Effect of implant temperature on transient enhanced diffusion of boron in regrown silicon after amorphization by Si^+ or Ge^+ implantation

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Si wafers were preamorphized by either Si^+ or Ge^+ ions at temperatures between 5 and 40 °C. The diffusion of low energy (4 keV) B^+ implants into the preamorphized Si was studied in order to monitor the flux of interstitials from the end of range (EOR) region toward the surface. Transient enhanced diffusion (TED) in the regrown silicon was observed for all implants. Increasing the implantation temperature of the Si^+ implant by as little as 15 °C can result in a marked decrease in the magnitude of the interstitial flux flowing from the EOR region toward the surface. This sensitivity to implant temperature appears to be even greater for Ge^+ implants. In order to better understand this effect, detailed transmission electron microscopy (TEM) studies were conducted. As-implanted cross-sectional TEM micrographs indicate a measurable decrease in the thickness of the amorphous layer (up to 300 Å) occurs when the implantation temperature increases from 5 to 40 °C as a result of ion beam induced epitaxial recrystallization. Upon 800 °C annealing, two types of defects are observed in the EOR region: {311} defects and dislocation loops. The {311} defects are unstable and the comparison of secondary ion mass spectroscopy and TEM data for annealed samples indicating the dissolution of these {311} defects is at least one of the sources of interstitials for TED in the regrown Si at 800 °C. The EOR dislocation loops are stable for the annealing conditions used in this study (800 °C for 15 min) and there appears to be an exponential dependence of the TED that occurs in regrown Si on the density of the EOR dislocation loops. © *1997 American Institute of Physics*. [S0021-8979(97)05709-5]

INTRODUCTION

Implantation induced amorphization is a technique commonly used to reduce the channeling tail of lighter dopants, such as boron, during silicon integrated circuit manufacturing. Typically amorphization is done either by implanting BF_2^+ for which fluorine is the amorphizing species or by preamorphization with a heavier isoelectronic ion such as Si^+ or Ge^+. After amorphization, a layer of damage exists beyond the amorphous/crystalline interface. This layer is supersaturated in excess interstitials,[1] both from the transmitted ions and the recoiled atoms. Upon low temperature (600 °C) annealing, the amorphous layer regrows by solid phase epitaxy. With increasing temperature, the excess interstitials in the end of range region either diffuse away or precipitate into extended defects.[2] Since excess interstitials can result in greatly enhanced diffusion of dopants, one of the key challenges in process simulation is to determine how to model the redistribution of these excess interstitials. In general, the interstitials from the EOR damage are thought to either precipitate into loops, diffuse into the bulk, or possibly diffuse toward the surface and recombine.[3–5]

To date, there have been many experiments attempting to discern the relative fluxes of these interstitials into the bulk versus toward the surface.[3,4,6–12] Several authors have reported little or no flux toward the surface.[3,4,7,9] Early speculation was that the loops that form in the EOR layers act as perfect barriers to diffusion.[4] This was supported by several groups, including a recent article by Chao *et al*.[13] showing no measurable back flow toward the surface upon annealing. Another interesting experiment recently reported that thinning amorphized layer from 1750 to 550 Å did not affect the concentration of EOR loops from which they concluded the loops are an effective barrier to interstitial flow toward the surface.[14] Other groups have reported measurable fluxes toward the surface.[10,15] It has recently been shown that there exist conditions under which there can be a significant amount of interstitial flow toward the surface from the EOR damage layer.[16,17] In this paper, results are presented which show that the backflow can vary with preamorphization species and implant temperature. A simple model is suggested which may help to explain the sensitivity of the interstitial flux toward the surface on what appears to be minor changes in implant conditions.

EXPERIMENT

For this study, 150 mm ⟨100⟩ Czochralski *n*-type 8–30 Ω cm Si wafers were implanted on an Eaton NV/GSD 200E series ion implanter. Preamorphization by Si^+ ion and by Ge^+ ion implants were studied. The tilt/twist angles for all implants were 5°/0°. The wafer temperatures were controlled to ±1 °C of the stated temperature. The beam current for the Si^+, Ge^+ implants was 5.6 and 4.3 mA, respectively. Two overlapping implants were used for each species to ensure a surface amorphous layer ~2400 Å deep. The Ge^+ implant conditions were 75 keV, $1\times10^{15}/cm^2$ followed by

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170 keV, $1\times10^{15}/cm^2$. The Si^+ implant conditions were 30 keV, $1\times10^{15}/cm^2$ followed by 120 keV, $1\times10^{15}/cm^2$. The implant temperature for the preamorphization was either 5, 20, or 40 °C. In order to monitor the backflow of interstitials in regrown Si wafers, a 4 keV, $1\times10^{14}/cm^2$ $^{11}B^+$ implant at 1.5 mA was done into the amorphized Si. Annealing was done at 800 °C in a furnace using fast push/pulls (1 min insert, 1 min removal) and a N_2 ambient. Plan-view and cross-sectional TEM samples were examined on a JEOL 200CX or JEOL 4000FX TEM using $\mathbf{g}_{220}$ weak beam dark field imaging conditions. The two principle defect types observed in the TEM were {311} defects and dislocation loops. The concentration of interstitials bound by the {311} defects was determined by using an image processing system to measure the total line length. The total length was then multiplied by 26 interstitials/nm (assuming the width of the {311} remained fairly constant at ~60 Å), and this value was divided by the area examined to yield the number of interstitials/cm^2.

For the dislocation loops, the image processor was also used. In this case, the loops with an aspect ratio less than 1.5 were assumed to be circular and counted as such. Those with an aspect ratio greater than 1.5 were assumed to be elongated and only the projection correction for the loop being on a {111} plane is applied. Multiplication of this adjusted area by the atomic density on the {111} plane of $\sim1.6\times10^{15}/cm^2$ and again dividing by the area examined yields the concentration of interstitials bound by the loops.

RESULTS AND DISCUSSION

It has previously been shown that transient enhanced diffusion (TED) of boron in preamorphized silicon can occur, and that the end of range damage in the region just beyond the amorphous/crystalline interface is responsible for the TED.[16,17] Figure 1(a) shows the effect of 800 °C 15 min annealing on the diffusion of the 4 keV B implant in the regrown Si as a function of the preamorphization temperature for samples preamorphized with Si^+ ions. It is apparent that increases of as little as 15 °C in the implant temperature produce marked changes in the amount of boron diffusion. The trend is clear that as the implant temperature increases the amount of interstitial backflow into the regrown Si decreases. This is also seen for samples pramorphized with Ge^+ ions [Fig. 1(b)]. The enhancement from the Ge preamorphization at 5 °C is even greater than the enhancement from the Si^+ implant at 5 °C. Complete annealing studies for times up to 2 h at 800 °C were performed and the boron profiles measured by SIMS. The shift of the boron profile, at a particular concentration ($5\times10^{17}/cm^3$), as a function of annealing time at 800 °C is plotted in Fig. 2 for four different preamorphization conditions. The diffusivity for the first 15 min is greatly enhanced over normal diffusion and appear to saturate for longer anneal times. At 800 °C the intrinsic diffusivity of boron over 2 h would lead to a broadening of ~100 Å.[18] The estimated enhancements for the first 15 min are therefore on the order of 50–100 times greater than the intrinsic diffusivity. It is also clear from Fig. 2 that for these implant conditions, changes of 35 °C (5–40 °C) in

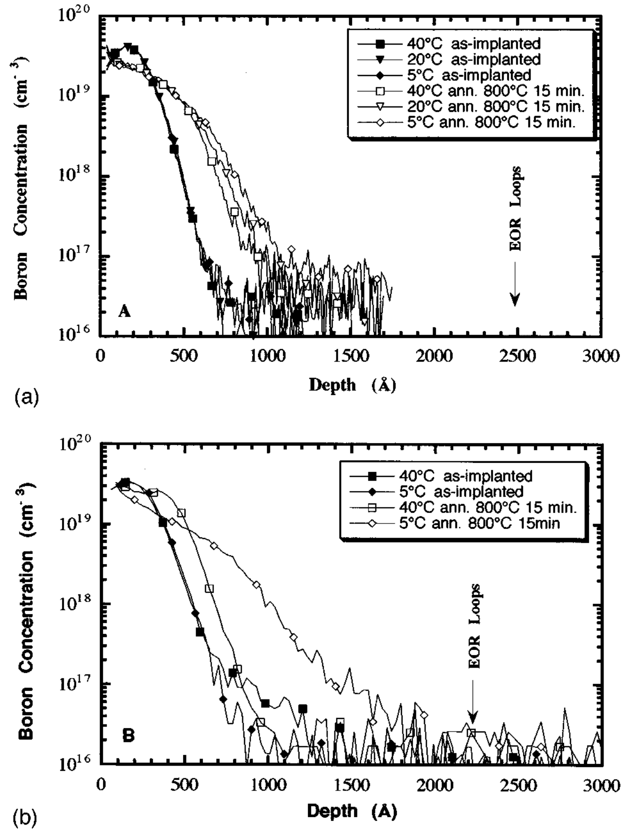

FIG. 1. Effect of preamorphization implant temperature on the diffusion of B^+ implants in the regrown Si. (a) Preamorphization by Si^+; 30 keV, $1\times10^{15}/cm^2$ followed by 120 keV, $1\times10^{15}/cm^2$, (b) preamorphization by Ge^+; 75 keV, $1\times10^{15}/cm^2$ followed by 170 keV, $1\times10^{15}/cm^2$. The preamorphization was followed by 4 keV, $1\times10^{14}/cm^2$ B implant and annealing at 800 °C, 15 min annealing.

the implant temperature resulted in greater changes of the interstitial backflow for preamorphizations done by Ge^+ ions than for preamorphizations done by Si^+ ions.

In order to better understand these trends, a careful study of the amorphous layer thicknesses as a function of implant conditions was done using cross-sectional TEM. The amor-

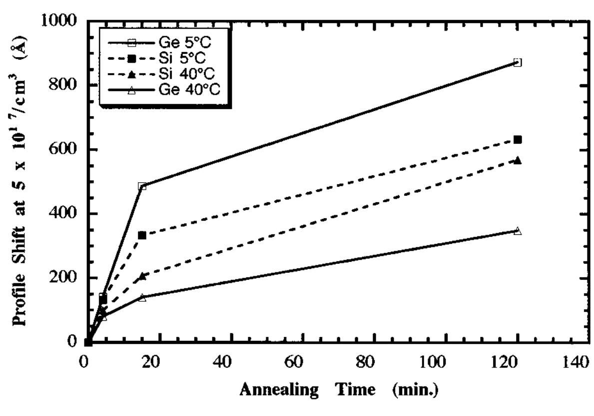

FIG. 2. Diffusion of the B profile in the regrown Si as a function of annealing time at 800 °C.

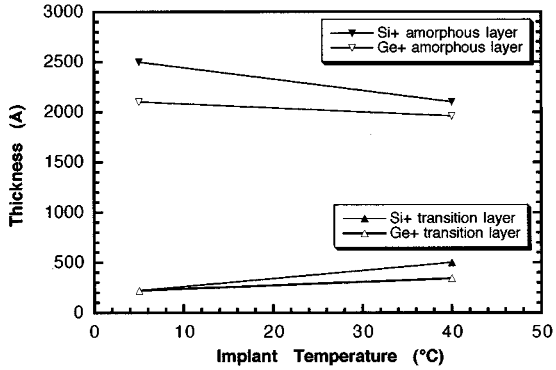

FIG. 3. Thickness of the amorphous/crystalline interface and the transition region in the end of range region as a function of the implant temperature.

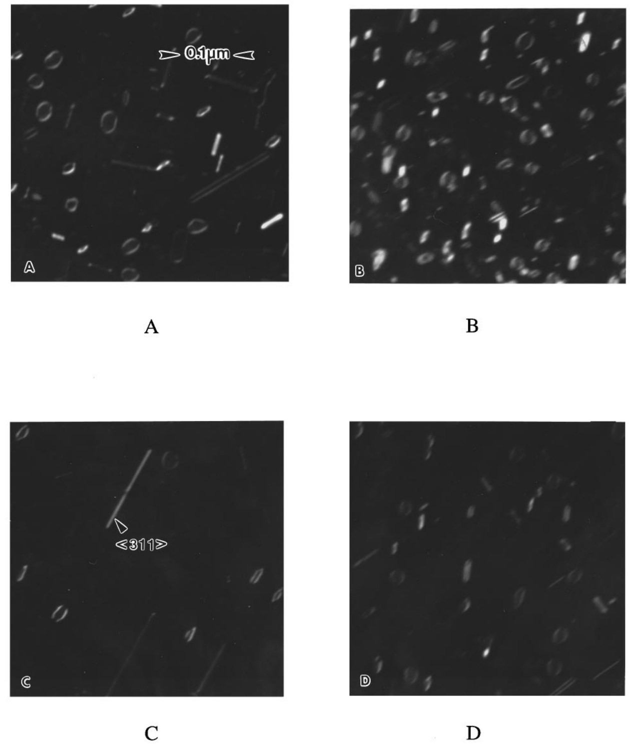

FIG. 4. Plan-view TEM micrographs of the EOR damage after annealing at 800 °C for 15 min. (A) Si^+ preamorphization at 5 °C, (B) Si^+ preamorphization at 40 °C, (C) Ge^+ preamorphization at 5 °C, (D) Ge^+ preamorphization at 40 °C. Note the increase in EOR loops with increasing implant temperature.

phous layer can be characterized by its thickness as defined by the depth from the surface down to the beginning of a heavily damaged transition region. A second measurement can be made of the thickness of this heavily damaged transition region. Figure 3 shows how the amorphous layer thickness and the transition layer thickness changed as a function of the implant temperature. For the Si^+ implant, changing the implant temperature from 5 to 40 °C results in the thickness of the amorphous layer decreasing from 2500 to 2100 Å. The decrease in layer thickness is accompanied by an increase in the transition layer thickness from 220 to 500 Å. The error bars on these measurements are approximately ± 30 Å. The increase in transition layer thickness is consistent with ion beam induced epitaxial recrystallization (IBIEC) being the source of the reduction in amorphous layer thickness.[19,20] For the Ge^+ implant the increase in implant temperature also results in IBIEC of the amorphous layer although not as great as the amount observed for the Si^+ implant.

Figures 4(a) and 4(b) show plan-view TEM micrographs of the Si^+ implanted samples preamorphized at 5 and 40 °C, respectively, after annealing at 800 °C for 15 min. Figures 4(c) and 4(d) show plan-view TEM micrographs of the Ge^+ implanted samples preamorphized at 5 and 40 °C, respectively, after annealing at 800 °C for 15 min. It is clear that as the implant temperature increases so does the EOR loop density for both amorphizing species. A number of {311} defects (rodlike defects) are still visible in the 5 °C Ge^+ preamorphized and Si^+ preamorphized samples. These are gone by 2 h at 800 °C and only the EOR loops remain. Complete TEM annealing studies of the {311} density and trapped interstitial concentration in the {311}'s indicate that, after annealing at 800 °C for 4 min, the {311} density in all samples is between 2 and $6\times10^{10}/cm^2$ and the trapped interstitial concentration in the {311} defects is between 2 and $4\times10^{13}/cm^2$. In all samples both the density and correspondingly the trapped interstitial concentration in {311} defects drops to an undetectable level ($<1\times10^{6}/cm^2$ and $<1\times10^{9}/cm^2$, respectively) after annealing at 800 °C for 2 h. No obvious trend in the {311} concentration as a function of implant temperature was observed but further detailed studies into this aspect of the TED are in progress. These results indicate the {311} dissolution process coincides well with the enhanced diffusion process observed in Fig. 2, implying they are at least one of the sources of interstitials. Unlike the {311} density, the EOR loop density does show a correlation with implant temperature. As shown in Fig. 4, as the implant temperature increases the EOR loop density increases. The loop density for a given implant was not observed to change significantly for the annealing times studied although it is difficult to determine after annealing times ≤ 4 min. After annealing for times between 15 min and 2 h, there does appear to be some increase in the loop density for the Si implants. This increase may be the result of unfaulting reactions transforming the {311} defects into loops. For the Si^+ implants the loop density after 15 min at 800 °C has been determined to be $1\times10^{10}/cm^2$ for the 5 °C implant, $2\times10^{10}/cm^2$ for the 20 °C implant, and $2.7\times10^{10}/cm^2$ for the 40 °C implant. Similar trends were observed for the Ge^+ implants but with fewer loops on average (e.g., when the implant temperature increases from 5 to 40 °C, the loop density after a 800 °C 15 min anneal increases from $5\times10^{9}/cm^2$ to $7\times10^{9}/cm^2$). For the Si and Ge implants it appears that increasing the EOR loop density decreases the amount of interstitial backflow from the EOR damage region. It is difficult to understand, based on loop density alone, why small changes in the implant temperature of the Ge^+ preamorphizations resulted in a much larger change in the interstitial backflow compared to the Si preamorphizations (Fig. 2). The answer to the differences between Si and Ge most likely lies in detailed quantitative analysis of the

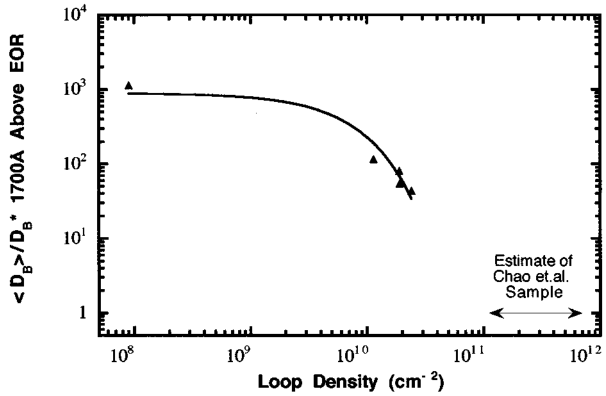

FIG. 5. The effect of changing the EOR loop density on the enhancement of the time averaged diffusivity observed 1700 Å above the EOR damage for Si^+ implants after 800 °C for 15 min. The curve shown is an exponential fit to the data.

EOR defect evolution combined with detailed calculations of the net excess interstitial concentration and distribution. The differences may also arise from the presence of Ge. Additional studies into the subtleties of the EOR excess interstitial distribution are needed before variations between Si and Ge can be understood. Such studies are currently in progress.

Comparing only Si^+ preamorphizations, the effect of loop density on the magnitude of the TED backflow is summarized in Fig. 5. Different Si^+ preamorphizations were each compared with a marker layer in the regrown Si. The backflow is measured as the time averaged diffusivity enhancement $\langle D_B \rangle / D_B^*$ over a 15–20 min, 800 °C anneal, 1700 Å above the EOR loops for the various Si^+ amorphizing implants. The enhancement, $\langle D_B \rangle / D_B^*$, was estimated by matching the diffused SIMS profiles with the calculated distribution using the process simulator program FLOOPS (Florida Object Oriented Process Simulator).[21] The EOR loop density was measured by TEM after the same time intervals. This figure includes new data from previously reported studies of 77 K implants[16] ($1 \times 10^8/\mathrm{cm}^2$ loop density). These previous studies had shown a nearly equivalent flux of interstitials into the sample and toward the surface. The reason for this large backflow appears to be the result of a very low EOR loop density in these samples (because they were implanted at 77 K). The curve in Fig. 5 is an exponential fit to the data implying an apparent exponential dependence of the enhancement of the boron diffusivity in the regrown Si on the concentration of EOR dislocation loops. An additional verification of this dependence was observed when TEM analysis was done on the samples from Chao *et al.*[13] These samples showed no TED in the regrown Si. Plan-view TEM analysis showed that the loop density had exceeded $1 \times 10^{11}/\mathrm{cm}^2$ and a network had formed. The network formation is believed to be due to IBIEC during implantation because of wafer heating. The result of their studies fits well with the exponential prediction in Fig. 5. As stated earlier, the amount of backflow may also depend on the interstitial distribution, total concentration, and evolution upon annealing. However, for Si^+ preamorphizations, after annealing at 800 °C for 15 min, which is sufficient to account for most of the TED from the EOR loops,[22] the dependence of the interstitial flux back into the regrown Si on the EOR loop density is modeled well by an exponential.

This apparent strong dependence of the backflow on the EOR loop density has important implications for process modeling. The EOR loop density is a very sensitive function of the implant conditions. If the endstation allows the wafer to heat up during the implant, even minimally, then one gets a higher concentration of interstitials in the EOR damage region which increases the loop density. While this reduces the interstitial backflow toward the surface, it may quite possibly increase the interstitial flux into the crystal. As the endstation temperature control improves and wafer heating is reduced, the amount of backflow is going to increase and accounting for this backflow will become essential for accurate process modeling.

CONCLUSIONS

In conclusion it is shown that the amount of interstitial backflow that is observed in preamorphized and regrown Si is very dependent on the implant temperature during preamorphization. This is true for both Si and Ge preamorphizations. Implant temperature changes as small as 15 °C around room temperature can result in significant changes in the amount of TED observed in regrown Si. For both species, the amount of backflow increases as the preamorphization temperature decreases. Differences in the EOR damage can account for the strong dependence of the boron diffusion on the preamorphization implant temperature. Decreasing the implant temperature from 40 to 5 °C results in an increase in the amorphous layer thickness of 100–300 Å and a factor of two decrease in the EOR loop density. The results for a given amorphizing species are consistent with the EOR loops acting as barriers to interstitial backflow. There appears to be an exponential dependence of the amount of backflow on the EOR loop density. Comparison of different preamorphizing species over larger annealing ranges will require additional detailed analysis of the EOR damage distribution and evolution. Accounting for this backflow is going to be essential for accurate process modeling.

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