Effect of Wetting Layers on Quantum Dash Laser Operation in Crosslight Pics3D

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***Abstract*— We discuss the integration of quantum dashes (QDashes) into laser simulations using Crosslight Pics3D, outlining the approach for developing a model featuring asymmetrical active regions. The importance of including wetting layers to accurately represent carrier transport is investigated using results obtained for an InAs/InP QDash laser. While leakage current across the active region is unaffected by the absence of wetting layers, their presence enhances Auger recombination losses in the active region, leading to lower overall device efficiencies.**

Keywords—numerical simulation, drift-diffusion, indium arsenide, indium phosphide, ridge waveguide, laser, quantum dot

I. Introduction

For semiconductor diode lasers, quantum confinement of carriers has been shown to improve device behavior by reducing lasing threshold current densities, increasing differential gain, and lowering emission linewidths while improving temperature stability [1]. Quantum dots (QDs) and dashes (QDashes) have demonstrated improved threshold current and linewidth enhancement compared to equivalent multi-quantum well (MQW) devices [2]. In order to further improve temperature stability and facilitate lasers capable of operating at elevated temperatures, loss mechanisms within the laser must be further understood. Numerical device simulations allow insights into in-situ lasing conditions not accessible experimentally.

II. Simulation Environment

Laser simulation is carried out using Crosslight Pics3D, a finite element-based (FEM) semiconductor simulation environment. It provides a syntax for device geometry and functional material parameter definition and a numerical solving algorithm for coupled drift-diffusion, heat transport, and optical mode calculations. Additionally, it can perform wavefunction and k·p calculations, the latter by evaluating a 4×4, 6×6 or 8×8 Luttinger-Kohn Hamiltonian for zincblende and wurtzite crystal structures. This allows for self-consistent steady-state and transient calculations of optoelectronic devices based on bulk as well as carrier-confining active structures [3].

A. Geometry Definition

To create the mesh and associated parameters for each node, Pics3D offers a tool to define geometries and populate them with a series of pre-defined material macros which can be altered and supplemented by the user. The macros associate material parameters with mesh nodes and inform the solver where more complex calculations are necessary, such as solving the Schrödinger equation within confinement structures or evaluating transition dipole moments in optically active layers. There are two main macro types that can be used for this purpose: symmetric and complex. Symmetric macros support isolated barrier-well-barrier type structures, with both barrier layers composed of the same material. Complex macros allow asymmetrical layer structures and support coupling between wells in close proximity but are computationally more costly [3].

B. Quantum Dash Integration

The repeated solution of the wavefunction for the large number of QDashes present in the active medium of a laser would result in a prohibitively long computation time. Pics3D circumvents this issue by importing energy levels calculated by a separate simulation of a single dot using the Schrödinger and k·p solvers. Their relative energetic alignment with respect to the device band structure is achieved via the definition of a dash layer (DL) and dash hosting layer (DHL). The DHL should employ the same material macro as the layer enveloping the top of the dash (Fig. 1). For dot-in-well (DWELL) structures, this would be the material of the well, while for capped dots this would be the material of the capping layer. The DL is an additional virtual layer that occupies the same space as the DHL. It must share the affinity and bandgap with the material containing the wave function in the single dot simulation to obtain accurate energy level incorporation, so it is generally advisable to use the same material macro in the dash calculation and DL. The bands of the DL act as reference energies for the placement of the dot levels. Similarly, the DHL levels function as a reference to place the DL levels in the context of the device simulation.

The upper and lower barrier materials of the dash simulation should correspond to the outer barriers of the well acting as the DHL.

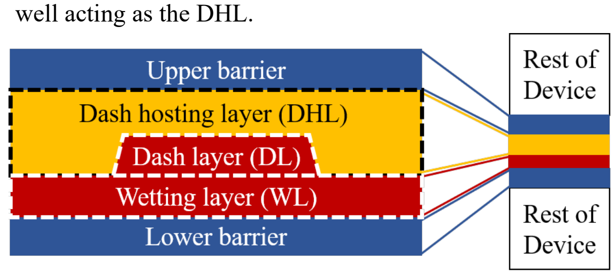

Fig. 1. Schematic cross-section of the active layer featuring material definitions for the dash sub-simulation and their equivalent position in the full device simulation.

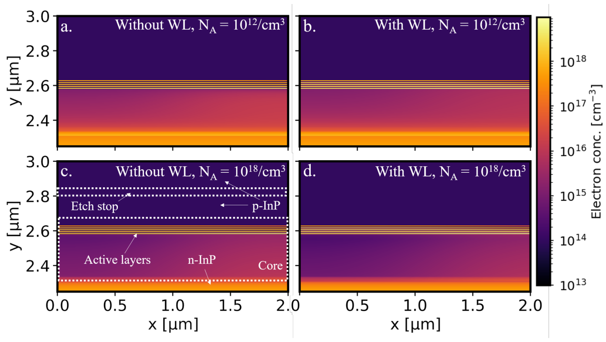

Fig. 2. Cross-sections of the electron concentration near the active region for a 1500 μm long ridge waveguide QDash laser at 85°C and 300 mA injection current, without (a, c.) and with (b, d.) wetting layers and with acceptor doping levels of the optically confining core of of $10^{12}/cm^3$ (a, b) and $10^{18}/cm^3$ (c, d).

C. Wetting Layers

In certain material systems, QD formation can be achieved via the Stranski-Krastanov layer growth mode. QDs are formed on a wetting layer (WL) of the same material ranging in thickness from a few monolayers to several nanometers [4]. The presence of this wetting layer can have a considerable influence on device transport characteristics, as it confines carriers in the vicinity of the optically active electronic states and presents an additional barrier to carrier escape across the active region. The wetting layer also plays a significant role in populating the dot states via carrier relaxation and thereby affects the gain bandwidth of the dot ensemble [5, 6].

III. Results

To illustrate the impact of the wetting layer on transport within the device, we present our results at elevated temperatures for a five-layer InAs/InP QDash laser with and without the inclusion of a WL near each DHL at different acceptor doping levels. Cross-sections of the electron concentration near the active region (Fig. 2) indicate a slight decrease in the ambient carrier concentration within the optically confining structure in the devices featuring WLs. This is due to carrier capture by the WLs, increasing their concentration near the active layers. To investigate the impact of these carriers, we present the relative contributions of Auger, Shockley-Read-Hall (SRH), and spontaneous as well as stimulated radiative recombination to the overall recombination current. The increased carrier density near the DHL results in more carriers available for recombination. Recombination via SRH or spontaneous radiative transitions remains nearly unchanged, while Auger mechanisms are the dominant source of any additional recombination. At the highest carrier injection levels examined, the external quantum efficiency drops from 67.0% without WLs to 58.7% with WLs for NA = $10^{12}/cm^3$. For the highly doped confinement region (N_A = $10^{18}/cm^3$), efficiency drops from 68.4% without WLs to 59.3% when they are included.

The absence of WLs can lead to increased current leakage across the active region, but we find no significant difference in minority carrier populations or recombination in the cladding layers on either side of the active region with or without WL inclusion.

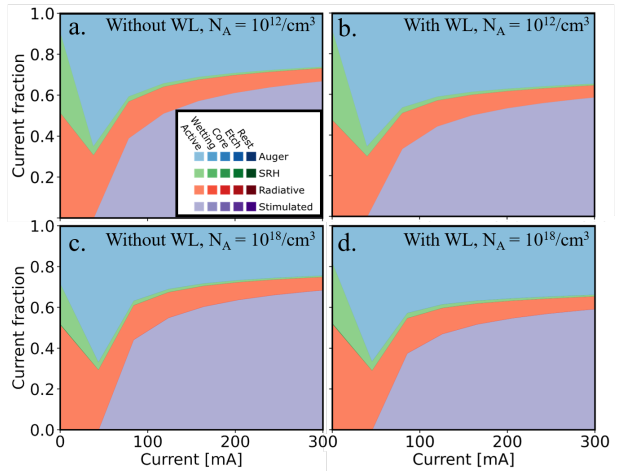

Fig. 3. Contribution to recombination current from different device regions and mechanisms as a function of injection current, without (a, c) and with (b, d) wetting layers present within the device. *Active* and *wetting* refers to the recombination occurring within the active and wetting layers, *core* refers to the remainder of the optically confining region, and *etch* encompasses all losses occurring within the etch stop (see Fig. 2c).

IV. Conclusion

Our results highlight the ability of numerical simulations to identify the impact of additional electronic barriers within the active region of a semiconductor laser. QDash semiconductor layers using the Stranski-Krastanov growth mode introduce an ultrathin quantum well on one side of the dash layers. Results show that carrier leakage variations is minimal in the InAs-InP material system for 1.55 μm lasing. However, the increased carrier concentrations near the active region resulting from confinement due to the WL leads to significantly higher Auger recombination losses, impacting the external quantum efficiency. As a result, the WL can have a significant effect on overall laser performance, and inclusion of the WL is important for accurate device simulation.

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