Codiffusion of Phosphorus and Carbon in Preamorphized Ultrashallow Junctions

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The diffusion of implanted carbon in preamorphized silicon was investigated with and without phosphorus coimplantation. Coupling effects were observed when carbon and phosphorus diffused simultaneously during junction formation. With an implantation dose of 1 × 10^{15} cm^{-2}, phosphorus diffusion resulted in interstitial supersaturation, enhancing the tail diffusion of carbon. However, the diffusion of carbon was not enhanced when the implantation dose of carbon was increased to 5 × 10^{15} cm^{-2}. This result indicates that high-dose carbon implantation inhibited the interstitial supersaturation that was caused by phosphorus diffusion. Accordingly, the tail diffusion of phosphorus was suppressed and box-shaped diffusion profiles were obtained in the region of high carbon concentration.

The size of metal-oxide-semiconductor (MOS) transistors has been reduced to improve the density and speed of integrated circuits. Source and drain must have low resistance to support a high switching speed of the MOS transistors. Since the dimensions of source and drain are reduced as the transistor is scaled, the active concentration of dopants in the source and drain junctions must be increased to maintain sufficient charges during device operation. Phosphorus has a high solid solubility, allowing ultrashallow junctions to contain a high concentration of active dopants. However, phosphorus suffers from high diffusivity during junction formation. Carbon coimplantation effectively reduces the transient enhanced diffusion (TED) in the tail region of phosphorus profiles by reducing interstitial concentration. Preamorphization of silicon caused by Ge coimplantation further suppresses TED because solid-phase epitaxial regrowth (SPER) of the amorphous Si (a-Si) layer increases the amount of substitutional carbon. Mechanisms of carbon diffusion and clustering have been proposed and applied to simulate phosphorus and carbon during junction formation. The clustering mechanism suggests that trapping of interstitials in carbon-interstitial clusters suppresses TED. However, interstitial-mediated carbon diffusion may cause local undersaturation of interstitials. Unfortunately, the mechanism by which phosphorus and carbon diffuse simultaneously is not well understood. Additionally, the influence of phosphorus on substitutional carbon is critical to the strained Si:C layer that is used in source and drain regions. Therefore, in this study, the codiffusion of phosphorus and carbon was investigated experimentally. The dependence of the diffusion coupling of phosphorus and carbon on the carbon implantation dose was identified in preamorphized ultrashallow junctions.

A 1 × 10^{15} cm^{-2} dose of germanium ions were implanted into (100) p-type silicon wafers at 40 keV to preamorphize the surface of the substrate. The depth of the surface amorphous layer was approximately 60 nm, based on cross-sectional transmission electron microscopy (TEM) observations, as shown in Fig. 1. The wafers were then subjected to carbon implantation at 5 keV with doses of 1 × 10^{15} and 5 × 10^{15} cm^{-2} to obtain carbon profiles inside the amorphous layer. Some samples were implanted with 1 × 10^{15} cm^{-2} phosphorus at 2 keV. Following implantation, the samples were annealed in a furnace at 600°C for 2 h in nitrogen to induce solid-phase epitaxial regrowth (SPER) of the amorphous layer. Finally, rapid thermal annealing (RTA) was utilized for various durations to cause carbon and phosphorus diffusion at 850°C. After the surface oxide had been removed, diffusion profiles of carbon and phosphorus were measured by secondary ion mass spectroscopy (SIMS) using Cs+ as the primary ion source at Evans Analytical Group. The depth profiles of phosphorus were acquired using a point-by-point corrected profile protocol. TEM was used to monitor the distribution of residual defects.

Figure 2 presents the carbon diffusion profiles without phosphorus doping. The SIMS profile of the sample that was implanted with carbon at a dose of 1 × 10^{15} cm^{-2} obtained after furnace annealing at 600°C, included a carbon segregation peak close to the region where the end-of-range (EOR) defects were observed. However, the redistribution of the carbon profile close to the projected ion range of implanted carbon was not evident. RTA at 850°C increased carbon segregation after furnace annealing at 600°C. The presence of carbon reduced the size and density of EOR defects, similar to that observed previously. During RTA at 850°C for 30 s, the concentration of the carbon segregation peak saturated and an exponential-like carbon profile was observed beyond the EOR segregation region. According to previous studies, substitutional carbon atoms are converted into carbon interstitials via a kick-out mechanism with silicon self-interstitials. In the experiment herein, carbon was implanted in the preamorphized region. SPER improved the formation of substitutional carbon atoms and thereby eliminated the implantation damage in the recrystallized region. Accordingly, the excess silicon self-interstitials beyond the EOR region reacted with the substitutional carbon atoms in the SPER region to form mobile carbon interstitials. Rapid migration of carbon interstitials yielded an exponential-like diffusion tail. The implantation peak profile of carbon became narrow and the peak concentration decayed during RTA at 850°C. The shape of the diffusion profiles obtained following carbon implantation at a high dose of 5 × 10^{15} cm^{-2} were similar even though the peak concentration exceeded the metastable solubility limit of carbon in silicon. Additionally, the concentration of the carbon diffusion tail and the EOR segregation peak in the samples that were implanted with 5 × 10^{15} cm^{-2} carbon did not exceed that in the samples that were implanted with 1 × 10^{15} cm^{-2} carbon. This result implies that the concentration of mobile carbon interstitials did not increase with the dose of implanted carbon. The diffusion of excess silicon self-interstitials from the EOR region toward the SPER region is the bottleneck in the formation of carbon interstitials. Therefore, the formation of carbon interstitials in the tail region governs the diffusion of carbon. The peak concentration of carbon in the samples that were implanted at 5 × 10^{15} cm^{-2} did not exhibit any evident decay during RTA at 850°C. The decay of carbon concentration was observed only close to the tail region of the implantation profile.

Figure 3a plots carbon diffusion profiles with and without phosphorus doping for samples with a carbon implantation dose of 1 × 10^{15} cm^{-2}. The influence of phosphorus doping on carbon diffusion was not evident when RTA was performed at 850°C for 5 s following furnace annealing at 600°C. Interestingly, phosphorus coimplantation significantly increased the concentration of the carbon diffusion tail during RTA at 850°C for 30 s. The carbon concentration in the peak region exhibited serious simultaneous decay indicating that more carbon atoms in the peak region became mobile carbon interstitials and diffused toward the tail region. Figure 3b shows the corresponding
phosphorus diffusion profiles. The phosphorus peak profile at concentrations above $2 \times 10^{20}$ cm$^{-3}$ does not show evident redistribution during annealing. The phosphorus diffusion profiles had plateaus beyond the phosphorus peak. Clearly, carbon tail diffusion was enhanced when phosphorus diffused through the carbon peak region during RTA for 30 s. This finding indicates that phosphorus diffusion promoted the formation of carbon interstitials. This phenomenon is similar to the emitter-push effect, which refers to the fact that phosphorus diffusion causes interstitial supersaturation owing to the chemical pumping of interstitials through dopant-interstitial pairs. The interstitial supersaturation promoted kick-out reactions forming more mobile carbon interstitials. Therefore, apart from the residual implantation damage beyond the EOR region, chemical pumping effect provided a very high number of interstitials. This fact explains why previous studies have reported that preamorphization alone cannot effective reduce the junction depth. The decay of the carbon peak concentration indicates that interstitial supersaturation promoted the kick-out of carbon, rather than the formation of carbon-interstitial clusters. This fact again verifies that the supply of silicon self-interstitials is the bottleneck of the formation of mobile carbon interstitials during junction formation.

Figure 4 presents the phosphorus and carbon profiles in samples that were implanted with carbon at a dose of $5 \times 10^{15}$ cm$^{-2}$. Surprisingly, the coimplantation of phosphorus did not increase the concentration of carbon in the diffusion tail even when the duration of RTA at 850°C was increased to 4 min. The corresponding phosphorus profile reveals that phosphorus had already diffused through the carbon peak region after 4 min of RTA. Phosphorus doping also did not have any evident effect on the peak concentration of carbon, implying that interstitial supersaturation by the chemical pumping of phosphorus disappeared as the carbon implantation dose was...
In summary, the codiffusion of carbon and phosphorus in preamorphized silicon was investigated. Enhanced tail diffusion of carbon was observed in phosphorus-doped samples with a carbon implantation dose of $1 \times 10^{15}$ cm$^{-2}$, indicating that phosphorus diffusion causes interstitial supersaturation, which promotes the kick-out mechanism of carbon. However, increasing the carbon implantation dose to $5 \times 10^{15}$ cm$^{-2}$ suppressed the interstitial supersaturation, resulting in box-shaped phosphorus diffusion profiles.

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References


