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Ion-implantation-induced Intermixing of Double Quantum Wells with Different Emission Wavelengths

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Abstract: In this work, phosphorus ion-implantation-induced intermixing of InGaAsP double quantum wells (DQWs) with different emission wavelengths was investigated by photoluminescence (PL) spectrum and cross-sectional transmission electron microscopy (TEM). After thermal annealing under specific conditions, the PL showed that the PL peaks of both wells always remain well separate under the condition of a low implanting dose (less than $7\times10^{11}/cm^2$), the bandgap blue-shift for each well appears a maximum as the implantation doses are increased from 10^{11} to $10^{12}/cm^2$, and the blue-shift from the upper quantum well (QW) is larger than that from the lower QW under the same conditions of implantation and annealing. When the ion dose is $10^{12}/cm^2$, the PL peak of the upper QW is nearly negligible and the peaks from DQWs appear to combine together as one peak. Comparing as-grown sample with annealed sample appearing maximum blue-shift by cross-sectional TEM, the boundaries of annealed sample between wells and barriers become vague, indicating that the ion implantation results in a total intermixing of two wells.

Key words: phosphorus ion implantation; double quantum wells; quantum well intermixing

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1 Introduction

Quantum well intermixing (QWI) induced by ion implantation is an attractive technique to modify the bandgap of QW in the photonic integrated circuits (PICs) and optoelectric integrated circuits (OEICs) applications due to its remarkable superiorities, such as the selectivity of ion, implanting region, the concentration and depth of implanting ion, are easy to control and manipulate. After implantation and rapid thermal annealing (RTA), defects generated by implantation enhance the interdiffusion of constituent atoms of quantum wells and barriers[1~11]. Generally, after intermixing, the efficient bandgap of intermixed region has an increasing, and the PL peak of intermixed region would be blue-shift than that of as-grown[2, 4~6]. For InGaAsP QW structure, Ga, As, and P ion are often selected as the implanting ions to induce QWI and create bandgap blue-shift, because they could not introduce impurity to target materials[2, 7, 10~15].

For a given ion energy, the degree of intermixing depends on the implantation dose, RTA temperature and time. The intermixing effect could be stronger with increasing implantation dose or annealing temperature and duration[14]. However, the lower dose implantation is more significant in achieving the smaller implantation damage and keeping the better crystal quality of QWs structures. In order to reduce damaging the QWs, the distribution of all

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vacancies generated by ion implantation should be closer to the well, but not cross the well.

For multiple quantum wells (MQWs), there are many reports on influence of QWI by ion dose, annealing conditions because they have only one emitting wavelength, however, the intermixing degree of each well is not likely to clearly understand and few papers have reported on it. In the letter, we investigated the intermixing effect of InGaAsP DQWs with different emission wavelengths induced by phosphorus ion implantation by means of PL spectrum and cross-sectional TEM.

2 Experiments

The samples investigated in this work were grown by gas source molecular beam epitaxy (GSMBE), they are InGaAsP double quantum well (DQW) structures with different emission wavelengths, as shown in Fig. 1. It can be seen from Fig. 1 that the emission wavelength of the upper QW is 1.52 μm and that of the lower QW is 1.59 μm.

p-InP($p=5\times10^{19}/cm^3$)	100 nm
1.15 μm $In_{0.82}Ga_{0.18}As_{0.40}P_{0.60}$($p=5\times10^{17}/cm^3$)	80 nm
1.24 μm $In_{0.76}Ga_{0.24}As_{0.525}P_{0.475}$(un-doped)	20 nm
1.52 μm $In_{0.61}Ga_{0.39}As_{0.86}P_{0.14}$	5 nm
1.24 μm $In_{0.76}Ga_{0.24}As_{0.525}P_{0.475}$(un-doped)	20 nm
1.59 μm $In_{0.57}Ga_{0.43}As_{0.94}P_{0.06}$	5 nm
1.24 μm $In_{0.76}Ga_{0.24}As_{0.525}P_{0.475}$(un-doped)	20 nm
1.15 μm $In_{0.82}Ga_{0.18}As_{0.40}P_{0.60}$($n=5\times10^{17}/cm^3$)	80 nm
n-InP ($n=5\times10^{19}/cm^3$)	150 nm
n-InP substrate	

Fig. 1 Structure of InGaAsP DQW with the same thickness of 5 nm, the emission wavelengths of two wells are 1.52 μm (the upper QW) and 1.59 μm (the lower QW), respectively.

The samples were divided into 5 mm × 5 mm squares. Considering the nonuniformity of GSMBE growth, the PL measurement of each square was performed at room temperature, and we picked out some squares with the same PL spectrum from them as experimental preparation, then, the phosphorus (P) ion implantation was carried out at the energy of 120 keV with different dose (from 1×10^{11} to $1\times10^{12}/cm^2$), the temperature of implantation is at room temperature, and the angle of incidence is about 10° deviation from normal of target plane. After implantation, all samples were covered with InP wafer face to face, then performed RTA at 700 ℃ for 30 s under N_2 surroundings. All annealed samples were once again put through PL measurement at room temperature.

The cross-sectional region of each well in DQWs was characterized by TEM. There are two ion thinning squares, one of which is as-grown sample, the other is annealed square with the implanted dose $7\times10^{11}/cm^2$. And both of them were characterized in the crystal structure and boundary of QW region by cross-sectional TEM.

3 Results and Discussion

The parameters about P ion implantation were designed by using TRIM-2000 simulation programme. The implanted vacancy distribution is shown in Fig. 2. As can be seen, the maximum of the vacancy density in the distribution is located at around 100 nm depth, and the far end edge of the minimum vacancy density in the distribution is at about 200 nm depth, which is closer to the upper well. The distribution of vacancies chiefly concentrates in the region from 50 nm to 150 nm under the surface of the sample, which implies that few damages occur in the regions of wells.

Fig. 3 shows the comparison of PL spectra of

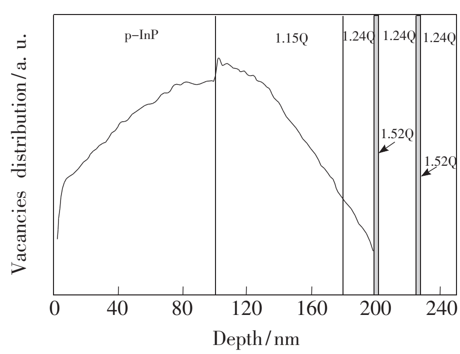

Fig. 2 Distribution of vacancies generated by 120 keV phosphorus ion implantation as a function of depth by TRIM-2000 simulation

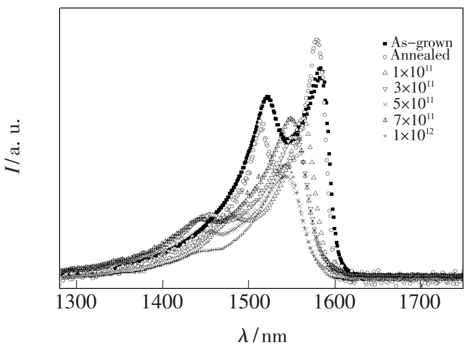

Fig. 3 Comparison of PL spectra of as-grown and phosphorus ion implanted samples for different ion doses from 1×10^{11} to $1 \times 10^{12}/cm^2$

as-grown sample, direct annealing sample, and implanted samples. Under the condition of low dose (less than $7 \times 10^{11}/cm^2$), the PL peaks of both wells always remain well separate, and the blue-shift of PL peak from the upper QW is larger than that from the lower QW as the implantation dose increasing. When the ion dose is $1 \times 10^{12}/cm^2$, the intermixing degree of 1.59 μm QW promptly enhance, the PL peak from the lower QW shifts to short wavelength more than that from the upper QW, which is nearly negligible, the peaks from DQWs appear to combine together as one peak. These show that the ion implantation with a low dose (~ $10^{11}/cm^2$) chiefly induces intermixing of the upper well.

Appearing two peaks or one peak in PL spectrum in different case is determined by the distance between two wells. If the distance is far, two wells could not form coupling under the excited states, and we can see two peaks appearing in PL spectrum, if not, we can see one peak. The defects generated from ion implantation enhance the interdiffusion of constituent atoms of wells and barriers in the course of rapid thermal annealing, the process also make interfaces between wells and barrier more near. So, as the ion implanting dose increasing, the degree of QWI is more and more stronger at the same conditions of annealing, and the PL peaks also change from two peaks to one peak.

However, the damage generated from ion implantation can not be ignored, it lowers the optical quality, especially, the PL peak from the upper QW slowly disappear as the ion dose increasing.

The bandgap blue-shifts of PL peaks of samples induced by p ion implantation with dose from 1×10^{11} to $1 \times 10^{12}/cm^2$ are summarized in Fig. 3. Fig. 3 shows that the blue-shift from 1.52 μm QW is larger than that from 1.59 μm QW because the former is the upper QW, which is closer to the ion induced vacancies. The results of PL measurement indicate that the depth of ion implantation influences on the bandgap blue-shift of QWs.

Furthermore, the cross-sectional region of each well is characterized by TEM. The cross-sectional TEM images of InGaAsP DQWs structure are shown in Fig. 5: (a) as-grown sample; (b) annealed sample with the implanting dose of $7 \times 10^{11}/cm^2$. As clearly seen in Fig. 5, compared with the barrier layer, the well layers appear as the brighter regions of which the upper one is corresponding to the 1.52 μm QW and the lower is the 1.59 μm QW. Judging from the electron diffraction images insetting in Fig. 5 (b), the crystal structure of both wells is retained

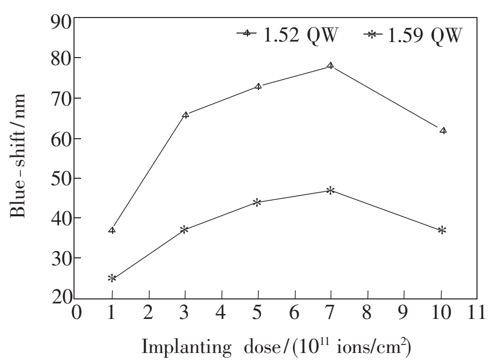

Fig. 4 The PL blueshift of the samples as a function depending on implanting doses

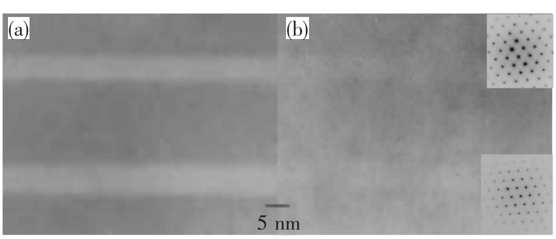

Fig. 5 Cross-sectional TEM images of InGaAsP DQWs structure. (a) as-grown sample; (b) intermixed sample with the implanting dose of $7 \times 10^{11}/cm^2$. The upper brighter region and diffraction image are corresponding to the 1.52 μm QW; and the lower ones, to the 1.59 μm QW.

well after ion implantation with the dose of $5\times10^{11}/cm^2$ and RTA, of which the upper one is from the 1.52 μm QW and the lower is from 1.59 μm QW. The boundary of QWs also becomes vague because of the interdiffusion of constituent atoms of wells and barriers enhanced by the defects generated from P ion implantation.

4 Conclusion

The results of PL measurement indicated that the depth of ion implantation influences the bandgap blue-shift of QWs. The blue-shift from the upper QW, which is closer to the ion-induced vacancies, is larger than that of the lower QW at the same implanting dose. the blue-shift for each well appears a maximum as the implantation doses are increased from $10^{11}\sim10^{12}/cm^2$, When the ion dose is less than $7\times10^{11}/cm^2$, the PL peaks of both QWs can basically separate. However, when the ion dose is $10^{12}/cm^2$, the PL peak of the upper QW is nearly negligible and the peaks from both wells appear to combine together as one peak. Comparing as-grown sample with annealed sample appearing maximum blue-shift by cross-sectional TEM, the boundaries of annealed sample between wells and barriers become vague, indicating that the ion implantation result in a total intermixing of both wells.

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离子注入诱导的具有两个不同发射波长的混合双量子阱结构

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摘要： 叙述了磷离子注入方法诱导具有不同发射波长的 InGaAsP 双量子阱结构的混合，并通过光致发光谱和断面透射电子显微术对量子阱混合的程度进行了研究。在特定条件下快速热退火处理后，光致发光谱显示，在离子注入剂量低于 $7\times10^{11}/cm^2$ 情况下，两个阱的谱峰能保持较好的分离，注入剂量从 $10^{11}/cm^2$ 增大到 $10^{12}/cm^2$ 的过程中，两个阱的带隙蓝移值都似乎存在一个极大值，并且在同样的条件下，上阱（发射波长为 1.52 μm）的带隙蓝移值较下阱（发射波长为 1.59 μm）大些。当离子注入剂量达到 $10^{12}/cm^2$ 时，上阱的谱峰近乎消失，双阱光致发光谱出现了一个谱峰。用断面透射电子显微术对原生长样品与带隙蓝移具有极大值的退火样品进行微结构比较，结果显示，对比原生长样品，退火样品的晶格原子基本得到修复，但阱与垒间的界面显得模糊，这说明离子注入导致两阱完全混合。

关　键　词： 磷离子注入；双量子阱；量子阱混合

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