J. Plasma Fusion Res. SERIES, Vol. 3 (2000) 270–273

Effect of Thin Film Coating on Reflectance of In-Vessel Metallic Mirror

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(Received: 18 January 2000 / Accepted: 23 May 2000)

Abstract

It was observed in many fusion experiments the appearance of a not absolutely transparent deposit on diagnostic windows of fusion devices. The deposit composition was shown to correlate with composition of materials of the most strongly eroded in-vessel components, or with the material of wall coating used for improving vacuum conditions and suppressing the influx of heavy atoms into the core plasma. The appearance of analogous deposit on diagnostic mirrors located inside the vacuum vessel will result in changing the reflectance which has to be taken into account when measuring and registering the radiation that comes out of plasma by use of these in-vessel mirrors. In the present paper the role of contaminating film on mirror reflectance is analyzed.

Keywords:

in-vessel mirror, contaminating film, reflectance

1. Introduction

With an aim to suppress the metal atom influx from the vessel walls of fusion devices into the plasma and to improve discharge performance, the protection of walls by low-*Z* materials is widely used. After successful results with carbonization of tokamak TEXTOR [1] this method of carbon film coating became a routine procedure in great many fusion devices. Several years later on this device for the first time the boronization procedure has been used to coat the vessel walls with a boron-based film [2], and later the boronization came up to take carbonization place in many fusion devices. In nowaday practice, the boronization is combined with graphite protection of wall areas subjected to strongest plasma impact. Thus the coating appearing on vessel walls and other inner components is the amorphous boron-carbon film with some amount of hydrogen (a-B/C:H) [3]. On those inner components that are not subjected to strong plasma impact, like diagnostic windows and the in-vessel mirrors, the film grows not only as a result of boronization but also during work discharges [2,4].

There are two publications with experimental data concerning effects of deposit on a transmissivity of diagnostic window in a fusion device [5,6]. In both

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cases the vessel walls were regularly carbonized. In [6] the chemical composition of deposited film was measured and it was found that the film is of *polyacrylonitrile* type.

At the same time, effects of deposit on reflectance of mirrors situated inside the fusion device chamber were not described in publications up to now, on our knowledge, and in this paper we are trying to analyze this role of deposit. We limit ourselves by study of boron-carbon film, as such films are most frequently met in large-scale fusion experiments. The wavelength range studied is 200–1100 nm, which is of interest for spectroscopy and Thomson scattering methods of plasma diagnosing.

2. Effect of Thin Film on Specular Reflectance (Experiment and Calculation)

It was shown (e.g. [7]) that effective reflectance, $R(\lambda)$, of metal mirror coated by a partly-transparent film of any given thickness (d) can be calculated using optical constants, i.e., refraction $n(\lambda)$ and extinction $k(\lambda)$ indices, of both - the substrate material and the film. In the present study for comparison with measured dependencies $R(\lambda)$, the calculations were provided using the following formula [8], which gives the effective reflectance of the metal mirror coated with thin partly transparent film at the normal incidence of light:

$$R=\frac{A_1^- \exp(k)+A_2^+ \exp(-k)+A_3^+ \cos(n)+A_4^- \sin(n)}{A_1^+ \exp(k)+A_2^- \exp(-k)+A_3^- \cos(n)+A_4^+ \sin(n)},$$

where $k = (4\pi k_1 d)/\lambda$, $n = (4\pi n_1 d)/\lambda$,

$A_1^\pm = [(1 \pm n_1)^2 + k_1^2]\,[(n_1 + n_2)^2 + (k_1 + k_2)^2]$,

$A_2^\pm = [(1 \pm n_1)^2 + k_1^2]\,[(n_1 - n_2)^2 + (k_1 - k_2)^2]$,

$A_3^\pm = 2[(1 - n_1^2 - k_1^2)\,(n_1^2 + k_1^2 - n_2^2 - k_2^2) \pm 4k_1(n_1k_2 - n_2k_1)]$,

$A_4^\pm = 4[(1 - n_1^2 - k_1^2)\,(n_1k_2 - n_2k_1) \pm k_1(n_1^2 + k_1^2 - n_2^2 - k_2^2)]$.

The complex indices $n_1 - ik_1$ and $n_2 - ik_2$ represent data for a film and substrate, correspondingly.

Effect of thin film on specular reflectance at normal incidence was checked using two stainless steel (SS) mirrors (of 316 type) coated with boron film, and molybdenum mirror coated with carbon film. The SS samples were coated up to ~7 nm and ~17 nm film thickness in the surface modification test stand (SUT) [9]. The Mo mirror was coated by means of vacuum arc between graphite electrodes, and the deposit thickness at different parts of mirror surface was ~23 nm, 35 nm and 56 nm.

The spectral dependencies of optical constants of a boron-carbon film, a-$B_{(1-x)}/C_x$:H, deposited in different conditions were measured by ellipsometry for several x values. In Table 1 such data at the wavelength 632.8 nm are presented for three samples with different C/B ratio. As seen, increasing the carbon component of film (samples #2 and #3) reveals a significant change of n but not k values.

The thickness of carbon films and their optical constants were measured at the wavelength 632.8 nm and for the clean Mo surface - in a wide spectral range. For these films, *n* and *k* from ellipsometric measurements were slightly different for different thickness, in spite of identical depositing conditions, and therefore the average $n = 2.7$ and $k = 0.5$ values were used when comparing measured $R_{eff}(\lambda)$ with calculation for this substrate-film pair.

The results of measurements for SS mirror coated with boron film (open points) and calculations for sample #2 (solid lines with solid points) presented in Fig. 1 demonstrate a quite reasonable qualitative agreement. Calculations for samples #1 and #3 give similar dependencies with a little shifted positions of minima for $R_{eff}(\lambda)$ curves. The data of Fig. 1 indicate

Table 1. Characteristics of boron films deposited under different conditions.

Sample	C/B ratio, x	d, nm	n	k
#1	0	300	2.58	0.058
#2	0.15	135	2.37	0.065
#3	0.48	147	2.19	0.065

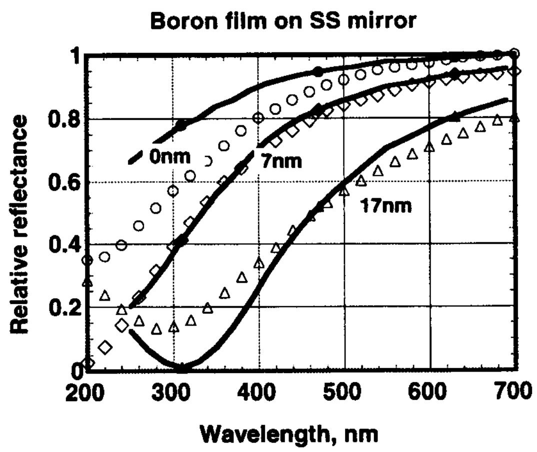

Fig. 1 Effect of boron film on reflectance of SS mirror. Open points – results of measurements, lines with solid points – calculations.

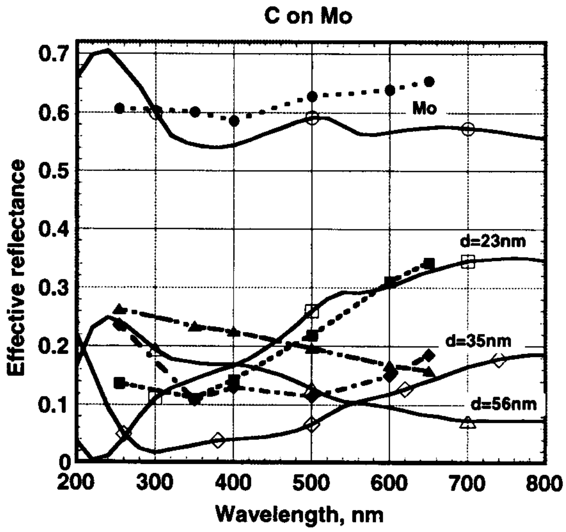

Fig. 2 Effect of different thickness carbon film on reflectance of Mo mirror. Closed points – results of measurements, lines with open points – calculations.

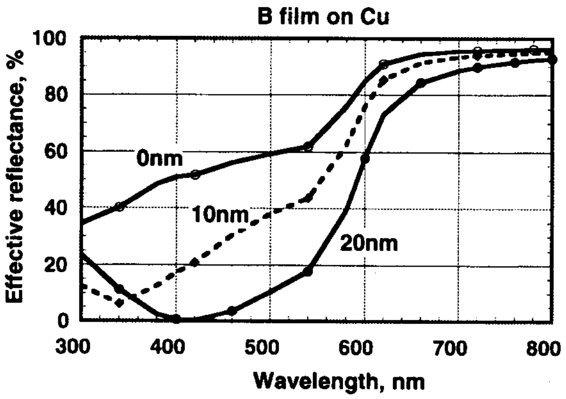

Fig. 3 Effect of boron film coating on reflectance of copper mirror.

that boron film effects on a SS mirror reflectance are especially strong in the UV part of spectrum.

The measured and calculated $R_{eff}(\lambda)$ dependencies for Mo substrate coated with carbon film of three different thickness are presented in Fig. 2 together with data for the clean Mo surface. It is seen that carbon film influences drastically the effective reflectance of C/Mo mirror in the whole spectral range where measurements were provided. Because of lack of n and k measurements for our carbon film in the wide spectral range, the spectral dependencies for both indices from [10] were used, corrected in accordance with the differences found at $\lambda = 632.8$nm.

As Fig. 2 shows, the agreement between measured and calculated data is more or less reasonable only for the thinnest film (d = 23 nm), but for two other film thicknesses the difference between calculated and measured $R(h)$ is not small. The possible reason of this can be the difference between the real spectral dependencies of optical constants for carbon film deposited in this experiment and for carbon film investigated by authors of [10].

Nevertheless, it may be concluded that a formul R can indeed be used for estimation of effective reflectance of mirror coated by contaminating film, if optical constants of both materials (film and metal substrate) are known.

As an example of such estimation, in Fig. 3 are shown results of calculations using the above-mentioned formula, of effects of boron film on copper substrate. As seen, in the visible part of spectrum a strong distortion of initial reflectance $R(\lambda)$ takes place already with d = 10–20 nm. At the same time, the typical thickness of B-C film deposited on the inner walls of fusion devices during every boronization significantly exceeds 20 nm, as it follows from publications presented at 9th and 10th Conferences on Plasma Surface Interaction in Fusion Devices [correspondingly, J. Nucl. Mater. vol. 176/177 and vol. 196-198].

3. Discussion

The above shown results indicate that the deposit of thin ($\leq$ 10 nm) boron-carbon film can change strongly the effective reflectance of a metal mirror in visible and nearest UV regions. Note that film appearance on the in-vessel mirror of a fusion device have to deteriorate the mirror reflectivity much stronger than the transmissivity of diagnostic window. This is because in practice the effective film thickness for reflected light is about 3 times of the real thickness: the light passes the film two times and not perpendicular to the surface. The effect of deposit growth on effective reflectance depends on the light wavelength, chemical composition of film and its thickness.

Principally, the change of reflectance can be predicted and taken into account if both the film thickness and film chemical composition are controlled, on the one hand, and if the correlation between film composition and optical properties is known from independent preliminary measurements, on the other hand. However, the latter is difficult to realize in common, due to strong influence of film composition on dependencies $n(\lambda)$ and $k(\lambda)$, as seen from data presented in Table. In addition, some data relating to the effect of variation of H concentration in the boron film on the n magnitude at (λ = 632.8 nm can be found in [11].

The best way to overcome the problem related to deposit growth is to find the effective methods to clean up the surfaces from a deposition. For optical windows, in addition to laser ablation method [6,12,13], the effectiveness of chemical cleaning by using the local ECR discharge in hydrogen was demonstrated in [14]. For the in-vessel mirrors the methods of cleaning up the boron-carbon deposit were not suggested yet. Therefore, for the in-vessel mirrors the methods of *in-situ* control of thickness and composition of B-C films have to be developed as well as methods of the *in-situ* re-calibration of the whole optical scheme for devices where the boron-carbon materials are used for the first wall protection. The scheme tested on TFTR with steady state glow discharge in hydrogen as a light source [5] looks quite promising for regular providing the *in-situ* calibration of optical characteristics of the in-vessel components of spectroscopy and laser plasma diagnostics. The low temperature plasma of a cw ECR discharge at frequency 2.45 GHz can probably be more prospect as a light source for the *in-situ* calibration in comparison to glow discharge. The influx of impurity atoms into ECR discharge plasma with T_e of a few eV would be negligible in comparison with the glow discharge case. However, stability and reproducibility of spectral radiance characteristics of such plasma in the large-scale machines were not investigated by now.

4. Conclusion

- The deposition of thin boron-containing or other contaminating films on the in-vessel mirrors of fusion devices deteriorates the mirror reflectivity and transmissivity of window. The effect of deposit on reflectance depends on the light wavelength, film thickness and film chemical composition.
- The knowledge of optical properties of boron-carbon-based films is not enough for the adequate prediction of final result of film deposition on mirror surface even if the film thickness is known from independent measurements. There is a need to obtain data for films with chemical and structural composition variation in a wide range following the most probable composition in fusion devices.
- The simple and reliable methods for the regularly provided *in-situ* calibration and control of reflectance of the in-vessel mirrors, as well as the methods of deposit cleaning have to be developed. The plasma properties of an ECR discharge in hydrogen (or deuterium) look rather promising for both these applications. However, the special experiments in large-scale fusion devices are necessary to be carried out to optimize the characteristics of ECR discharge for solving the problem of low Z material deposition on operation of inner mirrors.

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