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Effects of germanium and carbon coimplants on phosphorus diffusion in silicon

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The authors have studied the interactions between implant defects and phosphorus diffusion in crystalline silicon. Defect engineering enables ultrashallow \textit{n}+/\textit{p} junction formation using phosphorus, carbon, and germanium coimplants, and spike anneal. Their experimental data suggest that the positioning of a preamorphized layer using germanium implants plays an important role in phosphorus diffusion. They find that extending the overlap of germanium preamorphization and carbon profiles results in greater reduction of phosphorus transient-enhanced diffusion by trapping more excess interstitials. This conclusion is consistent with the end-of-range defects calculated by Monte Carlo simulation and annealed carbon profiles. © 2006 American Institute of Physics. [DOI: 10.1063/1.2347896]

In today’s state-of-the-art complementary metal-oxide semiconductor (CMOS) technology, the junctions of the source and drain regions are formed using low energy ion implantation and spike anneal with a fast ramp rate and a short dwell time at the maximum temperature. As the CMOS technology continues to scale down, dopant profile engineering on the source and drain regions would be of critical importance to the development of the aggressively scaled CMOS technology which requires shallower junctions and low sheet resistances, essential for short-channel effect control and high device performance.\textsuperscript{1} The emerging interest in the ultrashallow junction (USJ) formation has now sparked substantial interest in advanced junction formation techniques. An important hurdle in this context is the dopant diffusion resulted from thermal treatment that is required to activate the dopant impurities introduced into Si through ion implantation.

During the past few years, great efforts have been pursued in the boron USJs, the most commonly used \textit{p}-type dopant in the Si technology. Carbon has been demonstrated to form carbon-interstitial clusters and to reduce boron transient-enhanced diffusion (TED) caused by the excess interstitials that are introduced into silicon during the ion implantation and annealing processes.\textsuperscript{2,3} The primary effect of carbon on trapping excess interstitials would require substitutional incorporation of carbon atoms in silicon where carbon acts as a sink for excess interstitials during the annealing process.\textsuperscript{4,5} Preamorphized silicon substrates using germanium implant, for instance, have been widely utilized in Si manufacturing in order to suppress ion channeling effect during implantation and to form shallower implant profile. The regrowth of the an amorphous layer in silicon at temperature of 500–600 °C, known as solid phase epitaxy regrowth (SPER), incorporates more dopant impurities into substitutional sites owing to the nonequilibrium growth of SPER. The importance of carbon and germanium coimplants in boron TED reduction has been demonstrated by recent studies,\textsuperscript{3} which show that the placement of sufficient carbon dose between implant damage and boron essentially eliminates boron TED upon spike anneal and enhances boron solid solubility. The enhanced boron solid solubility can be understood as a result of lowered boron clustering with interstitials at high boron concentration, known as boron interstitial cluster.\textsuperscript{5} Nevertheless, on the other hand, the effect of carbon coimplant on the \textit{n}-type dopant diffusion, such as phosphorus whose diffusion mechanism is also dominated by TED, has been rarely explored and documented in the literature. In this context, we systematically examine the effects of germanium and carbon coimplants on phosphorus diffusion in silicon, revealing the importance of a preamorphizing implant (PAI) in phosphorus diffusion in the presence of carbon. Analysis of phosphorus and carbon profiles unveils a direct evidence of substitutional incorporation of carbon atoms in silicon using a Ge PAI layer, increasing the amount of interstitials trapped by carbon and enhancing TED suppression.

A series of 300 mm (001) \textit{p}-type Si wafers of 5–10 Ω cm nominal resistivity is implanted with germanium at a dose of \(1 \times 10^{15}\) cm\(^{-2}\) with energies ranging from 5 to 40 keV, followed by carbon and phosphorus implants at the dose of \(1 \times 10^{15}\) cm\(^{-2}\) with energies of 5 and 2 keV, respectively. Subsequently, the wafers are subjected to spike anneal at 1020 °C in an inert ambient. Secondary ion mass spectroscopy (SIMS) is employed to characterize the phosphorus, germanium, and carbon profiles and four-point probe sheet resistance measurements are performed. The PAI layer thicknesses are measured using cross-section transmission electron microscopy (XTEM). The coimplant conditions and associated junction characteristics are summarized in Table I.

In Fig. 1, we present the comparison of phosphorus profiles under various coimplant conditions, that is, P only, C

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+P, and Ge+C+P, both as-implanted and after spike anneal-
ing. Upon spike anneal, phosphorus displays typical TED profile with and without C coimplant, suggesting that C coimplant alone does not suppress phosphorus TED. The addi-
tion of Ge+C coimplants, however, significantly changes phosphorus profile. Comparing to P only and C+P implants, the phosphorus junction depth (at phosphorus concentration of $5 \times 10^{18}$ cm$^{-3}$) is reduced from 46.2 to 19.6 nm in the presence of Ge+C coimplants. The data demonstrate that Ge+C coimplants are required in order to reduce phosphorus TED.

Figure 2 depicts the comparison of phosphorus (left panel) and carbon (right panel) profiles as a function of Ge PAI energies. The data reveal a strong Ge PAI energy depend-
ence of phosphorus profiles. The phosphorus junction depth decreases with Ge PAI energy and the phosphorus profile becomes more boxlike with increasing Ge PAI energy. Com-
pared to P only and C+P implants (see Fig. 1), the solid solubility of phosphorus is increased in Ge+C+P implants, exhibiting a plateau of about $3 \times 10^{20}$ cm$^{-3}$ for the phosphorus diffusion. For Ge PAI energy less than 20 keV, as shown in Figs. 2(a) (5 keV) and 2(b) (10 keV), the phosphorus profile exhibits a plateau with a sharp slope followed

by a kink-and-tail region where the phosphorus displays a TED-like behavior. Increasing Ge PAI energy to 20 keV completely eliminates the kink-and-tail region and the annealed profile crosses the as-implanted profile at concentra-
tion below $5 \times 10^{17}$ cm$^{-3}$. We note that further increasing Ge PAI energy up to 40 keV does not result in additional change in the phosphorus profile (SIMS data not shown). The Ge-
PAI-induced changes in the phosphorus diffusion of Ge+C+P implants are also reflected in the associated carbon profiles. As seen in the right panel of Fig. 2, carbon profiles also show strong Ge PAI energy dependence, where the vertical dot lines represent the PAI thickness determined by XTEM. The carbon peak located $\sim 10$ nm underneath the surface resulted from carbon segregation in the phosphorus implant damages. The carbon peak located underneath the a/c inter-
face at various depths [22 nm in Fig. 2(a), 27 nm in Fig. 2(b), and 41 nm in Fig. 2(c)] can also be understood in this manner due to carbon segregation in the Ge PAI damages whose amorphous/crystalline (a/c) interfaces are located at 15, 21, and 34 nm, respectively. It is well established that the PAI damage, known as end-of-range (EOR) defects, provides excess interstitials causing TED.6,7 Upon annealing, carbon forms carbon-interstitial clusters and segregates towards EOR defects.

Detailed analysis on annealed carbon SIMS profiles al-

ows us to investigate the physics underlying the phosphorus diffusion in the Ge+C+P implants since they manifest how the defects interact with carbon atoms. A careful look at the carbon profiles in the depth of 10–20 nm shown in Fig. 2 reveals that the level of carbon concentration in this region determines the corresponding phosphorus diffusion profile. At Ge 20 keV implant energy, the carbon concentration in the region reaches a maximum concentration of $\sim 3 \times 10^{20}$ cm$^{-3}$ and the phosphorus TED is completely eliminated, strongly suggesting that more carbon atoms are needed in this region in order to reduce phosphorus TED.
This can be explained by the larger overlap of Ge PAI and carbon profiles and increased substitutional carbon concentration at higher Ge PAI energy, as discussed below.

During the initial stage of spike annealing in which SPER occurs, larger overlap of Ge PAI and carbon profiles would increase the amount of substitutional incorporation of carbon atoms in silicon, resulting in more carbon-interstitial clustering and hence greater phosphorus TED reduction. At Ge PAI energy of 20 keV, Ge PAI profile completely covers the carbon profile, resulting in maximum substitutional carbon concentration [Fig. 2(c)]. Further increasing Ge PAI energy does not increase more substitutional carbon concentration without increasing carbon implant dose and it is consistent with our observations in the wafers with higher Ge PAI energies. Such a process would also explain why the phosphorus diffusion in C+P implants exhibits typical TED behavior, since without a Ge PAI layer, C+P implants suffer deficiency of substitutional carbon atoms and the phosphorus TED persists. Next, we discuss the interaction of carbon and interstitials of the EOR defects located underneath the a/c interface and the associated carbon segregation. We examine the excess interstitials of the EOR defects using Monte Carlo simulation at different Ge implant energies. The interstitial profiles are calculated considering Frenkel pair recombination, as illustrated in Fig. 3 (the gray lines). Lower Ge implant energy generates more EOR defects located near the surface which overlaps carbon profile at higher carbon concentration, leading to greater carbon segregation at the EOR damage. Increasing Ge implant energy places EOR defects away from the high carbon concentration region. As a result, Ge 5 keV implant would have greatest carbon segregation and also lower the amount of carbon atoms left behind for substitutional incorporation into silicon during SPER, resulting in little TED suppression. As the Ge implant energy increases, less carbon atoms segregate towards EOR defects and more carbon atoms are located within the PAI layer and suppress phosphorus TED. This can be seen via the annealed carbon profiles as a function of Ge implant energy shown in Fig. 2. Nevertheless, a comprehensive diffusion model is needed in order to understand the detailed physics underlying the interaction of the carbon and EOR defects.

In summary, we have systematically investigated the interaction of implanted defects and phosphorus diffusion upon spike anneal using germanium and carbon coimplants. We find strong dependence of Ge implant on phosphorus diffusion of Ge+C+P implants. While P and C+P implants exhibit typical phosphorus TED after spike anneal at 1020 °C, above certain Ge implant energy, phosphorus TED is substantially suppressed in Ge+C+P implants under the same annealing condition. This observation is examined in terms of Ge PAI layer thickness and annealed carbon profiles. A model based on overlap of Ge PAI and carbon profiles is proposed to explain our data. We conclude that the Ge PAI condition is decisive for phosphorus diffusion in Ge+C+P implants and the a/c interface must be deep enough to maximize the amount of substitutional carbon concentration within the PAI layer for phosphorus TED suppression. Our results have important implications for the the ultrashallow junction formation using defect engineering in the aggressively scaled CMOS technology.

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8 SUPREM-4 User’s guide, version W-2005.10, Synopsys, 2005. Standard Monte Carlo ion implant model is used to calculate the interstitial profiles. No parameter adjustment is performed.