Arsenic Irradiation Induced Atomic Interdiffusion of $In_xGa_{1-x}As/InP$ Quantum Well Structures

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ABSTRACT

The atomic intermixing of $In_xGa_{1-x}As/InP$ quantum well structures induced by arsenic irradiation has been investigated using photoluminescence (PL) measurement. The ion doses used were varried from $5x10^{11}$ As/cm^2 to $1x10^{13}$ As/cm^2. Also, the irradiation temperature were carried out from -200^{o}C to 300^{o}C. The samples were annealed under Argon flow in rapid thermal annealer (RTA) at 750^{o}C for 60 second. The photoluminescence result showed that there was increase in energy shift at lower doses. However, the energy shift was saturated at higher dose. At elevated temperature implantation showed that the energy shift did not change significantly for all the samples (LM, TS, CS). In additon to this, the higher energy shift was observed in the Compressive Strain (CS) samples, but the lower of the energy shift was experienced in the Tensile Strain (TS) samples.

INTRODUCTION

The combination of lasers, modulators and waveguides on a single epitaxially grown substrate for the monolithic integration of photonic/optoelectronic devices requires the definition of regions with different bandgap energies. Two methods are generally used to implement this type of bandgap engineering, namely: selective area growth and etch-and-regrowth on a patterned substrate. However, both these techniques are complicated and costly. An alternative method that can be applied to the monolithic integration is a postgrowth quantum well intermixing (QWI). This method selectively modifies the bandgap of quantum well structures by intermixing the group V and group III atoms of the quantum well and barrier regions [1,2].

There are several methods for QWI were used, such as impurity induced disordering (IID) [3], impurity-free vacancy disordering (IFVD) [4-6] and ion irradiation (or ion implantation)-induced intermixing [7-9]. Among these various techniques, intermixing modify the bandgap energy since it enables to control precisely of the defects that are introduced into the sample, simply by varying the irradiation doses. Several studies on ion implantation enhanced interdiffusion have been performed on InGaAs/InP system using heavy ions such as arsenic ions [10,11].

In this study, the atomic intermixing of InGaAs/InP induced by arsenic ions was investigated using the photoluminesence by means obtaining the degree of energy shift between the quantum well and the barrier region.

EXPERIMENTAL METHODS

Three samples of a single InGaAs/InP QW structures with different indium composition were grown on semi-insulating (100) InP substrates by low pressure metalorganic chemical vapor deposition (LP-MOCVD) at 650^{o}C. Indium compostion was varried nominally 0.38, 0.53 and 0.68 which was corresponding to tensile-strained (TS), lattice-matched (LM) and compressively-strained (CS) QW, respectively. Each of the samples comprised of (from bottom) 600 nm InP, 5 nm thick $In_xGa_{1-x}As$ QW and 400 nm InP.

In this work, arsenic ions were used for high energy implantation at 1.4 MeV. Crushed GaAs wafer was used as a source material. Caesium vapour inside the SNICS (source of negative ions by caesium sputtering) ions source is ionized into Cs+ ions which are then attracted to a negatively biased cathode (10 kV). The cathode consists of a powder containing the material to be implanted. A positively-biased extractor (15 kV) then attracts

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the sputtered ions which are then accelerated further through a potential difference (80 kV) into a 90° magnet, with a path radius R, for mass filtering. A high voltage terminal resides in the middle of a tank containing pressurised SF6 gas for insulation purposes. A positive bias (up to 1.7 MV) applied to the terminal is sustained through a series of equi-potential rings separated by resistors. The beam paths at the two ends of the tank are kept at ground potential. The voltage stability of the terminal is ensured using a set corona point which forms part of a closed loop feedback system. The mass-filtered negative ions coming from the 90° magnet are electrostatically steered into the tank and accelerated towards the positive high voltage terminal. At this terminal, they are partially stripped of electrons in a nitrogen charge-exchange cell to become positive ions and as a result are further accelerated towards the other end of the tank (at ground potential).

Simulation program TRIM was performed to look the damage profile and the total vacancy distribution peak near the quantum well [12]. Based on TRIM calculation, the collisional displacement density caused by arsenic ions is expected to be about a factor of 1000 higher than that of protons. Thereby, arsenic implantation was performed using energy of 1 MeV ions with doses ranging from $5x10^{11}$ As/cm^2 to $1x10^{13}$ As/cm^2. The irradiation temperature was varied from liquid nitrogen (LN_2) temperature to 300°C. In order to provide a sample reference, half of each of the sample was masked during the irradiation. Subsequent thermal annealing was performed under Ar flow in a rapid thermal annealer (RTA) at 750°C for 60 sec.

Low temperature PL (77K) was performed to characterize the energy shift in the quantum well region using a diode-pumped solid-state frequency doubled green laser at 532 nm for excitation and a cooled InGaAs photodetector at the output slit of an 0.5 m monochromator.

RESULTS AND DISCUSSION

Heavier ion irradiation, such as arsenic, may be used to initiate the interdiffusion and obtain a large energy shift at a lower ion dose. However, prior to study the interdiffusion by arsenic irradiation, it is essential to first evaluate the thermal stability of InGaAs/InP samples, because the InGaAs/InP has poor thermal stability compared to InGaAs/GaAs or AlGaAs/GaAs system. For this purpose, the samples were annealed in a rapid thermal annealing with various temperature from 700°C to 800°C for 60 sec.

Figure 1 shows the PL energy shift of the samples annealed at different temperature for 60 sec. As shown in Fig.1, the PL energy shift increased as temperature increased. Higher annealing is much preferred in irradiation induced interdiffusion not only to initiate the intermixing but also to remove the irradiation induced defect. However, too high temperature annealing will result in a large energy shift due to thermal effect. Therefore, based on this study of the temperature dependence of interdiffusion, annealing the samples at 750°C for 60 sec was chosen to study the interdiffusion, so that any measurment of the peak energy shift can be attributed to irradiation induced interdiffusion.

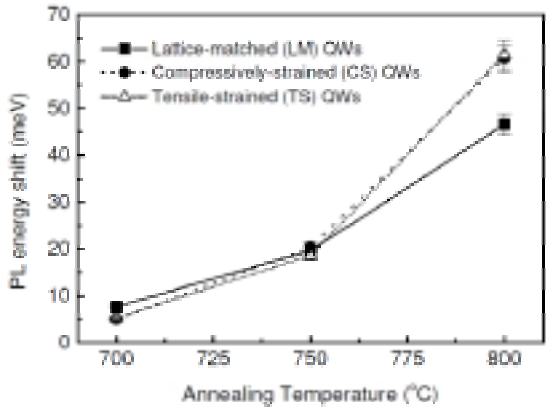

Fig. 1. The PL energy shift of lattice-matched (LM), compressive-strained (CS) and tensile-strained (TS) $In_xGa_{1-x}As/InP$ QWs annealed at various temperature from 700°C to 800°C for 60 sec.

Figure 2 shows the PL spectra of LM, CS and TS QWs implanted with As ions at four different doses and annealed at 750°C for 60s. It is clear from this figure that a very large wavelength shift were obtained for all doses used. However, the recovery of the PL intensity was not sufficient; especially for TS samples and this indicated that some defects were still left in the samples even after annealing at this temperature. These results are similar to the case of proton implantation except that much lower doses are required for the As case [13].

The PL energy shift of the LM, CS and TS QWs as a function of implantation dose is shown in Fig. 3. At a fixed dose, higher energy shift was obtained for the CS QW, followed by the LM QW and then the TS QW.These results are similar to that of previous studies using Proton ions. In addition to this, large energy shifts were obtained even at the lowest doses of $5x10^{11}$ As/cm^2. Further increase in the dose to $1x10^{12}$ As/cm^2 resulted in further energy shift. However, beyond this dose the degree of energy shift decreased for all samples. Hence, there

is an optimum dose where the degree of intermixing is a maximum which it starts to drop again. This trend should be compared with that of H case where the energy shift increases with dose until a saturation level is achieved at the highest dose [13].

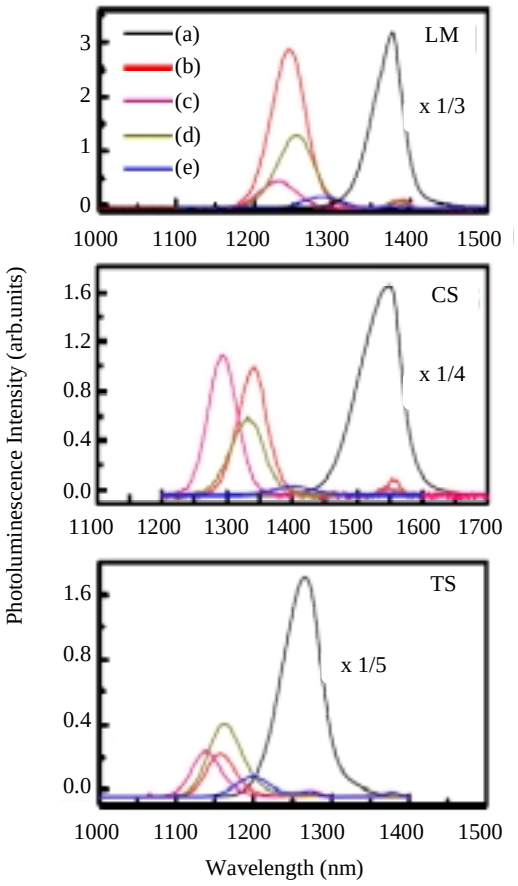

Fig. 2. The low temperature (77K) PL emission of lattice-matched (LM), compressively-strained (CS), and tensile-strained (TS) QW samples after implantation with As and annealed at 750°C for 60 sec. (a) unimplanted and annealed for reference, (b) $5x10^{11}$ As/cm^2, (c) $1x10^{12}$ As/cm^2, (d) $5x10^{12}$ As/cm^2, (e) $1x10^{13}$ As/cm^2.

Based on the results above, it can be pointed out that the arsenic irradiation behaviour is quite different with proton implantation in which is most likely due to different types of defect formation and mass implant species. In the case of the arsenic implantation, the large mass of the ions produce a larger volume of atomic displacement. At low implantation dose ($5x10^{11}$ As/cm^2) as shown in Fig. 3, although there were point defects available to promote significant intermixing, large defect clusters would also start forming. Formation of larger defect clusters is more efficient at very low doses. Consequently, increasing the arsenic dose resulted in the reduction of intermixing as point defect were consumed or agglomerate into large defect clusters. These large defect clusters at higher doses reduce the degree of interdiffusion, therefore intermixing was reduced. On the other hand, for proton implantation case, the displacement cascade densities are small and merely simple point defects and small disordered zones are formed even at high doses. As the dose was increased, proton implantation induced more intermixing and even at high dose protons were able to create a high concentration of point defects and dilute defect clusters. TRIM calculation show that the displacement density caused by proton is approximately 1000 times less than that caused by As. This suggest that stronger dynamic annealing occurs during proton implantation than in arsenic implantation, especially at lower doses.

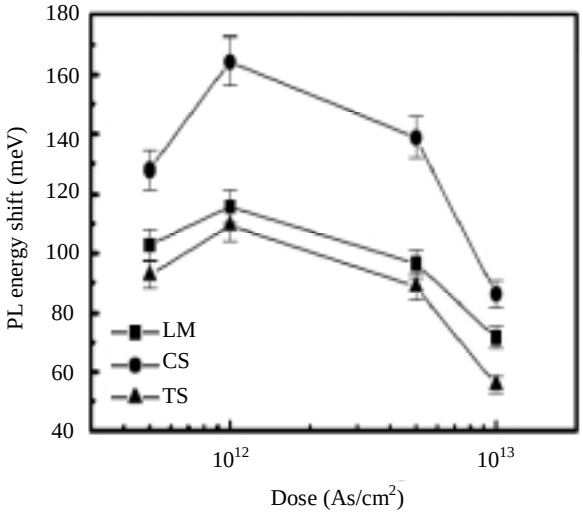

Fig. 3. The PL energy shift of LM, CS and TS QWs annealed at 750°C for 60 sec as a function of dose.

The study of implant temperature to the energy shift showed that it did not reveal any significant difference in the degree of energy shift for the temperature range investigated as shown in Fig. 4. It is well known that arsenic ions produced damage cascades. Also at elevated implantation temperature, the increase in defect mobility within the damage cascades results in the reduction of the total damage of InP [14]. However, according to this study, complete defect annihilation does not occur but rather certain stable point defects (such as antsite defects) and point defect complexes nucleate. Both large damage cascades and nucleation of point defects do not contribute to the interdiffusion since these defects are thermally more stable. This is most likely the explanation for the lack of implantation temperature depedence on energy shift as observed with the arsenic ions.

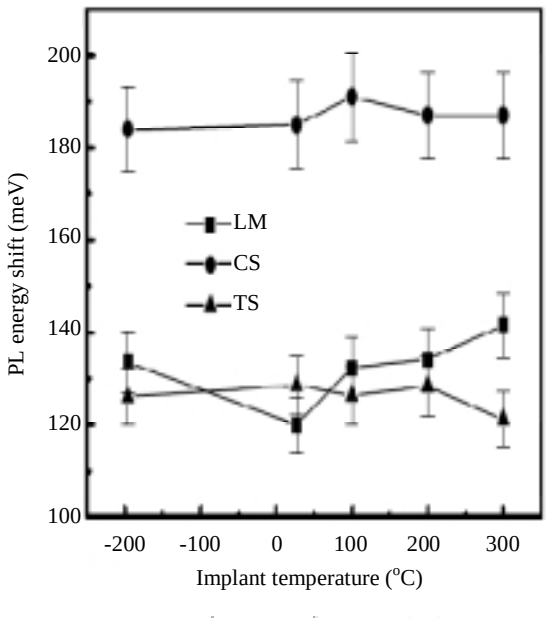

Fig. 4. The PL energy shift of LM, CS and TS QWs annealed at 750°C for 60 sec as a function of implant temperature. The implantation dose was $2x10^{12}$ As/cm^2 in all cases.

CONCLUSION

We have investigated the atomic intermixing of $In_xGa_{1-x}As/InP$ quantum wells induced by arsenic irradiation using photoluminescence. Photoluminescence results show that the formation of larger cluster is more efficient even at very low doses. At elevated temperature, the energy shift did not change significantly. This is due to the thermal stability of the large clusters formed at various implant temperatures.

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