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Nuclear Instruments and Methods in Physics Research B 96 (1995) 196–201

NIM B
Beam Interactions with Materials & Atoms

Studies of point defect/dislocation loop interaction processes in silicon

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Abstract

Studies of the interactions between point defects introduced during semiconductor processing and dislocation loops are reviewed. The processing steps studied include oxidation, ion implantation and silicidation. By using doped marker layers it is shown that the interaction kinetics between the point defects and the dislocation loops is strongly diffusion limited. It is also shown that these dislocation loops can be used to quantitatively measure the flux of point defects introduced. This has provided a novel means of better understanding the process of defect injection as well as the effect these dislocations have on the excess point defect concentrations.

1. Introduction

The interaction between ion implantation induced dislocation loops and point defects injected during the subsequent processing of silicon integrated circuits has been investigated [1–4]. The two principle reasons for studying these interactions is, one to use the loops to help quantify the total flux of point defects arising from each of the processing conditions studied and two to determine how dislocation loops interact with point defects to help improve the process modelling of dopant diffusion. The quantification of the processing induced point defect perturbations is possible because the loops are all extrinsic, confined to a layer that is possible to image by plan-view TEM. The loops also have an extremely high density which as will be discussed generally leads to a diffusion limited interaction process between the point defects and the loops. This makes it possible to directly measure the flux of point defects.

Ion implantation is the preferred method of introducing dopant during IC processing. It is well documented that this implantation process introduces excess point defects, some of which can evolve into dislocation loops upon annealing. This leads to possible interactions between these dislocation loops, excess point defects arising from implantation damage and dopant diffusion. This is summarized in Fig. 1. With respect to improved diffusion modeling, it is generally accepted that point defect/dopant pairs can form during processing [5,6]. This pairing interaction can result in greatly enhanced diffusivities of dopants, therefore understanding the concentration and evolution of excess point defects is essential to dopant diffusion modeling. These process induced dislocation loops can also indirectly influence dopant diffusion by interacting with the point defects introduced during subsequent processing. In addition, the dislocation loops can behave as gettering sites for the dopants thereby directly influencing the dopant redistribu-

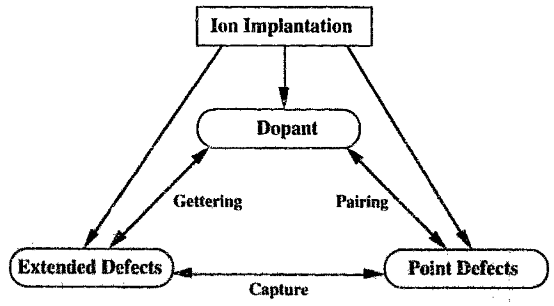

Fig. 1. The interactions between dopants, extended defect and point defects after ion implantation.

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SSDI 0168-583X(94)00482-X

tion process. Finally upon dissolution, the dislocation loops can act as sources of point defects again influencing dopant diffusion. For all of these reasons, it is imperative that dislocation loops be accounted for if accurate dopant diffusion modeling is to be realized.

This paper briefly summarizes some of the work we have been doing on the characterization of process induced point defect/dislocation loop interactions. The work began with basic studies into how the loop density and distribution changes with implant and annealing conditions. This is followed by a summary of work studying the interaction between the dislocation loops and point defects from dry oxidation, which provides a relatively low supersaturation of interstitials over a long period of time and ion implantation with boron which provides a very high supersaturation of interstitials over a short period of time. Finally some recent results from studies of Ti silicidation which inject vacancies are discussed.

2. Experimental

In all of the experiments discussed, ion implantation of either Si^+ or Ge^+ is used to form an amorphous layer. The energy and dose varied for each experiment but it is usually between 50 and 170 keV at doses between 5×10^{14}

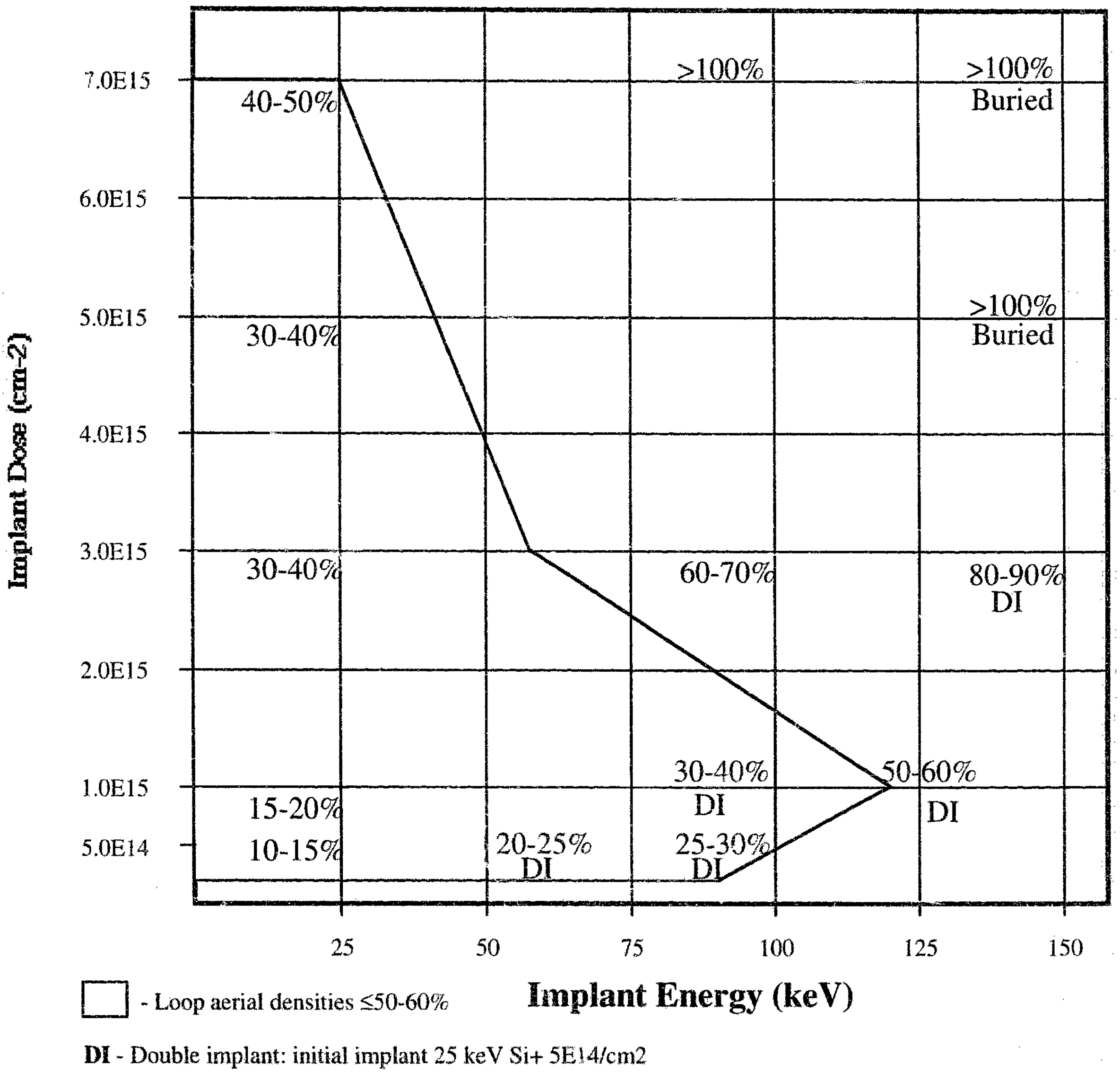

Fig. 2. The effect of implant energy and dose on the concentration of type II dislocation loops arising from room temperature Si^+ implantation.

and $2 \times 10^{15}/cm^2$. Upon furnace annealing at either 800 or 900°C the amorphous layer regrows and a layer of type II (end of range) dislocation loops forms just below the position of the amorphous/crystalline interface [7]. The density of these loops varies with the implant conditions but is typically between 10^{10}–$10^{11}/cm^2$ [8]. The loops typically grow for the first 30 min of annealing at 800°C after which they enter a coarsening phase. The loops for inert species under these conditions do not dissolve for annealing temperatures below 1000°C. Therefore most of the experiments using the dislocation loops as point defect monitors are done in this coarsening regime between 800 and 1000°C. Plan-view TEM is used to monitor the concentration of dislocation loops and their size distribution. Using weak beam dark field imaging, it is possible to determine the concentration of point defects bound by the loops from the loop density and size distribution [1].

For the experiments involving doped epilayers, the epilayers were grown by atmospheric pressure CVD at 850°C using dichlorosilane in H_2. Typically 3500–4000 Å of undoped silicon was grown followed by growth of a thin (FWHM of 400 Å) B doped ($N_p \sim 8 \times 10^{18}/cm^3$) layer and then finished with 8000 Å of undoped silicon. SIMS is used to measure the boron profile before and after point defect injection. Next FLOOPS (Florida object oriented process simulator) is used to determine the diffusivity of the boron profile and therefore the excess concentration of point defects reaching the doped epilayer. Using this method it is possible to determine the relative concentration of point defect captured by the loops when they are between the point defect source and the boron doped layer.

3. Inert annealing studies

The first fundamental question is how does the loop density and size distribution vary with implant conditions. Fig. 2 shows one of many studies done to determine how implant energy and dose affect the concentration of type II dislocation loops arising from room temperature Si^+ implantation. The values in this figure express the fraction of the plan-view TEM micrograph that is occupied by the dislocation loops. For certain high energy low dose conditions dual implants were necessary to form a continuous amorphous layer up to the surface. It is clear from this figure that for studies utilizing the loops as point defect detectors the ideal concentration of loops must be less than a 100% and is preferably less than 50% for interstitial injection studies. This limits the useful implant conditions for Si^+ to lower doses and energies and thereby shallower depths. Ge^+ implantation to form the loops offers a wider range of loop sizes, densities and depths because of its higher mass and in general it is relatively inert at the doses needed for loop formation. The second fundamental question is how do the loops evolve upon annealing. Recent exciting unpublished results indicate the growth rate of the loops are evolving through a point defect diffusion and climb mechanism not a glide and self climb mechanism. These studies into loop formation and evolution processes are on-going but enough was learned to enable studies of how the loops interacts with point defects to be started.

4. Oxidation studies

The first studies investigated the interaction between oxidation induced interstitial and type II dislocation loops. It was found that the implant species used to form the loops influenced the point defect injection process. Specifically when Ge^+ was used to form the loops, the interstitial injection process was reduced. This was attributed to a small amount of the Ge piling up at the oxidizing interface and thereby affecting the oxidation process [3,4]. When Si^+ was used to form the loops, the net concentration of interstitials trapped by the loops was found to increase proportional to the oxidation time [4] and was found to be directly related to the integrated enhancement measured by oxidation enhanced diffusion (OED) studies [9]. In separate experiments using doped marker layers it was determined that the interaction process between interstitials injected during 900°C dry oxidation and a layer of dislocation loops was primarily diffusion limited [10]. In this study it was found that a layer of dislocation loops effectively traps most of the interstitial flux during oxidation thereby preventing any enhancement in the boron doped layer below the loops. The change in the size of the loops during oxidation and their effects on the point defect concentration as a function of depth during oxidation have been modeled and inserted into the FLOOPS code [11]. Since it is known that the process is diffusion limited it has been possible to compare OED measurements with flux measurements from the dislocation loop studies. By integrating Fick's second law and using values from both experiments it was shown that the $D_I C_I^*$ product could be determined [12]. The results gave a $D_I C_I^*$ value of 8.9×10^4 $(cm\,s)^{-1}$, which is slightly larger than previously reported values by Bronner et al. (7.0×10^4) and Boit et al. (7.7×10^4) [13,14]. The slight increase may be due to the loops attracting the interstitials thereby increasing D_I.

5. Implantation studies

The interaction between implantation induced point defects and dislocation loops was also investigated [1]. Using fully coarsened dislocation loops it was determined that the concentration of interstitials captured by the loops is approximately equal to the boron implant dose when the loops are at the projected range of the boron implant. However the flux to the loops is less when the loops are below the boron implant profile. The effect of loop position on the concentration of interstitials trapped was fur-

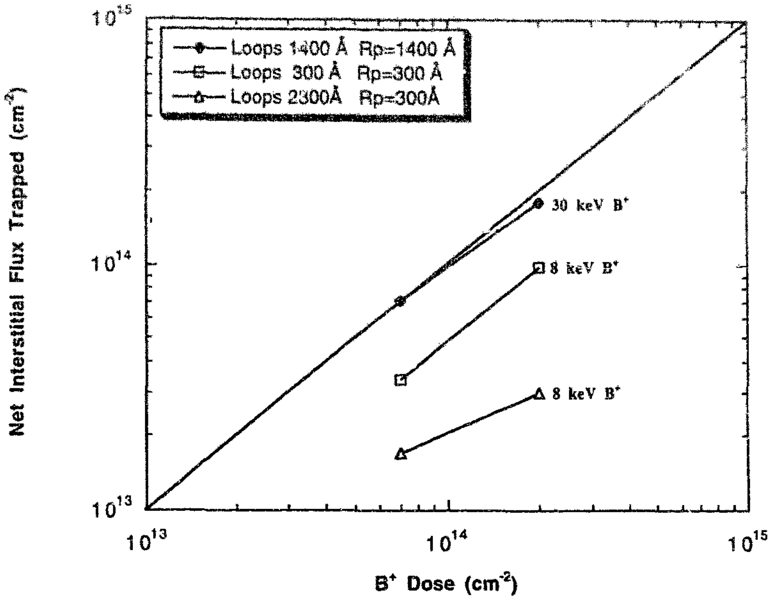

Fig. 3. The effect of varying the loop position relative to the projected range on the net concentration of interstitials trapped by the dislocation loops upon 800°C 30 min annealing. The loops were formed by Ge^+ implantation and were fully formed (800°C 30 min annealing) prior to B implantation and annealing.

ther investigated by using a dual implant of Ge^+ (75 keV $1\times10^{15}/cm^2$ and 190 keV $1\times10^{15}/cm^2$) to form a layer of dislocation loops 2300 Å deep. Next RIE (reactive ion etching) was used to vary the depth of the loops (1300 and 300 Å deep). Upon implantation with 8 keV B at doses below the type I defect formation threshold (7×10^{13} to $2\times10^{14}/cm^2$) and furnace annealing at 800°C it was found that the concentration of interstitials decreased from

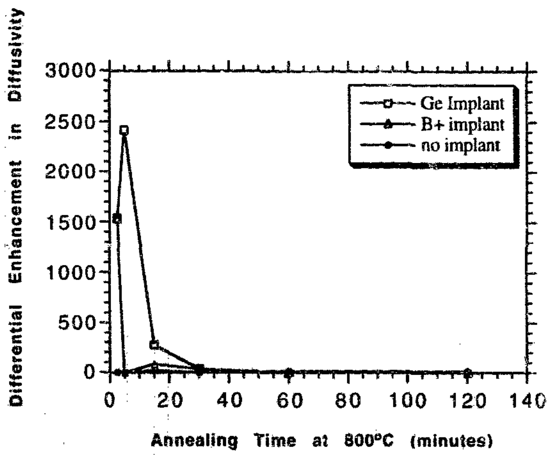

Fig. 4. The change in the differential enhanced diffusivity of the doped epilayer (8000 Å deep) induced by Ge or B implantation as a function of annealing time at 800°C. The Ge implant was a dual implant that produced dislocation loops at 2300 Å deep, while the B implant was an 8 keV $1\times10^{14}/cm^2$ implant which produced no dislocation loops.

about 50% of the dose for the loops at R_p to only 15–30% of the dose for the deepest loops. In addition it was noted that increasing the B energy increased the concentration of interstitial trapped. This is shown in Fig. 3 for several different doses of boron. It is believed that the loops at R_p affect the recombination of the Frenkel pairs by capturing interstitials before they have a chance to recombine. Another possibility is the loops are capturing the excess interstitial before they can recombine at the surface. In either case, the position of the loops clearly affects the concentration of interstitials they trap and this could have a significant bearing on how the loops affect dopant diffusion.

Subsequent boron doped marker layer studies have been done using a marker layer grown by CVD 8000 Å deep, a layer of loops 2300 Å deep and a shallow (8 keV) boron implant (R_p 300 Å). By comparing the diffusivity of samples with and without Ge^+ implantation it was possible to determine when the point defect transient for the loop forming implants was complete. Fig. 4 shows that at 800°C it takes about 30 min before the differential enhancement in B diffusivity decreases to its inert value. The transient for samples with low dose B alone decreases much faster being complete after only 5 min. The difference in the annealing behaviors is ascribed to the kinetics of loop formation and this is the first report of this delay in the transient annealing from loop formation. The peak in the enhanced diffusivity corresponds to a peak in the extended defect concentration. After 30 min the loops coarsen but the concentration of interstitials bound by the loops does not change significantly. When the loops were

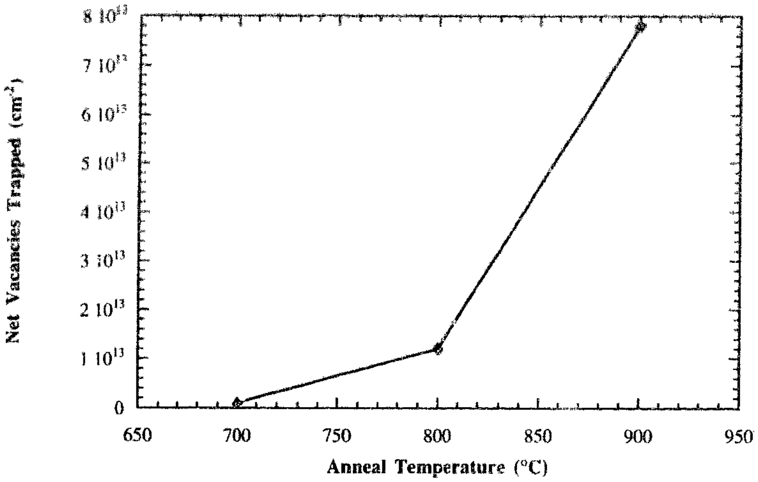

Fig. 5. The effect of annealing temperature (2 h anneals) on the concentration of vacancies trapped by a layer of type II dislocation loops after 300 Å of Ti is deposited and annealed at 700°C for 20 min to form the $TiSi_2$.

introduced and annealed for 30 min and then a subsequent B implant plus annealing done the enhancement from the B implant decreased from over 1500 × without the loops to an undetectable motion (less than 400 ×) with the loops present. This indicates that the loops are very effective in blocking the interstitial injection and the interaction kinetics appear to be diffusion limited. This is consistent with the blocking of transient diffusion reported previously [15,16].

6. Ti silicidation studies

It is also seen that type II loops can be used to study vacancy injection that occurs upon titanium silicidation of the silicon surface [2]. Understanding this vacancy injection process is important since $TiSi_2$ contacts are becoming the predominant method of contacting the source/drain regions of field effect transistors. These studies show that despite formation of the $TiSi_2$ at low temperatures (700–

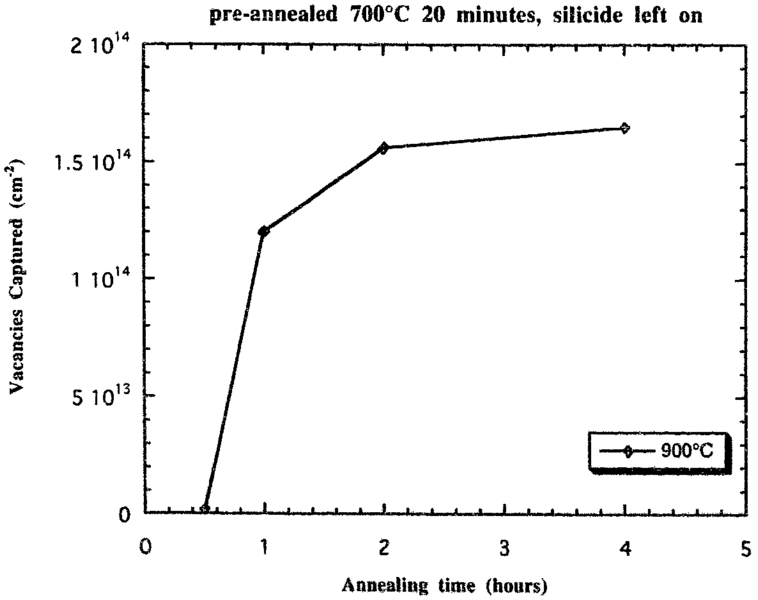

Fig. 6. The effect of annealing time on the concentration of vacancies trapped by a layer of type II dislocation loops after 300 Å of Ti deposited and annealed at 700°C for 20 min to form the $TiSi_2$.

750°C), significant vacancy capture by the loops is not observed until after subsequent high temperature annealing (Fig. 5). This is attributed to the slow diffusivity of the vacancies in the material. In addition it was observed that more vacancies ($1.7 \times 10^{14}/cm^2$ versus $1.1 \times 10^{14}/cm^2$) are captured when the Ti silicide is formed by a single 900°C 30 min anneal than when the Ti silicide is formed by a 700°C 30 min anneal followed by a 900°C 30 min anneal. This is consistent with a model in which the diffusivity of the vacancies is small enough at 700°C that they are consumed by the advancing silicide interface and therefore fewer are available for capture upon subsequent high temperature annealing. Another observation that the vacancies are present but not reaching the loops at low temperatures is that the $TiSi_2$ can be removed after the low temperature formation step and upon subsequent high temperature anneal, vacancy capture is still observed [2]. Finally Fig. 6 shows that upon 900°C annealing the concentration of vacancies trapped by the loops saturates. It is still not known if the vacancy injection process is complete or the loops which are decreasing dramatically in density during this process are simply no longer sufficient in concentration to capture the vacancies. This is being further studied by varying the effect of density of the starting loop concentration.

7. Conclusions

A review of several studies involving the interaction between the processing induced point defects and a layer of type II implantation induced dislocation loops is given. It is shown that it is possible to measure quantitatively the point defect flux from oxidation, ion implantation and silicidation. All of these studies also indicate that there is a strong interaction between dislocation loops and excess point defects. By characterizing this interaction it is possible not only to improve dopant diffusion modeling but to learn more about the point defect formation processes during IC manufacturing.

Acknowledgements

The authors would like to acknowledge the support of the NSF-PYI program and the IBM corporation.

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