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. 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 selectively 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. 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 the 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 (I_P) higher than ~2.0 x 10^{19} 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:P-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>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Fluence (x 10^{12} cm^{-2})</th>
<th>Tilt / Twist</th>
<th>Temperature (°C)</th>
<th>Amorphous layer thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i. 2.3 keV</td>
<td>1 x 10^{12} cm^{-2}</td>
<td>0° / 0°</td>
<td>t &lt; 60°C</td>
<td>25 nm</td>
</tr>
<tr>
<td>ii. 2.3 keV</td>
<td>2.3 x 10^{12} cm^{-2}</td>
<td>0° / 0°</td>
<td>t &lt; 60°C</td>
<td>25 nm</td>
</tr>
<tr>
<td>iii. 8 keV</td>
<td>2.3 x 10^{12} cm^{-2}</td>
<td>0° / 0°</td>
<td>t &lt; 60°C</td>
<td>43 nm</td>
</tr>
<tr>
<td>iv. 15 keV</td>
<td>1.5 x 10^{12} cm^{-2}</td>
<td>0° / 0°</td>
<td>t &lt; 60°C</td>
<td>10 nm</td>
</tr>
<tr>
<td>v. 15 keV</td>
<td>2.3 x 10^{12} cm^{-2}</td>
<td>0° / 0°</td>
<td>t &lt; 60°C</td>
<td>43 nm</td>
</tr>
</tbody>
</table>

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 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 diffusion and suppression of both Si interstitial clustering and vacancy clustering. 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 shows cross-sectional TEM images for Si⁻⁺-implanted sample [Fig. 2(b)]. In addition, the Si⁺-implanted sample at 15 keV [Figs. 3(a) and 3(b)] permit an increased amount of P diffusion during laser annealing at 1225 °C within sub-2 ms. In addition, cryo Si⁺-implantation at 8 keV, a “kink” appears in the P profile at a [P] of approximately ~1.5 x 10^{19} cm^{-3}, as represented in Fig. 3(b).

It is interesting to note that the P profile near the Si:P/Si substrate interface for the shallowest implanted (8 keV) sample at 1225 °C [Fig. 3(b)] is different compared to the non-implanted sample. As seen in Fig. 4, where the dependence of ρ_s measured by the linear 4PP on the nonmelt laser annealing temperature is represented. The ρ_s of Si:P samples 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.

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 Si:P samples 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.
Si⁺-implanted samples is the same compared to the 8 keV Si⁺-implanted 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 epitaxial grown film become reactivated efficiently by the cryo Si ion-implantation and nonmelt laser annealing recrystallization 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 10¹⁸ 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 10¹⁸ cm⁻² followed by nonmelt laser annealing higher than 1200 °C for sub-2 ms reactivates successfully inactive P atoms in the Si:P epitaxial grown film.

Acknowledgements
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References