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2002 Jpn. J. Appl. Phys. 41 L867

(http://iopscience.iop.org/1347-4065/41/8A/L867)

Jpn. J. Appl. Phys. Vol. 41 (2002) pp. L 867–L 869
Part 2, No. 8A, 1 August 2002

Express Letter

High-Density Plasma Enhanced Quantum Well Intermixing in InGaAs/InGaAsP Structure Using Argon Plasma

Hery Susanto DJIE, Ting MEI, Jesudoss AROKIARAJ and Periyasamy THILAKAN

Photonics Research Group, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

(Received June 10, 2002; accepted for publication June 21, 2002)

Photoluminescence was used to study the band-gap shift of argon (Ar) plasma induced quantum well intermixing in InGaAs/InGaAsP laser structure. Ar exposure for 5 min and subsequent annealing resulted in maximum blue shift of 61.4 meV. This is the first time to use the high-density plasma enhanced intermixing technique developed in inductively coupled plasma (ICP) machine to demonstrate the result of bandgap blue-shift with the improvement of crystalline quality as compared to plasma generated from pure RF power. This technique provides a promising approach of bandgap tuning for photonic integrated circuits (PIC), which demand high crystalline quality. [DOI: 10.1143/JJAP.41.L867]

KEYWORDS: quantum well intermixing, quantum well, inductively coupled plasma, argon plasma, photoluminescence

Selective quantum well intermixing (QWI) has been found to be a very useful method to achieve photonic integration due to its ability to fine tune the energy bandgap in different regions within the same epitaxial layer structure, through the interdiffusion between QW and adjacent barrier material. The QWI is a post-growth technique in tailoring the energy bandgap across single chip, which generates a considerable interest due to its simplicity, compatibility, and effectiveness for many photonics applications.[1)] The generation of desirable point defects in quantum well (QW) structures with subsequent annealing promotes intermixing between the QWs and its barriers to form alloy semiconductors. By controlling the amount of defects generated across a QW material, the energy bandgap can be spatially varied to suit the bandgap energy requirements of the device. Point defects on the surface of QW samples are created using a variety of methods[1)] including plasma induced intermixing.

Initial work on plasma induced QWI has been done using H_2 plasma glow discharge in a reactive ion-etching (RIE) system on GaAs/AlGaAs structures. Up to 9 cycles of H_2 plasma exposure and annealing is required to produce a maximum blue shift of about 42 meV.[2)] The QWI using Ar plasma generated by an electron cyclotron resonance (ECR) etcher was reported,[3)] which produced a blue shift of 72 meV. Recently, the ICP has been exploited for high etch rate, low etch damage applications and for depositing a wide variety of semiconductor materials including dielectrics and III-V semiconductors. The ICP reactor produces high-density plasmas (10^{11}–10^{12} cm^{-3}) within the plasma discharge at lower energy ion bombardment energies and low gas pressure ($<$ 10's mTorr). This plasma density is as much as two to three orders of magnitude higher than in conventional parallel-plate RIE systems. High ion fluxes comparable to an ECR can be generated by an ICP. The ICP allows a high-density of free radicals to be produced without generating a large number of highly energetic ionic species. The plasma contains highly unstable mixture of ions, electrons and neutral particles. Collision of the Ar ions with the sample structure appears to generate vacancies, interstitial and other point defects on the structure.[4)] Under certain conditions, argon plasma in ICP can be used to generate point defects to promote QWI in QWs samples.[5)]

In this letter, we report a QWI technique using ICP generated argon plasma on InGaAs/InGaAsP QW structures. Low temperature photoluminescence (PL) technique was adopted to investigate the argon plasma induced QWI mechanisms of the QW samples after plasma exposure and subsequent annealing. By exposing to argon plasma in ICP, a QW material is expected to experience both high-density plasma damage as well as physical ion bombardment damage, which enhances intermixing. For the first time, we demonstrate in ICP machine that the high-density plasma generated can enhance the intermixing instead of plasma from pure RF power and results in the improvement of crystalline quality.

The lattice-matched InGaAs/InGaAsP five quantum well samples used in the present investigations (as shown in Fig. 1) were grown by metal-organic vapor phase epitaxy (MOVPE) on a (100) oriented n$^+$-type S-doped InP substrates. The InGaAs/InGaAsP laser structure consists of five periods of 55 Å $In_{0.53}Ga_{0.47}As$ quantum wells with 120 Å InGaAsP barriers. The active region was bounded by a stepped graded index (GRIN) waveguide core consisting of InGaAsP confining layers. The thickness of these layers were 500 Å and 800 Å respectively. The structure was completed by an upper cladding of 1.4 μm with Zn doping of 5×10^{17} cm^{-3}. The contact layers consist of 500 Å InGaAsP (Zn-doped of 2×10^{18} cm^{-3}) and 1000 Å InGaAs (Zn-doped of 2×10^{19} cm^{-3}) respectively. The samples were resulted a room temperature PL peak

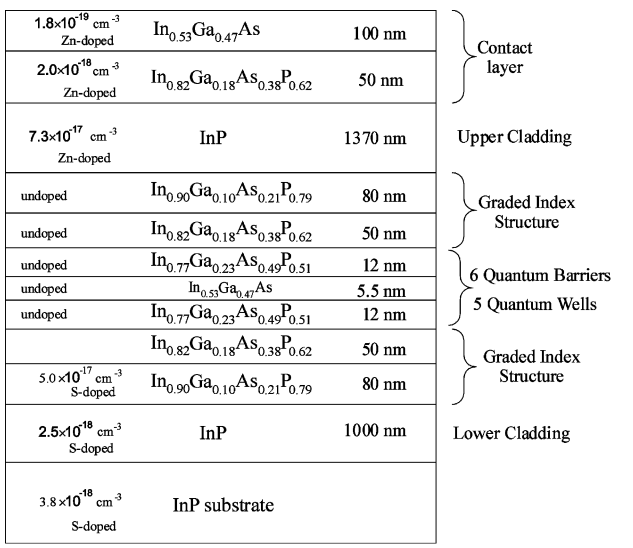

Fig. 1. A schematic structure of InGaAs/InGaAsP QWs laser grown on InP substrate.

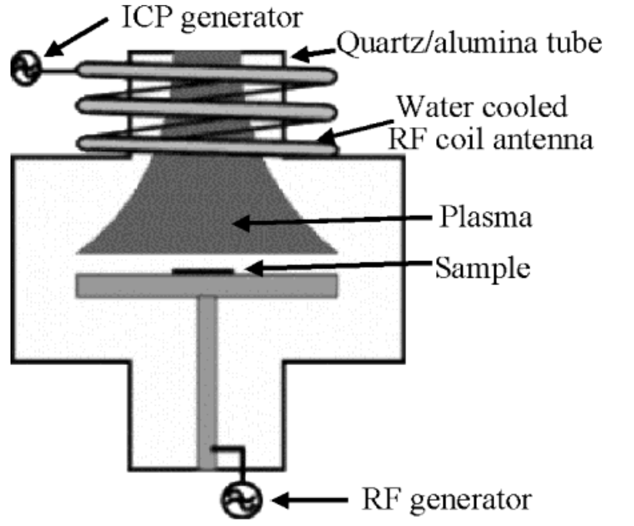

Fig. 2. A schematic diagram of the ICP reactor with remote inductive coil.

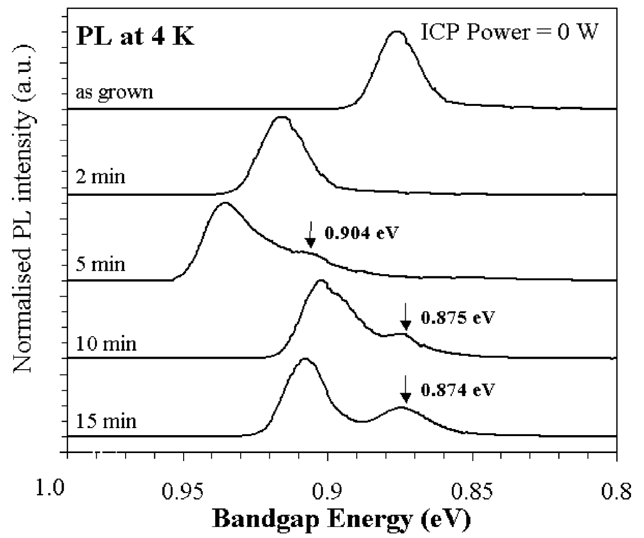

Fig. 3. Plot of normalised PL at 4 K spectra for different Ar ion exposure times. The ICP power was set to 0 W. The samples were annealed at 600°C for 2 min.

at $1.50 \pm 0.02\,\mu$m and low temperature PL peak (4 K) at $1.42 \pm 0.02\,\mu$m.

The plasma source generator ICP180 used in this experiment is shown in Fig. 2 and was built by Plasmalab System 100. The system uses inductive coil to generate high-density "remote" plasma with no direct contact between the plasma and the substrate. The 13.56 MHz radio-frequency (RF) and ICP power supply can provide the independent control of ion bombardment energy and ion current density with power up to 500 W and 3000 W respectively. The ICP parameter setting for the experiments was optimised by Taguchi method:[5] 100 sccm Ar flow rate, 80 mTorr chamber pressure, and 480 W RF power. After Ar plasma exposure, the bare samples were annealed using one step RTA at 600°C for 120 s in a flowing nitrogen atmosphere. The annealing conditions were obtained from a thermal stability test performed on as-grown samples. GaAs proximity caps were used to provide As over-pressure during the annealing step.

The PL measurements were carried out at 4 K in order to minimize the effect of phonon vibration on the PL emission using an Ar-ion (514.5 nm) laser for excitation and a liquid nitrogen cooled germanium detector associated with a conventional lock-in technique. The change of QW bandgap and the creation of sub-level states, depending on argon plasma exposure time, were assessed from the measured PL spectrum curves.

The exposure of Ar plasma and subsequent high temperature (600°C) one step annealing on the InGaAs/InGaAsP QW samples was found considerably modifying the optical properties of the QW structure. A control sample was annealed without argon exposure. Annealing step at 600°C for 2 min resulted in very small bandgap energy blue-shift (0.3 meV) on control samples mainly due to the thermal interdiffusion.

Figure 3 shows the normalised PL intensity of the intermixed InGaAs/InGaAsP QW samples under different argon ion exposure time. The PL spectra were obtained at 4 K after the annealing of argon ion exposed samples. The ionic species in plasma sheath region generated using pure RF power (ICP power = 0 W) is accelerated at normal incidence by electric field and is expected to dominantly induce highly energetic ion bombardment damage. This is mainly due to the high potential difference between the plasma and the sample, which could be as high as 1300 eV. The plasma exposure to the QW sample results in the ion bombardment dominated QWI. The annealing after exposure induces the propagation of created point defects towards QWs and promotes intermixing. As a result, the QW bandgap energy widens. It can be seen that the PL peak from QW active region emission shift towards higher energy with an increase in time of exposure until 5 min. The maximum bandgap shift at this condition is 61.4 meV (93 nm) as compared to unintermixed sample for 5 min exposure. This bandgap shift is higher than the reported QWI using 30 keV-Ar ion implantation-induced intermixing in InGaAs/InP QW samples.[6] The further increase in exposure time above 5 min results in the PL peak shift toward lower energy and an additional peak was found emerging in the low energy regime of the spectrum. Beyond this, the additional peak was found growing with the increase in exposure time (10 min and 15 min). The PL linewidth does not increase significantly as the exposure time increases, thus indicating that no significant degradation of the optical properties occurred in the intermixed QW samples. This implies that the high temperature annealing is also helping to minimize the ion bombardment induced damage in addition to the point defect propagation.[7]

It can be understood from Fig. 3 that there are two different types of mechanisms present during the increase in Ar exposure time. The initial exposure until 5 min causes the QWI and thus bandgap widening or blue-shifting. The further increase in argon exposure time results in the decrease of energy due to ion bombardment and the emergence of an extra peak in PL spectrum. This decrease of bandgap energy compared to 5 min exposure sample can be ascribed to more dominant interdiffusion of group-III sublattice (In and Ga atoms) than the interdiffusion of group-V sublattice (As and P atoms) during intermixing. Similar behavior has been theoretically reported on that either an increase or a decrease of the ground state transition energy depending the amount of interdiffusion in each sublattice.[8] It is suspected that the emergence of the extra PL peak is contributed by the additional level in the

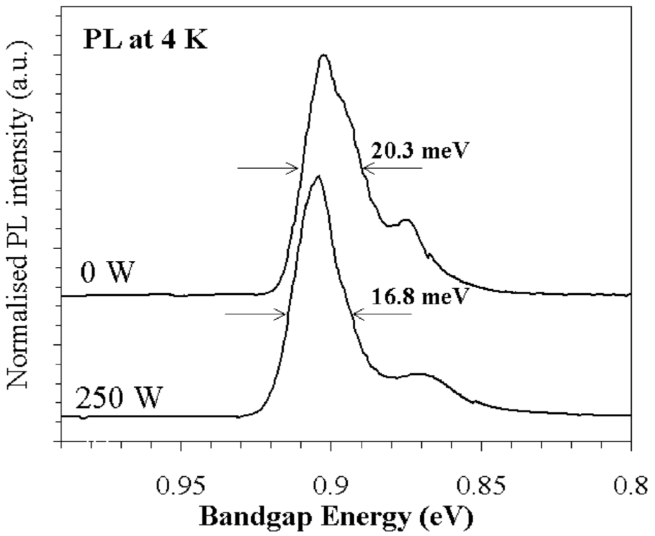

Fig. 4. The comparison of bandgap shift and linewidth broadening effect on higher density plasma exposure with and without ICP power application.

band structure of QW structures formed by redundant Ar induced point defects, which are electronically active and act as efficient radiative recombination centres. The diffused point defects enter the QW region and become electronically active. The additional increase in Ar exposure time above 5 min increases the carrier density of the sub-level. Thus, the PL emission between the band to this level becomes stronger and stronger. It was also observed that the energy difference of around 30 meV between the band edge peak and the sub-level peak is stable for different exposure time.

A comparative study was made to identify the intermixing effect on higher density plasma exposure with and without ICP power application. Increasing the ICP power (with the RF power constant) results in the increase in ion flux and a decrease in the ion bombardment energy. Figure 4 shows the PL spectra of Ar exposed samples to the Ar plasma with the same process conditions with the exception different ICP powers of 0 W (pure RF power) and 250 W. Reproducible results were obtained from other pieces of the same sample. It shows the comparable bandgap shift of 28 meV (61.5 nm) after intermixing for 10 min exposure time. The evolutions of energy blueshift and sub-level creation were also observed on QW samples exposed with different exposure times under 250 W ICP power. With the increase of ICP power at 250 W, the ICP machine produces higher ion current density and lower DC bias operation. The DC bias operation was −840 V at pure RF power and was reduced to −780 V when the ICP power was 250 W. The DC bias reduction leads to less ion bombardment induced damage. The comparable bandgap shift achieved using 250 W ICP power indicates that the high-density plasma application is also playing a strong role in intermixing the QW structures besides the pure ion bombardments. The application of ICP power induces more damage due to the plasma radiation together with high ion current density on the sample such as the relevant observation reported elsewhere.[9] The application of ICP power also widens the energy difference between the band edge emission peak to band to sub-level peak from 30 meV to 33.6 meV. The peak intensity related to the sub-level with respect to band edge normalised PL peak intensity was found decreased by a factor of 0.5. The integrated PL intensity of intermixed samples does not decrease as compared to the as grown sample. The linewidth broadening as compared to as grown samples was observed as low as 6.1 meV (7.81 nm) and 2.6 meV (1.98 nm) for ICP power at 0 W and 250 W respectively. These values are the lowest reported linewidth broadening compared to techniques such as high[10] and low[6,11] energy ion implantation induced intermixing. The improvement of QW quality is shown by smaller linewidth broadening as compared to pure RF power exposure.

In the present study, we have demonstrated a way to achieve bandgap using the Ar plasma exposure in ICP machine. The increase in Ar exposure time primarily results in bandgap shift and further exposure results in bandgap shift associated with the sub-level emission. The maximum bandgap shift was 61.4 meV under 5 min Ar exposure with pure RF power. The continuous increase in Ar exposure time above the certain level results in an increase in sub-level peak intensity with stable energy difference (30 meV). A comparable bandgap shift between ICP power of 0 W (pure RF power) and 250 W indicated the high-density plasma enhanced intermixing mechanism with a small linewidth broadening of 2.6 meV (1.98 nm). This technique provides a promising approach of bandgap tuning for the components in photonic integrated circuit (PIC), especially the active devices such as laser diodes, modulators, etc., which demand high crystalline quality.

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