Impurity-free vacancy disordering in InGaAs/InP and InGaAs/InGaAsP multiple quantum wells: Effects of $In_{0.53}Ga_{0.47}As$ cap layer and stoichiometry of dielectric capping layers

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The InGaAs/InP and InGaAs/InGaAsP multiple quantum well (MQW) structures are particularly attractive for optoelectronic device applications in long-wavelength optical communications. The quantum well intermixing (QWI) technique has recently received growing interest for area-selective control of the bandgap energies in the integration of optoelectronic devices [1]. Especially, impurity-free vacancy disordering (IFVD) is currently believed to be the most promising for QWI, since it is simple and flexible and can avoid any damage- or impurity-related drawbacks [2]. In the IFVD process, vacancies are selectively injected into the semiconductor region which lies under the dielectric capping layer, and these vacancies enhance QWI. SiO_2 and Si_3N_4 have frequently been employed as the dielectric capping material for IFVD. QWI of MQWs by IFVD can also be affected by the kinds of dielectric layers employed and their stoichiometry because the diffusivities of anion/cation vacancies are affected differently by stoichiometry of the dielectric layers employed [3]. In this work, we reported the effects of the stoichiometry of the SiO_x and SiN_x capping layers on the IFVD of the InGaAs/InP and InGaAs/InGaAsP MQWs when the $In_{0.53}Ga_{0.47}As$ cap layer is employed and not employed.

The InGaAs/InP MQW structure (λ_g= 1537nm) was grown on n-InP substrate. It consisted of a 300nm InP buffer layer, 7 MQWs with 60Å $In_{0.53}Ga_{0.47}As$ wells and 90Å InP barriers, and a 150nm InP cladding layer. The InGaAs/InGaAsP MQW structure is following: a 300nm InP buffer layer, 5 pairs of 38Å $In_{0.53}Ga_{0.47}As$ (λ_g=1650nm)/125Å $In_{0.81}Ga_{0.19}As_{0.37}P_{0.63}$ (λ_g=1125nm) MQWs, and a 150nm InP cladding layer [4]. All the layers were intentionally undoped. In some samples, a 100nm undoped $In_{0.53}Ga_{0.47}As$ cap layer was grown on the InP cladding layer to examine its influence on QWI. 100nm dielectric capping layers (i.e., SiO_2 and Si_3N_4) were deposited by PECVD. The stoichiometry of the SiO_x and SiN_x films was changed by the SiH_4 flow rate of 20-200sccm with a fixed N_2O flow rate of 800sccm, and of 100-200sccm with a fixed NH_3 flow rate of 30sccm, respectively. Then, rapid thermal annealing (RTA) was done in a nitrogen atmosphere. The PL measurements were performed at room temperature.

The bandgap energy shift, $\triangle E_g$, on the RTA temperature with a fixed RTA time of 25s for various InGaAs/InP MQWs with SiO_2 or Si_3N_4 capping layers and with or without the $In_{0.53}Ga_{0.47}As$ cap layer is shown in Fig. 1. At annealing temperatures above 750°C, the SiO_2 cladding layer induced a much larger blue shift than the Si_3N_4 capping layer when the $In_{0.53}Ga_{0.47}As$ cap layer was not introduced. Moreover, when the $In_{0.53}Ga_{0.47}As$ cap layer was inserted, the MQWs with the SiO_2 layers displayed highly enhanced $\triangle E_g$, while those with Si_3N_4 layers did not show any appreciable enhancement of $\triangle E_g$. Therefore, the trends shown in Fig. 1 manifest that SiO_2 is a better diffuser than Si_3N_4 for the anion vacancies. That is, the anion or cation vacancies should be supplied primarily through the dielectric capping layer, and the inserted $In_{0.53}Ga_{0.47}As$ only enhances the preferential diffusion of anion vacancies since the vacancy reservoir is the surface of the dielectric capping layer. Perhaps SiO_2 is a good diffuser for both anion and cation vacancies. Note that the cation intermixing reduces the bandgap energy of the well layer in the InGaAs/InP MQW structure. Thus, the inserted $In_{0.53}Ga_{0.47}As$ cap layer should block the cation vacancy diffusion and enhances the preferential diffusion of anion vacancies. With the Si_3N_4 capping layer, on the contrary, the diffusion of anion vacancies is rather limited compared to the case of the SiO_2 capping layer. Figure 2 shows bandgap energy shift, $\triangle E_g$, on the RTA temperature with a fixed RTA time of 30s for InGaAs/InGaAsP MQWs with different hybrid capping layers. The influence of the $In_{0.53}Ga_{0.47}As$ cap layer under the SiO_2 capping layer was largest at 700°C and then decreased as the temperature increased. This fact suggests that the amount of anion and cation vacancies diffused through the SiO_2 capping layer is rather considerable, and the $In_{0.53}Ga_{0.47}As$ cap layer enhances the preferential diffusion of anion vacancies by effectively blocking the diffusion of cation vacancies. At 750°C, the amount of anion vacancies diffused through the SiO_2 capping layer can be large enough, and thus the inserted $In_{0.53}Ga_{0.47}As$ cap layer may not have a decisive role in the increase of $\triangle E_g$. On the other hand, the amount of anion vacancies diffused through the employed Si_3N_4 capping layer can be much larger than that of the cation vacancies for the examined temperature range, even if the former is smaller than that through the SiO_2 capping layer. The effect of the blocking of anion vacancy diffusion should be more apparent than the enhancement of the preferential diffusion of anion vacancies. We believe that this phenomenon is also a consequence of the role of the $In_{0.53}Ga_{0.47}As$ cap layer as