Spatial control based quantum well intermixing in InP/InGaAsP structures using ICP*

Zhao Jianyi(赵建宜)[1,†], Guo Jian(郭剑), Huang Xiaodong(黄晓东), Zhou Ning(周宁), and Liu Wen(刘文)

[1]Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, College of Optoelectronic Science and Engineering, Wuhan 430074, China
[2]Accelink Technologies Company, Ltd, Wuhan 430074, China

Abstract: This paper presents a new method based on spatial controlling in quantum well intermixing in InP/InGaAsP structures using ICP technology. The degree of bandgap energy shift in the same wafer can be controlled flexibly using masks with different duty ratios. With an optimal condition including ICP-RIE etching depth, SiO_2 deposition, and RTA process, five different degrees of blue-shift with maximum of 75 nm were obtained in the same sample. The result shows that our method is an effective way to fabricate monolithic integration devices, especially in multi-bandgap structures.

Key words: inductively coupled plasma; photonic integrated circuits; quantum wells; quantum well intermixing
DOI: 10.1088/1674-4926/33/10/106001 **PACC:** 8140T

1. Introduction

Bandgap control in the same wafer is the key technology used in the fabrication of monolithic photonic integrated circuits (PICs)[1]. The bandgap needs to be spatially controlled across a wafer in order to fabricate different devices such as lasers, modulators, and passive waveguides. Several technologies for bandgap control have been developed, such as selective epitaxial growth[2], butt-joints[3], and quantum-well intermixing (QWI)[4]. However, in a conventional QWI technique, it is indirect and complicated to get more than two different bandgaps. Usually several lithography and annealing processes are required[5]. This increases the complexity and potential instability for multiple annealing processes.

Argon plasma enhanced intermixing using an inductively coupled plasma (ICP) etcher is a common processing tool to create defects, which plays a key role in QWI as it promotes the inter-diffusion between quantum wells and barriers. Compared to other technologies such as impurity free vacancy diffusion (IFVD)[4], ion implantation[6], the low temperature grown InP cap,[7] and laser induced disordering[8], argon plasma exposure does not need high temperature annealing and is simple with good spatial selectivity. However, it is still complicated to get more than two different bandgaps, as mentioned before. Multi-lithography and multi-annealing are the common methods used to obtain more than two different bandgaps[5].

In this paper, we propose a new method based on the gray mask to control the intermixing degree of the quantum wells and barriers. Using this method we can get many different bandgaps as they are designed in the same wafer, which just needs lithography and annealing only once. Complexity reduced greatly. Furthermore, it can even be used to get a bandgap gradient structure, which is hard to obtain using the traditional method. Here, the effect of ICP etching, the duty ratio of the gray mask, annealing temperature, and time are discussed.

2. Experiment

The samples used in this study were grown by metal-organic chemical vapor deposition (MOCVD) on a (100) InP substrate. The structures of the multiple quantum well (MQW) can be seen in Fig. 1. Sample A consists of eight $In_{0.726}Ga_{0.274}As_{0.810}P_{0.190}$ quantum wells sandwiched between 1.24-μm InGaAsP barriers. The thickness of the well and the barrier are 5 nm and 10 nm, respectively. A 1.5-μm p-doped InP upper cladding layer and 200-nm P^+-doped InGaAs contact layer follow. Sample B has a 500-nm InP sacrificial layer on the top. The plasma source used in the experiment is an Oxford Plasmalab System 100.

350-nm-thick SiO_2 was deposited on the surface of the samples using PECVD acting as a blocking layer. Then the structures shown in Fig. 2 as gray graphics were transferred to it by lithography, as can be seen in Fig. 3(a). The width of the stripe is 1.5 μm and the duty ratio is from 0.5 to 1. The exposed area of the samples was bombarded by Ar plasma generated by an ICP etcher. The Ar plasma etched the sample and introduced defects around the etching face, as can be seen in Fig. 3(b). Next, rapid thermal annealing was carried out at a temperature of 650 ℃ for 4 min. The defects diffused into the quantum wells. If the diffusion length is less than the stripe width in the depth of the QW, it will allow uniform intermixing at the QW depth through overlapping of the defect diffusion fronts, as can be seen in Fig. 3(c). From TEM (transmission electron microscope) work on MQW structures with similar composition, this diffusion length was found to be 3 μm for 1-μm deep QWs[4],

* Project supported by the State Key Development Program for Basic Research of China (No. 2010CB327603) and the National High Technology Research and Development Program of China (No. 2011AA010304).
† Corresponding author. Email: jianyi.zhao@accelink.com
Received 7 March 2012, revised manuscript received 23 April 2012

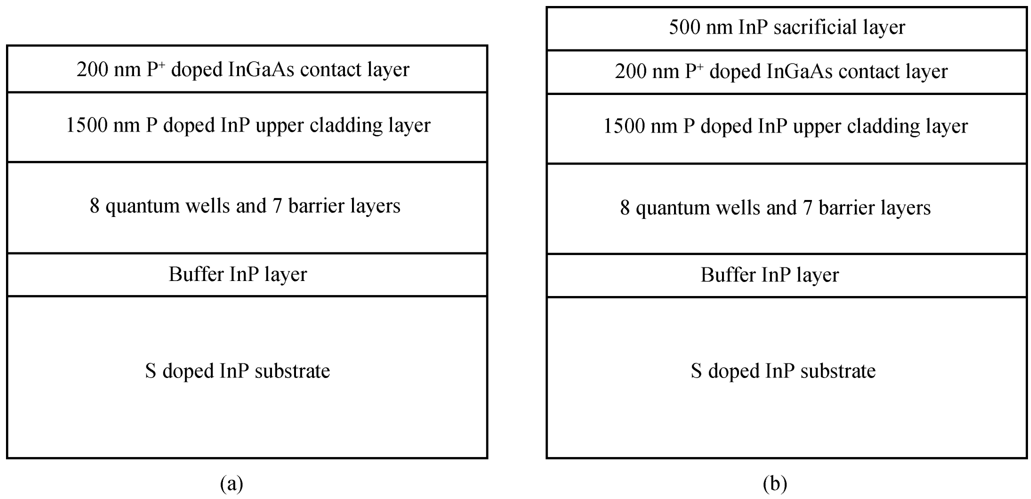

Fig. 1. Structure of (a) sample A and (b) sample B.

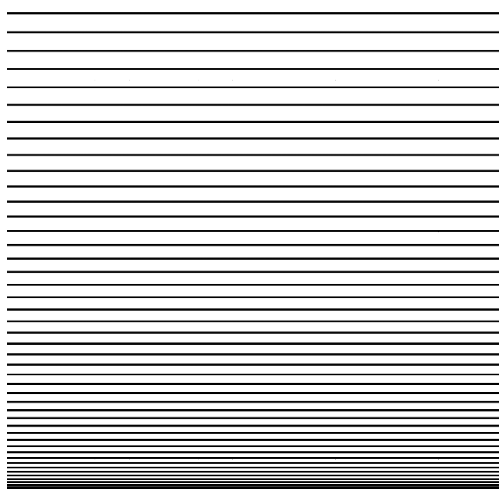

Fig. 2. The gray mask.

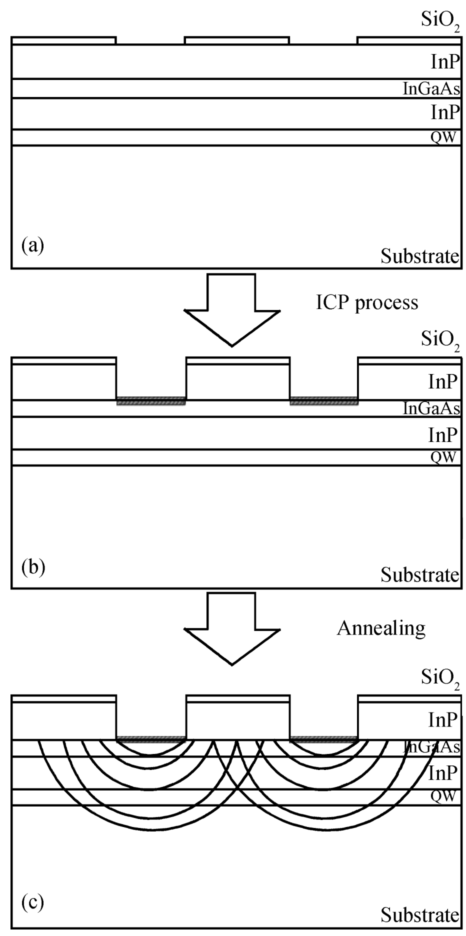

Fig. 3. A schematic diagram showing experimental process.

so the defects would be uniform. The properties of quantum wells after annealing were determined by using a photoluminescence (PL) system.

3. Results and discussions

As can be seen in Fig. 4(a), the PL results of sample A, in the same wafer with a different duty ratio of SiO_2, the wavelength shift almost increases with the duty ratio in direct proportion. Like most QWI experiments, the intensity decreases with the wavelength shift as the effect of the defects and annealing process in the QWs. However, in order to obtain the uniformity in the same area, we use HCl and H_2SO_4 solution to destroy the QWs in the exposed area and then the QWs under the SiO_2 mask are measured by PL. The results are presented in Fig. 4(b). The wavelength shift is not the same as that in the corresponding exposed area. The intensity is very weak because of the effect of solution as it is sideways etched to the QW under the mask. The results indicate that the diffusion length is shorter than the stripe width in the depth 1-μm high than the QW.

In order to solve the problem, we introduce a sacrificial layer on the top of the InGaAs layer. It has two main advantages. First, it acts as the defect generator and avoids damage to the structure under the InGaAs layer. When the process is finished, it can be removed by HCl solution easily. Second, as it is on the top of the InGaAs layer, enlarging the distance between the sacrificial layer and QWs then makes the diffusion length larger. And the uniform QWI is easier to obtain.

The results of the modified experiment are presented in

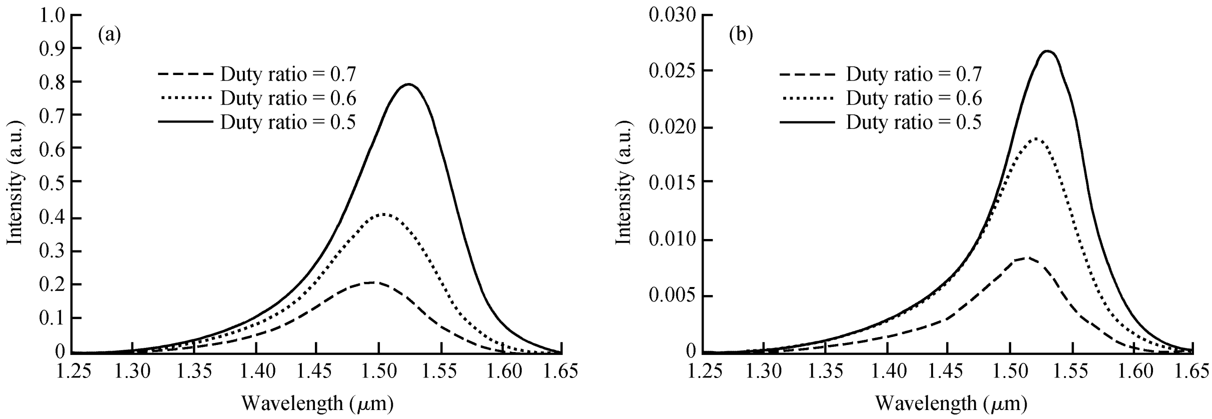

Fig. 4. (a) PL spectra of sample A with three different duty ratios before wet etching. (b) PL spectra of sample A after wet etching.

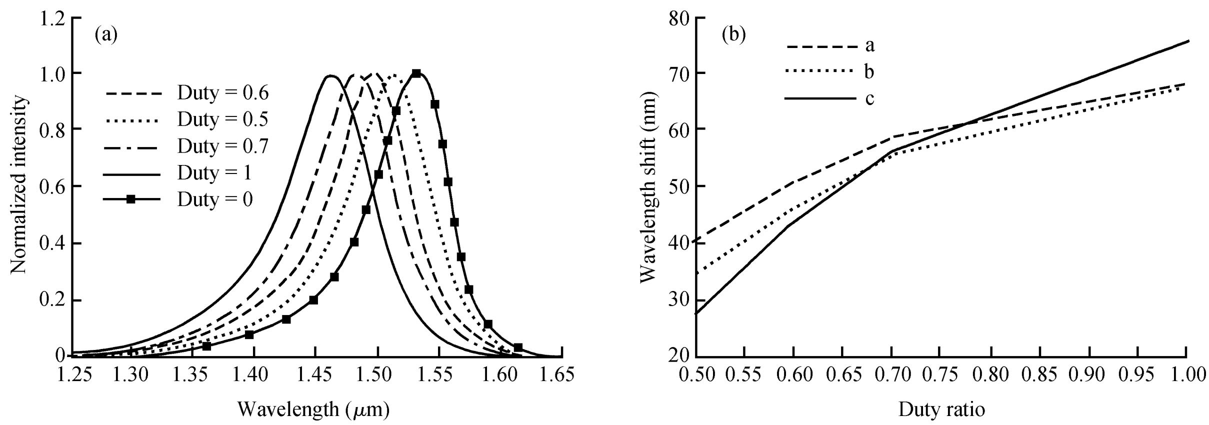

Fig. 5. (a) PL spectra of sample B with five different duty ratios. (b) Wavelength shift dependency on the duty ratio.

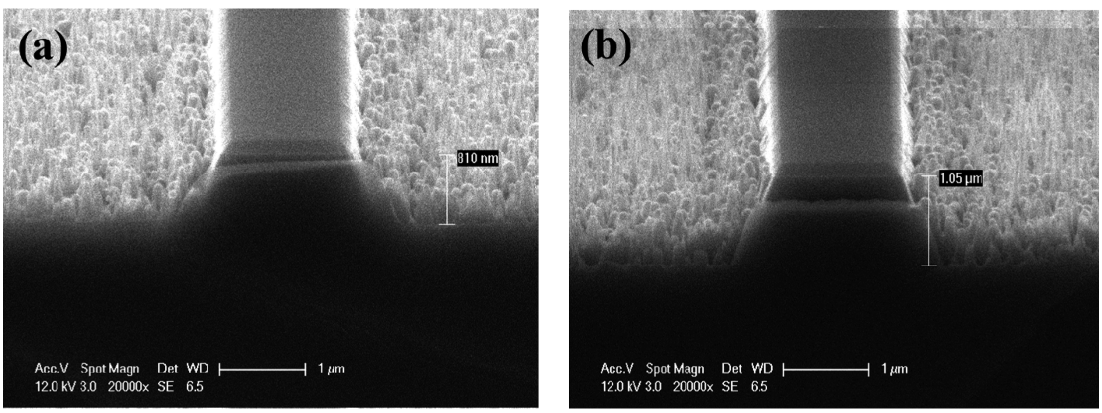

Fig. 6. The etching depth in the same sample with different duty ratios. (a) Duty = 0.7. (b) Duty = 0.8.

Fig. 5. Here, we use the normalized intensity, as the InGaAs layer is thinner than designed, in some areas it is broken by the ICP etch. When we use the HCl solution to remove the sacrificial layer, it gets into the InP layer under the InGaAs layer, so the layers above the QW are not the same. The normalized intensity is more suitable here. The right-most curve is the sample covered with SiO_2 avoiding the ICP process.

The wavelength shift varies with the duty ratio in different areas in the same wafer, which is presented in Fig. 5(b). In the ICP process, optimized experimental parameters are used: 50 sccm Ar flow rate, 12 mTorr chamber pressure, 200 W RF power, and 1000 W ICP power. However, the etching time in sample (a) is 4 min and in sample (b) is 3 min. The chamber pressure is 9 mTorr in sample (c) with 4 min. As can be seen in Fig. 5(b), the maximum wavelength shift is about 75 nm, and we find that in sample (a) and sample (b) in low duty ratio conditions, the wavelength shift is larger for a longer time, but in high duty ratio conditions the difference is smaller. This is because that in the etching process, the etching depth is not only related to the etching time but also to the duty ratio. As the etching here is a totally physical process, the residue is non-volatile. The etching rate is slower in the narrow slot as compared to the large etching area, which can be seen in Fig. 6.

So in the low duty ratio condition, the defect density is not saturated; the wavelength shift is in proportion to the etching time. But in the high ration condition, the defect density is saturated and the wavelength shift is the same. In sample (c) the chamber pressure is lower than sample (a). In the high duty ratio condition, the defects are in proportion to the ion energy. But in the low duty ratio condition, there is more residue from the mask and InP than in sample (a) and blocks the Ar plasma bombardment. So the wavelength shift is less than sample (a). In three samples, the curves have the same trend that the gradient is higher in low duty ratio conditions. We think that the slot effect which blocks the Ar plasma bombardment in the etching process is the main reason, which has been proved in Fig. 6. The experiment result shows that using a gray mask to control the wavelength is possible.

4. Conclusion

A technology for band gap controlling more than two bandgaps in the same device based on QWI has been developed. The experiment result shows that under careful mask duty ratio definition, the wavelength shift can be easily and exactly controlled. And we also found that the wavelength shift is not linear to the duty ratio, and the slot effect which blocks the Ar plasma bombardment in the etching process is the main reason. If we use gas with a smaller molecular weight like N_2[9], the performance will be better.

References

[1] Raring J W, Skogen E J. Widely tunable negative-chirp SG-DBR laser/EA-modulated transmitter. J Lightwave Technol, 2005, 23(1): 80

[2] Aoki M, Sano H, Suzuki M. Novel structure MQW electro-absorption modulator/DFB laser integrated device fabricated by selective area MOCVD growth. Electron Lett, 1991, 27: 2138

[3] Li B X, Hu X H, Zhu H L. Integrated electro absorption-modulated DFB laser by using an improved butt-joint method. Chinese Optics Letters, 2004, 2(4): 226

[4] Ooi B S, Street M W, Helmy A S. Selective quantum well intermixing in GaAs-AlGaAs structures using impurity free vacancy diffusion. J Quantum Electron, 1997, 33(10): 1784

[5] Jain S R, Sysak M N, Kurczveil G. Integrated hybrid silicon DFB laser-EAM array using quantum well intermixing. Opt Express, 2011, 19(14): 13692

[6] Xia W, Pappert S A, Zhu B. Ion mixing of III–V compound semiconductor layered structures. J Appl Phys, 1992, 71: 2602

[7] Haysom J E, Poole P J, Aers G C. Quantum intermixing caused by non stoichiometric InP. IPRM, 2000: 56

[8] Mclean C J, McKee A, Lullo G. Quantum well intermixing with high spatial selectivity using a pulse laser technique. Electron Lett, 1995, 31: 1284

[9] Peng S H, Zhang X, He J J. Nitrogen plasma enhanced quantum well intermixing in InGaAsP/InP laser structure. Communications and Photonics Conference and Exhibition (ACP), 2009: 1