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Improvement of Phosphorus Activation in In-Situ Phosphorus Doped Silicon Epitaxial Film by Cryogenic Silicon Ion-Implantation and Recrystallization Annealing

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Introduction

In scaled Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) device nodes, a low resistivity source and drain (S/D) formation is required for a reduction in parasitic series resistance of MOSFET. In-situ highly doped silicon (Si) alloys selective epitaxial growth (SEG) using chemical vapor deposition (CVD) can be the leading candidate.[1–3] However, high working temperatures, which are necessary for a high quality selective Si alloy epitaxy grown on different crystallographic planes, should lower doping in Si film. This can be interpreted in terms of clustering and/or precipitates of dopant atoms during high temperatures. Thus, especially concerning in-situ phosphorus (P) doped Si alloy (Si:P) SEG, many studies on sufficiently low temperature selective epitaxy process, such as the combination of non-selective deposition followed by selective removal of undesired material (so-called “pseudo” SEG), for heavy P-doping Si alloy with a low resistivity have been conducted.[4,5] However, regarding the “pseudo” SEG, the improvement of crystalline defects of Si:P grown on non-Si{100} plane is still a matter of research.

In this work, we apply Si ion-implantation followed by nonmelt laser annealing to improve the P-activation in Si:P film. We discuss impact of this approach on the diffusion and activation of P atoms in Si:P film.

Experimental Procedure

A Si:P film with a thickness of 40 nm and a P concentration ([P]) higher than ~2.0 x 10^{20} cm^{-3} was grown on p-type Si (001) substrate of 9~18 Ω-cm by reduced pressure CVD below 700 ˚C in a dichlorosilane – a diluted phosphine – hydrogen mixture. Si ions were implanted cryogenically (t < –60 ˚C) in the Si:P films for reduced implantation damage with a 0˚ tilt and a 0˚ rotation. Table I shows the conditions of cryogenic (cryo) Si^+-implantation, where the amorphous layer thickness as measured by cross-sectional transmission electron microscopy (TEM) is also indicated. Then, recrystallization annealing was performed using nonmelt laser annealing above 1200 ˚C within sub-2 ms with preheating below 600 ˚C.

The depth profiles of P in the Si:P film were measured by secondary-ion mass spectroscopy (SIMS) with Cs^+ as the primary ion at a sputter energy of 500 eV. The electrical properties of the Si:P film were evaluated by a linear four-point probe (4PP) method.

Table I Conditions of cryogenic Si^+-implantation.

	Energy	Fluence	Tilt / Twist	Temperature	Amorphous layer thickness
i.	2.3 keV	1 x 10^{15} cm^{-2}	0º/0º	t < –60 ºC	
ii.	2.3 keV	2.3 x 10^{15} cm^{-2}	0º/0º	t < –60 ºC	
iii.	8 keV	2.3 x 10^{15} cm^{-2}	0º/0º	t < –60 ºC	~25 nm
iv.	15 keV	1 x 10^{15} cm^{-2}	0º/0º	t < –60 ºC	
v.	15 keV	2.3 x 10^{15} cm^{-2}	0º/0º	t < –60 ºC	~43 nm

Results and Discussion

High SEG temperature increases growth rate but also reduces activation efficiency (a.e.) as seen in Fig. 1, while the [P] in Si:P film is independent of the investigated SEG temperature. The a.e. was estimated by using the values of [P] measured by SIMS, sheet resistance (ρ_s) measured by the linear 4PP, and thickness of the Si:P film. This implies that clustering and/or precipitates of P atoms by the high temperature causes the reduction of a.e.

The cryo ion-implantation can reduce the number of residual crystal defects after annealing due to a rapid amorphization and suppression of both Si interstitial clustering and vacancy clustering,[6,7] Figures 2 show cross-sectional TEM images for the Si^+-implanted samples at different temperature with a fluence of 1 x 10^{15} cm^{-2} after laser annealing at 1225 ˚C. Crystal defects could not be observed in the cryo Si^+-implanted sample [Fig. 2(a)]. But in contrast, the Si^+-implanted sample at room temperature after laser annealing at 1225 ˚C showed many residual crystal defects, such as dislocations, stacking faults, and end-of-range (EOR) defects, as represented in Fig. 2(b).

P diffusion in heavily cryo Si^+-implanted Si:P varies depending on Si^+-implantation conditions as seen in Fig. 3, where depth profiles of P atoms in the heavily cryo Si^+-implanted Si:P after laser annealing at 1225 ˚C is represented. No marked changes in P depth profiles are clearly observed in the nonmelt laser annealed samples without Si^+-implantation. The nonmelt laser annealing allowed extremely rapid heating and cooling within a few ms, so that P atoms could not be moved. Meanwhile, cryo Si^+-implantations at 8 [Fig. 3(b)] and 15 keV [Figs. 3(a) and 3(b)] permit an increased amount of P diffusion during laser annealing at 1225 ˚C within sub-2ms. In addition, with cryo Si^+-implantation at 8 keV, a “kink” appears in the P profile at a [P] of approximately ~1.5 x 10^{20} cm^{-2}, as represented in Fig. 3(b). These results can be due to ion-implantation damage induced transient enhanced diffusion of P atoms via self-interstitial Si (*I*) atoms during nonmelt laser annealing within sub-2 ms. Notice that the sample implanted at 15 keV shows a shallow P diffusion profile compared with the sample implanted at 8 keV, as shown in Fig. 3(b). By considering the Si:P thickness and a difference in excess *I* distribution created by cryo Si^+-implantation, since the excess *I* distribution is moved away from the P profile by increasing the implantation energy, it is likely to result in less enhanced P diffusion.

It is interesting to note that the P profile near the Si:P/Si substrate interface for the shallowest implanted (2.3 keV) sample remains the same compared to the non-implanted sample, as represented in Figs. 3(a) and 3(b). In addition, the P plateau profile changes its undulation at a depth deeper than ~10 nm. This implies that since the *I* excess produced by the shallow implantation are not distributed sufficiently to nearby the Si:P/Si substrate interface, diffused P atoms via excess *I* can not move beyond the interface during the laser annealing at 1200–1225 ˚C within sub-2 ms.

Electrical conductivity of heavily cryo Si^+-implanted Si:P film varies depending on Si^+-implantation energy and/or nonmelt laser annealing temperature as seen in Fig. 4, where the dependence of the ρ_s measured by the linear 4PP on the nonmelt laser annealing temperature is represented. The ρ_s of non-implanted sample decreases with increasing annealing temperature. The difference in ρ_s for the as-grown Si:P vs. the Si:P annealed at 1225 ˚C laser annealing is about 22%. This can be interpreted in terms of a thermal decomposition of P-containing clusters and/or precipitates and resultant activation of P atoms during laser annealing higher than 1200 ˚C. Meanwhile, note that the amount of reduction in ρ_s increases by the cryo Si^+-implantation. An approximately 6% ρ_s decrease is observed in the 2.3keV cryo Si^+-implantated samples in comparison with the non-implanted sample after laser annealing at 1225 ˚C (Fig. 4), while the 2.3keV cryo Si^+-implantation has no effect on P diffusion toward Si substrate during any of the investigated laser annealing temperature, as represented in Figs. 3(a) and 3(b). On the other hand, with cryo Si^+-implantations at 8 and 15 keV, ρ_s decrease markedly (Fig. 4) as P atoms are diffusing toward Si substrate as represented in Fig. 3(b). The ρ_s of 15 keV

Si$^+$-implanted samples is the same compared to the 8 keV Si$^+$-implantated samples. By considering the P profile of samples [Fig. 3(b)], the 15 keV Si$^+$-implantation is likely to increase a number of active P atom compared to the 8 keV Si$^+$-implantation, which can be interpreted with a thick amorphous Si:P created by the high energy Si ion-implantation. These results indicate that inactive P atoms in the Si:P epitaxal grown film become reactivated efficiently by the cryo Si ion-implantation and nonmelt laser annealing recrystalization at higher than 1200 ˚C for the sub-2 ms.

Conclusions

It is found that, Si:P epitaxial growth temperature higher than 675 ˚C reduces activation efficiency of P doping but also increases growth rate, while the [P] in Si:P film is independent of the investigated growth temperature. This can be interpreted in terms that clustering and/or precipitates of P atoms occur during high temperature epitaxy growth. The cryo (t < –60 ˚C) Si ion-implantation with a fluence of 1 x 10^{15} cm^{-2} can reduce the number of residual crystal defects after laser annealing at 1225 ˚C for sub-2 ms. Also, P diffusion via point defects after nonmelt laser annealing higher than 1200 ˚C for sub-2 ms varies depending on cryo Si$^+$-implantation energy, which can be due to the excess self-interstitial Si distribution created by the cryo Si$^+$-implantation. If the excess self-interstitial Si distribution is moved away from the P profile by increasing the implantation energy, it results in less enhanced P diffusion. It is likely that the heavy cryo Si$^+$-implantation with a fluence higher than ~1 x 10^{15} cm^{-2} followed by nonmelt laser annealing higher than 1200 ˚C for sub-2 ms reactivates successfully inactive P atoms in the Si:P eptaxial grown film.

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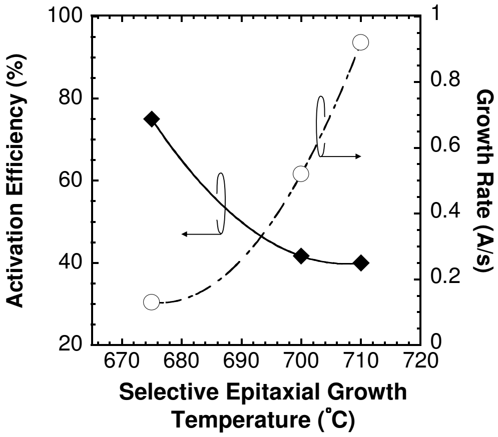

Fig.1 Activation efficiency (a.e.) and growth rate of Si:P epitaxial grown film as functions of growth temperature. The a.e. is estimated by using the values of P concentration, sheet resistance, and thickness of the Si:P film. High growth temperature increases growth rate but also reduces a.e..

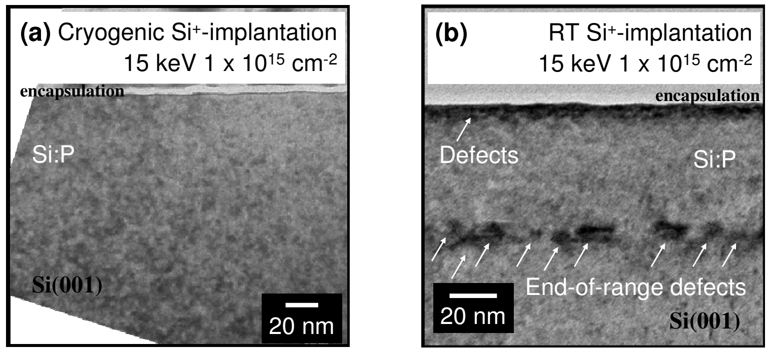

Fig.2 Cross-sectional TEM images for Si$^+$-implanted Si:P film at an acceleration energy of 15 keV with a fluence of 1 x 10^{15} cm^{-2} **(a)** at below –60 ˚C (cryo) and **(b)** at room temperature (RT) after laser annealing at 1225 ˚C for sub-2 ms. Crystal defects cannot be observed in the cryo Si$^+$-implanted sample [Fig. 2(a)]. In contrast, the Si$^+$-implanted sample at RT shows numerous residual crystal defects, such as dislocations, stacking faults, and end-of-range defects [Fig. 2(b)].

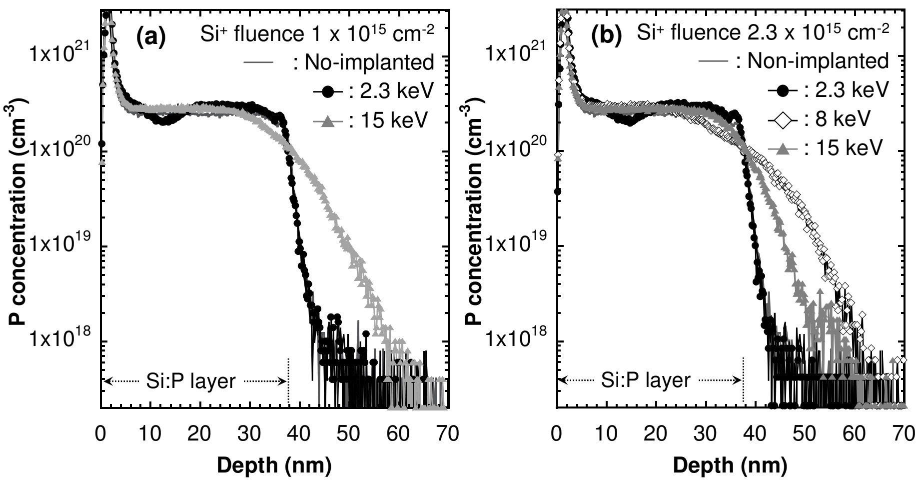

Fig. 3 Depth profiles of P in cryo Si$^+$-implanted Si:P with a fluence **(a)** of 1 x 10^{15} cm^{-2} and **(b)** of 2.3 x 10^{15} cm^{-2} after laser annealing at 1225 ˚C for sub-2 ms. The solid line indicates P profiles of non-implanted samples. The P profile near the Si:P/Si substrate interface for the shallowest implanted (2.3 keV) samples remain the same compared to the non-implanted samples. But in contrast, with cryo Si$^+$-implantations at 8 and 15 keV, P atoms are diffusing toward Si substrate.

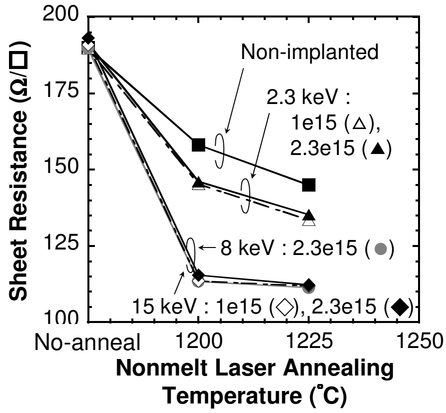

Fig.4 ρ_s of heavily Si ion-implanted Si:P layer with a high fluence higher than 1 x 10^{15} cm^{-2} after laser annealing recrystalization at higher than 1200 ˚C for sub-2 ms. The ρ_s of non-implanted sample decreases with increasing annealing temperature. Meanwhile, the amount of reduction in ρ_s increases by the cryo Si$^+$-implantation.