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RHODIUM AS THE PROMISING MATERIAL FOR THE FIRST MIRRORS OF LASER AND SPECTROSCOPY METHODS OF PLASMA DIAGNOSTICS IN A FUSION REACTOR

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To introduce a visible radiation into plasma or to extract radiation from the vessel of a fusion device it is necessary to use the set of mirrors the first of which does directly see the hot plasma. It will undergo all types of plasma radiation– electromagnetic, nuclear and particle fluxes. The most dangerous for mirror surface will be the bombardment by particles. To have an optical system in a working state it is necessary to choose the first mirror (FM) material, which will assure to maintain the mirror optical properties for as long time as required. The aim of this work is testing rhodium as the FM material which, as known beforehand, is one of the stable materials under particle impact and has a quite high reflectance. Because of high cost, Rh cannot be used as a solid piece for FM fabrication, and it is necessary to deposit Rh layers (<10 μm) on substrates of appropriate metals. In the presented report the results of experiments on fabricating Rh mirrors and testing their properties are discussed.

1. Introduction

The mirrors made of Ag, Al, Cu and Rh have better spectral characteristics of reflectance in visible region than many other metals (Fig.1). In usual atmospheric and vacuum conditions Al and Ag are used for metal mirrors. However, the environment conditions for mirrors in a fusion reactor are much more difficult. The surface of the first mirror (FM) - i.e. that nearest to the plasma, will undergo to influence of some kinds radiation of a hot plasma: electromagnetic, nuclear, (gammas

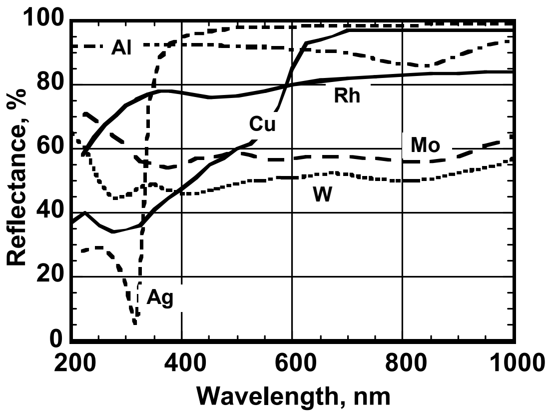

Fig.1 Spectral reflectance at normal incidence for several prospect metals.

and neutrons) and charge exchange atoms (CXA) with energy depending on the ion temperature at the plasma periphery. As was shown in previous investigation [1], the nuclear radiation leads to the mirror body heating resulting in some deformation of mirror but almost without surface degradation. In the case of Thomson scattering based on a multi-shot laser operation, the conditions can be realized (pulse power and frequency) at which mirror surface will deteriorate, but in other conditions, the repeated laser pulses can be used for cleaning the mirror surface from different kinds of deposit.

The most dangerous for the mirror surfaces are CXA fluxes that cause the surface sputtering and increase the scattering of incident light. Fig.2 shows the behavior of reflectance of mirrors fabricated of polycrystalline metals depending on the sputtered layer thickness. The data for thick Rh film (~10μm) obtained later than others, were added to results obtained earlier [2] (1μm correspond to ~5000 monolayers). As seen from Fig.2,

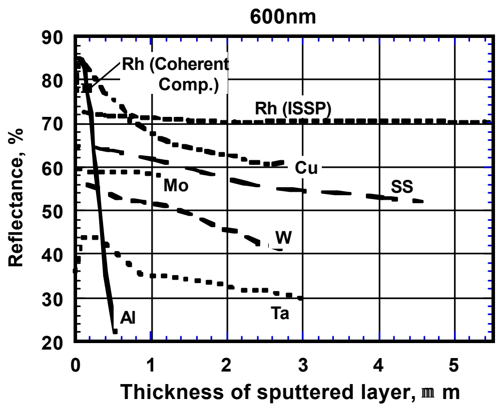

Fig.2. Reflectance of different metals dependenc on the sputtered layer thickness.

among all metals shown the Rh mirror was the most resistant one.

The figure of merit, i.e., the ratio of the reflectivity to sputtering yield is also much better for Rh than for many metals [1]. Other proper metals (stainless steel and Mo) have lower reflectance.

A rather high and uniform reflectance [3], important for diagnostics with laser radiation in use, and low sputtering yield under CXA bombardment allow to consider rhodium as candidate material for mirrors located in the most hard conditions inside the fusion reactor. At the same time, a very high cost of this metal forces to look for methods which give possibility to use not bulk, but thin reflecting rhodium films of reasonable thickness and quality.

2. Rhodium film-mirrors

Beside of high reflectivity in visible, rather small sputtering yield, relatively big thickness (up to 10 μm) and small grain size homogeneity there are two more important requirements for reflecting rhodium films: its reflectance must not change during long-term sputtering and adhesion of film to the substrate must be high. There are several ways of film deposition – electrodeposition [4], deposition of magnetron sputtered rhodium at an enhanced voltage [5] and electrolytic deposition with subsequent pressing of deposited film [6].

Unfortunately in Dr. Orsitto`s final report [4] there are no data on technology of Rh deposition and on results of test. In [5] the method of Rh film deposition on vanadium and stainless steel substrates in a magnetron discharge was developed and was found the good reflectance and rather small diffusive scattering. Adhesion was not measured and sputtering effect on reflectance was not studied.

By the last method [6], developed in the Institute of Solid State Physics (ISSP), the rhodium mirrors were fabricated by combination of chemical and electroplating deposition of Rh films on the copper and copper-nickel substrates followed by pressing and annealing treatments of rhodium coating.

The combination of chemical-electroplating deposition of Rh with pressing-annealing treatment of coatings gave a quite high adhesion (not less 5-10 MPa) as was confirmed by direct measurements at ISSP and indirectly by irradiation tests in Kharkov. Electron microscopy studies showed that such good adhesion is result of mutual penetration of Rh coating and substrate materials during the deposition and subsequent pressing and annealing.

The preservation of a high specular reflection of the coating during the removal of several microns of Rh film by an intensive ion irradiation turned out to be more problematic task. Traditional abrasive polishing of coatings produced a satisfactory initial level of specular optical reflection (up to 80 %), close to the ideal reflection from a Rh surface. But soon after beginning irradiation, when the first micrometers of the coating have been removed by ion sputtering, the specular reflectance decreased. This fall down of reflectance is explained by the irradiation etching of the structural defects, produced in the subsurface layer by the abrasive treatment, which induce the light scattering.

In order to achieve necessary optical parameters of Rh film mirrors, two main problems should be solved. The internal structure of Rh films should be nanocrystalline with homogeneously distributed grains having dimensions not bigger than 50 nm and the surface of film should be optically smooth and flat without abrasive treatment, disturbing the subsurface structure.

Experimental tests of Rh film mirrors subjected to ion sputtering, showed that some mirrors are close to these requirements: the initial specular reflectance at wavelengths 600-650 nm (Fig.3) was about 75-80 % and its decrease during sputtering removal of 2 - 3 μm did not exceed 5 %.

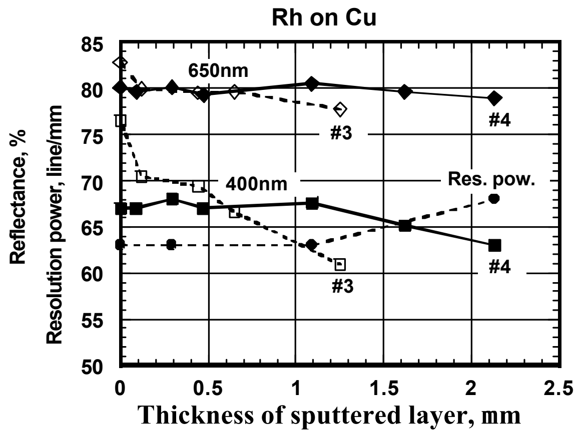

Fig.3. Dependence of reflectance and resolving power of Rh film on Cu substrate on the sputtered layer thickness.

The procedure of test included the step by step exposures to flux of ions of deuterium plasma with a wide energy spectrum (0.1-1.5 keV) [7] and measurements of mass loss and reflectance of the sample after every step. The best data for two Rh film mirrors fabricated as Rh films on Cu substrate are shown in Fig.4 (in relative units) for the wavelength 600 nm. For comparison similar data for polycrystalline copper and stainless steel mirrors are added. The adhesion of Rh film was good and on the interface surface there was not found bubbles which were observed in identical tests for some other film-substrate pairs.

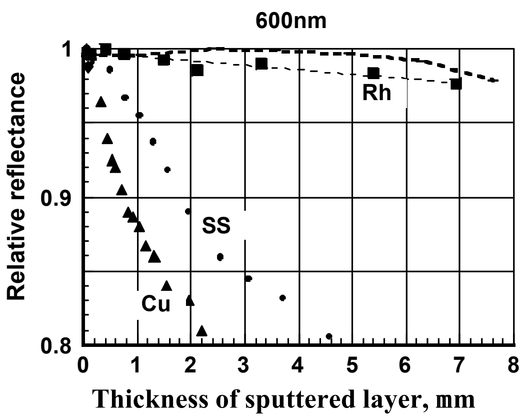

Fig.4. Dependence of relative reflectance for Rh film on Cu substrate, polycrystalline Cu and stainless steel mirrors on the sputtered layer thickness.

3. Discussion

It follows from results of the test that some Rh film mirrors maintained a high reflectance even after sputtering the surface layer of ~7μm thick. This result is the best among all polycrystalline mirror materials tested: Be, Al, SS, Cu, Mo, W, Ta, and film Be/Cu, Cu/Cu. Thus, rhodium film mirrors on a metal substrate look very promising for fabrication of the first mirrors, which will be able to maintain the initial reflectance during long time operation being subjected to expected CXA fluxes.

Investigations of the rhodium film by means of scanning and transmission electron microscopes have shown (Fig.5) that films have a fine-grained structure with the grain size of ~50 nm. The finesse of films is assured by a plastic deformation in the near surface layer of samples and thus the isotropy of film surface properties is realized. Therefore defects that are usually characteristic for materials with the relatively large sizes of volumetric polycrystals [7] do not appear when Rh films are subjected to a long–term ion bombardment. Thus, the microrelief of the film surface with small roughness (of the order of the grain size ~50 nm) being maintained during long-term ion bombardment, does not result in significant degradation of mirror reflectance. During the entire test, such mirrors retain a good image transmission properties, i.e. the high resolving power.

4. Conclusion

From comparative analysis of presented data and data on behavior of different mirror materials under analogous tests, one can make a realistic conclusion that rhodium is a prospect material for fabrication of mirrors which have to be installed inside the fusion reactor vacuum vessel and to be the plasma facing components.

In order to improve the initial optical quality of the surface without any abrasive usage it is supposed to apply combined chemical-mechanical and deformation treatments. When the main parameters of the process as a whole will be found (i.e. temperature and concentration of the solutions, duration of the deposition process, current density, mechanical pressure, etc.), it will be possible to proceed to development of the process for the manufacturing of large size rhodium film mirrors.

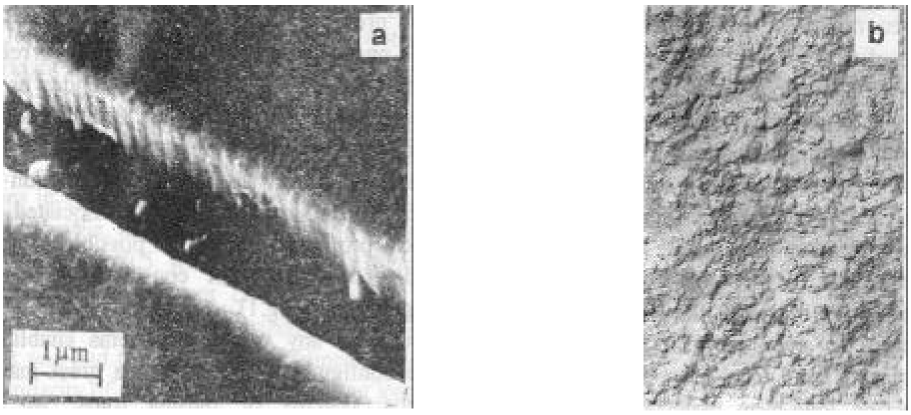

Fig.5. The structure of Rh film: a - SEM image of a rod-like structure in the fracture of film near the through crack, b - TEM photo of a surface replica

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