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Proton irradiation-induced intermixing in InGaAs/(Al)GaAs quantum wells and quantum-well lasers

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Proton irradiation with subsequent rapid thermal annealing was used to investigate intermixing of InGaAs/GaAs and InGaAs/AlGaAs quantum wells. Large photoluminescence (PL) energy shifts were observed in both materials. Comparatively, InGaAs/AlGaAs samples showed larger PL energy shifts than InGaAs/GaAs samples because of the presence of Al in the barriers and also better recovery of PL intensities, which is mainly due to dynamic annealing effects in AlGaAs during irradiation. Based on this, InGaAs/AlGaAs quantum-well lasers were fabricated and up to 49.3-nm-emission wavelength shift was observed in the proton-irradiated laser with no significant degradation in device characteristics. © *1999 American Institute of Physics.* [S0021-8979(99)09609-7]

I. INTRODUCTION

To monolithically integrate optoelectronic devices, for example, lasers, detectors, amplifiers, modulators, and waveguides, precise tailoring of the optical properties such as band gap energy, absorption coefficient, and refractive index is required. Quantum-well (QW) intermixing has been found to be a very useful method[1,2] to achieve this due to its ability to selectively fine tune the band gap in different regions within the same epitaxial layer structure through the interdiffusion between QW and adjacent barrier material.

Among various techniques[3–7] used to generate the quantum-well intermixing, ion implantation induced intermixing[7–9] has shown to be very effective due to its advantage of precise control of layer disordering by varying the irradiation dose. Many studies on ion implantation enhanced interdiffusion have been performed on GaAs/AlGaAs and InGaAs/GaAs systems using heavy ions[10–12] and GaAs/AlGaAs system using light ions, such as protons.[13] Also, some ion implanted, wavelength shifted InGaAs/InGaAsP/InP lasers[12] and GaAs/AlGaAs lasers[14] have been successfully fabricated. Compared with the heavier ions, protons are expected to be able to create a higher concentration of point defects and defect clusters with minimal formation of extended defects which lead to a high degree of intermixing. It has been observed in the GaAs/AlGaAs system that large energy shifts and good PL intensities could be achieved by proton irradiation.[13] In this work, 40 keV proton irradiation with subsequent rapid thermal annealing (RTA) was used to investigate intermixing in InGaAs/GaAs and InGaAs/AlGaAs QWs. Large energy shifts were observed at high irradiation doses in both materials. Comparatively, InGaAs/AlGaAs samples showed larger energy shifts and better PL intensities recovery. Based on this, InGaAs/AlGaAs quantum-well lasers were fabricated and significant wavelength shift was achieved with no significant degradation in device characteristics.

II. EXPERIMENT

The InGaAs/GaAs and InGaAs/AlGaAs structures used in this experiment were grown on semi-insulating (100) GaAs substrates by metalorganic chemical vapor deposition (MOCVD). The InGaAs/GaAs QW structure consisted of (from the GaAs substrate up) 1-μm-GaAs buffer layer, 50-nm-GaAs barrier, 5-nm-$In_{0.3}Ga_{0.7}As$ QW, 50-nm-GaAs barrier, 5-nm-$In_{0.15}Ga_{0.85}As$ QW, and 200-nm-GaAs barrier. The InGaAs/AlGaAs structure was similar except that the GaAs barriers were replaced by $Al_{0.2}Ga_{0.8}As$ barriers and terminated with a 5-nm-GaAs capping layer to prevent oxidation. All layers were undoped and grown at 680 °C. Proton irradiation was carried out at room temperature using 40 keV protons. Four different doses varying from 1×10^{15} to $4\times10^{16}\,cm^{-2}$ were chosen. Each sample was masked during irradiation to provide a reference region and was tilted 7° off the beam axis to minimize channeling effect. All the samples were then annealed under Ar flow in a rapid thermal annealer at 900 °C for 60 s. During the RTA process, the samples were protected from excessive loss of As by placing a fresh piece of GaAs substrate on the surface. Low temperature (12 K) photoluminescence (PL) measurements were performed using a green He–Ne laser (543.5 nm) as the excitation source and the luminescence was detected with a silicon CCD through a 0.27 m monochromator.

III. RESULTS AND DISCUSSION

The PL emission from the two QWs in the InGaAs/GaAs and InGaAs/AlGaAs samples at the doses of 1×10^{15} and $5\times10^{15}\,cm^{-2}$ are shown in Figs. 1(a) and 1(b), respectively. It can be clearly observed that after irradiation and annealing, the emission wavelengths from all the QWs were blueshifted to the shorter wavelengths compared with the

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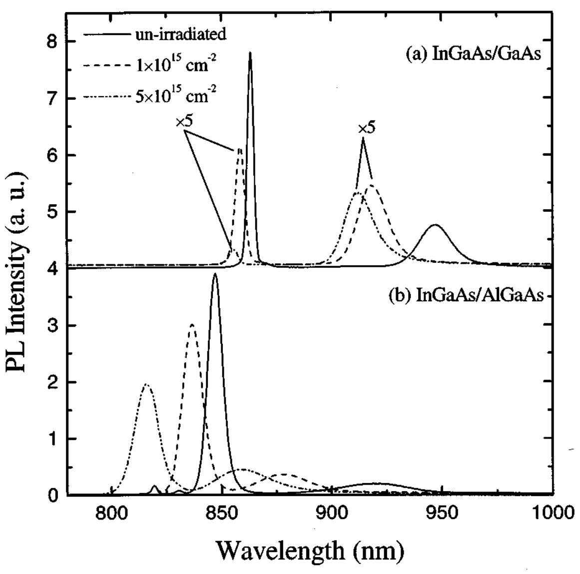

FIG. 1. Low temperature (12 K) photoluminescence spectra for samples irradiated at the dose of $1\times10^{15}\,cm^{-2}$, $5\times10^{15}\,cm^{-2}$, and annealed at 900 °C, 60 s: (a) InGaAs/GaAs; (b) InGaAs/AlGaAs. Also shown are the spectra from the unirradiated and annealed (reference) samples. Spectra from the irradiated InGaAs/GaAs samples were multiplied by a factor of 5 because of the low PL intensities.

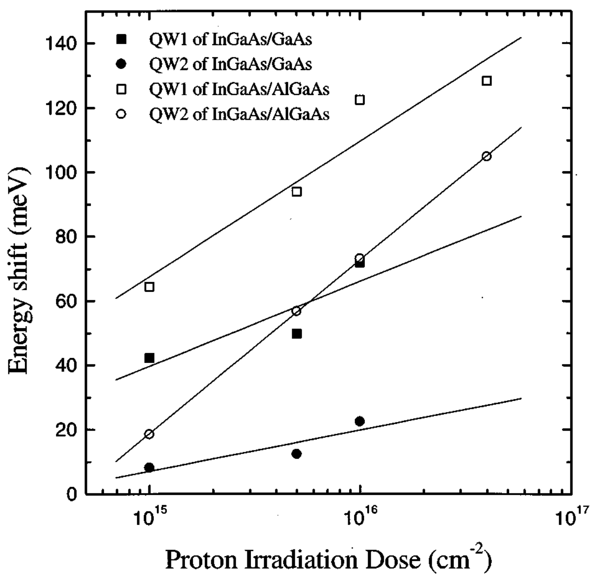

FIG. 2. The energy shift for each quantum well (QW1: $I_n=0.3$, QW2: $I_n=0.15$) as a function of irradiation dose for samples annealed at 900 °C, 60 s.

reference samples (unirradiated and annealed). In both reference samples, the peaks of QW1 ($In_{0.3}Ga_{0.7}As$) was lower and broader than the peaks of QW2 ($In_{0.15}Ga_{0.85}As$), which is most likely due to the presence of defects in the strained QWs near the critical thickness[15] and the nonuniformity of the QWs caused by the high indium composition. For the irradiated and annealed samples, the PL intensity of the InGaAs/GaAs QWs in Fig. 1(a) decreased with the increase of the irradiation doses indicating that the nonradiative recombination centers introduced by the irradiation were still present and not sufficiently removed by RTA. However, from the Fig. 1(b), very good recovery (>50%) of PL intensities for both QWs in InGaAs/AlGaAs samples were observed considering the large energy shifts obtained and high irradiation dose used. Previous studies proposed that the presence of AlGaAs offers some protection against damage accumulation in adjacent GaAs region due to the strong dynamic annealing of the mobile point defects generated in AlGaAs.[16–18] Similarly, for InGaAs QW sandwiched by two AlGaAs barrier layers, it is possible that during irradiation, a similar process may be happening and together with the simultaneous dynamic annealing in the AlGaAs layers which prevents the formation of large defect clusters, the residual defects in the sample are predominantly point defects. These point defects with lower thermal stability anneal much more easily than defect clusters (in the case of InGaAs/GaAs QWs) to promote intermixing and hence the remarkable recovery of the PL intensities of the InGaAs/AlGaAs samples.

Figure 2 shows the energy shift as a function of irradiation dose for each of the two QWs in both InGaAs/GaAs and InGaAs/AlGaAs samples. In contrast to the GaAs/AlGaAs system, thermal annealing is sufficient to cause significant energy shift[19] in the InGaAs system. Therefore, all shifts in Fig. 2 were obtained by comparing the peak positions of irradiated and reference (unirradiated) parts of the sample, both of which were annealed at the same time, to ensure that only the effect of irradiation was measured. No PL signal was detected at the highest irradiation dose ($4\times10^{16}\,cm^{-2}$) in the InGaAs/GaAs sample (thus the missing points on the curves) which was due to the large amount of nonradiative recombination sites remaining in the sample even after RTA. This is in stark contrast to the InGaAs/AlGaAs case, where reasonable intensities were still observed at this dose, again emphasizing the importance of the role of point defects in promoting the intermixing process and the lattice recovery.

In all cases, the energy shifts increased with irradiation doses. This is in agreement with the observations of the intermixing in GaAs/AlGaAs QWs induced by proton irradiation,[13] suggesting that proton irradiation is indeed able to generate high concentration of point defects and dilute point defect clusters with minimal formation of extended defects during annealing, so as to achieve efficient intermixing. Furthermore, the energy shifts of QW1 were much larger than those of QW2 and each QW of InGaAs/AlGaAs had much larger energy shifts than the corresponding QW of InGaAs/GaAs. It is well known that the blueshift of the InGaAs/GaAs structure is obtained from the interdiffusion of group III elements, indium and gallium, which changes the shape of the QW from square to a double-error function profile[20] and hence, leading to an increase in the effective band gap energy. The higher In gradient in the QW with higher In mole fraction (QW1) resulted in more In outdiffusion and hence, the larger energy shift. In addition, in the InGaAs/AlGaAs structure, two effects might contribute leading to the larger magnitude of energy shifts: (1) the additional Al composition gradient between QW and barrier and (2) the accumulation of point defects in the AlGaAs layer during irradiation.[16–18] Hence, during annealing, the point

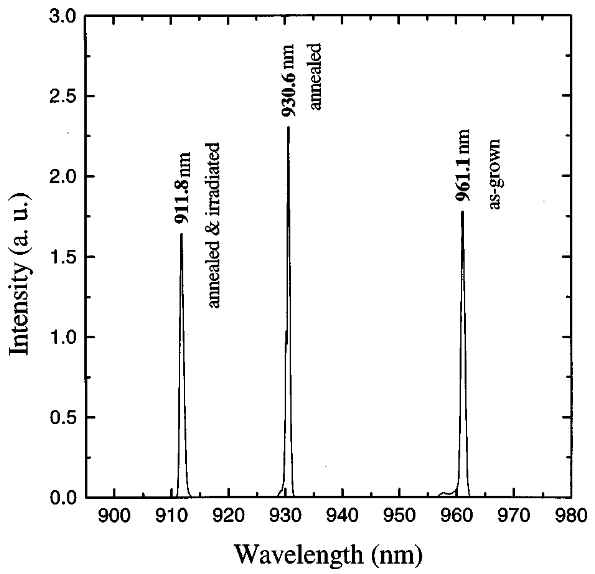

FIG. 3. Lasing spectra from the three InGaAs/AlGaAs quantum well lasers (as-grown, the unirradiated but annealed, the irradiated and annealed) at $1.5I_{th}$.

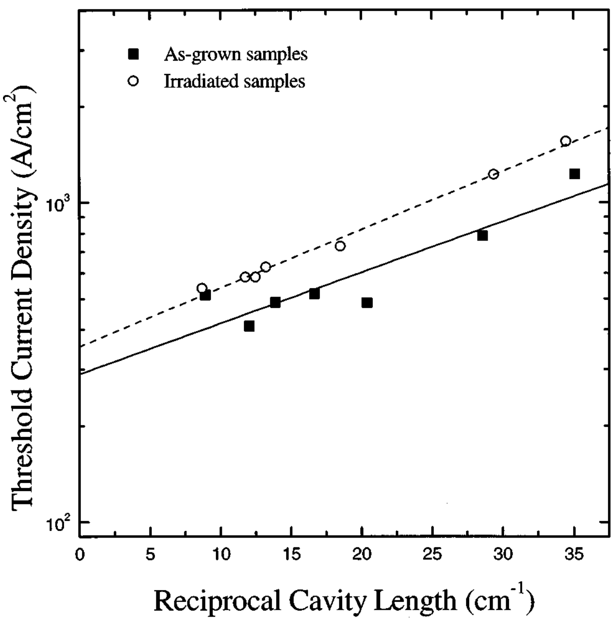

FIG. 4. The threshold current density (J_{th}) vs reciprocal cavity length for the as-grown lasers and irradiated lasers. The series resistance of all the lasers are similar and range between 3.3 and 4.5 Ω.

defects accumulated in the AlGaAs were efficiently injected across the QW to enhance the intermixing process among the In, Ga, and Al atoms. With Al diffusing into the QWs, the band gap energy was further increased.

From the results presented in Figs. 1 and 2, it is shown that larger energy shifts and better PL intensities can be achieved in InGaAs/AlGaAs material after ion irradiation and RTA than in InGaAs/GaAs material. Therefore, wavelength shift with little degradation in properties by proton irradiation and RTA in InGaAs/AlGaAs QW laser could be expected. To demonstrate this, a standard graded-index separate-confinement heterostructure (GRINSCH) laser was grown by MOCVD. The active region consisted of a 7-nm-$In_{0.2}Ga_{0.8}As$ QW sandwiched by 12-nm-$Al_{0.2}Ga_{0.8}As$ barriers; 220 keV protons were used in order to locate the damage peak near the active region. Half of the sample was masked (for reference) and the other half was irradiated with a dose of $1\times10^{15}\,cm^{-2}$ and the whole sample was then annealed at 900 °C for 30 s. After RTA, these samples together with an as-grown sample were fabricated into 4 μm wide, ridge waveguide lasers by conventional photolithography. Figure 3 depicts the lasing spectra from the three different lasers (as-grown, annealed but unirradiated, irradiated and annealed) at $1.5I_{th}$ under the pulsed conditions with 2 μs pulses of 5% duty cycle at room temperature. Wavelength shifts of 30.5 and 49.3 nm (compared with the as-grown sample) were obtained from the reference annealed sample and the irradiated annealed sample, respectively. It is clear that the 18.8 nm difference between these two devices was only due to the effect of irradiation induced intermixing. It is also noticed that the wavelength shift caused only by the thermal annealing was quite large (30.5 nm) compared with the irradiation induced shift (18.8 nm). We attribute this to the nonoptimized annealing and irradiation dose conditions. On the other hand, the outdiffusion of the Zn from the *p*-type cap layer may also play an important role in intermixing.[1] Further work is under way to identify the best condition to minimize thermally induced energy shift and study the effect of Zn induced intermixing. The comparison of the main performance parameters such as the threshold current density J_{th}, reciprocal external quantum efficiency $1/\eta_D$, internal quantum efficiency η_i, and internal loss α_i between the as-grown and irradiated devices were shown in Figs. 4 and 5. Although from Fig. 4, the increased intercept value on the *y* axis shows that the transparency current density of the irradiated devices is higher than that of the as-grown devices

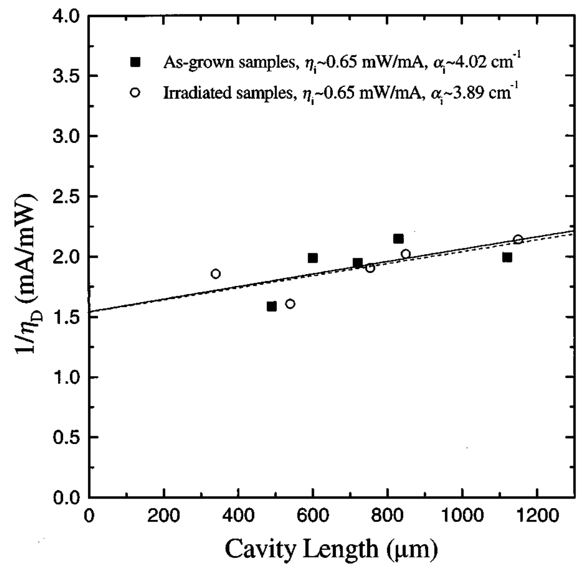

FIG. 5. Reciprocal external quantum efficiency ($1/\eta_D$) vs cavity length for the as-grown lasers and irradiated lasers. The solid curve and the dashed curve are the linear fits for the data from the as-grown devices and irradiated devices, respectively.

which is expected due to the change of density of states after QW intermixing, the η_D, η_i, and α_i in Fig. 5 indicate no degradation even after irradiation. Furthermore, all the parameters were tested under cw conditions without any coating or heat sink applied which also suggested the good quality of the irradiated lasers.

IV. CONCLUSIONS

In summary, the intermixing of InGaAs/GaAs and InGaAs/AlGaAs QWs by proton irradiation with subsequent RTA was studied. In each case, the energy shift increased with the increase of the irradiation doses. In comparison, larger energy shifts and better PL intensities recovery were observed in the InGaAs/AlGaAs material. A wavelength shift of 49.3 nm was obtained from the proton irradiated and annealed InGaAs/AlGaAs GRINSCH laser, showing that ion irradiation induced intermixing is a very promising technique in integrating lasers of different wavelengths or, integrating various devices of different functionality in photonic integrated circuits (PICs) and optoelectronic integrated circuits (OEICs).

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