

Performance of InGaN/GaN Laser Diode Based on Quaternary Alloys Stopper and Superlattice Layers

S. M. Thahab, H. Abu Hassan, and Z. Hassan

Abstract—The optical properties of InGaN/GaN laser diode based on quaternary alloys stopper and superlattice layers are numerically studied using ISE TCAD (Integrated System Engineering) simulation program. Improvements in laser optical performance have been achieved using quaternary alloy as superlattice layers in InGaN/GaN laser diodes. Lower threshold current of 18 mA and higher output power and slope efficiency of 22 mW and 1.6 W/A, respectively, at room temperature have been obtained. The laser structure with InAlGaN quaternary alloys as an electron blocking layer was found to provide better laser performance compared with the ternary $\text{Al}_x\text{Ga}_{1-x}\text{N}$ blocking layer.

Keywords—Nitride semiconductors, InAlGaN quaternary, laser diode, superlattice.

I. INTRODUCTION

THE group III-nitride wide-band-gap semiconductors have been recognized as leading materials not only for some high temperature and high power microelectronic devices [1,2] but also for many optoelectronic devices [3-5], such as light-emitting diodes(LEDs) and laser diodes (LDs). Compared with GaN, InGaN and AlGaIn, InAlGaIn quaternary alloys have attracted much research interest because the use of this quaternary material should allow almost independent control of the lattice constant and bandgap [6,7]. Enhanced luminescence in InGaIn multiple quantum wells with quaternary InAlGaIn barriers was demonstrated due to decrease of the piezoelectric polarization. Ultraviolet (UV) LEDs with AlGaIn quantum wells (QWs) as active layer have very low efficiency.

However, by introducing In into AlGaIn, a similar effect to that obtained in InGaIn QWs was expected for InAlGaIn quaternary alloys [8]. The luminescence would be enhanced in InAlGaIn quaternary alloy with indium-segregation. Growth of quaternary InAlGaIn was a challenge due to the different bond length and desorption temperature of the binary compounds, and the different surface mobility and desorption temperature of the growing species. The feasibility of InAlGaIn quaternary

alloys and InAlGaIn based UV-LDs and LEDs structures have been demonstrated by sophisticated growth procedures using metalorganic chemical vapor deposition (MOCVD) [4-9]. There are also some reports on InAlGaIn quaternary alloys grown by molecular beam epitaxy (MBE) [10], which mainly study the InAlGaIn quaternary alloys grown on MOCVD GaN templates or thick GaN layer.

The large lattice mismatch between AlGaIn and InGaIn is a problem since devices utilize the AlGaIn/InGaIn heterostructure. To avoid this, a well thickness of about 20 Å has been used [1]. Thus, in order to increase the InN% in the active layer, using an AlGaIn barrier layer imposes limitations on the range of heterostructures that can be grown. This can be avoided if the AlGaIn layer is replaced by the more versatile InAlGaIn alloy since the bandgap and lattice constant can be independently varied to achieve InAlGaIn/InGaIn lattice-matched structures. The InAlGaIn material system has the unique property that the bandgap energy can be engineered to cover wavelengths from the far ultraviolet to the red region of the electromagnetic spectrum.

In addition to the problems associated with In desorption and In metal formation discussed previously for In containing compounds, the growth of bulk InAlGaIn epitaxial films also has the problem of being more sensitive to the growth temperature. Al-based nitrides favor higher temperatures to obtain good quality material while In-based nitrides require much lower temperatures to aid in In incorporation. In this study, InAlGaIn quaternary alloys as stopper and superlattice layers in InGaIn/GaN laser diode were numerically investigated. Our laser diode structure is based on the experimental work done by Skierbiszewski *et al* [11].

II. LASER STRUCTURE AND PARAMETERS USED IN THE NUMERICAL SIMULATIONS

The laser simulation program [12, 13] 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 $C = 1 \times 10^{-34} \text{ cm}^6 \text{ s}^{-1}$ is estimated for GaN. Thus, even with large

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carrier densities, Auger recombination in nitride materials is negligible. In our strained InGaN quantum wells, GaN values are used for the deformation potentials. Our laser diode structure as shown in Fig. 1 is based on the experimental work done by Skierbiszewski et al. in which they present high output power InGaN laser diode grown on bulk GaN substrate [11].

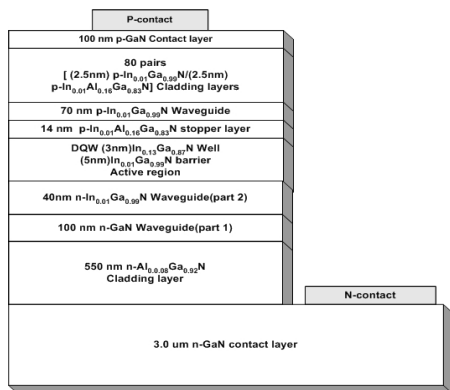


Fig. 1 Schematic diagram of the preliminary InGaN MQWs LD

We started our structure design simulation with n-type GaN layer that is $3\mu\text{m}$ in thickness which is assumed to grow first then followed by $0.550\mu\text{m}$ n-type $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}$ cladding layer, followed by a $0.1\mu\text{m}$ n-type GaN and $0.040\mu\text{m}$ $\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$ waveguiding layers. The active region of the preliminary laser diode structure under study consists of two well layers of 3 nm $\text{In}_{0.13}\text{Ga}_{0.87}\text{N}$ that is sandwiched between 5 nm $\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$ barriers. 14 nm p-type $\text{p-In}_{0.01}\text{Al}_{0.16}\text{Ga}_{0.83}\text{N}$ stopper layer is assumed to be grown on the top of the active region, followed by $0.070\mu\text{m}$ p-type $\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$ waveguiding layer, followed by $0.4\mu\text{m}$ of p-type (80 pairs of (2.5 nm) $\text{In}_{0.01}\text{Al}_{0.16}\text{Ga}_{0.83}\text{N}$ and (2.5 nm) $\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$) cladding layers. Finally $0.100\mu\text{m}$ of n-type GaN assumed to grow on the top of cladding layers. The doping concentration of n-type and p-type are $5 \times 10^{17}\text{ cm}^{-3}$ and $5 \times 10^{18}\text{ cm}^{-3}$ respectively. The laser cavity region length is $800\mu\text{m}$ and the reflectivities of both two ends of left and right facets are set to 30%.

III. RESULTS AND DISCUSSIONS

For the preliminary LD structure under study, the energy bandgap profile diagram, and the hole- electron quasi Fermi potential of the double quantum wells (DQWs) InGaN LD are shown in Fig. 2. 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.

From Fig. 3 it can be observed that the carrier distributions are inhomogeneous and are increasing towards the p-side. When the laser oscillation takes place, the hole injection becomes inhomogeneous among wells. This is ascribed to the poor hole injection due to the low mobility and thermal velocity of the hole. Thus the hole density becomes higher on the p-side and the electrons are attracted to the p-side. The electric field distribution inside our laser diodes is shown in Fig. 4. The electric field has a value of $8 \times 10^5\text{ V/cm}$ inside the active region. Applying a forward bias reduces this electric field,

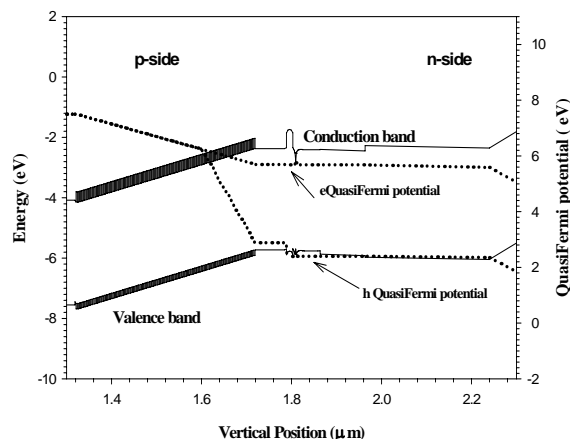


Fig. 2 Energy bandgap profile of the double quantum wells InGaN LD together with quasi Fermi potential profile

thereby countering the quantum confined Stark effect (QCSE) in the active region. We suspect that the polarization which is independent of applied bias induces a QCSE which red shift all spectral line. However, a second QCSE exists due to the electric field in the intrinsic material which blue shifts the spectral lines.

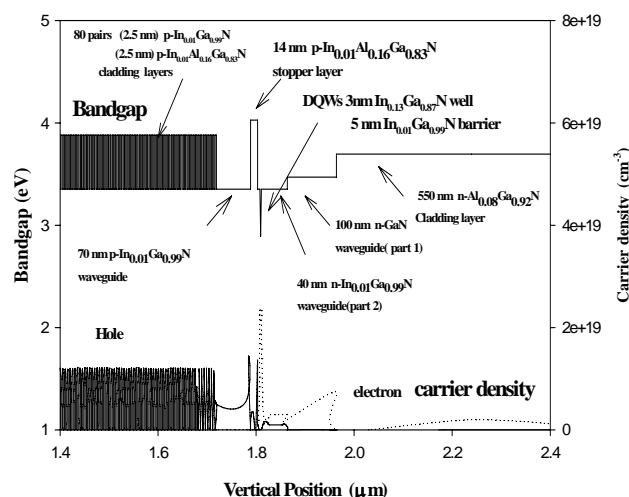


Fig. 3 Carriers density distribution profiles in the double quantum wells of InGaN LD

The net effects can be modulated by forward biasing; we would thus expect a blue shift with increasing current as observed in Fig. 5. The refractive indexes of nitride materials are extracted from GaN waveguide measurement using bandgap variations in the model for the calculation of optical wave intensity.

The vertical profiles of the refractive index and normalized optical wave intensity of the laser structure using $\text{In}_{0.01}\text{Al}_{0.16}\text{Ga}_{0.7}\text{N}$ as electronic blocking layer is shown in Fig. 6. As a result of enhanced optical confinement factor (Γ), using quaternary InAlGaIn is found to provide better laser performance than conventional $\text{A}_x\text{Ga}_{1-x}\text{N}$ electronic blocking

layer. The Γ values of InAlGa_N are increased according to the higher refractive index of InN. Subsequently, the optical wave intensity near the p-type active region is enhanced. Fig. 7 shows the output power and the bias voltage as a function of forward current of quaternary alloys stopper and superlattice layers in InGa_N/Ga_N laser diodes. Output power of 22 mW and threshold current of 18 mA are obtained with DQW laser diode. A turn-on voltage of 3V at laser diode bias voltage of 7.5V was observed. The laser structures with InAlGa_N electronic blocking layers are found to provide better laser performance.

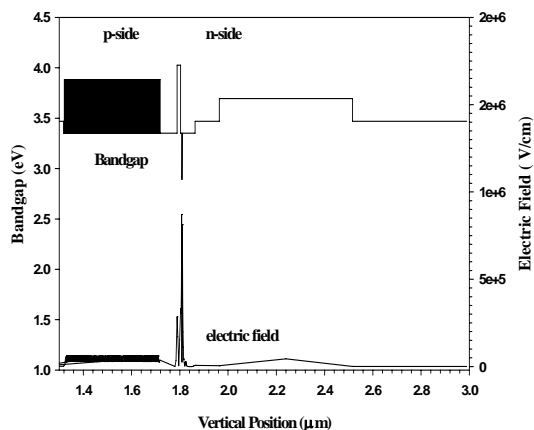


Fig. 4 Internal electric field of the InGa_N double quantum wells LD

During the crystal growth of conventional InGa_N QW LD structure, the growth temperature of InGa_N active region is near 750 °C and those of p-type layers including Al_{0.2}Ga_{0.8}N electronic blocking layer are about 1050 °C. The increased temperature for growing p-type layers may affect the crystal quality of InGa_N active region. Using quaternary InAlGa_N as electronic blocking layer is constructive to the prevention of In dissociation out of the InGa_N active region due to the growth temperature of InAlGa_N alloy is about 850 °C. Therefore, the laser performance can be better when using quaternary InAlGa_N as electronic blocking layer.

Fig. 8 shows the laser diode transparency current density (J_0) which is the current that provides just sufficient injection to lead stimulated emission just balancing absorption. In order to obtain the J_0 value, the curve of the logarithm threshold current density versus the inverse cavity length is plotted as shown in Fig. 8. The intercept of the linear fit line of the data plotted in this curve with the vertical axis provides us with the J_0 value.

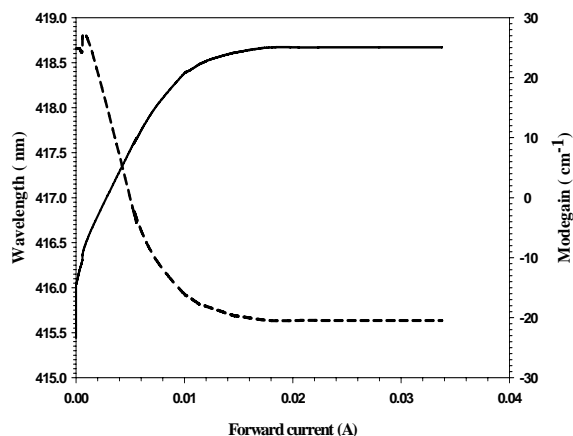


Fig. 5 The emission wavelength and mode gain as a function of the forward current of the double quantum wells InGa_N LD

It is observed that the quaternary geometry of InGa_N DQWs laser diode has a lower J_0 value of 678 A/cm². The internal quantum efficiency (η_i) is determined from the vertical axis intercept point ($1/\eta_i$) of the inverse external differential quantum efficiency (DQE) versus cavity length dependence linear fit line. Internal loss α_i is equal to the slope of the line multiplied by the $\eta_i \ln(1/R)$ parameter, where L is the laser cavity length in units of cm and R is the reflectivity of the mirror facets of the laser. Fig. 9 shows the calculation method for both parameters (η_i and α_i) with respect to inverse value of DQE as a function of the cavity length.

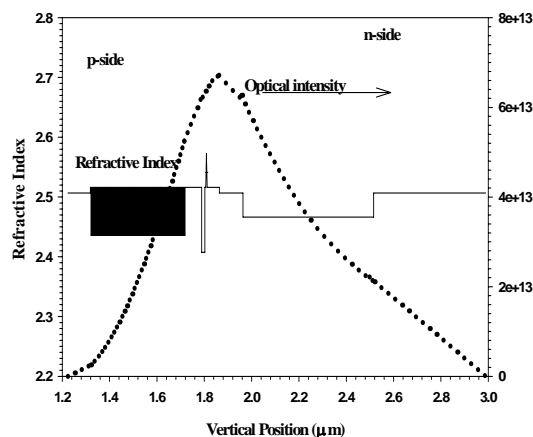


Fig. 6 Optical material intensity of the InGa_N double quantum wells LD

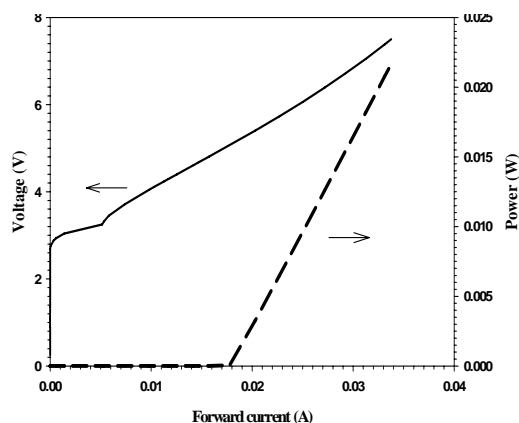


Fig. 7 Laser output power and bias voltage of DQW InGaN LD as a function of the forward current

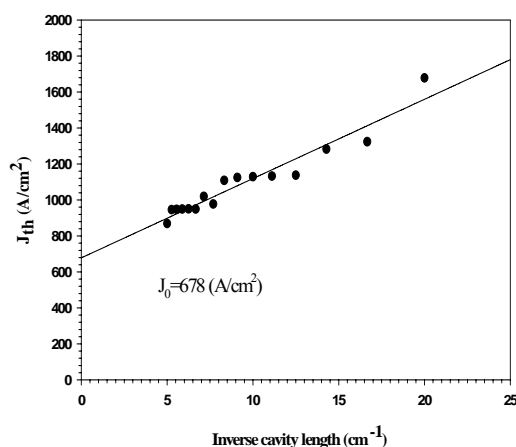


Fig. 8 The threshold current density as a function of inverse cavity length of DQWs InGaN LD

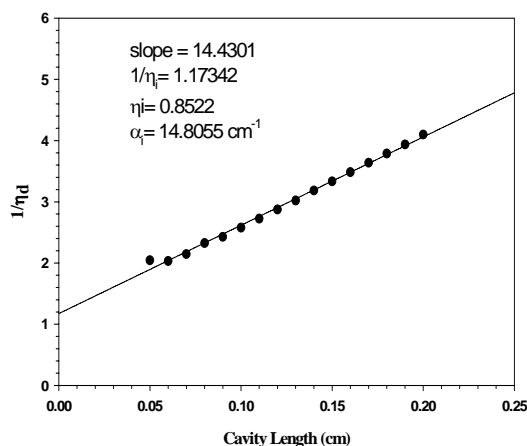


Fig. 9 Inverse of the external quantum efficiency as a function of cavity length of DQWs InGaN LD

We obtained values of 85% and 14.8 cm^{-1} for the internal quantum efficiency (η_i) and internal loss (α_i) respectively. These internal quantum efficiency (η_i) and the internal loss α_i values are a direct indication of the efficiency of quaternary alloys stopper and superlattice layers in InGaN/GaN laser diodes.

IV. CONCLUSION

The performance of InGaN DQWs LD based on quaternary alloys stopper and superlattice layers had been numerically studied and investigated. The most important operating parameters in InGaN LDs such as the internal quantum efficiency (η_i), the internal loss α_i , and the transparency current density J_0 were calculated. It was observed that laser structures with quaternary alloys InAlGa_{1-x}N as an electron blocking layer are found to provide better laser performance in comparison with its counterpart of Al_xGa_{1-x}N blocking layer.

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