Spatially Resolved Model for Carrier Dynamics in Tunneling Injection Quantum Dot Lasers

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***Abstract*—We present a detailed model for carrier dynamics in tunneling injection quantum dot lasers. The model includes the spatial dependence of the mobile carriers and the coupling between mobile carriers and confined carriers.**

I. INTRODUCTION

Self organized quantum dot (QD) lasers have demonstrated attractive characteristics. However, the dynamical properties of such lasers at room temperature limit their modulation capabilities. One seccessful technique to enhance the dynamical properties of QDs lasers is the tunneling injection (TI) scheme. TI scheme was originally demonstrated on quantum well (QW) lasers [1]. Dynamic modeling of tunneling injection quantum dot lasers have been proposed before [2]. Those models are not spatially resolved and do not address the seperate role of electrons and holes. Tunneling injection quantum dot lasers perform larger differential gain, high temperature stability and low linewidth enhancement factors. An accurate model for these properties must include the spatially resolved carrier distributions and the coulomb interaction between carriers.

II. MODEL DYNAMICAL CONCEPTS

The model incorporates two types of carriers electrons and holes and is based on a rate equations model, which was already demonstrated for QW lasers [3]. Each carrier type is divided into groups according to their energy separation. The first group includes the unconfined carriers, these are three dimensional (3D). The second group includes two dimensional carriers, these carriers are confined inside the injector well and quantum well (QW) like wetting leyers (2D). The third group includes the zero dimensional carriers (0D), which are confined in the quantum dots (QDs). Fig.1 describes the injection process conceptually. Electrons and holes are injectred from the N and P side, respectively. The electrons experience a potential barrier before reaching the QDs. As a result, the electrons are captured into the injector well and are injected via phonon assisted tunneling into the lasing state (QDs ground state). The holes do not experience the potential barrier before reaching the QDs. Since the holes are heavy and slow, they are well confined inside the QDs and QWs. The interaction between electrons and holes is modeled via the poisson equation, which in turns also modifies the confined energy states.

A. Tunneling Barrier Modeling

The tunneling injection is designed so its confined energy state is $36meV$ (one LO phonon energy) higher than an $In_{0.4}Ga_{0.6}As$ QD ground state. This allows an efficient phonon assisted tunneling of electrons from the injector well directly to the lasing state. In addition to injecting ”cold” electrons into the lasing state, phonon assisted tunneling is a fast process which is expected to increase the modulation bandwidth. The tunneling barrier is incorporated in the model through the discontinuity in the band structure. We assume most electrons are captured into the injector well and tunnel from there to the first quantum dots layer, hence, resonant tunneling is negligible.

B. Quantum dots Electronic States

The modeled structure is based on self-organized $In_{0.4}Ga_{0.6}As - GaAs$ QDs. Individual dots are pyramidal to lens like in shape with a base dimension of about twice the height. The QDs have two confined electrons energy states. The ground state has a double spin degeneracy. The first excited state has a double spin degeneracy and a twofold spatial degeneracy. We assume that the wave function of the carriers in the QDs can be described as a product of two wave functions $\psi(x, y, z) = \psi(x, y) \cdot \psi(z)$ where z is the growth direction and xy is the plane of the growth. This type of wave functions yield energy states of the form $E = E_{xy} + E_z$. Since the QDs' height is smaller than their base dimension, we assume the excited state is attributed to the first excited state in the plane defined by the growth direction.

III. RESULTS

The results presented here address the basic properties of QDs and hence, the QDs are assumed to be identical. In Fig. 2(a) distributions of 3D electrons and holes are presented. Near the N (P) side band edge a large concentration of electrons (holes) is seen, this is attributed to the quantum like potentials created near the heterostructure edges. The effect of the tunneling injection barrier is clearly noticeable. The electrons accumulate near the potential barrier and are captured into the injector well. The holes accumulate right after the potential barrier due to the coulomb interaction with the electrons. This result clearly indicates the differential gain improvement due to lower carrier concentration above the QDs

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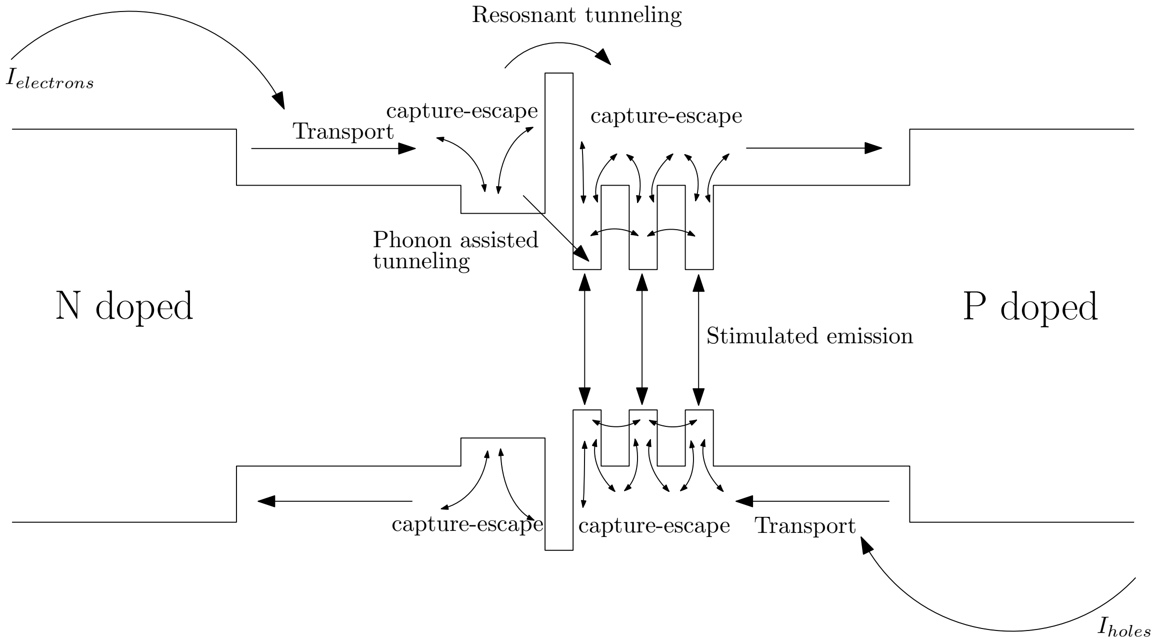

Fig. 1. Conceptual description of carriers dynamics. Classical transport of 3D carriers. Capture and escape of 3D carriers into 2D states. Capture and escape of 2D carriers into 0D states. Phonon assisted tunneling from injector well into QDs ground state and resonant tunneling between adjacent QDs layers.

layers. In Fig. 2(b) distributions of the confined carriers are presented. These population consist of the 2D confined carriers from the QW like wetting layers and 0D confined carriers inside the ground state and excited state of the QDs.

IV. CONCLUSION

The spatial distributions of carriers have an important influence on lasers performance. In order to understand the improved differential gain,low linewidth enhancement factor and high temperature stability, spatially resolved model is necessary. The tunneling injection barrier has two roles, in addition to fast injection of cold carrier to the lasing state, it also reduces the concentration of carrier at the higher energy levels. This reduction is higher energies concentrations improves the differential gain and the bandwidth.

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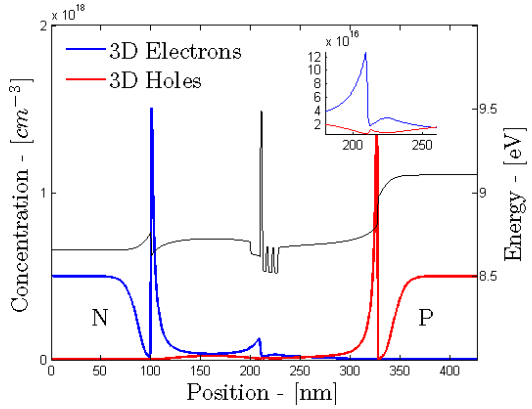
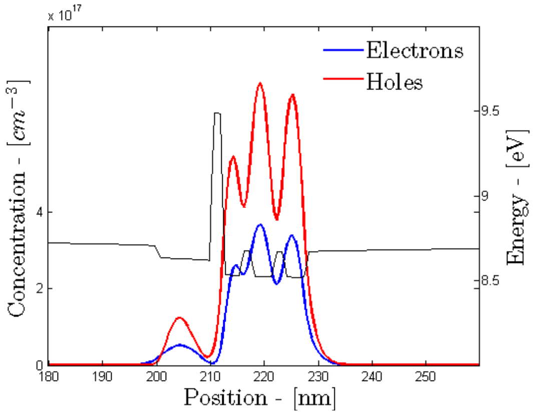


(a) Mobile carrier distributions



(b) Confined carrier distributions

Fig. 2. Steady state carrier distributions at 10mA