Carbon Incorporation into Substitutional Silicon Site by Molecular Carbon Ion Implantation and Recrystallization Annealing for Stress Technique in nMOSFETs

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Introduction

Strained Si channel has become an essential component of state-of-the-art high-perphormance MOSFETs. Recently, silicon-carbon embedded in source and drain (e-Si:C S/D) technology to improve nMOSFET drive current has been reported^[1-3]. Since the lattice constant of Si:C is smaller than that of Si, e-Si:C S/D can induce tensile stress in the channel^[1,2,4] and improve the electron mobility for nMOSFETs. A small concentration of substitutionally incorporated carbon concentration ([C]_{sub}), $1\sim 2$ %, is required to induce a meaningful strain.

A widely used approch for the formation of e-Si:C S/D is to recess S/D by etching and then deposit strained Si:C using a selective epitaxial growth process, which requires a complicated process integration^[1]. In contrast, the combination of C implantantation and annealing enables a relatively simple process integration to create e-Si:C S/D^[2,3]. However, due to the extremely low solid solubility of C in Si (3.5 x 10¹⁷ cm⁻³ at melting point), it is difficult to grow strained Si:C with $[C]_{sub} > 1$ %. Furthermore, the electron mobility decreases with increasing interstitial C concentration $([C]_{int})^{[5]}$. Formation of strained Si:C layer with low $[C]_{int}$, which means high ratio of substitution, is also vital for maximizing the strain effects of e-Si:C S/D technology.

In this work, the C ion implantation and recrystallization schemes employed to achieve strained Si:C film with high $[C]_{sub}$ and higher ratio of substitution are studied. We propose a molecular C implantation, an non-melt laser annealing and co-incorporation of dopant techniques for recrystallization of C densely incorporated in amorphous Si and confirm that these techniques can drastically improve the crystallinity of strained Si:C while keeping high $[C]_{sub}$ with high ratio of substitution.

Experimental Procedure

Split tests of the molecular C ion implantation and recrystallization were performed. $C_7H_7^+$ was implanted in p-type Si (001) substrates at room temperature with a 0 ° tilt and 0 ° rotation by using the Nissin Ion Equipment, Co. Ltd Cluster Ion Implanter : CLARIS ®. The different $C_7H_7^+$ implantation conditions in this study are summarized in Table I. Figure 1 shows SIMS C profiles for as-implanted specimens. Arsenic (As) co-implanted condition was set at 10 keV 3 x 10¹⁵ cm⁻². Recrystallized annealing was achieved using: 1) rapid thermal annealing (RTA) in the temperature range from 750 °C to 1000 °C for 5 s in nitrogen (N₂), 2) non-melt laser annealing in the temperature range from 1300 °C to 1350 °C within a few milliseconds (msec), such as 800 µs irradiation time, with preheated temperature in N₂ below 600 °C.

The quality of the crystalline structure of recrystallized layer was investigated with several techniques. The strain and $[C]_{sub}$ were derived from (004) high-resolution X-ray diffraction (HR-XRD) rocking curves and the best-fit between the simulated spectrum and the experimental spectrum based on dynamic scattering theory. Structural analysis was performed by cross-sectional transmission electron microscopy (XTEM). The C and As profiles were measured by secondary-ion mass spectroscopy (SIMS) with a primary ion of Cs⁺.

Results and Discussion

 $C_7 H_7^+$ implantation can make an amorphous Si layer without additional Si⁺ or Ge⁺ implantation, whereas C⁺ implantation is unable to do so^[6]. Uniform amorphized layer and smooth amorphous/crystal interface were obtained, as shown in Fig. 2.

Solid phase epitaxy (SPE) annealing achieves incorporation of atoms present in the amorphous material into the lattice even beyond the solid solubility limits because a metastable state can be realized due to the low process temperature. Figure 3 shows (004) reflection HR-XRD rocking curves for $C_7H_7^+$ with high C peak concentration ($[C]_{peak}$) such as 2 x 10^{21} cm⁻³ implanted samples after RTA. The maximum $[C]_{sub}$ value, 1.4 %, was obtained by the annealing at 750 °C for 5 s. However, the strained Si:C-related peak intensity and its ratio of substitution were drastically low. By increasing RTA temperature, the strained Si:C-related peak intensity was slightly increased. This suggests that the crystallinity of Si:C was improved. However, the strained Si:C-related peaks were shifted gradually closer to the ω values related to interplanar distance of Si. During high-temperature annealing involving diffusion of C atoms, it was supposed that the segregation of C atoms to interstitial site and the formation of

silicon-carbide (SiC) phase in Si lattice occurred owing to low solid solubility of C in Si.

In order to clarify the formation of SiC phase in Si lattice during high-temperature annealing, in-plane XRD analysis was performed. In the case of the annealing at 1000 °C for 5 s, the peak derived from 3C-SiC(111) was observed, as shown in Fig. 4(a). Whereas it was not observed in the case of the annealing at 750 °C for 5 s, as indicated in Fig. 4(b).

A high-temperature msec annealing such as non-melt laser annealing^[7] or flash lamp annealing^[8], suppresses dopant diffusion because of the extremely rapid heating and cooling within a few msec. Also, the process is metastable, which allows dopant activation beyond the solid solubility limit^[7,8]. The strained Si:C films with higher $[C]_{sub}$ of more than 1.9 % were realized by non-melt laser annealing recrystallization, as shown in Fig. 5. Furthermore, ratio of substitution of low $[C]_{peak}$ such as 1.2 x 10^{21} cm⁻³ implanted samples was above 90 %. In contrast, about half of the total C concentration was incorporated at interstitial sites in high $[C]_{peak}$ implanted samples.

Moreover, there was a remarkable difference in the cross-sectional morphologies corresponding to difference in $[C]_{peak}$. Many dislocations, {111} stacking faults and twins were observed at the region where the C concentration increases steeply to the surface. The local decrease in the recrystallization rate and the localized change in strain may initiate these crystal defects. Si recrystallization of high $[C]_{peak}$ implanted sample was suppressed remarkably when crystal defects were formed, resulting in remaining C densely incorporated in amorphous Si layer close to the surface, as shown in Fig. 6(a) In contrast, the flat profile realized by reducing $[C]_{peak}$ with C atoms clearly enabled to improve Si recrystallization even though many crystal defects were observed, as indicated in Fig. 6(b). The recrystallization of C densely incorporated in amorphous Si was partially grown to the surface. It is a key to achieving good crystalline strained Si:C film with high $[C]_{sub}$ to suppress the local decrease in recrystallization rate and the localized change in strain caused by C incorporation.

Furthermore, co-incorporation of dopant, such as As or phosphorus, which rise the rate of Si regrowth and has a covalent radius differing less from that of Si than dose that of C, is thought to be a means of promoting recrystallization for C densely incorporated in amorphous Si. As co-implantation improved the recrystallization for C densely incorporated in amorphous Si, which reached the surface, as indicated in Fig. 7. Figure 8 shows (004) reflection HR-XRD rocking curve for $C_7H_7^+$ implanted samples with low [C]_{peak} and As co-implantation after non-melt laser annealing. Compared to samples without As co-implantation as shown in Fig. 5, the strained Si:C-related new peak, which indicated lower strain and [C]_{sub}, appeared. Based on the above-mentioned experimental results, the strained Si:C-related new peak was speculated to relate recrystallization of strained Si:C layer close to the surface. The acceleration in recrystallization of C densely incorporated in amorphous Si due to As co-incorporation was confirmed. Also, As co-implantation had no influence on C profiles, as shown in Fig. 9. These effects are considered to be attributable to the change to the point defect population near C peak concentration.

Conclusions

The non-melt laser annealing that is a metastable process was found to provide higher [C]_{sub} with higher ratio of substitution beyond the solid solubility limit. Also, the segregation of C atoms to interstitial sites or the formation of SiC phase in Si lattice was suppressed. Suppression of the local decrease in the recrystallization rate and the localized change in strain caused by C incorporation is the key to achieving good crystalline strained Si:C. Furthermore, co-incorporation of a dopant such as As that rise the rate of Si regrowth and has a covalent radius differing little from that of Si drastically promoted recrystallization for C densely incorporated in amorphous Si and improved the crystallinity of strained Si:C film while keeping higher [C]_{sub} with higher ratio of substitution.

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