Multi-Component Plasma Interactions with Elemental and Mixed-Material Surfaces

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Abstract. This paper begins by describing the results from beryllium sputtering yield measurements conducted in the PISCES-B linear plasma device. Measurements made in the plasma environment of PISCES-B are consistently lower (by 3-10) compared to values predicted by TRIM codes. Possible errors in the measurement are described, but none can account for the differences observed. Similar reductions in sputtering yield from tungsten samples exposed to energetic helium ion bombardment are also presented, where TEM analysis of the surface structure provides clues to the reduced sputtering yield measurements. At high temperature, a model is presented for the competition between the growth and erosion of tungsten fuzz surfaces and this model is verified experimentally. Finally, past work is summarized on the impact of beryllium on the mitigation of carbon chemical erosion. The robustness of the resulting beryllium carbide surface layers when subjected to simultaneous argon bombardment indicates that the beneficial mitigation should also be expected during the injection of argon as a radiating species in the divertor.

1. Introduction

This paper will describe recent plasma-surface interaction activity in the PISCES Laboratory at UCSD. PISCES is involved in measurements in support of the ITER project and as such has the ability to perform high-flux plasma erosion measurements of beryllium targets. In addition, the PISCES-B device is equipped with a beryllium vacuum evaporator that can 'seed' plasma with a controllable and measureable amount of beryllium impurity ions [1]. This beryllium-containing plasma can then interact with carbon, or tungsten, targets to investigate the impact on erosion, or retention, of mixed-material formation.

In section 2, this paper will compare the measurements of sputtering yield in the PISCES-B plasma environment to TRIM [2] predictions and attempt to evaluate the possible errors present in the experiment. Measurements of tungsten nano-scale surface structures caused by helium plasma bombardment will then shown as a possible explanation for the lower than expected sputtering yields also measured during helium plasma sputtering of tungsten.

Section 3 will examine the evolution of the surface nano-structures in tungsten as a function of exposure temperature, eventually resulting in the appearance of tungsten fuzz [3-6]. A model balancing the growth rate of tungsten fuzz and the erosion rate of an incident plasma is described and verified experimentally using an erosion dominated plasma condition in PISCES-A.

Finally, measurements describing the chemical erosion mitigation of graphite targets exposed to a beryllium containing deuterium plasma are summarized. In ITER, the achievement of a detached divertor plasma solution requires the radiation from eroded carbon atoms in the divertor, so if this species is not present a radiating species, such as argon will need to be

intentionally added to the divertor plasma to achieve a detached divertor solution. However, the addition of argon to the incident plasma may sputter away the protective surface layers responsible for the chemical erosion mitigation. Experiments to address this question are then described.

2. Beryllium Sputtering Yield Measurements

The erosion of material by plasma bombardment has often been estimated using binary collision approximation (BCA) models, such as TRIM [7]. These BCA models have long been used and verified by way of extensive ion beam sputtering measurements. In the case of beryllium sputtering, ion beam measurements were originally hampered by the inherent oxide layer present on beryllium targets [8]. Only by heating the beryllium sputtering targets in excess of 600°C, where the beryllium substrate atoms can diffuse through the protective oxide layer and present a 'clean' beryllium surface for measurements, were the relatively low flux ion beam devices able to get reasonable agreement [8] with the predictions of TRIM.

In sputtering yield measurements in PISCES-B, the measured sputtering yield of beryllium targets by deuterium plasma is lower than TRIM predictions by a factor of 3-10 [9, 10]. The initial assumption was that this was a result of an oxide layer on the surface of the beryllium samples, similar to what was seen in ion beam sputtering experiments. However, during high temperature measurements at 650°C, the sputtering yield remained at the same reduced level. Subsequent measurements of the surface composition immediately (~500 seconds later) after plasma exposure using in-situ Auger Electron Spectroscopy revealed that the surface was essentially 'clean' beryllium during the plasma exposure. The change of the surface composition as the beryllium target getters impurities from the background residual gas is shown in Figure 1. Extrapolating these trends back to the end of the plasma discharge results in an impurity composition of less than 10% coverage of the surface during the plasma exposure.

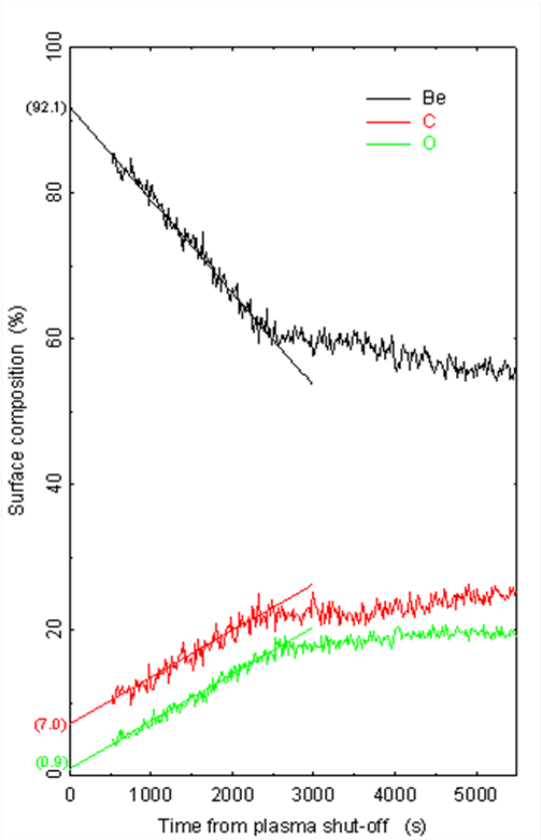

Figure 1 – Time evolution of surface composition of a Be sample after plasma exposure in PISCES-B

Other possible errors in the erosion measurements have also been investigated. Since the yield measurements are calculated based on the weight loss from a sample, the redeposited fraction will result in an error. Calculations made using the ERO code have estimated the redeposited fraction to be only 10-20% [11]. Although the absolute magnitude of the calculated photon flux in ERO is different from that measured by experiments, the shape of the axial profile of the light emission from sputtered beryllium atoms agrees with those measured experimentally. This also indicates that the source term for erosion, or the atomic physics calculations of photons per atom, may be incorrect, but the plasma terms

governing ionization and transport in the plasma are likely good. Other variables, such as the molecular ion fractions in the incident plasma [12] and the incident ion energy [13] are based on direct experimental measurements and cannot easily be off by enough to account for the large discrepancy.

As a final check of the weight loss measurement technique, a comparison was made between the weight loss from a beryllium sample exposed to a helium plasma (to avoid the added complication of the chemical activity of hydrogen isotopes) and a carbon sample exposed to an almost identical helium plasma. In the case of the beryllium sample the sputtering yield was measured to be a factor of ten lower than expected from TRIM, whereas the carbon sputtering yield was measured to be almost a factor of two larger than that calculated from TRIM. This comparison indicated that there was no systematic error involved in the measurement technique, but rather that there was some fundamental difference between calculation using TRIM and the sputtering rate expected from a beryllium surface exposed in a plasma environment.

One other major difference between an ion beam sputtering experiment (recall that such measurements agree with TRIM calculations) and a plasma experiment is the amount of background neutral atom flux to the sputtered surface. This coupled with the much larger ion flux into the surface typical of plasma exposures can easily result in a concentration of the bombarding species within the surface that exceeds the solubility limit of the material. Once this occurs the gas atoms will begin to precipitate, resulting in the formation of small gas filled voids that have the possibility of growing if the concentration of gas atoms in the surface remains above the solubility limit.

Although it is difficult to examine the surfaces of beryllium exposed samples using a TEM, since this will typically contaminate the apparatus used during the investigation, is has been possible to examine the surface of tungsten samples exposed to helium plasma bombardment. Figure 2 shows cross sectional TEM image of the surface of a tungsten sample after helium plasma exposure at 200°C [14]. The subsurface region is seen to be extensively populated with a series of nano-sized bubbles. Nano-scale porosity will tend to reduce the effective density of the surface, increase the penetration distance of the incoming energetic particle and reduce the probability for sputtering at any given incident energy. This has been verified by measuring the sputtering yield of high porosity tungsten surfaces as will be described in the next section.

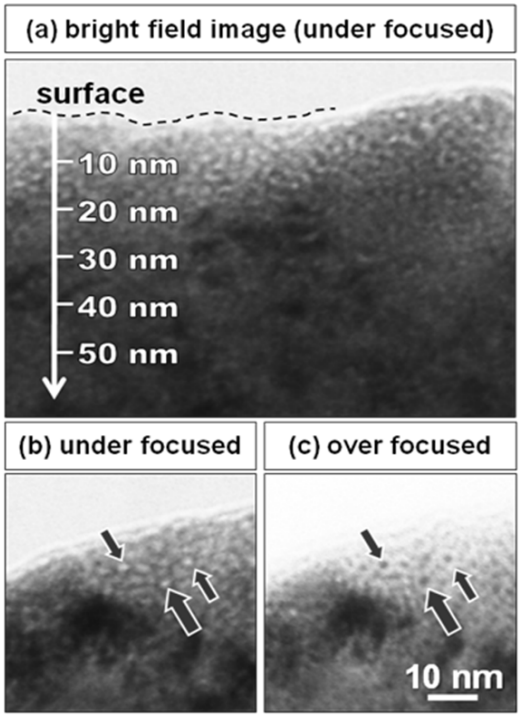

Figure 2 – TEM image of tungsten surface after He plasma exposure at 200°C

3. Equilibrium Tungsten Fuzz Thickness in an Eroding Plasma

The nano-sized bubbles observed following low temperature exposure of tungsten to helium bombardment are seen to exhibit a striking change as the temperature of the surface increases.

Figure 3 shows a similar TEM image of a tungsten surface flowing exposure to helium plasma at 500°C [14]. Here the bubbles can be seen to begin interconnecting with adjacent bubbles and creating pathways back to the sample surface. As the exposure temperature increase further, n as yet unidentified process becomes active and the formation of a nano-textured surface is seen to develop. This so-called, tungsten fuzz, layer will continue to grow in thickness as long as the plasma exposure conditions remain.

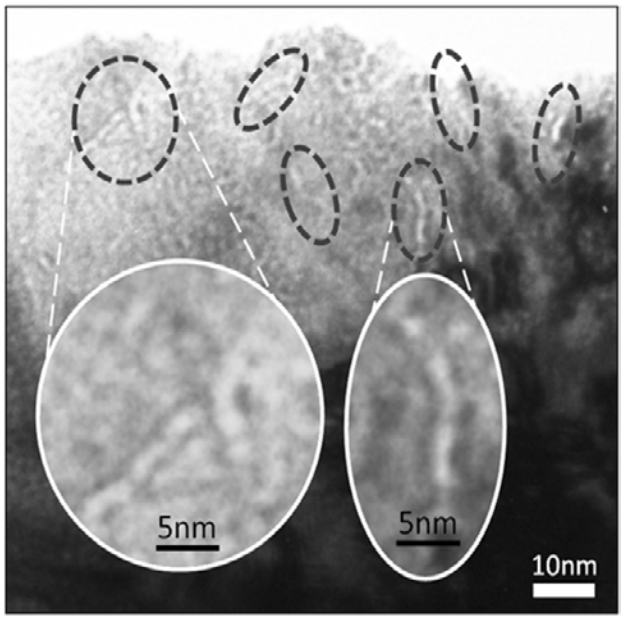

Figure 3 – TEM image of a tungsten surface after helium plasma exposure at 500°C

The resulting thickness of tungsten fuzz, λ, has been shown to obey Fick's Law, which involves a square root of time term [5]. When one calculates the growth rate of a fuzz layer, dλ/dt, an inverse square root of time dependence is obtained. It should be realized that at very short times the growth rate of fuzz will be extremely rapid, so the question of whether fuzz should be expected would be better formulated in terms of how long might the fuzz be expected to grow before the incident plasma limits it growth by eroding the fuzz as fast as it grows. Since the porosity of the fuzzy tungsten surface, ρ(λ), is related to the thickness of the fuzz [15], the effective consumption rate of the tungsten bulk, G_{eff}, is ρ(λ)*dλ/dt.

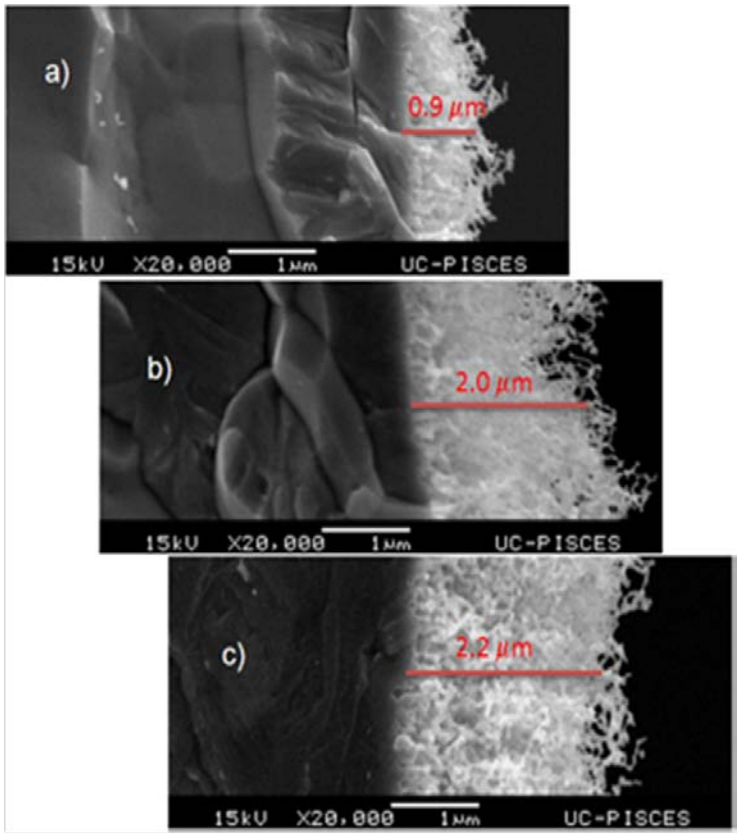

Figure 4 – Estimated tungsten fuzz surface layer thicknesses resulting from exposure to He^+ ions at a) 250 eV, b) 200 eV and c) 60 eV.

The net erosion rate in an eroding plasma will eventually balance the initially fast effective growth rate of the fuzz, G_{eff}, eventually resulting in the achievement of an equilibrium fuzz thickness. A series of experiments were, therefore, initiated in the PISCES-A facility [16] to verify the prediction of the equilibrium tungsten fuzz length in an eroding plasma environment. Three tungsten samples were exposed to helium plasma with an ion flux of 1×10^{23} $m^{-2}s^{-1}$ at a sample temperature of 1123 K for one hour. The target bias voltage was varied to provide incident ion energies from 60 eV up to 250 eV. The fuzz growth has previously been shown to be independent of ion energy above a threshold value

of about 35 eV [17]. The three resultant surface layers are shown in Figure 4 (a-c) corresponding to incident helium ion energies of 250, 200 and 60 eV, respectively. The SEM images of the surfaces have been offset with respect to each other to line up the interface between the bulk tungsten and the fuzz layer to accentuate the difference in the fuzz layer thicknesses. The estimated thickness of each layer is also shown in the figure.

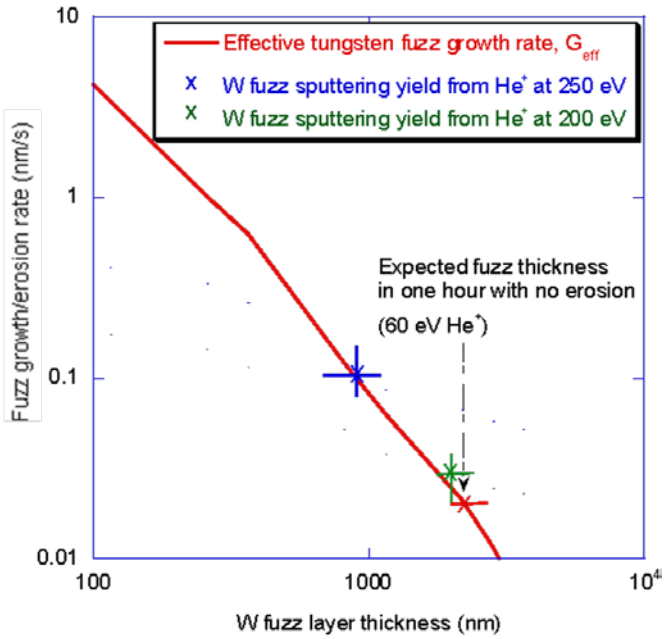

Figure 5 – Comparison of predicted and experimentally measured tungsten fuzz thicknesses resulting from one hour of He plasma exposure in PISCES-A with different incident ion energies.

The fuzz layer thickness, $\lambda(t)$, predicted for a tungsten surface at 1120 K is shown in Figure y. The measured fuzz thickness for the 60 eV incident ion energy exposure is also shown in the figure and is seen to agree with the prediction of the unencumbered fuzz growth rate. This is expected since 60 eV is below the sputtering threshold for helium on tungsten and, therefore, the net erosion rate, measured by weight loss, is zero. The other incident ion energy data shown in Figure 4 a&b show a thinner fuzz layer. Weight loss data obtained during the 250 eV plasma exposure resulted in an sputtering yield of approximately 3.4×10^{-4}. The resultant fuzz thickness of 0.9 micron, measured in Figure 4a, for the 250 eV exposure agrees with the expected equilibrium fuzz layer thickness for this net erosion rate. Similarly, the estimated net sputtering yield at 200 eV of 1.5×10^{-4} is also shown in Figure 5 and agrees with the predicted equilibrium layer thickness.

The experimentally validated model, balancing the consumption rate of the tungsten bulk during fuzz growth by the reduction of the fuzz layer thickness be the net erosion of the tungsten fuzz, can also be applied to conditions expected in ITER. The only location in the ITER divertor where tungsten fuzz is likely to grow is the outer divertor strike point [18]. Predictions for the equilibrium fuzz thickness at this location are underway.

4. Beryllium Mitigation of Carbon Chemical Erosion

Deuterium plasma containing a small amount of beryllium impurity ions has been observed to suppress the chemical erosion of an exposed graphite target [19, 20]. The reason for the mitigation has been identified as the formation of protective this beryllium carbide layers, which inhibit the formation of the hydrocarbon species. The problem encountered with this result is that ITER depends on the power radiated by carbon impurities in the divertor plasma to obtain a detached divertro solution. When the carbon chemical erosion is reduced the detached solution disappears and an additional radiating species, such as argon must be intentionally injected into the divertor to radiate the plasma power in the divertor. If this argon bombardment is included will the mitigation provided by the carbide layer survive the additional sputtering from the high-z impurity.

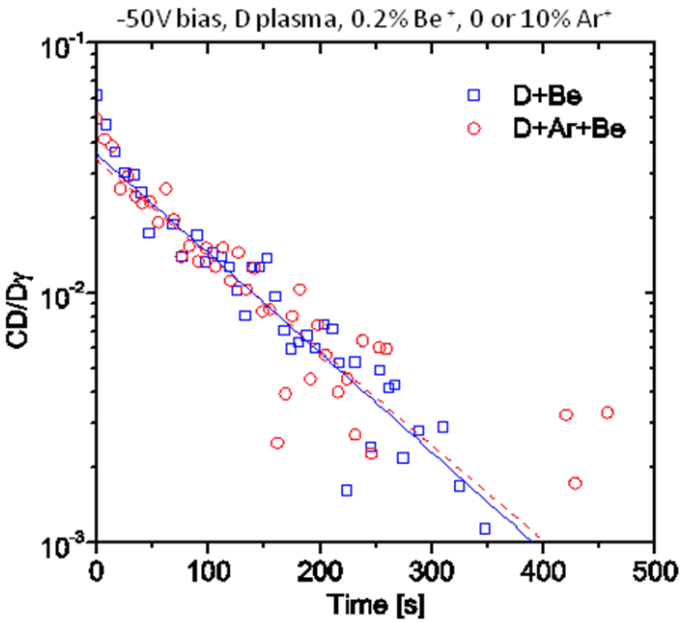

Figure 6 – Temporal behavior of chemical erosion (CD band) mitigation due to Be ions in D plasma, presence of Ar ions has no effect on suppression.

Experiments have been conducted incorporating the addition of controlled amounts of argon impurity ions in a beryllium-seeded deuterium plasma in PISCES-B. The results of the measurements are shown in Figure 6. The result indicates that the additional sputtering of beryllium carbide due to a small amount of argon, in this case 10%, is not significant enough to disrupt the formation of the carbide surface layer. In retrospect, this is understandable due to the predicted sputtering of either beryllium or carbon by argon being less than that expected deuterium [2]. This fact coupled to the concentration of argon being only 10% of that of the primary deuterium plasma component results in an insignificant affect of the addition of the radiating argon species.

Conclusions

Plasma-material interaction research in the PISCES Laboratory continues to be dedicated to issues impacting the success of the ITER mission. The lifetime of the Be first wall will likely be governed by physical sputtering and the magnitude of the yield in a plasma environment appears to be different from that predicted from binary collision approximations codes (like TRIM) and ion beam measurements. While conclusive proof is not yet available, it is hoped that sputtering yield measurements of tungsten surfaces that exhibit small nano-bubbles after He plasma exposure may provide the definitive answer to this question.

A predictive model has been developed for the equilibrium W fuzz thickness that should be expected to form on the ITER outer divertor strike point plate once W replace C for the D-T phase of operation.

Research also continues into mixed-material effects, where recently it has been shown that the addition of a radiating impurity into the ITER divertor plasma is not likely to counter act the chemical erosion mitigation due to beryllium bombardment of graphite surfaces.

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