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 $Al_xGa_{1-x}N$ 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 AlGaN, InAlGaN 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 InGaN multiple quantum wells with quaternary InAlGaN barriers was demonstrated due to decrease of the piezoelectric polarization. Ultraviolet (UV) LEDs with AlGaN quantum wells (QWs) as active layer have very low efficiency.

However, by introducing In into AlGaN, a similar effect to that obtained in InGaN QWs was expected for InAlGaN quaternary alloys [8]. The luminescence would be enhanced in InAlGaN quaternary alloy with indium-segregation. Growth of quaternary InAlGaN 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 InAlGaN quaternary alloys and InAlGaN 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 InAlGaN quaternary alloys grown by molecular beam epitaxy (MBE) [10], which mainly study the InAlGaN quaternary alloys grown on MOCVD GaN templates or thick GaN layer.

The large lattice mismatch between AlGaN and InGaN is a problem since devices utilize the AlGaN/InGaN 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 AlGaN barrier layer imposes limitations on the range of heterostructures that can be grown. This can be avoided if the AlGaN layer is replaced by the more versatile InAlGaN alloy since the bandgap and lattice constant can be independently varied to achieve InAlGaN/InGaN lattice-matched structures. The InAlGaN 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 InAlGaN 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, InAlGaN quaternary alloys as stopper and superlattice layers in InGaN/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 $C = 1\times10^{-34}$ $cm^6 s^{-1}$ is estimated for GaN. Thus, even with large

S. M. Thahab is with Nano-Optoelectronics Research and Technology Laboratory School of Physics, Universiti Sains Malaysia 11800 Penang, Malaysia (e-mail: sabahmr @ yahoo.com).

H. Abu Hassan is with Nano-Optoelectronics Research and Technology Laboratory School of Physics, Universiti Sains Malaysia 11800 Penang, Malaysia (e-mail: haslan@ usm.my).

Z. Hassan is with Nano-Optoelectronics Research and Technology Laboratory School of Physics, Universiti Sains Malaysia 11800 Penang, Malaysia (phone: 604-653-3650; fax: 604-657-9150; e-mail: zai@ usm.my).

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].

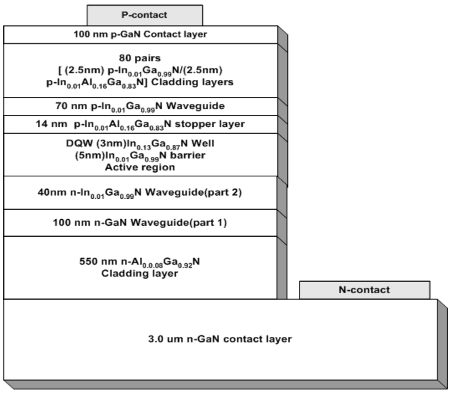

Fig. 1 Schematic diagram of the preliminary InGaN MQWs LD

We started our structure design simulation with n-type GaN layer that is 3μm in thickness which is assumed to grow first then followed by 0.550μm n-type $Al_{0.08}Ga_{0.92}N$ cladding layer, followed by a 0.1μm n-type GaN and 0.040 μm $In_{0.01}Ga_{0.99}N$ waveguiding layers. The active region of the preliminary laser diode structure under study consists of two well layers of 3 nm $In_{0.13}Ga_{0.87}N$ that is sandwiched between 5 nm $In_{0.01}Ga_{0.99}N$ barriers. 14 nm p-type p-$In_{0.01}Al_{0.16}Ga_{0.83}N$ stopper layer is assumed to be grown on the top of the active region, followed by 0.070μm p-type $In_{0.01}Ga_{0.99}N$ waveguiding layer, followed by 0.4μm of p-type (80 pairs of (2.5 nm) $In_{0.01}Al_{0.16}Ga_{0.83}N$ and (2.5 nm) $In_{0.01}Ga_{0.99}N$) cladding layers. Finally 0.100 μm of n-type GaN assumed to grow on the top of cladding layers. The doping concentration of n-type and p-type are 5×10^{17} cm^{-3} and 5×10^{18} cm^{-3} respectively. The laser cavity region length is 800μm 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 8×10^{5} V/cm inside the active region. Applying a forward bias reduces this electric field,

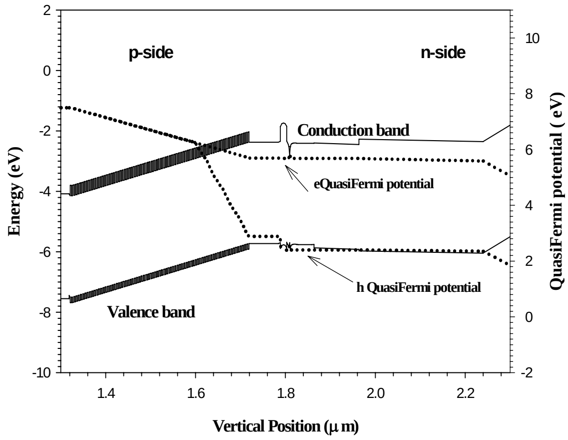

Fig. 2 Energy bandgap profile of the double quantum wells InGaN LD together with quasi Fermi potential profile

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.

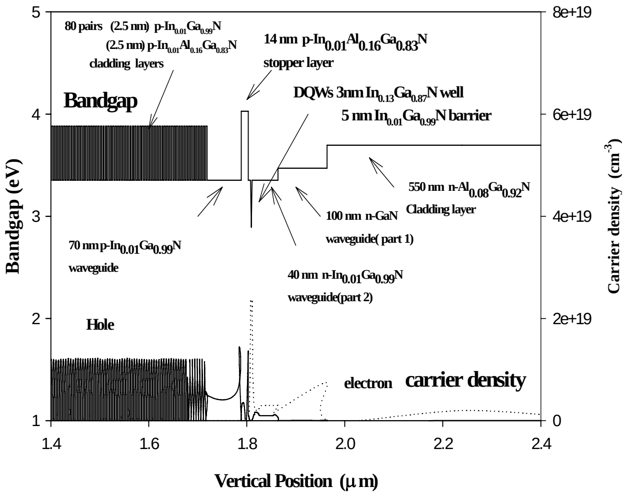

Fig. 3 Carriers density distribution profiles in the double quantum wells of InGaN LD

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 $In_{0.01}Al_{0.16}Ga_{0.7}N$ as electronic blocking layer is shown in Fig. 6. As a result of enhanced optical confinement factor (Γ), using quaternary InAlGaN is found to provide better laser performance than conventional $A_xGa_{1-x}N$ electronic blocking layer. The Γ values of InAlGaN 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 InGaN/GaN 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 InAlGaN electronic blocking layers are found to provide better laser performance.

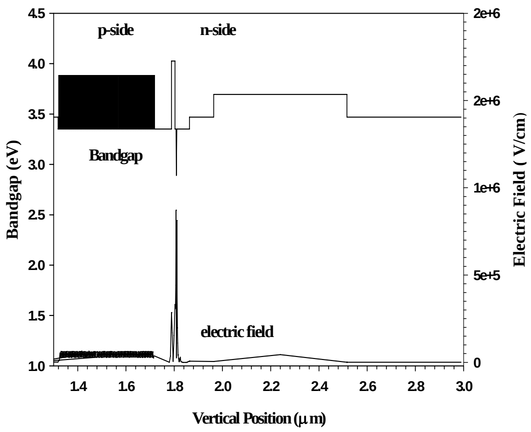

Fig. 4 Internal electric field of the InGaN double quantum wells LD

During the crystal growth of conventional InGaN QW LD structure, the growth temperature of InGaN 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 InGaN active region. Using quaternary InAlGaN as electronic blocking layer is constructive to the prevention of In dissociation out of the InGaN active region due to the growth temperature of InAlGaN alloy is about 850 °C. Therefore, the laser performance can be better when using quaternary InAlGaN 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.

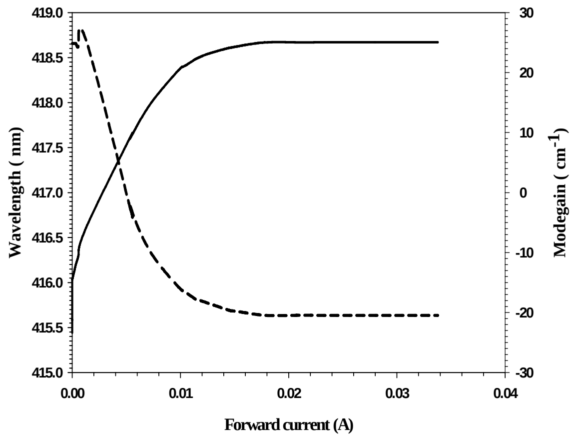

Fig. 5 The emission wavelength and mode gain as a function of the forward current of the double quantum wells InGaN LD

It is observed that the quaternary geometry of InGaN DQWs laser diode has a lower J_0 value of 678 A/cm^2. 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.

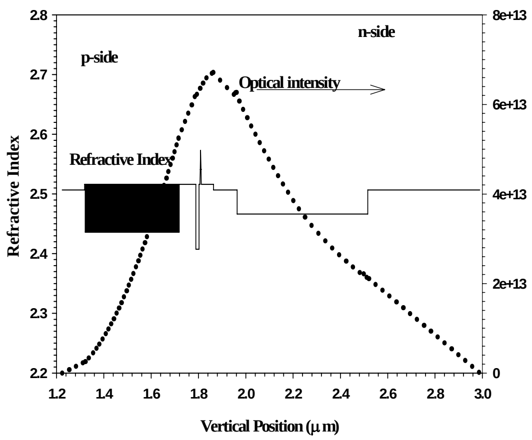

Fig. 6 Optical material intensity of the InGaN double quantum wells LD

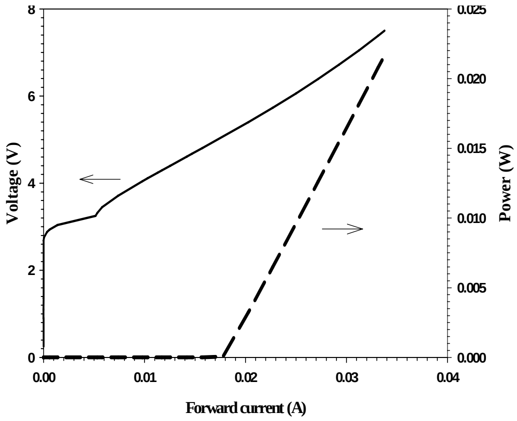

Fig. 7 Laser output power and bias voltage of DQW InGaN LD as a function of the forward current

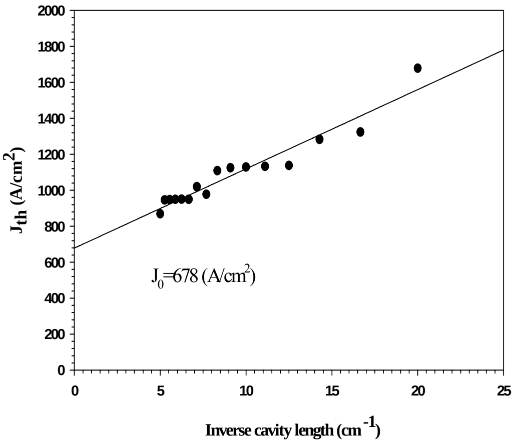

Fig. 8 The threshold current density as a function of inverse cavity length of DQWs InGaN LD

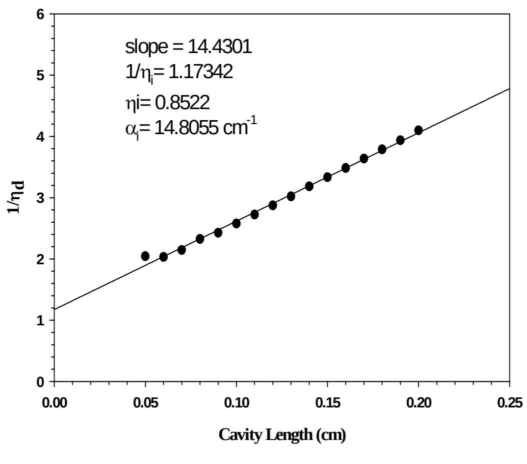

Fig. 9 Inverse of the external quantum efficiency as a function of cavity length of DQWs InGaN LD

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 fficiency 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 urrent density J_0 were calculated. It was observed that laser structures with quaternary alloys InAlGaN 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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References

[1] M. Miyoshi, H. Ishikawa, T. Egawa, K. Asai, M. Mouri, T. Shibata , M. Tanaka and O. Oda, "High-electron-mobility AlGaN/AlN/GaN heterostructures grown on 100-mm-diam epitaxial AlN/sapphire templates by metalorganic vapor phase epitaxy" Appl. Phys. Lett.85, p.1710, July 2004.
[2] L X Wang, M C Wang, X G Hu, X J Wang, S T Chen, G. Jiao , P J Li, P Y Zeng and M J Li, "Improved DC and RF performance of AlGaN/GaN HEMTs grown by MOCVD on sapphire substrates" Solid-StateElectronics, 49, pp. 1387-1390, Aug 2005 .
[3] V. Adivarahan, S. Wu, P J Zhang, A. Chitnis, M. Shatalov, V. Mandavilli, R. Gaska and A M Khan,"High-efficiency 269 nm emission deep ultraviolet light-emitting diodes" Appl.Phys.Lett, 84, p.4762, May 2004 .
[4] T. Nishida, H. Saito and N. Kobayashi, "Efficient and high-power AlGaN-based ultraviolet light-emitting diode grown on bulk GaN" Appl.Phys.Lett, 79, p.711, June 2001.
[5] C. Skierbiszewski, P. Perlin, I. Grzegory, R. Z Wasilewski, M. Siekacz, A. Feduniewicz, P. Wisniewski, J. Borysiuk, P. Prystawko, G. Kamler, T. Suski and S. Porowski," High power blue–violet InGaN laser diodes grown on bulk GaN substrates by plasma-assisted molecular beam epitaxy" Semiconductor. Sci. Tech, vol 20,p. 809, June 2005.
[6] H Hirayama, "Quaternary InAlGaN-based high-efficiency ultraviolet light-emitting diodes" J.Appl.Phys, 97, p.091101, April 2005.
[7] K H Cho, H K Lee, W S Kim, S K Park, H Y Cho and H J Lee, "Influence of growth temperature and reactor pressure on microstructural and optical properties of InAlGaN quaternary epilayers" J.Crystal Growth, 267,pp. 67-73, 2004 ,
[8] C H Chen, L Y Huang, Y F Chen, H X Jiang and J Y Lin, "Mechanism of enhanced luminescence in InxAlyGa1–x–yN quaternary alloys",Appl.Phys.Lett, 80,p.1397, February 2002..
[9] A Yasan, R. McClintock, K. Mayes, S. R Darvish, H. Zhang, P. Kung, M. Razeghi, K S Lee and Y J Han, "Comparison of ultraviolet light-emitting diodes with peak emission at 340 nm grown on GaN substrate and sapphire" Appl.Phys.Lett, 81,p.2151, July 2002 .
[10] E. Monroy, N. Gogneau, D. Jalabert, E. Bellet-Amalric, Y. Hori, F. Enjalbert, S L Dang and B. Daudin., "In incorporation during the growth of quaternary III-nitride compounds by plasma-assisted molecular beam epitaxy" Appl.Phys.Lett, 82,p.2242, February 2003 .

[11] C. Skierbiszewski, Z. R. Wasilewski , M. Siekacz, A. Feduniewicz, P. Perlin, P. Wisniewski, J. Borysiuk, I. Grzegory, M. Leszczynski, T. Suski, and S. Porowskib) "Blue-violet InGaN laser diodes grown on bulk GaN substrates by plasma-assisted molecular-beam epitaxy", High Pressure Research Center, PAS, Sokołowska 29/37, 01-142 Warsaw, Poland Appl.Phys.Lett., 86, 011114, December2005.
[12] Integrated System Engineering (ISE TCAD) AG, Switzerland, http://www.synopsys.com.
[13] S. M. Thahab, H. Abu Hassan and Z. Hassan, "Performance and optical characteristic of InGaN MQWs laser diodes" Opt. Exp., 15, No.5, p.2380 March (2007).