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Study of the Effect of Electron Irradiation on the Morphology and Conductive Properties of Silicon Oxide

Abstract: this article is devoted to the study of the effect of electron irradiation on single-crystal silicon wafers used to create solar cells. The methods of atomic force and scanning electron microscopy were used as research methods. The use of atomic force microscopy to study morphology showed a change in the degree of roughness and a significant change in the profile line. Electron microscopy makes it possible to visualize changes in the surface and track its dynamics. The studied samples were irradiated with electrons with energies of 1 MeV up to fluences of $3x10^{15}$, $1.15x10^{16}$ and $1x10^{17}$ ion/cm^2. The experimental part presents studies of changes in surface morphology after irradiation by electron and atomic force microscopy, as well as oxidation processes as a result of exposure to an electron beam, which leads to partial destruction of the near-surface layer, followed by a change in grain size and a decrease in roughness under the action of irradiation. It was shown that the action of the electron beam leads to the leveling of the surface layer and changes in the average grain size. Among other things, as a result of irradiation at the ELV-4 electron accelerator, a change in the conductive properties of silicon wafers is observed depending on the irradiation dose.

Keywords: monocrystalline silicon, radiation exposure, radiation annealing of defects, solar panels, thermal stability.

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Introduction. At present, the level of electrical engineering and instrumentation development is at such a level that all the possibilities for their further intensive development have been exhausted. Therefore, relevant and promising direction of research create and modify more efficient elements. Improving the quality of initial silicon crystals is one of the main ways to improve the quality of semiconductor products for microelectronics [1-2].

The main purpose of this article is to study the electrophysical properties of single-crystal silicon and reveal the modification features of the surface and crystal structure under the ionizing radiation. [3-5]

Materials and components of nuclear reactors, particle accelerators and generators of various radiations are exposed to the action of charged particles. Irradiation leads to a change in various physical properties: mechanical, electrical, thermal, optical, etc. Instruments and measuring equipment are placed in the irradiation zone can receive significant doses of radiation, which leads to a change in their parameters and failure of the instruments in some cases. All this also applies to devices and objects that are launched into outer space, where they are exposed to high-energy radiation [6].

Recently, studies of radiation effects in semiconductors have been widely developed. This is due to the fact that semiconductors have received an exceptionally wide range of applications in addition, their properties are highly sensitive to the effects of various radiations. In the literature, there are quite rare studies concerning the increase in the radiation resistance of silicon nanoelectronics, although such experiments are intensively carried out in [7].

Materials and methods. Single-crystal silicon wafers used as the basis for solar panels were chosen as objects.

The samples were irradiated at the ELV-4 accelerator in the Kurchatov city, Kazakhstan by electrons with energy of 1 MeV and three different fluences: 3x1015, 1.15x1016, 1x1017. (Figure 1). The electron beam is emitted into the atmosphere through a titanium foil window and a system of diaphragms.

Figure 1 – Linear electron accelerator ELV-4

Experimental conditions of irradiation and beam characteristics are given in Table 1.

Table 1 – Experimental Conditions for Sample Irradiation

[HTML]FFCB2F Sample	Current, mA	Energy, MeV	Fluence
1	1	1	3,00E+15
2	4		1,15E+16
3	35		1,00E+17

Results and discussion. The irradiated samples were studied by the EDA method. The results are presented in the form of energy dispersive spectra and maps of the distribution of elements over the surface in Figure 2.

Table 2 presents the results of energy dispersive analysis before and after irradiation. On the spectra and element distribution maps for each of the irradiated samples, it is clearly seen that with an increase in the irradiation dose, oxygen impurities appear. Moreover, the highest concentration of oxygen is in the zones of increased localization of defects on the surface, and to a slightly lesser extent at the grain boundary. We assume that the appearance of oxygen in the composition of the samples is due to local heating during irradiation and the oxidation reaction, since the irradiation process itself took place in an oxygen atmosphere.

Table 2 – Changes in the chemical composition of samples depending on the dose of radiation

[HTML]FFCB2F	Initial	$3x10^{15}$	$1,15x10^{16}$	$1x10^{17}$
Silicon	100	96.34	95.48	94.14
Oxygen	0	3,66	4,52	5,86

For a more detailed study of the irradiated samples surface, AFM and SEM were used, the results of which are presented in Figure 3.

It is clearly seen that in the process of electron irradiation of silicon, its surface is leveled. The Gwyddion 2.19 program also allows you to measure a whole set of profile characteristics, among which two parameters seem to be the most interesting: waviness and roughness, or rather their average and root mean square values (Table 3).

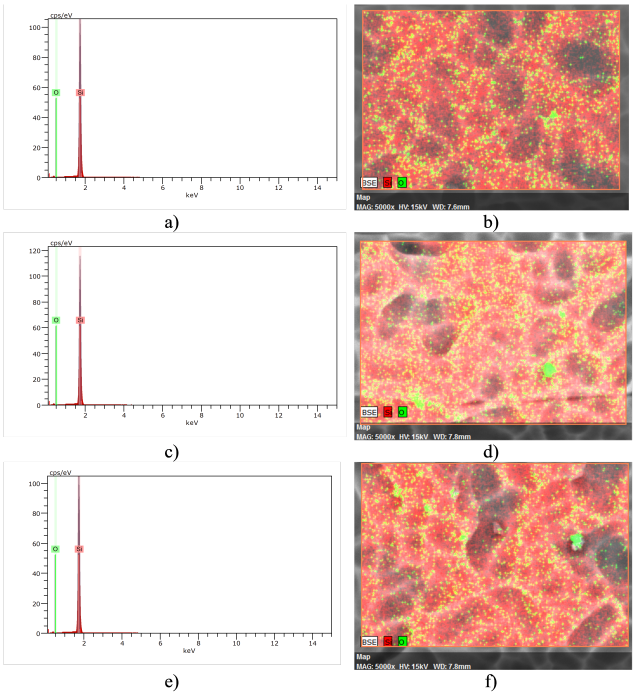

FIGURE 2 – EDX results of irradiated samples: a); c); e) EDX spectra for fluences 3x10^{15} , 1.15x10^{16} , 1x10^{17} , respectively; b); d); f) their corresponding element distribution maps

TABLE 3 – Roughness and waviness values for irradiated samples

[HTML]FFC000 Sample	Roughness	Roughness (rms)	Waviness	Waviness (rms)
3x1015	0,3012	0,3736	0,7938	0,9461
1,15x1016	0,2053	0,2546	0,4009	0,485
1x1017	0,2127	0,2685	0,4517	0,5556

The obtained values reflect the picture observed in Figure 4. As a result of electron irradiation, the surface is smoothed, as evidenced by a significant decrease in the profile waviness parameter. The roughness parameter, which is responsible for the high-frequency fluctuations of the profile, also decreases. SEM images of the surface of irradiated silicon were also taken (Figure 4). In the images during irradiation, the formation of zones of increased concentration of defects is observed, which increase as the fluence increases. It is in these zones that the greatest accumulation of oxygen atoms occurs, according to EDX data.

The scale on all images is the same, and it can be seen that with an increase in the radiation dose, a decrease in the average grain size occurs. To study the dependence of the change in the average grain size on the silicon surface on the dose of electron irradiation, a size distribution was constructed, which is shown in Figure 5.

It can be seen from these graphs that this resembles a normal distribution, and with an increase in fluence, the distribution broadens and shifts to lower values, and at the maximum radiation dose for our work, this distribution narrows and increases in intensity. To reveal the dependence of the conductive properties of single-crystal silicon on the dose of electron irradiation, the current-voltage characteristics of the samples were studied. The results obtained are shown in Figure 6, where the resistance values are normalized per unit area and presented as a bar graph.

This diagram clearly demonstrates that with an increase in fluence, a decrease in electrical resistance occurs. Obviously, this phenomenon is due to the degeneration of the surface of the samples

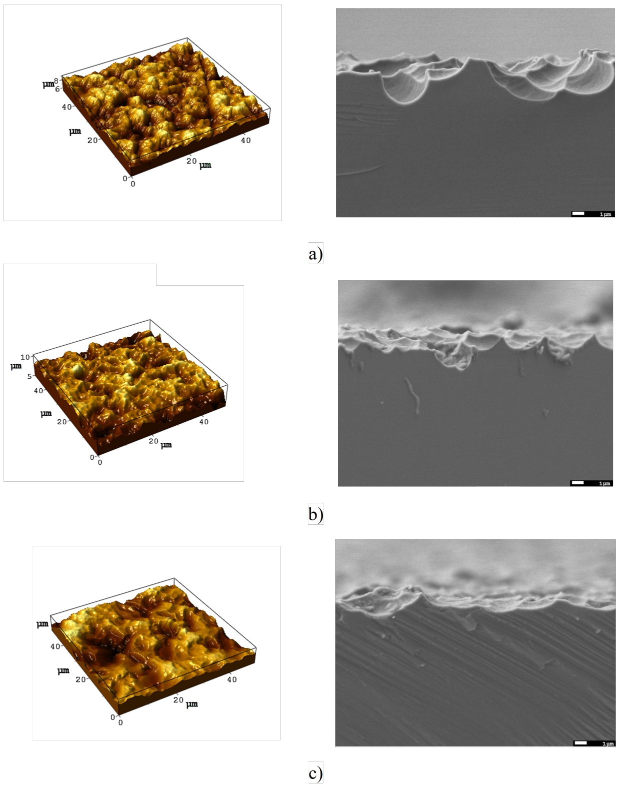

FIGURE 3 – AFM three-dimensional model of the surface and SEM image of the side cleavage of irradiated samples: a) 3x1015, b) 1,15x1016, c) 1x1017

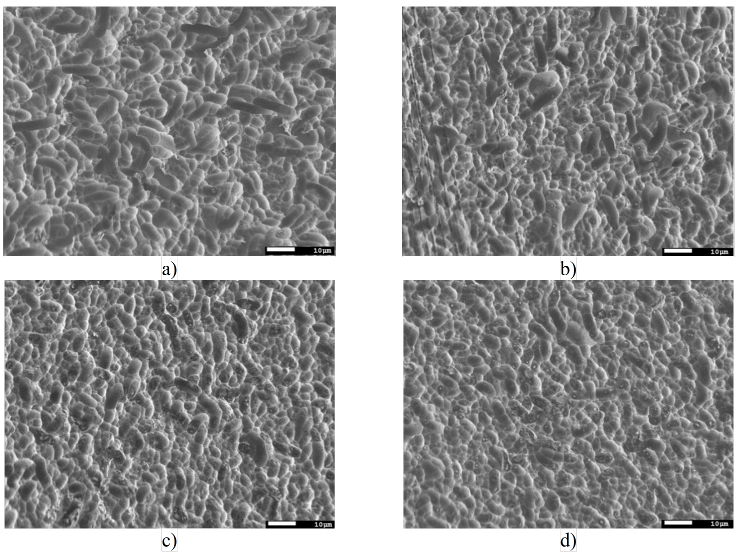

FIGURE 4 – SEM images of the sample surface: a) initial; b) $3x10^{15}$; c) $1,15x10^{16}$; d) $1x10^{17}$

under study, as well as the appearance of oxygen thermal donors as a result of local heating during irradiation with an electron beam in an air atmosphere. Thus, electron irradiation is an effective way to upgrade the characteristics of single-crystal silicon.

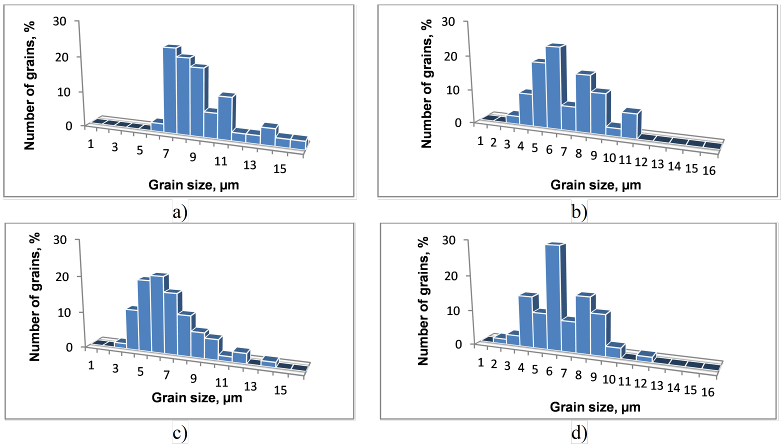

FIGURE 5 – Grain size distribution: a) initial b) 3x10 ^{15} ; c) 1,15x10 ^{16} ; d) 1x10 ^{17}

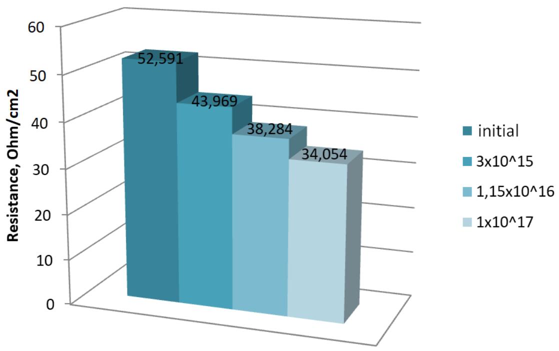

FIGURE 6 – Dependence of the change in electrical resistance on the irradiation fluence.

Conclusion. Thus, it can be said that as a result of electron irradiation, the surface is smoothed, as evidenced by a significant decrease in the profile waviness parameter. The roughness parameter, which is responsible for the high-frequency fluctuations of the profile, also decreases. As the irradiation dose increases, the average grain size on the surface of single-crystal silicon decreases. Studies have also shown that electron irradiation in an air atmosphere leads to the formation of oxide compounds on the surface, which is associated with local heating in the interaction zone.

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Электрондық сәулеленудің кремний оксидінің морфологиясы мен өткізгіштік қасиеттеріне асерін зерттеу

Аннотация. Бұл мақала күн батареяларын жасау үшін қолданылатын монокристалды кремний пластинкаларына электронды сәулеленудің әсерін зерттеуге арналған. Зерттеу әдістері ретінде атомдық күш және сканерлеуші электрондық микроскопия әдістері қолданылды. Морфологияны зерттеу үшін атомдық күш микроскопиясын қолдану кедір-бұдырлық дәрежесінің өзгеруін және профиль сызығының айтарлықтай өзгеруін көрсетті. Электрондық микроскопия беттегі өзгерістерді визуализациялауға және оның динамикасын бақылауға мүмкіндік береді. Зерттелетін үлгілер 3х 10^{15} , 1,15х 10^{16} және 1х 10^{17} ион/см ^{2} флюцияға дейін 1 МэВ энергиясы бар электрондармен сәулелендірілді. Эксперименттік бөлімде электронды және атомдық күштік микроскоппен сәулеленуден кейінгі беттік морфологияның өзгеруін, сондай-ақ беткейге жақын қабаттың ішінара бұзылуына, кейіннен өзгеріске әкелетін электронды сәуленің әсерінен тотығу процестерін зерттеу берілген. сәулелену әсерінен түйір өлшемдері мен кедір-бұдырдың азаюы. Электрондық сәуленің әрекеті беткі қабаттың нивелирленуіне және орташа түйіршік мөлшерінің өзгеруіне әкелетіні көрсетілді. Сонымен қатар, ELV-4 электронды үдеткішінде сәулелену нәтижесінде сәулелену дозасына байланысты кремний пластинкаларының өткізгіштік қасиеттерінің өзгеруі байқалады.

Түйін сөздер: монокристалды кремний, радиациялық әсер, ақауларды радиациялық күйдіру, күн панельдері, термиялық тұрақтылық.

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Исследование влияния электронного облучения на морфологию и проводящие свойства оксида кремния

Аннотация. Данная статья посвящена исследованию влияния электронного облучения на пластины монокристаллического кремния, используемые для создания солнечных элементов. В качестве методов исследования использовались методы атомно-силовой и сканирующей электронной микроскопии. Применение атомно-силовой микроскопии для изучения морфологии показало изменение степени шероховатости и существенное изменение линии профиля. Электронная микроскопия позволяет визуализировать изменения поверхности и отслеживать ее динамику. Исследуемые образцы облучались электронами с энергией 1 МэВ до флюенсов 3х 10^{15} , 1,15х 10^{16} және 1х 10^{17} ион/см ^{2} . В экспериментальной части представлены исследования изменения морфологии поверхности после облучения методами электронной и атомно-силовой микроскопии, а также процессов окисления в результате воздействия электронного пучка, что приводит к частичному разрушению приповерхностного слоя с последующим изменением по размеру зерна и уменьшению шероховатости под действием облучения. Показано, что воздействие электронного пучка приводит к выравниванию поверхностного слоя и изменению среднего размера зерна. Среди прочего, в результате облучения на ускорителе электронов ЭЛВ-4 наблюдается изменение проводящих свойств кремниевых пластин в зависимости от дозы облучения.

Ключевые слова: монокристаллический кремний, радиационное воздействие, радиационный отжиг дефектов, солнечные батареи, термостойкость.

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