SECTION 1
PHYSICS OF RADIATION DAMAGES AND EFFECTS IN SOLIDS

FEATURES OF HELIUM COMPLEXES BEHAVIOUR NEAR THE FREE SURFACE IN TUNGSTEN

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The formation of interstitial atoms by lattice tungsten atoms displacement by clusters of implanted helium, which is accompanied with the appearance of helium-vacancy complexes, was found. The stimulating effect of the free surface on the development of the processes of displacement and dissociation of complexes has been revealed. It is shown that this influence is caused by the action of image forces. The depth of the image forces was determined, which was about 2.5 nm.

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INTRODUCTION

The creation and development of efficient magnetic-confinement nuclear fusion reactor face significant problems of materials for facing the plasma structural elements. This primarily concerns the divertor and the first wall of the reactor. Tungsten, which has a high melting point and low sputtering values [1, 2] is considered as the most appropriate material for these elements. Since the burning plasma contains a mixture of helium and hydrogen, the surfaces of divertor and the first wall of reactor undergo the irradiation by intense fluxes of low-energy ions, which can cause significant surface erosion. Low irradiation energy is the main cause of surface damage. Short path lengths of bombarding particles in metals contribute to a significant accumulation of helium in the surface layer, that, with long exposure, can lead to the formation a tendril-like fuzz reminiscent the corals [3–7]. Currently, a large number of studies on low-energy irradiation of metals is carried out using computational methods and mat. modeling [8]. Extensive data have been obtained on the He solution energy, the ability to form various He clusters and their mobility, as well as the energetics of the processes that determine the behaviour of helium in the vicinity of interfaces [9–14]. However there are still few real atomic level experiments on this issue. This paper presents experimental data on the free surface effect on the behaviour of implanted helium atoms and their complexes in tungsten, obtained by field ion microscopy.

METHODS

The studies were carried out in a field ion microscope combined with a source of accelerated helium atoms to an energy of 0.15…5 keV (Fig. 1).

The requirement of irradiation with neutral particles was dictated by the need to observe the process of formation of defects right at the moment of irradiation. Since the type of microscope used in this work is characterized by the presence of strong electric fields, ion irradiation is not possible due to the deflection of charged particles in the field. The possible difference between the effects of irradiation with atoms and ions in the case of irradiation of metals can be neglected since these effects can be noticeable only for insulators and semiconductors.

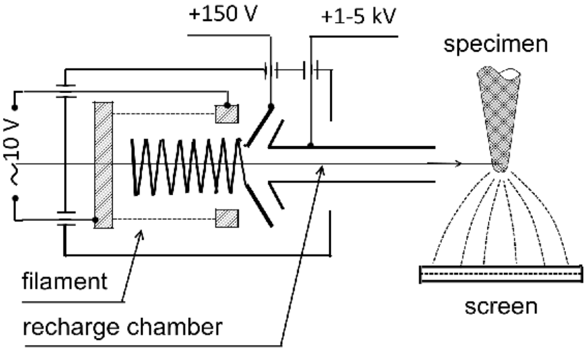

Fig. 1. Scheme of the accelerated helium atoms source

The study was conducted at a temperature of samples of 78 K and a pressure of the imaging gas (He) of $5 \cdot 10^{-3}$ Pa. The atoms of the imaging gas were also used as the bombarding particles. The source of accelerated atoms was an ion gun with a recharge chamber, made in the form of a narrow metallic channel (Fig. 1). The beam neutralization took place in the channel by ion sliding contacts with the channel walls, as well as by the resonant charge exchange on the imaging gas atoms. The samples with radii top of 15…15 nm were manufactured by electrochemical etching in 1N aqueous solution of NaOH from tungsten wire of purity 99.98 weight %. In the microscope the samples were initially cleaned by field desorption and then were subjected to evaporation in an electric strength field 58 V/nm to form an atomic-smooth hemispherical surface. Field ion images were formed by applying a positive potential to the samples in the range of 3…25 kV. The direction of irradiation was normal to the axis of the needle-shaped samples. This made it possible to simultaneously observe the irradiated and shadow sides of the sample surface. The flux intensity of the incident helium was $5 \cdot 10^{11}$ at./cm^2·s, which made it possible to get fluence to 10^{14} at./cm^2 during one experiment.

RESULTS AND DISCUSSION

Experiments have shown that, as a result of irradiation, the surface erosion takes place, especially noticeable from the incident beam side (Fig. 2,a,b). As can be seen, after irradiation there are many bright spots which are tungsten atoms in the position of adatoms. Since adatoms are characterized by low coordination number, the local field strength is increased above them. As the result, the adatoms were observed as bright emission centres in the ion image. The appearance of radiation adatoms on the surface can take place in two different ways. The first is the displacement along the surface of the atoms located on the edges of the atomic steps. In this case, surface vacancies appear on the steps. Such vacancies also contribute to radiation erosion. The second is the formation of classical Frenkel pairs in the volume of sample with subsequent interstitial atoms (SIA) migration toward the surface and their displacement in adatom position. It should be noted that radiation adatoms are observed on the irradiated side of the sample independent of their origin. In contrast, the appearance of adatoms on the shadow side was possible only by the formation of interstitial atoms. After the cease of irradiation, the rate of appearance of new adatoms on the surface dropped sharply.

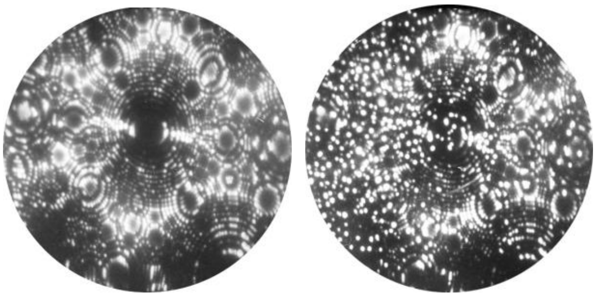
a *b*

Fig. 2. The surface of the tungsten sample before (a) and after (b) irradiation with a fluence of $2 \cdot 10^{13}$ at./cm^2

Field evaporation of the previously irradiated sample restored the perfect state of the surface, by removing the surface layer along with all the radiation adatoms. However, after further field evaporation of the irradiated sample, a repeated emerges of SIAs from the volume, was unexpectedly found. With time the emerges of new SIA were ceased. The appearance of SIA on the surface took place with a short time delay, which could reach ~ 5…30 s from the evaporation moment. For example Fig. 3,a,b shows the ion images of the surface of tungsten before (a) and after (b) the emerge of a single SIA. The process of SIAs emergence on the surface was repeatedly reproduced after each new evaporation and was observed with equal probability both as on the irradiated and as on the shadow side of the sample. In addition to single SIAs and their complexes in some cases, the emergence of compact SIA groups containing more than a dozen atoms was recorded. It should be noted that the repeated emergence of SIA occurred in the absence of irradiation and after a sufficiently large period of time after the end of bombardment.

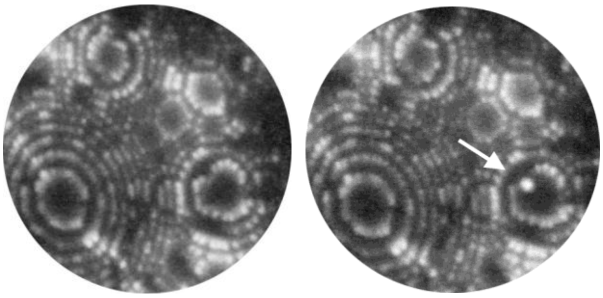
a *b*

Fig. 3. The field ion images of the irradiated tungsten sample obtained immediately after the removal of several surface layers (a) and after the appearance of an interstitial atom on the surface 12 s later (b)

This suggests that the repeated SIA emergencies are not related to the shock processes of the Frenkel pairs formation. Those SIA, which was formed directly at the time of irradiation, already left the volume of a sample before the new evaporation acts due to their high mobility at 78 K. Therefore they were removed together with the eroded surface layer at initial evaporation. Taking into account the noted above facts, it can be concluded that the formation of SIA after evaporation takes place directly at the moment preceding their appearance on the surface. So the observed effects are definitely associated with the presence of implanted helium in the lattice [15]. Since the mean path of 5 keV helium atoms in tungsten is less than the sample diameter, the almost all helium ultimately turn out in the lattice in the implanted state. Possessing zero solubility and high mobility (by tetra-positions) at 78 K, helium atoms are able to form clusters by the self-trapping mechanism [16]. When such helium clusters reach the size of several atoms they acquire the possibility to displace lattice atoms from its positions. It leads to the appearance of the complicated polyatomic complexes [SIA (V nHe)] [17]. The complexes are partial vacancies filled with helium atoms, which hold near themselves the partially displaced tungsten atoms. Under certain conditions, the complexes can dissociate and produce a mobile SIA and full vacancy, unable to migrate due to stabilization it by helium. Detaching of SIA from the complex can occur with additional absorption of helium atoms into a vacancy or with temperature increasing. In this experiment, we found one more reason for the complexes dissociation. It is the influence of the free surface. The proximity of the complexes to the surface leads to the appearance of image forces that stimulate the processes of displacement and complexes dissociation.

Each new act of field evaporation reduces the distance from helium clusters to the surface, causing the development of the processes of lattice atoms displacement and SIA detaching from helium-vacancies complexes. If a helium cluster turns out near the free surface, it falls into the region of image forces action. As is well known, image forces arise as a result of the reduction of full crystal energy in the case when any defect approaches a free surface. The magnitude of image forces increases with the distance to the surface decreasing. Therefore, if a mobile defect appears in the field of action of image forces, it inevitably leaves the volume. Taking into account the reason of image forces appearance, one can come to a conclusion that the SIA formation energy in the near-surface region regardless from the process should be less compared to the same process taking place in volume. Moreover, the closer to the surface this process develops, the less energy for the process of formation of SIA is needed. For this particular case with implanted helium, it means a decrease of helium atoms number capable of lattice atoms displacement with subsequent SIAs detaching from complexes.

According to modern data, the energy of formation of an SIA in tungsten is ~ 9 eV [18–20], and the most preferred configuration of an SIA is a crowdion, elongated along the close-packed direction <111> by 10 interatomic distances. As it is known the solution energy of helium in bcc metals is equal ~ 5…6 eV [21]. Comparing the formation energies of these two defects, one can make an assumption that process of tungsten atoms displacement is possible by only one helium atom in the case if this process occurs near the free surface. Considering the non-linearity of the distribution of the energy of a defect along the crowdion, we can obtain a rough estimate of the depth with which this process is possible. This equals to 3…4 interatomic distances or 8…10 Å from the surface. In this case, the helium atom migrating towards the surface does not leave the crystal and turns out in a bound state in a subsurface vacancy. On the contrary, a lattice tungsten atom is pushed out to the surface at the adatom position. At a small distance from the free surface, the processes of displacement and SIA detaching should merge into a uniform process, simple extrusion of a subsurface lattice atom from the volume along the direction of the spatial orientation of the crowdion – <111>. The small energy required for the implementation of this process in the immediate vicinity of the surface can be explained by the short-term (virtual) occurrence of a shortened crowdion configuration, which has substantially less energy than an SIA.

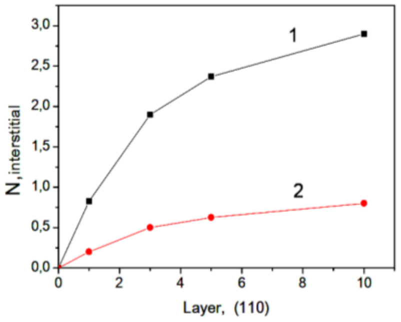

Fig. 4. The number of interstitial atoms emerging on the surface as a function of the removed layer thickness

Considering that SIAs have the highest formation energy among point defects, the depth of image forces action to SIA is also maximum. The dissociation of helium complexes found during evaporation makes it possible to determine the thickness of the surface layer, in which image forces influence the processes of the displacement of lattice atoms by helium and lead to the emerge of SIA from the volume. In Fig. 4 the number of interstitial atoms emerging on the surface after single evaporation acts depending on the thickness of the layer being removed is given. Dependencies are plotted separately for single SIA (curve 1) and double SIA complexes (curve 2).

Each evaporation act leads to the approach of the complexes to the surface by the value of the evaporated layer. At slight evaporation, a small number of complexes fall into the area of action of the image forces and, accordingly, after the dissociation, the same number of SIAs turn up on the surface. It is clear that in cases where the thickness of the evaporated layer is equal or greater than the depth of action of the image forces, the number of SIAs emerging on the surface should be constant and maximum. So the thickness of the evaporated layer at which the curves go to saturation corresponds the range of action of the image forces on the process that we study. As can be seen, both experimental dependencies tend to saturate, that makes it possible to estimate the image forces action range on the processes of formation and dissociation of vacancy – helium complexes with SIA. This depth exceeds 25 Å.

CONCLUSIONS

1. The stimulating influence of free surface on the process of lattice tungsten atoms displacement by implanted helium atoms and on the process of detaching of SIA from helium-vacancy complexes has been found.

2. It is shown that this influence is caused by the action of image forces and depends on the distance to the surface. The depth of action of these forces was determined. It is at least 25 Å.

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ОСОБЕННОСТИ ПОВЕДЕНИЯ ГЕЛИЕВЫХ КОМПЛЕКСОВ ВБЛИЗИ СВОБОДНОЙ ПОВЕРХНОСТИ В ВОЛЬФРАМЕ

И.В. Старченко, Е.В. Саданов

Обнаружено образование межузельных атомов путем вытеснения решеточных атомов вольфрама кластерами имплантированного гелия, которое сопровождается появлением гелий-вакансионных комплексов. Выявлено стимулирующее влияние свободной поверхности на развитие процессов вытеснения и диссоциации комплексов. Показано, что это влияние вызвано действием сил изображения. Определена глубина действия сил изображения, которая составила около 2,5 нм.

ОСОБЛИВОСТІ ПОВЕДІНКИ ГЕЛІЄВИХ КОМПЛЕКСІВ БІЛЯ ВІЛЬНОЇ ПОВЕРХНІ У ВОЛЬФРАМІ

І.В. Старченко, Є.В. Саданов

Виявлено формування міжвузельних атомів шляхом витіснення граткових атомів вольфраму кластерами імплантованого гелію, яке супроводжується появою гелій-вакансійних комплексів. Виявлено стимулюючий вплив вільної поверхні на розвиток процесів витіснення і дисоціації комплексів. Показано, що цей вплив викликано дією сил зображення. Визначена глибина дії сил зображення, що склала близько 2,5 нм.