Asymmetric Electron-Hole Model for Gain-Switched InAs/InP Quantum Dot Laser

Nuran Dogru*
Electrical&Electronics Engineering
Gaziantep University
Gaziantep, Türkiye
dogru@gantep.edu.tr

Isa Akkaya
Electrical&Electronics Engineering
Gaziantep University
Gaziantep, Türkiye
isaakkaya@gantep.edu.tr

***Abstract*— The electron-hole model of InAs/InP quantum dot laser under gain-switching condition is investigated. The results show that the threshold current of the excited state decreases while that of ground state increases slightly for electron-hole model. Therefore, the current range where gain-switched pulses are generated increases. However, it has been observed that since the pulses generated from the exciton and electron-hole models are not narrow, an optical pulse needs to be applied to the excited state to obtain short pulses from both models.**

Keywords—gain-switching, quantum-dot laser, short pulses, exciton model, electron-hole model

I. Introduction

Optical data communication, ultrafast spectroscopy, metrology and medical biotechnology etc. are fields that require short pulses with high frequency and peak power [1]. Due to the extraordinary properties such as low threshold current, chirp-free behavior, and temperature insensitivity of quantum dot lasers, they are preferred sources for these fields over quantum well lasers. Therefore, many studies have been conducted in this field using quantum dot (Q-Dot) lasers [2–3]. The symmetric exciton model and the asymmetric electron-hole model are two models used to theoretically investigate the nonlinear dynamics of quantum dot lasers. Although the excitonic model explains some characteristics of Q-Dot laser such as modulation and noise characteristics, the electron-hole model successfully describes the Light-Current characteristics [4], the temperature dependence of photoluminescence [5–6], and the phase and gain dynamics of the Q-Dot laser. To our knowledge, no work has been done to generate short pulses from Q-Dot lasers using the electron-hole model. Therefore, here we numerically studied the gain-switched characteristics of the InAs/InP Q-Dot laser using the electron-hole model. Since 1.55 µm laser emission is a significant demand in applications such as biomedical technology and optical communication, an InAs-InP(113)B Q-Dot laser, in which the InAs Q-Dot laser is grown on an InP substrate, is the most suitable choice with its emission wavelength [7].

II. Numerical Model

The numerical model used here is based on reference [2]. The carriers and photons rate equations in the ground state (Grs) and excited state (Exs) of the Q-Dot laser are used as the basis of the direct relaxation model. The Runge-Kutta method was used to resolve the rate equations of single-mode laser. This method is a numerical integration technique frequently used in solving differential equations. Q-Dot size fluctuations, line broadening and temperature effect were neglected in our analysis. Moreover, it was assumed that carriers are injected directly into the wetting layer (Wly) from the contact points. The laser rate equations include densities of electrons and holes for the Wly, Grs, Exs and the photon densities for Grs and Exs (i.e output is two state lasing). It was also assumed that the energy level spacing between the ground state and the excited state in the valence band is 0.5 times that in the conduction band since the holes have a much heavier effective mass than electrons [8]. Since the holes effective mass is a much heavier than electrons, the electron energy spacing in all InAs/InP Q-Dots is two times larger than that of the holes.

III. Results and Discussion

In our simulation, the values of laser parameters were taken from [2]. The gain compression factor was included and it was taken as $1\text{x}10^{-16}$ cm^{-3}. To obtain the short pulses in the simulation, the AC current given below was applied.

$$I(t) = I_f \, 2\,(|cos(2\Pi f t)| - cos(2\Pi f t))$$

Where I_f is the peak value of the current and f indicates the frequency. The frequency range in which gain-switching pulses were generated was obtained between 350 MHz–1 GHz for electron-hole model and 400 MHz–1 GHz for exciton model. 1 GHz was chosen as operating frequency.

The Light-Current characteristics of symmetric exciton model and asymmetric electron-hole model are given Fig. 1 and 2 and the corresponding threshold currents for Grs, Exs and total (Grs+ Exs) are summarized in Table 1.

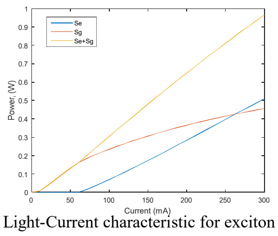

Fig. 1. Light-Current characteristic for exciton model.

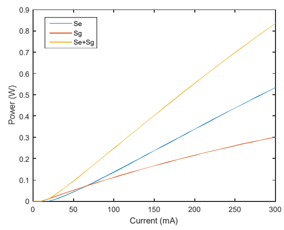

Fig. 2. Light-Current characteristic for electron-hole model.

As seen in the figures, for the electron-hole model threshold current of Exs decreases while the threshold current of Grs is approximately the same. In the electron-hole model, since electron energy spacing larger than the hole energy spacing, a smaller electron escape rate occurs compared to the hole escape rate. Therefore, for the electron-hole model, the threshold current of Exs decreases while the threshold current of Grs increases. Although similar behavior was observed in InAs/GaAs Q-Dot lasers, as the current increases, the power of Exs increases, while the power of the Grs decreases and eventually decreases to zero, making the laser a single state lasing [4]. However, in the exciton model of the InAs/GaAs Q-Dot lasers Grs saturated with the increasing current.

Table I. Threshold currents of Grs and Exs

	Grs, mA	Exs, mA	Total (Grs+Exs), mA
Exciton model	8	61	8
Electron-hole model	10	20	10

Fig.3 and Fig. 4 show output pulses of Grs and Exs for both models. As seen in the figures peak power of Exs increases whereas the peak power of Grs decreases for the electron-hole model due to low threshold current of Exs. The pulse width of the output pulses (Grs+Exs) are obtained 265 ps and 256 ps for the exciton and electron-hole model, respectively. These results showed that the pulses generated from both models are not narrow. To obtain shorter pulses, we need to apply optical pulses to Exs as seen in Figure 5. A Gaussian peak pulse of 20 mW and I_f of 60 mA give a pulse width of 47 ps and peak power of about 1 W.

Our results also show that the Exs threshold current decreases with fast electron escape time from Grs to Exs and slow capture time from Wly to Exs , while the Grs threshold current slightly change as seen in Fig. 6. However, slow electron escape time and fast capture time the Exs threshold current increases whereas the Grs threshold current remains approximately the same (see Fig. 7). These results confirm the results of the exciton model in [2]. However, in InAs/GaAs lasers it was observed that, the Exs threshold current first decreases with decreasing electron escape time from Grs to Exs and then it becomes constant, while the Grs threshold current first remains constant and then Grs lasing stop [4].

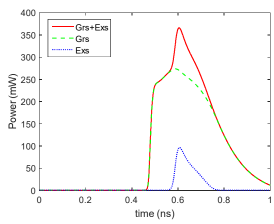

Fig. 3. Output power for exciton model for an I_f current of 100 mA.

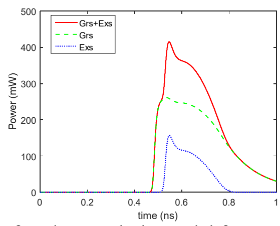

Fig. 4. Output power for electron-hole model for an I_f current of 100 mA.

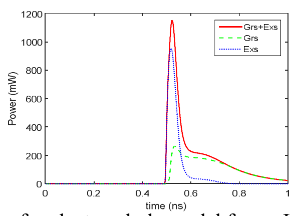

Fig. 5. Output power for electron-hole model for an I_f current of 60 mA and Gaussian peak pulse of 20 mW.

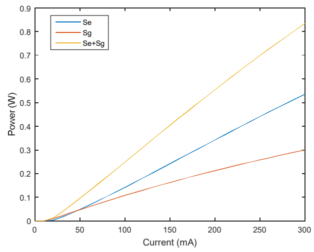

Fig. 6. Light-Current characteristic for fast electron escape time.

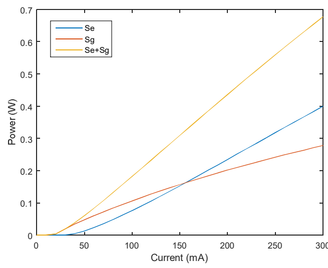

Fig. 7. Light-Current characteristic for slow electron escape time.

In summary, for the electron-hole model, as the current increases, the threshold current of Exs decreases and its power increases, but the threshold current of Grs increases slightly and its power decreases. Moreover, the fast electron escape time from Grs to Exs causes the threshold current of Exs to decrease. Our results also showed that optical pulses should be applied to Exs as in the exciton model to produce shorter pulses for the electron-hole model.

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