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EXPERIMENTS AND COMPUTER SIMULATION RESULTS OF ANGULAR DISTRIBUTION OF SPUTTERED PARTICLES

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Abstract A polycrystalline Be target is submitted to the impact of 5 keV krypton ion beam. The sputtered Be particles at different angles of incidence are measured. The SRIM code and OKSANA simulation program were employed to obtain the sputtering yields of Be atoms. The angular distributions of sputtered Be particles and sputtering yields were compared each other and revealed that both of them were in a fairly good agreement. The surface morphology is observed by scanning electron micrography. The resulting differences between simulations and experiment are explained quantitatively.

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1. Introduction

When ion beam of some keV interacts with a solid target, sputtering takes place given rise to the ejection of different particles such as the reflection of projectiles, electron emission and the sputtering of atomic and molecular species [1–8]. In most experiments of ion-surface interaction, a theoretical model based on linear collision cascade process [9,10] is able to qualitatively interpret results of sputtering yields. In the collision cascade model, the target atoms will experience a series of collision sequences by the incident ion and the sputtered particles are referred to the last collisions close to the surface of the target. It implies that the number of sputtered particles is heavily influenced by the bulk and surface structure of the target. The investigations of the angular distribution of sputtered particles had become an effective means to obtain the information on the surface topography, target materials, target structure and even incident beam energies [11].

In this article, a measurement of the angular distributions of sputtered beryllium atoms is reported, they are results induced by a focused 5 keV Kr^+ beam impacting a Be target. This is a metal of technological interest for plasma devices, which has motivated studies of its sputtering by light projectiles (D, He, Be) from randomly rough surfaces [12–14]. The sputtered material is collected on a Mylar™ cylindrical foil surrounding the target. Angularly resolved data on the amount of sputtered Be are obtained by dissolving the deposits and analyzing it quantitatively by inductively coupled plasma optical emission spectroscopy (ICP-OES). Both code-OKSANA [15] and code-SRIM [16] models, which are based on the collision cascade processes and structure of the target, have been used to obtain the theoretical sputtering yields of Be at different angles of incidence. Experimental results are discussed and compared with data. Also, the role of roughness is discussed.

2. Experimental set-up

The apparatus serving in this study has been described previously [17–19]. It comprises a VG Model EX05 ion source capable of producing ion beams with intensities up to 6 μA and fluences up to 50 $\mu A/mm^2$ in the energy range 0.1–5 keV. High purity grade krypton is the only used source gas. No mass or charge selection is performed, so that the beam contains not only Kr^+ ions, but also a few percent of Kr^{2+} and traces of other ions. In order to reduce the Kr^{2+} contribution, the electron energy is limited to a value not too far above the double ionisation energy. Contributions from oxygen, nitrogen and water impurities are reduced by strong outgassing and pumping during a few weeks before experiments. The ion optics comprises two electrostatic lenses and two pairs of deflection plates. At the target, the beam has a minimum diameter of 0.1 mm and can be displaced by 5 mm in both vertical and horizontal directions. Differential pumping is achieved by two turbo-molecular pumps rated at 50 and 200 l/s, respectively. The target chamber is a vertical cylinder with a radius of 125 mm and a height of 143 mm, evacuated by the 200 l/s turbo-molecular pump. The background pressure is less than 0.5×10^{-8} Torr without the Kr^+ beam and about 10^{-8} Torr with the beam on.

The method used to obtain the angular distribution has been described recently [19,20]. In brief, a polyethylene terephtalate (Mylar^{TM}) is used as a collector (see Fig. 1). It is rolled upon a vertical cylinder of radius R whose axis passes through the impact spot. The deposit of sputtered Be is then analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES), numerical simulations complete the treatment. In the investigated study, the projectiles are krypton ions and the surface roughness has marked structures. A horizontal beam of 5 keV Kr^+ hits the surface of the sample under an angle of incidence. The experiments were made at four angles of incidence: α=0°, 30°, 70° and 80°.

The simulations are done with the well-tested computer codes; OKSANA [15] and SRIM [16]. For the first computer code (i.e. OKSANA), the polycrystalline target is modelled by a single crystal of random orientation. Its temperature is 300 K. The heat of sublimation of Be (3.38 eV) is used for the planar surface barrier. The interatomic potential is either the WHB (KrC) [21] or ZBL [22] potential. A flat surface is assumed, but some fraction of vacancies is allowed in the first monolayer. For the second calculation, we have used the SRIM 2003 version of the TRIM program for a large number of incident ions and let the computer count the number of beryllium atoms emitted in the solid angle corresponding to each probe. SRIM requires several ingredients. Some of them (energy and incidence angle of the ions) are experimental. The other ones are three phenomenological energy parameters, namely E_d, the barrier a Be atom must overcome to be displaced, E_b, the energy loss in this displacement and E_s the surface barrier.

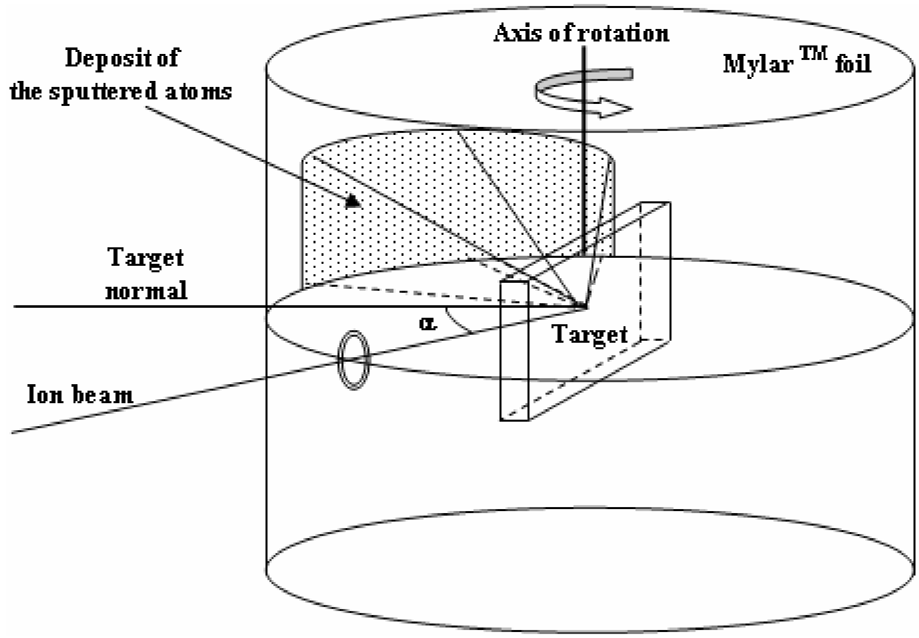

Fig. 1 Scheme of the collector geometry.

Many experiments have employed foils as collectors. Only two among the recent ones will be mentioned here. Tanemura et al. [23] investigated angular distributions of In and P atoms sputtered from an InP target by 3 keV argon and xenon ions. They used a cylindrical aluminum foil of 5 mm in diameter and estimated the deposit with an electron probe microanalyser. Chernysh et al. [24] bombarded NiTi alloys with 9 keV Ar^+ and determined the angular distributions using Rutherford backscattering analysis. The collector was an aluminum cylinder of 15 mm in radius. Fournier et al. [19] investigated the angular distribution of titanium target by 5 keV Kr^+ at near-normal incidence. Recently, silicon, germanium and indium phosphide targets are sputtered with a cesium ion beam. The energy of impact is changed from 2 keV to 10 keV and the incidence angle of bombardment is modified from 30° to 60° [25]. Emitted matter is collected on a semi-cylindrical copper foil. Subsequently, spatially resolved thicknesses and elemental compositions of the deposit are determined by means of SIMS depth profiles. Their experimental data show that the preferential direction as well as the spreading around this direction can be altered, with more or less efficiency, by the variation of the bombardment parameters. For the indium phosphide, the elemental composition of the deposit as a function of the emission angle was studied. It shows an increasing deviation from stoichiometry with increasing emission angle [25].

3. Results and discussion

In order to obtain an accurate data, a piece of clean and handle Mylar^{TM} was analyzed by ICP-OES. The results are given in Table 1. Table 1 shows the various element presents in the used foil. Specially, the quantity of the Be atoms in Mylar^{TM} is less than 0.0002 mg and, therefore, the measured Be atoms obtained by dissolving the piece of Mylar^{TM} comes directly from the beryllium target. In Table 2 are listed the values of different parameters during bombardment, such as times of bombardment, ion beam intensities, cross sections implied during sputtering and ion fluencies for each angle of incidence.

Table 1. List of the various elements present in Mylar^{TM} foil (analyze was effected in a piece of Mylar^{TM} of 25 mm² with ICP-OES method).

Element	Mylar^{TM} (clean) (weigh in mg)	Mylar^{TM} (handle) (weigh in mg)
Be	0.0002	0.0002
Cu	0.0005	0.0003
Al	0.2498	0.2585
Mg	0.0112	0.0100
Ni	0.0069	0.5858
Cr	0.0017	0.1373
Mo	0.0020	0.1403

Table 2. Values of different parameters during bombardment of Be.

	Time (hour)	Beam intensity (μA)	Cross section (mm²)	Fluence (10^{18} ions/mm²)
$\alpha = 0°$	59	2.10	0.95	2.90
$\alpha = 30°$	72	1.40	1.05	1.30
$\alpha = 70°$	92	0.69	1.25	0.38
$\alpha = 80°$	80	0.34	2.40	0.12

The angular distribution of the measured sputtered Be particles and the simulated sputtering yields of Be atoms/ion were shown together in Fig. 2. Fig. 2 indicates that the maximum of sputtering yield of Be particles in both experiment and simulations are at 70° and 74°, respectively. There exists a difference of 4° between peaks of the measured result and the simulated result. The difference may be arisen due to: (1) there is 2° or 4° inaccuracy in setting the normal incidence angle (0° in normal incidence angle), (2) the variation of the surface condition or the projectile's direction. SRIM simulation and OKSANA code obtained the same angular distribution of the sputtering yields of Be and they were shown in Fig. 2 too. Moreover, Fig. 3 shows that the slope of the experimental curve starts to increase very fast only from 34°and reaches maximum at 75° and the slope of simulated curve starts to increase from 30° and reach a maximum around 70°. This difference arose from the effect of the cleanness on the target surface. Because in simulation it is assumed the target surface without any impurity, but the target surface was only performed in situ Kr^+ bombardment cleaning in this measurement. It is believed that the sputtering yield depends strongly on the condition of surface under ion bombardment, specially the surface chemical state of the target [26,27]. In [28], experiments and simulated data with TRIM.SP code had shown that during ion bombardment of Be with 0.3 and 3 keV D^+ and He^+ ions, the maximum of sputtering yield for Be target was around 75°. The difference is referred to the following two reasons. (1) Sputtered target atoms are affected by the bulk structure of the target and collision processes, which confirmed by the SRIM simulated result. (2) Roughness of bombarded target; the surface morphology is observed by scanning electron micrography. Depending on the incidence angle, sputtering forms craters and rippled areas or deep grooves (see Fig. 3). It reveals craters of typical size 10 μm intertwined with rippled areas (see Fig. 3b). Fig.3d showes grooves parallel to the plane of incidence, with typical period and height of 10 μm, a typical length of 100 μm and sharp ends facing the incoming ion flux. Inside a groove smaller grooves appear at various scales. Ripples are known [29,30] to rise in the first stage of sputtering, then to give place to kinetic roughening with a growing roughness height.

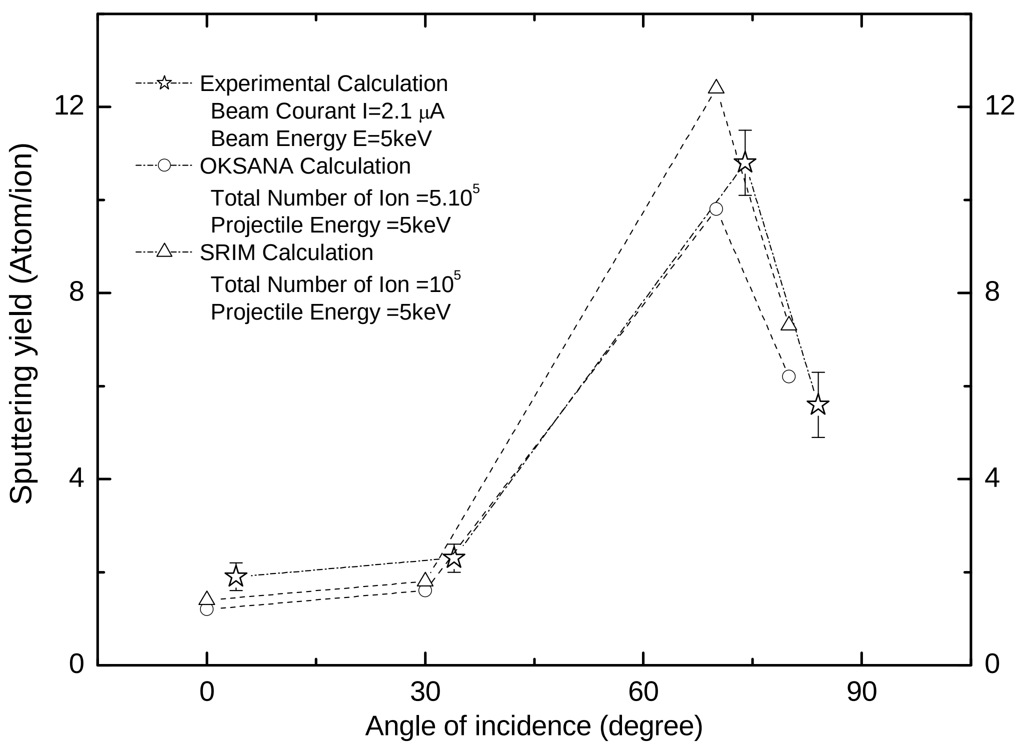

Fig. 2 Sputtering yield of Be atoms versus the angle of incidence during 5 keV Kr^+ bombardment of beryllium target.

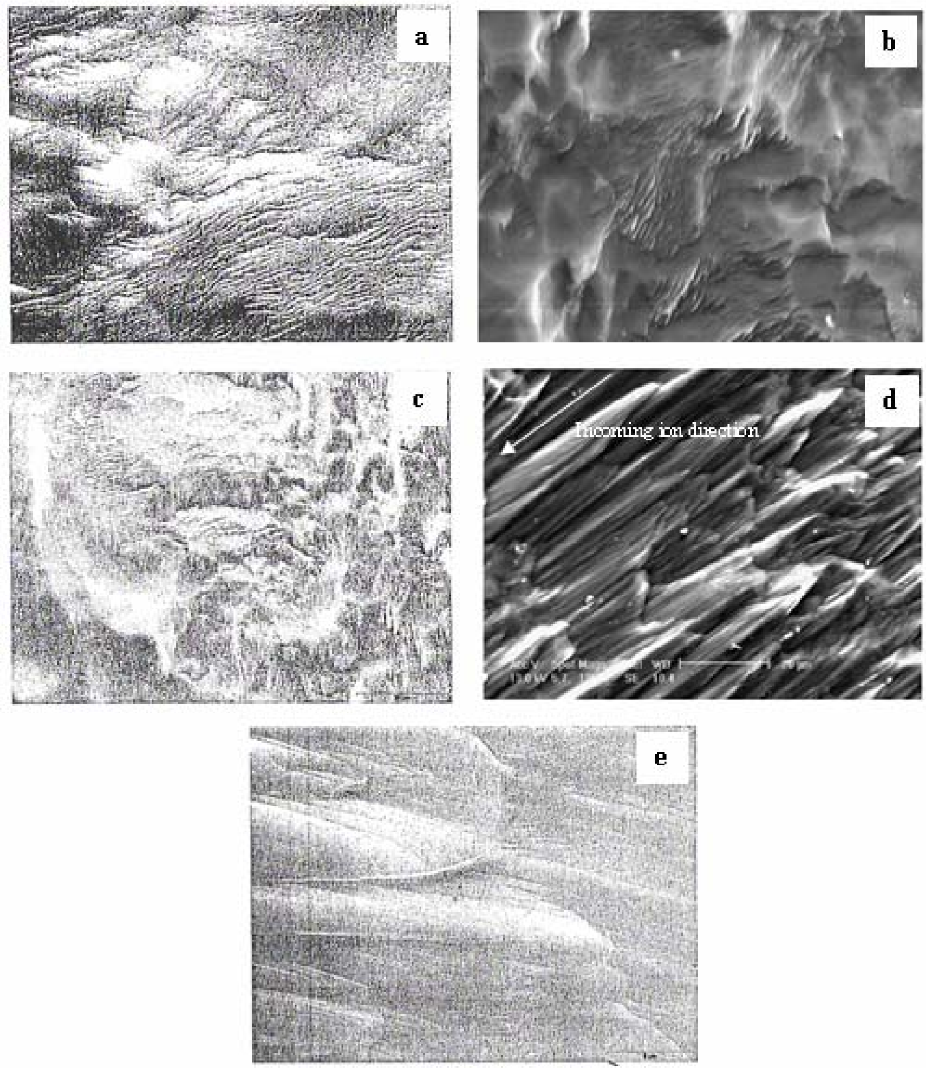

Fig. 3 A typical micrograph of the beryllium surface: a) before ion bombardment and after bombardment at b) 0°, c) 30°, d) 70° and e) 80°. Ions come from the right parallel to the grooves.

4. Conclusion

Angular distributions of sputtered Be particles were simultaneously and independently studied by experiments and computer simulation for the case of 5 keV krypton ion bombardment of beryllium at different angles of ion incidence. From experiment as well as simulation, we have shown that the angular distribution of sputtered target atoms is dependent on the structure and surface morphology of the target.

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