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Doped cap layer effect on impurity-free vacancy enhanced disordering in InGaAs/InP quantum well structures

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Strong influence on impurity-free vacancy enhanced disordering by the cap layer doping is studied on the InGaAs/InP quantum well structure with a doped cap layer. The observations are consistent with intermixing experiments using both Si_3N_4 and SiO_2 as encapsulation dielectric layers. The largest intermixing occurs in the *n*-InP capped samples and is explained by the enhancement in out-diffusion of positive ions by the built-in electric field.

Keywords: point defects, interdiffusion, built-in electric field.

1. Introduction

Quantum-well-intermixing (QWI) techniques, such as impurity-free vacancy enhanced disordering (IFVD) [1, 2], laser-induced intermixing [3, 4], ion implantation-induced disordering (IIID) [5, 6], plasma-exposure-induced disordering [7, 8], *etc*., have attracted researchers' attentions for their potential applications in photonic integrated circuits. The mechanisms involve defect generation, diffusion and enhancement in intermixing and need more researches to be understood comprehensively. Among different QWI techniques, IFVD has been investigated for both AlGaAs/GaAs [9] and InGaAs(P)/InP [10] material systems. For IFVD on InGaAs(P)/InP quantum well (QW), different choices of encapsulant dielectric caps, *e.g*., SiO_2, Si_3N_4, *etc*., have been studied. It has been revealed that the bandgap energy shift depends on different combinations of dielectric and semiconductor cap layers [11]. However, the influence on IFVD by the doping in the semiconductor cap layer, which could be different for different device structures and applications, has not been fully studied. It has been reported that built-in electric field plays an important role in plasma-induced QWI because diffusion of charged defects can be either enhanced or retarded [8]. In this paper, we investigate the IFVD in an InGaAs(P)/InP QW structure with the cap layer doped in different ways. The observed difference in intermixing for different caps is opposite to that in plasma-induced QWI [8], but can be explained by the built-in electric field effect.

2. Experiment and result

The sample used in the experiment is a lattice-matched $In_{0.53}Ga_{0.47}As$/InP single QW structure grown on a (100) oriented *n*-type sulfur-doped InP substrate using metal organic chemical vapor deposition (MOCVD). The single QW structure consists of a 3.5 nm-thick undoped $InGa_{0.53}As_{0.47}$ well sandwiched in 200 nm-thick undoped InP barriers. The sample structure is completed with a 800 nm-thick InP cap layer, which is either undoped (*u*-type, weakly *p*-type due to unintentional background doping), *p*-type doped with Zn to 2×10^{18} cm^{-3} or *n*-type doped with Si to 2×10^{18} cm^{-3}. The encapsulant dielectric cap is a 150 nm-thick layer of either SiO_2 or Si_3N_4 deposited on the sample surface by plasma enhanced chemical vapor deposition (PECVD). The PECVD was performed at 280 °C. For Si_3N_4 deposition, the flow rates of N_2, NH_3, SiH_4 (pure) and He were set at 300, 59, 28 and 76 sccm, respectively. The chamber pressure was set at 497 mTr and the RF power at 200 W with a DC bias of 85 V. For SiO_2 deposition, the flow rates of SiH_4 (pure), N_2O and He were set at 30, 400 and 184 sccm, respectively. The chamber pressure was set at 730 mTr and the RF power at 100 W with a DC bias of 65 V. The rapid thermal annealing (RTA) process was performed with a Si susceptor under N_2 ambient for 60 s at temperature of 750 °C, 775 °C, or 800 °C, respectively. Room temperature polarized photoluminescence (PPL) spectra at edge-emission [12] were measured using a 1064 nm Nd:YAG laser for excitation. The secondary ion mass spectra (SIMS) were tested on the samples annealed at 800 °C.

The measured transverse electric (TE)- and transverse magnetic (TM)-PPL spectra of samples annealed at 800 °C are shown in Fig. 1. The spectra of the three samples

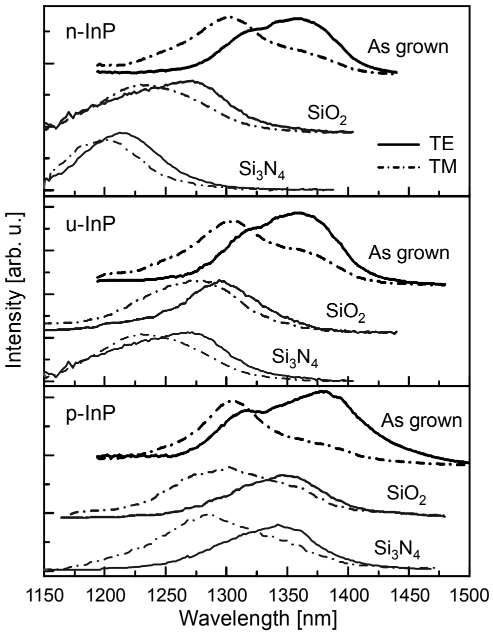

Fig. 1. Measured TE- and TM-PPL spectra for samples with *p*-, *u*-, and *n*-InP cap layers experienced RTA at 800 °C for 60 s.

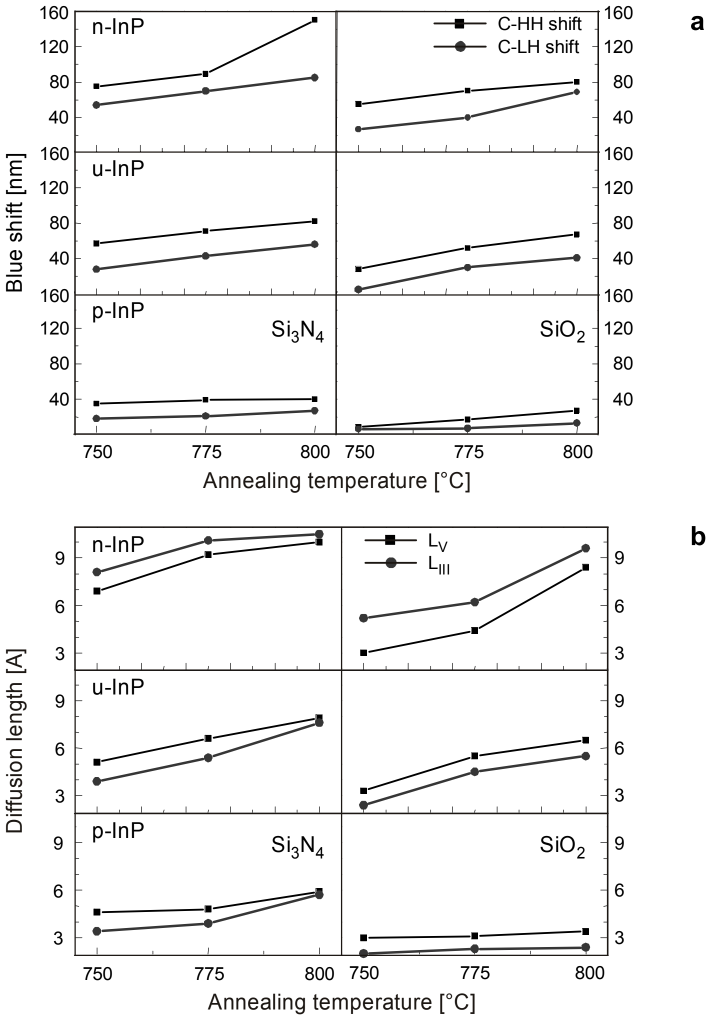

Fig. 2. Measured C–HH and C–LH blue shifts (**a**) and calculated group V and group III diffusion lengths (**b**) versus annealing temperature.

with differently-doped cap layers presented obviously different shifts. By fitting two--peak Gaussian curves to the TE- and TM- PPL spectra correlatively [13, 14], the peak wavelengths for electron–heavy hole (C–HH) and electron–light hole (C–LH) ground-state transitions were obtained. The diffusion lengths on the group V (L_V) and III (L_{III}) sub-lattice were calculated from C–HH shift and C–LH shift [12]. The blue shifts of C–HH and C–LH transitions and the derived L_V and L_{III} versus annealing temperature are shown in Fig. 2. Results obtained from *n*-, *u*- and *p*-InP cap samples all confirm that Si_3N_4 dielectric capping is more effective for IFVD on the single InGaAs/InP QW sample used than SiO_2 dielectric capping, which is in agreement with the observation reported for undoped InP capped QW structures in [2].

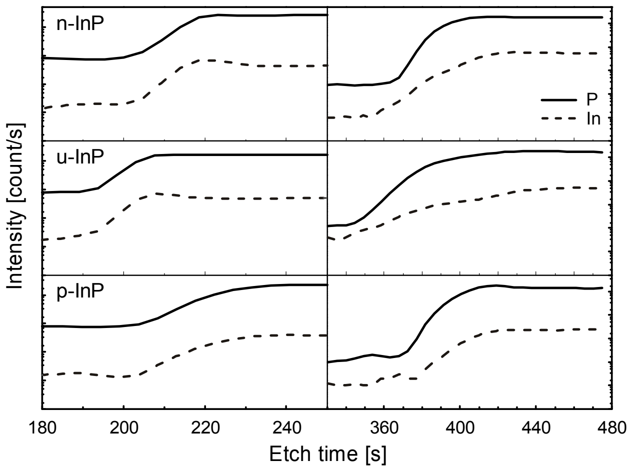

Fig. 3. Compositional profiles of P and In across the interface of InP and Si_3N_4 (**a**) and SiO_2 (**b**) in samples with *n*-doped, undoped and *p*-doped InP cap layers after annealing at 800 °C for 60 s.

Figure 2 shows that the effect of doping in InP capping layer obtained for both Si_3N_4 and SiO_2 dielectric capping is quite consistent, except that Si_3N_4 capping induces larger extent of intermixing. The intermixing increases greatly with increasing annealing temperature. It can be seen clearly that *n*-InP capped samples showed the strongest interdiffusion and *p*-InP capped samples the weakest. This trend is just opposite to what was observed in the plasma-enhanced QWI [8], implying a difference in the interdiffusion process. Figure 3 shows the measured SIMS results for the samples with differently doped cap layers under RTA at 800 °C. In all the three types of samples with *n*-, *u*- and *p*-doped InP cap layers, both In and P were found in the dielectric layers. The Si_3N_4/InP and SiO_2/InP interfaces were reached at 210 s and 390 s during etching, respectively.

3. Discussion

The IFVD comprises a process of ions out-diffusion into the encapsulant dielectric layer and a concurrent process of vacancies left-behind inward diffusion to promote intermixing in the quantum well. The out-diffusion process possesses higher activation energy than the defect diffusion process within lattice because higher energy is required for ions to go beyond the boundary of the semiconductor lattices. The plasma--enhanced QWI applied on the same samples can work at an annealing temperature as low as 525 °C [15], whereas the IFVD can only work for a temperature greater than 700 °C. Therefore, it can be understood that the ion out-diffusion is the dominating process in IFVD.

For a doped InP cap layer, the built-in electric field is formed at the interface between the InP and the dielectric layer due to carrier diffusion and redistribution. The directions of the built-in electric field are different for different doping types,

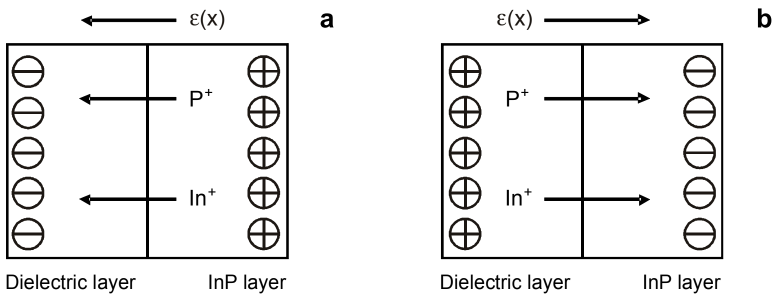

Fig. 4. Schematic space charge region showing electric force direction of the out-diffusion of positively charged ions from InP top layer to dielectric layer at the interface for *n*-InP (**a**) and *p*-InP (**b**).

which is illustrated in Fig. 4. The out-diffusion of the positive ions of In and P will experience the influence of the built-in electric field, which is different for the cap layer of different doping types. As seen in Fig. 4, in the *n*-InP cap layer, the electric field points toward the dielectric layer and benefits the out-diffusion process of positive ions, whereas the situation is opposite in the *p*-InP cap layer. This explains why the largest intermixing occurred in *n*-InP capped samples and the smallest intermixing in *p*-InP capped samples, whereas the *u*-InP cap samples presented an intermediate result.

It is also noted that intermixing did not take place on the group III and V sublattices equally. Group III interdiffusion was weaker than group V interdiffusion in *u*-InP and *p*-InP capped samples but the situation was inverted in the *n*-InP sample. This result is in agreement with the explanation that the influence of the built-in electric field on intermixing is more prominent for group III sublattice [8] due to greater charge number of In ions, since the built-in electric field in *n*-InP becomes different from the other two cases.

4. Conclusions

In conclusion, IFVD is influenced by the cap layer doping for the InGaAs/InP QW structure. The largest intermixing occurs in samples with the *n*-InP cap layer, but the smallest occurs in samples with the *p*-InP cap layer for both Si_3N_4 and SiO_2 encapsulant dielectric caps. The ion out-diffusion is enhanced in *n*-InP capped samples by the outward oriented electric field built at the dielectric and semiconductor interface. The difference of interdiffusion caused by different types of doping in the semiconductor cap layers is much more prominent than that caused by different encapsulant dielectric cappings. Therefore, this work has suggested a more effective approach to control and optimization of IFVD process.

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