Large Post-growth Energy Band-gap Tuning of The 980 nm High Power Laser Diode Structures

Tang Xiaohong[1*], Qiao Zhongliang[1, 3], Lim Peng Huei[2] and Bo BaoXue[3]

[1] OPTIMUS: Photonics Center of Excellence, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
[2] Temasek Laboratories, Nanyang Technological University, Singapore
[3] State Key Laboratory on High Power Semiconductor Lasers, Changchun University of Science and Technology, 130022, Changchun, Jilin, P.R. China
[*]The corresponding author, email: exhtang@ntu.edu.sg

Abstract–Post-growth energy band gap turning of the 980nm high power semiconductor laser structure through the quantum well intermixing (QWI) has been investigated. The QWI was carried out by depositing a thin film of SiO_2 on top surface of the laser structure samples and followed by high temperature annealing. By using the QWI technique, band gap energy of the 980nm quantum well structure has been blue shifted up to >220nm. High quality of the laser diode structure after the QWI has been confirmed by fabricating the high performance semiconductor lasers using the wafer after the QWI.

1.Introduction

Post-growth energy band gap tuning of the quantum well structures has very important application in developing novel photonic devices. Selective area quantum well intermixing (QWI)[1] has been reported as the post-growth band-gap energy tuning technique for developing photonic integrated circuits (PICs) and quantum well infrared photo-detectors (QWIPs). Comparing to other techniques, QWI is very attractive for the post-growth energy band gap tuning the semiconductor nanostructures because of its simplicity and effectiveness. Semiconductor nanostructures, e.g. quantum wells and quantum dots, have been largely used for developing high performance novel electronic and optoelectronic devices. Post-growth energy band gap tuning of the AlInGaAs/InP quantum wells has been reported with their photoluminescence (PL) wavelength blue shift of 110nm after the QWI[2]; by capping with a Si_3N_4 layer and annealing at 800 ^oC, the blue shift of an InGaAs/InP QW reaches 145nm[3]; The quantum wells/dots intermixing for the post-growth bandgap energy tunings have been intensively investigated[4-9], and very large energy band gap tuning has been received from the InGaAsP/ InGaAs/GaAs material system based QW and QD structures.

Different intermixing techniques for the post-growth band gap energy tuning of the semiconductor QW structures and QD structures have been developed[8]. Among the different intermixing techniques, quantum well intermixing by depositing a dielectric capping layer on top of the samples followed by rapid thermal annealing (RTA) is very attractive since it does not require sacrificial layers and avoids damaging the sample-surface by the high energy ion beams bombardment with other intermixing techniques.

In this research, the post-growth band gap energy tuning of a 980nm InGaAs/InGaAsP single quantum well high power laser diode structure through the QWI has been studied. The QW intermixing was carried out by using a SiO_2 layer to cap the sample and followed by rapid thermal annealing (RTA) at high temperature. A remarkably large blue shift up to 220nm of the QW laser structure has been achieved after the QW intermixing. This is the largest blue shift of 980nm QW laser structure through QW intermixing reported so far, which can be used for developing a multi- wavelength high power laser chip.

2. Experiment

The samples used in this study were $In_{0.24}Ga_{0.76}As_{0.52}P_{0.48}/In_{0.24}Ga_{0.76}As/GaAs$ single quantum well structures for a 980nm high power laser diode structure. Table 1 summarizes the layer structure of the samples used in this study.

Table 1 epi-layer structure of the 980nm InGaAs/InGaAsP SQW for QWI

Material	Thickness (nm)	Doping cm^{-3}	Remark
$Ga_{0.76}In_{0.24}As_{0.52}P_{0.48}$	100	undoped	waveguide
$Ga_{0.76}In_{0.24}As$	8	undoped	active layer
$Ga_{0.76}In_{0.24}As_{0.52}P_{0.48}$	182	undoped	waveguide
n-$Ga_{0.51}In_{0.49}P$	1500	$\sim 5x10^{17}$	Cladding
n-GaAs	500	$\sim 5x10^{17}$	Buffer
n-GaAs substrate		$>1x10^{18}$	Substrate

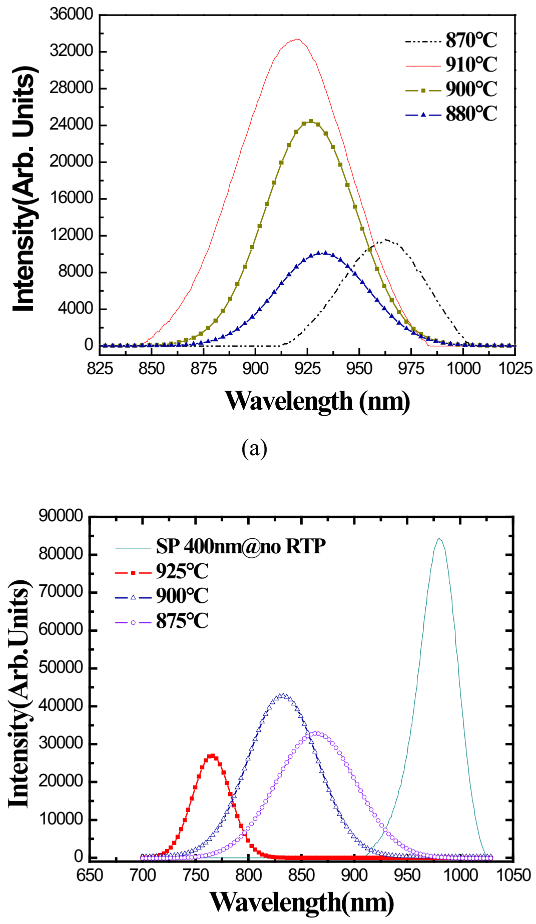
The QW structure was grown on the (100)-oriented GaAs (Si-doped: $\sim 1\times 10^{18}cm^{-3}$) substrates by metal organic vapor phase epitaxy (MOVPE). Before growing the QW structure, a 500nm GaAs (Si-doped:$\sim 5\times 10^{17}cm^{-3}$) buffer layer was grown at 720℃ to suppress the surface defect of the substrate, and then, a 1500nm n-type $Ga_{0.51}In_{0.49}P$ cladding layer (Si-doped:$\sim 5 \times 10^{17}cm^{-3}$) was grown at 680°C. After that, a 182nm undoped $Ga_{0.76}\ In_{0.24}As_{0.52}P_{0.48}$ lower waveguide layer was grown at 700°C, followed by growing the 8nm $Ga_{0.76}In_{0.24}As$ single quantum well layer. It was grown at 710°C. Finally, the 100 nm $Ga_{0.76}In_{0.24}As_{0.52}P_{0.48}$ upper waveguide layer was grown at 700°C.

For carrying out the QWI for the sample, the SiO_2 thin layers were deposited on top of the sample by the ion plasma sputtering, respectively. During the SiO_2 sputtering deposition, the Ar gas flow was set at 28sccm, the plasma power was 180W, the substrate temperature was set at 100 °C and the deposition time was 44mins. After the SiO_2 deposition, the samples were then thermal annealed by an RTA at different temperatures for the QWI. The annealing time was fixed at 60s, which is shorter enough to minimize the surface decomposition of the sample during the QWI.

To measure the band-gap energy changes of the quantum well structure after the QWI, the blue shift of the photoluminescence (PL) emission of the quantum well structure after the QW intermixing has been measured and investigated. To investigate the effect of the QWI, different SiO_2 cap layer thicknesses and annealed at different temperatures for the QWI have been investigated. The PL measurements were carried out at room temperature by using an argon ion gas laser with a wavelength of 475 nm as the excitation source. The laser excitation power was kept the same for all the measurements. The emission signals from the samples were dispersed by a monochromator and detected by a Si detector.

3. Results and Discussion

Figure 1 shows the measured photo-luminescence spectra of the samples after the QWI with different annealing



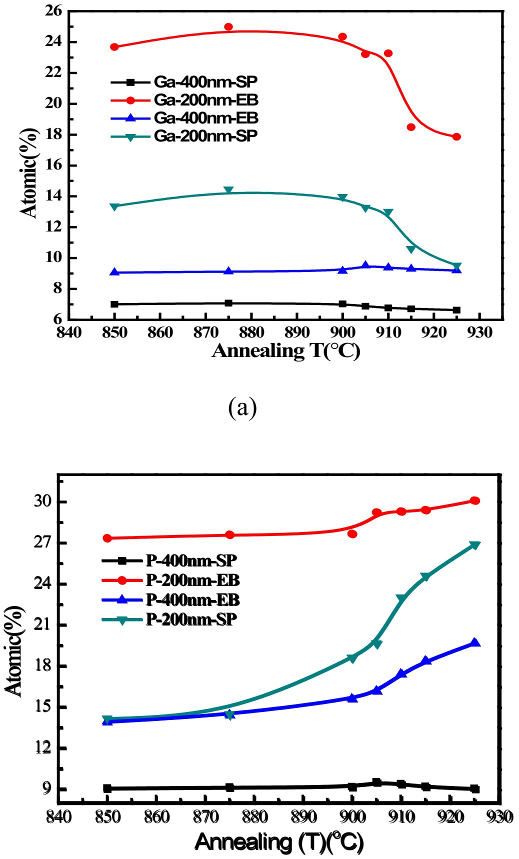
(a)

(b)

Fig.1. The measured photoluminescence (PL) spectra of the samples capped with different SiO_2 thickness (a) 200nm, (b) 400nm after intermix-ing at different annealing temperatures

temperatures. The SiO_2 cap layers with different thicknesses for the QWI were deposited by using the Ar plasma sputtering. Sample (a) was copped with 200 nm SiO_2 cap layer, while SiO_2 cap layer of samples (b) was 400 nm thick.

The shortest emission wavelength of sample (a) after the intermixing was measured at 919nm when the annealing temperature was at 880°C. The maximum blue shift of the emission wavelength of the samples after the intermixing was about 70nm. When the SiO_2 cap layer thickness was increased to 400nm, the shortest emission wavelength of the sample after the intermixing reached 760nm. The maximum blue shift of the sample after the intermixing reached 220nm after annealed at 925°C.



(a)

(b)

Fig. 2. The measured atomic percentage (gallium (a) and Phosphorus(b) of the sample by energy dispersive X-Ray spectroscopy (EDX) after the intermixing

Figure 2 shows the measured percentage of Ga element on top surface of the samples after the QWI. Fig.3(a) shows the changes of the Ga atoms on the samples' surface after the QWI with different annealing temperatures. It also compares the measured Ga atoms of the samples caped with 200 nm and 400 nm

SiO_2 layers deposited by using E-beam and sputtering, respectively.

The out-diffusion of gallium element of the sample after the intermixing will reduces the blue shift of the QW, while the out-diffusion of the arsenic element will increase the QW's blue shift. Out-diffusion of P element makes the samples blue shift stronger.

Figure 2 also shows the suppression of gallium and phosphorus atoms' diffusion with different thicknesses and different SiO_2 deposition methods. The different stabilities of Ga and P at different annealing temperature is the main reason that cause the PL wavelength blue shift.

It is well-known that sputter-deposited SiO_2 trends to be polycrystalline. The polycrystalline SiO_2 thin film has stronger suppression of the surface out-diffusion of the sample than that of amorphous SiO_2. At the same time, phosphorus element is much more volatile during the annealing process at high temperatures, especially, above the annealing temperature of 900°C. The thickness of the SiO_2 cap layer inevitably affects the out/in-diffusion of the phosphorus element. Increasing the SiO_2 thickness and reducing the quantity of pores will also increase the in-diffusion phosphorus, further blue-shifting the PL peaks.

808nm high power semiconductor lasers were fabricated from the samples with and without the QWI.

Figure 3 shows measured emission spectrum of the high power laser diode device fabricated from the wafer without QWI with the injection current above the threshold current. The device was measured lased at 808nm wavelength.

The device fabricated from the wafer after gone through the QWI was measured lasing at 792nm with injection current of 1.0A at room temperature. The QWI was carried out with the sample's SiO_2 cap layer of 500nm by sputtering and annealed at 800 ^oC.

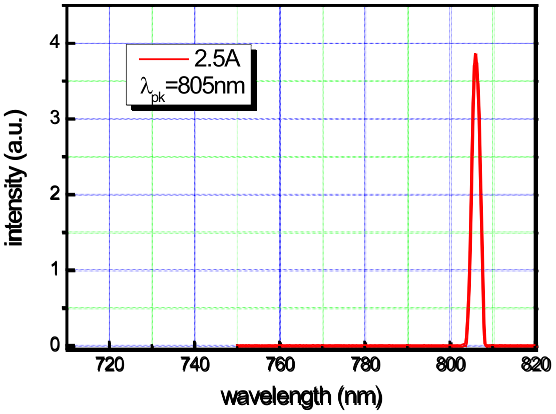


Figure 3 The measured emission spectrum of the high power laser diode fabricated form the wafer without QWI.

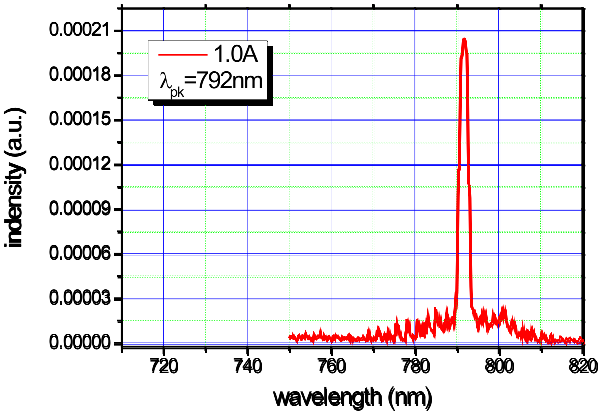


Figure 4 The measured emission spectrum of the high power laser diode fabricated form the wafer after the QWI.

It shows that lasing of the device fabricated from the wafer after the QWI has been received. The device performs well. But the lasing wavelength blue shift of the device with the QWI only about 16nm, which is limited. Further investigation is necessary.

4. Conclusion

Post growth energy band gap tuning of InGaAs/InGaAsP single quantum well 980nm high power laser structure through quantum intermixing has been investigated. The quantum well intermixing was carried out by depositing a thin layer of SiO_2 on top surface of the quantum well structure samples and followed by high temperature RTA annealing. Large blue shift of the sample's emission wavelength has been observed after the QWI with the 400 nm sputter deposited SiO_2 layer samples, the maximum blue shift of the quantum well structure's emission wavelength reaches up to 220nm after the intermixing. The blue shift of the sample after the intermixing was reduced when the SiO_2 cap layer thickness was reduced to 200nm.

Lasing has been received from the sample after the QWI and the emission wavelength was observed blueshited.

Acknowledgement

The authors wish to thank the Temasek Laboratories at Nanyang Technological University to award of a research grant to support this work.

References

1. B. C. Qiu, X. F. Liu, M. L. Ke, H. K. Lee, A. C. Bryce, J. S. Aitchison, J. H. Marsh, and C. B. Button, "Monolithic fabrication of 2× 2 cross point switches in InGaAs/InAlGaAs multiple quantum wells using quantum-well intermixing," IEEE Photon. Technol. Lett., vol. 13, no. 12, pp. 1292–1294, Dec. 2001.
2. Ko-Hsin Lee, Brendan Roycroft, James O'Callaghan, Chris L. L. M. Daunt, Hua Yang, Jeong Hwan Song, Frank H. Peters, and Brian Corbett, "Integration of AlInGaAs MQW Fabry–Pérot Lasers With Emission at Two Wavelength Ranges via Quantum-Well Intermixing", IEEE Photonics Technology Letters, Vol. 23, No. 1, January, 2011.
3. Yu-Peng An*, Yi-Ding Wang, Feng Cao, "Doped cap layer effect on impurity-free vacancy enhanced disordering in InGaAs/InP quantum well structures", Optica Applicata, Vol. XL, No. 1, 2010.
4. Deok Ho YEO, Kyung Hun YOON and Sung June KIM, "Characteristics of intermixed InGaAs/InGaAsP Multi Quantum well Structure", Jpn. J. Appl. Phys. Vol. 39(2000)pp. 1032-1034,Part 1,No. 3A, March 2000.
5. M.K. Lee, J.D. Song, J.S. Yu, T.W. Kim, H. Lim, Y.T. Lee1, "Intermixing behavior in InGaAs/InGaAsP multiple quantum wells with dielectric and InGaAs capping layers", Appl. Phys. A73, 357–360 (2001).
6. H. S. Djie,a) J. Arokiaraj, T. Mei, X. H. Tang, L. K. Ang, and D. Leong, "Large blueshift in InGaAs/InGaAsP laser structure using inductively coupled argon plasma-enhanced quantum well intermixing", J. Vac. Sci. Technol. B 21.4., Aug 2003.
7. Erik J. Skogena and Larry A. Coldren, "Multiple-band-edge quantum-well intermixing in the InGaAs/InGaAsP/InGaP material system", Applied Physics Letters 86, 241117 (2005).
8. Boon Siew Ooi, Teik Kooi Ong, and Oki Gunawan, "Multiple-Wavelength Integration in InGaAs/InGaAsP Structures Using Pulsed Laser Irradiation Induced Quantum Well Intermixing", IEEE Journal of Quantum Electronics, Vol. 40, No. 5, May 2004.
9. O. Hulko, D. A. Thompson, a, J. A. Czaban, and J. G. Simmons, "Quantitative analysis of compositional changes in InGaAs/InGaAsP quantum wells on GaAs induced by intermixing with a low temperature grown InGaP cap layer", Applied Physics Letters 89, 061915,2006.
10. M. N. Sysak, J. W. Raring, J. S. Barton, M. Dummer, D. J. Blumenthal, and L. A. Coldren, "A single regrowth integration platform for photonic circuits incorporating tunable SGDBR lasers and quantum-well EAMs," IEEE Photon. Technol. Lett., vol. 18, no. 15, pp. 1630–1632, Aug. 1, 2006