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Low internal loss GaInNAs laser diode with InGaAs/GaNAs/GaAs barrier

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We investigate the performance of GaInNAs laser diode at room temperature when the InGaAs and GaNAs barrier configuration is applied to the quantum well system in the active region. The simulation software PICS3D is used in this work. By measuring the light versus the current curve, we can extract the differential quantum efficiency, η_d and internal quantum efficiency, η_i for the laser. The internal loss of the laser is then determined by measuring the slope of the linear fit line to the inverse of external differential quantum efficiency versus cavity length data points. The inverse slope of the efficiency versus cavity length plot shows that the laser exhibits low internal loss of 2.8 cm^{-1} with η_i of 58%. This shows good simulation results of GaInNAs laser diode. Realizing that the actual growth experiments of GaInNAs laser diode which involves the MBE or MOCVD would cost be rather expensive, this simulation approach offers a low cost method of predicting the laser performance of the GaInNAs laser diode.

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Keywords: GaInNAs, Long wavelength lasers, Quantum well

1. Introduction

For many years, people believed that there were no other suitable alloy lattice matched to GaAs that would emit laser at >1.1um, making InGaAsP on InP was the only materials system that met the criteria. 100% of the long wavelength lasers currently in use today are fabricated from this InGaAsP on InP system.

In 1995, a new material of GaInNAs for long wavelength application has been proposed and created by M. Kondow. The reasons why GaInNAs become the noble candidate is because of for the same bandgap material, GaInNAs has a deeper conduction well, for better electron confinement and larger electron effective mass for better match of valence and conduction densities of states (due to the mass). Thus, higher operation temperature; higher efficiency; higher output power (high stability) [1].

Not only that, GaInNAs also do not require difficult compositional control over both column III and V and the compositional control and uniformity in GaInNAs is easy compared to AsP control in InGaAsP. It also can fabricate straightforward onto GaAs/AlAs mirror (lattice-matched), and can apply the AlAs oxidation for confinement technology and at the same reduce the manufacturing cost because GaAs is much cheaper than InP. GaInNAs on GaAs can provides easy monolithic integration with GaAs high speed electronics for high speed networks. An advantage for highly strained GaInNAs QW lasers is no noticeable penalty in crystal quality and their good temperature characteristics [2 – 4].

But, there are few problems and challenges of GaInNAs. GaInNAs is a new materials system, so there are so many unknown parameters that yet to discover. There are also problem in basic crystal structure and compatibility; because InGaN is hexagonal structure, while InGaAs is cubic (zincblende) – so they are having miscibility gap in alloy. InGaN and InGaAs are grown in very different temperatures, so it is very difficult to growth the compound. So, a very reactive N source is required to overcome this temperature difference [5].

In this letter, we demonstrate that the performances of the GaInNAs laser with different barrier configuration. Here, we simulate the structure to improve the performance of the GaInNAs, by adding the InGaAs/GaNAs/GaAs barrier.

2. Simulations

Internal photon losses can also be caused by carrier density independent mechanisms like photon scattering at defects. This is considered by a constant background loss coefficient, α_b of 7 cm^{-1}. The strain mediating layers of InGaAs and GaNAs were believed can improve the performance of the GaInNAs laser diode. The GaNAs barrier reported by Pavelescu *et al.* [6] was found to increase the wavelength emission of GaInNAs laser diode if compared to the structure of laser without the GaNAs barrier with exactly the same composition of nitrogen and indium the GaInNAs quantum well layer [6 – 7]. The elongation of the wavelength emission is due to the fact that we literally increase the nitrogen inside the active region (quantum well and barrier). Adding nitrogen in the active region means we decrease the energy band gap of the active region, thus increasing the emission wavelength. Not only that, GaNAs barrier can be acts like a stopper layer from diffusing out from the quantum well to the subsequence GaAs barrier at higher temperature, providing that the percentage of nitrogen in the GaNAs barrier is at least the same as in the quantum well or higher. However only in actual experimental, the out diffusion of the nitrogen from the quantum well to the barrier can only significantly be observed under high temperature either by annealing or by self heating. On the other hand, InGaAs strain mediating layer reported by Kim *et al.* [11] was believed can actually reduce the high compressive strain of the GaInNAs QW, acting like the intermediate layer between highly compressive GaInNAs quantum well and tensiled strain GaNAs barrier. They also observed that when the thickness of the GaNAs and InGaAs were increased, it affects the elongation of the spectrum emission of the laser [8]. In this simulation, we try to combine both InGaAs and GaNAs layers, sandwiching the GaInNAS QW and observe the performance of this barrier configuration as compared to the GaInNAs laser diode with just having the GaAs barrier, and GaNAs/GaAs barriers. Theoretically, we expect that the crystalline structure is improved with InGaAs/GaNAs/GaAs barrier configuration and thus enhancing the laser performance.

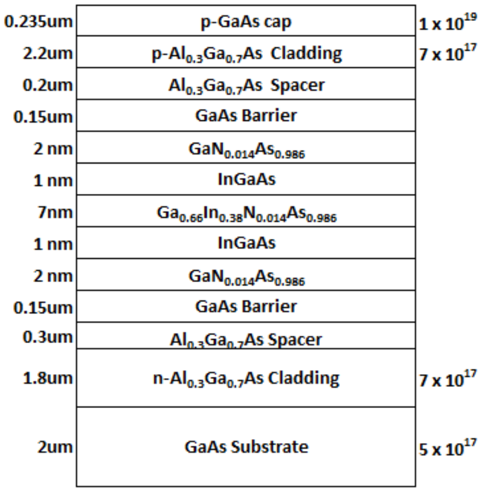

Fig. 1. The Structure of the GaInNAs laser diode with the InGaAs/GaNAs/GaAs barrier configuration.

3. Device design

Generally, a broad area laser (BAL) active region consist of a single 7 nm $Ga_{0.62}In_{0.38}N_{0.014}As_{0.986}$ located at the centre of the 300 nm GaAs waveguide where 0.2 μm and 0.3 μm thickness of undoped $Al_{0.3}Ga_{0.7}As$ spacers were sandwiching the active region. Between the spacers layer, 1 nm InGaAs and 2 nm thickness of GaNAs with the same composition of nitrogen as in the QW were sandwiching the quantum well as strain mediating layers. On each side of the active region there is 1.8 μm n-$Al_{0.3}Ga_{0.7}As$ and 2.2 μm p-$Al_{0.3}Ga_{0.7}As$, where both cladding layers were doped with 7×10^{17} cm^{-3}. The laser has a highly doped layer of p-GaAs doped with 1×10^{19} cm^{-3} contact layer to decrease the contact resistance. This broad area laser has the width of 200 μm and cavity length of were varied from 1200 μm to 2000 μm long.

Our main objective is to have an emission wavelength of about 1.31 μm by using the GaInNAs as the active material, and the effect of the barrier configuration to the performance of the laser. For simplification, we fixed the nitrogen percentage in the QW as 1.4% while the indium percentage is 38%. From the bowing parameter of -20eV for GaInNAs reported by Buyanova *et al.* [9] we make a curve fitting the bowing parameter at this percentage of nitrogen and indium so that it can lead to the spectrum emission of merely 1.31 μm by using this PICS3D software. The reason of choosing the low percentage of nitrogen of 1.4% and high percentage of indium of 38% is because of the nitrogen effect is more crucial and giving more impact to the wavelength elongation as compared to indium. In fact, that only 1% on nitrogen is needed to redshift of 0.16 μm wavelength while 10 % of indium is needed to redshift the wavelength of the same amount [11]. Moreover, lower nitrogen percentage and higher indium percentage are believed to achieve a lower transparency carrier density, and higher slope efficiency. Not only that, it is actually difficult to grow GaInNAs epilayer with a large amount of nitrogen due to the large difference in the atomic size of nitrogen and arsenic, which can produce a miscibility gap of the alloy (atomic radius As = 119 pm; covalent radius N ≈ 71 pm). In the GaInNAs laser structure, the percentage of nitrogen in the GaNAs barrier is also fixed to be at 1.4% to reduce the complexity of the simulation design and to compare the performance of the laser with other barrier configuration.

4. Results and analysis

The threshold current density, J_{th} and the external differential quantum efficiency, η_d values are the parameters of laser diodes that were depending on the cavity length. From the *L-I* curve of a laser diode, we can measure the slope of the curve, ($\Delta P/\Delta I$) of various cavity length laser diode and calculate the η_d values. The value of the slope, $\Delta P/\Delta I$ must be multiplied by 2 because the set of the *L-I* characteristic is related to a laser diode with a cleaved mirror facets and emitting equal amounts of light from back and front mirrors facets. However, the light that is only come out from the front mirror will be detected and measured. Figure 2 shows the *L-I* curve of the GaInNAs laser diode with InGaAs/GaNAs/GaAs barrier configuration at different cavity length. While Figure 3 shows the comparison of the *L-I* curve of the GaInNAs laser diode with different barrier configuration. With the InGaAs/GaNAs/GaAs barrier configuration, the laser power is significantly increase as compared to the other barrier configuration. With the facet reflectance of $R = 0.30$ for both mirrors, and we fixed the background loss parameter of $\alpha_b = 7$ cm^{-1}. The simulator yields the parameter η_i as 58% with α_i of 2.79 cm^{-1} for this laser diode as shown in Figure 4.

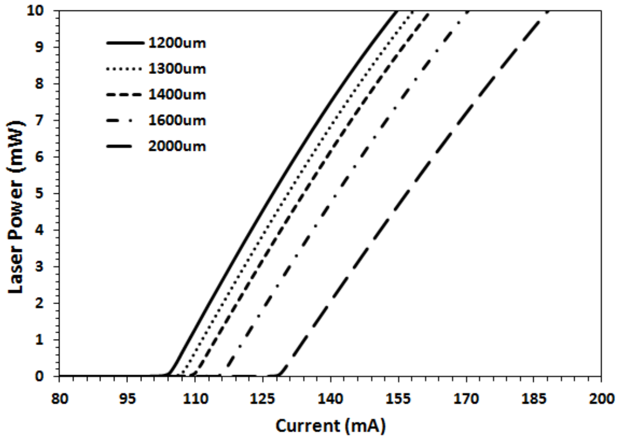

Fig. 2. The L-I curve of GaInNAs laser diode with InGaAs/GaNAs/GaAs barrier configuration at different cavity length.

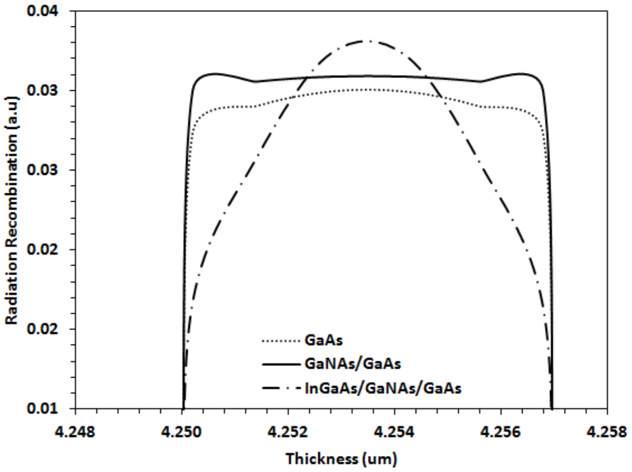

Fig. 5. The extracted value of the radiation recombination inside the GaInNAs quantum well region.

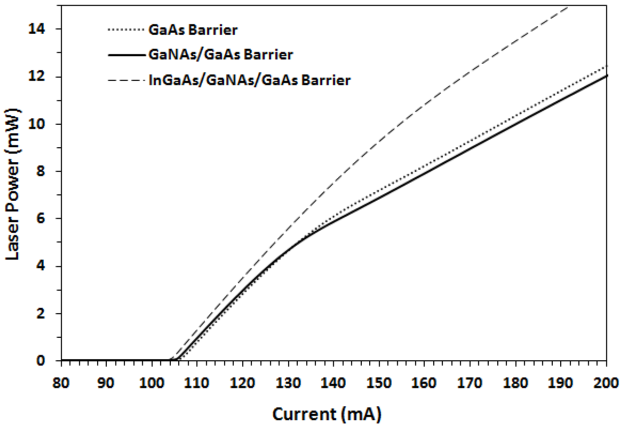

Fig. 3. Comparison of the L-I curve of GaInNAs laser diode with different barrier configuration.

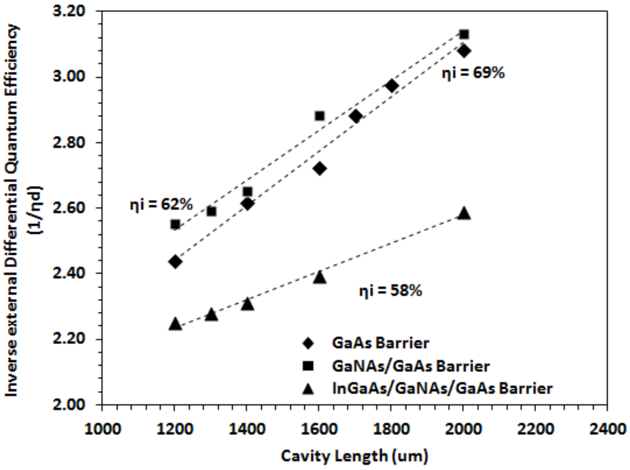

Fig. 4. The calculated internal quantum efficiency, η_i, of GaInNAs laser diode at different barrier configuration.

Note that there is a difference between internal quantum efficiency, η_i and external differential quantum efficiency, η_d. The internal quantum efficiency is a direct indication of the efficiency of a laser in converting electron-hole pairs (injected current) into photons (light) within the laser diode structure. But remember that not all of the photons that are generated find their way out of the device; some of them are reabsorbed due to various internal loss mechanisms. As a result, the external differential quantum efficiency is an indication of the efficiency of a laser in converting electron-hole pairs (injected current) into photons emitted from the laser device (output light). From the value η_i of 69%, the GaInNAs laser diode with only GaAs barrier has the highest ability of converting electron-hole pairs (injected current) into photons (light) within the laser diode structure even though the radiation recombination of electron and hole in the quantum well is almost comparable with the GaInNAs laser consist of GaNAs/GaAs barrier configuration as shown in Figure 5. However, due to the highest internal loss of 6.7 cm^{-1} as compared to the other barrier configuration, InGaAs/GaNAs/GaAs barrier configuration seems has the solution to increase the performance of the GaInNAs laser diode with the lowest internal loss, thus reduces the transparent threshold current density, J_o as in Figure 6.

Table 1 shows the summary of the laser performance with the different configuration of the barrier.

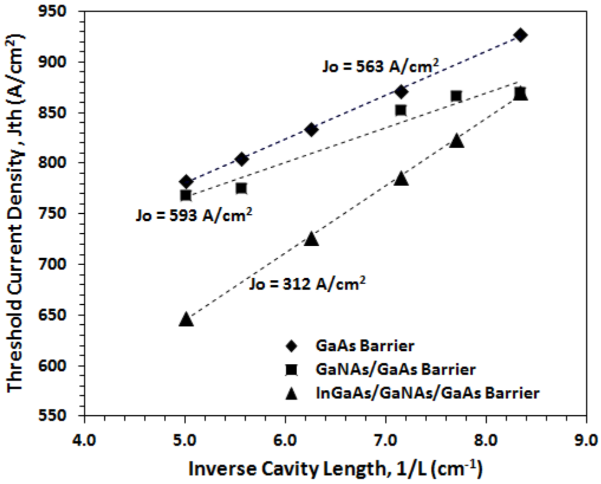

Fig. 6. The transparent current density, J_o of the GaInNAs laser diodes at different barrier configuration.

Table 1 Summary of the GaInNAs laser diode performance with different barrier configuration.

Barrier Configuration	Transparent Threshold Current Density, J_o (A/cm^2)	Internal Quantum Efficiency, η_i	Internal Loss (cm^{-1})
GaAs	563	69	6.7
GaNAs/GaAs	593	62	5.9
InGaAs/GaNAs/GaAs	312	58	2.8

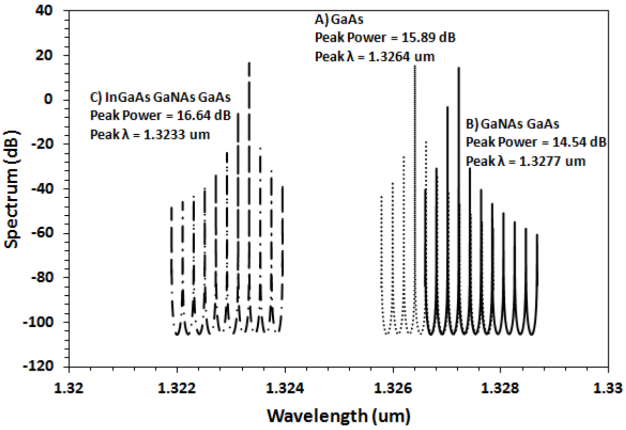

Fig. 7. The spectrum emission of the GaInNAs laser diode.

Fig. 7 shows the spectrum emission of all three barrier configurations of the GaInNAs laser diode. Since the GaInNAs quantum well is having a highly compressive strain, GaNAs with tensile strain induced the GaInNAs quantum well to become more compressive stress thus redshifting the emission wavelength to longer range. On the other hand, by sandwiching InGaAs between GaInNAs quantum well and GaNAs barrier, its larger lattice constant highly reduced the compressive strain of the quantum well, thus blueshifting the previous emission wavelength.

5. Conclusion

As the conclusion, we can say that the GaInNAs laser structure with InGaAs/GaNAs/GaAs barrier configuration exhibit a promising performance in term of higher output power, very low internal loss, and low threshold current density as compared to other barrier configuration. In term of wavelength emission, these three barrier configuration seems comparable and not very crucial since the variance is not significant.

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