the Auger recombination coefficient.

This diagram shows the effect of recombination terms on the output power. In other words, if we eliminate each of the non-radiative recombination, the Auger recombination and the non-radiative spontaneous emission coefficient the output power increases. As can be seen from the diagram, elimination of the non-radiative spontaneous emission coefficient causes a significant increase in output power and so we can consider the non-radiative spontaneous emission a loss because it radiates in all directions, only a small part of it is coupled into the waveguide. On the other hand, the Auger recombination has little effect on the output power of SLED.

B. *The Effect of Temperature on the Output Power by Varying the Auger Recombination*

In SLEDs, the bandwidth of the gain spectrum is a key characteristic for evaluating its output power. Therefore, we first obtain the gain spectrum for conditions where the Auger coefficient does not exist and in normal conditions with the Auger coefficient. Figure 3 clearly shows the changes in the gain spectrum width.

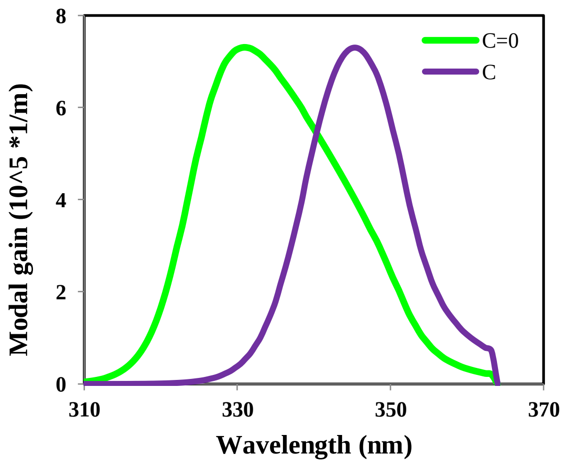


Fig. 3. Modal gain spectrum in two conditions; considering the Auger coefficient and without it.

According to the gain spectra, the full width at half maximum (FWHM) for these diagrams was calculated and shows that in the case without Auger recombination coefficient FWHM is equal to 23.7 nm, and greater than a normal condition with FWHM=15nm. Since more bandwidth is more desirable for the SLED, we expect to get more output power in these conditions. Confirmation of this result was shown in Fig. 2.

Figure 4. compares the output power characteristics of a 1200 μm long SLED versus temperature for the bias current of 400 mA in two cases; a) the Auger recombination coefficient has its original value and, b) the Auger recombination coefficient is zero.

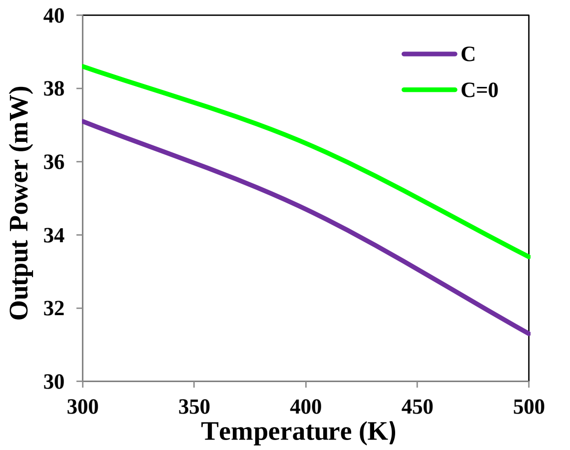


Fig. 4. The output power as a function of bias current by changing the temperature and the Auger recombination coefficients

It can be seen that increasing the temperature reduces the output power because at higher temperatures carriers are distributed over a wider range of energy and consequently the gain decreases. However, by controlling the Auger recombination this negative effect is greatly reduced. The diagram of the gain spectrum at two different temperatures for the SLED is shown in Fig. 5.

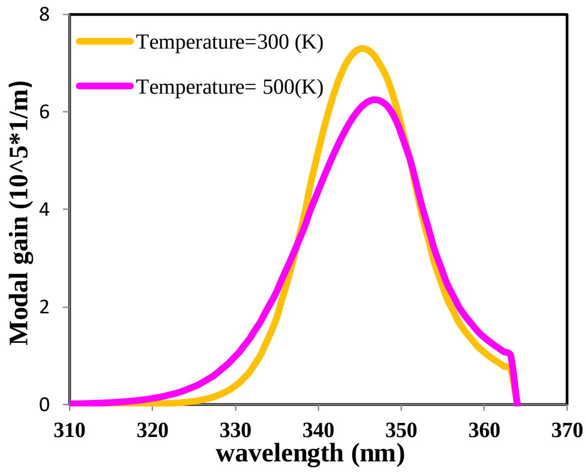


Fig. 5. Modal gain spectrum in two different temperatures, 1200 μm long SLED and 400 mA bias current.

C. *The Effect of Non-Radiative Spontaneous Emission*

In this section, the effect of the elimination of the non-radiative spontaneous emission coefficient has been investigated. As in the previous section, the gain spectrum is shown in two situations. The value obtained for FWHM in these conditions is equal to 18 nm, which is also more than the normal condition (Fig. 6).

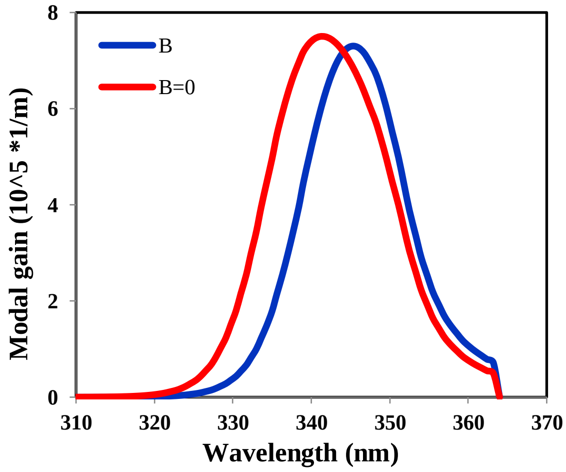


Fig. 6. Modal gain spectrum in two conditions; considering the non-radiative spontaneous emission coefficient and without it.

The output power concerning temperature changes for 400 (mA) bias current has been plotted in Fig. 7.

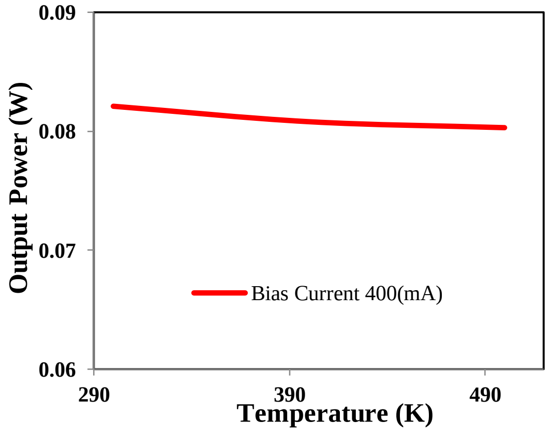


Fig. 7. The output power of SLED for zero non-radiative spontaneous emission coefficient and by varying the temperature at bias current 400 (mA).

As can be seen from the diagram, the effect of eliminating the non-radiative spontaneous emission coefficient on the output power is such that it covers almost all the negative effects of temperature increase and the output power results in almost the same at all three temperatures.

IV. Conclusion

In conclusion, the behavior of SLED based on nitride QDs was shown by changing the recombination coefficients and considering temperature changes. The results show that by limiting and controlling the Auger recombination coefficients and non-radiative spontaneous emission coefficients the output power can be increased, which is due to the increase in the gain spectrum width. So that the negative effect of temperature increase is partially eliminated.

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