Effects of Strained Single Quantum Well on the Performance of InGaN Laser Diode

S. M. Thahab and R.A. Sahib

Abstract—Built-in strains in single-quantum well (SQW) layer significantly modify the electronic band structures, especially the valence bands. In this work, the optical properties of strained and unstrained SQW laser diodes are numerically studied using Integrated System Engineering (ISE TCAD) simulation program. The strained SQW laser shows reduction in the threshold current and improvements in laser performance compared with their unstrained counterpart. The improvements can be attributed first to the reduction of the effective mass of holes in the compressively strained SQW lasers. The smaller effective mass of holes increases its Fermi level more quickly with respect to the increase in injected carriers, which leads to a large value of differential gain and a small value of injection carrier density to achieve the necessary threshold gain. The strain induced reduction in various non-radiative recombination is also responsible for the improvement in the laser diode performance.

Keywords—Compressively strained, InGaN, Laser diode, Quantum well

I. INTRODUCTION

STRAINED quantum well lasers have been under intensive investigation because of their potential applications for low threshold current operation, high power pump lasers, and laser printers [1]. The early theoretical and experimental work on strained quantum wells focused on compressively strained structures. Both compressively and tensile strained quantum well lasers have been shown to have superior operational characteristics compared with those for the unstrained quantum well lasers [2]. The major reasons are that the compressively strained quantum wells have a reduced effective mass for the top heavy hole subband in the plane of the quantum well.

This reduced effective mass reduces the density of states and, therefore, reduces Auger recombination rate and lowers the threshold current density [3]. Low threshold current densities have been achieved in compressively strained quantum-well lasers. As a result, the gain is improved with small the threshold current density [4].

The modeling [5], of strained quantum well lasers requires valence band mixing since the coupling of the heavy hole and light hole bands in the presence of strain in a quantum well structure is usually strong and the strain deformation potentials are required.

In this work, the optical properties of strained and unstrained SQW laser diodes are numerically studied. The strained SQW laser shows reduction in the threshold current and improvements in laser performance compared with its unstrained counterpart.

II. LASER STRUCTURE AND PARAMETERS USED IN THE NUMERICAL SIMULATIONS

The laser simulation program [6-8] solved the Poisson equation, the current continuity equations, the photon rate equation and the scalar wave equation using the two-dimensional (2-D) simulator. The carrier drift-diffusion model which includes Fermi statistics and incomplete ionization were included in our simulation models. The Shockley Read–Hall (SRH) recombination lifetime of electrons and holes is assumed to be 1 ns; however, this is a rough estimate since the type and density of recombination centers are sensitive to the technological process. From its band gap dependence in other materials, a very small Auger parameter of $C = 1 \times 10^{-34}$ cm$^6$ s$^{-1}$ is estimated for GaN. Thus, even with large carrier densities, Auger recombination in nitride materials is negligible. In our strained InGaN quantum wells, GaN values are used for the deformation potentials. n-type GaN layer that is 3 µm in thickness is assumed to grow first then followed by 0.4 µm n-type Al$_{0.07}$Ga$_{0.93}$N cladding layer, followed by a 0.1 µm n-type GaN guiding layer. The active region of the preliminary laser diode structure under study consists of SQW with 3 nm In$_{0.13}$Ga$_{0.87}$N well that is sandwiched between 6 nm GaN barriers. 0.020 µm p-Al$_{0.15}$Ga$_{0.85}$N stopper layer is assumed to be grown on the top of the active region, followed by 0.1 µm p-type GaN guiding layer then 0.4 µm p-Al$_{0.07}$Ga$_{0.93}$N cladding layer and 0.1 µm p-GaN contact layer. The doping concentration of n-type and p-type are $5 \times 10^{17}$ cm$^{-3}$ and $5 \times 10^{18}$ cm$^{-3}$, respectively. The active region length is 800 µm and the reflectivity of the two ends left and right facets assumed as Fabry–Perot cavity waveguide is $R=0.30$. 

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III. SIMULATION RESULTS AND DISCUSSION

Figure 1 shows the energy band diagram and carrier distribution of the InGaN SQW LD structure. The right side of the diagram is the n-side and the left side is the p-side of the laser diode, the horizontal axis is the distance along the crystal growth direction. The built-in polarization field leads to a strong deformation of the usually rectangular quantum well diagram. As a consequence, the electrons are moved to one side and the holes are moved to the other side of the quantum well. Since the photon emission rate depends on the overlap of the wave functions, the carrier separation reduces the light emission intensity.

The InGaN/GaN QW structure has compressively strained InGaN well and unstrained GaN barrier. The strain-induced normal piezoelectric (PZ) polarization, $P_{PZ}$, is zero for the barrier in the InGaN/GaN structure. The normal piezoelectric PZ polarization is important because the QW structure has quantized energy levels along the growth direction.

The normal PZ polarization leads to the accumulation or depletion of carriers at the interfaces and creates a piezoelectric field [9]. However, it is often believed that the high density of quantum well carriers in InGaN laser diodes compensates for the built-in field.

![Fig.1 The bandgap profile and the carrier density of InGaN SQW LD.](image1)

Figure 2 shows with increasing carrier density the charge of the carriers leads to a screening of the internal electric fields. This reduces the quantum confined Stark Effect (QCSE) and results in a blue shift of the emission wavelength of our laser diode. The blue shift of the emission wavelength becomes higher in the strained quantum well design due higher screening and higher reduction in the internal electric field from 0.45 MV/cm without strained quantum well to 0.28 MV/cm with strained quantum well as shown in Fig. 3. Without strain, the spin–orbit interaction leads to only slight separations between the three valence band edges. The InGaN light hole and heavy hole bands hardly separate under compressive strain. This contributes to the high quantum well carrier densities and lower threshold current observed with InGaN-based lasers [10].

![Fig.2 The blue shift in laser peak wavelength as a function of forward current due to polarization and the screening in the internal electric field of InGaN SQW LD.](image2)

Figure 4 shows the output power of the InGaN SQW LD with and without strained quantum well. The threshold current reduces from the value of 18.5 mA to 14.5 mA and the output power increases from 24 mW to 28 mW with a quantum well strained value of 0.8%. The strain induced reduction in various nonradiative recombinations which is also responsible for the improved performance.

Figure 5 shows the reduction in the InGaN SQW LD threshold current with the variation in the values of strain. Lowest threshold current is obtained at quantum well strained value of 0.8%. This improvement can be seen in Fig. 6 which shows the influence of increasing the quantum well strain on the slope and differential quantum efficiency DQE of InGaN LD in the strain range from 0.2 to 1%.

![Fig. 3 The internal electric field with and without strained quantum well of InGaN SQW LD.](image3)
Compressively strained InGaN SQW laser diode structure shows reduction in the threshold current and improvements in laser performance as compared with its unstrained structure. A reduction in the threshold current from the value of 18.5 mA to 14.5 mA and an increase in the output power from 24 mW to 28 mW with strain value of 0.8% were observed. This is attributed to the reduction of the effective mass of holes in the compressively strained SQW lasers.

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REFERENCES