



# THE DEVELOPMENT OF SIMULATION MODEL OF CARRIER INJECTION IN QUANTUM DOT LASER SYSTEM

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## ABSTRACT

The development simulation model of quantum dot (QD) laser is performed based upon rate equations for the carriers and photons in energy states. The rate equation is solved by using Matlab, Runge-Kutta method. In this paper shown that by increasing carrier injection to the active medium of laser, switching-on and stability time of the system would decrease while output power at peak and stationary will be increased. Indirect (non-instantaneous) carrier injection into QD is an essential component of our model and it describes the actual situation for QD laser.

**Keywords:** semiconductor quantum dot laser, carrier injection, rate equations, simulation.

## INTRODUCTION

Semiconductor InAs/GaAs quantum dots nanostructures are valuable in which carriers injection movement are limited in three dimensions of the confinement layer. The discontinuity of QD in the density of energy states, [1] pointed that as “artificial atoms” similarity behavior with atoms particle. Previous studies have reported [2] that the Stranski-Krastanow QDs is larger size about 10% in homogeneity have been successfully employed in devices.

The inhomogeneous broadening of the discrete density states for self organized QD ensembles hampers detailed investigations of the excited state spectrum and of energy relaxation (and recombination) processes, which are both of physical interest for design and performance of devices. Several studies by [3] have revealed that though self organized QDs are easily incorporated in conventional device structures and have been proposed for different applications from the ultraviolet to the far infrared spectral range. The interdependent nature of the QD density and size makes the adaptation of the QDs to the device needs difficult. In fact, [4] studies have confirmed that it is often necessary to distinguish between extrinsic ensemble effects and intrinsic properties of single QDs, for example in describing the carrier dynamics. [5] lists the possibility of the extremely low threshold current densities, high temperature stability, potential low chirp, fast carrier dynamics, and modified density of states function which would improved performance. In recent years, extensive work has been devoted to simulation of quantum well semiconductor laser diode.

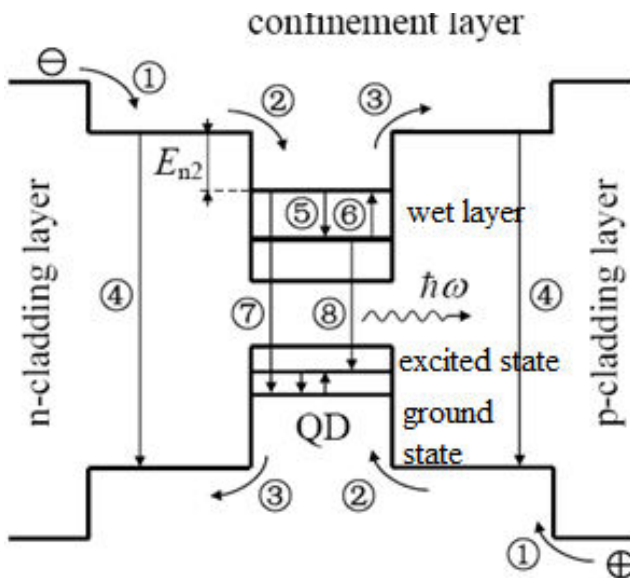
In this paper, we designed laser which its parameter at temperature of 297.15K, the density layer of  $4.3 \times 10^{22} \text{ m}^{-3}$ , the active medium length about 1000  $\mu\text{m}$ , waveguide width 4  $\mu\text{m}$ . Modeling and simulation of the QD laser based on rate equations for the density of carriers injection and photons, can predict its performance which can be used in the actual devices. Rate equations are solved by using MATLAB software which applied Runge-Kutta numerical method. Through calculation solving these equations, we can presented the carrier, photon

density, laser switching-on, laser output power, and stability time of the system.

## Rate equations description

The rate equations are coupled with two equations of carrier density and photon density. In this paper, the carrier injected is considered to be constant. The carrier injection process would increase the number of electron-hole pairs in the system where electrons in the conduction band and holes in the valance band. Four energy states of the confined carriers in the QD such as the confinement layer, wetting layer, excited states and the ground state.

From Figure-1 in optical responses of semiconductors, an electron and a hole excited respectively in conduction and a valence band, which their composite particle called an exciton, play central roles [6]. Initially, carrier is injected into confinement layer (CL), which leads to increase electron-hole pairs and thus raising carrier density in the band. The carriers in the confinement layer steady state into WL at a time  $\tau_{CL}$ , and then experience another fast relaxation into the excited state (ES), at a time  $\tau_{ES}$ . Most of the carriers are captured into ES, and some of the carriers decay ( $\tau_{qr}$ ), and WL obtains few carriers which are escaped back from ES ( $\tau_{ES}$ ). Processes occur for carriers in the ground state (GS) and ES are in the same way. [7] demonstrates that some parts of the carriers perform decay due to the effect of spontaneous and Auger effects ( $\tau_r$ ). It shown that electrons are injected from the n- layer, while holes are injected from the p-cladding layers. In the active medium, electrons and holes recombine via spontaneous and stimulated recombination thus generating photons. The generated emission is confined within the optical confinement layer. Photons leaving the cavity from its facets form the output of a laser the remaining carriers contribute in the stimulated emission to produce laser photons.



**Figure-1.** Schematic diagram of the components in QD lasers. The levels are related to confinement layer (CL), wetting layer (WL), excited state (ES), and the ground state (GS) of a QD.

The time dependent differential equations for photons and carrier injected which are involved in each process, were examined to investigate balance between generation or recombination of electron-hole pairs and generation or absorption of photons over time. The relation between the number of excitons and the optical responses is a long standing problem in exciton physics. Under a weak excitation condition [8] observed that, only an electron and a hole are created, which form a bound state due to the Coulomb attraction.

In this context, continuous wave and steady state rate equations model are used to calculate the output optical power. This paper intends to focus on the effect of excited states the carrier capture into and escape from the QD ground state occur via the excited state. In assumption that the electron and hole densities are equal in the confinement layer, and the occupancies of the electron and

hole ground states (excited states) are equal in a QD (charge neutrality). The separate the effect of excited state mediated capture on ground state lasing; the internal optical loss is ignored.

#### Analysis of carrier injection for a QD

The rate equations of carrier density and photon density in equation (1) to (6) respectively:

$$\frac{dN_{CL}}{dt} = \eta_i \frac{I}{qV_a} - \frac{N_{CL}}{\tau_{CL}} - \frac{N_{CL}}{\tau_{sr}} + \frac{N_{WL}}{\tau_{eWL}} \quad (1)$$

$$\frac{dN_{WL}}{dt} = -\frac{N_{WL}}{\tau_{qr}} + \frac{N_{CL}}{\tau_{CL}} + \frac{N_{ES}}{\tau_{eES}} - \frac{N_{WL}}{\tau_{eWL}} - \frac{N_{WL}}{\tau_c} (1 - f_{ES}) \quad (2)$$

$$\begin{aligned} \frac{dN_{ES}}{dt} = & -\frac{N_{ES}}{\tau_r} - \Gamma v_g g_{ES} (2f_{ES} - 1) S_{ES} - \frac{N_{ES}}{\tau_{eES}} \\ & + \frac{N_{WL}}{\tau_c} (1 - f_{ES}) + \frac{N_{ES}}{\tau_{eES}} (1 - f_{ES}) \end{aligned} \quad (3)$$

$$\frac{dN_{GS}}{dt} = -\frac{N_{GS}}{\tau_r} - \Gamma v_g g_{GS} (2f_{GS} - 1) S_{GS} - \frac{N_{GS}}{\tau_{eGS}} (1 - f_{ES}) \quad (4)$$

$$\frac{dS_{ES}}{dt} = -\frac{S_{ES}}{\tau_s} + \Gamma v_g g_{ES} (2f_{ES} - 1) S_{ES} + \beta_{sp} \frac{N_{ES}}{\tau_{sp}} \quad (5)$$

$$\frac{dS_{GS}}{dt} = -\frac{S_{GS}}{\tau_s} + \Gamma v_g g_{GS} (2f_{GS} - 1) S_{GS} + \beta_{sp} \frac{N_{GS}}{\tau_{sp}} \quad (6)$$

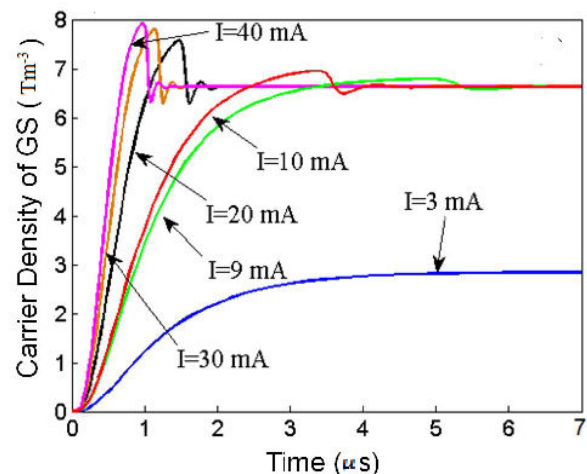
Table-1 shows the following physical quantities and terms:

**Table-1.** The physical quantities and terms.

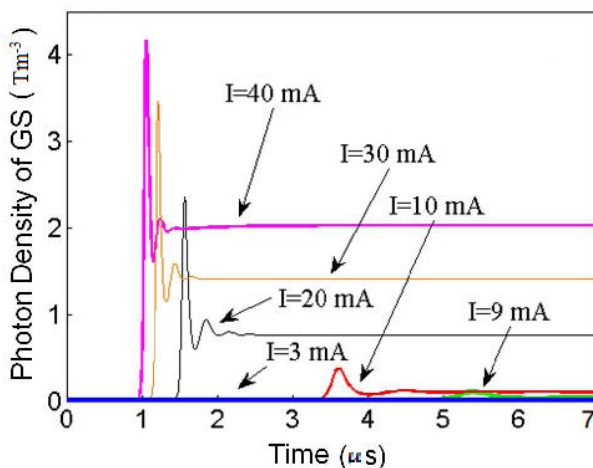
Physical quantities	Terms
$N$	carrier density in current state.
$N_{CL}$ , $N_{WL}$ , $N_{ES}$ , and $N_{GS}$	the density of carriers in the $CL$ , $WL$ , $ES$ and $GS$ respectively.
$SGS$ , $SES$	the density of photons in the $GS$ and $ES$ level respectively.
$\eta i$	coefficient of injected current rate ( $I$ , injected current).
$q$	unit charge.
$Va$	volume of active medium.
$-\frac{N_{CL}}{\tau_{CL}}$ , $-\frac{N_{WL}}{\tau_{gr}}$ , $-\frac{N_{ES}}{\tau_r}$ , $-\frac{N_{GS}}{\tau_r}$	decay rates of carrier density in $CL$ , $WL$ , $ES$ and $GS$ respectively.
$-N(1-f)/\tau_e$	carrier escape rate from the current level to higher level.
$\tau_e$	carrier escape time.
$-\frac{N_{WL}}{\tau_c}(1-f_{ES})$	carrier relaxation rate from the $WL$ to $ES$ .
$\tau_c$	carrier relaxation time.
$\tau_c$	corresponding to photon decay rates.
$\frac{S_{GS}}{\tau_s}$ , $\frac{S_{ES}}{\tau_s}$	photon lifetime.
$\tau_s$	photon generation rate by spontaneous recombination.
$\beta_{sp} \frac{N_{GS}}{\tau_{sp}}$ , $\beta_{sp} \frac{N_{ES}}{\tau_{sp}}$	spontaneous emission coupling factor.
$\beta_{sp}$	spontaneous recombination time.
$\tau_{sp}$	photon generation rate (+)
$\Gamma v_g g_{GS} (2f_{GS} - 1) S_{GS}$	due to stimulated emission.
$\Gamma v_g g_{ES} (2f_{ES} - 1) S_{ES}$	carrier recombination rate
$\Gamma$	(-) due to stimulatoptical
$v_g$	confinement factor.
$g$	group velocity.
$f$	peak gain of material.
$\mu$	occupation probability.
	degeneracy.

## SIMULATIONS RESULTS

From figures 2 and 3 the carrier and photon densities for different reach steady states after viewing relaxation oscillations at the early stages of injection carrier. [5] mentions the significant relation that at below threshold current, there is no oscillation, and the photon densities of each injection carrier are very small. [9] investigated that as injection carrier increases, photon density would increase and the QD lasing begins. The increasing will continue until the density reaches a constant value and then further injection carrier increasing with time does not change the photon density.

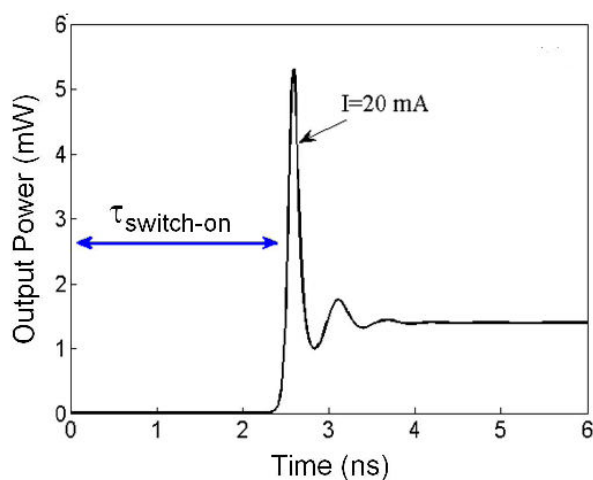


**Figure-2.** Graph carrier density versus time in the  $GS$  for different injected carrier.



**Figure-3.** Graph photon density versus time in the GS for different injected carrier.

In the Figure-4 output power versus time for the GS is depicted when injected current was 20 mA. Calculation shows the switch-on time value is 2.7 ns, and the laser reaches steady state after about 4.8 ns following some fluctuations. The switch on and stability times decrease with increasing injection carrier and the power's peak and also the achieved steady power of the laser would increase this finding is consistent with findings of past studies by [9]. At power exceed 5 mW, the laser is saturated, and therefore by further increasing of the injection carrier, laser's stabilized power remains unchanged, but the turn on time continues to its decreasing this finding is consistent with findings of past studies by [10].



**Figure-4.** Output power of laser versus time for the GS with injected carrier 20 mA.

## CONCLUSIONS

In this paper, the development simulation model of quantum dot (QD) laser is performed based upon rate equations for the carriers and photons in four energy states. The rate equation is solved by using Matlab, Runge-Kutta method. Simulation results shown that by

increasing carrier injection to the active medium of laser, switching-on and stability time of the system would decrease while output power at peak and stationary will be increased this finding is consistent with findings of past studies by [9]. The power increase would exist until photons emissions at each injection carrier level reach steady state. [5] mentions the significant relationship that QD lasers have lower threshold currents in comparison with the conventional laser. Subsequent to stabilization of emission power in each energy level, the upper level will start to emit photons, and contributes in the output of the device. Indirect (non-instantaneous) carrier injection into QD is an essential component of our model and it describes the actual situation for QD laser.

This research has thrown up many questions in need of further investigation. Further research might explore the qualitatively similar character of the recombination rates in the OCL and the wetting layer (both are superlinear in the corresponding carrier density), and of the captures from the three-dimensional and two-dimensional regions into QDs, such an extension will introduce significantly new results and an novelty in future research.

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