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## Luminescent Characteristics of InGaAsP/InP Multiple Quantum Well Structures by Impurity-Free Vacancy Disordering

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### ABSTRACT

InGaAsP/InP multiple quantum wells have been prepared by Impurity-Free Vacancy Disordering (IFVD). The luminescent characteristics was investigated using photoluminescence (PL) and photoreflectance (PR), from which the band gap blue shift was observed.  $\text{Si}_3\text{N}_4$ ,  $\text{SiO}_2$  and SOG were used for the dielectric layer to create the vacancies. All samples were annealed by rapid thermal annealing (RTA). The results indicate that the band gap blue shift varies with the dielectric layers and annealing temperature. The  $\text{SiO}_2$  capping was successfully used with an InGaAs cladding layer to cause larger band tuning effect in the InGaAs/InP MQWs than the  $\text{Si}_3\text{N}_4$  capping with an InGaAs cladding layer. On the other hand, samples with the  $\text{Si}_3\text{N}_4$ -InP cap layer combination also show larger energy shifts than that with  $\text{SiO}_2$ -InP cap layer combination.

### INTRODUCTION

In fabricating luminescent devices for integrated optoelectronic and photonic application, InGaAsP/InP multiple quantum well (MQW) structures have attracted research interests. Post-tuning of optical band gap energy can be achieved from these MQW structures, which posses the advantage to avoid the complicated post growth processing. Several technical approaches have been explored to achieve this purpose, including (1) Impurity Induced Disordering (IID) [1,2], (2) Implant Induced Composition Disordering (IICD) [3-6], and (3) Impurity-Free Vacancy Disordering (IFVD) [7,8]. Among them, IFVD technique shows more promising because it can keep high crystal quality and low optical propagation loses as well as it does not introduce free-carrier concentration. IFVD, utilizing a dielectric layer such as  $\text{SiO}_2$  and  $\text{Si}_3\text{N}_4$  as Ga sink at elevated temperature, could result in the redistribution of Ga vacancies in MQWs to enhance the quantum well intermixing and thus to enhance the luminescence [9,10].

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In this paper, a systematic investigation on luminescent characteristics of InGaAsP/InP MQW system using SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub> and SOG (spin on glass) as dielectric layers in IFVD is reported. Photoluminescence (PL) was measured by a Fourier Transform Infrared (FT-IR) PL system. Photorefectance (PR) measurements on these samples were used to investigate further the behavior of band gap blue shift. To our knowledge, there was no report published with measuring band gap blue shift by PR for this material system yet. We found that the different combinations of cladding layer and dielectric layer, such as InP-SiO and InP-SiN, also affect the band gap luminescent characteristics, which was also rarely reported.

## EXPERIMENT

Two typical samples were chosen in this paper. Both samples A and B are InGaAsP/InP laser structures, consisting of three quantum wells, designed to emit at wavelength of 1.57  $\mu\text{m}$  and 1.55  $\mu\text{m}$ , respectively. They were grown by Gas Source Molecular Beam Epitaxy (GSMBE). The detail structures of samples are shown in Table 1, in which "1.15Q" means "InGaAsP layer with the bandgap wavelength of 1.15  $\mu\text{m}$ ", and "ud" does "un-doped". Sample A was cut and divided into three groups with capped dielectric layers of SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub> by PECVD and SOG by spin coating at 3000 rpm for 45 second. The thickness of all the dielectric layers is about 200 nm. Samples with the SOG cap were then baked at 200 °C for 2 hours under pure nitrogen ambient protection. Sample B was divided into two groups remarked B1 and B2. B2 was etched InP cladding layer away using corrosive solution (HCl:H<sub>3</sub>PO<sub>4</sub>=1:1). Then samples B1 and B2 were deposited SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub>, respectively, by PECVD. The thickness is also about 200nm.

**Table 1.** Schematic layer structure of the InGaAsP/InP MQW samples studied.

Sample A			Sample B		
He*-InP	p=1e18	100nm	100nm	InP	(ud)
InP	p=6e17,	25nm	5nm	InGaAs	(ud)
1.15Q	InGaAsP	p=5e17, 80nm	200nm	InP	p=1e18
1.24Q		70nm	200nm	InP	p=5e17
1.58Q		5nm	40nm	He* InP	p=5e17
1.24Q		10nm	5nm	InP	p=5e17
1.58Q		5nm	100nm	1.15Q	p=5e17
1.24Q		10nm	60nm	1.24Q	(ud)
1.58Q		5nm	3*5nm	QW's ; 2*10nm Barriers (QW~In <sub>0.758</sub> GaAsP <sub>0.17</sub> )(Barrier-In <sub>0.758</sub> GaAsP <sub>0.475</sub> )	
1.24Q		70nm	30nm	1.24Q	(ud)
1.15Q	n=5e17	80nm	30nm	1.15Q	n=5e17
InP	n=1e18	500nm	500nm	InP	n=1e18
n+ InP substrate			n+ InP Substrate		

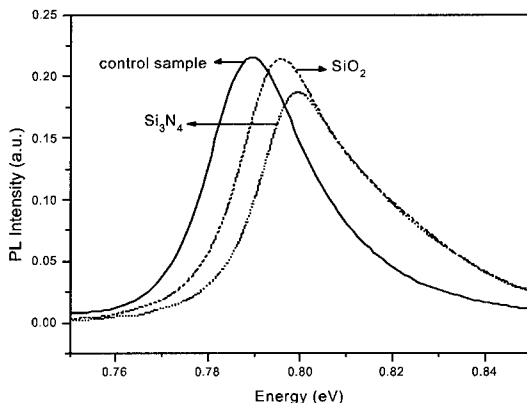
After the GSMBE growth, samples were then annealed in a rapid thermal annealing (RTA) furnace at the temperature ranged from 650 °C~850 °C in 50 °C steps. The annealing time for all samples was kept for 30 seconds. During the RTA the samples were covered with a piece of

semi-insulating-GaAs face to face to minimize the decomposition of InP and possible contamination. All annealing processing are under the pure nitrogen protection.

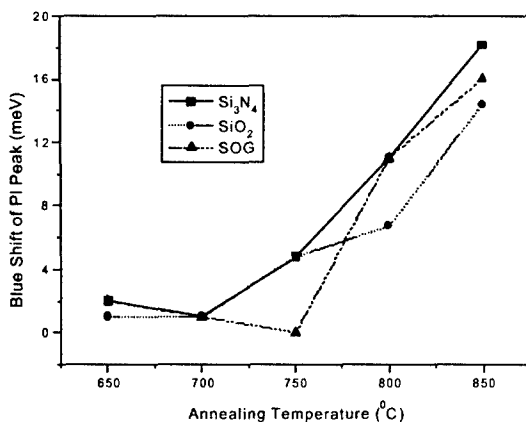
Photoluminescence measurements were performed at the temperature 300K. The excitation source was an Argon ion laser with the wavelength of 514.5 nm. The Photoreflectance (PR) spectra were measured at the optoelectronic laboratory of Nankai University. The modulation source was a He-Ne laser with the wavelength of 632.8nm.

## RESULTS AND DISCUSSION

Room temperature PL spectra are shown in Figure 1 for the as-grown sample A and disordered InGaAsP multi-quantum well structures after RTA at 800<sup>0</sup>C for 30s with SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub> encapsulating layer, respectively. The peak position of the PL spectrum for the as grown sample A is at 1.571 μm (0.789 eV), corresponding to the electron transition from the first level of electronic subband to the first level of heavy hole (E1-HH1) and light hole subband (E1-LH1). From the figure 1, we can find that the band gap blue shift depends on the dielectric layer. The sample A with a Si<sub>3</sub>N<sub>4</sub> capped layer obtained larger blue shift. In order to find the dependence of the band gap blue shift on the annealing temperature, the samples covered with Si<sub>3</sub>N<sub>4</sub>, SiO<sub>2</sub> and SOG were annealed at the temperature of 650, 700, 750, 800 and 850<sup>0</sup>C, respectively. Figure 2 shows the annealing temperature dependence of band gap shift. It can be observed that the band gap of PL peak varies with the RTA temperature. For low annealing temperature range of 650~750<sup>0</sup>C, the PL peak has little change, however, when the annealing temperature was beyond 750<sup>0</sup>C, the PL peak moves to short wavelength evidently.

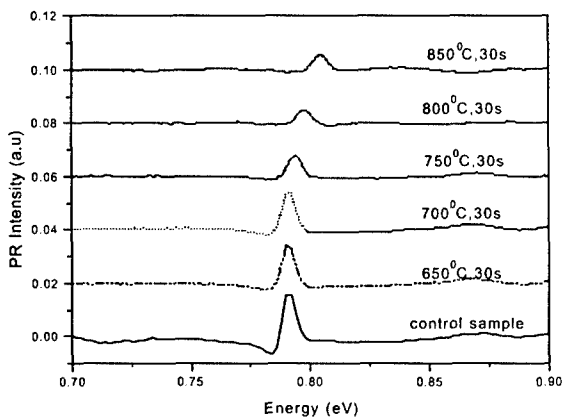


**Figure 1.** The PL spectra of the control sample and SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub> covered samples.



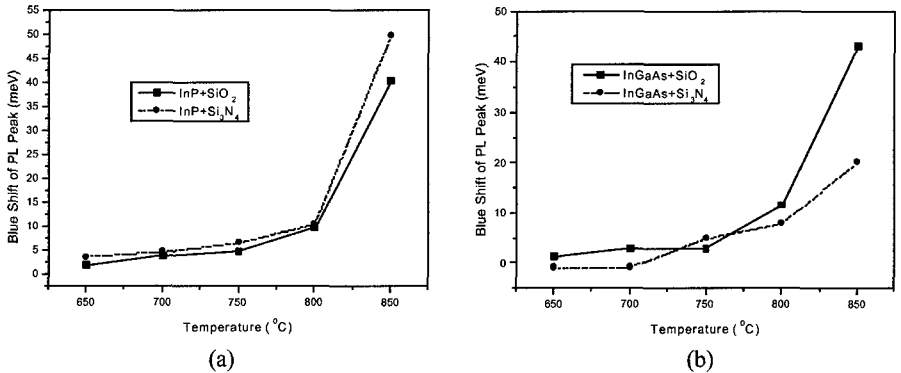
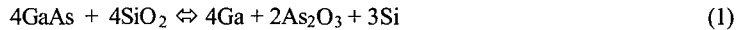
**Figure 2.** The temperature dependence of blue shift for different dielectric covered samples.

On the other hand, we also performed photoreflectance (PR) measurements in accordance with the results of PL spectra, as shown in Figure 3. It shows that PR results are consistent with the PL results. This indicates that PR can be used as a supplementary way to study the luminescent characteristics of the band gap shift. Furthermore, PR spectra can provide some other information, for example, some detailed data about different layer luminescent characteristics through analyzing PR spectra, which to be done in a separate paper.



**Figure 3.** Band gap blue shift measured by PR with different annealing temperature.

In order to find the effects on the combination of the cladding layer and dielectric covered layer, the annealing temperature dependence of the bandgap blue shift for sample B1 and B2 with different dielectric layers were further studied, based upon the PL data. Sample B1 has an InP cladding structure, and sample B2 has an InGaAs cladding layer. Both samples B1 and B2 have the same MQWs except for the cladding layer. These two types of samples were measured under the same experimental condition, to examine their band gap blue shift. Figure 4 shows the dependences of the blue shift PL peak on the annealing temperature, caused by different covered layer of  $\text{Si}_3\text{N}_4$  and  $\text{SiO}_2$ , respectively. It can be observed that the induced blue shift from the sample with the InP- $\text{Si}_3\text{N}_4$  combination is larger than that with the InP- $\text{SiO}_2$  combination. For example, the blue shift of the sample with the InP- $\text{Si}_3\text{N}_4$  cap layer combination reaches 50 meV at  $850^\circ\text{C}$ , but the blue shift of the sample with the InP- $\text{SiO}_2$  cap layer combination is only 40 meV at the same annealing temperature. On the other hand, the combination of InGaAs- $\text{Si}_3\text{N}_4$  covered layer caused 20 meV, however the combination of InGaAs- $\text{SiO}_2$  reached 43 meV. From these results, we can conclude that the combination layer of InP- $\text{Si}_3\text{N}_4$  or InGaAs- $\text{SiO}_2$  can create larger band gap blue shift than the combination of InP- $\text{SiO}_2$  and InGaAs- $\text{Si}_3\text{N}_4$  ones. The reason for these experimental results is not very clear, but in our opinion, it can be explained as follow: The vacancies are produced in both group III and V. It is known that in GaAs material the following reactions are prompted to produce large number of vacancies at the interface:



**Figure 4.** The temperature dependences of blue shift for the samples with (a) InP- $\text{SiO}_2$  and InP- $\text{Si}_3\text{N}_4$  combination layers, and (b) InGaAs- $\text{SiO}_2$  and InGaAs- $\text{Si}_3\text{N}_4$  combination layers.

Our results indicate that the vacancies generated by the InP- $\text{SiO}_2$  combination are less than that by the InGaAs- $\text{SiO}_2$  combination layers because of the absence of Ga. As for the group V vacancies, we can not provide the detailed reactions as to how the vacancies are produced. This may be the reason for the effects on the combination of the cladding layer and dielectric layers.

## CONCLUSION

In conclusion, we have studied the dependence of the band gap blue shift on the annealing temperature and dielectric layers from the InGaAsP/InP multiple quantum wells prepared by Impurity-Free Vacancy Disorder (IFVD). Both PL and PR results, which are consistent each other, showed that this band gap blue shift increases with the annealing temperature for all samples. To our knowledge, this is a first report on the band gap blue shift measured by PR. Our results indicate that PR can also be used as a supplementary way, in addition to PL, to study the band gap blue shift. On the other hand, to obtain larger energy shift the optimal selected cap layer combination is necessary. From our experiments the combination of InP-Si<sub>3</sub>N<sub>4</sub> or InGaAs-SiO<sub>2</sub> is better than the combination of InGaAs-Si<sub>3</sub>N<sub>4</sub> or InP-SiO<sub>2</sub>.

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