Indonesian Journal of Physics
Vol 20 No. 1, January 2009

Interdiffusion of $In_xGa_{1-x}As/InP$ Quantum Well Structures Induced by Proton Implantation

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Abstract

We have investigated the atomic intermixing of $In_xGa_{1-x}As/InP$ quantum well structures induced by proton implantation using photoluminescence. Photoluminescence results showed that energy shift was systematically increased as doses increased. As the dose further increased, Saturation in energy shift was observed. At elevated temperature irradiation revealed that the magnitude of the energy shift decreased as the irradiation increased followed by a broadening of the PL linewidth and reduction of the PL intensity. This indicated that dynamic annealing and mobility of the defects play an important role in the type and concentration of residual defects.

Keywords*: Proton implantation, Atomic intermixing, InGaAs/InP QWs*

1. Introduction

$In_xGa_{1-x}As/InP$ quantum well structures have been extensively studied for many years due to their application in lasers that operate in the wavelength range of 1.3 to 1.55 μm, which is suitable for long haul optical-fiber communications[1,2)]. For future optoelectronic device integration, it is desirable to produce lasers, modulators and waveguides on the same wafer. One technique that can be used to achieve integration is post-growth quantum well intermixing (QWI) technique where the band gap is selectively modified by intermixing of the group III/V atoms between the quantum well and barrier region[3,4)]. There are several methods commonly used to generate the well-barrier intermixing such as impurity induced disordering[5)], impurity-free vacancy disordering (IFVD)[6)] and ion irradiation-induced intermixing[7)]. Among these various techniques, intermixing by ion irradiation with subsequent thermal annealing has been shown to be very effective due to its advantage of precise control of defects generation to induce intermixing by varying the irradiation conditions. Several studies on ion irradiation enhanced interdiffusion have been reported in InGaAs/InP system using heavy ions[8)], but considerably less using light ions such as protons.

Compared to heavier ions, proton irradiation is expected to be able to generate dilute damage cascades with high concentration of point defects (and minimal formation of extended defects) which are available during annealing, leading to higher degree of intermixing. In this study, we investigate the intermixing mechanism of InGaAs/InP which is caused by proton irradiation by identifying the energy transitions from the quantum well regions using photoluminescence measurements.

2. Experiment Details

Three samples of single InGaAs/InP QW structures were grown on semi-insulating (100) InP substrates by low pressure metalorganic chemical vapor deposition (MOCVD) at 650^{o}C. The indium composition was nominally 0.38, 0.53 and 0.68 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. Proton irradiation was carried out using 50 keV ions with doses ranging from $5x10^{14}$ H/cm^2 to $1x10^{16}$ H/cm^2. The irradiation temperature was varied from room temperature to 300^{o}C. During implantation half of each of the sample was masked so as to provide a reference. Subsequent thermal annealing was performed under Ar flow in a rapid thermal annealer (RTA) at 750^{o}C for 60 sec. This temperature was chosen after our study of thermal interdiffusion which showed that at this temperature, the diffusion caused by thermal component could be kept low. Thus, by annealing the implanted samples at this temperature, any measured peak energy shift could be assigned solely to the effect caused by implantation. 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.

3. Results and Discussion

Figure 1 displays the 77K PL spectra for implanted TS, LM, and CS QW samples annealed at 750^{o}C for 60 sec for doses ranging from $5x10^{14}$ H/cm^2 to $1x10^{16}$ H/cm^2. It can be clearly seen from this figure that after implantation, blueshift was observed for all implanted and annealed in comparison to the reference samples (unimplanted and annealed). However, the magnitude of the energy-shift became saturated at the high implantation doses, followed by a reduction of the PL intensity and the broadening of the PL linewidth. It is worth mentioning that prior to annealing, PL emission was not observed due to defects that formed after irradiation which act as non-radiative recombination centres. After annealing, the PL emission was recovered, but the PL intensities were still lower than unirradiated samples indicating that defects were still present and not sufficiently removed after annealing at this temperature.

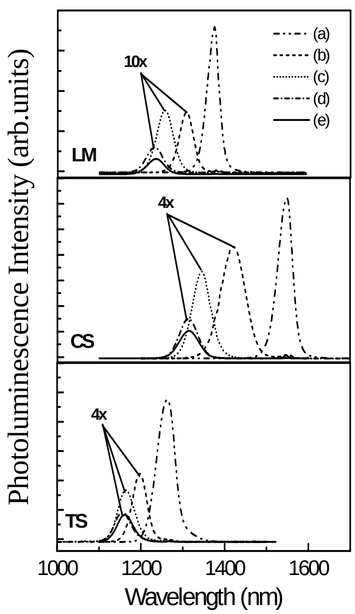

Figure 1. PL spectra of lattice-matched (LM), compressively-strained (CS) and tensile-strained (TS) $In_xGa_{1-x}As/InP$ QWs after implantation and annealing at 750oC for 60 sec for (a) reference unimplanted and annealed, (b) $5x10^{14}$ H/cm^2, (c) $1x10^{15}$ H/cm^2, (d) $5x10^{15}$ H/cm^2 and (e) $1x10^{16}$ H/cm^2.

A plot of the energy shift for TS, LM, CS samples after annealing at 750^{o}C for 60 s as a function of dose is shown in Figure 2. In all cases, the energy shift initially increased as the dose was increased and it reached a maximum at $5x10^{15}$ H/cm^2. As the dose was further increased to $1x10^{16}$ H/cm^2, a saturation in the energy shift was observed. These results are in contrast to the previous studies of InGaAs/AlGaAs and AlGaAs/GaAs QWs using proton irradiation in which the energy shift was not saturated even at highest doses ($5x10^{16}$ H/cm^2)[7]. This may be due to differences in the types of defects formed in various material systems. In addition to this, it is well known that in AlGaAs/GaAs and InGaAs/AlGaAs system the well-barrier interdiffusion during the annealing occurs only on the group III sublattice (In,Ga,Al). However, in the InGaAs/InP system both the group-III and group-V sublattices may contribute to interdiffusion. Blue shift is observed when the diffusion rate of group-V sublattice is larger than the diffusion rate of group-III sublattice, while a redshift is observed if the group III sublattice diffusion is more dominant. At low doses, the results show that group V diffusion is dominant. At high doses, it is possible that the group III diffusion rate is enhanced (or the reduction in the group V diffusion rate), thereby leading to the saturation in the blueshift. However, it is more likely that at high doses, extended defects such as large clusters are formed and these defects are thermally more stable than the simple point defects. Since only point defects (vacancies, interstitials) contribute to the well-barrier intermixing, these clusters would result in lowering the concentration of available point defects to promote intermixing during annealing. Our results also consistently show that at high doses the recovery of the PL intensity is much worse which strongly support this argument.

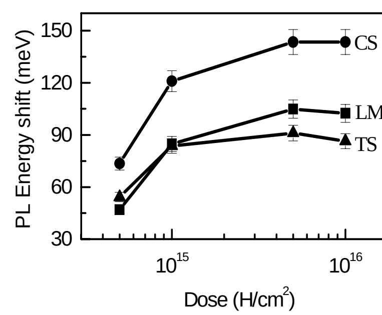

Figure 2. The PL energy shift of lattice-matched (LM), compressively-strained (CS) and tensile-strained (TS) $In_xGa_{1-x}As/InP$ QWs as a function of implantation dose after annealing at 750^{o}C for 60 s.

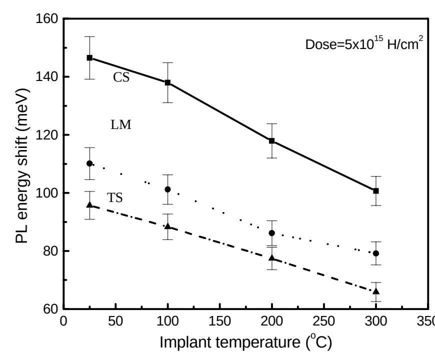

Figure 3. The PL energy shift of lattice-matched (LM), compressively-strained (CS) and tensile-strained (TS) $In_xGa_{1-x}As/InP$ QWs as a function of implantation temperature.

The effect of implantation temperature on intermixing was also studied. The implantation was carried out using dose at $5x10^{15}$ H/cm^2 in the temperature range of 20-300°C. The plots of the energy shift as a function of irradiation temperature is shown in Figure 3. For all samples, there was a decrease in the amount of the PL energy shift as the irradiation temperature was increased. It has been reported previously that the magnitude of the energy shift in AlGaAs/GaAs QWs decreased as the irradiation temperature is increased[7)] which agrees with our results for InGaAs/InP system. The reduction in the degree of energy shift and PL intensities as the irradiation temperature increased can be explained by the following: At elevated implantation temperature, dynamic annealing and the mobility of the defects play an important role in the type and concentration of residual defects. Since proton irradiation creates dilute damage cascades, there could be significant annihilation of vacancies and interstitials at elevated temperature which lead to lowering the concentration of residual point defects. Also, at elevated temperature the increased mobility of the point defects may result in the agglomeration of large clusters or the formation of extended defects. Since interdiffusion relies on the availability of points defects during the annealing, both of these result in less interdiffusion at elevated temperature. However, it is more likely that the latter scenario occurs at elevated irradiation temperature based on observed lower PL intensities.

It is interesting to note from Figure 2 and Figure 3 that at the same dose the blue shift in the CS QW was the largest, followed by the LM while the smallest blueshift was observed in the TS case. It is expected that the group III sublattice diffusion rate will be the highest for the TS samples since it has the highest In-Ga concentration gradient, followed by LM and CS samples. Assuming that the group V sublattice diffusion rate is the same for all the samples, hence the higher group III diffusion rate of the TS samples would counter the effect of blueshift caused by the group V diffusion more efficiently than the other two samples. Hence the lower degree of energy shifts. However, this simplistic argument does not take into account the effect of the strain during the interdiffusion. It is known that compressive strain may enhance the interdiffusion during annealing, whereas tensile strain suppresses it[9)].

4. Conclusion

We have studied the atomic intermixing of $In_xGa_{1-x}As/InP$ quantum wells induced by proton implantation using photoluminescence. Photoluminescence results show that the energy shift saturates at high dose indicating that the concentration of available point defects is reduced at high doses due to the formation of extended defects.

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