EFFECT OF NITROGEN CONCENTRATION ON THE OPTICAL AND ELECTRICAL PERFORMANCE OF Ga$_{0.66}$In$_{0.34}$N$_y$As$_{1-y}$/GaAs QUANTUM WELL LASER DIODES

S. N. SUPARDAN, M. FAIEZ ALI, R. FAUZI, M. H. HASSAN, N. SAZANI, K. MOHAMED & M. KAMIL ABD-RAHMAN

Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

ABSTRACT

Design optimization of Ga$_{0.66}$In$_{0.34}$N$_y$As$_{1-y}$ quantum well (QW) for long wavelength semiconductor laser is conducted by using RSoft LaserMOD. The effect of different nitrogen (N) concentration ranging from 2.0 to 3.2 % with a stepped of 0.3 % in Ga$_{0.66}$In$_{0.34}$N$_y$As$_{1-y}$ QW system is investigated in term of its electrical and optical performances. It was found that the increment of N concentration up to 2.6% significantly elongating the emission of lasing wavelength ($\lambda$) up to 1.44 $\mu$m, elevating the output power ($P_{\text{out}}$) to 83.5 mW and reducing the threshold current density ($J_{\text{th}}$) to 431.25 A/cm$^2$.

KEYWORDS: GaInNAs, Quantum Well (QW), Laser Diodes (LD), Nitrogen Concentration

INTRODUCTION

The GaInNAs/GaAs system has attracted great interest in optical communications field since it was proposed back in 1995 by Kondow et al. [1, 2]. GaInNAs material posses interesting properties compared to the conventional III-V alloys (AlGa As, GaInAs and GaIn AsP) such as a large bandgap bowing [3] and an increase in the electron effective mass [4]. Generally, GaInNAs is a light-emitting material with a bandgap energy suitable for near-infrared LDs (1.3-1.55 $\mu$m and longer wavelengths) and can be grown pseudomorphically on GaAs substrate resulting in a type 1 band lineup which is essential in improving electron confinement in the QW layer and hence offers many advantages in terms of lasing performances.

The operating $\lambda$ of GaInNAs can be extended by increasing the N concentration in the GaInNAs QW [5-7]. Previous reported work suggests that the N incorporation leads to the strong redshift of the bandgap when the N concentration is increased to above 0.01% [8]. However, this is typically accompanied by a very large degradation of all laser characteristics, in particular a very large increase in $J_{\text{th}}$ [9-10]. This deterioration is suggested to be due to some possible reasons including the existence of a larger miscibility gap in the alloy phase diagram of GaInNAs materials [11], interface roughness, and N compositional inhomogeneity [12-14]. Therefore, it is important to optimize N concentration in GaInNAs in order to realize LD operating at longer $\lambda$ emission and having low threshold current ($I_{\text{th}}$) and $J_{\text{th}}$. In this work, the effect of N concentration increment on the optical and electrical performance of Ga$_{0.66}$In$_{0.34}$N$_y$As$_{1-y}$ QW LD is presented.
DEVICE DESIGN AND SIMULATION

Figure 1 show schematically the studied structure of GaInNAs broad area laser (BAL) which is based on previous work of W. Li et al. [15] with the cavity length of 1600 µm and a stripe width of 20 µm. The active region consists of a single $\text{Ga}_{0.66}\text{In}_{0.34}\text{N}_y\text{As}_{1-y}$ ($y = 0.02$, $0.023$, $0.026$, $0.029$, and $0.032$) layer sandwiched between two $\text{Ga}_0\text{N}_{0.02}\text{As}_{0.98}$ barriers. The waveguide layer is made of GaAs. Both n-type and p-type $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ cladding layers and doped with $5 \times 10^{17}$ and $9 \times 10^{17} \text{ cm}^{-3}$. Finally, p+ GaAs contact layer is heavily doped to $3 \times 10^{19} \text{ cm}^{-3}$ in order to minimize the contact resistance. The modeling of LD epitaxial structure and device design are performed by using RSoft LaserMOD software [16] for analyzing the optical and electrical characteristic of the $\text{Ga}_{0.66}\text{In}_{0.34}\text{N}_y\text{As}_{1-y}$ QW LD.

RESULTS AND DISCUSSIONS

Optical Properties

Material gain of $\text{Ga}_{0.66}\text{In}_{0.34}\text{N}_y\text{As}_{1-y}$ QW as a function of wavelength for various N concentrations is presented in Figure 2. It was found that as the percentage of N increased from 2.0 to 3.2%, the gain peak broadens and the wavelength red-shifted from 1.32 to 1.48 µm. However as higher N concentration is incorporated into the QW, the peak material gain is significantly increased indicating a great amount of carrier density is needed in the BAL in order to start lasing action. The increased in peak material gain profile reflects $J_{th}$ profile which will be discussed later in Figure 6. This degradation is suggested to be caused by the in homogeneity of compositions [12-14] in the structure.
Effect of Nitrogen Concentration on the Optical and Electrical Performance of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs Quantum Well Laser Diodes

Figure 2: Material Gain of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs QW with Different N Concentrations

Figure 2 illustrates the material gain of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs QW with different N concentrations. As the N concentration increases from 2.0 to 3.2%, the material gain broadens and red-shifts, indicating an increase in the peak wavelength emission from 1.32 to 1.48 $\mu$m, which correlates with the previous plotted material gain profile. However, the intensity is slightly dropped when the N concentration is increased. The broadening of the peak wavelength emission and the dropped intensity might be the result of crystalline quality deterioration, N out-diffusions, and phase segregations [17, 18].

Figure 3: PL of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs QW with Different N Concentrations

Figure 3 illustrates the photoluminescence (PL) spectrum for Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs QW at different N concentrations. Here, it was found that the increment of N concentration from 2.0 to 3.2% also broadens and red-shifts the peak wavelength emission from 1.32 to 1.48 $\mu$m which correlated with the previous plotted material gain profile. However, the intensity is slightly dropped when N concentration is increased. The broadening of the peak wavelength emission and the dropped intensity might be the result of crystalline quality deterioration, N out-diffusions, and phase segregations [17, 18].

Electrical Properties

Figure 4 illustrates the graph of $P_{out}$ versus $I_{th}$ of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$/GaAs QW at different N concentration ranging from 2.0 to 3.2%. This graph indicates that $I_{th}$ is decreased from 162 to 138 mA with increasing N concentrations from 2.0 to
2.6\% respectively. However at above 2.6\% of N concentration, $I_{th}$ is increased until reached the maximum of 162 mA at 3.2\% of N concentration. This is could be due to the result of lower potential barrier in the valence band with further increase of N concentration which causes higher holes leakage and hence influencing the $I_{th}$ to be increased [19,20]. In term of $P_{out}$, as N is increased to 2.6\%, a maximum value of 83.5 mW is recorded, however as N is further increased to 3.2\% the value slightly deteriorated to 70.24 mW.

Figure 4: The $P_{out}$ versus $I_{th}$ of Ga$_{0.34}$In$_{0.66}$As$_{1-y}$QW LD for Different N Concentrations

Figure 5 illustrates the pattern $P_{out}$ and $J_{th}$ of Ga$_{0.66}$In$_{0.34}$N$_{y}$As$_{1-y}$ QW as a function N concentration. All $J_{th}$ values are calculated using $J_{th} = I_{th}/A$ where $I_{th}$ is threshold current measured in mA and $A$ is the area of LD = width x cavity length measured in cm$^2$. Here it was found that there are two dissimilar patterns describing N concentration is increased from 2.0 to 2.6 \% and from 2.6 to 3.2 \%. First, $J_{th}$ is found to decrease from 504.69 to 431.25 A/cm$^2$ correspond to increment of N concentration from 2.0 to 2.6 \% then increased from 431.25 to 506.25 A/cm$^2$ correspond to increment of N concentration from 2.6 to 3.2\%. As stated earlier, the increment of $J_{th}$ might be caused by the deterioration of crystalline quality of GaInNAs QW at higher N concentration. Furthermore this degradation is suggested to be originated from the reduction of the carrier injection efficiency which is related to carrier recombination losses in the barriers, the optical absorption losses and the defect-related recombination coefficient which are found to increase at larger N concentration [13]. Based from the simulated profiles it is found that the lowest $J_{th}$ and highest $P_{out}$ are 431.25 A/cm$^2$ and 83.5 mW at recorded at 2.6\% of N concentration.
Effect of Nitrogen Concentration on the Optical and Electrical Performance of Ga$_{0.66}$In$_{0.34}$As$_1$N$_y$/GaAs Quantum Well Laser Diodes

Impact Factor (JCC): 1.8207 - This article can be downloaded from www.impactjournals.us

Figure 5: $P_{out}$ and $J_{th}$ Curve as a Function of N Concentrations

Figure 6 shows the external differential quantum efficiency ($\eta_d$) calculated for the Ga$_{0.66}$In$_{0.34}$N$_y$/GaAs QW at different N concentrations. The $\eta_d$ is calculated using $\eta_d = 2(\Delta P/\Delta I) [q\lambda/hc]$ where $\Delta P/\Delta I$ is slope of $PI$ curve or slope efficiency, $h$ is Planck’s constant, $q$ is electric charge, $c$ is the speed of light, and $\lambda$ is the lasing wavelength of the device. $\eta_d$ is used to indicate the efficiency of a laser device in converting the injected electron hole pairs (input electric charges) to photon emitted from the device (output light) [21]. It was found that $\eta_d$ increased gradually with increasing N concentration from 2.0 to 2.6% but decreased when is above 2.6%. The highest $\eta_d$ of 27% is recorded at 2.6% of N concentration. However here the internal quantum efficiency $\eta_i$ is not calculated since no variation in term of cavity length is made throughout this study.

Figure 6: $\eta_d$ of Ga$_{0.66}$In$_{0.34}$N$_y$/GaAs QW with Different N Concentrations
CONCLUSIONS

Comprehensive analysis involving electrical and optical performances of Ga_{0.66}In_{0.34}N_{y}As_{1-y}/GaAs QW LD have been studied based on different nitrogen concentrations ranging from 2.0 to 3.2%. Improvement in term of the λ emission and $P_{out}$ are obtained with only a small incorporation N in Ga_{0.66}In_{0.34}N_{y}As_{1-y} QW. In this simulation works, the optimal value of N concentration in Ga_{0.66}In_{0.34}N_{y}As_{1-y} QW is suggested to be at 2.6% resulting in λ emission of 1.44 µm, $P_{out}$ of 83.5 mW, and a low $J_{th}$ of 431.25 A/cm^2.

ACKNOWLEDGEMENTS

The work has been supported by E-Science Fund (E-Science) – 100-RMI/SF 16/6/2 (9/2012).

REFERENCES

10. A Hierro, J. M. Ulloa, E. Calleja, B. Damilano, J. Barjon, J. Y. Duboz, and J. Massies, Room temperature performance of low threshold 1.34-1.44 µm GaInNAs/GaAs quantum-well lasers grown by molecular beam
Effect of Nitrogen Concentration on the Optical and Electrical Performance of Ga0.66In0.34As0.5Y/GaAs Quantum Well Laser Diodes


