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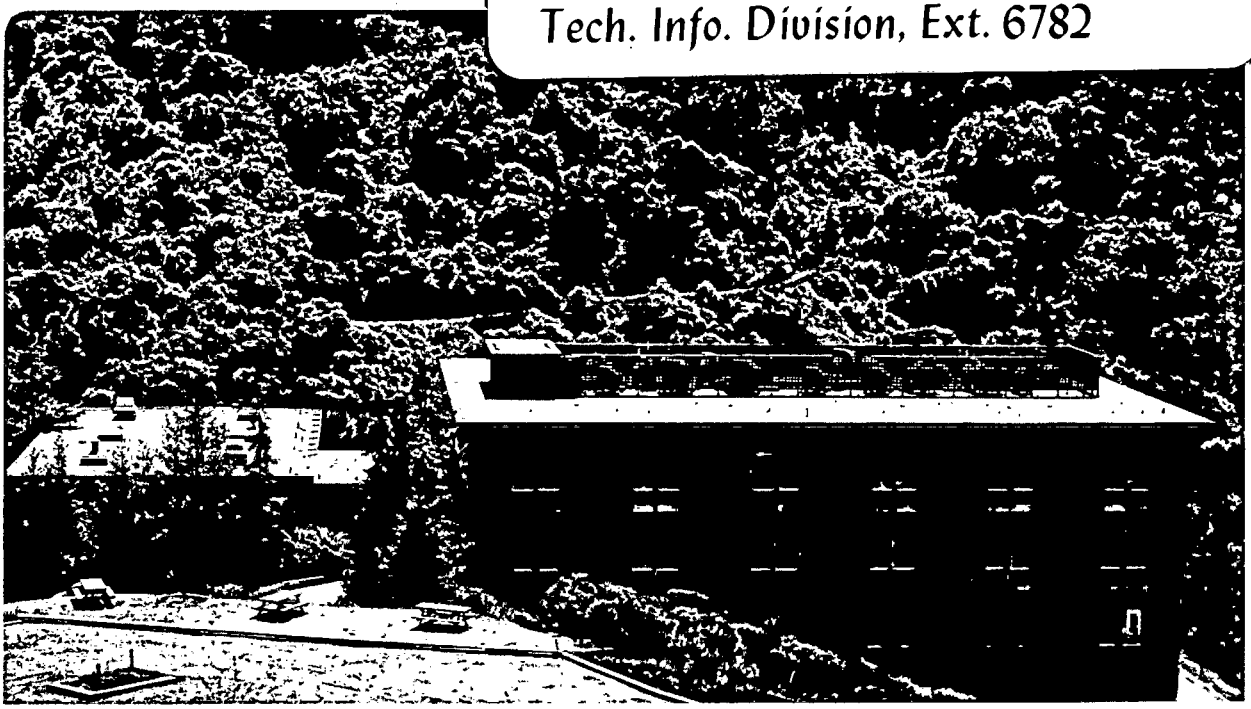

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EFFECT ON ELECTRICAL PROPERTIES OF SEGREGATION OF IMPLANTED P^+ AT DEFECT SITES IN Si*

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ABSTRACT

The aim of this work was to study the furnace annealing behavior of buried amorphous layers formed due to P^+ implantation into Si and to investigate the effects of annealing on the electrical properties of the implanted layer. For this purpose, P^+ was implanted into (111) Si in a non-channelling direction at 120 KeV to a dose of $3 \times 10^{14}/cm^2$ at RT. The implanted samples were subsequently annealed at 750°C. 90° cross-sectional TEM, MeV He^+ channelling, SIMS and electrical results were obtained from the same specimen. The TEM results showed that the annealing at 750°C resulted in the formation of two discrete damage layers at depths of 600Å and 1100Å. However, the MeV channelling measurement indicated the presence of three damage regions; the third region being beyond the second damage layer observed by TEM. The SIMS measurements showed pronounced 'pile-ups' of phosphorous atoms at three damage regions. The carrier concentration profile followed the atomic distribution curve. However, the mobility profile showed decreases only at the the two deeper lying damage regions.

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The regrowth behavior of ion-implanatation induced damage layers in Si and GaAs using transmission electron microscopy (TEM) has been studied extensively by earlier workers.[1-5] The results obtained by TEM showed that the geometry and type of secondary defects left after subsequent furnace annealing depended critically on the implantation conditions.[3,6,7] For example, cross-sesctional TEM work showed that if the starting damage configuration consisted of a buried amorphous layer, the subsequent furnace annealing at 950° gave rise to the formation of two discrete layers of dislocation loops.[8] However, if the starting damage configuration consisted of a continuous amorphous layer extending to the specimen surface, the resulting residual damage after subsequent furnace annealing consisted of a high density of twin lamellae, dislocation networks and dislocation loops. This study is aimed at understanding the formation of secondary defect layers and their effect on the electrical properties in the regrown material.

Boron doped (111) Si wafers with resistivities of 5-10 ohm cm were implanted at room temperature with 120 KeV P^+ ions in a non-channelling direction to a dose of $3 \times 10^{14}/cm^2$ using a few kHz scanning phosphorous ion beam. These implantation conditions corresponded to an LSS theoretical projected range of 1500Å with a straggling of 530Å.[9] Furance annealing of the implanted wafers was carried out in the temperature range 400-1050°C in a nitrogen ambient. However, only the results for a 750°C specimen has been included in this paper to demonstrate the impurity interaction with the secondary structural defects.

For TEM studies, '90°cross-sectional' and 'plan' view specimens were prepared. For the 'cross-sectional' specimens, the implanted wafer was cleaved, mechanically polished and subsequently thinned using a low energy (6 keV) Ar^+ ion-beam. Strong beam bright-field and weak-beam dark-field methods were used to image the defects present in the annealed specimen. A 1.5 MeV He^+ beam channelled along a <111> direction was also used to detect the disorder present in the as-implanted and also in the subsequently annealed specimen.[10] The carrier concentration vs depth and mobility vs depth profiles were obtained by van der Pauw's method in conjunction with anodic stripping. The atomic profiles of phosphourous were obtained by secondary ion mass spectrometry (SIMS) using a positive Cs ion source.[12]

Figures 1 and 2 show results from unannealed and annealed P^+ implanted samples, respectively. For the unannealed sample, the TEM cross-section specimen showed a buried amorphous layer, 1350Å wide, located at a mean depth of 1100Å (Fig. 1a). The microdiffraction pattern taken from different regions of 'Q' using convergent beam method indicated that the central region (~300Å) in this layer was amorphous in nature.[13] The MeV He^+ channelling measurements indicated the presence of a buried damage layer (Fig. 1b). The SIMS measurements gave a standard gaussian distribution of phosphorous atoms with a projected range of 1330Å for the above specimen (Fig. 1c).

The TEM results showed that as the annealing temperature was increased, the regrowth of the amorphous layer became rapid above 550°C .[13] For 650°C annealing, no amorphous layer remained but the specimen showed two discrete layers of secondary damage. The first layer

was well defined and consisted of dislocation loops while the second layer consisted of fine defects. The channelling spectrum from this specimen also showed that no amorphous material remained; however, there was still a considerable amount of dechannelling in the deeper part of the crystal indicating the presence of residual disorder in this region. The SIMS measurements showed an onset of phosphorous redistribution near the secondary damage regions (micrographs and profiles not included in the text).

The TEM cross-section micrograph of a 750°C annealed specimen showed two well defined damage layers 'S' and 'T' at mean depths of 600Å and 1100Å (Fig. 2a). Both these layers contained dislocation loop defects. The analysis of these defects indicated that the Burgers vectors of the loops were of two types, a/2<110> and a/3<111>. The mean diameter of the loops was 150Å. The channelling spectrum from the same specimen showed that the material was a single crystal but there were three damage regions at depths of 600Å, 950Å and 1700Å respectively, as indicated by three peaks, namely, 'A2', 'B1' and 'C' in Fig. 2b. The peaks 'A2' and 'B1' corresponded to the layers 'S' and 'T' of dislocation loops seen in the TEM cross-section micrograph (Fig. 2a). Peak 'C' at a depth of 1700Å corresponding to the damage region beyond layer 'T' in Fig. 2a is thought to arise due to interstitial point defects or their clusters at that depth. The phosphorus atomic profile obtained by the SIMS measurements showed two pronounced peaks 'P2' and 'P3' at depths of 950Å and 1520Å respectively. There was also a shoulder 'P1' at a depth of 600Å in the atomic profile. Shoulder 'P1' and the first peak 'P2' in Fig. 2c corresponded to two damage layers 'S' and 'T' respectively in the TEM micrograph (Fig. 2a), and also to peaks 'A2' and 'B1' respectively in the

channelling spectrum (Fig. 2b). However, peak 'P3' in Fig. 2c corresponded to peak 'C' in Fig. 2b but there was no detectable coarse damage in the TEM micrograph at this depth. The electrical profiles, namely, carrier concentration vs depth, and mobility vs depth taken from another part of the same specimen, showed that the carrier distribution very closely followed the atomic distribution as obtained by the SIMS measurements. The carrier concentration profile showed three peaks at 600Å, 1000Å and 1700Å corresponding to peaks 'P1', 'P2' and 'P3' respectively in Fig. 2c. However, the mobility profiles showed two pronounced dips at depths of 900Å and 1700Å respectively, corresponding to the deeper lying damage layers.

The reasons for formation of the secondary damage layer 'S' at a depth of 600Å (~0.35 R_p) is not yet clear but this could probably arise due to clustering of vacancies formed during implantation near the upper edge of damage layer 'Q'. Collision of an incoming phosphorous atom with a host Si atom causes a vacancy near the surface and two interstitials (deflected Si and P atoms) deeper into the material. Subsequent annealing at 750°C should cause clustering of these vacancies resulting in the formation of the observed dislocation loops (100-150Å across) at layer 'S'. Similar vacancy clustering to form stacking fault tetrahedra has been reported previously.[13] The second damage layer at a depth of ~1100Å (~0.7R_p) forms at the center of the original amorphous-layer 'Q'. This is caused by regrowth of the layer beginning simultaneously both at its upper and lower boundary during annealing. The oppositely moving interfaces eventually meet at the depth of the middle of the original amorphous region Q. The extra silicon and phosphorous interstitials contained within the amorphous layer form the interstitial

dislocation loops seen in layer 'T'. Segregation of the phosphorous atoms at secondary damage regions 'S' and 'T' is thought to occur during the annealing process. Some of the phosphorous atoms in the amorphous layer are probably swept along with the moving amorphous/crystalline interfaces or with migrating vacancies giving the 'pile-up' regions in the atomic profile (Peaks 'P1' and 'P2' in Fig. 2c). Peak P3 in Fig. 2c probably does not arise from concentration of phosphorous atoms but rather due to the presence of a zone denuded of phosphorous atoms on the left side of it. However, a significant migration of phosphorous atoms does occur to depths of ~ x $3R_p$ to ~ x $4R_p$ (notice the broadening of phosphorous profile, Fig. 2c); i.e., well beyond the projected range, indicating that point defects are formed or migrate into the implanted material much deeper than speculated earlier.

Although the segregration of impurities at the damage regions has been suspected for the last several years, we believe this is the first study of its kind that gives a direct experimental evidence. From the practical point of view these findings are important because a significant fraction the of implanted ions become concentrated in the damage regions.

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FIGURE CAPTIONS

Fig. 1 $P^+ \rightarrow$(111) Si, 120 KeV, 3 x $10^{14}/cm^2$, RT.

a. TEM cross-section micrograph showing a buried amorphous layer.

b. Channelling spectrum (1.56 MeV He^+) from the same specimen (continous line).

c. Phosphorous (SIMS) distribution curve for as-implanted Si from the same specimen.

Fig. 2. $P^+ \rightarrow$(111) Si, 120 KeV, 3 x $10^{14}/cm^2$, 750°C annealed for 20 minutes.

a. TEM cross-section micrograph showing two discrete layers of dislocation loops.

b. Channelling spectrum (1.56 MeV He^+) from the same specimen (continuous line).

c. Phosphorous (SIMS) (continuous line), carrier concentration (broken line X) and Hall mobility (broken line ▲) distribution curves from the same specimen.

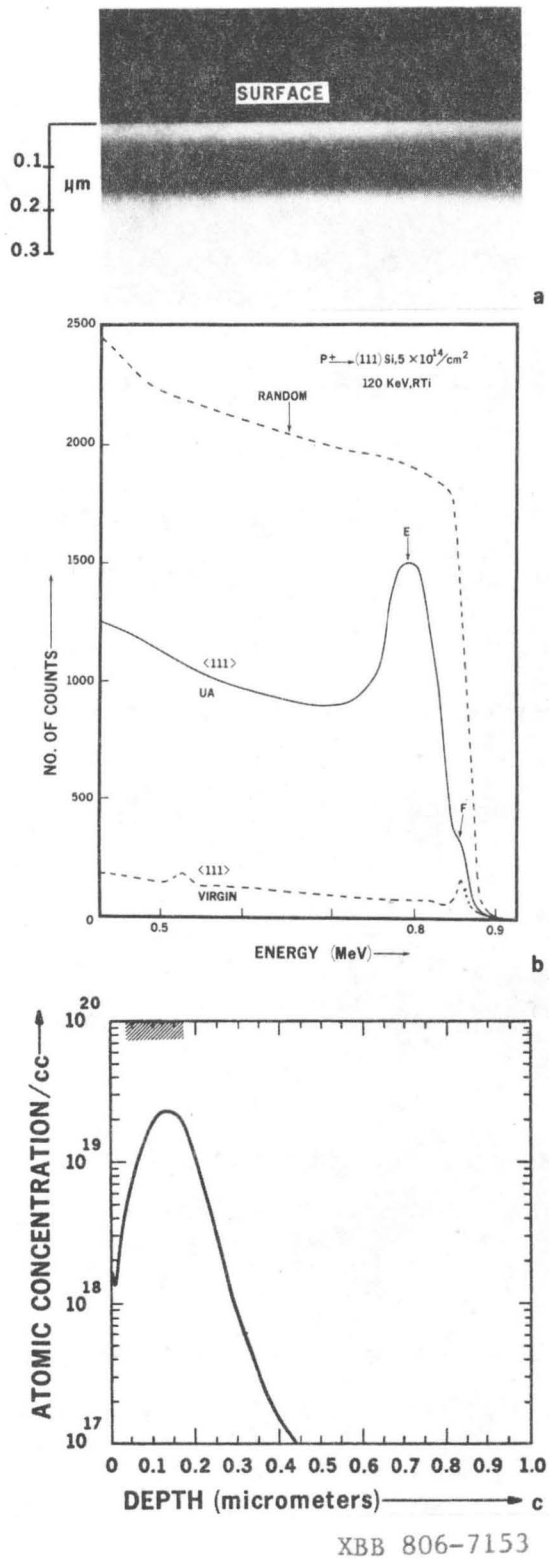

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Figure 1

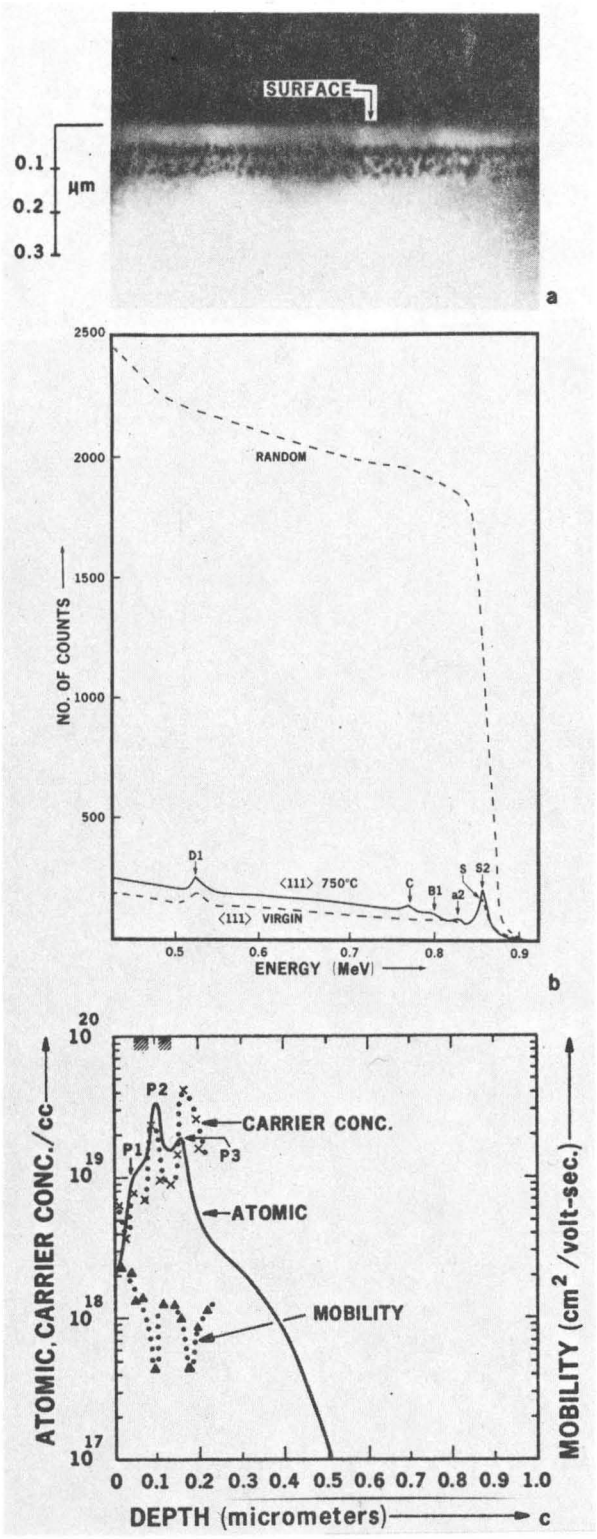

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Figure 2

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