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EFFECT OF THE LOW ENERGY ION BOMBARDMENT ON THE OPTICAL PROPERTIES OF METALLIC MIRRORS

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Schemes of several methods of plasma diagnostics in ITER in a high degree must be based on utilization of the reflective optics. In this connection there appeared the problem of the first mirrors (FM), i.e., mirrors directed to plasma under investigation. The FMs will be subjected to bombardment by charge exchange atoms (CXA) and to deposition of contaminating materials. The CXA energy distribution will be very different for different mirrors, namely, it will be much higher with long tail in the case of mirrors for the core plasma than for mirrors in the divertor region. In this paper we present some results of investigations of effect of the long-term bombardment by deuterium ions with sub- or near-threshold energy on reflectance of metallic mirrors.

1. Introduction

The employment of the plasma facing mirror is requisite for the plasma diagnostic systems of the present large-scale fusion devices and future experimental fusion reactor. Even though these mirrors are located far away from the hot plasma, they are bombarded with charge exchange atoms (CXA) that lead to the surface modification due to erosion, redeposition and implantation of hydrogen isotopes. There are only few data relating the change of the optical properties of mirror materials due to CXA-bombardment in fusion devices under operation. In [1] the lifetime prediction for mirrors used in ITER has been estimated based on the observed surface modification and the reflectivity change of carbon, aluminum and nickel samples exposed to the JET plasma taking into account the energy distribution of the CXA-flux measured at ASDEX-U [2-5]. In that estimation for an incident flux with an energy distribution Ã(E) an effective sputtering yield Y_{eff} was defined by

$$Y_{eff}= (1/\Gamma_{tot})\int Y(E)\,\Gamma(E)\,dE, \qquad (1)$$

Here $\tilde{A}_{tot}$ is the total incident flux, $\Gamma_{tot} = \int \Gamma(E)dE$ and $Y(E)$ is the energy dependent sputtering yield taken from [6] where data for sputtering of mono-species were reported. It should be noted that with such an approach, a contribution of atoms with energy below the threshold energy is automatically neglected, while the lower energy component of CXA-flux is orders of magnitude higher with respect to the amount of high energy atoms [1]. In the case of the first mirrors for diagnosing the divertor plasma, the CXA flux will probably not contain high energy atoms. However, even with a projectile energy below the threshold for sputtering, some kinds of defects can be produced in the near-surface layer of mirrors. For example, the cluster formation in Mo was demonstrated under bombardment by hydrogen atoms with energy below the sputtering threshold [7]. As another example of importance of the low energy projectiles, there is the experimental evidence that the presence of only 0.1% oxygen atoms in the deuterium flux results in reducing the effective threshold energy for W from 341 eV [6] down to 44.5 eV [8] or 20-150 eV [9]. The objective of present study is to simulate the behavior of the first mirrors for the divertor plasma (DFM) and to evaluate the optical degradation of the mirror caused by low energy deuterium bombardment, which allows to complement the early papers [10-13] on the influence of fusion reactor conditions on optical properties of plasma-viewing mirrors.

2. Experimental

The experiments were carried out with the super low energy particle irradiation system (SLEIS) [14] where a high density ion beam at low energies can be formed. The species of charged particles with acceleration voltage of 200V were analyzed by means of a magnetic mass analyzer). Under a certain gas pressure and arc power, ~83.5% of the total charged particles were extracted as D_3^+ ions and ~14% as D^+ ions. Also ~2.5% of impurity ions, mostly oxygen, have been detected. This means that ~94%, ~5% and ~1% in the total flux were deuterons with energy 67eV and 200eV, and impurity ions, respectively. The fluence of each incident species is calculated from measured ion beam current and known composition of the ion beam. A test sample was placed about 10 cm downstream from the ion source. The temperature of the sample was measured by thermocouples during irradiation (< 80°C for all the irradiated targets). Mirrors of Mo (22 mm in diameter, 3 mm thickness), SS No1 (22 mm in diameter, 3 mm thickness), and SS No2 (22×22×4 mm^3) were prepared by mechanical polishing, and a diamond-turned Cu mirror (22×22×4 mm^3) was manufactured of an oxygen-free material. The reflectance R(λ), for the wavelengths λ = 190-2500 nm and the target weight change Δm were measured, reproducibility, using a standard monochromator with reproducibility of ~1% and the Mettler AE240 microbalance with an absolute accuracy 0.01 mg, after step by step exposures of mirrors to the ion beam. In the case of SS mirrors all the surface area was irradiated whereas a Mo diaphragm (0.5 mm thickness) with a 8 mm hole in diameter was placed at 1 mm above the Mo and Cu mirrors, that allows to compare a reflectivity of irradiated and unirradiated areas of the same mirror after every exposure.

3. Results and discussion

The effective sputtering yields determined by the mass loss method for deuterium ions bombardment of Mo, Cu and SS samples are compared in Fig.1 and Table 1 with those calculated using data from [6]. Effects of impurity ions were neglected in the calculation.

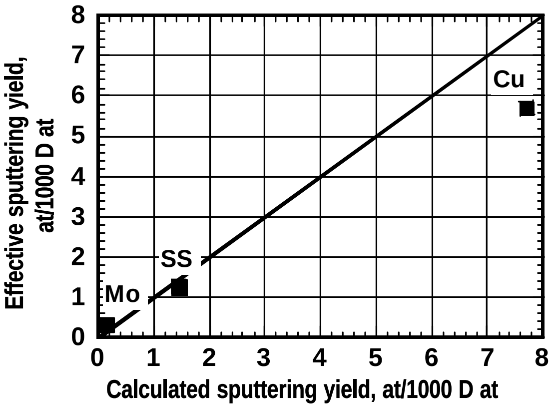

Fig.1. Comparison of calculated and measured effective sputtering yields in atoms per one thousand of projectiles (D atoms). The sputtering data from ref. [6] were used for the calculations.

Good agreement between experimentally obtained and calculated data indicates that the physical sputtering of mirror materials due to deuterium ions dominates the erosion process. Since the energy of 94% of total incident deuterium ions is below the threshold energy for Mo sputtering, the estimated thickness of the sputtered layer is the lowest for the Mo mirror (4.1×10^{-8} m) and increases up to 0.2×10^{-6} m for the Cu mirror. It is considered that the decrease of the reflectivity of eroded mirrors is due to development of surface roughness during sputtering or/and change of chemical composition of the near-surface region, e.g., by deposition of a thin layer of contaminants, i.e., materials of cathode, W, or accelerating grids, Mo.

As was shown in [1], the mean surface roughness of an Al layer on the carbon substrate increased approximately linearly with increasing thickness of sputtered layer. The maximum thickness of sputtered layer reached ~400nm and the corresponding CXA fluence was estimated to be $\sim2.5\cdot10^{24}$ at/m^2, i.e., several times smaller than that typical for the present experiments. If one assumes the proportionality of surface roughness to the thickness of sputtered layer, like in [1], then the mean roughness of the Mo mirror would be of the order 40 nm, as follows from Table 1. The surface microrelief of such size, principally, could be responsible for the small decrease of Mo mirror reflectance that was observed. However, in the case of SS1 mirror a significant improvement of reflectance was found after layer of about factor two thicker was sputtered, (Table 1 and Fig.2). The mirror SS2 behaved very similar to SS1 being bombarded at incident angle 45°. Therefore, the microrelief developing on the mirror surface cannot play a significant role in our experiments with low energy projectiles.

The improvement of specular reflectance of stainless steel mirrors due to long-term bombardment with low energy deuterium ions is not fully understood yet. However the role of deposit of cathode (W) or grids' (Mo) materials of the ion source have to be excluded as the reflectance of these metals in visible and near-visible regions, where the highest increment of SS mirror reflectance was observed, is lower than reflectance of SS mirrors tested (Fig.2). Thus, the improvement of reflectance should be prescribed to

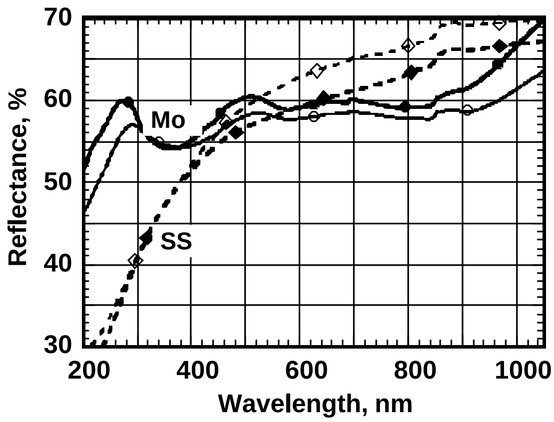

Fig.2. Reflectance of Mo (solid lines) and SS (dashed lines) mirrors. Closed symbols – before ion bombardment, open symbols – after ion fluences of 9.1×10^{20} D/cm^2 for Mo and 7.4×10^{20} D/cm^2 for SS mirrors, correspondingly.

modification of the surface of SS mirrors. Between possible reasons the following ones are most probable: (i) cleaning from the uncontrolled contaminants, including an oxide film, (ii) change of the surface composition, i.e., faster sputtering of that SS component that has the lowest reflectivity, and (iii) additional polishing of the surface by low energy deuterium ions.

It was demonstrated for mirrors of different polycrystalline materials that sputtering of the same thickness of a near-surface layer resulted in different degradation rate of the optical properties [12]. The mirrors fabricated of the same stainless steel as in present experiments (i.e., the 316 type) demonstrated a quite high survivability in maintaining the optical properties in comparison to mirrors of several other metals (Be, Al, Cu). And what is important, it was shown at least, for two metals, Cu and SS, that the rate of reflectance degradation strongly decreased with decreasing the ion energy [10,13]. As distinct from our experiments, however, in works [10-13] the accelerating voltage was varied in the range 0.35-1.5 kV, i.e. the mean energy of projectiles exceeded the sputtering threshold even for such metals as Mo and W. That is why the results of simulation experiments [10-13] cannot be used directly for shedding light on the better understanding of results obtained in the present paper.

With small sputtering rate which will be characteristic for DFM operation, the appearance of deposit on the DFM surface probably cannot be avoided, as it follows from results of some presentations from ASDEX, D-IIID, and JET at the last PSI conference (May 2000, Rosenheim, Germany). In particular, it was found that in the divertor region the rate of growth of the carbon deposit could be as high as 3 nm/s. Therefore, the effects of contamination of DFM surfaces have to be investigated in simulation experiments in addition to effects of sputtering by low energy hydrogen (deuterium) atoms.

4. Conclusion

It is thus concluded from the optical measurement and theoretical evaluation that low-energy CXA bombardment of the first diagnostic mirrors for a divertor plasma in a fusion reactor will not lead to serious degradation of DFM optical properties. Much stronger effects on the DFM reflectance will probably occur due to deposition of contaminants such as carbon if collector plates are fabricated of the carbon-carbon composite, as is planned now. Therefore the special simulation experiments at the nowaday tokamaks with divertor (JET, JT-60U, TEXTOR, D-IIID) have to be provided.

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Table 1. Material properties and calculated and measured sputtering data in the present experiment. The mirrors SS1 and SS2 were irradiated at incident angles of 0^o and 45^o respectively.

	M_2 g/mol	ρ g/cm^3	E_{th} [6] eV	Y_{eff} [6] 10^{-3} at/D	Y_{eff} 10^{-3} at/D	Φ 10^{24} D/m^2	Δm 10^{-3}g	h μm
Mo	96	10.2	77	0.15	0.24	4.15	0.03	-
						9.1	-0.02	0.041
						12.7	-0.03	0.058
SS1	55.1	7.45	39	1.47	1.28	2.57	-0.11	0.039
						7.42	-0.23	0.081
						11.5	-0.51	0.180
SS2	55.1	7.44	39	-	3.15	2.6	-0.37	0.100
						7.46	-1.04	0.290
						11.8	-1.63	0.450
Cu	64	8.93	32	7.67	6.65	2.08	-0.05	0.110
						3.33	-0.09	0.200
						7.47	-0.26	0.580