The Effect of Dose Rate and Implant Temperature on Transient Enhanced Diffusion in Boron Implanted Silicon

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The effect of ion implantation dose rate and implant temperature on the transient enhanced diffusion (TED) of low energy boron implants into silicon was investigated. The implant temperature was varied between 5 and 40°C. The beam current was varied from 0.035 to 0.35 mA/cm^2. Three different defect regimes were investigated. The first regime was below the formation of any extended defects (5 keV B^+ 2 × 10^{14}/cm^2) visible in the transmission electron microscope. The second regime was above the {311} formation threshold (2×10^{14}/cm^2) but below the subthreshold (type I) dislocation loop formation threshold. The final regime was above both the {311} and dislocation loop formation threshold (10 keV 5×10^{14}/cm^2). TED for these conditions is shown to be over after annealing at 750°C for 15–30 min. Secondary ion mass spectroscopy results for the three different damage regimes indicate that there is no measurable effect of dose rate or implant temperature on TED of boron implanted silicon for any of the damage regimes. It should be emphasized that the dose and energy of the boron implants is such that none of these implants approached the amorphization threshold. Above amorphization dose rate and implant temperature have dramatic effects on TED, but it appears that below the amorphization threshold there is little effect. These results suggest that for a given energy it is the ion dose not the extent of the implant damage that determines the extent of TED in boron implanted silicon.

Key words: Amorphization, dose rate, implant temperature, ion implantation

INTRODUCTION

Low energy boron ion implantation without pre-amorphization is becoming a viable option for forming shallow p^+ junctions in ultra large scale integration (ULSI) devices. Pre-amorphization is often used to reduce the random channeling tail that occurs for non-amorphized boron implants. Current et al. showed results that suggested below 2 keV boron implants without pre-amorphization may actually produce shallower junctions than with pre-amorphization despite the random channeling tail. This was because the extent of transient enhanced diffusion (TED) was less without pre-amorphization.

Transient enhanced diffusion of boron implanted silicon has long been attributed to the damage from the implant. However, recently studies have suggested the source of transient enhanced diffusion in non-amorphized ion implanted silicon depends more on the dose than the damage. Based on early observa-

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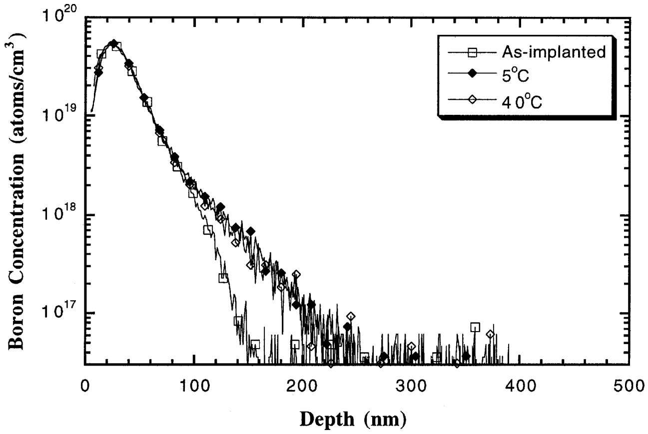

Fig. 1. SIMS results with no extended defects observed.

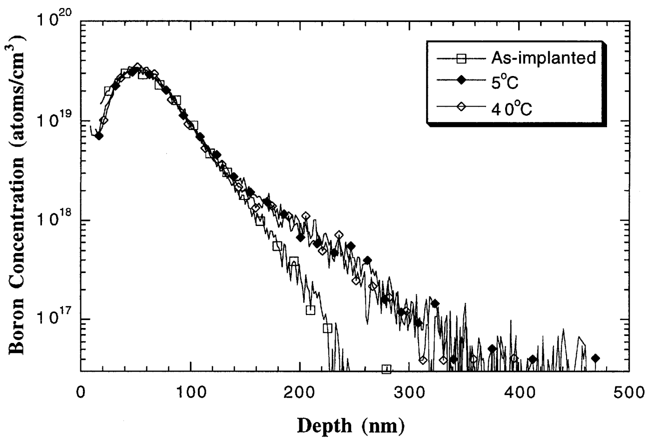

Fig. 2. After annealing at 750°C for 30 min, no effect of varying the implant temperature on TED.

tions that the trapped interstitials in the subthreshold loops paralleled the dose,[1] it was suggested by Giles that the residual damage in the crystal is proportional to the dose of the implant (the plus one model).[2] Recent studies of Si implants in Si[3,4] TED arises from {311} defect dissolution and that these {311} defects depend only on the dose of the implant. For low energy boron implants, it is clear the situation is more complicated because of the formation of boron interstitial clusters[5] but it is also clear the duration of TED is controlled by {311} defects for this system as well.[6] Thus, from the standpoint of testing whether the dose depth and distribution of the ions is more important than the total damage on TED, studying the effect of dose rate and implant temperature offers a unique opportunity. This is because varying the dose rate and implant temperature changes the amount of damage without changing the number of ions implanted or their depth. Thus, the plus model would predict little dependence of TED on the dose rate and implant temperature for non-amorphizing implants. Whereas the damage model would predict a dependence proportional to the amount of damage.

From a technology standpoint, understanding the role of dose rate and implant temperature on TED is critical to machine design. If a strong dependence is observed then the control of these parameters becomes critical for future implanter design for non-amorphizing implants. Thus, to test whether the plus model holds as a function of dose rate and implant temperature and to determine the sensitivity of TED for non-amorphizing boron implants to these parameters, a series of implant experiments were conducted.

EXPERIMENTAL

For this study, all implants were kept below the amorphization threshold. There are three known regimes for extended defects in boron implanted silicon.[7] The first is below the extended defect formation threshold where the defects are dominated by B-I pairs and immobile boron interstitial clusters. The next regime is similar to the first except {311} defects form. The formation of these {311} defects appears to prolong TED.[6] The third regime is at even higher doses where both {311} defects and dislocation loops are visible in the microstructure. In order to thoroughly investigate, the effect of dose rate and implant temperature on TED samples in each of the three regimes were studied.

The substrates in these experiments were 150 mm, n-type <100> phosphorus doped Czochralski grown Si wafer with a resistivity of 8–20 ohm-cm. The implants were performed in the Eaton Beverly Demo Lab on Eaton NV/GSD implanter. A stationary beam and wafer spinning were used to minimize the divergence and water cooling was used maintain a constant wafer temperature. The chiller reservoir temperature is controlled to about ±1°C. For the first defect regime of no extended defects, a 5 keV $2 \times 10^{14}/cm^2$ B^+ implant was done. Only implant temperature was varied for this implant condition and the dose rate was fixed at 0.4 mA/cm^2. For the second defect regime with {311} defects, implants of 10 keV $2 \times 10^{14}/cm^2$ B^+ were performed. For one set of wafers, the implant temperature was fixed at 20°C and the dose rate varied from 0.035 to 0.35 mA/cm^2. For a second set of wafers, the dose rate was fixed at 0.4 mA/cm^2 and the implant temperature varied between 5 and 40°C.

For the third defect regime with both dislocation loops and {311} defects, implants of 10 keV $5 \times 10^{14}/cm^2$ B^+ were done. For one set of wafers, the implant temperature was fixed at 20°C and the dose rate varied from 0.035 to 0.35mA/cm^2. For a second set of wafers, the dose rate was fixed at 0.4 mA/cm^2 and the implant temperature varied between 5 and 40°C.

The samples were annealed after implantation at 750°C for times of 15 min, 30 min, and 2 h in a nitrogen ambient. The secondary ion mass spectroscopy (SIMS) depth profile of boron for as-implanted and annealed samples were measured by Physical Electronic 6600 PHI System in University of Florida. A 3 keV Cs^+ incident beam was used with a current of 101 nA. The raster size was 350×350 μm^2 and the ion collected from the central 30% of the sputtered crater to avoid edge effects. The plan-view transmission electron microscopy (PTEM) samples were made by the standard jet etching procedure using $HF{:}HNO_3$ = 1:3 solution. TEM was done on a JEOL 200CX microscope using weak beam dark field imaging conditions and defect quantification was done via image processing.

RESULTS

Figure 1 shows the SIMS results from the regime which no extended defects were observed (however B-I pairs and boron interstitial clusters [BICs] still exist). As stated the implant energy was 5 keV and the boron dose was $2 \times 10^{14}/cm^2$. Shown in the figure is the as-implanted profile as well as the profile after annealing at 750°C for 30 min. Annealing studies as a function of time were done at 750°C and TED was found to saturate after less than 15 min, consistent with previous findings.[5] Because of this only the results after 30 min are plotted. There is no measurable effect of implant temperature (between 5 and 40°C) on the extent of TED for the first defect regime.

By doubling the implant energy to 10 keV and keeping the dose fixed at $2 \times 10^{14}/cm^2$, it is possible to enter the next defect regime consisting of BICs and {311} defects. The reason for the forming of {311} defects with increasing energy is believed to be associated with the formation of fewer BICs because of the increased straggle. Figure 2 shows that again after annealing at 750°C for 30 min, there is no effect of varying the implant temperature on TED. Figure 3 shows that varying the dose rate also does not effect the extent of TED for this defect regime. The same annealing time of 750°C for 30 min is plotted.

Upon increasing the dose to $5 \times 10^{14}/cm^2$ but keeping the energy fixed at 10 keV, it is possible to enter the third defect regime in which BICs, {311}s, and dislocation loops are present. Figure 4 shows the effect of annealing at 750°C for 30 min on the TED. Again no effect of implant temperature on TED is observed. Figure 5 shows that varying the implant dose rate in this regime also did not effect the TED process.

In addition TEM studies were done on the microstructures of the 10 keV $5 \times 10^{14}/cm^2$ sample after annealing at 750°C for times from 15 to 120 min. The concentration of interstitials in the {311} defect was found to decay exponentially from $8 \times 10^{13}/cm^2$ after 15 min to $6 \times 10^{12}/cm^2$ after 120 min at 750°C. There was no effect of dose rate or implant temperature on the concentration of interstitials trapped in the {311} defects. This is consistent with the lack of any TED dependence on these variables.

The original question was whether the damage model or the "plus" model can explain TED in non-amorphizing implants of boron. The lack of dependence of TED on implant temperature or dose rate would suggest that TED depends more on the dose of the implant ("plus" model) than on the amount of damage done to the crystal. It should be emphasized that this is not true for amorphizing implants where strong dose rate and implant temperature effects have been observed.

CONCLUSION

In conclusion, the effect of implant temperature and implant dose rate on TED for non-amorphizing boron implants into silicon was studied. Three different defect regimes, no visible defects, {311} defects alone, and {311} defects and dislocation loops, were investigated. It was found that the extent of transient enhanced diffusion for non-amorphizing implants of boron was independent of the dose rate over a range of 0.035 to 0.35 mA/cm² and independent of implant

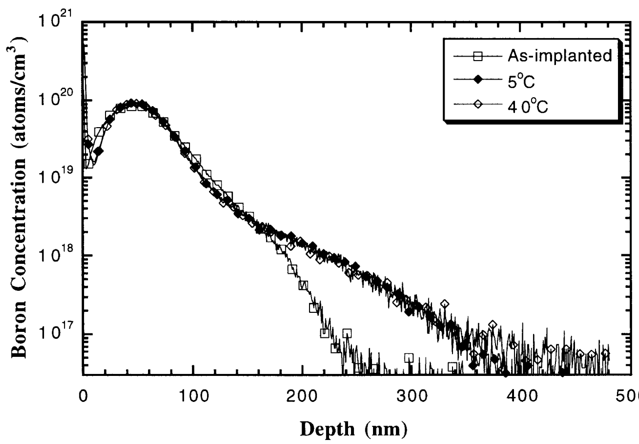

Fig. 4. Effect of annealing at 750°C for 30 min on the transient enhanced diffusion.

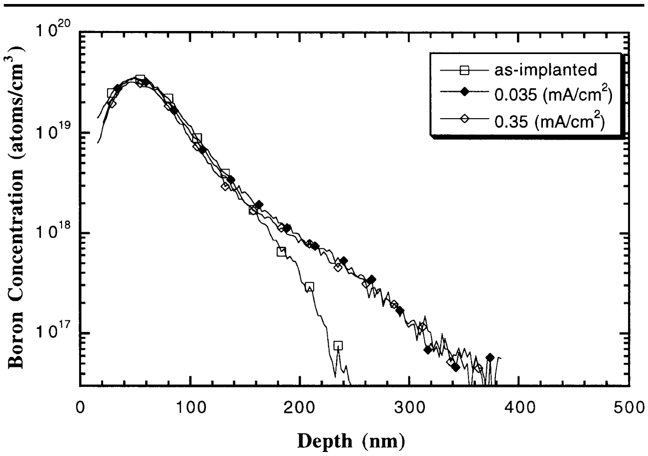

Fig. 3. No effect with variation of dose rate.

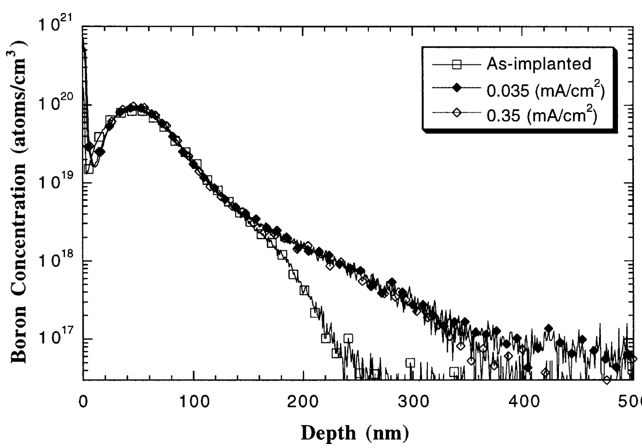

Fig. 5. No effect on TED process with variation of implant dose rate.

temperature over a range of 5 to 40°C. In addition, the trapped interstitials in {311} defects was also found to not depend on either the implant temperature or dose rate. All of these results suggest that below the amorphization threshold, TED is independent of the amount of damage done to the crystal. This would support a "plus" model for B diffusion which accounts for the formation of boron interstitial clusters as was recently proposed by Pelaz et al.[8]

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