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Sputtering effects on mirrors made of different tungsten grades

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HIGHLIGHTS

- The reflectance of W mirror specimens pre-damaged with W ions to a dose of 0.45 and 1.45 dpa behave just as the undamaged specimens when being subjected to sputtering with ions of Ar or D plasmas.
- Behavior of the reflectance depends significantly on the W grade, namely, on the microstructure of W, such as distributions of grains on their size and orientation relative to the surface of the sample.
- The dominant factor that defines the reflectance and surface roughness is the difference between the heights of grains with different sputtering rates of faces differently orientated relatively to the sample surface.

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ABSTRACT

Because tungsten (W) is used in present fusion devices and it is a reference material for ITER divertor and possible plasma-facing material for DEMO, we strive to understand the response of different W grades to ion bombardment. In this study, we investigated the behavior of mirrors made of four polycrystalline W grades under long-term ion sputtering. Argon (Ar) and deuterium (D) ions extracted from a plasma were used to investigate the effect of projectile mass on surface modification. Depending on the ion fluence, the reflectance measured at normal incidence was very different for different W grades. The lowest degradation rate of the reflectance was measured for the mirror made of recrystallized W. The highest degradation rate was found for one of the ITER-grade W samples. Pre-irradiation of a mirror with 20-MeV W^{6+} ions, as simulation of neutron irradiation in ITER, had no noticeable influence on reflectance degradation under sputtering with either Ar or D ions.

1. Introduction

The high melting temperature, low retention of hydrogen isotopes, and low erosion yield of tungsten (W) have made it the reference plasma-facing material in high heat-flux divertor areas in the experimental fusion reactor ITER [1,2], with a total area of W tiles $\approx 150\,m^2$. The authors of paper [3] also considered the case where beryllium, which is a reference material for the first wall in ITER, may be replaced by tungsten. Two "full-W-wall" tokamaks are already under operation (ASDEX-Up [4] and WEST [5]), and one more (JT-60SA) is planned to be operated in the future [6]. Moreover, W is considered as one of the candidate materials for the first mirrors of optical diagnostic systems if the sputtering rate of the mirror with charge exchange atoms is too high for other materials such as molybdenum. Under the impact of harsh ITER environments, some important characteristics of W can deteriorate over time under ITER operation, such as the sorption capacity of deuterium and tritium, rate of sputtering by charge exchange atoms, development of surface roughness, and ability to reflect and absorb electromagnetic radiation emanating from a plasma.

In this paper, we present experimental results on the long-term

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sputtering of different W grade samples, which can be subjected to charge exchange atom bombardment in fusion environment [7]. Several samples were preliminary irradiated with 20-MeV W ions to simulate the effects of neutron irradiation on W components facing the plasma. All the samples were polished to a mirror quality to have more possibilities for the characterization of their surface after the sputtering procedures.

The focus of the present paper is not on the effects of neutron irradiation on the retention of hydrogen isotopes, which have been reported in Refs. [8–14]. In the present paper, the effects of pre-irradiation of polycrystalline W specimens with 20-MeV W ions on the surface morphology development due to sputtering by argon and deuterium ions are investigated. To completely elucidate the behavior of self-ion damaged W under sputtering, we present some results published earlier [15,16].

The paper is organized as follows. After description of experimental conditions in Section 2, the effects of long-term sputtering on surface relief and optical properties are presented in Sections 3.1 and 3.2–3.3, respectively. Sputtering rates are compared in Section 3.4, and conclusive remarks are presented in Section 4.

2. Experimental details

The samples were as follows: (i) ITER-grade W produced by A.L.M.T. Corp., Japan (WI-J), (ii) W produced by A.L.M.T. Corp., Japan, recrystallized at 2073 K for 1 h after cutting and polishing (WR-J), (iii) ITER-grade tungsten WI, and (iv) WP type tungsten. Both WI and WP were produced by Plansee AG.

European and Japanese ITER-grade W samples (WI and WI-J, respectively) were deformed (rolled, swaged, and/or forged) and then subjected to appropriate heat treatments for obtaining better mechanical properties, e.g., strength and toughness, following the sintering process. WI and WI-J samples had grains oriented preferentially normal to the surface [8,10]. Thus, these types of tungsten substantially satisfied the requirements stated in Ref. [17] for ITER reference W. However, the grain elongation was more pronounced in the case of WI samples produced by Plansee than that in WI-J (A.L.M.T. Corp.). WP samples had grains preferentially elongated to be parallel to the mirror surface [10], and recrystallized WR-J samples had no definite texture. Table 1 presents a brief description of the samples.

All W specimens were prepared as high-optical quality mirrors to investigate changes in optical properties and surface modifications that develop under sputtering. The size of specimens was 10×10 or 10×12 mm with a thickness of 1–2 mm. Some samples were pre-irradiated with 20-MeV W ions at room temperature to damage levels of 0.45–1.45 dpa with a damage peak at a depth of 1.35 μm [10,11].

In previous papers [8–10], the Monte Carlo code SRIM [18], “full cascade options,” with a recommended displacement energy of 90 eV [19] was applied to calculate displacements per atom (dpa). These calculations showed that a fluence of 1.4×10^{18} W/m^2 produces 0.89 dpa at the damage peak located at a depth of 1.35 μm. However, recent papers [11,12,20,21] have shown that the calculations in “full cascade options” can result in incorrect value of dpa. Using the methodology described in Refs. [20,21], it was calculated in Refs. [11,12,20] that a fluence of 1.4×10^{18} W/m^2 produces 0.45 dpa at the damage peak. The calculations were performed using the SRIM code in the Kinchin-Pease mode with an effective threshold displacement energy of 90 eV [11,12,20].

Specimens WP-3, WP-4 and WI-3, WI-4 were in couples sputtered by Ar or D ions to a depth of about 4 μm, which exceeds the depth of the damaged zone, which is ~2.4 μm according to the SRIM calculations [11,12,20].

To simulate the long-term bombardment of W in ITER by charge exchange atoms (D and T atoms of wide energy distributions [22]), the samples were bombarded with argon or deuterium ions from a plasma generated in DSM-2 where a stationary plasma (n_e~10^{10} cm^{-3}, T_e~5 eV) was produced in conditions of electron cyclotron resonance in double-mirror magnetic configuration [23].

The large difference in sputtering rates by Ar and D ions [24] allows us to study the effect of projectile mass on surface modification development due to the long-time sputtering. Plasma ions were accelerated to the sample surface by applying a negative potential to the water-cooled sample holder. The energy of Ar ions was ~600 eV. In the case of D plasma, the applied voltage was −1000 V. The ion flux composed of D^+, D_2^+, and D_3^+ ions, and it was not mass separated. Thus, there were three groups of

Table 1
Description of samples and irradiation conditions.

Name	Company	Specification	Comments	Projectiles
WI-J	W ITER grade Japan, A.L.M.T. Corp.	Grains preferentially elongated to be perpendicular to the irradiated surface	Pre-irradiated with 20-MeV W ions (1.45 dpa)	Ar – 600 eV
WR-J	W recrystallized Japan, A.L.M.T. Corp.	WI-J recrystallized at 2073 K for 1 h. No preferential orientation of grains	Pre-irradiated with 20-MeV W ions (1.45 dpa)	Ar – 600 eV
WI-1	W ITER grade Europe, Plansee AG	Grains preferentially elongated to be perpendicular to the irradiated surface. This grain elongation is more pronounced than that in WI-J	Un-irradiated	Ar – 600 eV
WI-2	W ITER grade Europe, Plansee AG	…	Pre-irradiated with 20-MeV W ions (0.45 dpa)	Ar – 600 eV
WI-3	W ITER grade Europe, Plansee AG	…	Un-irradiated	Ar – 600 eV
WI-4	W ITER grade Europe, Plansee AG	…	Un-irradiated	D – 1000 eV
WP-1	Plansee AG	Grains preferentially elongated to be parallel to the irradiated surface	Un-irradiated	Ar – 600 eV
WP-2	Plansee AG	…	Pre-irradiated with 20-MeV W ions (0.45 dpa)	Ar – 600 eV
WP-3	Plansee AG	…	Un-irradiated	Ar – 600 eV
WP-4	Plansee AG	…	Un-irradiated	D – 1000 eV