Study of point defect detectors in Si*

SHEN Dingyu, CHEN Jian, ZHAO Qiang, WANG Xuemei
(*Department of Technical Physics and Institute of Heavy Ion Physics, Peking University, Beijing 100871*)

Abstract The importance of point defects in semiconductor and function materials has been studied in detail, but effective means for detecting point defects has not been available for a long time. The end of range defects in Si, produced by 140 keV Ge^+ implantation, were investigated as detectors for measuring the interstitial concentratión created by 42 keV B^+ implantation. The concentration of interstitial resulting from the B^+ implantation and the behavior of the interstitial flux under different annealing condition were given. The enhanced diffusion in the boron doped EPI marker, resulting from mobile non-equilibrium interstitials was demonstrated to be transient. Interstitial fluxes arising from processing can be detected by transient enhanced diffusion (TED) of doped marker layers as well.

Keywords Dislocation loop, Point defect, Detector, Ion implantation, Marker layer, Anomalous diffusion

1 Introduction

The formation and motion of point defects in semiconductor devices significantly affect the properties of the devices. For example, damage created during ion-implantation processing increases anomalous diffusion of dopant, resulting in the extension of junctions and the increase of leak current. The ability to control dopant profiles for shallow junction fabrication is becoming more important. For long time there were short of efficient means for defecting point defects. One can only measure macroscopic profiles of damage (for instance, by Rutherford back scattering-channeling) and the relative concentration of point defects.[1] Several years ago Jones K S *et al.*[2] proposed that one could use the end of range (EOR) damage as "detectors" for quantifying interstitial fluxes in ion-implanted silicon.[2]

The EOR damage is commonly observed in ion-implanted silicon at an implanted dose above the amorphism threshold and located below the amorphous/crystalline interface. Upon annealing, a solid-phase epitaxial layer on the amorphous layer is formed first and then the damage evolves typically into a layer of extrinsic dislocation loops. These extended defects can act as either sources or sinks for release or capture of the point defects from the environment supersaturated by the point defect, resulting in shrinkage or expansion of the loop size. By means of transmission electron microscopy, the density and size of the dislocation loop can be directly observed and the total number of atoms bound by loops (i.e., trapped interstitial atoms)[3] can be determined. For dislocation loops used as detectors, their depth and density can be adjusted by varying the implantation energy and dose.

In another method, TED of a doped marker layer was induced by point defect injection. The flux of point defect can be measured by diffusivity of the dopant. The

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result of the diffusion of the buried boron marker was reported.

2 Experiments

The (100) Si wafers were implanted with $1\times10^{15}/cm^2$ or $2\times10^{15}/cm^2$ Ge^+ at 140 keV at room temperature. The dose rate was $0.1\,\mu A/cm^2$. This resulted in the formation of a surface amorphous layer approximately 150 nm thick, which was measured by Rutherford back scattering-channeling. Then the wafers were annealed at 800°C for 30 min in dry nitrogen. Thus a stable layer containing dislocation loops in Si was formed. The depth of the layer was ~170 nm. The concentration of excess atoms bound by extrinsic dislocation loops was measured with Plan-view Transmission Electron Microscopy (PTEM). Quantitative analysis was performed using weak-beam dark field (g_{220}) images. The fraction of the area covered by dislocation loops could be determined by dividing the total loop area by the observed area of the negative (magnification 100,000×). Finally, by multiplying $1.5\times10^{15}/cm^2$ (the planar density of atoms) the concentration of atoms bound by the loops could be estimated. The above process was accomplished by a computer image processing software NIH Image 1.61 to the scanned image.

Samples with buried "detector" layers were subsequently used to study the point defect fluxes induced by low-dose B^+ implantation. The energy of B^+ ion was selected to make the projected range of B^+ close to the depth of the dislocation loop layers. The implanted dose was less than the threshold ($\sim2\times10^{14}/cm^2$)[4] for forming sub-threshold defect (i.e. type-I defects) to avoid the perturbation of the type-I defect on observation of the EOR defect. The B^+ ions at 42 keV with dose of $1.5\times10^{14}/cm^2$ were implanted. Subsequent furnace annealing at 800°C was performed for both samples implanted with B^+ and those without B^+ which are used as control samples. The annealing times were 15 min, 30 min, 1h and 3 h, respectively. The average concentrations of atoms bound by the dislocation loops for the samples with and without B^+ implantation are measured with PTEM. Calculations of the net flux of interstitials captured by the loop detectors was performed by subtracting the concentration of captured interstitials in the control sample from that in the B^+ implanted sample.

For the experiments involving the doped marker layer, a ~23 nm B doped epilayers were grown by chemical vapor deposition (CVD). A ~740 nm undoped epitaxial Si layer was grown over the boron doped epilayer. The first set of samples was used to show the effect of the transient enhanced diffusion arising from the low-energy B^+ implantation on the buried marker layer. The samples were implanted with $1\times10^{14}/cm^2$ B^+ at 30 keV and then annealed at 800°C for 2.5 min, 10 min or 30 min, respectively. The second set was used to determine the effect of different doses of B implantation on TED of the buried marker layer. The doses of the B implantation were $5\times10^{13}/cm^2$, $1\times10^{14}/cm^2$, $2\times10^{14}/cm^2$ and $5\times10^{14}/cm^2$, respectively. The implanted energy of B was 30 keV. Annealing was done at 800°C for 30 min. The boron profiles were measured with secondary ion mass spectroscopy (SIMS). Diffusion enhancement data for each experimental condition were calculated by subtracting the diffusivity of the control sample from that of the corresponding experimental samples. The diffusivity is represented by the diffusion length at 1×10^{17} atoms/cm^3 B concentration.

3 Results and discussions

Fig. 1(1)~1(4) is the PTEM micrographs of some samples with a buried dislocation loop layer. Fig.1 shows the formation of stable dislocation loop layers resulting from a 140 keV $2\times10^{15}/cm^2$ Ge^+ implantation followed by annealing at 800°C for 30 min. The average concentration of the interstitials trapped by the loops is approximately $7\times10^{13}/cm^2$. (See Fig.2)

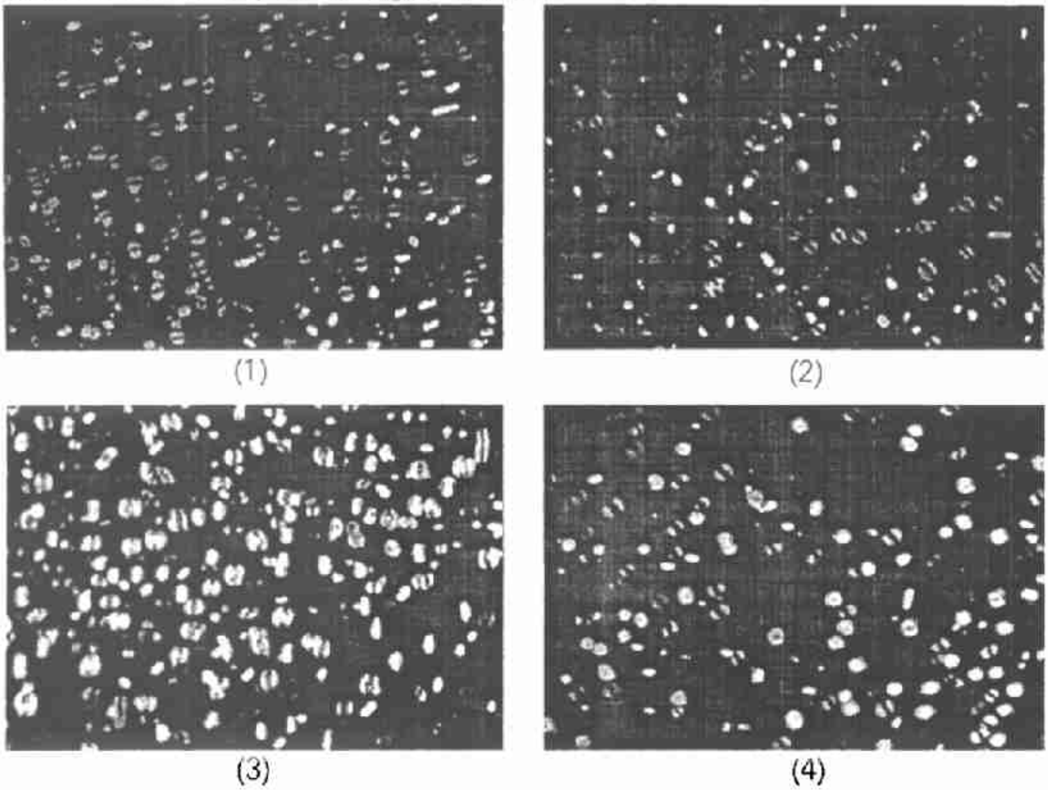

Fig.1 PTEM micrographs comparing EOR dislocation loops arising from annealing at 800°C without B^+ implantation for (1) 30 min and (2) 3 h; with B^+ implantation for (3) 30 min and (4) 3 h

The PTEM micrographs of the control in Fig.1 show that the dislocation loops as detectors are basically stable, but the pattern of the loops changes with the annealing time at 800°C. The number of the big loops increased with time for annealing time from 15 min to 30 min and decreased gradually after 30 min~1h due to dissociation. Finally, the number of the loops of various sizes also decreased. This implies that for annealing time less than 1h the growth-rate of the dislocation loops was higher than the dissociation-rate, leading to the growth of the EOR defects formed. After 1.5 h, the reverse was the case. Fig.2 shows the measured average concentrations of interstitials captured by the loops as a function of annealing time at 800°C. It is observed from the figure that the average concentration reached the maximum during annealing for 30 min~1h.

In Fig.1, the PTEM micrographs of the control samples and those implanted with B^+ are compared. The area fraction occupied by all of the dislocation loops in control sample is usually less than that in B^+ implanted sample. This implies that the ion implantation induced many defects of the interstitial type, which were captured by the dislocation loops through diffusion, so that the average interstitial concentrations trapped by the loops are increased. Fig.2 shows the measured interstitial concentrations captured in the loop detectors for the samples with and without B^+ implantation. The difference between them would be the net interstitial fluxes captured by the detectors, resulting from B^+ implantation.

For the experiments of the boron marker layer, the first observation was made on the samples without B^+ implantation after annealing at 800°C for 2.5, 10 and 30 min, respectively. The diffusion of marker in these samples is intrinsic. The intrinsic diffusion lengths are 0.9 nm, 6.8 nm and 14.4 nm for 2.5 min, 10 min and 30 min, respectively. The diffusion length of marker for samples implanted with $1\times10^{14}/cm^2$ 30 keV B^+ is much greater than that of the control because of the induced point defect. The diffusion lengths are 127.6 nm, 130.4 nm and 136.8 nm, respectively. The anomalous diffusion only lasts for about 2.5 min (800°C). It can be referred to as transient enhancement diffusion. Fig.3 shows the intrinsic diffusion (b) and the anomalous diffusion (c) of the B marker layer.

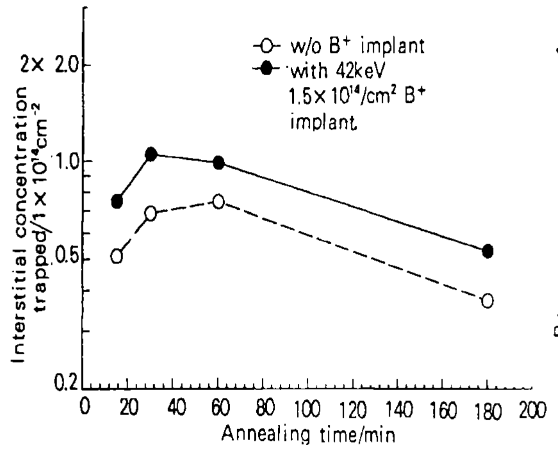

Fig.2 Interstitial concentration trapped by the EOR dislocation loops for wafer with and without B^+ implantation as a function of annealing time at 800°C

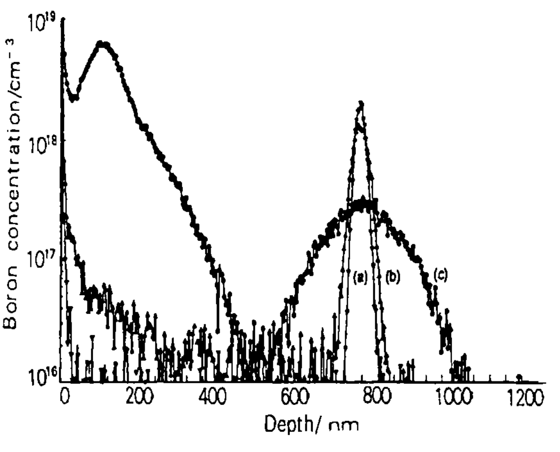

Fig.3 SIMS profiles of boron epilayer. (a) as-grown, (b) after annealing at 800°C for 30 min without B^+ implantation and (c) after implantation with 30 keV $1\times10^{14}/cm^2$ B^+ and annealing at 800°C for 30min

According to the kick-out mechanism[5], during annealing the mobile non-equilibrium interstitial Si arising from B^+ implantation kick out the substitutional B atoms from the lattice sites. Since interstitial boron atoms are regarded as fast diffusers, they result in boron anomalous diffusion. Anomalous boron diffusion persists as long as mobile non-equilibrium interstitial silicon atoms are available. As the doses of the implanted B^+ increase, more interstitial Si atoms are formed on the surface of samples. Upon annealing at 800°C for 30 min, they move towards the marker layer and kick out more substitutional boron. Fig.4 shows the diffusion length of the boron marker layer for dose of boron varying from 5×10^{13}

to $5\times10^{14}/cm^2$ and annealing at 800°C for 30 min. The curve shows when the doses $\leq 2\times10^{14}/cm^2$, the relation between the diffusion lengths and the implantation doses of B^+ is nearly linear. When the dose is more than $2\times10^{14}/cm^2$ the curve appears to be saturated. It is caused by formation of some type-I defects upon annealing. A fraction of interstitial Si were trapped by type-I defect and stayed nearby the end of range, so that the marker diffusion was prevented.

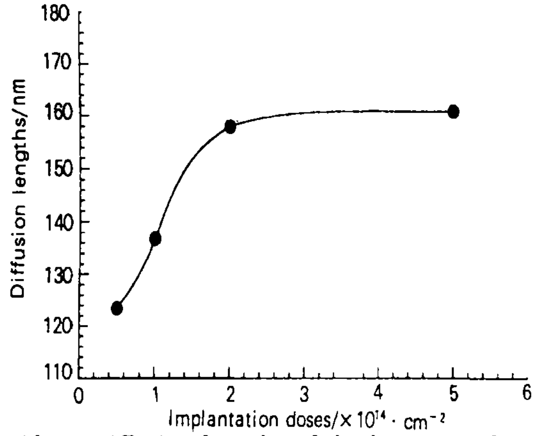

Fig.4 Diffusion lengths of the boron marker layer after annealing for 30 min at 800°C as a function of the doses of 30 keV B^+ implantation

Further observation of TED in the boron marker layer upon annealing was made on the samples with B^+ implantation in Ge^+ pre-amorphism Si wafer. The result indicated that the anomalous diffusivity of the marker layer in Ge^+ pre-amorphous Si wafer is far less than that obtained by algebraic sum of individual anomalous diffusivity caused separately by Ge^+ and B^+ implantation. It suggested that during annealing the interaction between the secondary defects arising from Ge^+ implantation and the interstitial Si formed by B^+ implantation made the non-equilibrium interstitials moved to the boron epilayer to be eliminated significantly. A large fraction of interstitials was captured by the secondary defects and they could not move to B epilayer. It is useful for further study of the point defect kinetics.

4 Conclusions

It has been shown that Ge^+ ion implantation and sequent annealing at 800°C for 30 min is a favorable means to introduce a stable and controllable layer of EOR dislocation loops which can be used as very sensitive point defect detectors in silicon. The interaction between the dislocation loops and the excessive point defects result in the growth or shrinkage of the loops. It is the basis for using the EOR defects as detectors. The trapped interstitials resulting from B^+ implantation in Si have been quantitatively measured by the above means.

We have demonstrated that the anomalous diffusion in the boron marker layer resulting from mobile non-equilibrium interstitials is transient. The enhanced diffusivity changes with the net interstitial flux. Therefore, TED of doped marker layer can monitor the interstitial fluxes induced by device processing.

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