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TRACK EFFECTS IN SILICON IRRADIATED BY SWIFT HIGH ENERGY HEAVY IONS

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1. INTRODUCTION

In the last few years, the continuous efforts have been undertaking for a better understanding of the damage arising in various materials due to the swift heavy ion irradiation. Oxides appeared to be investigated best of all [1]. Recently a phenomenological description of a latent track formation has been done for dielectric and semiconductors [2] and for magnetic insulators [3]. Metals have been considering for a long time as not showing any track formation processes. Track formation has recently been found in alloys $NiZr_2$ and NiTi at the value of electronic stopping power, $S_e = (dE/dx)_e$, of more than 40 MeV/μm, and in stainless steel Cr18Ni10T S_e was approximately of about 33 MeV/μm [4]. Even more recently, an experimental evidence for the tracks produced in Ti by 845 MeV Pb ions, and by 18 MeV ^{60}Co ions has shown that metals are suitable for such a track formation. The tracks in silicon with the diameters of 8.4 and 10.5 nm were found after the irradiation by fullerenes with energy of 30 (S_e = 48 MeV/μm) and 40 MeV (S_e = 57 MeV/μm) [5], correspondingly. However, semiconductors seemed to receive much less attention. Some articles presented the experimental results in semiconductors irradiated by high energy heavy ions (see, for example refs.[6-8]). The goal of this report is to present experimental data had been obtained in the silicon samples, irradiated by various heavy ions with or without a post-irradiation heat treatment by scanning electronic microscope (SEM), X-ray analysis, RBS technique or electrical methods.

2. EXPERIMENTAL RESULTS AND DISCUSSIONS

All samples had been irradiated by heavy ions in vacuum at U-400 accelerator of the Flerov Laboratory of Nuclear Reactions. For irradiation the heavy ions were used, such as ^{86}Kr with energy 210 and 305 MeV, ^{129}Xe with energy 129 MeV. Some of the samples were annealed at the ranges from room temperature up to 1000^0C. In modern technologies for the production of various electronic devices are very important to obtain a homogeneous distribution of impurities for the creation of conductive and isolated layers and optically active centers in semiconductors and insulators. Several works (see, for example [5]) were dedicated to the optimization the thermal annealing conditions for incorporation of these impurities in the host lattice and to their diffusion in depth. The processes of impurity migration include the several stages of treatment. There are the following stages: the low energy electrically active impurity implantation (the energy of implantation was from 100 to 500 keV and the fluence from 10^{13} up to 10^{16} ion/cm^2) or the deposition of thin layers (the thickness of the deposited layers was about 30-200 nm) of impurities on the surface of semiconductor or dielectric single crystals. Then the heat treatment of the amorphous layers in the case of impurity implantation; and the irradiation of the implanted and heat treated samples by swift heavy ions with the high level of inelastic energy loss (the ions like Kr or more heavier ones). The last stage was the heat treatment of the samples in optimized temperature range).

The samples of single crystals of silicon were covered by thin layer of Ta (the structure of the layer was following: the silicon substrate with the thickness of 300 μm, plus 165 nm of Ta). The samples were irradiated by Kr ions by the fluence of 10^{12} ion/cm^2. The annealing treatment was carried out in vacuum at temperature of 470^0C during one hour. RBS analysis for irradiated and unirradiated samples was undertaken using a 2 MeV He ion beam generated by Van Graff accelerator of the Frank Laboratory of Neutron Physics of JINR [9]. As a result the depth profiles Ta, Si and O were obtained.

In Fig.1 one can see the characteristic RBS spectra of irradiated (+) and unirradiated (•) samples of silicon covered by Ta layer with the thickness of 165 nm. Very easy to see the big difference between the curves. In Fig.2 the distributions of Ta, Si and O are presented for unirradiated and annealed (A, dashed curves) and for irradiated and annealed (IA, solid curves) samples. From the Fig.2 seen that after annealing and irradiation the depths of migration of Ta and O atoms are of about $R_d^{IA} \cong 5200$ A and only $R_d^{A} \cong 3500$ A and 2300 A for unirradiated samples.

The increasing of depth migration of Ta and O atoms in samples irradiated by Kr ions can be connected with the so called "track structure" (destructive zone along the projected range of Kr ions). The integration of Fick diffusion equation leads to the following solution for the impurity profile after the annealing duration: $C(x,t) = Q/(\pi Dt)^{1/2} * \exp(-x^2/(4Dt))$, where Q is the remaining amount of atoms per square units, which was measured after annealing, D is the diffusion coefficient and t is the annealing time. Satisfactory fit of the experimental profiles for O atoms can be carried out in both cases: for the annealed samples (A) and annealed plus irradiated samples (IA) and for Ta atoms in the case of only annealed samples (A). For the Ta concentration curve in the case of annealed and irradiated samples possible to provide fiting too, but with the big mistakes, because there was a practically constant level of concentration from 1500 up to 3750 A in depth. The following values of the adjustable parameters for diffusion of oxygen atoms D_{IA}^{O}, D_A^{O} and Ta atoms D_{IA}^{Ta}, D_A^{Ta} have been found: $D_{IA}^{O} \cong 6.3 * 10^{-}14$ cm^2/s and $D_A^{O} \cong 1.5*10^{-14}$ cm^2/s, $D_{IA}^{Ta} \cong 6.8*10^{-14}$ cm^2/s and $D_A^{Ta} \cong 1.5*10^{-14}$cm^2/s. The big differences of diffusion coefficients in cases A and IA allow to conclude that the migration rate of impurities in the samples irradiated by swift heavy ions more in comparison with the unirradiated samples of silicon. In the Ref.[8] the Kr ion track diameter in silicon has been calculated as R_{tr}= 5.7 A. The relative total square of damaged area had been calculating and has a value $\Delta S/S = Ft*\pi*(R_{tr})^2 = 0.306$. If the migration of impurities for IA samples takes a place through the ion's tracks then the migration coefficient D_{AR} should be recalculating for the reduced square $\Delta S/S$. And D_{IA} would be higher.

The implantation of Kr (210 MeV) in silicon caused the heavy ion track formation with the decreased density in the tube with the diameter $2*R_{tr}$ in the comparison with the undamaged material. So the impurity atoms can diffuse more easily along the projected range of Kr ions in area with the reduced density.

The samples of silicon single crystals were irradiated by ^{129}Xe ions with the energy of 124 MeV at room temperature. The fluences of irradiation were the

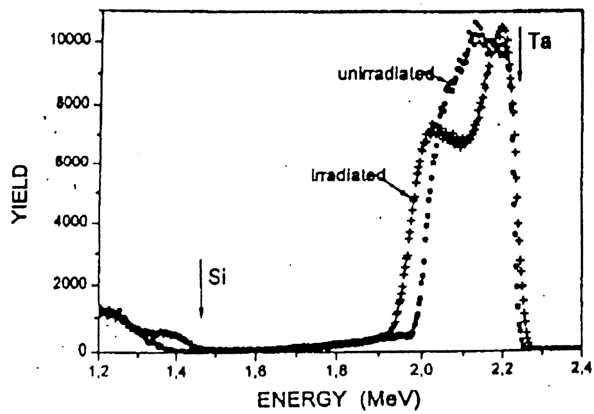

Fig.1. The typical RBS spectra of Ta/Si samples for unirradiated (•) and irradiated (+) ones.

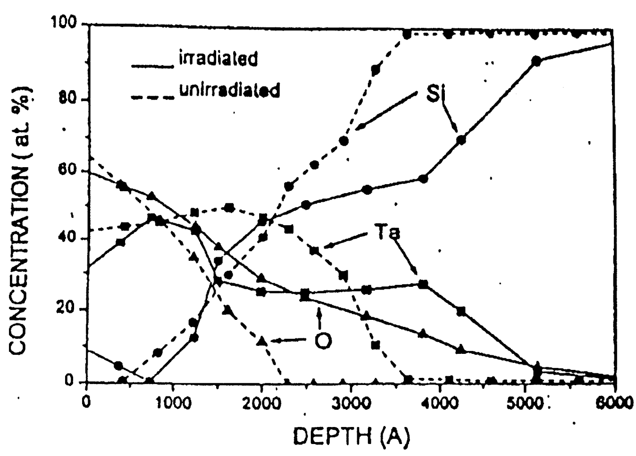

Fig.2. The depth distribution of Si, O and Ta atoms in Ta/Si for annealed samples (solid line) and for irradiated and annealed samples (dashed line).

following: 10^{13}, 10^{14}, 10^{15} and $3*10^{16}$ ions/cm^2. The surface structures of irradiated and unirradiated samples had been studying by SEM and the Electron Channeling Method (ECM). The SEM study of the silicon surface after the irradiation allowed to conclude that up to the fluence of xenon ions of about of a few times 10^{14} ion/cm^2 the quality of the surface became the same as for the initial samples (see, Fig.3, photo 1). The scratches on the surface that had been producing in the stage of the polishing of the silicon plates in the process of production became more visible. This fact could be explain by the inelastic sputtering or thermal evaporation of surface silicon atoms under heavy ion bombardment.

More interesting phenomena were obtained on the samples irradiated by ^{129}Xe ions at fluences of 10^{15} and $3*10^{16}$ ion/cm^2 (see, Fig.3 photos 2,3). At the silicon samples irradiated with a fluence of 10^{15} ion/cm^2 the big black spots with the flat top have been observed. The surface density of the spots is equal to 10^5 cm^{-2} and their size changed from 10 to 20 μm. The height of this structure was about a few μm. The shapes of spots are not symmetrical one. Along the scratches we have observed the hillocks with the sizes of a few μm and less in diameter. The surface density of these hillocks much more than the density of spots. Practically the hillocks are absent between the scratches. The height of the hillocks up to a few μm. Also at this fluence of about 50-60 % of surface area conserved the undamaged character zone. The surface of silicon samples irradiated by the fluence of $3*10^{16}$ ion/cm^2 contains the same kind of surface defects. However, the surface density of the spots turned out to be $7.5*10^4$ cm^{-2} with the wide distribution in sizes from of about 10 to 60 μm. Between the spot's surface covered by hillocks, and the hillocks with maximum height dispose along the scratches. Also necessary to note that the spots have practically black colour on the SEM photos, it means that from these spots the coefficient of electron emission and backscattering is smaller than from the another parts of irradiated silicon samples.

The ECM study of the samples irradiated at fluences described above has been shown that with the growth of irradiation fluence the images of electron channeling pattern change very strongly. At the fluence of 10^{15} ion/cm^2 the presence on electron diffraction pattern of the system of concentric circles allows to conclude that on the surface there are a mixture of amorphized zones and perfect single crystal zones. At fluence of $3*10^{16}$ ion/cm^2 the electron channeling pattern corresponds to the amorphized silicon.

The silicon single crystal samples were irradiated by ^{86}Kr ions with the energy of 305 MeV up to the fluence of approximately $(2\text{-}3)*10^{15}$ ion/cm^2 for the comparison. Both methods SEM and ECM did not show any changes of the irradiated surface. This fact had been allowing to conclude that the volume near the surface was practically undamaged. The levels of inelastic energy losses in silicon irradiated by ^{129}Xe and ^{86}Kr are 14 MeV/μm and 10 MeV/μm respectively. This value was obtained with the use of computer code TRIM-95.

It was shown that in amorphous silicon and germanium, prepared by vacuum evaporation and subsequently irradiated with swift heavy ions (from 100 MeV ^{16}O to 207 MeV ^{197}Au), tracks consist of small recrystallized particles [10]. This effect occurs above a S_e threshold dependent on the target ($S_{eth} \cong 5$ MeV/μm in Ge and $S_{eth} \cong 15$ MeV/μm in Si) and was interpreted in the framework of the thermal spike model [11]. The level of inelastic energy loss S_e for ^{129}Xe practically has the same value as follows from the ref.[10] and the track formation processes by ^{129} Xe ions can take place in silicon. From the point of view that presented in refs.[6, 10, 11, 13] the track formation by ^{86} Kr ions impossible or has the low probability in silicon because the $S_e < S_{eth}$. At high fluences of Xe ions Si single crystals begin to amorphize from the surface to the projected range of ions. And near the surface, where the $S_e \geq S_{eth}$, the opposite process, e.g. the crystallization of amorphized zone can take place. As it is well known there is the difference between the average lattice constant of amorphized silicon and the lattice constant of single crystal $\Delta a = 4*10^{-4}$ A. Crystallized and amorphized areas can be like a mixture on the surface. This fact can change the smooth structure of crystal before irradiation surface on rough (amorphized area) and smooth (crystallized area) regions under the irradiation. This effect obtained at fluence of 10^{15} ion/cm^2 is shown in Fig.3, photo 2. The recrystallization processes can take place in materials under the irradiation if the temperature into ion track (T_{tr}) is higher than melting temperature (T_{melt}) in framework of the thermal spike model (see, as example refs.[2, 6, 11].

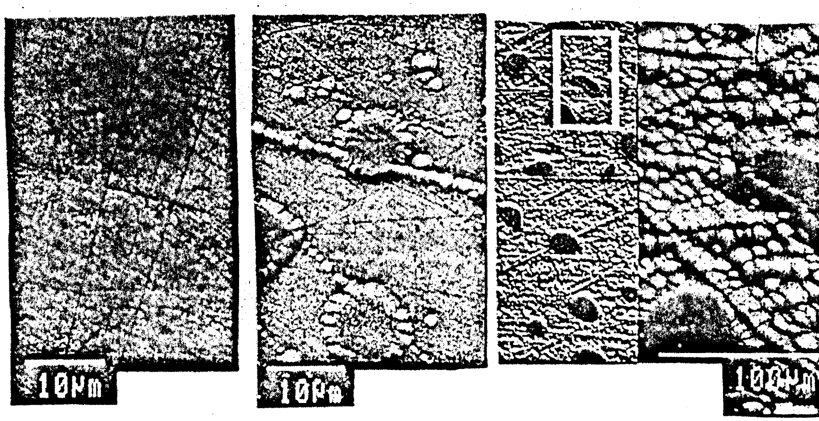

Photo 1 Photo 2 Photo 3

Fig.3. The surface of silicon irradiated by ^{129}Xe ions with energy of 1 MeV/amu. The photos 1, 2 and 3 correspond to images of surface at ion fluences of 10^{14}, 10^{15} and $3*10^{16}$ ion/cm^2 respectively.

The evaporation [2] or inelastic sputtering [12] of atoms of target from the irradiating surface will take place if track temperature (T_{tr}) is higher than the evaporation temperature (T_{evap}) of material, i.e., $T_{tr} > T_{evap}$ and dissipated density of power of ion (P_d) exceeds the critical evaporation power density (P_{cr}), i.e. $P_d > P_{cr}$ [2, 4].

The diameters of craters along the path (the diameter was about 85 nm) in a parallel irradiation geometry for in depth characterization of damage produced by ^{86}Kr ions (210 MeV) in silicon [8] were measured with the use of atomic force microscopy. So the evaporation of atoms from the surface parallel to ion trajectory takes a place. Also the calculations of the temperatures into Xe and Kr ion tracks [4, 6] and using the diameters of tracks [5, 8] and expression $R \sim (Se)^{1/\alpha}$, where $\alpha = 2, 3, 6$ from various experimental data and models allow to conclude that $T_{tr} > T_{evap}$. Therefore the processes of evaporation should be from the irradiating surface of silicon. It is necessary to perform direct measurements of surface features on silicon. The exact mechanism of production of these features on silicon surface under the irradiation by ^{129}Xe ions is not clear yet.

3. CONCLUSION

The implantation of Kr (210 MeV) and Xe (5.6 GeV) in silicon caused the heavy ion track formation with the decreased density in comparison with the undamaged material. As it was shown here the use of fourth stages processes (the low energy impurity implantation, the post implantation annealing, the irradiation by heavy ions with the high level inelastic energy loss, and final heat treatment of semiconductors) allows to increase the impurity migration and to produce the necessary type of conductivity in semiconductors without the long time annealing. The application of the method is promising in the new technology related to semiconductor device production.

The big differences between the surface structure after the irradiation by ^{129}Xe (129 MeV) and ^{86}Kr (305 MeV) ions may be connected with the very strong evaporation processes of silicon atoms under the irradiation by ^{129}Xe ions and the absence or small evaporation in the case of irradiation by ^{86}Kr ions. Another possible reason of such behaviour is the difference between projected ranges of ^{129}Xe (17 mm) and ^{86}Kr (37.9 mm). The accumulation of xenon inert gas near the surface can produce big mechanical tension and as a result the amplification of the surface damage production processes.

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Трековые эффекты в кремнии,
облученном тяжелыми ионами высоких энергий

Представлены экспериментальные результаты в монокристаллическом кремнии, облученном быстрыми тяжелыми ионами. Для облучения были использованы следующие тяжелые ионы: ^{86}Kr (210 МэВ и 305 МэВ) и ^{129}Xe (129 МэВ). Коэффициенты диффузии (D_A и D_{IA}) и глубины проникновения атомов Ta (R_A и R_{IA}), нанесенных на поверхность монокристаллического кремния, были исследованы с применением обратного резерфордовского рассеяния в отожженных (О) и отожженных и облученных (ОО) образцах кремния. Было обнаружено, что коэффициенты диффузии и глубины проникновения в ОО образцах возрастают по сравнению с О образцами. Поверхность кремния, облученного большими флюенсами ионов ^{129}Xe, была изучена с помощью электронной сканирующей микроскопии. На поверхности кремния, облученного ионами ксенона при флюенсах более 10^{15} ион/см^2, были обнаружены образования в виде выступов различной формы. Обсуждены возможные механизмы рассмотренных эффектов для всех полученных экспериментальных результатов.

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Didyk A.Yu. et al. E14-2000-107
Track Effects in Silicon Irradiated by Swift High Energy Heavy Ions

This paper presents the experimental results in silicon single crystals irradiated by swift heavy ions. For the irradiation the following ions were used: ^{86}Kr (210 and 305 MeV) and ^{129}Xe (129 MeV). The diffusion coefficients (D_A and D_{IA}) and the migration depth (R_A and R_{IA}) of Ta atoms covering the silicon surface were studied by RBS technique in annealed samples (A) and annealed and irradiated by Kr ions silicon samples (IA). An increase in the diffusion rate for the IA samples in comparison with the A samples has been found. The surface of silicon irradiated with high fluence of Xe ions was investigated with the help of scanning electron microscopy. Some special features on the silicon surface after the irradiation by xenon ions at fluences of more than 10^{15} ion/cm^2 were observed. Possible mechanisms of the considered effects for all obtained experimental results are discussed.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions and at the Frank Laboratory of Neutron Physics, JINR.

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