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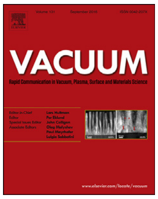

Anomalous rapid diffusion of phosphorus caused by heavily implanted carbon in pre-amorphized ultrashallow junctions

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ABSTRACT

Anomalous enhancement of phosphorus diffusion in pre-amorphized ultrashallow junctions was observed when the dose for carbon co-implantation was increased to 5×10^{15} cm^{-2} at 5 keV. Simulation was performed to verify the diffusion mechanism and mimic the experimental box-shaped profiles of phosphorus. The enhanced diffusion was dominated by the rapid diffusion in the residual amorphous layer as the rate of solid-phase epitaxial regrowth was severely retarded at the peak region of the implanted carbon profile. The diffusion in the amorphous silicon layer did not show concentration dependence. No evident phosphorus segregation was observed at the interface of the amorphous layer and the bulk crystalline silicon. The rapid diffusion in the amorphous layer produced a flat profile near the surface region while a steep phosphorus profile near the amorphous/crystalline interface was observed due to low diffusivity in the bulk crystalline region. This explains similar box-shaped profiles at low temperatures because the phosphorus redistribution was mainly controlled by the thickness of the residual amorphous layer.

1. Introduction

Series resistance in metal-oxide-semiconductor (MOS) transistors becomes important with the scaling of device geometries. Dopant activation in source and drain regions must be improved so that the contact resistance can be reduced due to easier carrier tunneling through the depletion region under the contact. Pre-amorphization implantation (PAI) has been performed to increase dopant activation because solid-phase epitaxial regrowth (SPER) of amorphous silicon produces more dopants in substitutional lattice sites than that in equilibrium [1,2]. Similarly, combination of PAI and carbon implantation promotes the incorporation of carbon atoms at substitutional lattice sites [3]. Substitutional carbon atoms may react with self-interstitials to suppress interstitial-mediated dopant diffusion [4–6]. Incorporating carbon in the source and drain regions may induce mechanical stress to modulate the carrier mobility in the channel region [7]. Phosphorus is frequently used in source and drain junctions for low resistance. However, there was less attention to the influence of high carbon doping on phosphorus diffusion, especially for the diffusion near the surface region. The redistribution of phosphorus near the surface actually affects the width of the depletion region under the contact. This paper demonstrated that PAI and high-dose carbon co-implantation induced anomalous rapid diffusion of phosphorus. Such diffusion was caused by retardation of SPER and rapid redistribution of phosphorus in the residual amorphous layer.

2. Experimental

⟨100⟩-oriented p-type wafers were implanted by germanium at 40 keV with a dose of 1×10^{15} cm^{-2} to form an amorphous layer with a thickness of 60 nm for PAI. Then co-implantation of carbon and phosphorus was performed at energies at 5 and 2 keV, respectively. A dose of 5×10^{15} cm^{-2} was chosen for heavy carbon implantation and the implantation dose of phosphorus was 1×10^{15} cm^{-2}. Subsequent annealing was performed in nitrogen at various temperatures for different times to induce SPER and phosphorus diffusion. Secondary ion mass spectrometry (SIMS) was performed at Evans Analytical Group to analyze the profiles of carbon and phosphorus. A point-by point profile correction protocol was adopted for phosphorus SIMS [8] in order to exclude the influence of the surface oxide layer on the measurement of ultra-shallow depth profiles. Cross-sectional transmission electron microscopy (XTEM) was used to measure the thickness of the residual amorphous layer after annealing.

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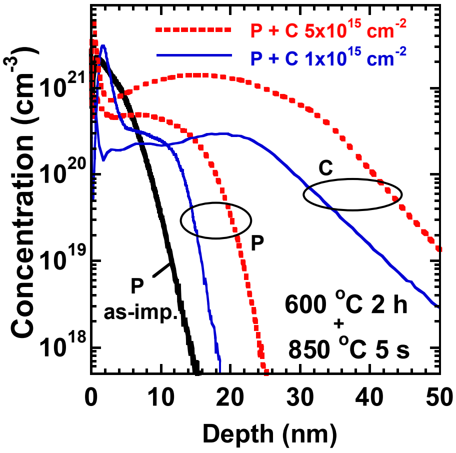

Fig. 1. SIMS profiles of carbon and phosphorus during annealing at 850 °C with different carbon implantation doses.

3. Results and discussion

Previously, we investigated co-diffusion of phosphorus and carbon in pre-amorphized ultrashallow junctions [9]. Fig. 1 shows that the junction depth of phosphorus during annealing at 850 °C for 5 s became deeper when the carbon implantation dose was increased from 1 × 10^{15} cm^{-2} to 5 × 10^{15} cm^{-2}. However, all literatures reported that carbon reduced junction depth due to suppression of transient enhanced diffusion (TED) caused by excess interstitials [4–6]. Such difference suggests a new diffusion mechanism associated with heavy carbon doping. The carbon doping level is about 2% at the peak region of the carbon profile implanted at a dose of 5 × 10^{15} cm^{-2}. Fig. 2 demonstrates the diffusion profiles of phosphorus at 720 °C with carbon implantation at a dose of 5 × 10^{15} cm^{-2}. Most of the phosphorus redistribution occurred within 75 s during annealing. There was no evident junction movement between the annealing periods of 75 and 135 s. XTEM image indicates no residual amorphous layer after annealing for 75 s. There were end-of-range (EOR) defects at the original amorphous/crystalline (a/c) interface. A dark band was observed near the surface due to defects caused by high-concentration carbon, similar to that in our previous study [9]. The XTEM picture indicates that SPER finished within 75 s. This indicates that the diffusion of phosphorus in crystalline silicon is minimal, based on the SIMS profiles with annealing for 75 and 135 s.

Fig. 3 demonstrates XTEM images for samples annealed at 600 and 660 °C. A residual amorphous layer with a thickness of about 25 nm was observed after annealing at 600 °C for 2 h, as shown in Fig. 3(a). It is known that SPER is retarded by implanted carbon [10]. However, Strane et al. reported incomplete SPER caused by severe retardation of the regrowth rate for amorphous silicon doped by carbon at a concentration of 1.9% [3]. The a/c interface almost stopped at the middle of the amorphous layer when defects were formed during SPER. The peak of the carbon profile in this study is at a depth of about 20 nm with a concentration of 2%. Therefore, a significant retardation of SPER was expected to occur when the a/c interface was near the carbon peak. This resulted in a layer of residual amorphous layer with a thickness of about 20 nm. Fig. 3(b) presents incomplete SPER after annealing at 660 °C for 180 s. The thickness of the residual amorphous layer is approximately 20 nm, similar to our expectation.

Fig. 4 shows the SIMS profile of phosphorus during annealing at 660 °C for 180 s. Since the corresponding XTEM image of the sample shown in Fig. 3(b) demonstrates an amorphous layer, phosphorus redistribution near the surface region should be mainly contributed by the diffusion in the amorphous layer. The flat SIMS profile near the surface indicates a rapid diffusion mechanism. When the phosphorus profile reached the a/c interface, the slow diffusion in the crystalline silicon caused a steep tail profile. The

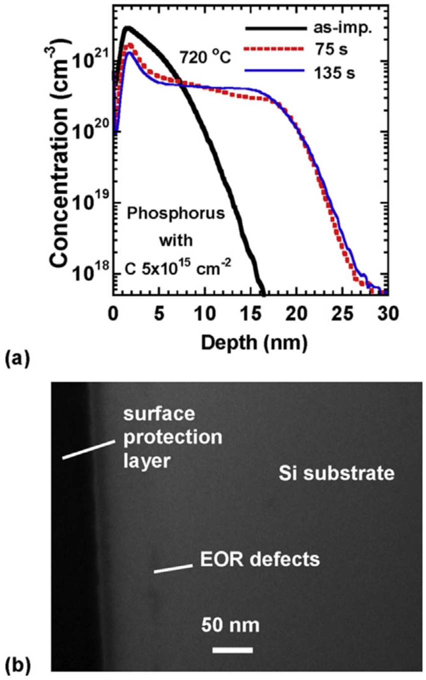

Fig. 2. (a) SIMS profiles of phosphorus during annealing at 720 °C and (b) the XTEM image of the sample annealed at 720 °C for 75 s.

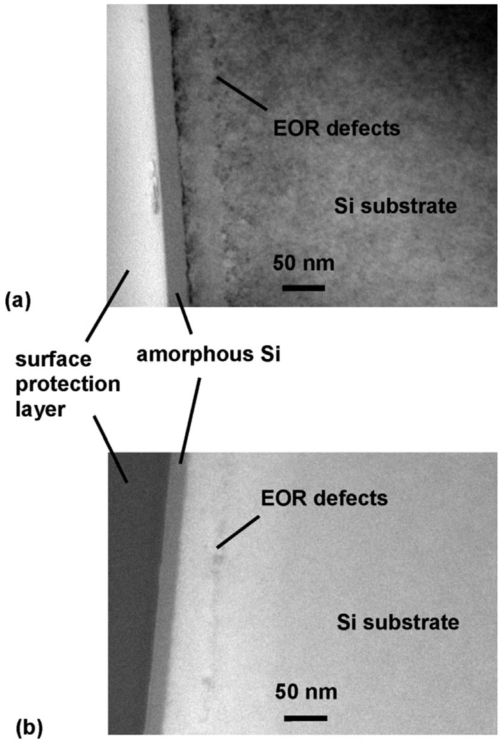

Fig. 3. XTEM images of the sample annealed (a) at 600 °C for 2 h and (b) at 660 °C for 180 s.

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