Pulsation Effects of Incident Ion Energy on W Fuzz Growth

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Fuzzy nanostructure growth occurs on tungsten (W) surfaces by the exposure to helium (He) plasmas. We investigated pulsation effect in the incident energy of He ions on W fuzz growth. It is shown that He irradiation contributes to the growth of fuzzy layer even if the incident ion energy was less than the threshold energy of 20 - 30 eV. When the duty cycle of the pulse was 1 - 10 %, 7 - 8 eV He ion irradiation have contributed to the fuzz growth in addition to high (> 60 eV) energy ion irradiation, and the growth rate was enhanced.

Keywords: pulsation, tungsten, helium plasma, fuzz, nanostructure

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Fuzzy nanostructures are grown by helium (He) plasma irradiation on tungsten (W) by the growth of He bubbles [1]. Because the layer significantly changes the material properties from those of bulk material, the influence on the transients in fusion devices accompanied by edge localized modes (ELMs) is one of the concerns [2]. An issue to be investigated further is whether such morphology changes will actually occur on plasma facing materials in fusion devices. It is known that the growth requires the surface temperature range of 1000 - 2000 K and the incident ion energy, E_i, of greater than 20 - 30 eV [3]. Thus, detached plasmas, in which the temperature is lower than several eV [4], are thought to have an inhibiting effect on the growth of the fuzzy structure, because E_i could be lower than the threshold energy. It is of importance to investigate the effects of transients such as ELMs, because they will convey higher energy particles even for a short period of time. Transient heating effects on fuzz growth have been investigated by Yu *et al.* using pulsed laser irradiation [5]; it was found that an enhanced fuzz growth was identified by transient heating events. In this study, we will investigate the effect of cyclic pulsation in E_i on W fuzz growth.

Experiments were conducted in the linear plasma device NAGDIS-II (Nagoya divertor simulator-II). He plasmas were produced in steady state, and a W sample (0.2 mm thick) was installed in the downstream of the cylindrical plasma; E_i was controlled by biasing the sample using a bipolar power supply. The sample surface was in parallel to the magnetic field. Figure 1 (a) shows a schematic of the temporal evolution of E_i. The incident ion energy was pulsated cyclically from E_L (< 30 eV) to E_H (65 - 95 eV) at a frequency, f, of 10 or 100 Hz for 1 ms; the duty cycle, D, was 1 or 10 % at f = 10 or 100 Hz, respectively. It is noted that transient variation in the surface temperature was not significant, as was previously discussed [6]. Here, we define He fluences at E_L and E_H as Φ_L and Φ_H, respectively.

Figures 1 (b) and (c) show SEM micrographs of the samples exposed to the He plasmas at the surface temperature, T_s, of 1100 and 1300 K, respectively. The total irradiation time was 10000 s and f = 100 Hz for both samples. Fuzz was formed on the surface in Fig. 1 (b), whereas no fine structures were identified in Fig. 1 (c). Because Φ_L and Φ_H did not differ between the two cases, differences in T_s should have caused the difference in the morphology changes. The mechanisms to cause the difference will be discussed later.

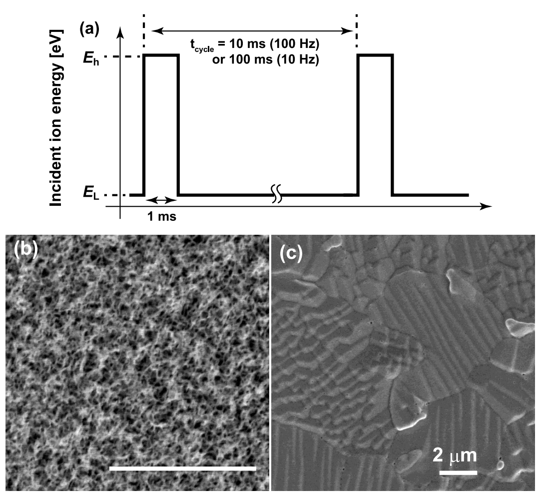

Fig. 1 (a) A schematic of the temporal evolution of the incident ion energy and SEM micrographs of the samples exposed to the He plasmas at T_s of (b) 1100 and (c) 1300 K. The irradiation condition was as follows: E_L = 7 - 8 eV and Φ_H = 1.5 - 1.8 × 10^{25} m^{-2} and D = 10 %.

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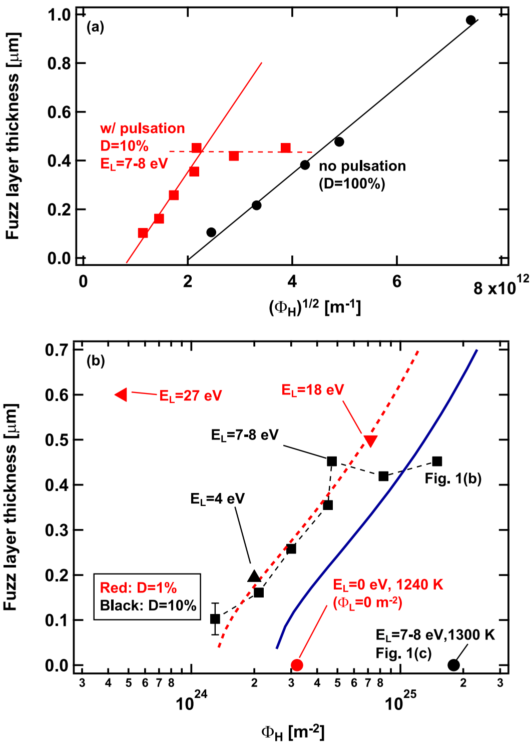

Fig. 2 (a) Fuzzy layer thickness as a function of Φ_H with pulsation (D = 10 %) and without pulsation, i.e. D = 100 %. (b) Fuzzy layer thickness as a function of Φ_H for various D and E_L cases. Lines in (b) are the calculated thickness as a function of Φ_H using Eq. (1).

Figure 2 (a) shows the fuzz layer thickness as a function of Φ_H with pulsation at D = 10 % and $T_s \sim 1100$ K and without pulsation, i.e. D = 100 %, for reference from [6]. The thickness increased in proportional to the square root of Φ_H up to $5 \times 10^{24}\,\mathrm{m}^{-2}$ with the pulsation; it saturated at the thickness of ~0.45 µm. The incubation fluence, Φ_0, obtained from the zero intercept was $0.8 \times 10^{24}\,\mathrm{m}^{-2}$ for D = 10 %, which was meaningfully smaller than that without pulsation ($4 \times 10^{24}\,\mathrm{m}^{-2}$). Petty *et al.* assessed $\Phi_0 = 2.5^{+1.5}_{-1.0} \times 10^{24}\,\mathrm{m}^{-2}$ considering the data including various devices [7]. Recent comparison of the thickness of fuzz layer grown in the gaps of castellated W in PISCES-A between experiments and particle simulation have suggested the accuracy of the value [8]. Thus, a decrease in Φ_0 by the pulsation suggested that the He irradiation at 7 - 8 eV played some role to compensate the incubation (saturation of He density and growth of He bubbles). Also, a saturation in the thickness occurred with pulsation; a potential mechanism is discussed later.

Figure 2 (b) shows the fuzz layer thickness as a function of Φ_H for various D and E_L cases. The growth model of fuzzy layer has been developed and the thickness without sputtering erosion can be written as

$$x(\Phi) = (C(\Phi - \Phi_0))^{1/2}, \qquad (1)$$

where C is a coefficient; following fit values were obtained [7]: $C = 2.36^{+1.54}_{-0.56} \times 10^{-38}\,\mathrm{m}^4$ and $\Phi_0 = 2.5^{+1.5}_{-1.0} \times 10^{24}\,\mathrm{m}^{-2}$.

The solid line in Fig. 2 (b) represents the thickness obtained from Eq. (1) assuming that $\Phi = \Phi_H$ in Eq. (1). Comparing with the case of $E_L \sim 7$ - 8 eV and D = 10 % (black square markers), it is seen that experimental data were always in the left side of the solid line. If the low energy irradiation contributed to the fuzz growth, Φ in Eq. (1) can be expressed as $\Phi_H + \alpha\Phi_L$ in Eq. (1) using a contribution factor α. The red dotted line in Fig. 2 (b) is the calculated thickness at $\alpha = 0.1$ as a function of Φ_H. The contribution of the low energy irradiation shifted the curve to the left; the calculation was almost consistent with the experimental results.

Experiments were conducted at different E_L: ∼ 0, 5, 10, 18, and 27 eV. No growth was identified when $E_L \sim 0$ eV, i.e., $\Phi_L = 0\,\mathrm{m}^{-2}$, whereas the thickness follows the red dotted lines at E_L = 4, 7 - 8, and 18 eV. This was almost consistent with the temperature dependence of the bubble formation; the density of bubbles decreased significantly below ∼ 15 eV [9]. The case of E_L = 18 eV and D = 1 % also followed the red dotted line, indicating that α could alter and be lower than 0.1 because Φ_L was much higher in this case. Moreover, the contribution of Φ_L became more significant if E_L was higher than ∼ 20 eV. Previously, the growth termination has been identified from the equilibrium between growth and annealing [6]. It was likely that the growth saturation occured around 0.45 µm for E_L = 7 - 8 eV due to the effects of annealing. Moreover, similar mechanism might have been worked in the case of Fig. 1 (c), where no growth occurred at 1300 K even though $\Phi_H > 10^{25}\,\mathrm{m}^{-2}$.

In this study, the contribution of Φ_L to the fuzz growth was identified even at 4 eV. We should say that the value included some ambiguity, typically ±5 eV from fluctuation of the plasma, as was discussed in [9]. It is of importance to investigate the minimum required energy for the effect and whether the same effects can be identified even in detached plasmas in future. This work suggested the necessity to consider the modulations in the incident ion energy as well as the surface temperature [5] to determine the morphology changes by He plasma irradiation in future fusion devices.

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