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Formation of vacancy-helium complexes at low-energy irradiation of tungsten

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The structure of subsurface area of tungsten after low-energy irradiation by helium ions was investigated by the method of field-ion microscopy. The emerging of the compact groups of interstitial atoms to the surface was registered. It was found the depleted zones consisted with vacancy–helium clusters, which arise as the result of crowding out own lattice atoms by helium. The depleted zones spatial configuration was investigated as a function of the dose. The processes of forming of vacancy–helium complexes and depleted zones in subsurface area at the high concentration of the implanted helium atoms were analyzed. The correlation between the size of depleted zones and the range of image forces was shown.

Keywords: vacancy, interstitial atom, field evaporation, electron emission, adatom, radiation, erosion, vacancy-helium clusters.

Методом польової іонної мікроскопії досліджена структура підповерхневих областей вольфраму після низькоенергетичного опромінення іонами гелію. Зареєстрований вихід на поверхню компактних груп міжвузельних атомів. Виявлені збіднені зони, утворені вакансійно - гелієвими кластерами, виникаючими внаслідок витіснення гелієм власних граткових атомів. Досліджено просторові конфігурації збіднених зон в залежності від дози опромінення. Проаналізовано процеси поведінки та формування вакансійно - гелієвих комплексів і збіднених зон в приповерхневій області в умовах високої концентрації впроваджених атомів гелію. Показано зв'язок розмірів збіднених зон з областю дії сил зображення.

Ключові слова: вакансія, міжвузельний атом, польове випаровування, електронна емісія, адатом, опромінення, ерозія, вакансійно – гелієвий кластер.

Методом полевой ионной микроскопии исследована структура подповерхностных областей вольфрама после низкоэнергетичного облучения ионами гелия. Зарегистрирован выход на поверхность компактных групп междоузельных атомов. Обнаружены обедненные зоны, образованные вакансионно - гелиевыми кластерами, возникающими в результате вытеснения гелием собственных решеточных атомов. Исследованы пространственные конфигурации обедненных зон в зависимости от дозы облучения. Проанализированы процессы формирования вакансионно - гелиевых комплексов и обедненных зон в приповерхностной области в условиях высокой концентрации внедренных атомов гелия. Показана связь размеров обедненных зон с областью действия сил изображения.

Ключевые слова: вакансия, междоузельный атом, полевое испарение, электронная эмиссия, адатом, облучение, эрозия, вакансионно - гелиевые кластеры.

The low-energy irradiation of metals is an accompanying the process of the work of many vacuum technological devices. The short projectile path lengths of the low energy ions are a cause of the surface damage. The low-energy irradiation intensifies the processes of surface diffusion [1] and ultimately leads to radiation-induced erosion [2]. The problem of interaction of helium atoms with the surface in tungsten is relevant in the light of the intended using this metal for the elements of construction of the first wall and divertor in the controlled thermonuclear fusion reactor. Previously, it was shown that at relatively high concentrations of helium in a perfect crystal, it is able to produce the displacement of lattice atoms into the interstitial positions [3-5]. Field emission microscope gives an opportunity to conduct a simulation of the irradiation conditions which is similar conditions of divertor work and to obtain information about the state of surface at the atomic level. This paper presents the results of ion-microscopic research of subsurface vacancy - helium formations, arising by the low-energy helium irradiation of tungsten.

Method of experiment

The experiments on the low-energy irradiation of tungsten surface were realized in the two-chamber field ion microscope, at a temperature of samples 78 K. The samples were prepared by the method of electrochemical etching in water solution of potassium hydroxide. The wire for samples had diameter 10 microns. The final shaping and cleaning of the samples surface were conducted by the field evaporation in the chamber of microscope. The layer by layer analysis of the tungsten nanocrystal irradiation structure on a depth was conducted in the mode of the impulsive field evaporation, providing remove less than one atomic layer for the one act of evaporation. To obtain reliable information on atomic level the irradiation of the investigated objects was conducted "in situ" in order to avoid any surface contamination under contacting with air. The bombardment was conducted by the helium ions which also were used as the imaging gas. The irradiation was produced in the electron mode of a microscope operation. The negative potential at the voltage 400 V – 500 V was supplied to the pointed specimen in a presence of the imaging gas at a pressure of $5 \cdot 10^{-3}$ Pa. At this led to the appearance of the cold field emission. The atoms of imaging gas were ionized by the stream of emitted electrons. The imaging gas ions were accelerated under the electric field and bombarded the sample surface with an average energy of about 140 eV. The fluence of falling particles depended on the density of imaging gas and the current of electron field emission. These parameters were chosen and controlled during experiments. Calculations of the total numbers of particles N which fall on the top of sample were obtained using expression, proposed in [6].

$$N = 14,4 \frac{p}{kT} \frac{i}{e} r_0 \sigma(V) \qquad (1)$$

where: **i** – is an electron field current, **p** – is a gas pressure, $\mathbf{r_0}$ – is a radius of the sample, $\sigma(V) = 2,24 \cdot 10^{-18} cm^2$ - is an ionization cross section. An irradiation was conducted at the size of electron field currents within the limits of ~ 0,4 µm, which provided the fluence of bombarding ions of helium $2 \cdot 10^{13} ion/cm^2 \cdot sek$. Four series of irradiations were conducted from a dose $6 \cdot 10^{14} ion/cm^2$ to $3,6 \cdot 10^{16} ion/\text{cm}^2$.

Results

As a result of irradiation atomically smooth tungsten surface by low-energy helium atoms is appear a lot of atoms displaced to the adatoms position on the surface. In image, such atoms were observed as bright emission spots (1a, b). The positions adatoms is characterized by low coordination numbers, therefore in an electric field it leads to a local increasing of the field strength over these atoms. This factor is cause of their high contrast.

The analysis showed that only a part of the observed atoms appeared during the irradiation stage. Because a formation of Frenkel pairs by classic way is impossible by the subthreshold irradiation. The second part of the adatoms the most important for our consideration, has already appeared in image in the research process at the constant voltage after irradiation. The appearance of this part of the adatoms can not be associated with a direct exposure of the bombarding beam to the surface. Since the second part of atoms emerging out volume, they passed the stage of interstitial condition. Atoms come out to the surface, generally in the complex forms or compact groups. An example of a compact group, which appeared through 5 second after evaporation of two atomic layers (001) is shown in Fig. 2 (a). The group consists of three dozen interstitials. A feature of the emerging of polyatomic interstitial groups is their surface localization and simultaneous appearance on the image. Delay time between the moment of emerging and a moment of evaporation was typical for the groups of interstitial atoms. In some cases, the delay time could be several minutes. The emerging of interstitial atoms was stopped after field evaporation layer which is greater than the length of the projected range of helium with energy of 140 eV in tungsten (~ 3-4 nm). It is show, that presence of helium in the surface layer was a necessary condition for the formation groups of interstitial atoms. Thus, the observed effects of the emergence of interstitial atoms, confirmed the possibility realization the process of crowding out lattice atoms from the site positions by implanting helium atoms [3-5] and not by the impact.

The mechanism of crowding out supposes the formation of the vacancy-helium defects. This statement has been experimentally verified in process of controlled field evaporation of the irradiated sample. Vacancy type defects were always detected at a depth of 1-5 atomic layers bellow the crowded out interstitial atom groups. The structure of these defects is similar to depleted zones. An example of such vacancy defects, which is observed as a dark area, is shown in Fig. 2 (b).

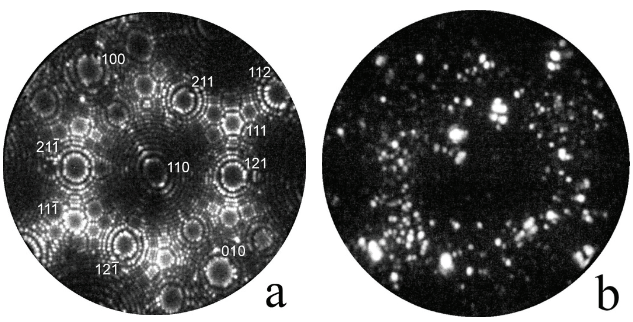

Fig.1 . Ion microscopic image of the sample surface W before irradiation (a) and after irradiation (b).

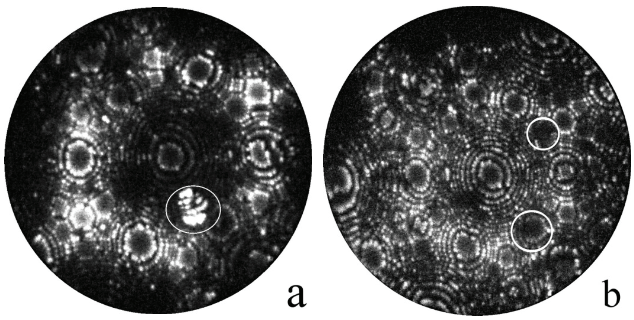

Fig.2. (a) The polyhydric interstitial complex on the surface, (b) the ion- microscopic image vacancy-helium depleted zones .

The observation and unambiguous interpretation of the individual vacancies by field ion microscopy, is an extremely rare event. It is possible only in cases where the vacancy is located on a full resolution surface area. Depleted zone is an area with increased concentration of the vacancies, where a lot of atoms are having low coordination. Thereby bonding energy of atoms with crystal in the depleted zones is reduced. This is the reason of local removing of material from area with a high content of vacancies by the field evaporation. In this place on the surface is formed a deepening. The field strength on this area with a negative curvature of the surface is lower than on the rest parts of the pointed sample. It reduces the rate of gas ionization and decrease a brightness of the image on the vacancy defect area.

The transverse (in the image plane) and longitudinal (depth in the crystal) sizes of depleted zones were obtained by a series of images. The size distributions of the depleted zones are shown in Fig. (3), and (4a, b). The transverse size of the depleted zones was practically unchanged with irradiation dose increasing and was ~ 13 Å. The longitudinal sizes of the depleted zones in the depth of the crystal were increased with dose increasing. The average value of the longitudinal sizes of the depleted zones was about 25Å at the maximum dose of radiation.

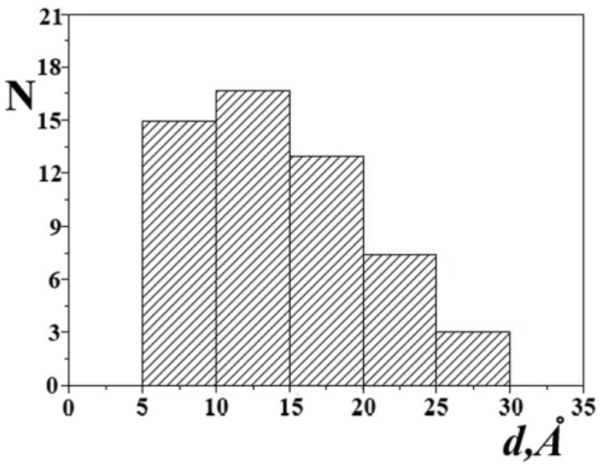

Fig. 3. Distribution of depleted zones on the transverse dimensions.

It should be noted that in this experiment the energy of helium was insufficient to create the Frenkel pairs by classical way in a tungsten crystal. Therefore, the experimentally observed effects of the emergence groups of interstitial atoms and large vacancy formations are the result of helium implantation. Helium is mobile at a temperature of 78 K therefore it form an inactive cluster by the mechanism of self-trapping [5]. In the cluster the crowding out process of the lattice atoms in to the interstitial positions can develop at the sufficiently high local helium concentration. At the same time the vacancy is form.

In this case, some of the helium atoms are in a bound

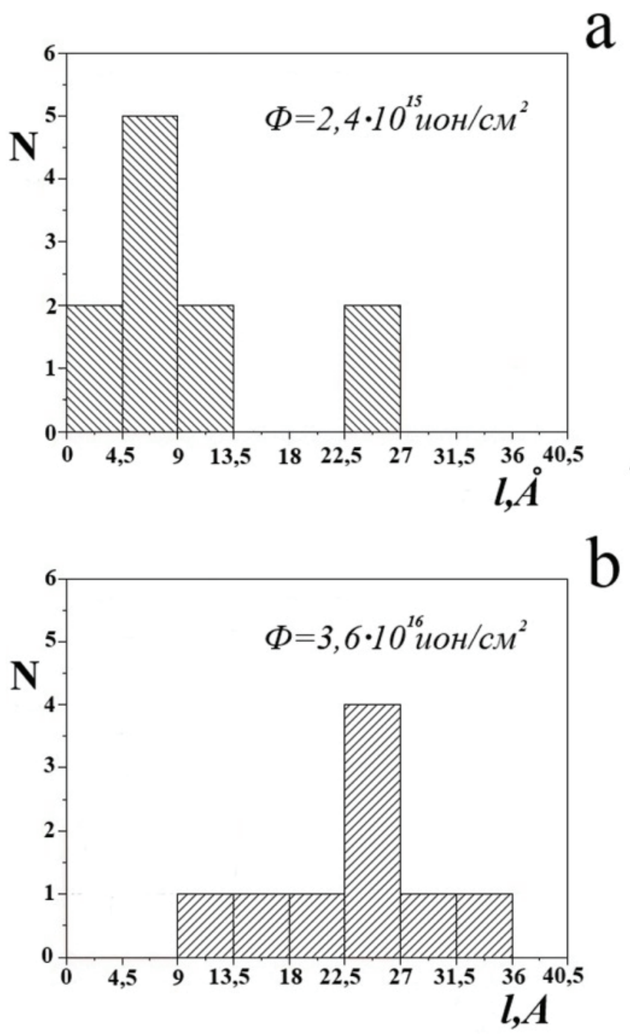

Fig. 4. Distribution of depleted zones on the longitudinal dimensions for the two doses min (a) and max (b).

state, occupying the volume of vacancy, thereby stabilizing it and making immobile. The immobile vacancy-helium clusters, formed as a result of this process, hold the displaced interstitial atoms nearby. Detaching of the interstitial atoms from the complexes is possible at the additional absorption of helium by vacancy or when the temperature increase.

In this experiment we found another opportunity to initiate the crowding out. It is based on a fact that the processes of crowding out were observed only after acts of field evaporation. The each act of evaporation removes small surface layer and resulted in a decrease of the distance from the helium clusters to the free surface. Nearness to the free surface promoted to the development the processes of crowding out of the lattice atoms by the implanted helium.

In the subsurface area on any defects are forces seeking to bring them out of volume. It is image forces. For the own interstitial atoms, which arise as a result of crowding out, depth action of the image forces in the crystal is greater than 25 Å. The received data on the longitudinal dimensions of the depleted zones are satisfactory agreement with the area of image forces. This indicates that the thickness of the layer, containing the vacancy – helium complexes is determined by the depth action of the image forces. Therefore can be assumed that the number of helium atoms in the clusters, capable to produce the crowding out and create a vacancy - helium clusters should fall with decreasing of the distance to the free surface.

Thus, at low-energy irradiation of tungsten helium, the most part of the implanted atoms turns out in a subsurface layer in the connected state. Helium is located near the surface within the action of the image forces and exists in depleted zones, consisting of vacancy- helium complexes. On the greater depth helium is concentrated in slow-moving helium clusters.

The simultaneous output from the volume of the interstitial atom groups and the appearance under them the localized vacancy-helium educations (depleted zones) allows to assuming that the process of output has collective character and develops as avalanche. The developments of collective processes of the crowding out were previously found in the experiments carried out by the method of molecular dynamics [7]. Apparently, the incidental emerging of the interstitial atom induces the development of the avalanche processes in the surrounding area. The eventually formed subsurface layer, consisting of a series of depleted zones, saturated with helium. Data on the longitudinal dimensions of the depleted zones give us an idea about spatial distribution of helium, which present in vacancies and is not able to migrate.

Conclusions

1. The depleted zones consisting of vacancy - helium complexes are found in a subsurface area at the low-energy irradiation of tungsten helium.

2. It was found, that the implanted helium at the low-energy irradiation is localized in a subsurface area, where is in the bound state.

3. It was shown, that the main factor leading to the formation subsurface vacancy - helium depleted zones is the action of image forces.

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