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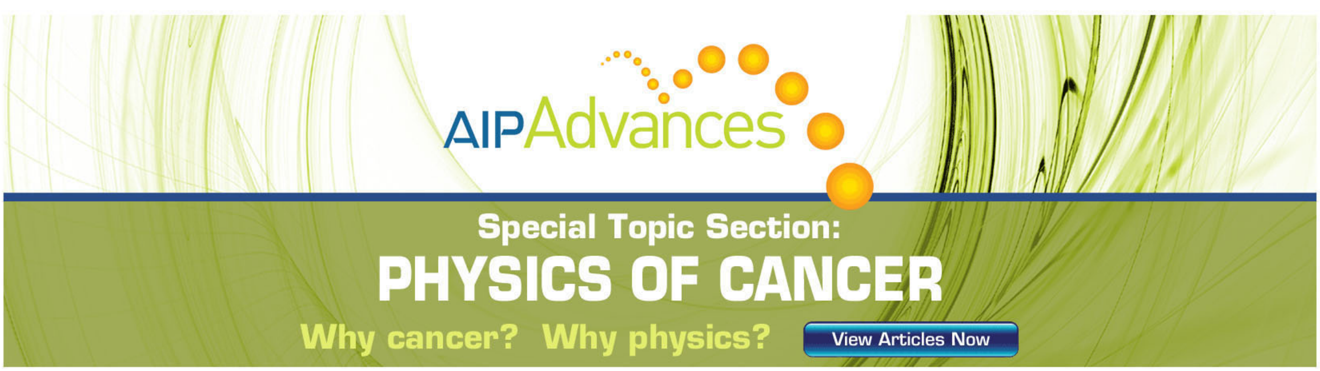

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Optical characterization of plasma facing mirrors for a Thomson scattering system of a burning plasma experiment

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(Presented on 19 June 2000)

The general requirements for a plasma facing mirror (PFM) of a Thomson scattering system (TS) for a burning plasma experiment are (i) high and approximately constant reflectivity in the wavelength spectral range 400–800 nm; (ii) low sputtering yield and low erosion; (iii) high power damage threshold; (iv) good thermo-mechanical properties to preserve quality imaging. Rhodium-coated mirrors are chosen because they meet these requirements. Rhodium coated mirror were realized with substrates of copper and vanadium. The detailed optical characterization of these mirrors is presented: i.e., surface planarity measurements as well as roughness and reflectivity figures are presented. These data can be used for the choice of the PFM of a TS system for international thermonuclear experimental reactor. © *2001 American Institute of Physics.*
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I. INTRODUCTION

The general requirements for a plasma facing mirror (PFM) of a Thomson scattering system (TS) for a burning plasma experiment[1] are: (i) high and approximately constant reflectivity in the wavelength spectral range 400–800 nm; (ii) low sputtering yield and low erosion; (iii) high power damage threshold; (iv) good thermo-mechanical properties to preserve quality imaging. The choice of the material for the mirror coating exhibiting these characteristics is among Ag, Rh, and Mo (mass number ~100).[2] Rhodium-coated mirrors are chosen because: (i) reflectivity of 0.7–0.8 in the spectral range 400–800 nm; (ii) high melting threshold for laser shots (the melting threshold is ~0.73 J/cm^2 for short pulses of ~1 ns); (iii) low erosion (~0.006 monolayer removed per discharge of 1000 s).[3] A peculiarity of a PFM for TS is that it must be an imaging mirror: so its optical quality should be unchanged under heating due to laser irradiation, causing a thermo-mechanical fatigue effect between the rhodium reflecting layer and the substrate. This effect decreases the mirror damage threshold at long term, and is minimal for a rhodium coating on vanadium substrate, because the thermal dilatation coefficients of these two metals are very close. In this work a detailed optical characterization of rhodium-coated copper (Rh/Cu) and vanadium (Rh/V) mirrors is presented: both types of mirrors are candidates as PFM of a TS system. Rh/Cu mirrors with rhodium layer close to 1 μm thickness were realized by electrodeposition of rhodium on copper substrate previously covered by a thin mechanical buffer of nickel. The planarity of Rh/Cu mirrors resulted to be close to $<\lambda/2$ in the visible spectral range, with roughness of 8.41 nm RMS at center, and 8.91 nm as average on the surface. The measured hemispherical (i.e., specular +diffused) reflectivity of Rh/Cu mirrors at 45° angle of incidence for *s* polarization is 0.7–0.8 in the spectral range 400–800 nm. The Rh/Cu mirrors surfaces are sensitive to baking cycles. The Rh/V mirrors were obtained by electrodeposition of rhodium on polished vanadium substrates. Layer thickness of rhodium close to 1 μm was obtained with this technique. The planarity of Rh/V mirrors resulted to be between $\lambda/8$ and $\lambda/18$ in the visible spectral range, with roughness close to 14 nm RMS averaged on the surface. The measured hemispherical (i.e., specular+diffused) reflectivity of Rh/V mirrors at 45° angle of incidence for *s* polarization is 0.55–0.75 in the spectral range 400–800 nm. The optical characterization of Rh/Cu and Rh/V mirrors can be inserted

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in the database useful for the choice of the best candidate for the PFM of a TS for a burning plasma experiment. The present article is organized in three sections. Section II is dedicated to the presentation of measurements on rhodium coated mirror with copper substrates, while Sec. III is devoted to the rhodium coated vanadium mirrors, the conclusions are given in Sec. IV, where a first short synthesis of the mirror work is presented and the future work is outlined.

II. RHODIUM MIRRORS WITH COPPER SUBSTRATE (Rh/Cu)

Various mirrors were produced with rhodium layer thickness ranging from 0.2 to 0.8 μm by electrodeposition of rhodium on copper substrates, where a thin layer of nickel was previously deposited to make easy the uniform rhodium deposition. The surface planarity is within $\lambda/2$ in the visible, the roughness is close to 10 nm, while the hemispherical [specular+diffused (scattering) reflectivity] at 45° for *s*-polarization is between 0.7 and 0.8 in the interval of 400–800 nm. So in the light detecting and ranging (LIDAR) TS configuration the mirror will absorb about 20%–30% of the collected scattered radiation. The laser incident light is also absorbed by ~15%, since its wavelength is $\lambda=850$ nm, i.e., the titanium sapphire laser.[4]

A. Construction of Rh/Cu mirrors

The rhodium mirrors were built by electrodeposition of rhodium on substrates of copper, suitably prepared.[5] Plane parallel copper substrates were built by means of the diamond fly cutting machine obtaining an optical tolerance close to $\lambda/2$ at the visible light (He–Ne, $\lambda=632.8$ nm), on the entire field, as was measured using a Wyko interferometer. A small layer of nickel, whose thickness is of the order of 1 μm, is deposited on the copper substrate for the best uniformity of the deposition of the rhodium on the substrate.

Using this technique four rhodium plane mirrors with various diameters (5–8 cm) were built, the rhodium layer thickness ranging from 0.2–0.8 μm.

B. Optical characterization of Rh/Cu mirrors

The characterization of mirrors was aimed to the determination of the following figures: (i) surface planarity, (ii) surface roughness, (iii) hemispherical reflectivity, (iv) damage threshold, (v) baking cycles effects on mirror reflectivity and surface. The complete tests were carried out on a mirror with 80 mm diam, thickness 14 mm, with a rhodium layer of 0.8 μm thick (hereafter named M1). Optical tests (measurements included in the previous four points) are also available for Rh/Cu(Ni) with 50 mm diam and rhodium layer thicknesses of 0.6, 0.4, and 0.2 μm (named, respectively, MN1, MN2, and MN3). Figure 1, for example, shows the roughness of the MN1 Rh/Cu(Ni) mirror measured using the interferential microscope three-dimensional (TOPO-3D) in a central region of the mirror of dimension 512×512 μm^2. The different colors in Fig. 1 are related to different ranges of roughness (R) measured: for example, brown stands for $R>10$ nm, yellow, green, and blue for $R<10$ nm. Detailed measurements of roughness in four other positions lead to an average surface roughness of 8.91 nm root-mean-square (rms). The hemispherical reflectivity of mirror M1, which is a sum of the diffused and specular reflectivity, measured at a reflection angle of 45°, for *s* and *p* polarizations, is shown in Fig. 2. The theoretical curve shown in Fig. 2 (and Fig. 3) is the reflectivity calculated taking into account the rhodium index of refraction and Fresnel formulas.

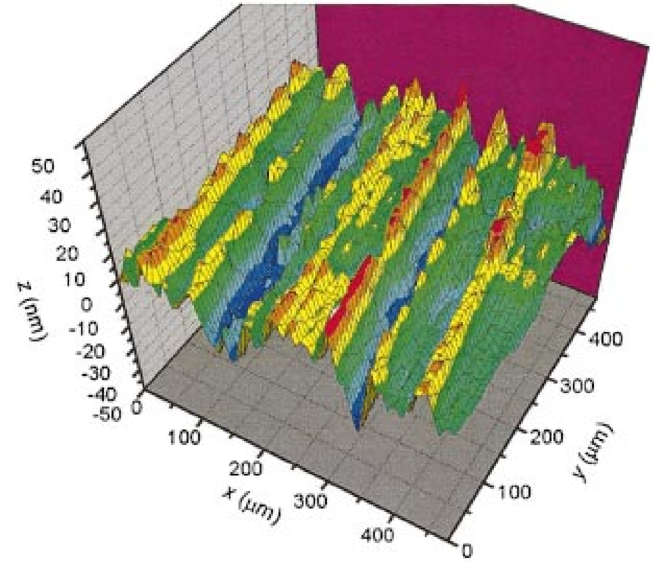

FIG. 1. (Color) Roughness of the MN1 Rh/Cu(Ni) mirror surface as measured using the interferential microscope TOPO-3D/Wyko.

C. Damage threshold of Rh/Cu(Ni) mirrors

The damage threshold (DT) of Rh/Cu(Ni) mirror M1, was measured using a 1 Hz ruby laser ($\lambda=694.3$ nm), with duration of 300 ps used presently in the Joint European Torus (JET) LIDAR Thomson scattering system. The figure of a DT of 308 mJ/cm^2 was measured at 45° incidence angle and *s* polarization. This figure was measured inspecting on the mirror the appearence of a mild laser beam pattern on the mirror.

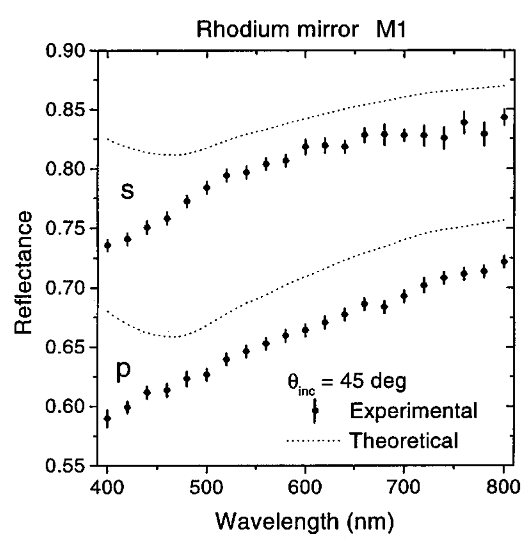

FIG. 2. Reflectivity at 45° for *s* and *p* polarizations, for mirror M1.

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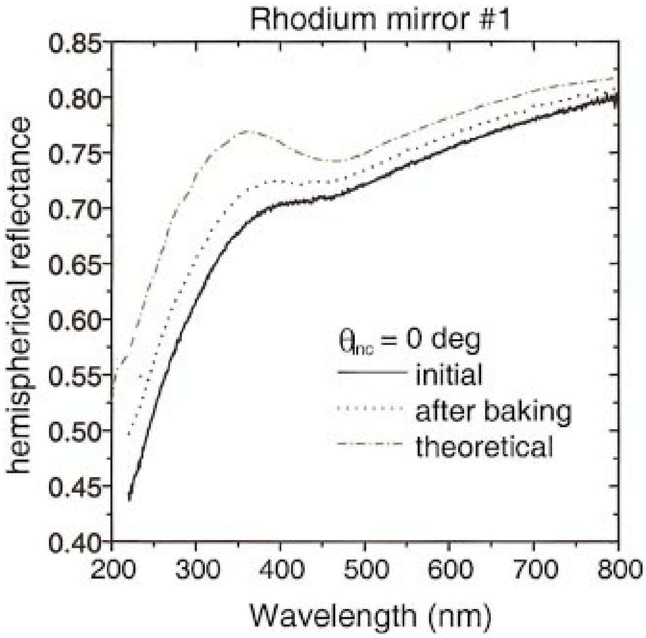

FIG. 3. (Color) Hemispherical reflectivity of mirror M1, at 0° incidence angle, measured before and after the baking, using a Perkin Elmer Lambda9 spectrophotometer.

D. Effects of baking cycles on Rh/Cu(Ni) mirror reflectivity and surface

The mirror M1 was baked for about 24 h at 200 °C. The temperature during the baking was rised and lowered at about 40 °C/h. The hemispherical reflectivity of mirror M1 after baking was measured using a Perkin Elmer Lambda9 spectrophotometer, and it is shown in Fig. 3. The effect of the baking on the global reflectivity is very low. It appears that the baking increases the reflectivity (specular+diffused) by 1%–2%, and this is due to the increased diffused reflectance.

The surface change was somewhat higher since small scale corrugations appeared on the surface. This effects was also made evident baking copper substrates without rhodium film. In the case of Rh/Cu mirrors the imaging properties are seriously compromised when temperature cycles are performed.

III. RHODIUM MIRRORS WITH VANADIUM SUBSTRATES

The motivation of building rhodium mirrors with vanadium substrates is due essentially to the fact that Rh and V have the same thermal expansion coefficient: the thermal stresses between the rhodium film and the vanadium substrate are minimized during the baking cycles. Table I reports some figure related to thermal and mechanical properties of rhodium, vanadium, and copper, where some similarities of rhodium and vanadium can be noted.

A. Construction of rhodium mirrors with vanadium substrates

A rod (1 in. diam) of vanadium sinterized was sliced in small disks of 10 mm thickness. A normal procedure of surface polishing using diamond powder with small dimension (0.35 μm) was applied to obtain optically finished surfaces. In this way ten vanadium mirrors (V mirrors) were produced. A optical characterization of these V mirrors was carried out. The rhodium was put directly on top of the vanadium mirrors using the electrodeposition technique, in this way RH/V mirrors were obtained.

TABLE I. Rhodium, vanadium, and copper thermomechanical figures.

	Cu	Rh	V
TEC[a] (10^{-6}/°C)	16.5	8.3	8.3
Th Cond[b] (cal/cm s °C)	0.94	0.21	0.074
Specific heat (kcal/kg °C)	0.092	0.059	0.120
Fus Temp[c] (°C)	1083	1966	1900
Y Mo[d] (GPa)	120	385	126

[a]Thermal expansion coefficient.
[b]Thermal conductivity.
[c]Fusion temperature.
[d]Young module.

B. Characterization of vanadium substrates

Some of the vanadium substrates (V mirrors) were characterized in terms of optical figures using Wyko interferometer (for the optical surface) and TOPO-3D interferential microscope (for the roughness), while the hemispherical reflectivity was measured and the diffused reflectivity as well by means of the Lambda9 spectrophotometer. In this case a complete characterization of the V mirror substrates was carried out. The samples numbered 2P, 6, 7, and 8 were tested. The average roughness measured for these mirrors was 13 nm rms. The hemispherical reflectivity and the diffused (scattering) reflectivity were also measured, and they are shown in Figs. 4 and 5, respectively. The hemispherical re-

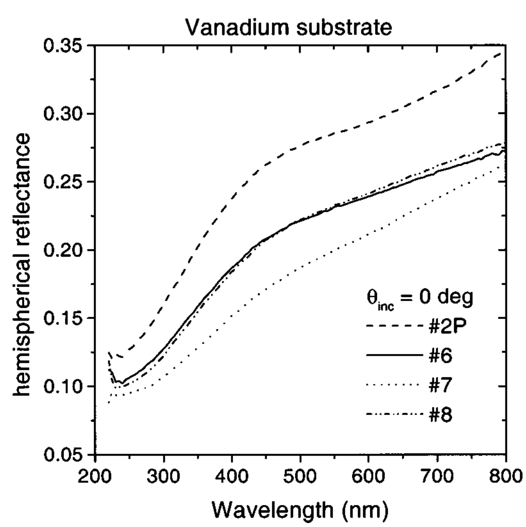

FIG. 4. Hemispherical reflectivity of vanadium substrates.

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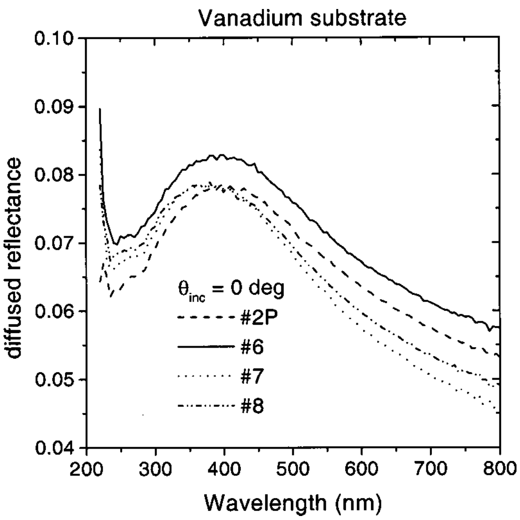

FIG. 5. Diffused reflectivity of the vanadium substrates.

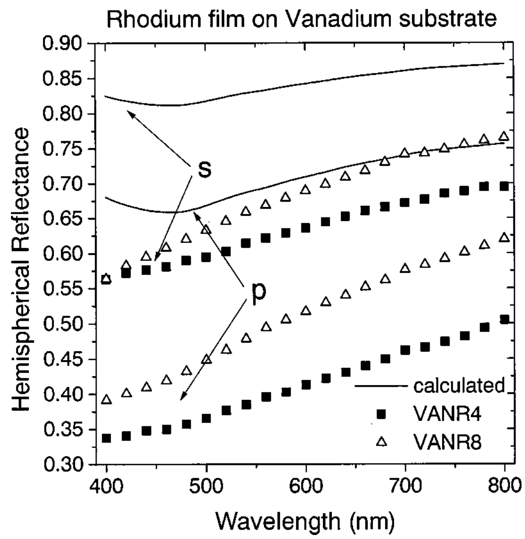

FIG. 7. Hemispherical reflectivity of the rhodium, mirrors with vanadium substrates.

flectivity ranges between 20% and 35% in the spectral interval of 400–800 nm, while the diffused reflectivity is less than 8%, in the same interval.

C. Optical characterization of rhodium mirrors with vanadium substrates

The measurements were carried out with the same instruments as for the Rh/Cu mirrors. For example the elaboration of the Wyko400 interferometer give a clear representation of the mirror surface. Figure 6 shows the 3D representation of the mirror Rh/V (#8): it is shown that the surface is planar within 35–76 nm, i.e., the optical tolerance is between $\lambda/18$ and $\lambda/8$ (the Wyko wavelength is $\lambda=632.8$ nm).

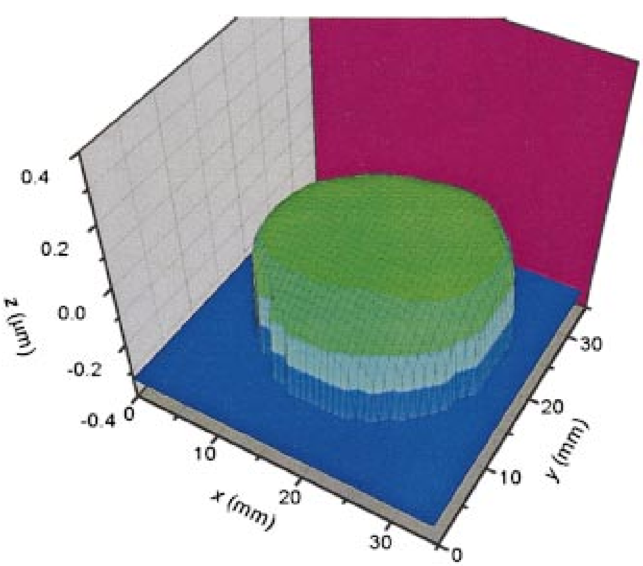

FIG. 6. (Color) 3D representation of the mirror Rh/V (#8) as measured by the Wyko400 interferometer.,

D. Reflectivity measurements for Rh/V mirrors

The most interesting measurement for the application to Thomson scattering is the measurement of the hemispherical reflectivity at 45° incidence angle for *s* and *p* polarization. The *s* polarization will be used. The measurements related to Rh/V mirrors VANR (#4) and VANR (#8) are shown in Fig. 7: a difference of the order of 20% between the theoretical value of the reflectivity and the measured one is detected. The index of refraction (used in the calculations) of rhodium at $\lambda=620$ nm is $n-ik=2.12-i5.51$. The absorption length is $\delta=\lambda/4\pi k\sim 9$ nm, which is very less than the layer thickness of rhodium on vanadium (~ 1 μm). So, for this layer thickness we can consider the rhodium reflectivity as due only to the rhodium, neglecting the effect of the substrate. Possible explanations of the difference between the measured and calculated reflectivity are: (i) the purity of the chemical bath used for the electrodeposition is high, but not very well known, so the layer deposited on the substrate could have impurities, affecting the reflectivity; (ii) the rhodium film can have superficial microporosity, whose spatial scales are smaller than the testing wavelength. In this case the presence of such microporosities does not give rise to enhanced scattering reflectivity, but the testing radiation could see the microporosities as a thin film of a material with optical constants intermediate between rhodium and air. The microporosity can be caused by the particular structure of the used vanadium substrate.

IV. CONCLUSIONS

This article reports the detailed characterization of prototypes of rhodium mirrors built on copper (Rh/Cu) and vanadium (Rh/V) substrates. Mirrors Rh/Cu have been built meeting all the optical characteristics required for a PFM for TS system. The effects of baking on the surface of the Rh/Cu mirror seem prevent the conservation of imaging property of the mirror, if it is used in strong and periodic variation of the

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temperature. On the other hand, Rh/V mirrors have been built with good surface property, but the reflectivity must be improved.

ACKNOWLEDGMENT

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