SURFACE CHANGES OF Si[111] SINGLE CRYSTALS IRRADIATED BY HIGH-DOSE SWIFT HEAVY IONS

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The surface changes of silicon [111] crystals under high-dose swift heavy ion irradiation were investigated. Si samples irradiated by ^{84}Kr ions with the energy 253 MeV in fluence interval (1-3)x10^{15} ion/cm^2 didn't discover any features on the surface and the amorphism of the volume. The damage doses in the area near the surface and near the damage Bregg peak of target for krypton and xenon ions at ion fluence $(F{\cdot}t)$ = 1x10^{15} ion/cm^2 are calculated. The surface features observed on Si irradiated with 124-MeV ^{129}Xe ions up to fluences 2.9x10^{16} ion/cm^2 seems to due the flecking and blistering. The creation of semi-spherical hillocks and other structures may be connected with the gas molecules accumulation near the surface under the irradiation, i.e.gas diffusion and desorption processes could take place.

Introduction

Swift ion irradiation is a technique for modifying the structure of solids and hence its physical properties. Continuous efforts have been undertaken for studying a damage introduced by swift ion irradiation [1-3]. Most thoroughly investigated are oxides [4-5]. At some conditions, swift ions formes so-called latent tracks in solids. They are extended and narrow cylindrical defect zones surrounded with undamaged host matrix. A phenomenological description of latent track creation had been given for dielectric [6] and magnetic insulators [7]. Semiconductors, however, seem to have received less attention and this field is somewhat controversial [8-11]. Track presence in traditional semiconductor crystals is questioned by some authors. At the same time the tracks with the diameters of 8.4 and 10.5 nm were recorded by means of transmission electron microscopy in silicon irradiated with 30 and 40 MeV fullerenes beams. The inelastic energy losses S_{inel} for 30 and 40 MeV fullerenes beams were 48 and 57 keV/nm correspondingly [12]. Track formation occurs if S_{inel} exceedes some threshold value of inelastic energy loss (S_{thes}) This effect is interpreted in the frame of the thermal spike model [3-5]. The latent track formation in semiconductors during swift ion irradiation are also described in [13-16]. Up to now low dose regimes swift ion irradiation of semiconductors were investigated because it is a possibility of single latent track formation at low doses. A knowledge of semiconductor structure modification under high-dose swift ion irradiation is still quite limited. in the present paper, the surface and changes of silicon crystals under high-dose swift heavy ion irradiation were investigated by means of scanning electron microscopy (SEM), atomic force microscopy (AFM) and electron channeling method (ECM).

Experimental

The samples of silicon [111] single crystals with polishing/chemical etched surfaces were irradiated with 253-MeV ^{84}Kr to fluences 1x10^{14}, 1x10^{15} and 2.6x10^{15} ions/cm^2 and with 124-MeV ^{129}Xe to fluences 1x10^{15} and 2.9x10^{16} ion/cm^2 in vacuum at room temperatures at U-400 and U-300 accelerators of the Flerov Laboratory of Nuclear Reactions. The surface of the initial and irradiated crystals were studied by the scanning electron microscopy, atomic force microscopy and the electron channeling method (ECM).

Results and discussion

SEM study of the silicon surfaces after the irradiation showed that the surface quality became similar to the initial samples up to the fluence of krypton ions of $(F{\cdot}t)_{Kr}$ = 2.6x10^{15} ion/cm^2. Here F is the average ion flux, t is the time of irradiation. Then the irradiated samples were studied using AFM method. The characteristic images of the initial and irradiated surfaces are presented in Fig.1. The relief inhomogenelties of initial and irradiated silicon surface were measured as ±0.25 nm and +2.0 nm correspondingly. it is interesting to compare the surface images from our paper with the results of the AFM investigation of Si irradiated with high-dose low-energy ions [17]. The AFM topographs of Si(100) surfaces sputtered with 100-eV Ar to $(F{\cdot}t)_{Ar100}$ = 5.26x10^{17} ion/cm^2 (A) and with 300-eV Ar to $(F{\cdot}t)_{Ar300}$ = 4.8x10^{17} ion/cm^2 (B) are presented in [17]. The *rms* height roughnesses as AFM measured are approximately 0.16 (A) and 0.31 nm (B). The lateral size scales of the features in the topographs (A) and (B) are approximately 35-40 nm and 90-100 nm correspondinly. At our studies the *rms* height roughnesses as measured by the AFM are approximately 0.049 nm (Fig.1a) and 0.598 nm (Fig.1.b). The lateral size scale of the features in the Fig.1b is approximately 40-60 nm. These features have the semispherical shape and in height their size are about 30-40 nm. So the changes of the Si surface irradiated by ^{84}Kr ions with E = 253 MeV and $(F{\cdot}t)_{Kr}$ = 2.6x10^{15} ion/cm^2) are more essential then in the Ar ions case [17]. One can conclude that in our case the sputtering yield must be higher then in [17] (cases A and B). This conclusion is correct if the observed surface features were produced by sputtering mechanism of course.

The sputtering yield for 300-eV Ar ions was calculated on the base of elastic sputtering model using the TRIM-98 computer code. The sputtering yield equals to Y_{Ar300}= 0.226 atom/ion. The surface bond energy (sublimation energy) was 4.7 eV. We estimate the sputtering yield of silicon in our case using the comparison of the characteristic features on the surfaces (ref.[17] (B) and Fig.1b) as: $Y_{Kr} > (F\cdot t)_{Ar300}\cdot Y_{Ar300}/(F\cdot t)_{Kr}$ = 40 atom/ion.

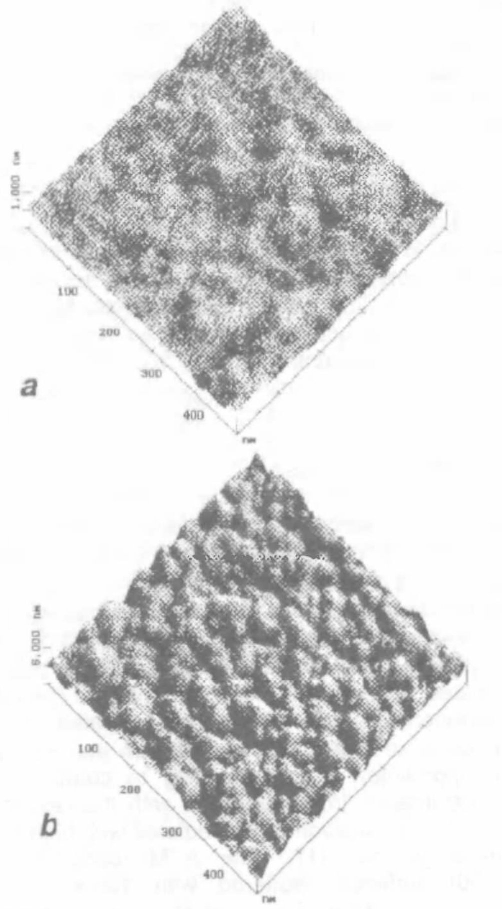

Fig.1. The characteristic 3d images of the initial (*a*) and irradiated (*b*) surfaces of silicon samples. The fluence and energy of ^{84}Kr ions were 2.6x10^{15} ion/cm and 253 MeV correspondingly

The damage creation cross-sections $\sigma_{Kr/Ar}$ and inelastic energy losses for ^{84}Kr and Ar ions near the surface are: σ_{Kr} = 2.9x10^{-17} dpa cm^2/ion, σ_{Ar} = 5.4x10^{-16} dpa cm^2/ion, and S_{inel}^{Kr} = 9.32 keV/nm, S_{inel}^{Ar} = 0.07 keV/nm. The damage creation threshold energy for Si was taken E_d = 15 eV. It is clear that $\sigma_{Kr} << \sigma_{Ar}$, however $S_{inel}^{Kr} >> S_{inel}^{Ar}$. It is impossible to explain the strong increasing of the sputtering yield for Kr ions in comparison with one of Ar ions by elastic sputtering model. It can conclude the silicon sputtering of swift Kr ions should be described by inelastic sputtering [18], i.e. the thermal spike model [4-6,14]. The Kr ions elastic energy losses damage increases with the growth of ion fluence. It should to cause the decreasing of free path length of "hot-excited" electrons and as a result - the localization of energy in a small volume around the heavy ion trajectory and increasing of temperature over the melting point (see [14])

The surface images of Si samples irradiated with 124-MeV ^{129}Xe ions up to the fluences 1x10^{15} (a) and 2.9·1x^{16} (b) ion/cm^2 are presented in fig.2a,b.

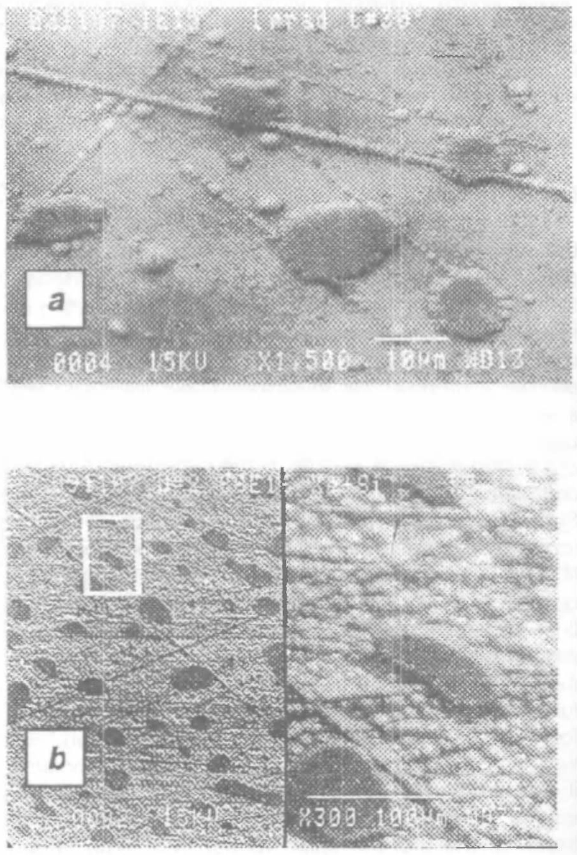

Fig.2. The surfaces of Si irradiated with ^{129}Xe with energy 124 MeV up to the fluences 1x10^{15} (a) and 2.9x10^{16} ion/cm^2 (b). One can see an initial scratches produced by scribbling of the Si surface

In fig.2a one can see an scratches produced by scribbling at the process of Si surface polishing. Along the scratches one can see the semi-spherical hillocks with the sizes up a few µm in diameter. There are also the rare semi-spherical hillocks with the diameters from 1 up to 5 µm and flat top spots with the characteristic sizes about 8-15 µm between the scratches. The spots shape are not symmetrical. The hillocks density is much more than spots density. Practically the hillocks are absent between the scratches. The hillocks height achieves to a few μm too. The undamaged surface area is about 50-60 %. The surface of silicon sample irradiated with $(F{\cdot}t)_{Xe}=3\times10^{16}$ ion/cm^2 is characterized by the same kinds of surface features, but the spots density turned up ~7.5×10^{4} cm^{-2} with the sizes distribution from 10 to 60 μm. The surface is covered by the hillocks between the spots, and the hillocks with a maximum height disposed along the scratches.

The electron channeling study of the ^{129}Xe ions irradiated samples has shown the substantial changes of the electron channeling pattern with the fluence growth, and the presence of the concentric circles system on the electron diffraction pattern under the fluence 1×10^{15} ion/cm^2 allows one to conclude that there are a mixture of amorfisized zones and perfect single crystal zones on the surface. At the fluence 3×10^{16} ion/cm^2 the electron channeling pattern corresponds to the amorphism of silicon.

Conclusions

The both SEM and ECM studies of the Si samples irradiated with the 253-MeV ^{84}Kr ions in fluence interval $(1\text{-}3)\times10^{15}$ ion/cm^2 didn't discover any features on the surface and the amorphism of the volume.

The damage doses in the subsurface area and near the damage Bregg peak of target for krypton and xenon ions at fluence $F{\cdot}t=1\times10^{15}$ ion/cm^2 are $D_{Kr}(x \cong 0.35\ \mu m) = \sigma_{Kr}{\cdot}F{\cdot}t = 0.03$ dpa and $D_{Kr}(x \cong 32.2\ \mu m) = 2.29$ dpa for ^{84}Kr ions, $D_{Xe}(x \cong 0.25\ \mu m) = \sigma_{Xe}{\cdot}F{\cdot}t = 0.15$ dpa and $D_{Xe}(x \cong 16.5\ \mu m) = 3.37$ dpa. The inelastic energy losses near the surface and the depths of implantation for ^{84}Kr and ^{129}Xe ions near are $S_{inel}^{Kr}=9.32$ keV/nm and $S_{inel}^{Xe}=12.8$ keV/nm and $R_p^{Kr}=32.2$ μm and $R_p^{Xe}=16.5$ μm, correspondingly.

The features observed on the ^{129}Xe ion irradiated Si surfaces look like the surface phenomena produced by the fleking and blistering ones. The creation of semi-spherical hillocks and other structures may be connected with the gas molecules accumulation near the surface under the irradiation, i.e.gas diffusion and desorption processes could take place. It means that the gas atoms and molecules absorbed by Si crystals in the processes of production and the implanted ions can move to the surface by the diffusion mechanism. As well known the damage zone is a good area for the diffusitivity and gettering of impurities. So implanted Xe ions could reach the area near the surface more easy then Kr ones because $R_p^{Kr} > R_p^{Xe}$.

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