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A comparative Study on Ridge Waveguide Laser Diode with Single GaAs Quantum Well

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ABSTRACT

A typical ridge waveguide laser diode with single GaAs quantum well is theoretically designed and characterized using simulation software PICS3D. The simulator self-consistently combines 3D simulation of carrier transport, self-heating, and optical wave-guiding. Simulation results show that proposed laser structure operates with single mode state at about 0.834 micron with proper threshold current, output power and active region temperature.

1. Introduction

The semiconductor lasers were initially developed in 1962 by Robert Hall with the advent of this technology patents and articles started to publish; however, the technology was not mature to achieve the laser action at higher temperatures. This issue was resolved by a proposal given in 1963 by Herbert Kroemer to improve the laser action by Double Heterostructures. This made it possible to produce inexpensive, commercially available diode lasers and subsequently revolutionized optical communications. diode lasers are common optical communication light sources for high-speed data transmission. They are embraced as “the laser of the future”, due to their unique features such as easy integration and high optical output powers. Coherent emission is generated in these lasers by stimulated emission, and the gain is produced in the semiconductor active medium by electrical injection. These diode lasers aresmall; therefore, they are constructed on a large scale using very perfect production technologies. Diode lasers are very impassive in transforming

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electrical power into optical power. The basic laser diode structure can be divided into ridge waveguide type and buried hetero-structure (BH) type for either FP (Fabry-Perot) or DFB (Distributed Feed Back) or DBR (Distributed Bragg Reflector) lasers [1].

Ridge-type lasers are easy to manufacture and are produced at a lower cost than BH-type lasers. BH lasers have better performance such as lower thresholds and higher efficiency, but the complex and critical manufacturing process creates inferior results and higher manufacturing costs [2]. Ridge waveguide lasers have attracted much attention for low-cost light sources due to their simple fabrications and process compatibilities, high performances over a wide temperature ranges, low parasitic features and high efficiencies [3].

Nano scale semiconductor constructions are mostly at the center of modern optoelectronic industry. Their small sizes and structure complexities cause the computer simulation to be a main instrument for designing better systems that meet ever-rising operation requirements. The current need to use simulation software in optoelectronics follows the trend observed in the 1980s with software for simulating silicon devices. Today, software for technology computer-aided design (TCAD) and electronic design automation (EDA) represents a fundamental part of the silicon industry. In optoelectronics, advanced commercial device software has emerged, and it is expected to play an increasingly important role in the near future [4].

Here, a ridge waveguide laser diode with single GaAs quantum well is theoretically proposed and characterized using simulation software PICS3D [5]. PICS3D is a three dimensional simulator which solves, self-consistently, Poisson's equation, the current continuity equations, and the three dimensional scalar wave equation. The drift-diffusion equation solver is applied to many different 2D cross-sections while the optical wave equation in all three different dimensions are solved.

This paper is organized as follows. In Section 2 and 3, we introduce device structure and the simulator used in this study. The simulation results are presented in Section 4.

2. Proposed laser Structure

The simulation example in this article is a typical GaAs single quantum well (QW) laser diode. ***Figure 1*** shows a schematic of the structure for proposed laser diode. The well thickness is considered 7.6 nm. The QW is sandwiched between 146.2 nm Al$_x$ Ga$_{1-x}$ As linear grading (grade from x=0.71 to 0.33 below layer, grade from x=0.33 to 0.71 top layer) confinement layers which act as a waveguide. The laser structure completed by n and p doped contact layers with 1.35 micron thickness Al$_{0.71}$ Ga$_{0.39}$ As layer. The doping levels of these layers are $1\times \mathbf{10^{24} m^{-3}}$. The laser cavity length and the mirror reflectivity are 400 micron and 32%, respectively.

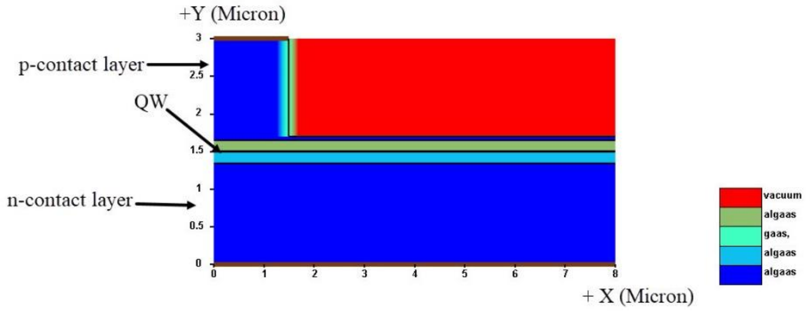

Figure 1. Schematic of the proposed laser structure.

3. Theoretical Models

For describing the electrical behaviour of laser diodes s and other active semiconductor photonic devices, the hole and electron (p and n) density continuity and electrostatic potential (v) Poisson equations are considered in PICS3D. The electronic equation is connected to the optical behaviour using the optical recombination rate:

$$-\boldsymbol{\nabla}.\left(\frac{\varepsilon_0\varepsilon_{\mathrm{dc}}}{\mathrm{q}}\boldsymbol{\nabla}\mathrm{v}\right) = -\mathrm{n} + \mathrm{p} + \mathrm{N_D}(1 - \mathrm{f_D}) - N_A + \sum_j N_t\left(\delta_j - f_{tj}\right) \tag{1}$$

$$\boldsymbol{\nabla}.\boldsymbol{J_n} - \sum_j R_n^{tj} - R_{sp} - R_{st} - R_{Aug} + G_{opt}(t) = \frac{\partial n}{\partial t} + N_D\frac{\partial f_D}{\partial t} \tag{2}$$

$$\boldsymbol{\nabla}.\boldsymbol{J_p} + \sum_j R_p^{tj} + R_{sp} + R_{st} + R_{Aug} - G_{opt}(t) = -\frac{\partial p}{\partial t} + N_A\frac{\partial f_A}{\partial t} \tag{3}$$

In ***Eq. (1)***, ε_0 and ε_{dc} are respectively shown as the dielectric constants of vacuum and the semiconductor material; n and p are respectively the electron and hole concentrations; N_D and N_A are respectively the doping densities of shallow donors and acceptors; tj presents the J_{th} deep trap level, and N_{tj} and f_{tj} are respectively its density and occupancy; finally, f_D and f_A are respectively the occupancy of donor levels and acceptor levels. In ***Eqs. (2) and (3)***, G_{opt} represents the photon generation rate; R_{sp}, R_{st}, and R_{Aug} are spontaneous, stimulated, and Auger recombination emission rate, respectively; and J_p and J_n show the hole and electron current densities, respectively [4].

For the treatment of device heating, the thermoelectric power and the thermal current induced by temperature gradient were solved utilizing the method provided by Wachutka [6]. Various heat sources, including Joule heat, generation/recombination heat, Thomson heat, and Peltier heat, are taken into account in this specific study. The software solved the scalar Helmholtz equation to obtain a transverse component of the optical field. The lateral components were given by Bessel functions.

4. Simulation results

In the pumped MQW system, the carriers travel through the barriers and fall into the quantum wells. The addition carriers split the Fermi level into two quasi Fermi levels. The separation between the two quasi-Fermi levels depends on the pumping power. When the pump is strong enough to a separation equal to the material bandgap, the material becomes transparent for photon energies equal to the bandgap. Optical gain is achieved when the system is pumped beyond transparency condition. ***Figure 2*** shows the material gain-wavelength plots for three different carrier concentration, as it is obvious the proposed laser diode operates at the wavelength range of 0.8-0.85micron because of QW's positive produced gain.

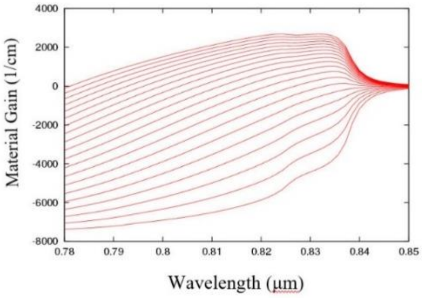

Figure 2. Calculated gain vs wavelength**.**

Figure 3 indicates the mode spectra of the proposed structure. By considering this figure, can be understood that the laser diode operates in single mode state because of the observed one in its output spectrum. This shows again that the proposed material composition of the active region is suitable for operating the laser diode in 0.83 nm wavelength because of the output wavelength that lies within the appropriate wavelength range.

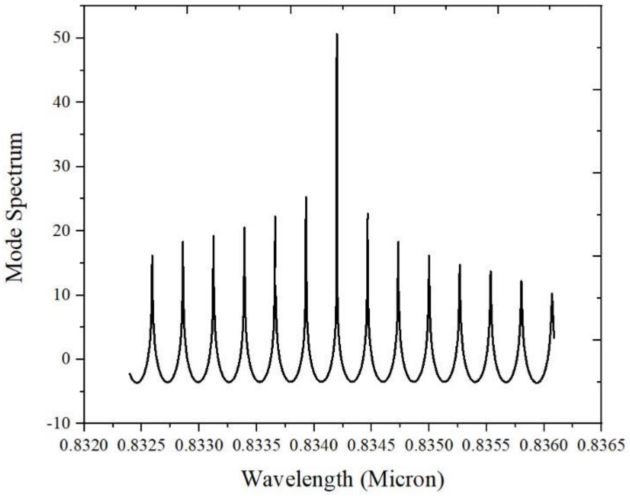

Figure 3. Calculated mode spectrum vs wavelength.

The intensity distribution of the optical wave is the one of the goals of this study. Since the shape of the optical mode distribution affected the laser performance. The 2D optical field distributions of the proposed laser diode is plotted in ***Figure 4***.

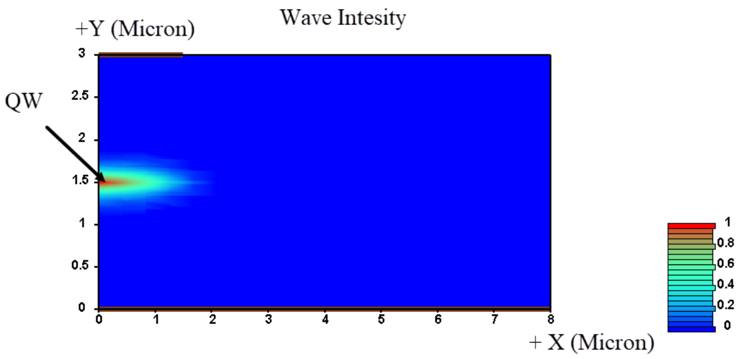

Figure 4. 2D optical field distribution of optical mode**.**

It can be seen from this figure, there is the maximum wave intensity of the fundamental TE mode on the front of face of the laser diode, where the laser beam exits. Therefore, this mode has a proper overlap with the active region. As it is known, optical confinement factor is an effective parameter in the laser diode designing. The fundamental optical mode overlap with the active layer is introduced by the optical confinement factor. The overlap shown in this figure leads to the optimal optical confinement factor for proposed structure.

Determination of the power-current characteristic is required for evaluation of threshold current and slope efficiency. Since the invention of the semiconductor laser, lowering the threshold current and increasing the slope efficiency have been the driving forces behind the development of this important type of laser. Threshold current and laser diode slope efficiency require a bit more explanation here. The threshold current is the current that must be applied to the laser diode to generation output beam. The laser diode slope efficiency is the slope of the black line from the threshold current to the operating current or the maximum current allowable for one laser diode. ***Figure 5*** shows the simulated power- current plot for the proposed laser diode.

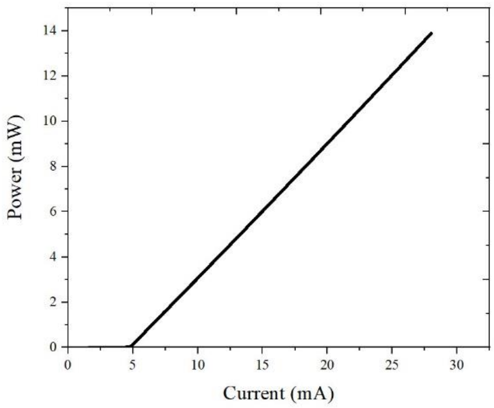

Figure 5. Power- current curve for proposed laser diode.

By considering this plot, the maximum output power, threshold current and slope efficiency are 9 mW, 5 mA and 0.57 $\frac{W}{A}$, respectively.

The current-voltage curve of laser diodes gives important information concerning the electrical characteristics of the device. A diode is a semiconductor device that allows current to flow in only one direction. This can be seen in the I-V curve. At positive voltages, the curve increases exponentially, indicating that current can flow freely through the device. At negative voltages, the current remains almost zero. ***Figure 6*** shows current -voltage plot for proposed structure. The threshold voltage is 1.5 V and 1.7 Ω electrical resistivity that are reasonable for laser diode operation.

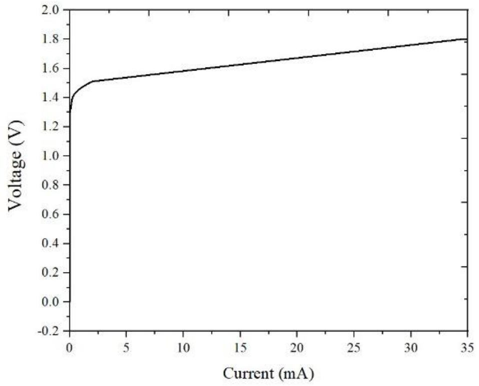

Figure 6. Voltage- current curve for proposed laser diode.

For a proper laser operation, not only at higher outer temperatures but also at room temperature, carefully designed thermal properties of the device are of the great importance, since the internal temperatures inside of the laser can be much higher than the ambience temperature. The 2-dimensional temperature distribution of the proposed laser diode is plotted in ***Figure 7***.

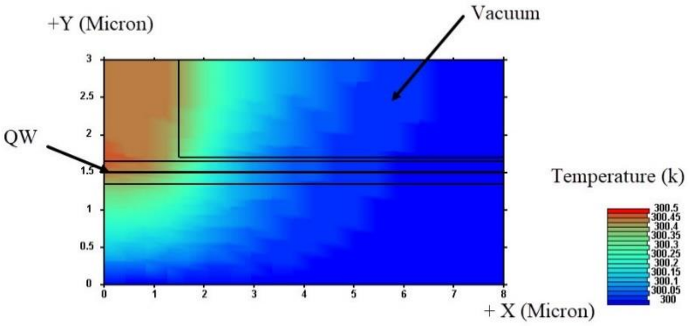

Figure 7. 2D Temperature distribution of proposed laser diode.

The maximum operation temperature is 300.5 K that occurs in QW. Due to the presence of hot carriers in this region, such an increase is predictable.

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