Material choice for first ITER mirrors under erosion conditions

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Abstract

The behaviour of different candidate materials for ITER mirrors under erosion conditions is investigated in TEXTOR tokamak. Results of experiments are presented along with an assessment of applicability of the studied mirror concepts for ITER diagnostics. It is shown that all studied mirror concepts can be applied in ITER under mild erosion conditions (as in equatorial ports) when protective techniques are applied. Molybdenum single crystal mirrors demonstrated the best performance under stronger erosion conditions, corresponding to those expected in the upper diagnostic ports of ITER with gas fueling.

Introduction

ITER will require accurate and reliable measurements of a wide range of plasma parameters necessary for the machine protection, basic plasma control and research program [1]. For this reason ITER will be equipped with a large set of diagnostics. All optical diagnostics will use metallic mirrors as first plasma-viewing elements which will suffer from such adverse effects as neutron and gamma irradiation, nuclear heating and high particle fluxes. The lifetime of mirrors represents a critical issue [2]. Erosion of the mirror surface and deposition of impurities have the strongest impact on the mirror performance. Surface erosion by charge-exchange atoms with typical flux ranging from $(1\div4)\times10^{19}$ to 1.7×10^{21} atoms/m^{2}s [3] with energies up to several keV can significantly change optical properties of mirrors and lead to a shutdown of the respective diagnostics. The reflectivity of mirrors under erosion conditions strongly depends on mirror material [4]. Therefore a proper material and manufacturing technique have to be chosen. To investigate the behaviour of different candidate materials for ITER mirrors under erosion conditions, experiments were performed in TEXTOR tokamak.

Mirror manufacturing and characterization

Rhodium (Rh) and molybdenum (Mo) coated mirrors on different substrate materials were studied along with single crystal (SC) molybdenum mirrors. Advantages of SC Mo mirrors in comparison with polycrystalline Mo mirrors were investigated earlier [5]. While SC mirrors are limited in size, coated mirrors represent an alternative option. Coated mirrors for this study were produced at the University of Basel [6]. Optical and surface characterization of mirrors was performed in Basel and in the MirrorLab at Forschungszentrum Jülich (FZJ) [7]. For depth profiling and elemental composition measurements, secondary ion mass spectrometer (SIMS) at FZJ was used. Scans of SIMS craters by DEKTAK stylus profiler were performed to measure the layer thickness. The total and diffuse reflectivity of mirrors was measured with double-beam spectrophotometer Lambda 950 at the MirrorLab.

Erosion experiments in the TEXTOR tokamak

Two experiments were performed with a test limiter with 3 mirrors exposed in the scrape-off-layer (SOL) plasma under ITER-relevant erosion-dominated conditions. Mirrors were installed at 20 degrees to the toroidal field direction (Fig.1). Edge plasma parameters were monitored with the supersonic helium beam diagnostics. First experiment was performed under mild erosion conditions: the total particle fluence to the center of each mirror was about 5.9×10^{24} ions/m^2. Plasma parameters near the mirror surface averaged over all discharges were $n_e = 2.6\times10^{18}$ m^{-3} and $T_e = 36$ eV. The surface temperature of mirrors during discharges did not exceed 570°C. For this exposure mirrors with Rh and Mo coatings on Mo substrates made by evaporation technique were used together with a SC Mo mirror. Surface oxidation during coating growth and flaking of some regions of coatings were observed before the exposure.

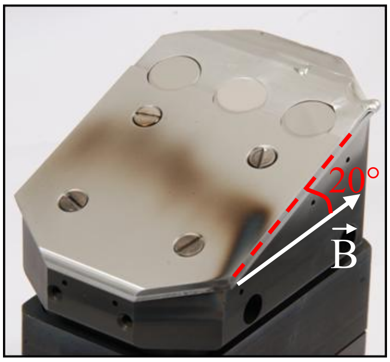

Figure 1. Test limiter with mirrors after exposure

The second experiment was performed to explore the limit of applicability of mirrors under higher erosion fluences. During this experiment, SC Mo mirror was exposed together with Rh-coated tungsten (W) and Mo-coated molybdenum mirror samples. Mo coating was made by the magnetron sputtering technique. Rh coating on W was considered to be the most robust concept of Rh-coated mirrors for this experiment at high temperatures of a mirror. The total particle fluence to the center of each mirror was about 1.4×10^{25} ions/m^2 – a factor of 2.3 higher than in the previous experiment. An averaged plasma density near the mirrors was 3.6×10^{18} m^{-3} at the electron temperature of 30.6 eV. The surface temperature of mirrors during the exposure was in the range 670°C-1300°C.

Experimental results

In the first experiment, all mirrors demonstrated acceptable performance: overall changes in the total reflectivity after exposure did not exceed 4% in the wavelength range 250-2500 nm.

Rh coating made on W substrate and selected for the second experiment had several flaked areas on its surface even before exposure in TEXTOR. The density of flaked regions with sizes larger than 10 μm was about 120 per 100 mm^2 (Fig. 2a). The total area of flakes did not exceed 1% of the surface. After the exposure the mirror was non-homogeneously sputtered (340 nm in the center of the mirror), which caused an increase of the surface roughness (Fig. 2b) and led to a growth of the diffuse reflectivity (Fig. 3a) with corresponding drop of intensity of specular reflected light (by up to 25% in the ultraviolet (UV) wavelength range (Fig. 3b). The Mo-coated mirror demonstrated good performance: the surface of mirror remained smooth except for few small damaged regions after erosion of 120 nm. The diffuse reflectivity increased up to 2.5% in UV being around 1% in visible (VIS) and infrared (IR) ranges. The specular reflectivity decreased by 4% in the IR range and by 12% in the UV (Fig. 4a).

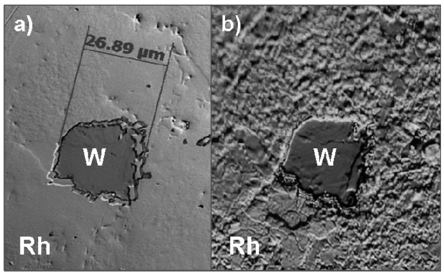

Figure 2. Rh-coated tungsten mirror with a flaked region before (a) and after (b) exposure (optical microscope)

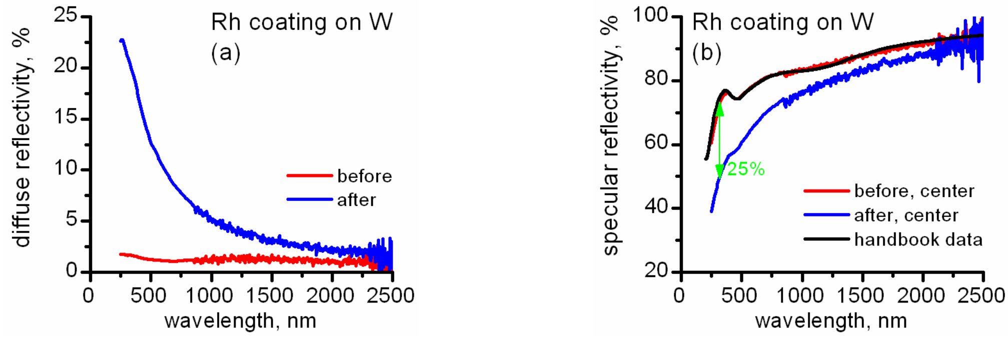

Figure 3. The diffuse (a) and specular (b) reflectivity of the Rh-coated mirror before and after exposure (handbook data according to [8])

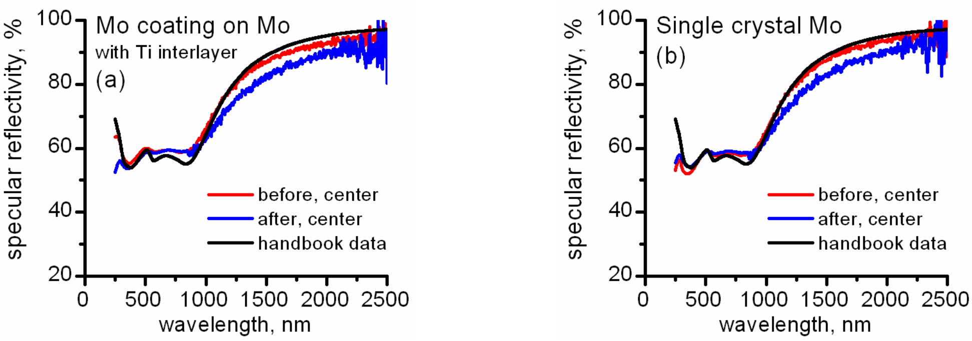

Figure 4. The specular reflectivity of the Mo-coated mirror (a) and SC Mo mirror (b) before and after exposure (handbook data according to [8])

The roughness R_a of the SC Mo mirror surface remained at the level of ~2 nm. This low value was supported by the low diffuse reflectivity ~1%. Such a homogeneous sputtering of SC Mo mirror is explained by the same crystal orientation over the entire surface and is the advantage of single crystals. The specular reflectivity decreased by 4% in the IR (Fig. 4b) similar with all studied Mo mirrors regardless of the amount of eroded material. On a contrast, the typical roughness of Rh-coated mirror was about 20 nm.

Discussion and outlook

All mirrors demonstrated acceptable performance under mild erosion conditions. The total accumulated fluence in the first experiment can be compared to more than 350 ITER-discharges for mirrors located in equatorial ports and to approximately 10 discharges for mirrors installed in the upper ports with gas fuelling. Estimates are given for mirrors in diagnostic ducts located close to the first wall position [3]. In the second experiment the accumulated fluence corresponded to about 850 ITER discharges for mirrors in equatorial ports or 25 discharges for mirrors in the upper port plug equipped with a gas fuelling system. Molybdenum mirrors preserved their optical properties, for Mo-coated mirror slight degradation of reflectivity in the UV range was noticed. Sputtering and particle implantation led to a drastic drop of the reflectivity of the Rh-coated mirror reaching ~25% in UV range.

The realistic scenario, however, suggests first mirror installation in port plugs of ITER together with application of protective techniques such as shutters, which will be open only during measurements and can decrease the particle fluence to the mirror surface by orders of magnitude [9, 10]. Under such assumptions all tested mirror concepts can be applied in ITER. SC Mo mirrors are preferable for use under erosion-dominated conditions in ITER. Efforts to be made to increase the mirror size, since largest available SC Mo mirrors measure ~10 cm in diameter [11]. Coated mirrors represent the promising alternative for ITER diagnostics and the technology of their manufacturing have to be further developed at the industrial level.

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