Intermixing of InGaAs/GaAs Quantum Well Using Multiple Cycles Annealing

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***Abstract*- The authors investigate the effect of intermixing in shallow InGaAs/GaAs quantum well structure using impurity free induced disordering (IFVD) technique. The degradation of the photoluminescence (PL) signal is due to the severe loss of As from the material during high temperature annealing at above intermixing activation energy. The recovery of the PL signal from the intermixed InGaAs/GaAs quantum-well has been found to be achieved by applying a cycle-annealing at 800 °C which is below activation temperature.**

I. INTRODUCTION

Quantum well intermixing (QWI) methods has been successfully implemented to engineer the optical and material properties of semiconductor quantum heterostructures over the past decades [1]. The technique enables various benefits such as excellent alignment, negligible reflection losses, and intrinsic mode matching between integrated devices, hence providing a very enticing vision for the future of high-density photonic integrated circuits (PICs). Intermixing can be achieved using several techniques such as impurity free vacancy disordering (IFVD) [2], impurity induced disordering (IID) [3], laser-induced disordering [4], and plasma irradiation induced intermixing [5]. The intermixing process usually involves the introduction of defects especially vacancies and interstitials to the quantum well (QW) material. During high temperature annealing, the impurities or created point defects enhance the atomic interdiffusion rate between the quantum nanostructure and the barriers, and promote intermixing. As a result, the technique spatially modifies the material bandgap profile.

IFVD technique using SiO_2 cap to induce group-III outdiffusion into the dielectric layer hence increases the Ga vacancy concentration, and promotes group-III interdiffusion between the QW and surrounding barriers during high temperature annealing. Under high temperature annealing with only the GaAs proximity, the semiconductor sample capped with porous SiO_2 film will suffer from severe As loss that depletes the group-V element in a shallow QW sample and increases the group-III interstitials in the material. In an undoped QW structure, both the acceptor-like group-III vacancies, and donor-like group-III interstitials will be supported, which will contribute to an increase in the QWI rate [6, 7]. However, excessive loss of As from the sample during high temperature annealing for the shallow QW will result in the degradation of material quality.

In this paper, we investigate a QWI process using IFVD effect to induce QWI in an undoped GaAs-based shallow QW structure. The excessive loss of As in the material has been found to degrade the quality of the QW structure, as evident from the weak and noisy photoluminescence (PL) signal. In this work, an extended cycle annealing technique has been introduced at an annealing temperature below the activation energy to re-crystallize the material and to restore the optical quality of the structure.

II. EXPERIMENTS

The InGaAs/GaAs double quantum well (DQW) structure grown by metal-organic vapor phase epitaxy (MOVPE) technique was used in this experiment. The DQW region was undoped and consisted of two 12 nm wide InGaAs QWs, separated by a 10 nm thick GaAs barrier and surrounded by 40 nm of GaAs. The structure was completed by 70 nm of additional separate confinement heterostructure (SCH) layers on each side and a 2000 nm thick lower cladding. The top capping layer consists of 300 nm thick undoped $In_{0.49}Ga_{0.51}P$. The as-grown material exhibits two photoluminescence peaks at 825 nm from the GaAs barrier layers and 900 nm from the InGaAs QW at 77 K.

Samples were deposited with a 250 nm thick SiO_2 layer using plasma enhanced chemical vapor deposition (PECVD). The intermixing stage was carried out by a rapid thermal processor (RTP). Samples were annealed under various temperatures for 2 minutes. The samples were placed face down, sandwiched between two fresh pieces of GaAs proximity caps to provide an As overpressure environment during annealing process. The samples were characterized using PL spectroscopy after intermixing. The PL measurement was performed at 77 K using a 62.5-μm-diameter optical fiber as a signal probe and a 532 nm diode pumped solid state laser as an excitation source.

III. Results and Discussions

Fig. 1 shows the 77 K PL spectra from the annealed SiO_2 capped InGaAs/GaAs DQW samples at temperature from 800 ºC to 900 ºC. The degree of intermixing progressively increases with increasing annealing temperature. A bandgap shift of 38 nm (61 meV) was observed from the SiO_2 intermixed sample annealed at 900 ºC. Considering the small band offset between the barrier and the quantum well of 125 meV, the 61 meV blue shift represents almost 50 % of group-III elemental interdiffusion, which is considerably large.

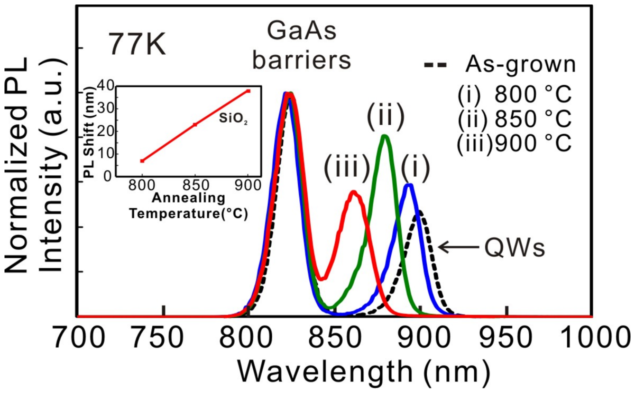

Fig. 1. PL spectra at 77 K from the InGaAs/GaAs DQW samples after annealed at various temperatures from 800 ºC to 900 ºC for the intermixed sample. For clarity, all PL signals are normalized with the barrier signal of the as-grown sample.

The postulation of excessive As-outdiffusion is evident by the observation of significant PL degradation from sample annealed at 850 ºC for 2 minutes (Fig. 2). In our case, the QWs are placed ~ 480 nm below the surface. Small depletion of As in the QW might have contributed to the significant degradation of the PL signal. To overcome this issue, we employed a cycle-annealing approach at below activation temperature to minimize the As-outdiffusion aiming at re-crystallize the sample and fully restoring the crystal quality of the material.

The cycle-annealing process is achieved by subsequent annealing the intermixed samples (i.e. sample capped with SiO_2 and annealed at 850 ºC for 2 minutes) with cycles of RTP at 50 ºC below the intermixing temperature (i.e. 800 ºC for 2 minutes). The cycle of annealing performed at below the intermixing activation energy allows re-crystallizing the material without significantly extending the bandgap shift.

The sample intermixed at 850 ºC for 2 minutes exhibits a PL integral power of 40 dB lower than the as-grown sample. With subsequent annealing at 800 ºC for 2 minutes, the PL strength increases by 13 dB. Fig. 2 shows the evolution of the PL intensity for sample subjected to 2-8 annealing cycles. The signal of the PL makes a fully recovery after sample is annealed at 800 ºC for 8 cycles.

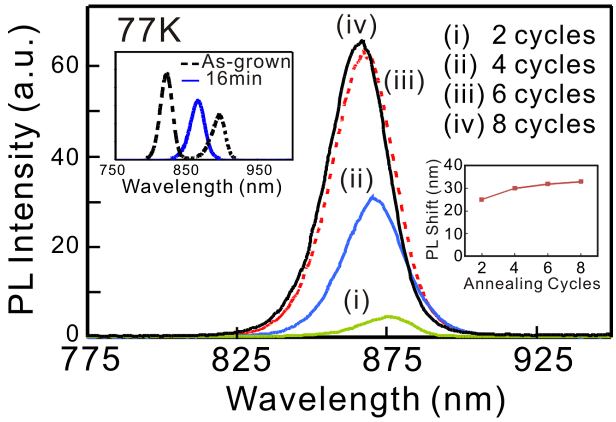

Fig. 2. 77 K PL spectra from the intermxed InGaAs/GaAs DQW sample after annealed at 800 ºC for [(i) 2 , (ii) 4 , (iii) 6, (iv) 8 cycles].

The right inset in Fig. 2 summarizes the wavelength blueshift versus the number of annealing cycles, while the left inset compares the PL signal from the as-grown sample. Compared to the 850 ºC intermixed sample, narrower PL linewidths were observed from the subsequent annealed sample suggesting an improvement of material quality (Fig. 3).

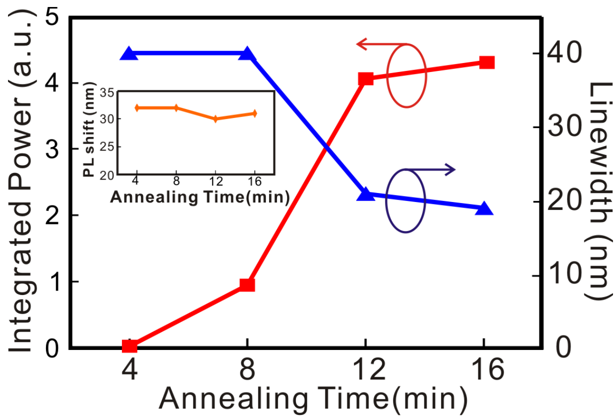

Fig.3. Integrated Power and Linewidth vs. annealing time from the InGaAs/GaAs DQW samples annealed at 800 ºC

IV. Conclusions

In summary, we have demonstrated a highly selective and reproducible SiO_2 intermixing in InGaAs/GaAs QWs heterostructure. A differential blueshift as large as 38 nm (61 meV) has been observed from the intermixed sample. Extended cycle annealing technique has been introduced to recover the crystal quality of the active epitaxy layer, and to restore the optical quality of the structure. The signal of the PL makes a fully recovery after annealing at 800 ºC for 8 cycles.

V. Acknowledgments

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