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Journal of Nuclear Materials 241–243 (1997) 1117–1121

journal of nuclear materials

Investigation of beryllium self-sputtering

M.I. Guseva *, S.N. Korshunov, V.M. Gureev, Yu.V. Martinenko, V.E. Neumoin, V.G. Stoljarova

Institute of Nuclear Fusion, Russian Research Center "Kurchatov Institute", Moscow 123182, Russia

Abstract

The angular dependence of the beryllium self-sputtering yield (Y_S) has been investigated. The self-sputtering yield was measured as a function of the angle of ion incidence in the angle range of 0–85°. The measured data agree with those of the computer simulation at the angles of incidence: 0°, 30°, 45° and 85°. The maximum value of both the experimental and calculated beryllium self-sputtering yield occurs at the same angle of incidence −75°, but the experimental yield is reduced by a factor of 1.75 compared to the calculated value. The self-sputtering yield of beryllium is determined by the surface relief of microscopic scale created by ion bombardment.

Keywords: Plasma–wall interaction simulator; Physical erosion; Low Z wall material; Fusion technology

1. Introduction

Beryllium has been considered as a plasma-facing material in future fusion devices. In previous studies, the experimental data for the self-sputtering yields of beryllium were not given. Self-sputtering yield is necessary to predict the lifetime of ITER's first wall, because the process of redeposition essentially affects the erosion rate of the plasma facing components. The uncertainty of the redeposition coefficient consequently results in great errors in the lifetime prediction.

The first experimental results on self-sputtering of beryllium were presented at the PSI 11th in 1994 [1,2]. The energy and temperature dependencies of the beryllium self-sputtering yield were presented in 1995 [3,4].

In this paper we present the angular dependence of beryllium self-sputtering yield for well polished target surfaces.

2. Experimental procedure

Commercial hot-pressed, powder metallurgy produced beryllium of TShP-Russian and S-65B (from Brush Wellman) types were used in the experiments. Before irradiation, the beryllium sample surfaces were polished with a diamond paste and then electrolytic polishing (14 class surface) was used. A few beryllium samples were used without prior polishing (7 class surface).

The beryllium targets were irradiated in the chamber of a 180°-ion implanter. Be^+-ions were extracted from the plasma of the high temperature ion source. Beryllium was used as the charge material and beryllium oxide was used as the crucible in the ion source. The Be-ion flux was 4×10^{19} m^{-2} s^{-1} The irradiation area in our experiments was about 4.5×10^{-3} m^2. The targets were circles 1.7×10^{-2} m in diameter, and each was about 2×10^{-3} m thick. During irradiation, with 1 keV Be-ions, the temperature was 670 K. Pressure was about 10^6 Torr, and during bombardment it always rose to $(2–3) \times 10^5$ Torr.

It should be noted, that the large area of irradiation made it possible to perform simultaneous irradiation of seven samples, which were orientated at ion incidence

* Corresponding author. Tel.: +7-095 196 1711; fax: +7-095 196 1700.

PII S0022-3115(96)00683-6

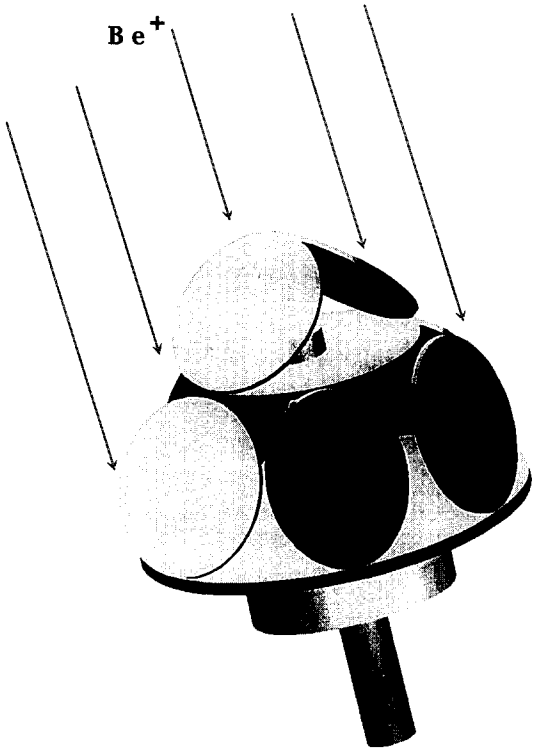

Fig. 1. Target arrangement for measuring the angular dependence of beryllium self-sputtering.

angles of: 30°, 45°, 60°, 70°, 75°, 80° and 85°, respectively. Seven targets were mounted on target holders having different diameters (Fig. 1). To compare the self-sputtering yields of the various beryllium types with different surface treatments, a target of TShP-type, and two targets of S-65B-type, with both polished and untreated surfaces, were simultaneously irradiated with Be^+-ions at an angle of incidence of 60°.

Both before and after irradiation the samples were examined by a JEOL scanning electron microscope. The chemical composition of the Be surface was measured by Rutherford back scattering (RBS) at the angle of 160°. The energy of the incident He^+-ions was 1,5 MeV.

3. Experimental results and discussion

The experimental self-sputtering yield of beryllium-TShP sample, as a function of the angle of ion incidence, for an ion energy of 1 keV, at the temperature of 670 K, is shown in Fig. 2. The calculated curve $Y_{self} = f(\alpha)$ and experimental data for beryllium self-sputtering from [2] are also shown. The self-sputtering yields, measured at angles of incidence: 0°, 30°, 45° and 85°, concur with those from the computer simulation [2,5]. The maximum values of both experimental and calculated sputtering yield take place at the same angle of incidence, $\alpha = 75°$. The calculated sputtering yield, however, is a factor of 1.75 higher than the experimental value. With increasing of the angle of incidence from 60° to 75°, the difference between the experimental and calculated self-sputtering yield values increases. The value of Y_{self} for the 3-65B-type beryllium sample, corresponds to the value for the TShP-type beryllium within the uncertainty of the yield measurement.

At the angles of incidence: 0°, 45° and 60°, our experimental data for polished targets agree with those measured by Roth et al. for untreated surfaces [2].

Our measurements show, that for polished and untreated surfaces of the S-65B-type beryllium irradiated with Be^+-ions at the angle of incidence $\alpha = 60°$, the values of Y_{self} are equal to 0.88 at/ion and 0.82 at/ion, respectively. Thus it follows, that the beryllium self-sputtering yield is practically the same for both untreated and polished surfaces. We can conclude, therefore, that the discrepancy between the calculated and experimental values of Y_{self} is not connected with a surface relief of macroscopic scale.

For an explanation of the discrepancy between the calculated and experimental values of the self-sputtering yield, the composition and microstructure of a beryllium surface irradiated by Be^+-ions, at different angles of incidence, were investigated.

Fig. 3 shows the RBS spectra of helium ions, scattered at an angle of 160°, upon beryllium both before and after irradiation by 1 keV Be^+-ions at incidence angles of 45° and of 70°. In the spectra of the unirradiated beryllium (Fig. 3a) and in that of irradiated at an angle of 70° (Fig. 3e) peaks of carbon and oxygen are present. The spectrum

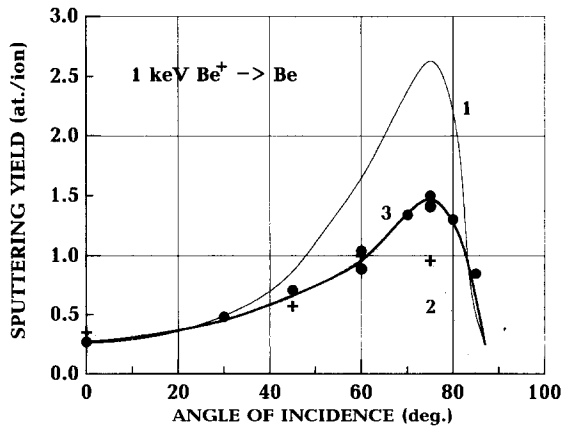

Fig. 2. Self-sputtering yield of beryllium versus the angle of 1 keV Be^+-ion incidence: curve 1 (————) TRIM.SP calculated curve from [2]; curve 2 (+ + +) experimental data obtained by Roth et al. [2]; curve 3 (· · ·) experimental data obtained for the TShP-type beryllium.

in Fig. 3b differs from the others two by the presence of an intense broad peak extending directly beyond the peak of oxygen and overlapping with the channel of carbon. As a result of beryllium sputtering by Be^+-ions, the carbon peak is reduced from 12 at% in the initial sample to 5.5 at% ($\alpha = 45°$) and 4 at% ($\alpha = 70°$) after bombardment. The irradiation by Be^+-ions causes an oxygen enrichment in surface and an increase the thickness of a layer containing oxygen atoms (Fig. 4). As shown in Fig. 4a, when the angle of incidence is 45°, the peak of oxygen on the surface is joined by a second peak on the oxygen profile, which includes up to ~ 25 at% of oxygen at the peak. The minimum in the oxygen depth distribution profile, formated in the process of irradiation, is probably connected with the radiation enhanced segregation of oxygen atoms to the surface. The production of a sublayer enriched with oxygen is due to the fact that the self-sputtering yield of beryllium is less than unity at this angle of incidence. This means that the amount of Be^+-ions incident upon the target is greater than the number of sputtered Be-atoms.

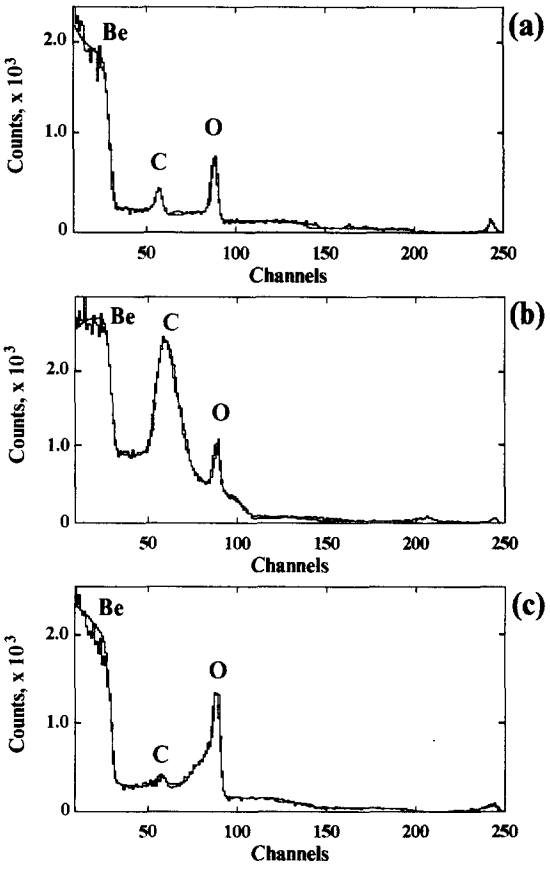

Fig. 3. RBS-spectra of the helium ions scattered at the angle of 160° on the untreated TShP-type beryllium (a) and after irradiation by 1 keV Be^+-ions at the angles of incidence 45° (b) and of 70° (c).

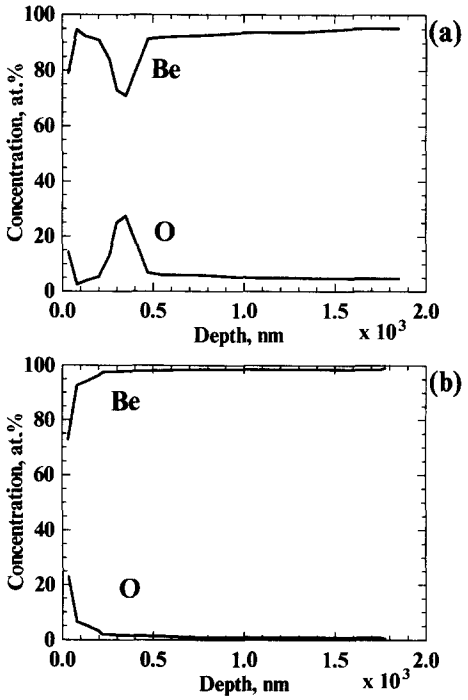

Fig. 4. Oxygen depth distribution in the TShP-type beryllium irradiated with Be^+-ions at the angles of incidence 45° (a) and of 70° (b).

Thus a beryllium-layer is formed on the target surface and this results in beryllium capture of oxygen atoms.

Fig. 4b illustrates the depth distribution of oxygen in the beryllium target irradiated by Be^+-ions at the angle of 70°, when the sputtering yield is equal to 1.35 at/ion and the build up of the sublayer with two oxygen peaks does not occur.

Thus the experimental values of the self-sputtering yield were obtained for a Be surface, which was slightly enriched with oxygen atoms. Hence, the self-sputtering, yield of beryllium is not influenced by a surface layer with a slight oxygen enrichment.

Fig. 5 shows several SEM micrographs of beryllium surfaces after irradiation at 670 K with 1 keV Be^+-ions at different fixed angles of incidence: 45°, 60°, 70°, 75°, 80° and 85°.

An ordered structure is formed on beryllium surface under tilt ion beam bombardment. This structure is determined by the angle of incidence, α. A wave-like, ripple type relief with a wavefront perpendicular to the ion beam plan is observed after bombardment at $\alpha = 60°$ (Fig. 5b). Such microrelief determines the real angles of ion incidence. The bombardment at $\alpha = 85°$ creates the wave-like relief with a wave-front parallel to the beam plan (Fig. 5f). In this time, the initial angle of incidence ($\alpha = 85°$) does not change under sputtering, and the experimental beryl-

lium self-sputtering yield concurs with the calculated value of Y_{self}.

The relief influence is at a maximum at the angle $\alpha = \alpha_m = 75°$, where a small slope variation results in a significant change in the sputtering yield and Fig. 5d shows that after the irradiation at $\alpha_m = 75°$, the entire surface is covered by hills elongated primarily in a direction perpendicular to the ion beam. About 30% of the surface is covered by the hills. The height of the hills (determined from the shadow of the SEM image) is ~ 1 μm. The slopes of hills are symmetric, indicating that surface diffusion and growth are the primary cause of the hills formation. The shadows from the hills during the ion bombardment at α_m covers the entire background surface. The real angles of incidence are thus determined by the shape of the hills. This explains the disagreement between the theoretical predictions of an ideal surface and the experiment results. Such a relief formation has already been observed earlier [6]. In accordance with theory [7], a relief should be formed under the ion bombardment with preferential planes for which the angles of incidence are $\alpha = 0$ and $\alpha = \alpha_m$. These are the planes with the minimum and maximum sputtering yields.

On a preliminary untreated beryllium surface, the scale relief after sputtering is remained (see Fig. 6b). The bombardment induced relief however, is superimposed on a preexisting relief and determines the angle of incidence. The initial relief therefore, plays a relatively small role, and the real angle of incidence is determined by the relief formed under sputtering.

Thus the angular dependence of the beryllium self-sputtering yield, is determined primarily by the microscopic surface relief created by ion bombardment.

The smaller scale relief vanishes partly and the rough-

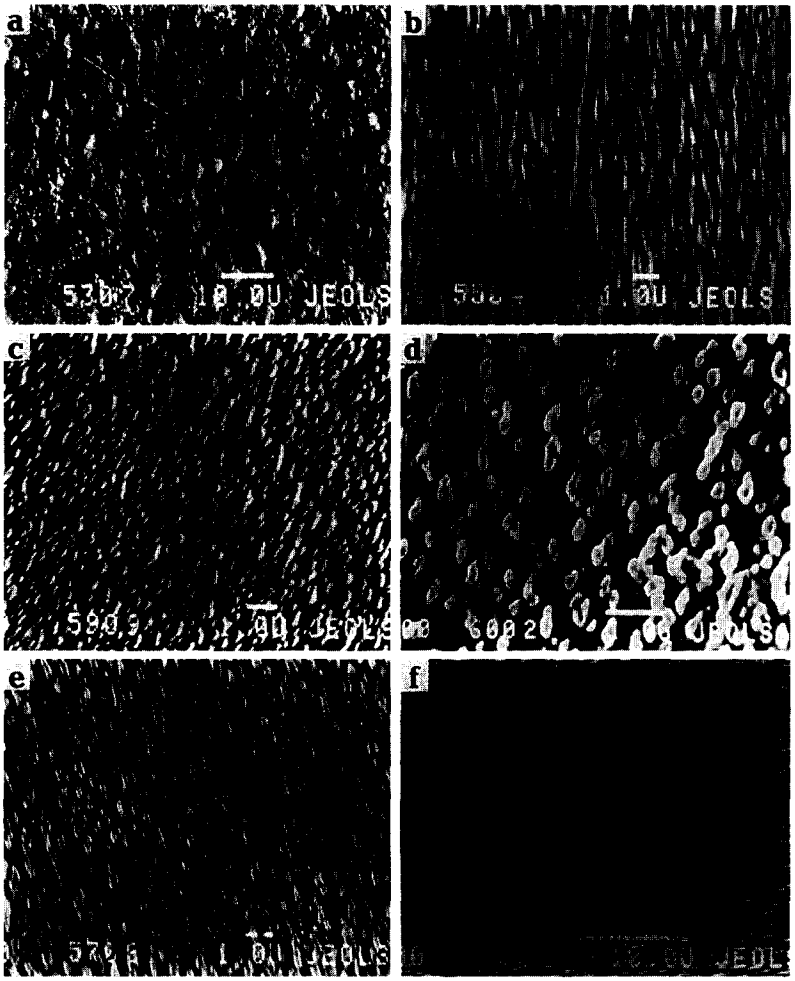

Fig. 5. Microstructure of the TShP-type beryllium surface after irradiation by 1 keV Be^+-ions at $T_{in} = 670$ K and at the angles of incidence: (a) $-45°$; (b) $-60°$; (c) $-70°$; (d) $-75°$; (e) $-80°$ and (f) $-85°$.

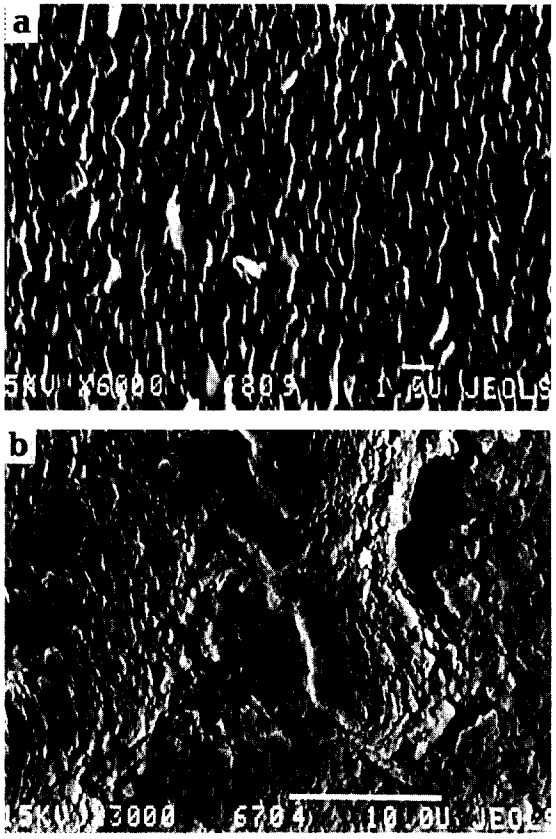

Fig. 6. Microstructure of polished (a) and untreated (b) S-65B-type beryllium surface after irradiation with 1 keV Be^+-ions at the angle of incidence 60°.

ness with scale lower then the size of the collision cascade does not influence the sputtering yield [6].

4. Conclusions

(1) At angles of incidence: 0, 30°, 45° and 85°, the experimental beryllium self-sputtering yield agrees with the corresponding computer simulation.

(2) The surface topography developed during sputtering at the initial angles of incidence between 60° and 80° changes the real angles of incidence and reduces the sputtering yields by a factor of about $1.6 \div 1.8$ compared to the calculated values.

(3) At the angle of incidence $\alpha = 85°$, when the wave-like relief with wave-front parallel to the beam plan is formed, the self-sputtering yield coincides with the calculated value.

(4) The difference between the self-sputtering yield values for polished and untreated beryllium surfaces is less than 10%. The self-sputtering yield of beryllium is determined by the surface relief of microscopic scale created by ion bombardment.

(5) As a result of beryllium sputtering by Be^+-ions at an energy of 1 keV, the concentration of carbon in a subsurface layer is reduced by a factor of about 3, but the concentration of oxygen increases.

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