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W nano-fuzzes: A metastable state formed due to large-flux He^+ irradiation at an elevated temperature

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HIGHLIGHTS

- W nano-fuzzes microscopic evolution during annealing or He^+ irradiated have been measured.
- W nano-fuzzes are thermally unstable due to He release during annealing.
- He are released from the top layer of W fuzzes by annealing.
- Metastable W nano-fuzzes are formed due to He^+ irradiation at an elevated temperature.

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ABSTRACT

W nano-fuzzes have been formed due to the large-flux and low-energy (200eV) He^+ irradiation at W surface temperature of 1480 °C. Microscopic evolution of W nano-fuzzes during annealing or low-energy (200 eV) He^+ bombardments has been observed using scanning electron microscopy and thermal desorption spectroscopy. Our measurements show that both annealing and He^+ bombardments can significantly alter the structure of W nano-fuzzes. W nano-fuzzes are thermally unstable due to the He release during annealing, and they are easily sputtered during He^+ bombardments. The current study shows that W nano-fuzzes act as a metastable state during low-energy and large-flux He^+ irradiation at an elevated temperature.

1. Introduction

He-induced W nano-fuzzes have been widely recognized as a potential drawback for the plasma facing W material in a D + T fusion reactor [1–3]. The growth of W nano-fuzzes does not strongly depend on the W grades, and He-induced nano-fuzzes have been observed under a wide range of plasma conditions [3,4]. Up to now, it has been widely accepted that W nano-fuzzes can be formed due to He^+ irradiation of polycrystalline W at the surface temperature of 900–1800 °C [3–5]. To form the W nano-fuzzes, He^+ energy and fluence are >20eV and $>10^{25}/m^2$, respectively. It has been believed that the formation of W nano-fuzzes is related to a He-trapping mechanism which is self driven [3]. Kajita proposed that the formation and growth of W nano-fuzzes can be attributed to the diffusion and coalescence of He nano-bubbles at an elevated temperature [6]. Our previous study indicates that the diffusion and coalescence of He atoms in W surface layer can control the growth and structure of nano-fuzzes [7]. Coral-like or tree-like nano-fuzzes can be formed due to low-energy He^+ irradiation, depending on the energy and flux of He ions.

He-induced nano-fuzzes have low thermal conductivity and poor mechanical properties, which cause several concerns such as enhanced erosion and dust formation [5]. Sputtering yields (Y_F) of He-induced W nano-fuzzes have been measured as a function of Ar/He energy and W fuzz thickness [8,9]. A large fraction of sputtered W atoms can be deposited onto neighboring fuzz nanostructures, resulting in the significant reduction in Y_F. The thickness of W nano-fuzzes decreases with increasing He energy from 200 to 500eV. The effect of crystallographic orientation on W surface morphology was investigated in the linear plasma device by exposing the high-density He plasma to ITER grade W [10]. Because of different W areal density at crystal grains, W surface morphology shows the dependence on their crystal orientation. The deformation of W nano-fuzzes during annealing has been investigated by

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means of in-situ cross-sectional observation using transmission electron microscopy [11]. W nano-fuzzes were found to be unstable, and their surface shrinkage and coalescence occurred around 800–900 °C.

The purpose of this current study is to explore the stability of W nano-fuzzes during annealing or He^+ bombardments, and analyze their growth process under large-flux He^+ irradiation at an elevated temperature. The effects of annealing temperature and He^+ bombardments on W nano-fuzzes are investigated by scanning electron microscopy (SEM), and the thermal stability is analyzed by thermal desorption spectroscopy (TDS). The growth process of W nano-fuzzes as a metastable state formed due to large-flux He^+ irradiation is discussed based on the experimental measurements.

2. Experimental procedures

Polycrystalline W (Honglu, Xiamen) with a size of 1 cm × 1 cm × 2 mm was used as the specimen. To generate the W nano-fuzzes, the polished W specimen was irradiated with low-energy (200eV) and large-flux ($1.3 \times 10^{22}/m^2 \cdot s$) He^+ plasmas in our LP-MIES system described previously [7,12]. The radio frequency power of 7.5 kW was injected into the inductively coupled plasma (ICP) source, resulting in W surface temperature of 1480 °C. A negative bias of −180 V was applied onto W specimen, which accelerated He^+ in the plasma sheath. The energy of He^+ was 200eV when taking into account the plasma potential of 20 V. He^+ irradiations were performed at the fluence of 5.0×10^{25}ions/m^2, leading to the growth of W nano-fuzzes.

After the growth of W nano-fuzzes, W specimen was annealed or bombarded with He^+ plasma in our MIES system [13]. The chamber background pressure was $<3.0 \times 10^{-4}$Pa. A variable-power semiconductor laser was used to heat the backside of W specimen, and W surface temperature is adjustable in the range of 25–1000 °C. The temperature was measured with an infrared STL-150B pyrometer. Annealing temperature was changed at 200 °C increments from room temperature (R.T.) to 1000 °C. The specimen was heated to each temperature at a heating rate of 3.3 °C/s. After the annealing for 60 min, the temperature was decreased to R.T., then SEM was utilized to observe the microstructural change in W fuzzes.

He^+ bombardments of nano-fuzzes at W surface were carried out at the energy of 200eV and the flux of $1.1 \times 10^{20}/m^2 \cdot s$. The He^+ bombardments were performed at the W temperature of R.T. or 600 °C, and He^+ fluence was changed at $7.5 \times 10^{23}/m^2$ increments from $7.5 \times 10^{23}/m^2$ to $6.0 \times 10^{24}/m^2$. Then, SEM was utilized to observe the microstructural change in W fuzzes due to He^+ bombardments. Thermal desorption spectroscopy (TDS) was used to investigate the thermal desorption property of the fuzz W. In TDS analysis, W specimen was heated continuously up to 1000 °C at a heating rate of 1 °C/s.

3. Results

3.1. Effect of annealing temperature on W nano-fuzzes

To analyze the microstructural evolution of W nano-fuzzes during annealing, SEM observations were performed for the same locations of W specimen annealed at different temperatures. Fig. 1 shows the effect of annealing temperature on the microstructure of W fuzzes. High-density W nano-fuzzes are formed due to low-energy (200eV) and large-flux ($1.3 \times 10^{22}/m^2 \cdot s$) He^+ irradiations, as shown in Fig. 1(a). Prior to He^+ bombardments, W nano-fuzzes are 15–30 nm in diameter. When the annealing temperature increases from 200 °C to 800 °C, the density of W nano-fuzzes slowly decreases, as shown in Fig. 1(b)-(e). Plenty of nanometer-sized W grains can be observed at the annealing temperature of 1000 °C, as shown in Fig. 1(f). However, the diameter of W nano-fuzzes does not strongly depend on the annealing temperature (Table 1), and it remains almost constant when the annealing temperature varies from 200 °C to 1000 °C. The cross-sectional views of W nano-fuzzes

Table 1
The diameter of W nano-fuzzes under different annealing temperature.

Specimen	Annealing temperature (*T*) (°C)	W nano-fuzz diameter (nm)
11	unannealed	25 ± 5
12	200	24 ± 4
13	400	27 ± 5
14	600	26 ± 4
15	800	26 ± 5
16	1000	24 ± 4

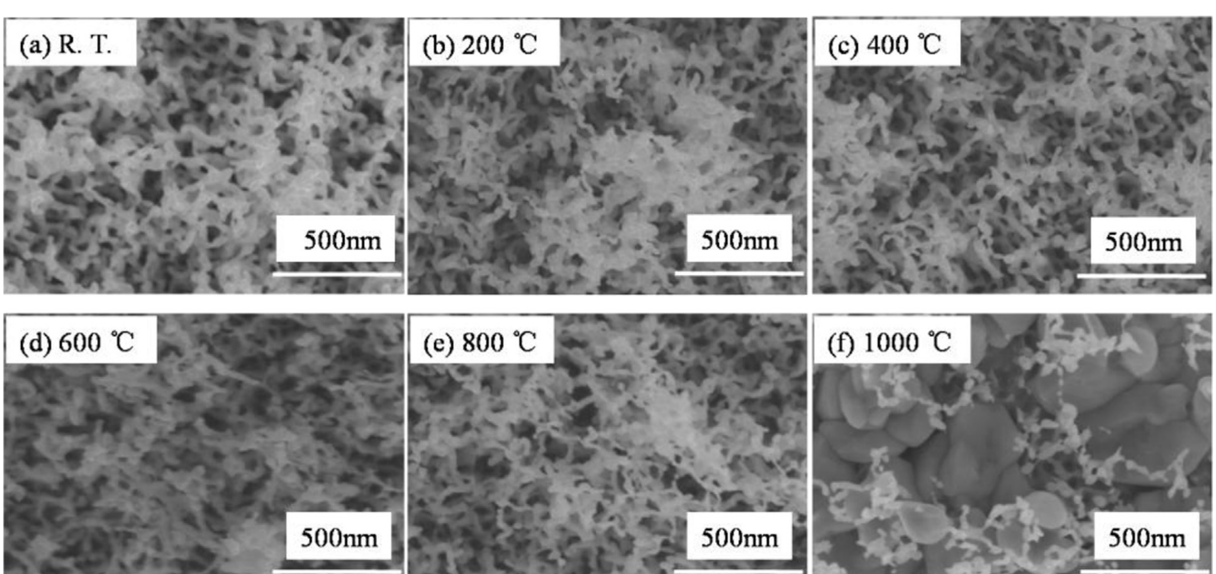

Fig. 1. The effect of annealing temperature on the microstructure of W fuzzes. SEM observations were performed for the same location of W specimen.