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THE FORMATION OF AMORPHOUS SILICON BY LIGHT ION DAMAGE

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THE FORMATION OF AMORPHOUS SILICON BY LIGHT ION DAMAGE

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ABSTRACT

A model for formation of amorphous silicon by light ion implantation is proposed. It is suggested that accumulation of point defects and/or complexes is required at the initial stage of the amorphization process. Amorphous zone can only form at the end of incoming light ion tracks when the pre-accumulated concentration of point defects reaches a critical value. Depending on the uniformity of point defect distribution, two possibility for the second stage of amorphization are suggested for the ion implantation at different temperature.

Silicon wafers implanted with Boron ions at various temperatures with below and above the critical amorphization dose have been investigated using cross section specimens in high resolution TEM. The amorphization process has as well been studied by Electron Paramagnetic Resonance of the same samples investigated by TEM, allowing the identification of dangling bonds in amorphous zones and point defect clusters. (113), 1/3(111) extrinsic and other smaller distortion l/x(111) stacking faults were also found during the amorphization process. Liquid nitrogen temperature and/or high beam current were found to be necessary to amorphize Silicon by Boron ion implantation.

INTRODUCTION

A continuous amorphous layer of silicon formed during ion implantation has been found to be necessary to obtain complete recovery of electrical activity at low temperature (~600°C) and to avoid formation of secondary defects in <100> ion implanted silicon [1,2]. The low temperature annealing is required to avoid dopant redistribution due to thermal diffusion at high temperature. Therefore, it is of interest to try to better understand the amorphization mechanism. Nuclear stopping dominates the energy loss process for heavy ions but electronic stopping, which does not produce displacement damage, dominates through most of the penetration of light ions except near the end of the ion track [3]. A single heavy ion (e.g. As⁺) can produce a high enough concentration of point defects near the end of its track so that amorphization occurs instantly in a small zone centered on the track. However, a light ion with the same energy as the heavy ion can only displace a few lattice atoms to form isolated point defect pairs even near the end of its track. Hence, two amorphization models, heterogeneous and homogene­ous nucleation, have been used to describe heavy ion implantation at low temperature and light ion implantation at high temperature by many authors [4-7]. The heterogeneous nucleation model, which describes formation of continuous amorphous layers by overlapping the individual amorphous zones created by each ion, is easy to understand and is clearly proved [8]. Nevertheless, the amorphization mechanism for light ion damage is more complicated than a simple explanation of homogeneous nucleation and is still unclear in nature. The homogeneous nucleation model, which suggests that amorphization occurs when the accumulation of point defects and clusters produced by light ion damage reaches a critical value, cannot satisfactorily explain the two stage increase of refractive index with increasing light ion fluence as demonstrated in the infrared reflection experiment of E. Baranova et al. [9] (Fig. 1). In the present work, two possible mechanisms based on previous experimental results and theories are proposed. Experiments have been performed to clarify the true mechanism for Boron ion implanted silicon.
Amorphization Mechanism

Two possible amorphization mechanism, both of them involving two stages in the amorphization process, are proposed for light ion room temperature implantation.

1. Mechanism of Point Defect Complexes Accumulation Followed by Heterogeneous Formation of Amorphous Zones

The first stage of amorphization is thought to be the accumulation of uniformly distributed point defect clusters and complexes, which should be primarily the smallest size of point defect clusters which are stable at room temperature, such as divacancies, $V_B$, $V_C$, $V_O$ complexes, di-interstitials, or 4 vacancies clusters etc. After the concentration of these point defect complexes reaches a critical value, it is assumed that at the end of even a light ion track there is enough additional damage to form a new amorphous zone. This results in the rapid increase of amorphous volume fraction in the second stage of amorphization, consistent with the second stage of refractive index increase in the infra red experiments.

2. Mechanism of Amorphous Nucleation and Growth

During the accumulation of point defects clusters in the first stage, a few small amorphous zones may be formed due to overlapping of several ion tracks in a short period of time. These amorphous zones may act as nuclei for growth of larger amorphous regions in the second stage of amorphization. Because of the lesser density of the amorphous state compared with that of the crystalline state, there would be strain fields around the amorphous nuclei. Vacancies would tend to diffuse toward and accumulate around the nuclei to reduce strain energy. Higher concentration of point defect clusters and complexes could thus be obtained near the boundaries of amorphous nuclei than elsewhere. When this higher accumulation near the nuclei reaches a critical value, the amorphous nuclei could grow when an additional ion track ended near the interface. If the strain field around an amorphous nuclei is strong enough to attract point defect, a non-uniform accumulation of point defect clusters could be built up; the growth of amorphous nuclei would then be responsible for the rapid amorphization in the second stage.
The two stages of the amorphization process for these two proposed mechanisms are also shown schematically (Fig. 2).

**Mechanism (a)**
- Stage I: Accumulation of point defect cluster and complexes.
- New amorphous zones formation.

**Mechanism (b)**
- Stage I: Amorphous nuclei formed by ion track overlapping.
- Stage II: Growth of amorphous nuclei.

Fig. 2. Schematic figure of two suggested amorphization models.

**Experiments**

The cross section view of the amorphous-crystalline transition region affords a continuous picture of the crystalline to amorphous transformation process, where the amorphous material first forms at the depth of damage peak then expands in both directions as the implanted dose increased. Lattice images taken by a JEOL 200CX high resolution TEM were used to identify the amorphous zone and crystalline regions. (100) silicon wafers of 5-10 Ω cm, p type were implanted by 80 KeV Boron ions of 5x10^15, 1x10^16, 2x10^16 and 3x10^16/cm^2 dose at room temperature with 1-2 μA low beam current. A liquid nitrogen temperature implantation with 1x10^16/cm^2 Boron at 80 KeV and a high beam current (~2 mA) implantation with 5x10^15/cm^2 Boron at 35 KeV and room temperature are also performed to prepare two specimens to discover the effects of low temperature and high beam current implantation.

Two specimens of double implantation B, Si or Si, B of Boron 5x10^15/cm^2, 80 KeV and Silicon 5x10^14/cm^2, 125 KeV were prepared to provide two different kinds of first stage to further substantiate the proposed mechanisms.

The amorphization process was as well studied by Electron Paramagnetic Resonance of the same samples investigated by TEM, allowing the identification of dangling bonds in amorphous zones and point defect clusters.

**RESULTS AND DISCUSSION**

No observable defects in the specimen of 5x10^15/cm^2 Boron room temperature implantation were found by TEM microstructural investigation even by high resolution lattice images. However, a cross section view of silicon implanted with 1x10^16/cm^2 Boron ions at room temperature and 80 KeV shows that small bright spots were observed near the depth of peak damage in the
Weak Beam Dark Field image (Fig. 3). High resolution lattice image of these spots reveals that they are damaged zones losing periodic atomic arrangement (Fig. 4). Electron Paramagnetic Resonance Spectra from the specimens of 5x10^15, 1x10^16, 3x10^16/cm^2 Boron ion implanted silicon are shown in Fig. 5. These spectra were obtained with the magnetic field parallel to a <111> direction of the specimens at a condition of 9.39 GHz frequency, 10 dB power, 2 Gauss modulation and 20° K temperature. The spectrum of 5x10^15/cm^2 dose was orientation dependent showing that it was due to small anisotropic defect clusters. An isotropic peak, which is the second peak from the left in the middle spectrum of Fig. 5, starts to appear in the 1x10^16/cm^2 specimen. This isotropic peak gets stronger in the 3x10^16/cm^2 specimen. The isotropic peak in the spectra of 1x10^16 and 3x10^16/cm^2 doses was due to dangling bonds of random orientation and therefore was associated with amorphous zones or regions. The detailed identification of the point defect clusters is still in progress. The damaged zone in Fig. 4 is considered to be an amorphous zone buried in crystalline material.

With higher ion fluence 3x10^16/cm^2, larger areas of amorphous and two kinds of stacking faults were observed (Fig. 6). One kind of stacking fault is extrinsic bounded by 1/3<111> Frank partials, formed by the condensation of interstitial atoms (Fig. 7). The other type of stacking fault also lay on the (111) plane but had a very small distortion (Fig. 8). Its structure has not yet been identified. It is probably Boron or Boron compound precipitation, because the concentration of Boron (-1.9x10^21/cm^3) near the average projected range exceeds the maximum solubility of Boron in silicon (-4x10^20/cm^3 at 1000°C) [10]. A continuous amorphous layer is not formed at room temperature and low beam current (1-2 µA) implantation. More and larger point defect clusters and stacking faults form with increasing dose.

Specimens either implanted at liquid nitrogen temperature and 80 KeV with 1x10^16/cm^2 Boron or a high beam current (-2 mA) with 5x10^15/cm^2 Boron at 35 KeV and room temperature were found eventually to contain continuous amorphous layers extending all the way to the surface (Figs. 9, 10). Both low temperature and short time high flux implantation can suppress the recombination of point defects during ion implantation. A wide crystalline-amorphous transition region (~750Å) was obtained by high beam current implantation (Fig. 10), while a sharp and smooth interface was obtained in the specimen implanted at liquid nitrogen temperature (Fig. 9). A wide transition region, which is the origin of profuse secondary defects, can be very detrimental to electrical properties of post-annealed specimens.

The lattice images of the two double implantation specimens showed that the first Boron and second silicon implanted specimen had a larger...
Fig. 5. EPR spectrums of three specimen with \(5 \times 10^{15}\), \(1 \times 10^{16}\), \(3 \times 10^{16}/\text{cm}^2\) Boron implanted silicon with magnetic field parallel to \langle111\rangle direction of specimens.

Fig. 6. Larger areas of amorphous regions(a) and \langle111\rangle stacking faults (which arrows indicate) in the specimen of \(3 \times 10^{16}/\text{cm}^2\) Boron implanted silicon. XBB 851-919A

Fig. 7. HREM of extrinsic \langle111\rangle stacking fault bounded by \(1/3\langle111\rangle\) Frank partials in \(3 \times 10^{16}/\text{cm}^2\) specimen. XBB 852-1238A

Fig. 8. HREM of the other \langle111\rangle stacking fault with very small distortion in \(3 \times 10^{16}/\text{cm}^2\) specimen. XBB 851-925A

Fig. 9. Cross section view of \(1 \times 10^{16}/\text{cm}^2\) Boron implanted silicon at liquid nitrogen temperature and 80 KeV. XBB 851-917

Fig. 10. Cross section view of \(5 \times 10^{15}/\text{cm}^2\) Boron implanted with a high beam current (-2 mA) at 35 KeV and room temperature. XBB 851-916
size of amorphous zones than the first silicon and second Boron implanted specimen (Figs. 11, 12). It is suggested that either the silicon or Boron in the first implantation provided enough accumulation of point defects for the beginning of the second stage. Because silicon is a heavier ion it was expected that preimplantation of silicon would result in a less uniform density of point defects than does preimplantation of B. The following additional bombardment by Boron or silicon was expected to form new amorphous zones. The silicon ion, which is heavier than Boron, produced larger amorphous zones than did Boron as expected. However, the number of amorphous zones in Figs. 11 and 12 was estimated to be far below the number expected if it is assumed that one amorphous zone is formed at the end of each ion track. This suggests the amorphization mechanism at room temperature is more complex than either of the two proposed mechanisms. It is likely that when point defects are mobile there is not a clear separation between Stage 1 and Stage 2 because of a nonuniform distribution of defect clusters throughout the volume. The critical density of point defect clusters necessary for formation of an amorphous zone at the end of an ion track may exist in only a fraction of the irradiated volume. If defect clusters are formed preferentially in the strain field of already existing amorphous volume then most of the new amorphous material may be formed adjacent to an already existing amorphous region resulting growth rather than random coalescence. At a low enough temperature (e.g., liquid nitrogen temperature), the vacancies are immobile and cannot diffuse toward and cluster near the boundaries of preexisting amorphous nuclei. Therefore, the amorphization mechanism at low temperature would be expected to be dominated by the random formation of amorphous zones. (113) stacking faults, which are the condensation of interstitial atoms, are also shown in Fig. 12.

Fig. 11. Lattice image of amorphous zones in the specimen of first Boron second silicon double ion implantation. XBB 854-2832

Fig. 12. Lattice image of small damaged zones and (113) stacking faults in the specimen of silicon first and Boron second ion implantation. XBB 852-1397

CONCLUSIONS

1. Amorphization during light ion damage consists of two stages: first stage, point defects and or larger clusters and complexes built up to a critical concentration; second stage, amorphous zones are formed near the end of an ion track when it terminates within a volume having more than the critical concentration of point defect, and or complexes.

2. No amorphous material was detected by EPR for specimen implanted with Boron at room temperature to a fluence of 5x10^15 ion/cm^2.

3. At low temperature where vacancies are immobile the buildup of point defects and complexes is uniform throughout the irradiated volume and continuous amorphous layers result from the eventual overlap of amorphous zones formed with random distribution.
4. At room temperature migration of point defects results in larger average size of the point defect complexes and in their nonuniform density within the irradiated volume. There is a less clear separation between stage 1 and 2, because at a given fluence the critical point defect density may exist in only a fraction of the irradiated volume. When some amorphous regions are formed, their strain fields may increase the nonuniformity of point defect clustering so that new amorphous material is preferentially formed near already existing amorphous zones.

5. For Boron, continuous amorphous material cannot be formed at room temperature unless a high beam current is employed, presumably because the rate of annihilation of vacancy-interstitial pairs is great enough to prevent achievement of the critical concentration of point defects necessary for completion of stage two throughout the irradiated volume.

6. At room temperature where point defects and implanted Baron atoms are mobile (113), 1/3(111) extrinsic and other smaller distortion 1/x(111) stacking faults are formed in the still crystalline material during the amorphization process.

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