International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:3, No:7, 2009

InAlGaN Quaternary Multi-Quantum Wells UV Laser Diode Performance and Characterization

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

***Abstract*—**The InAlGaN alloy has only recently began receiving serious attention into its growth and application. High quality InGaN films have led to the development of light emitting diodes (LEDs) and blue laser diodes (LDs). The quaternary InAlGaN however, represents a more versatile material since the bandgap and lattice constant can be independently varied. We report an ultraviolet (UV) quaternary InAlGaN multi-quantum wells (MQWs) LD study by using the simulation program of Integrated System Engineering (ISE TCAD). Advanced physical models of semiconductor properties were used in order to obtain an optimized structure. The device performance which is affected by piezoelectric and thermal effects was studied via drift-diffusion model for carrier transport, optical gain and loss. The optical performance of the UV LD with different numbers of quantum wells was numerically investigated. The main peak of the emission wavelength for double quantum wells (DQWs) was shifted from 358 to 355.8 nm when the forward current was increased. Preliminary simulated results indicated that better output performance and lower threshold current could be obtained when the quantum number is four, with output power of 130 mW and threshold current of 140 mA.

***Keywords*—**Nitride semiconductors, InAlGaN quaternary, UV LD, numerical simulation.

I. Introduction

THE quaternary InAlGaN layers have been shown to be a good choice for fabricating heterojunctions lattice matched with GaN [1-7].It has also been demonstrated that In-incorporation in the ternary layers of AlGaN significantly improves their structural [8] and optical properties [9]. Further, the quaternary InAlGaN layers can be lattice matched either to AlGaN or InAlGaN by a proper selection of alloy compositions. However, the conventional metal–organic chemical vapor deposition (MOCVD) of InAlGaN faces an optimal growth temperature contradiction. For AlGaN growth high temperature is favorable to get high quality material, whereas for InGaN low temperature growth is preferred, because In would not incorporate at high temperatures.

High quality AlGaN cannot be grown at low temperatures by the conventional MOCVD because Al-ad-atoms have relatively low surface mobility. Recently, some researchers employed a unique called pulsed atomic layer epitaxy (PALE) approach for depositing the InAlGaN layers of InAlGaN MQWs active region [10-12]. At the Palo Alto Research Center ((PARC), Palo Alto, CA) [13], researchers have produced hetero-structures for UV LDs constructed from the InAlGaN alloy system grown on sapphire substrates. The devices operated with threshold current densities near 5 kA/cm^2 with light output powers greater than 400 mW at wavelengths between 368 and 378 nm.

The bandgap of AlGaN alloys can be tuned over a wide wavelength range. With GaN QWs, lasers emit at about 363 nm. Decreasing the wavelength further into the UV spectral region requires the introduction of increasing amounts of Al; for example, at 280 nm, the Al concentration in the AlGaN QWs is close to 50%. The semiconductor bandgap energy is increased by raising the aluminum content of the AlGaN alloy. This simultaneously reduces the number of free carriers in the material. The carrier reduction, in turn, leads to increased electrical resistance with consequent device heating, lowered overall device efficiency, and reduced device lifetime. Demonstrating lasers at such low wavelength will require resolving a number of materials, growth, and device design issues. The development of efficient MQWs active regions of quaternary InAlGaN in the UV region is an engaging challenge by itself. In this work UV InAlGaN MQWs laser diodes were studied and investigated by using the simulation program of ISE TCAD. Advanced physical models of semiconductor properties were used in order to obtain an optimized structure.

II. Laser Structure and Parameters Used in the Numerical Simulations

The numerical simulation of ISE TCAD [14, 15] self-consistently combined and 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 was 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 and its alloys. Thus, even with large carrier densities, Auger recombination in nitride materials is negligible. As shown in Fig. 1, the UV LD structure was assumed to be grown first on GaN layer of 3 µm in thickness, then followed by 80 pairs of

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, phone: 604-653-3200; fax: 604-657-9150;(e-mail: haslan@ usm.my)
Z. Hassan is with Nano-Optoelectronics Research and Technology Laboratory School of Physics, Universiti Sains Malaysia 11800 Penang, Malaysia. (e-mail: zai@ usm.my)

[(2.5 nm) n-$Al_{0.1}Ga_{0.9}N$/(2.5 nm) n-GaN] modulation doped strained layer superlattices (MD-SLS) cladding layers, followed by a 0.1 µm n-type GaN guiding layer. The active region of the preliminary LD structure under study consists of double quantum wells (DQWs) of a 3 nm quaternary $In_{0.06}Al_{0.08}Ga_{0.86}N$ well that is sandwiched between 5 nm $In_{0.01}Al_{0.10}Ga_{0.89}N$ barriers. 0.020 µm p-$In_{0.1}Al_{0.25}Ga_{0.65}N$ stopper layer is assumed to be grown on the top of the active region, followed by 0.1 µm p-GaN guiding layer, then 80 pairs of [(2.5 nm) p-$Al_{0.1}Ga_{0.9}N$/(2.5 nm) p-GaN] MD-SLS cladding layers and 0.1 µm p-GaN contact layer. The doping concentration of n-type and p-type are 5×10^{17} cm^{-3} and 5×10^{18} cm^{-3}, respectively for all relevant layers. The active region length is 800 µm and the reflectivity of the two ends (left and right facets assumed as Fabry–Perot cavity waveguide) equals to 0.30.

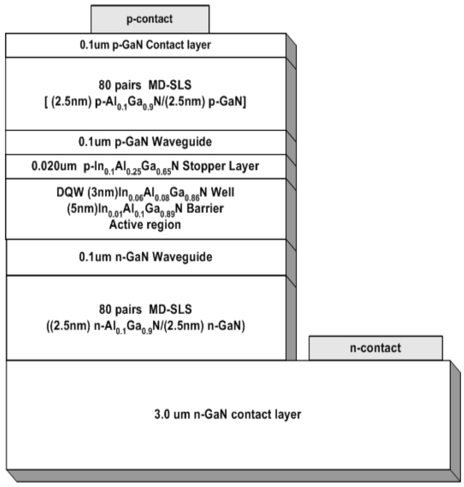

Fig. 1 Schematic diagram of the preliminary InAlGaN MQWs UV LD.

III. Results and Discussion

Fig. 2 shows the energy bandgap diagram of DQWs ($In_{0.06}Al_{0.08}Ga_{0.86}N$/ $In_{0.01}Al_{0.10}Ga_{0.89}N$) structure. The built in polarization field leads to a strong deformation of the usually rectangular quantum well diagram. 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 strongly tilted potential in the QW also drastically reduces the overlap between the electron and hole wave functions, so that the oscillator strength for the exciton recombination process gets considerably reduced. The optical intensity together with the refractive index profile are shown in Fig. 3. Maximum optical intensity was observed at the ($In_{0.06}Al_{0.08}Ga_{0.86}N$/$In_{0.01}Al_{0.10}Ga_{0.89}N$) active region due to the higher optical confinement achieved by the refractive index profile provided by the GaN waveguide and AlGaN/GaN MD-SLS cladding layer. Fig. 4 shows the output power and the bias voltage as a function of forward current of the DQWs LD. Output power of 60 mW and threshold current of 720 mA are obtained with a turn-on voltage of 3 V at laser diode bias voltage of 7.5 V. Fig. 5 shows the internal electric field distribution of the ($In_{0.06}Al_{0.08}Ga_{0.86}N$/ $In_{0.01}Al_{0.10}Ga_{0.89}N$) DQWs quaternary LD structure. A maximum value of 2.7×10^{5} V/cm is obtained inside the laser diode active region. The presence of the built-in electric field modifies the electronic states in QWs and lowers the optical gain of the active region of the laser.

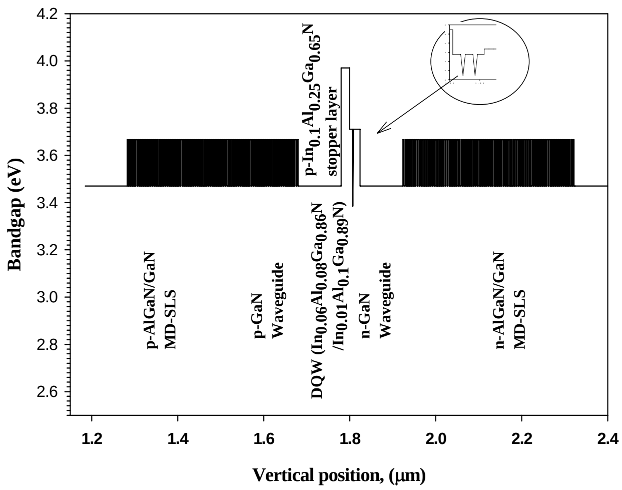

Fig. 2 Energy bandgap profile of the DQWs InAlGaN UV LD.

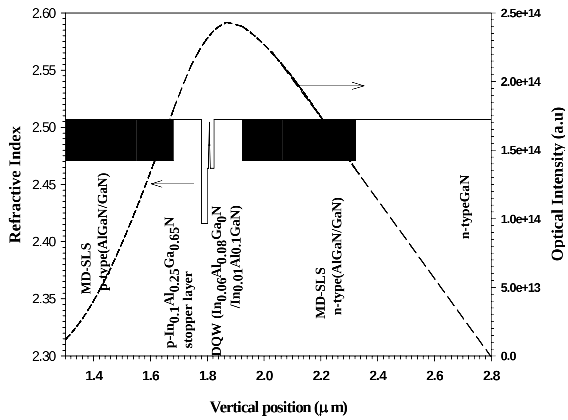

Fig. 3 Refractive index and optical material intensity of the InAlGaN DQWs UV LD.

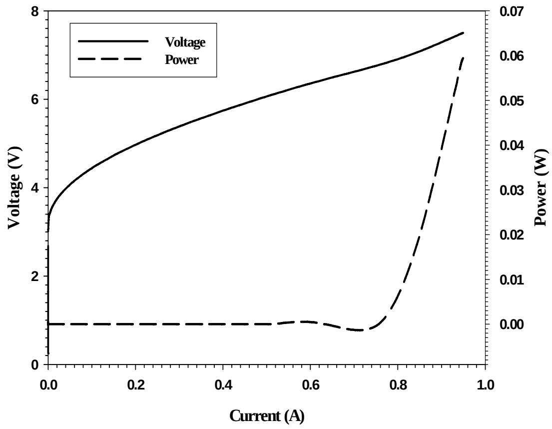

Fig. 4 Laser output power and bias voltage as a function of the forward current of DQWs InAlGaN UV LD.

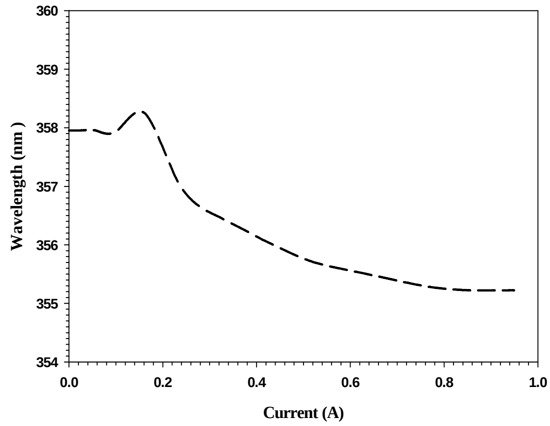

Fig. 6 Output wavelength of DQWs InAlGaN UV LD as a function of forward current.

The electrons and holes are, indeed, spatially separated by the polarization field, but the free carrier induced field is opposite to the polarization field. The two fields tend to cancel each other out for higher sheet densities, thus re-establishing the conditions for the electron hole recombination emission. The wavelength of the light emitted from the LD QWs depends not only on the band gap, but also on the large internal electric field due to piezoelectric (PZ) and spontaneous polarization. The PZ field arises from the strain due to the lattice mismatch between the $In_{0.06}Al_{0.08}Ga_{0.86}N$ wells and the $In_{0.01}Al_{0.10}Ga_{0.89}N$ barriers and causes red shift in the optical transition energy.

A blue shift of the emission wavelength from 358 nm to 355.8 nm with an increase in the forward current has been observed as shown in Fig. 6. Applying a forward bias reduces the electric field, thereby countering the quantum confined Stark effect (QCSE) in the active region [16-19].

We suspect that the polarization which is independent of applied bias induces a QCSE which red shift all spectral line. A second QCSE exists due to the electric field in the intrinsic material which blue shifts the spectral lines.

However, the spectral blue shifting of the InGaN MQWs with the current injection indicated that the net effect can be modulated by forward biasing; thus a blue shift with increasing current as observed in Fig. 6.

Moreover, in this work we investigated the effect of the number of quantum wells of $In_{0.06}Al_{0.08}Ga_{0.86}N$ layers on the performance of our UV laser diodes with emission wavelengths less than 360 nm. We varied the number of quantum wells from one to four and investigated the emission power versus the forward current as shown in Fig. 7. The lowest threshold current at 140 mA was obtained when the number of well layers was four. This threshold current increased when the number of $In_{0.06}Al_{0.08}Ga_{0.86}N$ well layers was reduced due to presumably the small conduction band offsets in the active region.

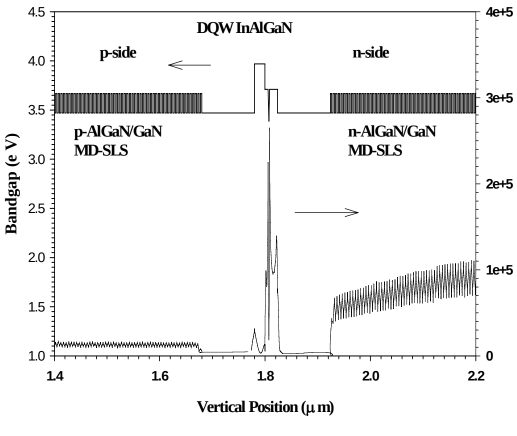

Fig. 5 Internal electric field of the InAlGaN DQWs UV LD.

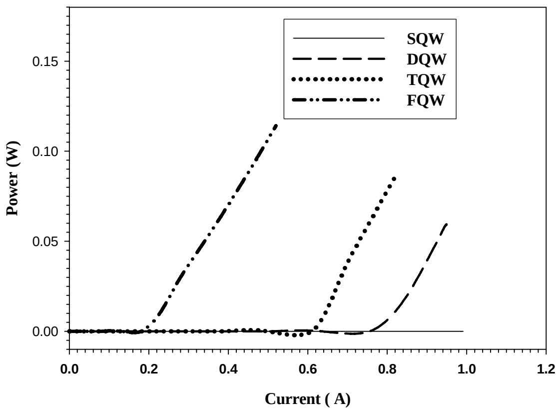

Fig. 7 Laser output power of SQW and MQWs InAlGaN UV LD as a function of the forward current.

The output power increased as the number of quantum wells was increased to four (130 mW). Due to the quantum confinement effect, the use of a MQWs structure in the active layer results in higher gain than the normal double hetero-structure and so leads to increased device efficiency.

IV. Conclusion

We have numerically investigated the laser performance of quaternary InAlGaN MQWs UV LD and characterize the effect of quantum well number on its performance by using ISE TCAD simulation program. The lowest threshold current of 140 mA was obtained when the number of InAlGaN well layers was four at our laser emission wavelength of 355.8 nm. We concluded that the composition of the quaternary MQWs and its quantum well number play important roles in determining the UV LD performance.

Acknowledgment

This work was conducted under Science Fund, Cycle 2007, of The Ministry of Science, Technology and Innovation, Malaysia. The financial support from Universiti Sains Malaysia is gratefully acknowledged.

References

[1] T. Deguchi, K. Sekiguchi, A. Nakamura, T. Sota, R. Matsuo, S. Chichibu, and S. Nakamura, "Quantum-confined Stark effect in an AlGaN/GaN/AlGaN single quantum well structures," Jpn. J. Appl. Phys., vol. 38, pp. L914–L916, Aug. 1999.

[2] F. Bernardini, V. Fiorentini, and D. Vanderbilt, "Spontaneous polarization and piezoelectric constants of III-V nitrides," Phys. Rev. B, vol. 56, pp. R10 024–R10 027, Oct. 1997.

[3] M. Kariya, S. Nitta, S. Yamaguchi, H. Kato, T. Takeuchi, C. Wetzel, H. Amano, and I. Akasaki, "Structural properties of Al In N ternary alloys on GaN grown by metalorganic vapor phase epitaxy," Jpn. J. Appl. Phys., vol. 37, pp. L697–L699, June 1998.

[4] M. Kariya, S. Nitta, S. Yamaguchi, T. Kashima, H. Katoh, H. Amano, and I. Akasaki, "Structural characterization of Al In N lattice-matched to GaN," J. Cryst. Growth, vol. 209, pp. 419–423, Feb. 2000.

[5] S. Yamaguchi, M. Kariya, S. Nitta, H. Amano, and I. Akasaki, "Anomalous features in the optical properties of AlInN on GaN grown by metal organic vapor phase epitaxy," Appl. Phys. Lett., vol. 76, pp. 876–878, Feb. 2000.

[6] M. A. Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, H.-C. Zur Loye, G. Tamulaitis, A. Zukauskas, D. J. Smith, D. Chandrasekhar, and R. Bicknell Tassius, "Lattice and energy band engineering in 1161–1163, Feb. 2000.

[7] M. A. Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, and A. Bykhovsky, "Piezoelectric doping in AlInGaN/GaN heterostructures," Appl. Phys. Lett., vol. 75, pp. 2806–2808, Nov. 1999 .

[8] G. Tamulaitis, K. Kazlauskas, S. Jursenas, A. Zukauskas, M. A. Khan, J. W. Yang, J. Zhang, G. Simin, M. S. Shur, and R. Gaska, "Optical bandgap formation in AlInGaN alloys," Appl. Phys. Lett., vol. 77, pp. 2136–2138, Oct. 2000 .

[9] J. P. Zhang, J.W. Yang, G. Simin, M. Shatalov, M. A. Khan, M. S. Shur, and R. Gaska, "Enhanced luminescence in InGaN multiple quantum wells with quaternary AlInGaN barriers," Appl. Phys. Lett., vol. 77, pp. 2668–2670, Oct. 2000 .

[10] J. P. Zhang, E. Kuokstis, Q. Fareed, H. Wang, J. W. Yang, G. Simin, M. A. Khan, and R. Gaska and M. S. Shur, "Pulsed atomic layer epitaxy of quaternary AlInGaN layers," Appl. Phys. Lett., vol. 79, pp. 925–927, Aug. 2001 .

[11] J. Zhang,V. Adivarahan, H. M.Wang, Q. Fareed, E.Koukstis, A. Chitnis, M. Shatalov, J.W. Yang, G. Simin, M. A. Khan, M. Shur, and R. Gaska, "Quaternary AlInGaN multiple quantum wells for ultraviolet light emitting diodes," Jpn. J. Appl. Phys., vol. 40, pp. L921–L924, Sept. 2001

[12] .M. A. Khan, V. Adivarahan, J. P. Zhang, C. Chen, E. Kuokstis, A. Chitnis, M. Shatalov, J. W. Yang, and G. Simin, "Stripe geometry ultraviolet light emitting diodes at 305 nanometers using quaternary AlInGaN multiple quantum wells," Jpn. J. Appl. Phys., vol. 40, pp. L1308–L1310, Dec. 2001.

[13] J. Carrano, A. Khan, M. Kneissl and N. Johnson, "Progress in semiconductor UV optical sources benefits security and defense". Palo Alto Research Center and Pacific Scientific Instruments (s pi e's **oe** m a g a z i n e) j u n e 2 003 .

[14] Integrated System Engineering (ISE TCAD) AG, Switzerland, http://www.synopsys.com.

[15] 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, Mar. 2007.

[16] P.Perlin, C.Kisielowshi, V.Iota, B.A.Weinstein, L.Mattos, N.A.Shapriro, J.Kruger, and E.R.Weber"InGaN/GaN quantum wells studied by high pressure, variable temperature, and excitation power spectroscopy", Appl.Phys.Lett., vol. 73, pp. 2778, Sep. 1998 .

[17] T.Takeuchi, S.Sota,M.Katsuragawa, M.Komori,H.Takeuchi, H.Amano, and I.Akasaki "Quantum-Confined Stark Effect due to Piezoelectric Fields in GaInN Strained Quantum Wells", Jpn.J.Appl.Phys., Part 2 vol. 36, pp. L382-L385, February (1997).

[18] T.Takeuchi, C.Wetzel,S.Yamaguchi,H.Sakai,H.Amano, and I.Akasaki, Determination of piezoelectric fields in strained GaInN quantum wells using the quantum-confined Stark effect", Appl.Phys.Lett., vol. 73, p. 1691 Sep. 1998 .

[19] M.D.Nardelli, K.Rapcewicz, and J. Bernholc, Polarization field effects on the electron-hole recombination dynamics in $In_{0.2}Ga_{0.8}N/In_{1-x}Ga_xN$ multiple quantum wells", Appl.Phys.Lett., vol. 71, p.3135, Nov. 1997.