Proton Irradiation Induced Intermixing in In$_x$Ga$_{1-x}$As/InP Quantum Wells

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Abstract—We have investigated the quantum well interdiffusion of In$_x$Ga$_{1-x}$As/InP QWs with different In composition using proton irradiation. 50 KeV proton implantation with various doses from 5x10$^{14}$ H/cm$^2$ to 1x10$^{16}$ H/cm$^2$ with subsequent annealing at 750° for 60 sec were used to induce the atomic intermixing process. Photoluminescence was performed to measure the bandgap energy shift between the unimplanted and implanted region of the structures. Initially, the energy shift increased with increasing dose, but then saturated at the highest doses. The energy shift was also found to decrease with increased implantation temperature. Time resolved photoluminescence was performed to investigate the carrier dynamic of the quantum wells after intermixing.

key words: Proton irradiation, interdiffusion, intermixing, InGaAs quantum wells

I. INTRODUCTION

In$_x$Ga$_{1-x}$As/InP quantum well structures have been widely investigated due to their potential in producing lasers that operate in the range of 1.3 to 1.55 μm wavelength, which is suitable for long-haul optical-fiber communication [1], [2]. For future optoelectronic device integration, it is desirable to achieve lasers, modulators, and waveguides on the same wafer using the post-growth quantum well intermixing technique where the band gap of QW structure is selectively modified by intermixing the group III/V atoms in 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 have been shown to be very effective due to its advantage of precise control of defect introduction to generate the intermixing by varying the irradiation dose. Several studies on ion implantation enhanced interdiffusion have been performed in InGaAs/InP systems using heavy ions [8], but less studies using light ions such as proton. Compared to heavier ions implantation, proton irradiation is expected to be able to generate a dilute damage cascades with a high concentration of point defects (with minimal formation of extended defect) which are available during annealing, leading to a higher degree of intermixing. Previous studies in AlGaAs/GaAs and InGaAs/AlGaAs systems have shown that large energy shift were achieved at high doses without any saturation effect by using proton irradiation [9], [10]. However, our results in InGaAs/InP quantum well system showed a saturation in energy shift was observed at high doses. In this work, we study the effect of 50 KeV proton irradiation on In$_x$Ga$_{1-x}$As/InP QWs with different In composition, corresponding to lattice-matched, compressively strained and tensile strained system.

II. EXPERIMENTAL

Three samples of In$_x$Ga$_{1-x}$As/InP QW structure were grown on semi-insulating (100) InP substrate by low pressure metalorganic chemical vapor deposition (MOCVD) at 650°C. The In composition were nominally 0.38, 0.53 and 0.68 correspond to tensile-strained, lattice-matched, and compressively-strained QWs, respectively. Each structure comprise of (from the bottom) 600 nm InP buffer layers, 5 nm thick In$_x$Ga$_{1-x}$As QW and 400 nm InP. Ion implantation was carried out with proton at 50 KeV with various doses ranging from 5x10$^{14}$ H/cm$^2$ to 1x10$^{16}$H/cm$^2$. The implantation temperature was either at RT, 100°C, 200°C and 300°C and the flux used ranged from 0.26μA/cm$^2$-0.55μA/cm$^2$. Based on TRIM simulation in 50 KeV energy, the damage peak lies in the vicinity of the quantum well layer [11]. Each sample was masked during implantation to provide a reference region and was oriented 7° off from the beam axis to minimize the channeling effect. Subsequent thermal annealing was performed under Ar flow in a rapid thermal annealer (RTA) at 750°C for 60s. This temperature was chosen after our previous study into the effect of thermal interdiffusion caused by annealing in these QW structures which showed at 750°C or lower, very little energy shifts were obtained. Therefore by annealing the implanted samples at this temperature, any measured peak energy shift could be safely assigned to the effects caused by irradiation-induced defects. During the annealing process, the samples were sandwiched using an InP proximity cap to minimize phosphorus loss from the sample surfaces. Low temperature photoluminescence (PL) at 77K was performed to characterize the energy shift emitted in the active region using a diode-pumped solid-state frequency double green laser at 532 nm for excitation and a cooled InGaAs photodetector at the output slit of a 0.5 m monochromator. The shift of
The time resolution of our system was approximately 200 fs. The pulse width was 80 fs and the repetition rate was 1 kHz. The laser was tunable between 910 and 950 nm, and consists of a model-locked Ti:sapphire oscillator, using a BBO crystal. The laser was tunable between 910 and 950 nm, the pulse width was 80 fs and the repetition rate was 1 kHz. The time resolution of our system was approximately 200 fs.

### III. RESULTS AND DISCUSSION

Figure 1 displays the PL spectra of lattice-matched, compressively strained, and tensile-strain InGaAs/InP QWs annealed at 750°C for 60 sec with various irradiation dose from $5 \times 10^{14}$ H/cm$^2$ to $1 \times 10^{16}$ H/cm$^2$. All the irradiated samples showed a blue shift in the emission wavelength after annealing. It is worth mentioning all irradiated samples did not show any PL emission from the QWs prior to annealing due to any PL emission from the QWs prior to annealing. The PL intensities were recovery after annealing, were still much lower than those of the unirradiated samples. In addition to this, the line width of the peaks becomes relatively broad in comparison to the reference sample. These results indicated that the defect was still present and not sufficiently remove after annealing.

A plot the energy shift after annealing at 750°C for 60 s as a function of dose is depicted in Fig. 2 for all the samples. In all cases, the energy shift was initially increase with increase in dose and reach a maximum shift at $5 \times 10^{15}$ H/cm$^2$. As the doses further increase to $1 \times 10^{16}$ H/cm$^2$, the energy shift was saturated. These results are different to the previous studies in InGaAs/AlGaAs and AlGaAs/GaAs system using proton irradiation in which the energy shift was not saturated even at very high doses ($5 \times 10^{16}$ H/cm$^2$). It is well known that in AlGaAs/AlAs and InGaAs/AlGaAs system the group-III sublattice (In, Ga) is the cause of intermixing. However, in the InGaAs/InP system both of group-III and group-V sublattice may contribute to the intermixing between quantum well and barrier region. If group III dominates the intermixing process, then a red shift of the emission wavelength is expected since the QW would be effectively be more In-rich (or Ga deficient). On the other hand if group-V sublattice diffusion dominates, then a blue shift is expected as the QW would be P-rich.

The effect of irradiation temperature was also studied. The irradiation were carried out using two doses of $1 \times 10^{15}$ H/cm$^2$ and $5 \times 10^{15}$ H/cm$^2$ at room temperature, 100°C, 200°C, and 300°C. The plots of the energy shift as a function of irradiation temperature for the two different doses are shown in Fig. 3. For all the samples, the amount of the PL energy shift decreases as the irradiation temperature was increased. These results are in agreement with the previous work (InGaAs/AlGaAs, AlGaAs/GaAs QWs) reporting that the energy shift is less as the irradiation temperature is increased [7]. It is also worth noting that the PL intensities at elevated temperature were much lower than at room temperature. The reduction in the degree of energy shift and PL intensities as the irradiation temperature is increase can be explained by the the following. At elevated temperature implantation dynamic annealing and the mobility of the defects play an important role in the type and concentration of residual defects. Since proton implantation creates dilute defect cascades, there could be significant annihilation of vacancies and interstitial at elevated temperature which lead to lowering the concentration of residual defects. At elevated temperature the defects could also agglomerate into larger...
clusters or forming extended defects due to their increased mobilities. Since interdiffusion relies on the availability of point defects during annealing, both of these result in less interdiffusion at elevated temperature. Furthermore, these large clusters or extended defects which are thermally more stable during annealing could also reduce the PL intensities as they act as efficient non-radiative recombination.

Another significant result from Fig. 2 and Fig. 3 is that under the same doses and elevated temperature implantation, the compressively strained QWs shows the biggest blueshift, followed by the lattice-matched and finally the smallest blueshift observed in the tensile-strained QWs. It is expected that the As-P (group V) interdiffusion to be the same in all three set of samples. However, the In-Ga (group III) interdiffusion should be the highest in the case of tensile-strain QW since the concentration gradient to the barriers is highest. Since group III interdiffusion is expected to give blueshift, the redshift from the tensile-strain QW would be partially offset by the group III intermixing. Hence, the smallest blue shift was obtained from this set of samples. However, this simplistic argument does not include the effect of strain. It is known that compressive strain may enhance interdiffusion during the annealing stage while tensile strain suppresses it [12].

Figure 4 displays the carrier dynamics for lattice-matched, compressive-strained and tensile-strained QWs for both the reference and irradiated samples with annealing at 750°C for 60 sec measured at T = 8K.

In summary, the intermixing of In$_x$Ga$_{1-x}$As/InP quantum wells lattice-matched (LM), compressive-strained (CS) and tensile-strained (TS) reference and irradiated sample with annealing at 750°C for 60 sec at low temperature (8°K). In general, all the samples showed that the decay time of PL for irradiated sample was faster than that the unirradiated sample. It is well known that ion implantation generate a range of non-radiative defects which act as trapping centre thereby reducing the carrier life time in the sample, and has been reported previously by other studies [13]. In addition to this, it was observed that the carrier life time is dependent on the dose. The decay time was reduce significantly at the dose of 5x10$^{15}$ H/cm$^2$ in comparison with the dose of 1x10$^{15}$ H/cm$^2$ indicating that at high doses more residual defects were present in the samples after annealing. These results correlated well with the reduction in PL intensities as the irradiation dose was increased although a larger energy shift could be obtained at higher doses.

**IV. Conclusion**

In summary, the intermixing of In$_x$Ga$_{1-x}$/InP QWs using proton irradiation with subsequent annealing was studied. It was found that the energy shift was saturated at the highest dose. Irradiation temperature dependent studies showed that

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*Fig. 3. The PL energy shift of In$_x$Ga$_{1-x}$As/InP lattice-matched (LM), compressive-strained (CS) and tensile-strained (TS) respectively as a function of implant temperatures for all the samples annealed at 750°C for 60 sec. (a) 1x10$^{15}$ H/cm$^2$, (b) 5x10$^{15}$ H/cm$^2$.

*Fig. 4. The time-resolved photoluminescence of In$_x$Ga$_{1-x}$/As/InP quantum wells lattice-matched (LM), compressive-strained (CS) and tensile-strained (TS) reference and irradiated sample with annealing at 750°C for 60 sec measured at T = 8K.*
the energy shift decreased significantly with the increased in irradiation temperature and the PL intensity was much reduced. These were attributed to annihilation of point defects and/or the formation of extended defects due to the higher mobility of the defects at higher irradiation temperature. Time resolved photoluminescence measurement confirmed the presence of these residual defects where the decay times for irradiated samples were significantly faster than those of the unirradiated sample.

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