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Large intermixing in the InGaP/InAlGaP laser structure using stress engineering at elevated temperature

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ABSTRACT

In this paper, a thermally induced dielectric strain on quantum well intermixing (QWI) technique is employed on tensile-strained InGaP/InAlGaP laser structure, to promote inter-diffusion, in conjunction with cycle annealing at elevated temperature. A bandgap blueshift as large as $\sim 250\text{meV}$ was observed for samples capped with a single and bilayer of the dielectric film ($1\mu\text{m-SiO}_2$ and $0.1\mu\text{m-Si}_3\text{N}_4$) and annealed at a high temperature ($700\text{-}1000^\circ\text{C}$) for cycles of annealing steps. Samples subjected to this novel QWI technique for short duration and multiple cycle annealing steps shown a high degree of intermixing while maintaining strong photoluminescence (PL) intensity, narrow full wave at half maximum (FWHM) and good surface morphology. Laser devices fabricated using this technique, lased at a wavelength of 608nm with two facet power of $\sim 46\text{mW}$, indicating the high quality of the material. Our results show that thermal stress can be controlled by the engineering dielectric strain opening new perspectives for QWI of photonics devices.

Keywords: InGaP/InAlGaP, Visible lasers, Dielectric stress, Quantum well intermixing, Cycle annealing

1. INTRODUCTION

There is a strong Interest for visible light emitters for several important applications in solid-state lighting, Li-Fi, underwater visible light communication, medicine, and photodynamic therapy (PDT)¹⁻³. Visible light emitters are nitride-based (InGaN/GaN) covering the $\sim 405\text{-}530\text{nm}$ or phosphide-based (InGaP/InAlGaP) covering the $630\text{-}690\text{nm}$ wavelengths⁴⁻⁹. The optoelectronic devices, emitting in the green to orange spectral region $550\text{-}620\text{nm}$ suffer from low quantum efficiency, and therefore there is a "gap" in the visible region. Large strain and Indium segregation prevent efficient laser devices beyond 540 nm in the III-N material system⁵. As for the InGaP/InAlGaP material system, Al incorporation shortens the emissions wavelength; however, efficiency is severely affected by oxygen-related defects. Also, the small band offset between the quantum well (QW) and the barrier leads to large current leakage. The lowest reported wavelength with Al content was 615nm ⁴. The bandgap of $\text{In}_x(\text{Al}_y\text{Ga}_{1-y})_{1-x}\text{P}$ quantum well can also be tuned by controlling the In content; however, it will lead to lattice mismatch with GaAs substrate. By applying high external

pressure and low temperature yellow lasing was demonstrated from red InGaP/InAlGaP laser diodes¹⁰. However, this method is not viable for commercial applications. The other route explored by researchers, was to utilize the post-growth quantum well intermixing (QWI). Negligible wavelength shift was observed for devices capped with plasma-enhanced chemical vapor deposition (PECVD) -deposited HfO₂ and SiO₂ dielectric films.¹¹⁻¹³

In this work, thermally induced dielectric strain is employed on tensile-strained InGaP/InAlGaP laser structure to promote interdiffusion via application of a single (SiO₂, Si₃N₄) and bilayers (SiO₂/Si₃N₄) of dielectric films at elevated temperature. A bandgap blueshift as large as 250-300meV was observed for samples capped with a single layer of 1μm-SiO₂ and 0.1μm-Si₃N₄ and annealed at an elevated temperature for cycles of annealing steps. We discuss wavelength tuning by QWI and suppression by the engineering dielectric strain (single and bilayer), opening new perspectives for QWI of photonics devices.

2. EXPERIMENT

The laser structure has a single QW InGaP/InAlGaP sandwich between In_{0.5}Al_{0.5}P cladding layers and the GaAs contact layer and grown on GaAs substrate as shown in Figure.1. The device structure is lattice-matched to the GaAs substrate; the composition of thin 6nm In_{0.47}Ga_{0.53}P quantum well is designed to have a peak emission at 635±3 nm with a limited amount of strain. In our study, samples are prepared using two capping materials a 1-μm thick film of SiO₂ and 0.1-μm Si₃N₄ using Plasma enhanced chemical vapor deposition (PECVD). These samples were annealed using rapid thermal processing in a nitrogen ambient at temperature values of 700°C to 1000°C in steps of 25°C for annealing durations between 30s to 240s, along with an uncapped as-grown sample. A GaAs proximity cap is used for arsenic overpressure to minimize arsenic desorption during annealing. A room-temperature PL spectroscopy apparatus equipped with a 473nm cobalt laser used as the excitation source to measure the induced blueshift by the above process. Electroluminescence emissions were measured on sample blueshifted to the red-yellow region by applying front and back contacts.

Fig. 1 The InGaP/InAlGaP laser structure with a single In_{0.47}Ga_{0.53}P quantum well.

3. RESULTS AND DISCUSSION

Previously we have studied the effect of annealing temperature on group III intermixing for a 1 μm - SiO_2 -capped sample at different temperatures from 700°C to 1000°C, for 120s annealing duration. We found that the annealing temperature of 925°C is the threshold temperature above which degree of intermixing rapidly increases ⁶⁻⁹. A similar study is conducted for 0.1 μm - Si_3N_4 samples for annealing temperature ranging from 700-1000°C, for the 120s duration as shown in Fig.2. Up to 900°C, all the samples capped with 0.1 μm - Si_3N_4 (and also 1 μm - SiO_2) retained high photoluminescence intensity with a negligible increase in full-width at half maximum (FWHM) while maintaining good surface morphology. Above, this temperature the interface between the top contact layer of InGaP/InAlGaP and the Si_3N_4 starts to crack (inset Fig.2) and in some cases peeled off the top contact layers (Inset Fig 2). No intermixing observed from these samples in the temperature range 900-1000°C and the inevitable effect does not allow further exploration.

Interestingly, we have observed intermixing in the range of 700°C to 900°C for Si_3N_4 capped samples with wavelength blueshift rapidly above 800°C. The sample maintained strong PL intensity and narrow full wave at half maximum (FWHM) and preserved epitaxial quality as observed from Transmission Electron Microscopy (not shown). Some surface damage was apparent after annealing as can be seen from the optical micrograph in the inset of Fig.2, which needs to be avoided to ensure the high quality of the laser structure after the QWI process for further device fabrication.

The surface damage is detrimental to the optoelectronic devices, under a high injection current densities, defects can migrate into the active region and promote the non-radiative recombination. Understanding and solving these issues are keys to attaining high-performance devices. Based on the above analysis, 800 °C, is considered as the critical temperature for enhanced intermixing in this material system for Si_3N_4 dielectric film.

Fig.2 The peak wavelength shift as a function of annealing temperature for InGaP/InAlGaP with a 1- μm thick PECVD-deposited SiO_2 and 0.1- μm thick Si_3N_4 capping layer annealed for 120 s. Inset shows optical micrograph of the semiconductor surface after rapid thermal annealing (RTA) at 800 °C and fragmented dielectric after annealing at 950°C.

Fig. 3 (a) The peak wavelength shift for a multilayer dielectric film with a 1- μm thick SiO_2 and 0.1- μm thick Si_3N_4 . The inset shows the schematic of the novel quantum well intermixing (Si_3N_4) and suppression (SiO_2) investigated in the study. (b) the relationship between the film thickness of SiO_2 and the amount of blueshift on the InGaP/InAlGaP laser structure.

Fig.3 (a) shows the peak wavelength shift for a bilayer of dielectric 1- μm thick SiO_2 and 0.1- μm thick Si_3N_4 annealed at 800 $^\circ\text{C}$ for a duration of 120s. The inset shows the schematic of the novel quantum well intermixing and suppression from bilayer of dielectric. Previously, we increased the strain by increasing the thickness of SiO_2 capping from 200-2000nm to emphasize the relationship between strain and QWI⁶⁻⁹. As can be seen from Fig 3(b), as the thickness increases the blueshift increase and saturates above 1000nm thickness. So it is safe to assume that the bilayer $\text{SiO}_2/\text{Si}_3\text{N}_4$, do not increase the QWI amount as shown by PL measurement in Fig. 3(a). In fact, from Fig 1, the single layer of SiO_2 act like a suppressant cap for QWI below 925 $^\circ\text{C}$, which is also clearly evident from the study of bilayer cap in Fig. 3(a). QWI by Si_3N_4 and suppression by SiO_2 in the single layer and bilayer of dielectrics at 800 $^\circ\text{C}$ offers high quantum efficiency, improved surface quality (except few defects), and good quantum well-intermixing selectivity in the InGaP/InAlGaP. These results are contrary to what is reported earlier in the case of multi-layer InGaAs/GaAs quantum well laser structure¹⁴⁻¹⁵.

Fig. 4. (a) Room temperature photoluminescence Peaks of InGaP/InAlGaP laser samples with thick 1 μm - SiO_2 annealed at 950 $^\circ\text{C}$ for 1,2 and 3 cycles for different annealing duration⁶. (b) Dielectric strain induced orange semiconductor laser emitting at 608nm⁶.

Previously we achieved the largest degree of QWI (~ 250 meV) for an annealing duration of 240s at 950°C , but the decreases in PL intensity and broadening of FWHM suggests degradation of the epitaxial quality. We noted that cycles of annealing (see Fig4 (a)) enhance the material quality for the shorter duration of annealing, in our case 30s. As a proof of material quality after intermixing, QWI was performed with the optimum parameters of 950°C and 30s. The samples were annealed for 2, 5 and 9 cycles to obtain the desired wavelengths of red (620 nm), orange (595 nm) and yellow (575 nm), respectively⁶⁻⁹. An efficient orange lasing around 608nm demonstrated for the laser structure annealed for 5 cycles at 950°C for the 30s, as shown in Fig 4(b). Fig4 (a), also shows that annealing for a longer duration (120s) and lower temperature (900°C) enhance QWI for few cycles of annealing (in this case 3), presented similar PL characteristics and surface morphology as that at 950°C for the 30 and 60s annealing duration.

Fig.5. (a) Room-temperature PL Peaks of InGaP/InAlGaP laser samples capped with Si_3N_4 and SiO_2 annealed at 800°C and 950°C for 1, 2, 3 and 4 cycles. (b) Peak PL emission spectra after 4 cycles of annealing.

We applied the novel QWI process for short duration of the 30s on Si_3N_4 capped dielectric samples and compared with SiO_2 capped samples of Fig.4. Samples are annealed for 1, 2, 3 and 4 cycles each of 30s duration, as shown in Fig.5 (a). We noticed no fracture of Si_3N_4 after 4 cycles of annealing and the surface shows no visible defects after etching the dielectric. QWI was improved in the samples capped with Si_3N_4 as compared to SiO_2 dielectric film, this is evident by the bandgap blueshift from red (~ 640 nm) to yellow (~ 590) for Si_3N_4 and red (~ 640 nm) to orange (~ 600) for SiO_2 capped samples as shown in Fig. 5 (b). Considering cumulative annealing time of 120s (4 cycles of 30sec) and one cycle of 120s, the short duration and multiple cycles of annealing is the key to enhance the QWI. In our case, we noticed an increased blueshift ~ 25 nm for 4 cycles of the 30s, as compared to one cycle of 120s for the Si_3N_4 capped dielectric film at 800°C . Using this method wavelength tunability from ~ 640 nm to ~ 555 nm (~ 300 meV) is demonstrated for both the capping samples for multiple (~ 14 -17) cycles of annealing of short duration. Details of this characterization will be reported elsewhere.

4. CONCLUSION

We presented a thermally induced dielectric strain on quantum well intermixing (QWI) technique on a tensile-strained InAlGaP/InGaP red laser structure that induces the large degree of bandgap blueshift. A maximum bandgap shift of ~250-300 meV with an original wavelength of 640nm is observed in this material system with a single and bilayer of the dielectric film for short duration and multiple cycles of annealing. The fabricated QWI samples were characterized for electroluminescence and photoluminescence which indicated high-quality of the material.

5. ACKNOWLEDGEMENTS

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