Retardation of boron diffusion in silicon by defect engineering

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By judiciously placing vacancy and interstitial defects at different depths, we are able to enhance or retard boron diffusion. This opens up a new approach for the formation of shallow $P^+/n$ junction in silicon. After preimplantation with 50 or 500 keV Si$^+$ ions to produce a surface vacancy-rich region, we studied the diffusion of deposited B on predamaged samples with annealing between 900 and 1010 °C. Boron diffusion retardation was observed in both implantation conditions after low temperature annealing with enhancement occurring in a 50 keV implanted sample at high temperature. Choosing high energy implantation to separate vacancies and interstitials can reduce the boron diffusion significantly. Such suppression became more obvious with higher implant doses. A junction less than 10 nm deep (at $1 \times 10^{17} \text{cm}^{-3}$ according to carrier concentration profiles) can be formed. © 2001 American Institute of Physics. [DOI: 10.1063/1.1361280]

As complementary metal–oxide–semiconductor (CMOS) device dimensions continue to shrink, 10 nm junctions will be expected in the near future according to The National Technology Roadmap for Semiconductors. It is well known that the boron experienced transient enhanced diffusion (TED) during annealing due to interaction with interstitial Si. Agarwal et al. have reported that another mechanism of enhanced diffusion called boron-enhanced diffusion (BED) exists in the proximity of a silicon layer containing a high boron concentration. BED is attributed to a silicon boride phase which injects interstitials during annealing. Both TED and BED can limit junction depths since high concentration B regions are necessary in any doping method. There are, however, few papers that report on the understanding and control of BED. One, for example, whether or not enhanced B diffusion from high concentration layers can be reduced by employing preamorphization is still unclear. An extreme condition for low energy B implantation with high B concentration can be represented by surface deposition of B. In this letter, we will show that boron diffusion can be retarded or enhanced by silicon vacancies or interstitials. We will demonstrate boron diffusion manipulation using surface deposited boron on a silicon which is pre-damaged by Si. Using an e-gun deposited boron layer as a diffusion source, we want to study the influence of boron diffusion by vacancies, therefore avoiding the complication of boron implantation in this experiment.

According to Giles’ so called +1 model, spatially correlated vacancies and interstitials recombine either dynamically during irradiation or subsequently during postimplant annealing. Extra atoms corresponding to the implant dose at the ion’s range are responsible for TED. However, the forward momentum imparted to the interstitial causes their distribution to be deeper than that of vacancies. Therefore, an excess vacancy rich region was formed close to the surface and excess interstitials were left in the deep range due to spatially separated Frenkel pairs. The separation between the vacancy distribution and interstitial distribution increases when the implantation energy increases. TRIM calculation of the excess defect population in Fig. 1 shows a net vacancy region that has formed with the maximum concentration at the surface. We treated Si substrates as amorphous structures since the implants discussed were done at a tilt angle of 7°. The dashed lines are extra atoms introduced by implantation and the solid lines are the defect distribution from spatially separated Frenkel pairs, where a negative concentration means vacancy and positive concentration means Si self-interstitial or excessive Si implants. Since the depth distribution of the vacancy and self-interstitial of Si can be tailored by selecting the energy of the Si implantation, B diffusion can be manipulated to demonstrate our concept. In this letter we illustrate such an effect, and its application on retardation of boron diffusion for shallow junction formations.

The 10–20 Ω cm n-type Czochralski-grown Si (100) wafers were implanted with $5 \times 10^{14} \text{cm}^{-2} \text{Si}^+$. Two energies, 50 or 500 keV, were selected to get two distinct conditions. The

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**FIG. 1.** TRIM simulation of (a) 50 and (b) 500 keV, $5 \times 10^{14} \text{cm}^{-2} \text{Si}^+$ ions implanted into Si. The dashed lines are extra atoms introduced by implantation and the solid lines are the defect distribution from spatially separated Frenkel pairs. A negative concentration corresponds to a vacancy while a positive one corresponds to interstitial defects.
low energy bombarded sample is for the condition that vacancies (near the surface region) were distributed with interstitials very near the vacancy rich region [see Fig. 1(a)]. The high energy bombarded sample is for the condition that vacancies were distributed also near the surface region, but with interstitials located almost 0.7–1 μm deep, separated by a neutral region [see Fig. 1(b)]. After a 50 or 500 keV Si⁺ implantation at a tilt angle of 7° under room temperature, 10 nm thick boron layers were deposited onto an ion-irradiated substrate by electron-gun deposition. HF etches were performed both before implantation and before deposition to remove the native oxide. Deposition was performed at a rate of 0.1 nm/s under a base pressure of 3×10⁻⁶ Torr, and the substrate was cooled down to liquid N₂ temperature to avoid surface diffusion and boron island formation. After deposition, the samples were annealed using a rapid thermal processor AG Associate Heat pulse 210T under continuous N₂ flow. Rutherford backscattering spectrometry (RBS) and channeling measurements were carried out with 2.0 and 3.05 MeV He⁺ ions to obtain the damage profiles. Figure 2(a) shows the RBS channeling profiles of the samples with 5×10¹⁴/cm² 500 keV Si ions and profiles for these samples after 900 °C 15 s RTA. The RBS analysis was performed with 2.0 MeV He⁺ in (a) and 3.05 MeV He⁺ in (b).

Although the density of extended defects that was formed depends on the implantation dose, it does not necessarily follow that the additional damage reduces the anomalous diffusion. Added damage creates more interstitial clusters and the density of free interstitials, which is the controlling factor for the anomalous diffusion and is determined by details of the coalescence of the clusters into extended dislocations and their subsequent growth. Figure 5 shows the spreading resistance profiles (SRPs) of the boron carrier concentration, which will give a more reliable result when the depth is shallower than 20 nm because SIMS cannot be used to study cross-sectional specimens at (011) orientations. It was confirmed by TEM that most end of range (EOR) defects were annealed out under such an annealing condition. Annealing of end-of-range dislocations produced by high energy implantation is difficult. More time will be needed for 500 keV implanted Si due to its deep defects. We found that a large region with dislocation loops existed in the 500 keV Si irradiated sample even after 1010 °C 15 s annealing [Fig. 3(b)]. From TEM, no residual defect is observed up to a depth of 700 nm in 500 keV implanted and annealed samples, however at a depth of 700–850 nm a band of dislocation loops is observed after 1010 °C, 15 s annealing. Near the surface where B was doped for device formation, both TEM and RBS channels show a well-crystallized region after annealing.
be greatly affected by mixing from surface residual B. Samples were first implanted with 500 keV Si ions with a dose of \(1 \times 10^{14}\) or \(5 \times 10^{14}/\text{cm}^2\), respectively, then 10 nm boron was deposited onto Si. Subsequent annealing was under 900 °C for 10 s. It is shown that when the implanted Si dose is increased, the profile of the B carrier concentration becomes shallower. For an annealed sample with a \(5 \times 10^{14}/\text{cm}^2\) 500 keV Si implantation, the B profile shows a SRP profile with a junction depth at \(1 \times 10^{17}\) as shallow as 6 nm, while \(R_s = 1200 \Omega/\square\). Since the return of the gas-phase doping concept is now being observed for a scaled device with improved concentration control,9–11 it shows a great potential to form a shallow junction by combining defect engineering with thermal diffusion. Complete removal of end-of-range damage is desirable since the presence of dislocation loops in the depletion region of a junction is detrimental to device performance. However, the end-of-range loops are harmless when they are not near the depletion region. In the MeV coimplantation experiments reported by Saito et al.12,13 the junction depth of 10 keV B implants was reduced by adding 1 MeV F implants.11 The carrier activation was the same with and without MeV implants and MeV-implanted samples had reduced junction leakage currents.

In conclusion, we have shown that surface deposited boron experienced suppressed diffusion during annealing if a Si substrate was preimplanted with 50 or 500 keV, \(5 \times 10^{14}/\text{cm}^2\) Si ions. B diffusion became more suppressed when the dose of preimplanted Si was increased. The concept of boron diffusion control can be used as an approach to form ultrashallow junctions.

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1 The National Technology Roadmap for Semiconductors (Semiconductor Industry Association, San Jose, CA, 1997).