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L. Marot, G. Arnoux, E. Meyer
and JET EFDA contributors

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L. Marot[1], G. Arnoux[2], E. Meyer[1]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Department of Physics, University of Basel, Association EURATOM-Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne (EPFL), CRPP, CH-1015 Lausanne, Switzerland
[2]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
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ABSTRACT
The aim of this work was to provide a comprehensive insight concerning coated films to be used for ITER first mirrors. The influence of the mirror crystallite size has been addressed as well as the coating techniques to provide nanocrystalline films. Review of coated mirror tests in laboratories or in tokamaks has been presented. A wide angle camera system has been installed in JET-ILW which is composed of a mirror box with 3 stainless steel mirrors coated with Rh viewing the torus through a conically shaped aperture. The system delivered the required image quality for plasma monitoring and wall protection, a new system was already installed in JET.

1. INTRODUCTION
In current fusion experiments the plasma is viewed directly, which will not be possible in future tokamaks (e.g. ITER) due to the high level of neutron radiation expected. Therefore, metallic mirrors are foreseen to play a key role in guiding the plasma light towards the optical diagnostics. As these so-called first mirrors (FM) directly view the plasma, they will be subjected to a harsh environment of particle fluxes due to charge exchange neutrals and neutrons, as well as UV, x-ray and gamma radiation [1].

Molybdenum (Mo) and rhodium (Rh) are two important candidate materials for FM. Molybdenum, due to its low sputtering yield, is more advantageous under erosion conditions [2]. Rhodium, on the other hand, provides a better reflectivity (between 70-80%) in the visible range [3]. Rh has also low chemical reactivity, preventing oxide and carbide formation [4,5]. In the case of polycrystalline mirrors composed of many grains with random orientation of faces, the sputtering yield can vary strongly over the material surface depending on the crystallographic plane of each individual grain and its orientation with respect to the incoming particle flux [6,7,8]. It is also important to keep the surface relief pattern i.e. the roughness of a polycrystalline mirror small compared to the wavelength of reflected light in order to minimize the effect of diffuse reflection in the measurements. Generally, this indicates that the mirrors must have small grain sizes and preferably similar crystal orientation to be homogeneously sputtered. These requirements can be fulfilled, for instance, by using a single crystal or by coating the surface with nanometer-size crystallites. Moreover, test of amorphous metal alloy mirrors were carried under ion bombardments, even though these mirrors have no crystalline structure the initial optical quality under long-term sputtering were not maintained [9, 10]. Due to technological difficulties in producing large size Mo single crystals, coating might be considered as an alternative.

1.1 REALISATION OF COATED MIRRORS
The preparation of such coated mirrors were reported by magnetron sputtering [3,11], evaporation [12] and pulse laser deposition [13-15] technique for Rh, Mo and W coatings. Silver and aluminum coatings with a thick protective dielectric layer with low rate of sputtering and chemical modification (Al_2O_3, ZrO_2) were also investigated [16,17]. Several proven techniques offer the possibility

to produce coated mirrors at least on laboratory size with nanometric crystallites and a dense structure. Industrial-type ITER FM mock-ups prepared by magnetron sputtering have already been manufactured [18].

1.2 LABORATORY TESTS

Mo, Rh coated mirrors were tested in laboratory in terms of mechanical properties i.e. adhesion to the substrate [14, 19], chemical reactivity towards typical tokamak impurities or elements eroded from the first wall [4, 20, 21]. It appeared that the adhesion increased with increasing substrate hardness and increasing deposition temperature. Ion bombardment and especially deuterium plasma exposures were performed for Mo and Rh mirrors [22–24]. For example, Mo coatings will remain functional in most of the cases in ITER, however higher energy of impinging charge exchange neutrals or lower surface temperature of the coatings can lead to gradual or sudden failure of the coatings [25]. Rh mirrors exposed to D_2 plasma show a drop in the reflectivity which can be associated with a formation of a subsurface rhodium deuteride (RhD_x, $x \leq 2$), which has optical constants different to those of Rh [21].

1.3 TOKAMAK EXPOSURES

Tests were carried out in TEXTOR [3] [26], in DIII-D [27], JET-C [28] and JET-ILW [29] and showed no critical failure of the coated mirrors like delamination or strong degradation of the optical properties. Mostly, Rh and Mo coated mirrors were investigated and JET has also had these mirrors during the 2013–2014 campaign. Despite these results no further experiments from the JET First Mirror Test was started in 2013 and 2014. However, optical system using coated mirrors for plasma monitoring and wall protection are used nowadays in JET-ILW; this last point is developed in the present paper including characterizations of these mirrors. Moreover, results of coated FM mock ups exposure in a linear plasma device (Magnum–PSI) are also reported here.

2. WIDE ANGLE VIEWING SYSTEM AT JET-ILW

After the previous examples of tokamak tests of coated mirrors it was important to demonstrate a complete optical diagnostic system operating in a metallic tokamak and especially at JET. During the JET-ILW shutdown a wide angle camera system has been installed [33]. The 2011–2012 campaigns exposure lasted 18.9h in total with approximately 13.1h of X-point operation and after that the mirrors were exposed also to 19h in total with 12h of X-point operation for the 2013–2014 campaigns. This system is composed of a mirror box with 3 stainless steel mirrors coated with Rh viewing the torus through a conically shaped aperture (Fig.2 in reference 33). Rh film (175nm thick) was evaporated on polished flat stainless steel mirrors (60×40mm) or on stainless steel parabolic mirrors (64×45mm) covered by a Ni layer (100mm) for polishing reason. The characterisations of the films were carried out on witness samples (25mm in diameter). The diffuse reflectivity was below 3% in the range 250–2500nm and the specular reflectivity was similar to the reference one

[3]. Reflectivity measurements were also performed at incidence angles of 40, 50, 60, 70 and 80° for s and p polarized lights with a spectral ellipsometer SENTECH S 850, and are plotted in Fig.1. SEM observations show small crystallites (few tens of nm) typical for evaporated Rh films [12]. Chemical analyses of the surface by XPS after 6 hours annealing at 600°C in air revealed a Rh metallic surface covered with adsorbed molecules (oxygen, carbon) and a thin rhodium oxide layer (Figure 2) as described in our previous paper [3] but nothing else. No degradation of the optical reflectivity was observed after this annealing in contrary to Mo mirrors which oxidised in air [29] showing a reflectivity decrease of more than 10% in the visible range between the mirror production and JET installation. The system delivered the required image quality for JET plasma monitoring and wall protection.

For the 2013–2014 campaigns a new system was installed in JET i.e. the KL14 system (Figure 3) using the lower left limiter guide tube. An identical mirror box as previously described is used and a new flat stainless steel mirror (165×80mm) coated also with Rh was added to transport the beam (Figure 4). This system was also given the same measurements quality. For both systems optical characterisations of these mirrors are foreseen.

CONCLUSIONS

Metallic coated mirrors were extensively studied for ITER's FM purpose. Tokamak tests showed no critical failure of the coated mirrors like delamination or strong degradation of the optical properties. Moreover, mock ups (109mm in diameter) including water cooling were realised [18] and recently exposed to H_2/Ar (10%) plasma in the Magnum-PSI linear plasma device [34]. Two complete diagnostics using Rh coated mirrors i.e. wide angle viewing systems were installed in JET-ILW, they delivered the required image quality for plasma monitoring and wall protection.

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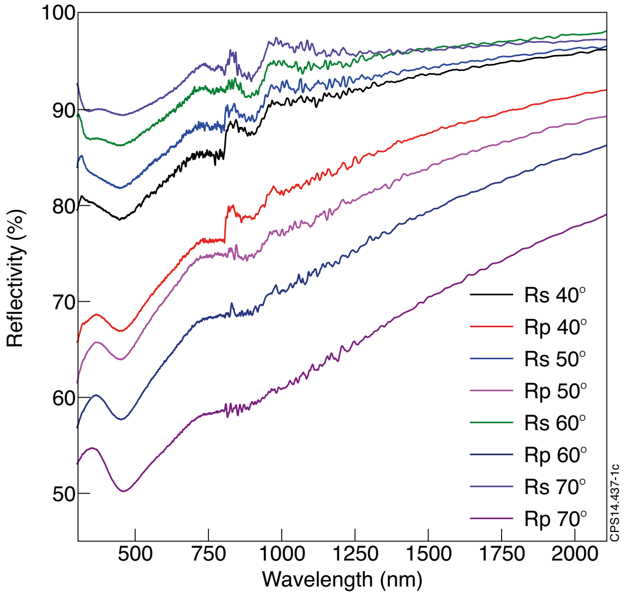

Figure 1: Rhodium reflectivities at 40°, 50°, 60°and 70° for s and p polarization after 6 hours annealing at 600°C in air.

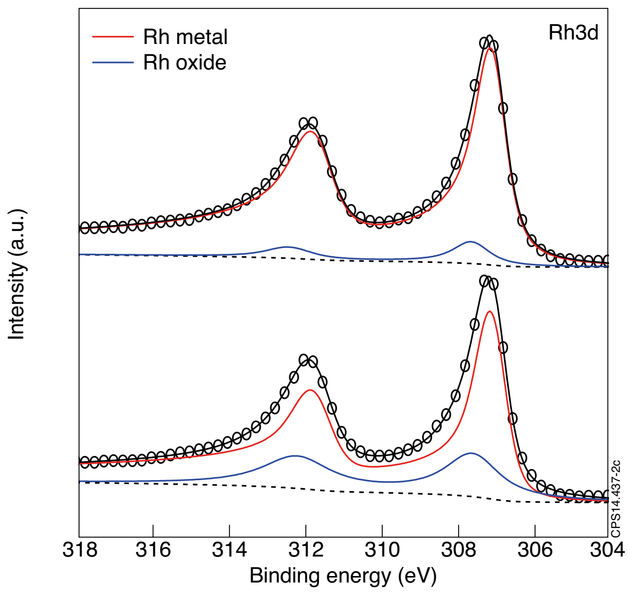

Figure 2: Rh3d core level spectra measured by XPS of Rh mirrors after 6 hours annealing at 600°C in air, a) with a Ni intermediate layer and b) without. In all cases, the spectra have been normalized for comparison, open circles are measured data and full lines are mathematical fit. The red and blue lines correspond to the Rh metal and Rh oxide, respectively, the black one to the fit sum and dashed lines is the background of inelastically scattered electrons.

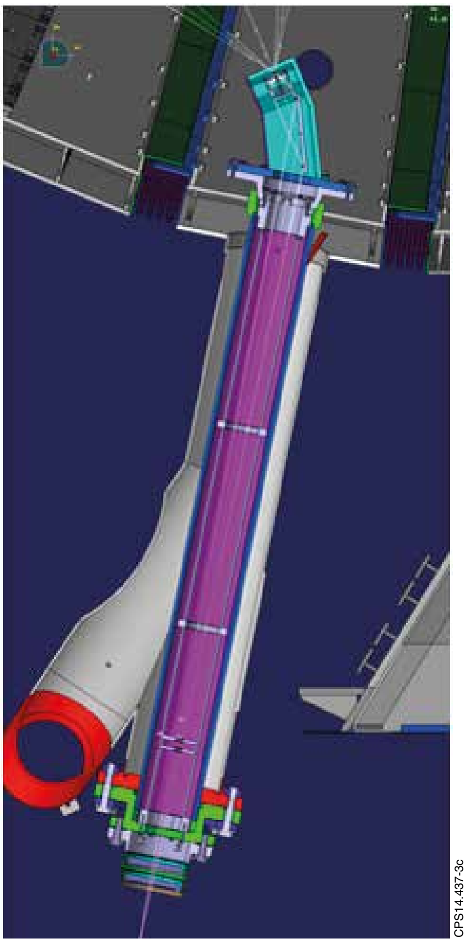

Figure 3: Schematic view of the system from the top showing the optical path of the KL14 wide angle viewing system using the lower left limiter guide tube.

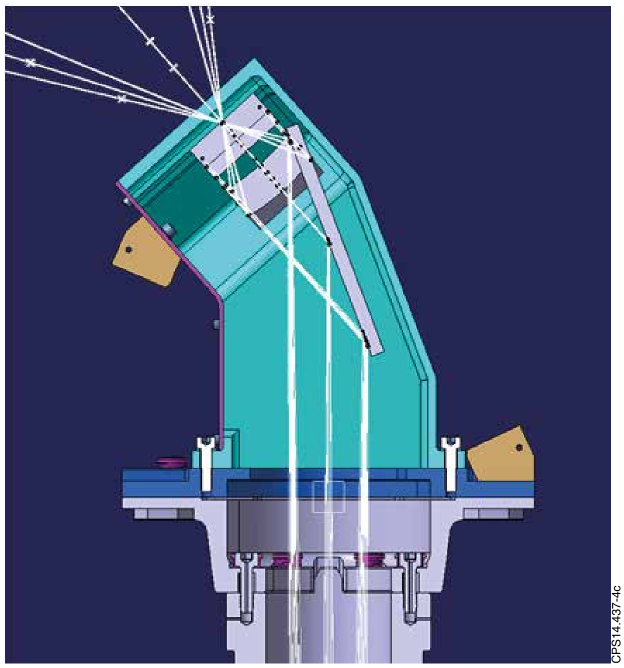

Figure 4: Top view of the mirrors in the KL14 system including optical path.