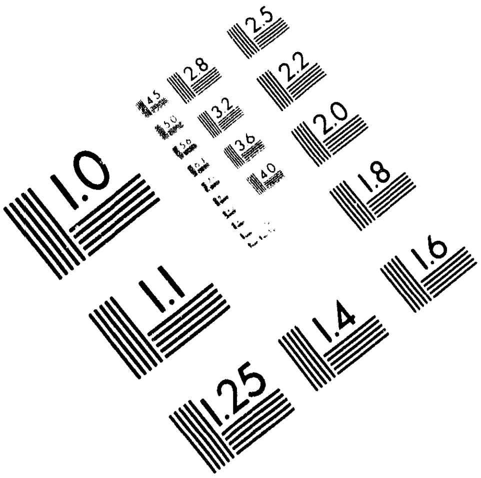

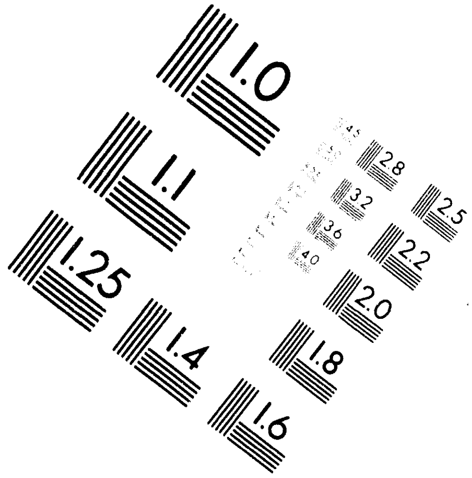

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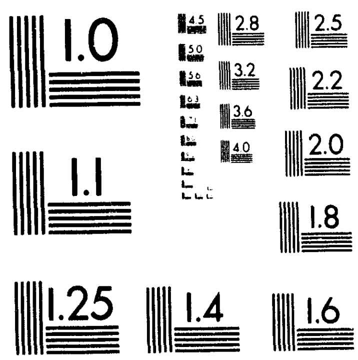

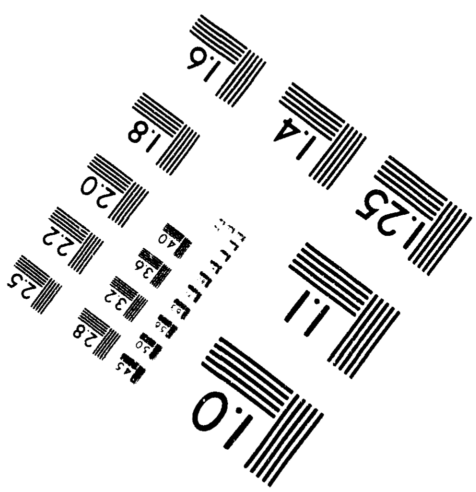

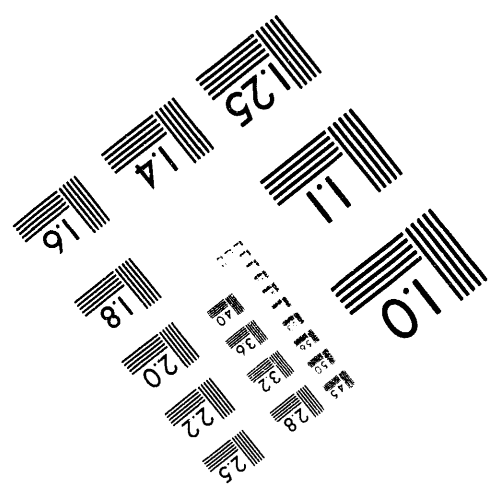

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Defects and Diffusion in Si^{+} Implanted GaAs

K. S. Jones and H. G. Robinson
University of Florida
Gainesville, Florida

T. E. Haynes
Oak Ridge National Laboratory
Oak Ridge, Tennessee

M. D. Deal and C. C. Lee
Stanford University
Stanford, California

E. L. Allen
San Jose State University
San Jose, California

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Oak Ridge, Tennessee 37831
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DEFECTS AND DIFFUSION IN Si^+ IMPLANTED GaAs

K.S. JONES*, H.G. ROBINSON*, T.E. HAYNES,** M.D. DEAL***, C.C. LEE*** and E.L. ALLEN****
*Department of Materials Science and Engineering, University of Florida, Gainesville, FL
**Oak Ridge National Laboratories, Oak Ridge, TN
***Stanford University, Stanford, CA
****San Jose State University, San Jose, CA

ABSTRACT

The effect of extended defects on the diffusion of ion implanted species is an area of concern in the development of process simulators for GaAs. This study explores the effect of type I extended defects including voids and dislocation loops on the diffusion of Si implanted into GaAs. <100> Semi-insulating GaAs wafers were implanted with $1 \times 10^{14}/cm^2$ Si^+ at implant temperatures between -51°C and 80°C and at energies ranging from 20 keV to 200 keV. SIMS results show that the diffusivity of Si decreases with both increasing implant temperature and increasing implant energy. At the same time extrinsic dislocation loop concentrations also increased. For the implant conditions studied, no voids were observed. The diffusion results can only be reconciled with the TEM results if the dislocation loops are behaving in a reactive rather than proactive manner. In other words, the changes in vacancy concentration that are affecting the diffusivity are also affecting the loop concentration. This model is supported by evidence that Si diffusivity is enhanced over the same time interval the dislocation loops are dissolving which is consistent with the loops having a reactive role. It remains unclear whether the existence of loops significantly affects the total concentration of vacancies and thus diffusion by acting as a competing sink.

INTRODUCTION

Ion implantation is the accepted method of doping GaAs based microelectronic devices. Upon annealing ion implanted GaAs a variety of extended defects have been observed to form. These defects have been classified previously based on the as-implanted morphology [1-3]. One of the long standing questions has been what effect, if any, do the implantation induced extended defects have on the diffusion and electrical activation of implanted or pre-existing dopants. This paper will focus on GaAs implanted with Si^+. The defects that form upon annealing Si^+ implanted GaAs can include stacking faults and microtwins, dislocations, dislocation loops, voids and precipitates. Implanted Si activation saturates at higher doses from self compensation thus the doses in these studies were kept at or below $1 \times 10^{14}/cm^2$. Also since poor Si activation is observed upon annealing amorphized GaAs, this study focuses on Si^+ implant conditions below the amorphization threshold. Thus this study focuses on the effect of type I [4] dislocation loops and voids on silicon diffusion in GaAs.

Chen has shown that voids can form in non-amorphized region of GaAs [1]. These voids can getter Si thereby reducing Si diffusion and they can compensate the electrical activation of Si in GaAs [5]. It has even been proposed that voids be used as an implant isolation scheme because of their stability upon high temperature annealing [5]. It was also found that increasing the implant temperature resulted in both fewer voids and an increase in the amount of Si diffusion. This is presumably because increasing the temperature increases the amount of point defect recombination which reduces the concentration of vacancies below the concentration necessary for void formation. Without the competing vacancy sink of the voids there are more vacancies available for Si diffusion.

It has been shown that there appears to be no effect of implantation induced dislocation loops on the electrical activation of silicon in GaAs [6]. This is somewhat surprising since it has also been reported that variations in the grown-in dislocation density across the GaAs wafer are responsible for shifts in the threshold voltage due to increased Si activation near the dislocation core [7-9]. This study shows there is a correlation between the amount of diffusion and the concentration of dislocation loops, however the results indicate the loops are reacting to internal changes in the vacancy concentration. It is unclear if their presence significantly affects the changes in vacancy concentration which could indirectly affect the amount of diffusion.

EXPERIMENTAL

<100> semi-insulating LEC GaAs wafers were implanted with $1 \times 10^{14}/cm^2$ $^{29}Si^+$ at various implant temperatures and energies. The wafers used in the implant temperature experiment were mounted to the wafer holder using silver paint and the temperature was monitored to within 2°C. The current density for these experiments varied between 0.1 and 0.4 microamps/cm^2. The RBS was done either immediately after the implant or the samples were kept at 77K until the RBS could be done. A 900Å Si_3N_4 cap was deposited by PECVD prior to furnace annealing. SIMS analysis after annealing was done at Charles Evans and Associates. Cross-sectional TEM samples were prepared using the standard cutting of strips, lapping and Ar ion milling. Plan-view TEM samples were jet etched using a bromine-methanol solution. TEM observations were done on either a JEOL 200CX or a JEOL 4000FX instrument. All bright-field micrographs were taken using a g_{220} two-beam condition.

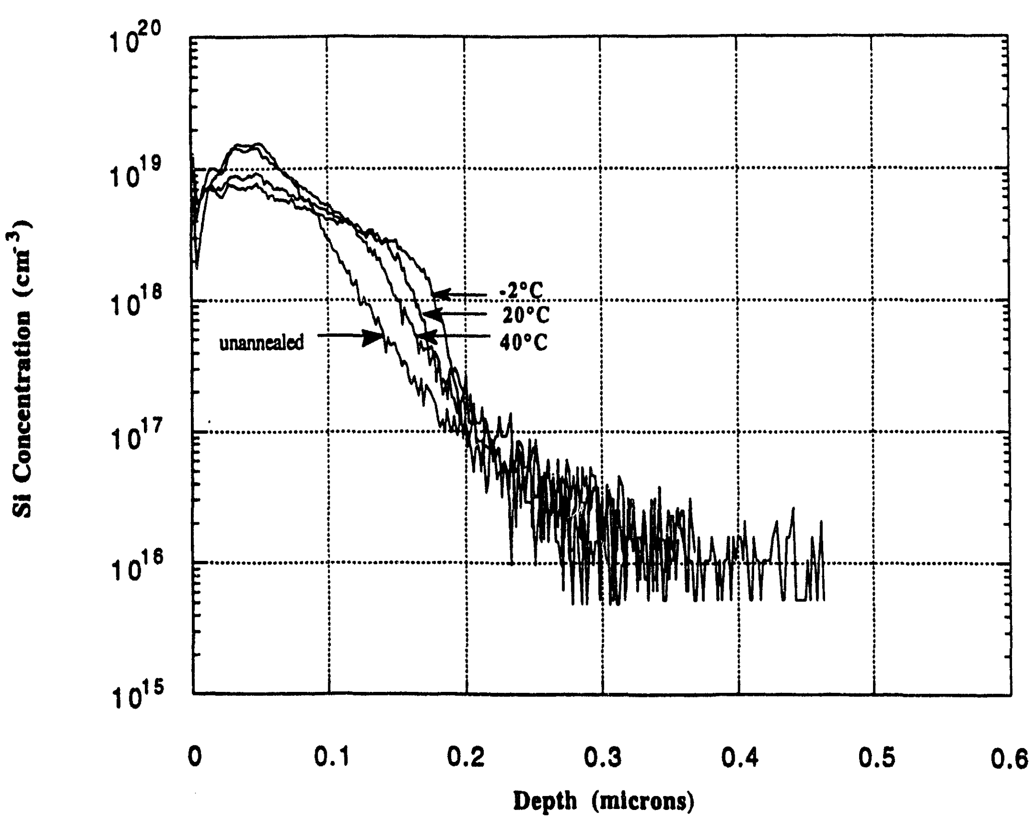

Figure 1: SIMS illustrating the effect of implant temperature on Si redistribution upon

RESULTS AND DISCUSSION

Figure 1 shows the effect of increasing the implant temperature on the diffusion of silicon. It is apparent that as the implant temperature is increased the amount of anomalous diffusion decreases. Since Si diffusion in GaAs is believed to occur via a vacancy assisted mechanism the increase in diffusivity with decreasing implant temperature implies that the vacancy concentration is higher at lower temperatures. It should be mentioned that when the implant temperature was decreased to -51°C amorphization was observed by both XTEM and RBS. Upon annealing at 900°C for 5 minutes no extended defects were observed by TEM and no diffusion of the silicon was observed by SIMS.

Figure 2 shows plan-view and cross-sectional TEM micrographs of the same samples in figure 1 after annealing. It is apparent that as the implant temperature is increased the concentration of extrinsic type I dislocation loops increases. This would imply that either the interstitial concentration is increasing with increasing implant temperature or the vacancy concentration is decreasing with increasing implant temperatures. Previous observations of increasing point defect recombination with increasing implant temperature would not be consistent with an increase in the interstitial concentration but rather the decrease in the total point defect concentration. The diffusion results in figure 1 would imply that the vacancy concentration is decreasing with increasing implant temperature. Thus it would appear that the dislocation loops are reacting to the same decrease in vacancy concentration that is affecting the silicon diffusion. It should be emphasized that careful studies using both diffraction and phase contrast imaging were done on all of these samples to determine if voids were present. In none of the samples discussed in this paper were voids observed. This is consistent with the previous work by Chen et. al.[10] that indicate the threshold dose for void formation by silicon implantation at energies less than or equal to 220 keV is at least $3 \times 10^{14}/cm^2$.

Figure 3 shows the effect of annealing at 900°C on the diffusivity of silicon. It is obvious that a significant amount of diffusion is occurring at 900°C between 5 minutes and 30 minutes. It can also be seen that the amount of diffusion for the sample implanted at 40°C is greater than the sample implanted at -2°C. This would imply that the source of the excess vacancies contributing to high silicon diffusivity between 5 minutes and 30 minutes is different from the vacancy source for the first 5 minutes since over the first 5 minutes the diffusivity is higher for the sample implanted at the lower temperature. Both plan-view and cross-sectional TEM results of these same samples show that after 30 minute annealing the type I dislocation loops have completely dissolved. If the loops were strongly influencing the silicon diffusion then one would expect the release of interstitials by the extrinsic dislocation loops to slow the diffusion down. The fact that the diffusion was high implies over this time interval implies that the vacancy concentration was high. This again is consistent with the loops reacting to an external change in the vacancy concentration. Experiments are in progress to determine if there is a further increase in silicon diffusivity just after the loops dissolve. This could indicate if the absorption of vacancies by the loops significantly affects the total concentration of vacancies and thus indirectly affect the silicon diffusivity.

Additional experiments have been conducted varying the implant energy for room temperature Si implants. Figure 4 and 5 show that increasing the implant energy from 20 to 40 keV significantly decreases the diffusivity of the silicon upon annealing. In this case the anneals were done at 800°C. Plan-view and cross-sectional TEM results of the same samples, shown in Figure 6, indicate there is a large increase in the type I dislocation loop concentration with increasing implant energy. It appears that the vacancy concentration is higher at lower implant energies and this leads to significantly more diffusion and fewer dislocation loops. This is consistent with the variable implant temperature results previously discussed.

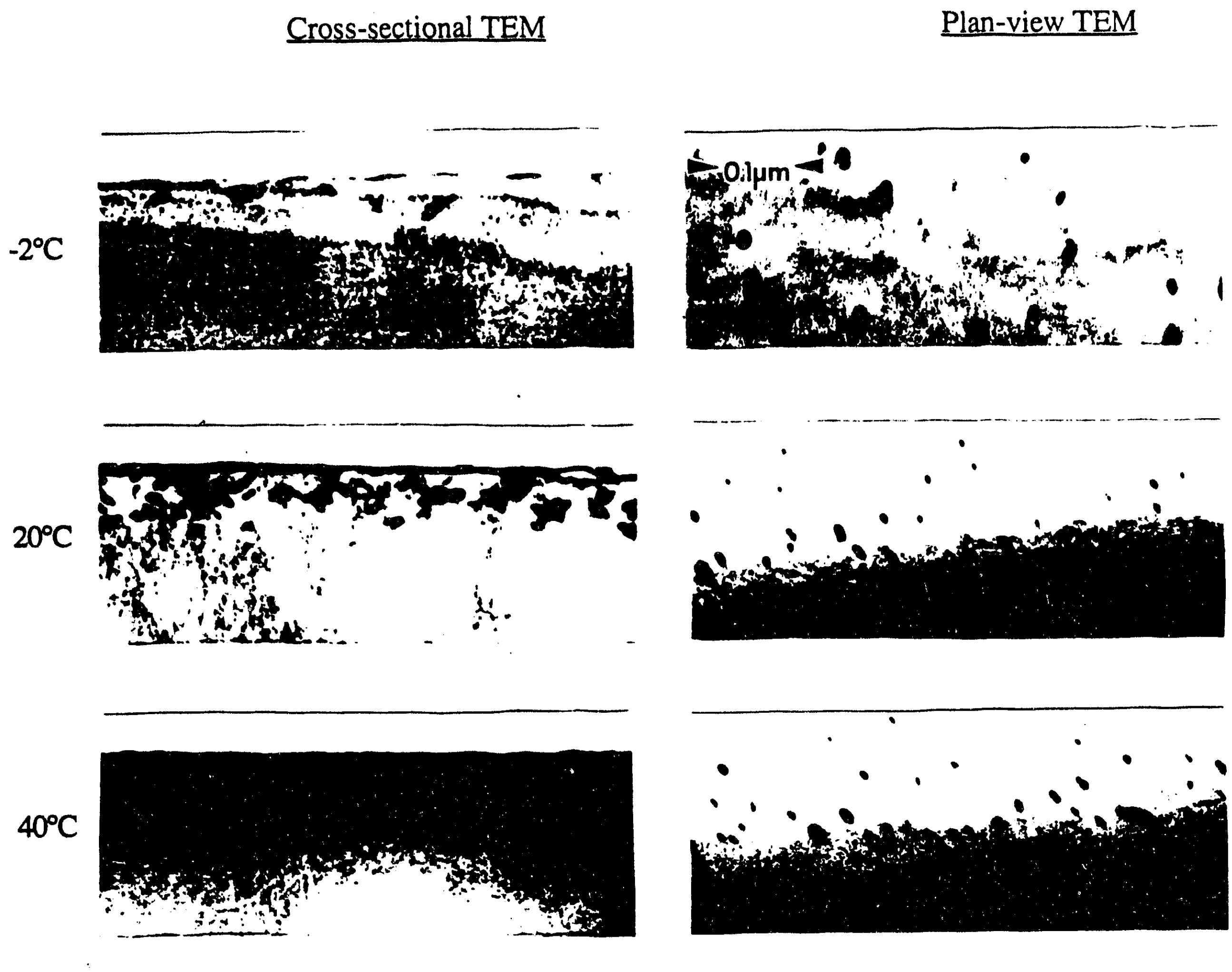

Figure 2: Plan-view and cross-sectional TEM micrographs of the same samples in figure 1 after the same 900°C 5 minute annealing.

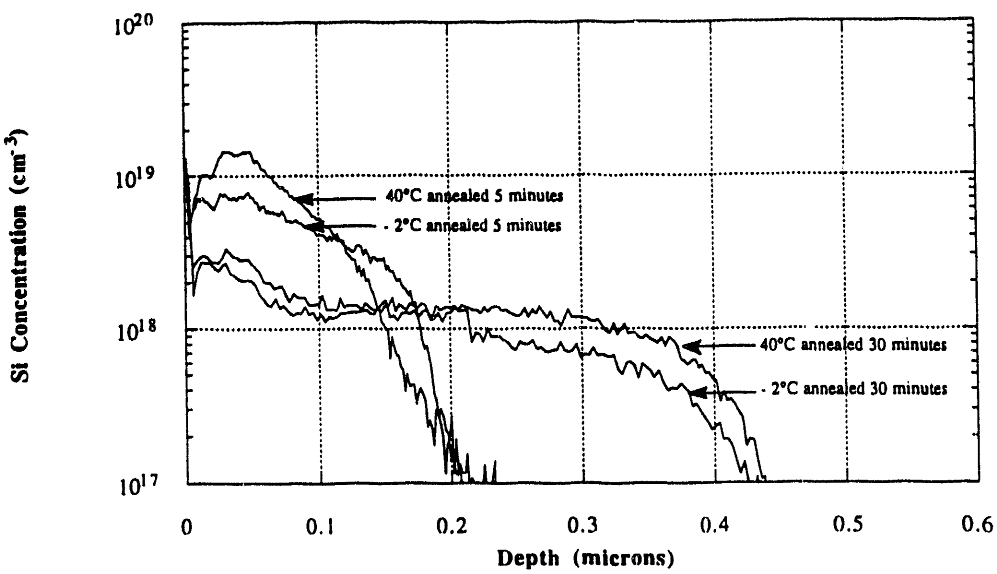

Figure 3: SIMS results showing the redistribution of Si during 900°C annealing. 40 keV $^{29}Si^+$ 1

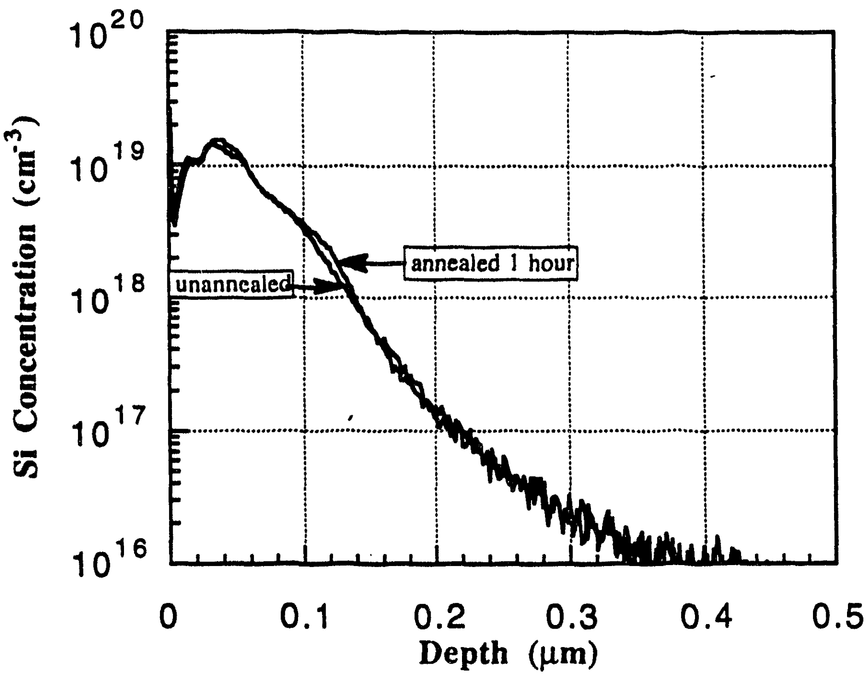

Figure 4: Effect of implant energy on diffusion of **40 keV** $^{29}Si^{+}$ $1 \times 10^{14}/cm^2$ annealed at 800°C.

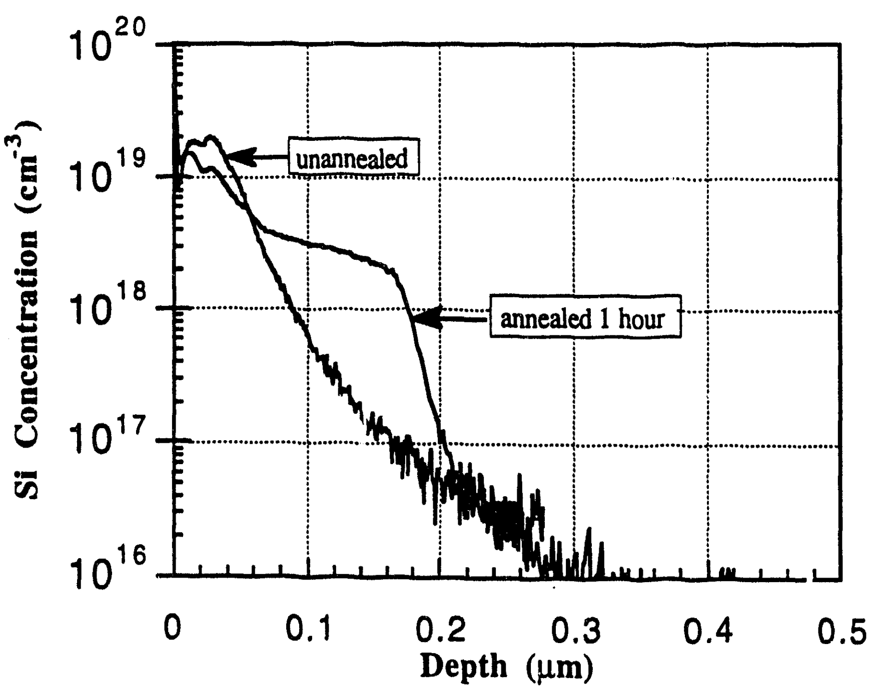

Figure 5: Effect of implant energy on diffusion of **20 keV** $^{29}Si^{+}$ $1 \times 10^{14}/cm^2$ annealed at 800°C.

One interesting question is what is the dominant type of point defect during annealing vacancies or interstitials. This is further complicated in GaAs by the two possible sublattices. Considering just interstitials and vacancies, if the dominant type of point defect during the annealing of these implants is interstitials then increasing the implant temperature would be expected to decrease the concentration of point defects through recombination (and a significant decrease in the RBS channeling yield with increasing implant temperature, from 88% for the -2°C implant to 13% for 40°C implant, was observed for these samples) then the concentration of dislocation loops should decrease not increase with increasing implant temperature. Thus it is proposed that upon annealing the dominant point defects are vacancies and the changes in diffusion and dislocation loop concentration both reflect these changes. However, there is no direct dependence of silicon diffusion on the dislocation loops which is additional evidence that Si is diffusing by a vacancy mechanism in GaAs. It remains unclear if the loops are having an indirect effect on the silicon diffusivity by acting as a sufficient vacancy sink to affect the diffusivity of the silicon. Figure 7 on the next page summarizes how implantation related defects are presently believed to interact with Si activation and diffusion in GaAs.

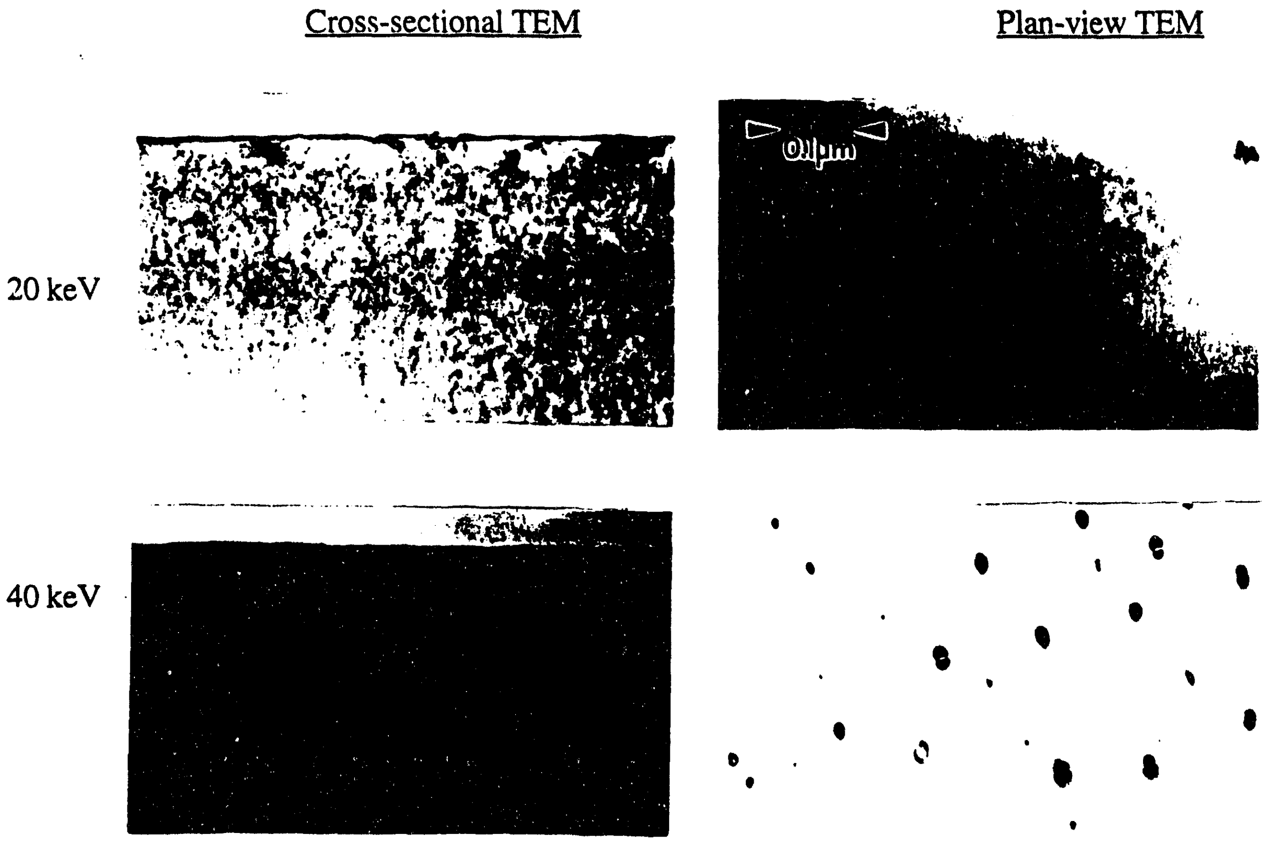

Figure 6: The effect of implant energy on type I dislocation loops Plan-view and Cross-section

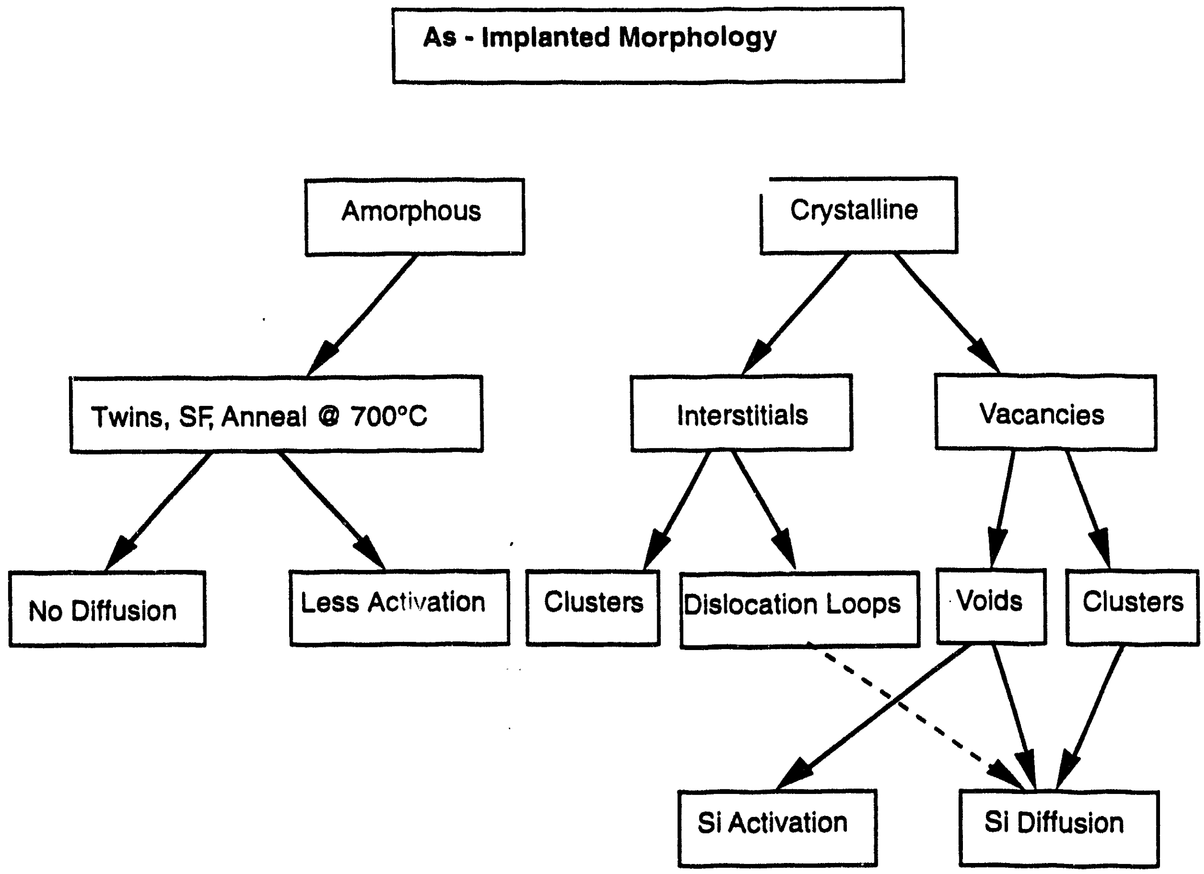

Figure 7: Schematic of Si^+ implantation in GaAs

CONCLUSIONS

It has been shown that by increasing the implant temperature or increasing the implant energy of Si^+ in GaAs the amount of diffusion decreases and the concentration of dislocation loops increases. It was also observed that upon annealing the silicon diffusivity was high while the dislocation loops were dissolving. All of these observations are consistent if one assumes silicon diffuses via a vacancy mechanism in GaAs and the formation and dissolution of the type I extrinsic dislocation loops does not directly affect the silicon diffusivity, rather the loops are reacting to the same changes in vacancy concentration that are affecting the diffusing silicon. In addition the results appear consistent with the dominant point defects in the system being vacancies. It remains possible that the loops have an indirect affect on the silicon diffusivity by acting as a significant vacancy sink.

Acknowledgments

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