Multiple Bandgap Control Using Inductively Coupled Argon Plasma-Enhanced Quantum Well Intermixing

T. Mei[1*], H.S. Djie[1], D.Nie[1], Y.X.Wang[2] and X.H. Tang[1]

[1]School of Electrical and Electronic Engineering
Nanyang Technological University, Singapore 639798
[2]Institute for InfoCommunication, Singapore
*Email address: etmei@.ntu.edu.sg

The ability to modify bandgap energy across a single substrate is a key requirement for the monolithic photonic integration. Quantum well intermixing (QWI) techniques are attractive due to their simplicity and effectiveness. In our work on high-density inductively coupled argon plasma (ICP) QWI, the bandgap blueshift as large as 104 nm on InGaAs/InGaAsP QW structures was achieved [1] and the material quality improvement has been evidenced by the photoluminescence (PL) enhancement results [2]. In the ICP-enhanced QWI, argon plasma exposure is done in an ICP machine where the interaction between Ar plasma ion species and the sample create near-surface mobile point defects. The presence of ICP power promotes much high degree of intermixing due to a high density plasma interaction. High density remote plasma also creates a radiation regime in the vacuum ultraviolet (VUV) energy band of 4-30 eV that is also regarded to have a pronounced effect on the thin QW structure leading to annealing out of grown-in defects, which explains the PL intensity enhancement. The subsequent annealing enables the diffusion of point defects down to the active QWs region, thus promoting the intermixing between the QW and the barrier.

A practical integration technique needs to create different bandgaps in selected areas over a substrate. To integrate laser, optical amplifiers, modulators, detectors and passive devices into a PIC, at least three bandgaps should be implemented over a substrate. Since the ICP-enhanced QWI process separates the point defect generation and the point defect interdiffusion in two independent processing steps, i.e., exposure and annealing, we have a simple and easy way to achieve multiple bandgap control, e.g., via the plasma exposure dose, rather than manipulating the critical annealing process.

The plasma exposure dose can be controlled in multiple exposure steps with a series of masking layers. The exposed areas are redefined by wet-etching the underneath layers after each exposure. In the experiment, a SiO_2 and a photoresist layers are used for implementing three bandgaps that involves two steps of photolithography, wet etching and Ar plasma exposure processes, followed by a single step rapid thermal annealing (RTA) process. The bandgap blueshift on the masked area is less than 3 nm, negligible compared with those on the exposed areas. The well-distinguished bandgap blueshifts at different areas were clearly observed, indicating that the exposure time is an effective controlling factor for bandgap modification. Besides, no significant PL linewidth broadening has been observed on these two-step exposed areas. By adjusting the exposure time combination of the two exposed areas on different samples, different combinations of bandgap modification have been obtained. The bandgap blueshift on the two exposed areas under different combinations of exposure times are listed in Table 1. These results indicate that this method is promising for three bandgaps modification. However, for areas undergoing the same amount of total exposure time, bandgap blueshift varies for different time combinations. This is due to the interruption of the exposures and probably the intermediate wet etching process also affects the surface morphology in the plasma exposed area.

The plasma exposure dose can also be controlled by the exposure area percentage of a patterned mask. Since most defects are generated on the near surface of the substrate, the lateral diffusion of defects during annealing can be utilized to average the defect concentration when the defects reach the QW region under the spatially patterned mask, and thus different degrees of intermixing can be obtained. The spatial defect modulated intermixing was studied using variable exposure window and multiple bandgap control was implemented in a single plasma exposure. Eight different plasma exposure area percentages (0, 30, 40, 45, 50, 75, 90 and 100%) in a mask formed by 2.5 μm period SiO_2 strips were used to control the intermixing degree. Figure 1 shows the bandgap shifts observed from PL peak wavelengths. The degree of intermixing increases linearly with increasing exposure area percentage, indicating the correlation between the amount of created mobile defects on the surface and the achieved bandgap shifts.

In conclusion, we have used ICP-enhanced QWI technique for multiple bandgap control for the purpose of photonic integration. Multiple bandgaps ove a single substrate are achieved by controlling the plasma exposure dose without manipulating the critical annealing process.

[1] H. S. Djie, J. Arokiaraj, T. Mei, X. H. Tang, L. K. Ang, D. Leong, J. Vac. Sci. Technol. B., 21 (4), L1-4, 2003
[2] H.S. Djie, T. Mei, and J. Arokiaraj, Appl. Phys. Lett. 83 (2003) 60.

Table 1 Bandgap blueshift on different areas under different combinations of exposure time

Two exposures		One exposure	
Time (min)	Blueshift (nm)	Time (min)	Blueshift (nm)
2+1	42	1	12
2+2	68	2	10
2+3	84	3	66
3+2	40	2	14

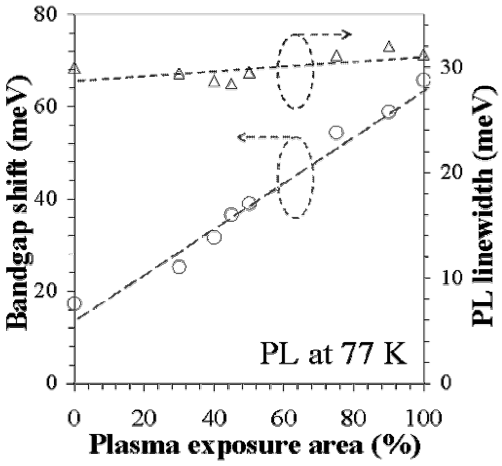

Figure 1 Bandgap buleshift and linewidth of PL spectra versus plasma exposure area percentage.