Deuterium Retention in Ion-Damaged ITER-Grade Tungsten Exposed to Low-Energy, High-Flux Pure and Helium-Seeded Deuterium Plasmas
低エネルギー・高フラックスプラズマ曝露下での ITER グレード W 中の重水素滞留挙動 －照射欠陥および He の影響－

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Samples prepared from polycrystalline ITER-grade tungsten were damaged by irradiation with 20 MeV W ions at room temperature to a fluence of 1.4×10^{18} W/m^2. Due to the irradiation, displacement damage peaked near the end-of-range, 1.35 μm beneath the surface, at 0.89 displacements per atom. The damaged as well as undamaged W samples were exposed to low-energy, high-flux (10^{22} D/m^{2}s) pure D and helium-seeded D plasmas to an ion fluence of 3×10^{26} D/m^2 at various temperatures. Trapping of deuterium was examined by the D(^{3}He,p)^{4}He nuclear reaction at ^{3}He energies varied from 0.69 to 4.0 MeV allowing determination of the D concentration at depths up to 6 μm. It has been found that (i) addition of 5% helium ions into the D plasma at exposure temperatures of 440-650 K significantly reduces the D concentration at depths of 0.5-6 μm compared to that for the pure plasma exposure; (ii) generation of the W-ion-induced displacement damage significantly increases the D concentration at depths up to 2 μm (i.e., in the damage zone) under following exposure both to the pure D and helium-seeded D plasmas.

1. Introduction

Due to its favorable physical properties, tungsten (W) is employed as a candidate material for plasma-facing high heat-flux structures in future fusion reactors. As plasma-facing material in the fusion reactors, W will be subject to intensive fluxes of energetic deuterium (D) and tritium (T) particles as well as helium (He) ions and 14 MeV neutrons (n) from the D–T fusion reaction. Neutron irradiation causes modification of the W microstructure and creates displacements in the bulk. One of the ways to investigate the influence of n-produced defects on the hydrogen isotope inventory is to simulate displacement damage in tungsten using irradiation with energetic ions. The objective of this work are comparison studies of D retention at displacement damage in ITER-grade W exposed to pure D and He-seeded D plasmas at elevated temperatures.

2. Experimental

Polycrystalline ITER-grade W (A.L.M.T. Corp., Japan) is deformed (rolled, swaged and/or forged) followed by appropriate heat-treatments to obtain better mechanical properties after the sintering process. In consequence, the W microstructure consists of anisotropically elongated grains along the deformation axis. The grain size is 1-3 μm in section and up to 5 μm in length. Individual elongated cracks observed between grains are due to the deformation treatments. Tungsten samples were so prepared by the manufacturer that the irradiated surfaces were perpendicular to deformation axis.

Some of the W samples were irradiated with 20 MeV ions to a fluence of 1.4×10^{18} W/m^2 at room temperature. As a result, the near-surface layer of the samples was damaged to 0.89 displacements per atom (dpa) at the damage peak situated at a depth of 1.35 μm. The damage profile was calculated using the program SRIM-2008 [1] with a displacement energy of 90 eV [2].

The damaged as well as undamaged W samples were exposed to low-energy, high-flux pure and helium-seeded deuterium plasmas at elevated temperatures (440-720 K) [3]. For exposure to the pure D plasma, plasma beam with species of D_2^+ (over 80%) and D^+ (less than 20%) was obtained. A bias voltage of -80 V was applied to the W sample, resulting in incident energy of 76 eV for D_2^+, taking into account the plasma potential of about -4 V. The incident deuterium ion flux was fixed at 10^{22} D/m^{2}s.

The concentration of He ions in the He-seeded D plasma was 10% [4]. The samples were exposed to the pure D and He-seeded D plasmas to a D ion fluence of 3×10^{26} D/m^2.

Deuterium depth profiles in the plasma-exposed W samples were analyzed by the D(^{3}He,p)^{4}He nuclear reaction. To determine the D concentration at larger depths, an analyzing beam of ^{3}He ions with energies varied from 0.69 to 4.0 MeV was used. The proton yields measured at different ^{3}He ion energies allow measuring the D depth profile at depths of up to 6 μm [5].

3. Results

The D depth profile in the undamaged ITER-grade W exposed to the pure D plasma at temperatures of 460 and 560 K is characterized by a concentration of 0.1-0.2 at.% at depths of 1-6 μm (in the sub-surface layer). Concentration minima at depths up to 1 μm (Fig. 1a) may be connected with the appearance of small blisters and accompanying porosity development [6]. At $T_{\rm exp}$ = 640 K, the D concentration in the sub-surface layer does not exceed 10^{-2} at.%. A further increase of the exposure temperature leads to a decrease of the D concentration (Fig. 1a).

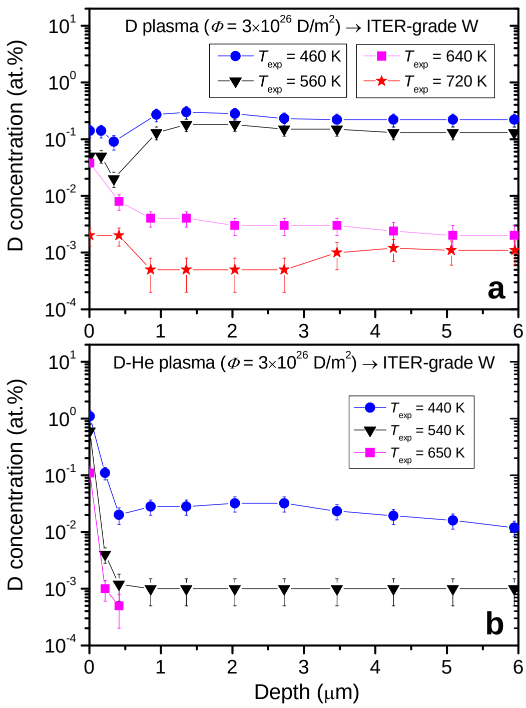

Fig. 1. Depth profiles of deuterium retained in undamaged ITER-grade W after exposure to pure D plasma (76 eV D_2^+) (a) and He-seeded D plasma {76 eV (D_2^+ + 10% He^+)} (b) with D ion fluence of 3×10^{26} D/m^2 at various temperatures.

Seeding of helium ions into the D plasma at exposure temperatures of 440-650 K significantly reduces the D concentration at depths of 0.5-6 μm (Fig. 1b). At $T_{\rm exp}$ = 440 K, the D concentration is described by a sharp near-surface concentration maximum of about 1 at.%, and, at depths above 0.5 μm, by a concentration of about 3×10^{-2} at.% slowly decreasing into the bulk. As the exposure temperature increases up to 650 K, the near-surface D concentration decreases to about 0.2 at.%, whereas the sub-surface D concentration becomes below 5×10^{-4} at.% (Fig. 1b).

Generation of ion-induced displacement damage and following exposure both to pure D plasma and D-He plasma significantly increases the D concentration at depths up to 2 μm (i.e., in the damage zone) (Fig. 2). However, for all exposure temperatures, the D concentrations at depths of 4-6 μm in the undamaged and damaged W samples are comparable in a value (Figs. 1 and 2).

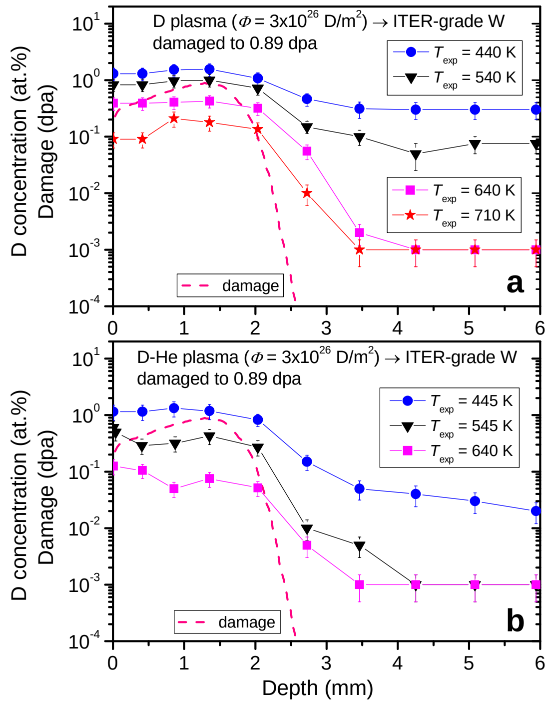

Fig. 2. Depth profiles of deuterium retained in ITER-grade W, damaged to 0.89 dpa by irradiation with 20 MeV W ions at room temperature, after exposure to pure D plasma (76 eV D_2^+) (a) and He-seeded D plasma {76 eV (D_2^+ + 10% He^+)} (b) with D ion fluence of 3×10^{26} D/m^2 at various temperatures.

References

[1] http://srim.org.
[2] Q. Xu, T. Yoshiie, H.C. Huang, Nucl. Instr. and Meth. **B 206** (2003) 123.
[3] G.-N. Luo, W.M. Shu, H. Nakamura, S. O'Hira, M. Nishi, Rev. Sci. Instrum. **75** (2004) 4374.
[4] V.Kh. Alimov, W.M. Shu, J. Roth, K. Sugiyama, S. Lindig, M. Balden, K. Isobe, T. Yamanishi, Phys. Scripta **T138** (2009) 014048.
[5] V.Kh. Alimov, M. Mayer, J. Roth, Nucl. Instr. and Meth. **B 234** (2005) 169.
[6] S. Lindig, M. Balden, V.Kh. Alimov, A. Manhard, C. Höschen, T. Höschen, B. Tyburska-Püschel, J. Roth, Phys. Scripta (2011) (in press).