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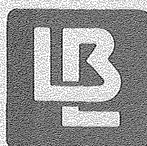

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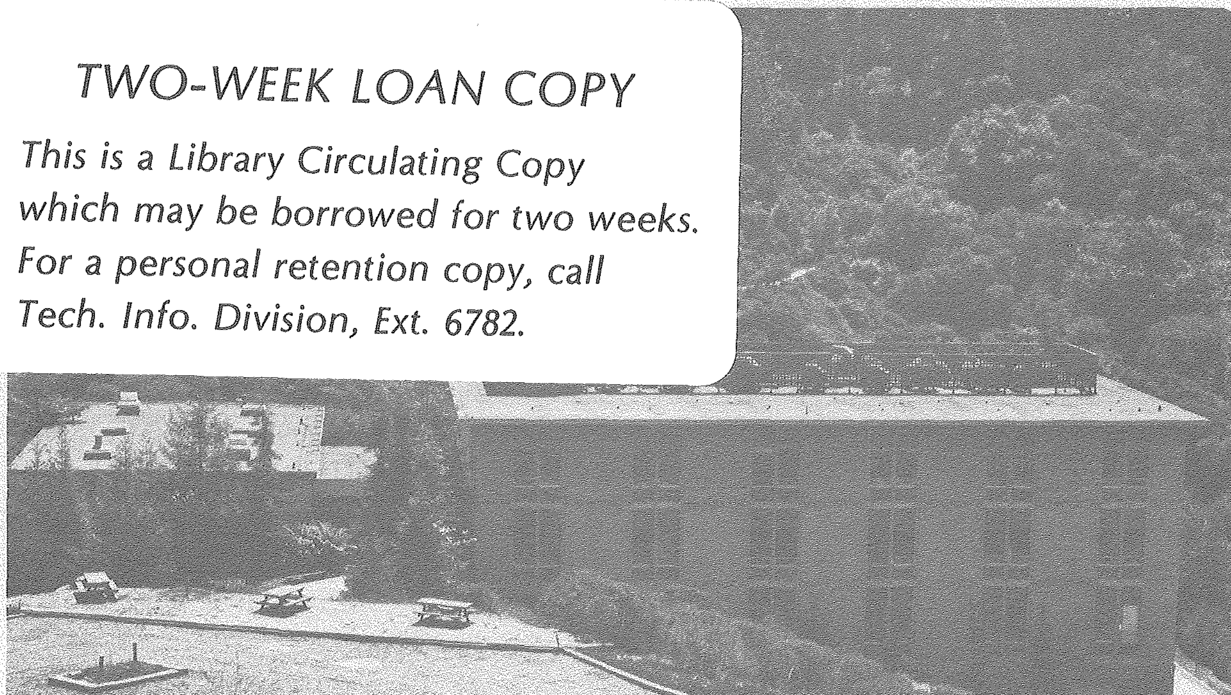

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REGROWTH BEHAVIOR OF THREE DIFFERENT DAMAGE STRUCTURES IN P^+ IMPLANTED AND SUBSEQUENTLY LASER ANNEALED Si

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ABSTRACT

The aim of the work was to study the regrowth behavior of three different damage structures, namely, a buried amorphous layer, a continuous amorphous layer extending from the surface of the specimen and a buried layer of clusters in P^+ implanted (111) Si. These structures were obtained by implanting P^+ at 120 KeV to doses of $5x10^{14}$, 10^{15} and $5x10^{15}/cm^2$ at implantation temperatures RT, 150° and 350^oC respectively. A Q-switched ruby laser with a wavelength of 0.695 nm and at an energy either $0.7J/cm^2$ or $1.5J/cm^2$ was used for laser annealing. TEM was used to examine the damage in a 90° 'cross-sectional' view. At $0.7J/cm^2$, two-thirds of the continuous amorphous layer regrew to give a poly-crystalline layer. The buried amorphous layer regrew leaving dislocation loops and clusters and the buried layer of clusters remained unaffected. However, at $1.5J/cm^2$, dislocations and stacking faults extended from the surface for all the structures and were in direct contact with the deeper lying damage containing clusters. The density of dislocations, stacking faults and

deeper lying clusters progressively increased with the dose of the implanted phosphorus.

INTRODUCTION

The potential applications of high energy pulsed laser beams for the regrowth of damage layers in ion implanted semiconductors has drawn world-wide interest because of the simplicity of the process. By suitable choice of laser parameters, such as the energy, pulse length, etc, epitaxial regrowth of the damage layers resulting from implantation can, in principle, be carried out either in the solid phase or molten phase (1-3). However, the mechanism of regrowth is not yet fully understood. The present study is therefore aimed at studying the regrowth behavior of three different types of damage structures in P^+ implanted Si resulting from pulsed laser annealing at different energies. For all the work described here, TEM was used to examine the damage structures in 90° 'cross-sectional' and 'plan' views before and after the laser annealing. A mechanism for the regrowth has been suggested based on the observations made here.

EXPERIMENTAL

a. Implantation. P-type 17 ohm-cm (111) Si wafers of 5 cm diameter were implanted in a non-channelling direction with 120 KeV P^+ ions using doses of either $5x10^{14}$, 10^{15} or $5x10^{15}/cm^2$. The implantation energy of 120 KeV corresponded to an LSS projected range of 1510

$\pm$ 690 Å. The implantation time in all instances was 10 minutes. The implantation temperatures in the three cases were RT, 150°, and 350°C. The increases above RT in the latter two cases being due to ion beam heating.

b. Laser. A Q-switched ruby laser operating at a wavelength of 0.695 nm was used. The multiple beam output was passed through a diffusing screen coupled to a light guide in order to achieve a flat and uniform intensity distribution (4). The laser energies of 0.7J/cm^2 and 1.5J/cm^2 were used for each specimen. The pulse length for all the specimens was $\sim$30 n sec.

c. TEM. For TEM studies, 90° 'cross-section' and 'plan' view specimens were prepared. The 'cross-section' specimens were obtained by cleaving the slices and then mechanically polishing followed by low energy ion-beam thinning as described previously (5). The micrographs from these specimens correspond to the $(1\bar{1}0)$ plane perpendicular to the original (111) specimen surface plane. All of the TEM examinations described here were performed using bright-field strong-beam diffraction contrast conditions. Transmission electron diffraction (TED) patterns were also obtained to aid in the identification of the damage, using either the standard selected area method or microdiffraction techniques.

RESULTS

a. Buried Amorphous Layer. For the specimen implanted to a dose of $5x10^{14}/cm^2$, the TEM 'cross-section' micrograph showed a ∿1150 Å wide buried amorphous layer 'A' located at a mean depth of ∿850 Å from the surface (Fig 1a). The region between the surface and the top edge of damage layer 'A' had sparsely distributed clusters.

After the specimen had been laser annealed at $0.7J/cm^2$, the region between the surface and ∿1600 Å depth, marked as 'B' in Fig. 1b, consisted of dislocation loops (mean diameter ∿100Å) and clusters. The density of dislocation loops obtained from 'plan' view micrograph (not included in the text) was ~ $6x10^{10}/cm^2$. The regrown region 'B' was followed by a second damage layer 'C' ∿250 Å wide, consisting of dense fine structure and was located at a depth immediately below the bottom edge of layer 'A' in the as implanted specimen (Fig. 1b).

After the specimen had been laser annealed at $1.5J/cm^2$, the first damage layer 'B' in the previous specimen was no longer present. The previous second layer 'C' was much less in evidence and consisted mainly of small damage clusters in the layer 'D' (Fig. 1c). Occasionally, single dislocations extending from the surface to the clusters layer were observed.

b. Continuous Amorphous Layer. For the wafers implanted to a dose of $10^{15}/cm^2$, the TEM 'cross-section' micrographs showed a continuous amorphous layer 'E' extending from the surface to a depth of ~1800 Å. At the lower edge of this layer there was a narrow irregular

zone $\sim$250 Å wide corresponding to heavily damaged but not amorphous material (the narrow dark layer in Fig. 2a).

After the specimen had been annealed at 0.7J/cm^2, a first damage layer 'F' comprising polycrystalline material with mean grain size $\sim$1000Å extended from the specimen surface to a depth of 1500 Å (Fig. 2b). A second damage layer 'G' consisting of dense fine structure and $\sim$500Å wide occurred and was in direct contact with the first damage layer (6).

After the specimen had been laser annealed at 1.5J/cm^2, a first damage layer 'H' comprising single cyrstal material containing mainly stacking faults but also dislocations extended from the surface to a depth of $\sim$1800 Å (Fig. 2c). The stacking faults density (from 'plan' view micrographs) at the surface was $\sim 10^9/cm^2$. A second damage layer 'I' consisting of dense fine structure and $\sim$200 Å wide occurred and was in direct contact with the first damage layer.

c. <u>Buried Clusters Layer</u>. For the specimens implanted to a dose of $5x10^{15}/cm^2$, the TEM 'cross-section' micrographs showed a buried layer of clusters 'J', $\sim$1200 Å wide, in single crystal material that was located at a mean depth of $\sim$2000 Å (Fig. 3a). There were 'visible damage' free regions on either side of layer 'J' (the term 'visible damage' refers to the damage visible by TEM). After the specimen had been laser annealed at 0.7J/cm^2, no noticeable change in the damage structure or distribution occurred (Fig. 3b).

However, for the specimen laser annealed at $1.5J/cm^2$, the results were similar to that of $10^{15}/cm^2$ except that the densities of dislocations and stacking faults (from 'plan' view micrographs) were now $\sim 10^{10}/cm^2$ and $\sim 7X10^{11}/cm^2$, respectively. The first damage layer containing stacking faults and dislocations is marked as 'L' and the second damage layer containing small clusters is marked as 'M' in Fig. 3c.

DISCUSSION

A striking feature of the laser annealing is that two distinctly different annealing zones are sometimes present within individual specimens (Figs. 2b, 2c and 3c). We suggest the following mechanism for the formation of the observed regrown structures.

For the as implanted specimens with buried damage layers (Fig. 1a and Fig. 3a), the near-surface region although damaged, is still single crystal as shown by TEDs (not included in the text). However, for the 10^{15} P^+/cm^2 specimen, the near-surface region is amorphous. As a result, the energy absorption in the 'buried layer' specimens occurred over a larger volume as compared to the 'continuous amorphous layer' specimen. This is because of different absorption coefficients for amorphous and single crystal Si. Therefore, at lower energies, i.e., $0.7J/cm^2$ the 'buried damage layers' either partially recover in solid phase (Fig. 1b) or remain unaffected (Fig. 3b) depending on the thickness and the extent of damage in the near-surface region. However, for 'continuous amphorous layers' strong absorption of energy nearer to the surface causes melting of the surface layer, but the deeper lying damage still anneals in the solid phase. The

molten upper layer in this case regrows on a heavily damaged or amorphous substrate forming the polycrystalline layer.

At $1.5 J/cm^2$, the laser energy absorption is high enough to melt the main damage layer in all three specimens but the solidification of the molten material on deeper lying clusters still gives rise to the formation of the dislocations and stacking faults. The density of these clusters increases progressively with the dose of the implanted P^+ ions. Consequently, the density of dislocations and stacking faults in the regrown layer also increases.

CONCLUSIONS

1. The regrowth structures from damaged layers in P^+ implanted Si resulting from laser annealing at $0.7 J/cm^2$ critically depend on the crystallinity of the specimen in the near-surface region.

2. At a laser energy of $1.5 J/cm^2$, the regrowth of the damage layer occurs via melting for all cases. The perfection of the regrown material then depends on the depth of melting relative to the depth of the original implantation damage.

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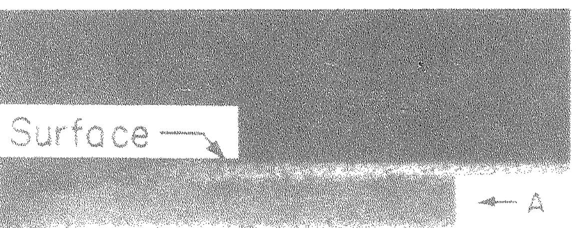
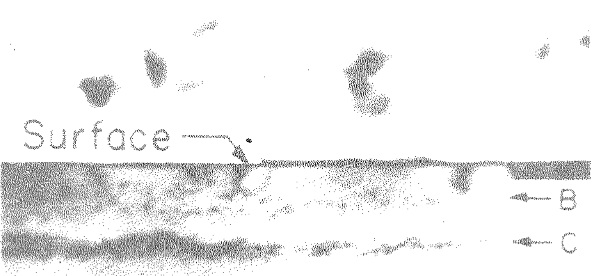
FIGURE CAPTIONS

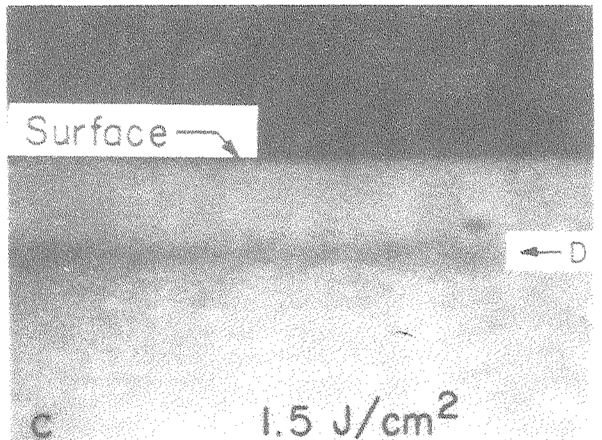
Fig. 1. TEM 'cross-section' micrographs showing the laser annealing sequence for P^+ implanted (111) Si. (Ti = RT, N_{P+} = $5X10^{14}/cm^2$, Ei = 120 Kev)

Fig. 2. TEM 'cross-section' micrographs showing the laser annealing sequence for P^+ implanted (111) Si. Ti = 150°C, N_{P+} = $10^{15}/cm^2$, Ei = 120 KeV)

Fig. 3. TEM 'cross-section' micrographs showing the laser annealing sequence for P^+ implanted (111) Si. (Ti = 350°C, N_{P+} = $5X10^{15}/cm^2$, Ei = 120 KeV)







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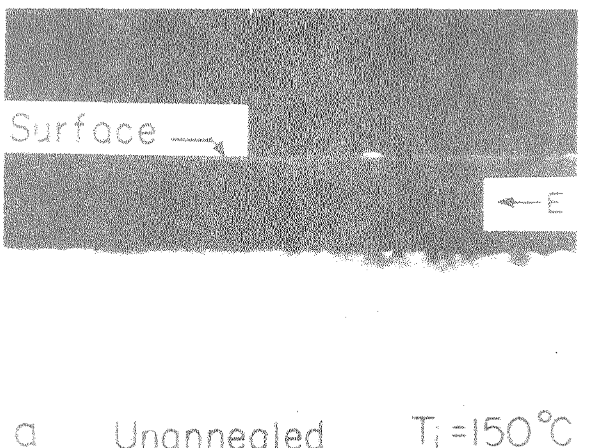

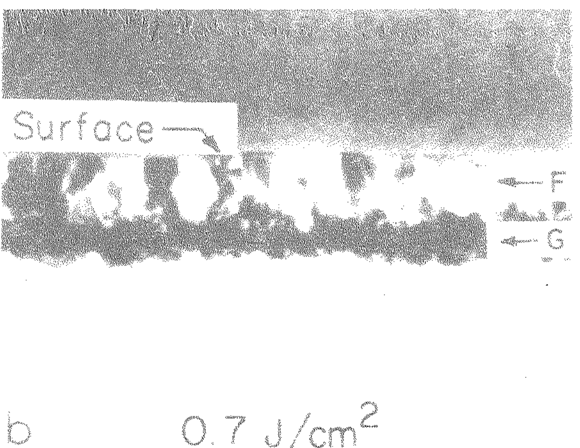

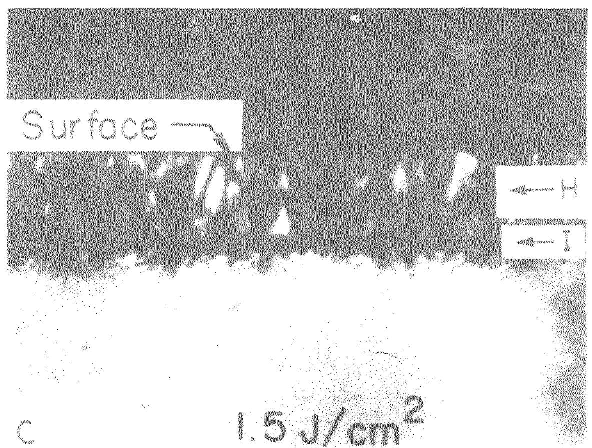

a Unannealed T_i=150°C b 0.7 J/cm^2 c 1.5 J/cm^2

0.4 μm

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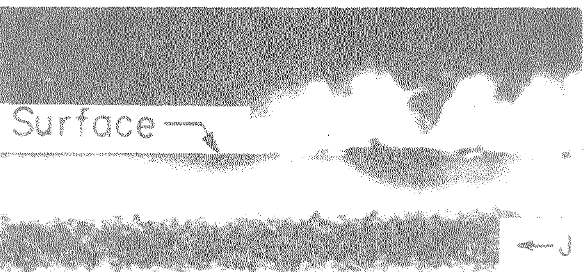

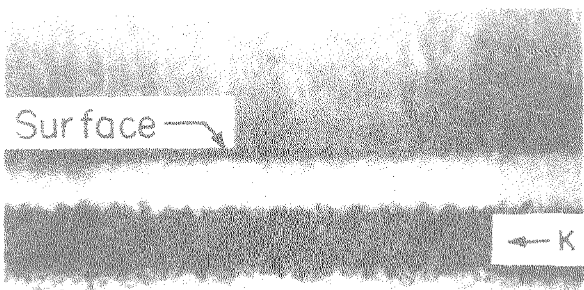

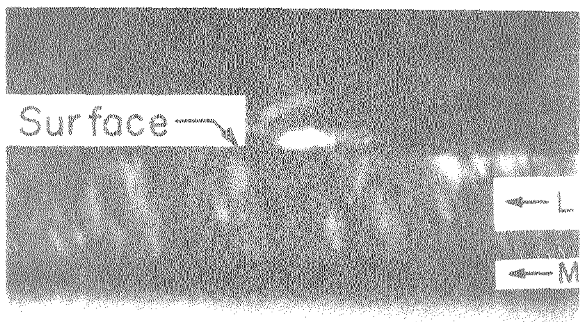

a $T_i = 350°C$ b 0.7 J/cm^2 c 1.5 J/cm^2

0.4 μm

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