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Effects of Implanted Helium on Radiation Damage in Tungsten by Heavy ions
タングステンにおける重イオン照射損傷に与える注入ヘリウムの効果

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Helium is considered to affect irradiation damage by neutrons, because it has strong interaction with defects. In the present work, therefore, synergistic irradiation effects of low energy helium and high energy heavy ions in tungsten was studied by comparing damages with helium irradiation, heavy ion irradiation and the simultaneous irradiation. In case of the simultaneous irradiation, small helium bubbles were formed preferentially near the incident surface because, implanted helium was trapped in vacancy clusters and voids formed by heavy ions irradiation.

1. Introduction

In a fusion reactor, plasma-facing materials are bombarded with 14MeV-neutrons and particles (hydrogen isotope, helium) with high flux. It is known that the former cause displacement damage and nuclear reaction the latter cause various phenomena in materials. In particular, helium will affect irradiation damage with neutrons because helium diffuses easily in metallic materials and has strong interaction with lattice defects. Though these irradiations occur simultaneously, their synergistic effects have not been investigated extensively so far. The objective of the present work is, therefore, to make clear the synergistic irradiation effects of low energy helium and high energy heavy ions in tungsten, which is a promising candidate of PFMs, by comparing damages with helium irradiation, heavy ion irradiation and the simultaneous irradiations.

2. Experimental Procedures

Tungsten sheet (0.1mm-thick) of nominal purity of 99.95% was used. Samples for TEM observation were manufactured as following. Disks of 3mmϕ were punched out from the sheet, and heated for 15 minutes at about 2273K in a good vacuum to recrystallize. These samples are almost defects free. Samples for analysis of depth distribution of helium were prepared as following. Platelets of 12×12mm were made by cutting the sheet and heated for 3 hours at 1273K to release residual stress. Conditions of helium irradiations are following; irradiation energy is from 0.25keV to 5keV, irradiation temperature from room temperature to 1073K, and irradiation dose from 10^{20} to 10^{21} He^+/m^2. On the other hand, those of heavy ion (Cu^{2+}) irradiations are following; irradiation energy is 2.4MeV, irradiation temperature from room temperature to 1073K, and irradiation dose from 0.01 to 1dpa. Calculation using TRIM-code indicates that displacement damage distributes up to about 600nm with a peak at 300nm. The irradiation conditions were selected by taking into account the circumstances of fusion reactors. Microstructures of the samples were observed by using TEM and FIB, and depth distribution of helium was analyzed by GD-OES.

3. Results and Discussions

3.1 *Heavy ions irradiation*

Fig.1 shows a typical TEM image of a cross-sectional sample irradiated with 2.4MeV Cu^{2+} to 1 × 10^{19} Cu^{2+}/m^2 at room temperature. Small dislocation loops and their clusters arraying were formed. They distributed up to 1000nm, which is much deeper than that estimated by the TRIM-code. Density of the interstitial loops is about two orders of magnitude higher than that estimated by using a rate theory, in which interstitial loops are assumed to be nucleated by combining two free interstitials. This means that most of the dislocation loops must be nucleated by cascade collisions. Furthermore, each loop can not grow larger individually but aligned loops grow by coalescing. It is worth to note that nano-voids were also densely formed near the incident surface.

3.2 *He irradiation*

Fig.2 shows cross-sectional TEM image and depth distribution of helium in tungsten irradiated with 0.25keV to 2.0×$10^{21}$$He^+/m^2$ at 1073K. In regard to graph of analysis by GD-OES, horizontal axis is depth from the incident surface and vertical axis is ratio of helium and tungsten (He/W) which is calculated on the assumption that all of the implanted helium stay in tungsten. In TEM image, helium bubbles are observed up to a depth of 100nm. In contrast, GD-OES also detects helium up to a depth of 100nm. The region that helium bubbles exist in TEM image corresponds well with depth distribution from these results. In addition, large helium bubbles with tens of nm are observed in TEM image. It is considered that they become larger by migration and coalescence of small helium bubbles because they become mobile at 1073K. Furthermore, because concentration of helium decreases in large bubbles, He/W in the region where large bubbles exist is small in comparison with region that dense small bubbles exist.

3.3 *Simultaneous irradiation*

Fig.3 shows depth distribution of helium in tungsten irradiated with 0.25keV-He^+ and 2.4 MeV-Cu^{2+} to $2.0\times10^{21}He^+/m^2$ and 1×10^{19} Cu^{2+}/m^2 at 1073K simultaneously and that of helium in tungsten irradiated by helium alone. The lower graph shows detail at shallow region less than 100nm in depth. In case of the simultaneous irradiation, helium is detected greater than helium only irradiation in neighborhood of surface. This indicates that small helium bubbles were formed because implanted helium was trapped in vacancy clusters and voids induced by heavy ions irradiation. In addition, in case of simultaneous irradiation, profile is not completely flat in deeper region. This indicates that helium may be trapped up to detection limit by GD-OES.

In the presentation, not only analysis by GD-OES of the simultaneous irradiation but also TEM images of that will be presented.

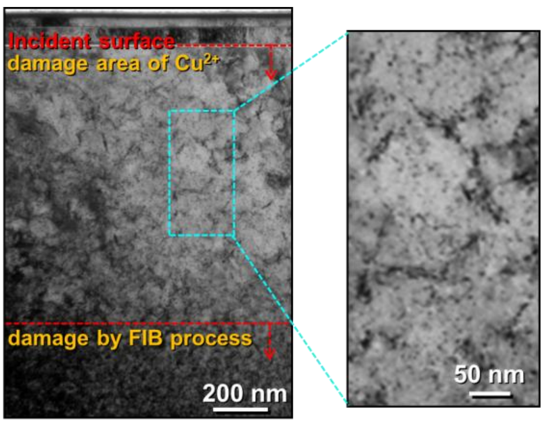

Fig.1 TEM image of W irradiated by Cu^{2+}

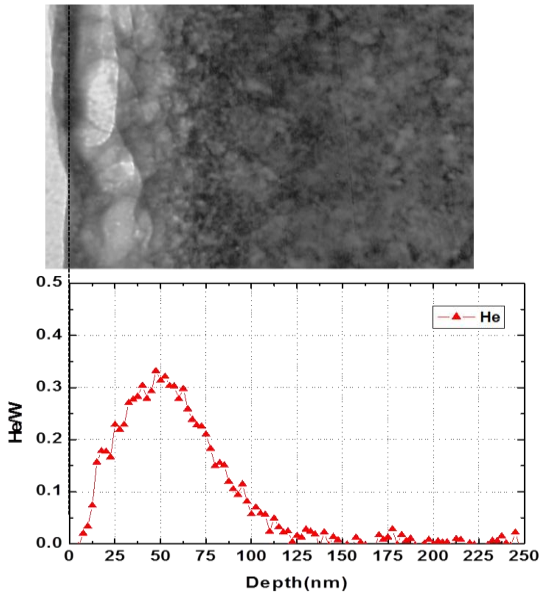

Fig.2 TEM image and depth distribution of He of W irradiated by He^+

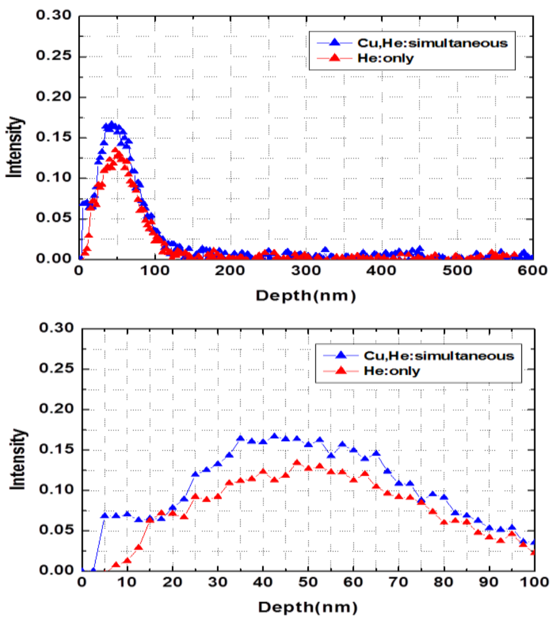

Fig.3 depth distribution of He of simultaneous and He irradiation