InGaN Double Heterostructure (DH) Laser Diode Performance and Optimization

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Abstract

The laser performances of the blue DH InGaN laser diode (LD) structures have been numerically investigated by using ISE TCAD software. We have selected $In_{0.13}Ga_{0.87}N$ as the active layer with thickness of 15 nm sandwiched between two layers of 70 nm $Al_{0.15}Ga_{0.85}N$ separate confinement heterostructure (SCH). The output power with a value of 84 mW was obtained at a threshold current of 110 mA and with peak emission wavelength at 426 nm. We investigated the effect of graded $Al_{0.15}Ga_{0.85}N$ layer on the output power and threshold current of our laser diode structure. The enhancement in the output power and a decrease in the threshold current resulting from graded layers effect were observed.

1. Introduction

The first semiconductor laser diodes (LDs) were made by heavily doping a p-n junction and then cleaving reflecting facets at either end of its Fabry-Perot (F.P) resonant cavity [1]. This design is less efficient than the double heterostructure (DH) and multi quantum well (MQW) designs that would follow since, in a p-n junction, there is no clearly defined region where recombination takes place. Carriers can easily be lost to diffusion before recombination can occur. This means a high threshold current is necessary to achieve stimulated emission and lasing [2]. Threshold currents were reduced with the development of the DH LD.

The DH consists of a narrow bandgap material sandwiched between two wider bandgap materials which very effectively confine carriers within the active region when a forward voltage is applied. DH is usually used to confine the injected carriers and the optical field to the same spatial region, thus enhancing the interaction of the charge carriers with the optical field[3,4].

The Separate confinement Heterostructure (SCH) is a modification of the DH design which provides additional carrier confinement. This is advantageous since the carriers tend to remain there until they recombine. It thus became possible to control where the radiative transitions would occur within the device. The secondary advantage is that the wider bandgap materials tend to have lower indices of refraction. This means that they act as cladding layers to guide the light propagating through the active layer. The addition of a stripe contact to the top surface of the device allows for the current flow to be confined to a small region of the device. The advantage of edge emitting lasers is a possibility to provide light output through a small output aperture and at a very high power density per facet area. This geometry enables high power single transverse mode operation. The disadvantage of standard edge emitting FP laser is poor wavelength stabilization and broad emission spectrum.

M.A.Khan et al, H.Amano etal, and A.S.Zubrilov etal. have been among those developing Separate confinement Heterostructure (SCH) edge emitting GaN lasers since 1971.[5-7].

In this study we numerically investigate the laser performance of InGaN active layer with an emission of 426 nm. Our laser structure based on the experimental work done by Takashi EGAWA [8], the laser output power, carrier distribution, optical gain and other parameters were extracted and investigated through the simulation software. Effects of graded cladding layers on the output power and the threshold current were also investigated [9].

2. Laser structure and parameters used in numerical simulations

A schematic diagram of $In_{0.13}Ga_{0.87}N$ blue laser diode under study is shown in Fig. 1. The band gap energy E_g of the $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ is governed by Eq.(1) and Eq. (2) respectively, at room temperature (298 K) [10].

$$E_g(In_xGa_{1-x}N) = xE_{InN} + (1-x)E_{GaN} - bx(1-x) \quad (1)$$

$$E_g(Al_xGa_{1-x}N) = xE_{AlN} + (1-x)E_{GaN} - bx(1-x) \quad (2)$$

Where E_{InN}, E_{AlN} and E_{GaN} are band gap energy of InN, AlN and GaN respectively, with corresponding values of 0.77eV, 6.28 eV and 3.42 eV [11], while b is the bowing parameter and has values of 1.4 eV and 1.3 eV respectively, for $In_xGa_{1-x}N$ and $Al_xGa_{1-x}N$ [12].

Our simulation was conducted by choosing the following models; carrier concentration, mobility with high field saturation, effective intrinsic density (with no band gap narrowing), Fermi model and recombination (Shockley Read Hall). The doping levels are $5*10^{18}/cm^3$ for p-type and $1*10^{18}/cm^3$ for n-type. All other parameters like hole electron mobility and nonradiative lifetime for all materials used were involved in the simulation parameters. For photon energies close to the bandgap, the refractive index is a strong function of wavelength. For the design of optical waveguide, the compositional change of the refractive index is often more important than its absolute value. The refractive indexes of the alloys ($In_xGa_{1-x}N$, $Al_xGa_{1-x}N$) were calculated from Eq. (3) and Eq. (4) respectively [13].

$$n(Al_xGa_{1-x}N) = 2.5067 - 0.43x \qquad (3)$$

$$n(In_xGa_{1-x}N) = 2.5067 + 0.9x \qquad (4)$$

The cavity length for our laser diode was set to 800 µm and the left and right facet power reflectivities were set to 0.3 for both. Temperature was set to 298 K. We assumed that the InGaN laser diode is grown on a 3 µm n–GaN layer followed by 1.2µm n-$Al_{0.07}Ga_{0.93}N$ thick cladding layer.

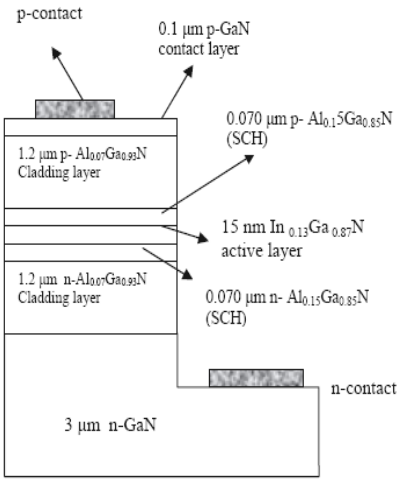

Fig. 1: Schematic diagram of the InGaN LD structure under study.

The active region of the preliminary laser diode structure consists of 15nm $In_{0.13}Ga_{0.87}N$ layer. The active region is sandwiched by 0.070 µm n-$Al_{0.15}Ga_{0.85}N$ and p-$Al_{0.15}Ga_{0.85}N$ separate confinement heterostructure (SCH) layers, followed by 1.2 µm of p-$Al_{0.07}Ga_{0.93}N$ cladding layer and finally 0.1 µm p-GaN contact layer.

3. Simulation results and discussion

For our laser diode, Fig..2 shows the energy band gap and electrostatic potential distribution inside the active region. We observed that the $In_{0.13}Ga_{0.87}N$ has lower bandgap compared to that of the $Al_{0.15}Ga_{0.85}N$ (SCH), this allowed more carriers to be accumulated in the active region as shown in Fig. 3. High electrostatic potential was also observed in the active region. From Fig. 3, we can observe the maximum carriers distribution inside the InGaN active region.

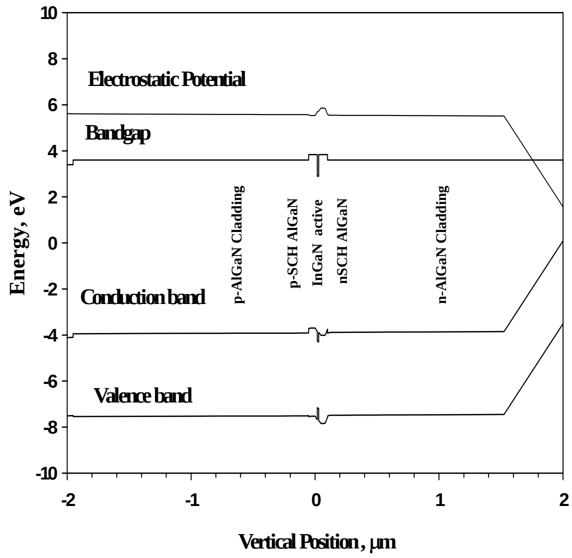

Fig. 2: Band diagram and electrostatic potential distribution for our LD structure.

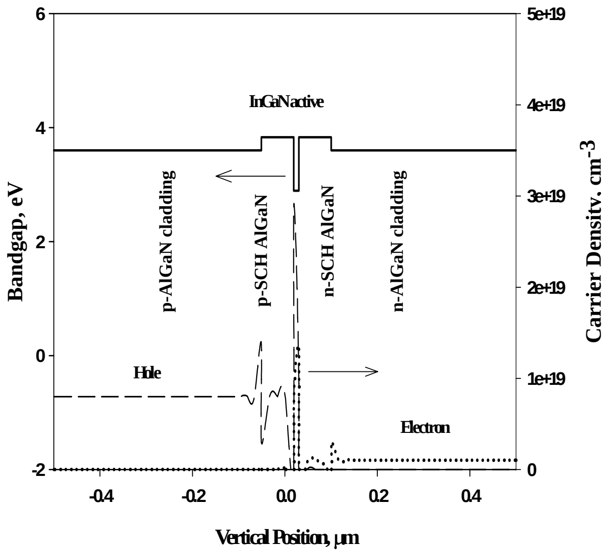

Fig. 3: The carrier density distribution profile inside InGaN DH LD

Carrier's confinement was achieved by the SCH and producing high radiative recombination rate inside the active region, which consequently, produces high optical gain and output power. Figure 4 shows the maximum optical gain at the InGaN active layer due to higher recombination value. Optical material gain of

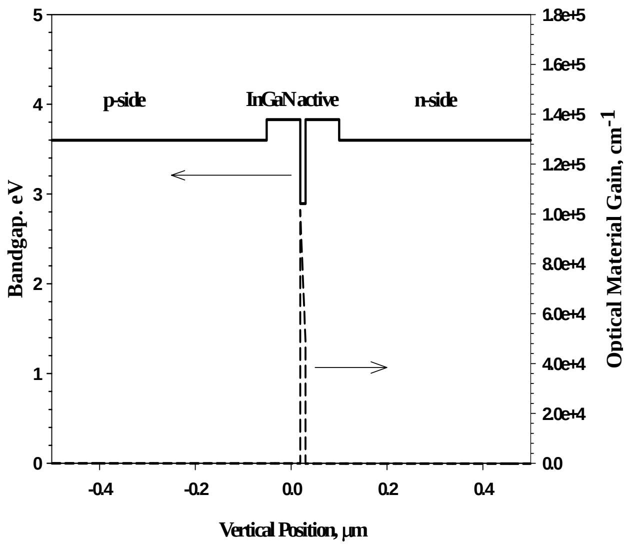

Fig. 4: Optical material gain in the InGaN DH LD.

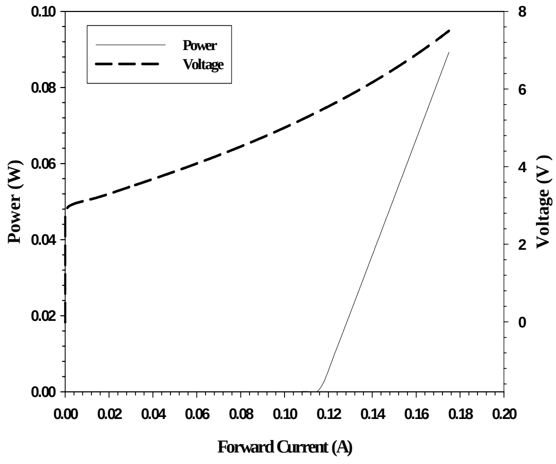

Fig. 5: Laser output power and bias voltage as a function of the forward current of the InGaN DH LD.

value $1*10^6$ cm^{-1} was obtained from the InGaN active region. This is an indication of the advantage of using InGaN as active region in laser diode.

Output powers of 84 mW and thresh-old current value of 110mA were obtained from our ungraded SCH DH laser diode with laser emission wavelength of 426.2 nm. Turn-on voltage of 3 V was obtained with a laser bias voltage of 7.5 V as shown in Fig. 5. A higher threshold current for our laser diode indicates that the laser diode will generate more heat as the laser operates. This will limit laser performance with operation time and requires the use of heat sink or cooling system to keep the laser power and emission wavelength stable for long operation time.

It is well known that for lasing to occur, the gain must be greater than or equal to the loss of photon energy within a peak wavelength. This is attributed to the laser being built with a resonant cavity in which a significant photon density arises in a supported cavity recombination in a chain-reaction fashion. Since the photons density is high at the peak energy, they stimulate the most transition. This means that the output spectrum grows and narrows simultaneously. Thus two conditions for lasing are required: (1) the gain must be at least equal to the losses in the medium. 2) The radiation must be coherent. Figure 6 shows the mode gain spectrum at room temperature..

This mode gain is a measure of the power transferred from the active region into propagating modes. In regions below the threshold current we cannot expect any lasing and this is related to the first condition mentioned above ($\Gamma g_{th} \geq losses$ (Eq. (5)) and clearly shown in Fig. 6 and Fig. 7.

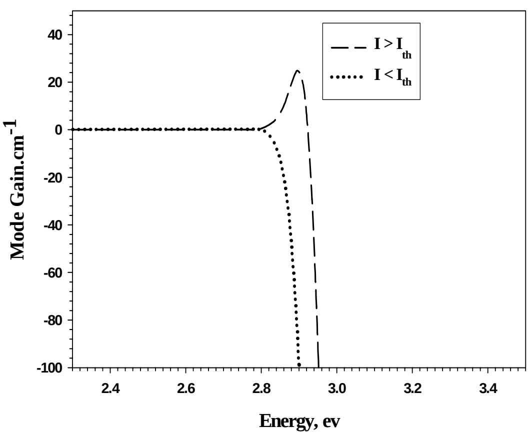

Fig. 6: InGaN DH LD mode gain spectrum as a function of energy.

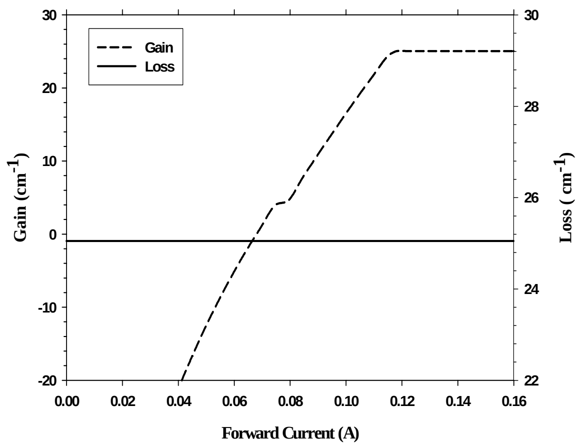

Fig. 7: InGaN DH LD gain spectrum as a function of forward current.

$$\Gamma g_{th} = \alpha_i + \frac{1}{L}\ln\frac{1}{R} = \alpha_i + \alpha_m \qquad (5)$$

Where α_i is the internal loss in the medium, and α_m is the loss due to mirrors or facets with reflectivity R and laser cavity length L. The minimum gain g where the device starts lasing operation determines the threshold gain Γg_{th}, where Γ is the confinement factor which depends on the overlap of the optical mode pattern with the gain region of the laser.

Small blue shift of the emission wavelength from 428 nm to 426.2 nm with an increase in the forward current was observed as shown in Fig. 9. The spectral blue shifting of the InGaN DH emission with the current injection resembles the competition processes between the band gap renormalization and band filling effects that are known to conventional III-V laser, this is due to the fact that the band gap renormalization scales with the reduced dimensionality.

Figure 9 shows the optical intensity together with the refractive index profile. The optical intensity profile introduced due to the optical confinement achieved by the refractive index profile provided by the SCH and $Al_{0.07}Ga_{0.93}N$ cladding layer. Multi transverse modes with second order mode development for higher output power were expected from our laser diode.

It is observed that the graded factor reduced the barrier height between the confinement layers and the active region. This will allow for more carriers to be accumulate in the active region and resulting in enhancement of the stimulated recombination rate in the active layer.

Figure 10 shows the bandgap for AlGaN (SCH) with and without graded confining layers. The graded factor is assumed to be 0.1, that is change of the mole fraction of AlGaN SCH up to the value of 0.15.

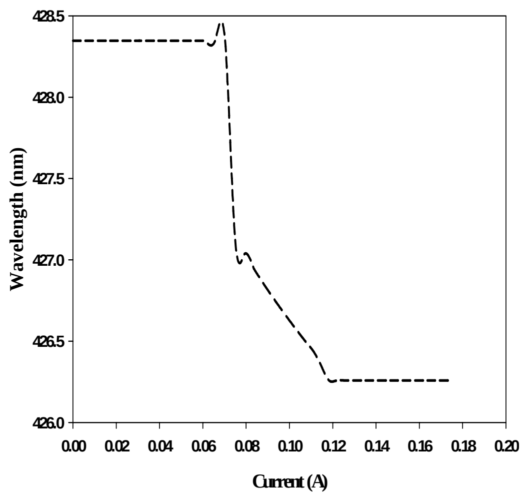

Fig. 8: The emission wavelength as a function of the forward current for InGaN DH LD.

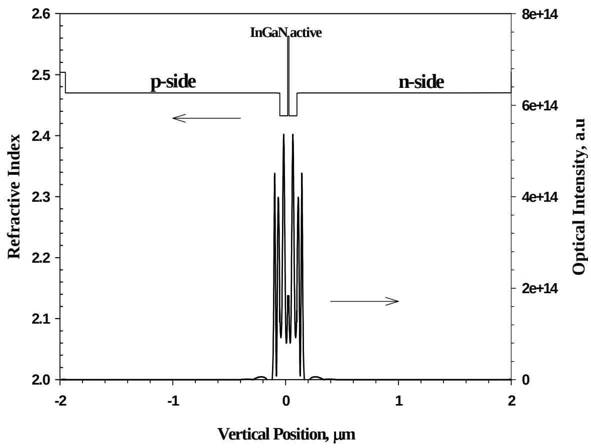

Fig. 9: Optical material intensity and refractive index profile of the InGaN DH LD.

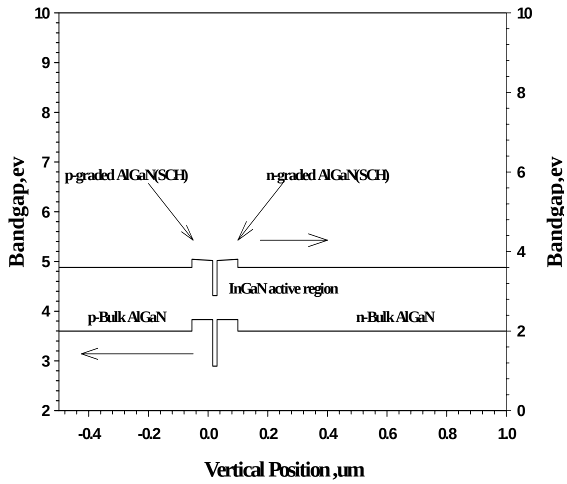

Fig. 10 : The bandgap energy of the InGaN DH LD with and without graded $Al_{0.15}Ga_{0.85}N$ SCH layer.

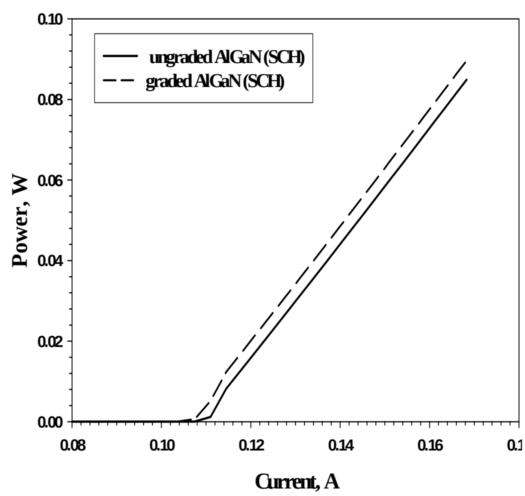

Fig. 11: The output power as a function of forward current for DH LD without and with graded $Al_{0.15}Ga_{0.85}N$ SCH layer.

More carriers are expected to accumulate in the InGaN active region. Figure 11 shows the reduction in the threshold current and the increase in the output power with graded $Al_{0.15}Ga_{0.85}N$ layers. It was observed that the laser threshold current decreased from 110 mA to 105mA, and the output power increased from 84 mW to 90 mW indicating that the graded layers enhanced the laser performance in our laser diode.

4. Conclusions

$In_{0.13}Ga_{0.87}N$ DH LD performance and device optimization were studied through simulation. The laser output power and threshold current of 84 mW and 110mA were obtained. Blue shift for the laser emission wavelength from 428nm to 426.2nm was observed. It was found that graded $Al_{0.15}Ga_{0.85}N$ SCH layer will enhanced the laser output power value and decreased the laser threshold current. This is due to the graded $Al_{0.15}Ga_{0.85}N$ SCH layers effect in reducing the barrier heights at the interface with the $In_{0.13}Ga_{0.87}N$ active layer. Consequently, more carriers are accumulated in the active region and enhanced radiative recombination to produce high intensity light emissions.

Acknowledgments

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