Visualization of the gas flows that formed above the thin-film coatings under VUV radiation influence

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Abstract. The plasma focus of a magnetoplasma compressor is a unique source of high-brightness broadband VUV (with photon energy of 5 to 100 electron volt) radiation. When such radiation affects on the surfaces of materials, it is possible to generate rather complex gas-dynamic structures due to the evaporation of the material and ionization of its vapors. A separate task is to study the processes of a gas-dynamic response to the exposure of the specified radiation fluxes on the surface of interference antireflection and reflective multilayers, which are used in modern laser technology, high-power optoelectronics, etc. In this report, we used schlieren photography for studying the features of gas-dynamic structures that arise at irradiation of coatings. Radiation resistant (in the visible and near IR ranges) HfO₂/SiO₂ and ZrO₂/SiO₂ multilayer structures (with a total thickness of 140–3700 nanometers and a number of layers of from 2 to 24) were used as prototypes for testing their stability under the VUV exposure.

1. Introduction

Nowadays multilayer thin interference films based on HfO₂/SiO₂ and ZrO₂/SiO₂ systems are considering as radiation resistant coatings to laser radiation [1, 2]. HfO₂ layers exhibit a high stability of refractivity under the influence of external factors (primarily incident radiation) [1]. ZrO₂ coatings have the advantages of a high refractive index [2]. Therefore, the ZrO₂/SiO₂ pair has a larger refractive index difference compared to the HfO₂/SiO₂ pair, thus allowing the use of coating designs with fewer layers. But there are no data on the properties stability of the specified material pairs under influence of a high-brightness VUV/UV radiation. High-current pulse discharges of modern plasma coaxial accelerators [3] make it possible to generate powerful (with an intensity of 10⁷–10⁹ W/cm²) broadband VUV/UV radiation [4], the spectrum of which is limited by the chemical composition of the gas atmosphere in the chamber [5]. The maximum energy of the emitted quanta is limited by the first ionization potential for inert gases (≈ 12–22 eV) [6] or by absorption in the Schumann-Runge bands for oxygen-containing media (≈ 6 eV) [7]. Thus, the presented experimental results can be considered as model tests to identify factors that can deteriorate the optical characteristics of the coatings exposed to extreme radiation in different spectral ranges.

2. Experimental technique

Samples of radiation-resistant antireflection and reflective coatings based on multilayer (with a number of layers of from 2 to 24) HfO₂/SiO₂ and ZrO₂/SiO₂ pairs were obtained by ion assisted electron beam evaporation. The total thicknesses of the multilayers were varied from 140 nm to 3700 nm.

The scheme of the experimental setup and its optical system is presented in figure 1. Generation of
compressed plasma flows and VUV/UV radiation were fulfilled with a coaxial (with a PTFE bush) erosion-type magnetoplasma compressor (MPC) (1) in air and neon (with a pressure of ≈ 300–400 Torr). A stored energy in a capacitor (2) was up to \( E_c \approx 3.6 \) kJ. A circuit was commutated by a high frequency thyratron (3) (Pulsed systems, Ltd.). Current and voltage waveforms were measured with Pearson 110 current monitor (4) and a voltage divider probe (5) and recorded by an oscilloscope (6).

**Figure 1.** Scheme of experimental setup: 1 – MPC, 2 – capacitor, 3 – thyratron, 4 – current monitor, 5 – voltage divider probe, 6 – oscilloscope, 7 – sample, 8 – laser, 9 – CCD camera, 10 – pulse delay generator, 11 – lens, 12 – diaphragm, 13 – interference filter, 14 – polarizer, 15 – screen, 16 – chamber and 17 – charger.

Laser schlieren photography in the “bright field” mode [8] was used to visualize gas-dynamic flows arising from the exposure of powerful energy fluxes on the samples (7). The triggering of the laser (\( \lambda = 532 \) nm) (8) and photographic recording (with Videoscan camera (9)) of the process occurred during at the end of second half-period of the current with BNC 575 pulse delay generator (10). The forming of the required parameters of the laser beam was fulfilled with an optical systems included lenses (11), a diaphragm (12), an interference filter (\( \lambda = 532 \) nm, \( \Delta \lambda = 10 \) nm) (13), a polarizer (14). The image was projected onto a screen (15).

The samples were installed in a steel chamber (see figure 2, 3). Two modes of radiation exposure were studied: in air and neon. One side of the sample was turned to the MPC barrel and the opposite

**Figure 2.** Fixed sample with coating.  **Figure 3.** Positioning of sample with coating relativity coaxial MPC.
side was covered with a copper screen. Between the radiation exposures the sample was turned 180° around. As noted above, the spectrum was limited by a chemical composition of the medium in the chamber. Therefore, the radiation energy was concentrated in the visible and near ultraviolet range (with a wavelength of less than 200 nm) in air. On the other hand, the spectrum was limited by lesser wavelengths less than 60 nm for neon.

3. Experimental results and discussion
The measured current waveform and photodiode signal are presented in figure 4.

![Figure 4. Waveforms of current (blue) and photodiode signal (yellow).](image)

The maximum recorded current was \( \approx 140–170 \text{ kA} \). The photodiode signal indicated that the presented photos corresponded to a moment of time \( \approx 12–14 \mu\text{s} \). This moment corresponded to an advance stage of the discharge that generated the powerful broadband radiation.

With data on a position of coated samples relatively the plasma focus it was possible to estimate a heat flux in the surface. So a portion of the energy \( E_r \) converted into radiation could be calculated as \( E_r \approx \eta_e \eta_r E_c \), where \( \eta_e \approx 0.6–0.7 \) is the efficiency of an energy conversion in the discharge and \( \eta_r \approx 0.1–0.5 \) is the efficiency of an energy conversion in the radiation [9]. Meanwhile, a greater values of \( \eta_r \) corresponded to hard quanta. Then estimations demonstrated that the heat flux was [10]

\[
q = \Delta \frac{E_r \cos \varphi}{4\pi R^2 \tau_r},
\]

where \( \varphi \) is an angular orientation of the sample, \( R \) is a radius vector of the sample orientation relativity the plasma focus, \( \Delta \) is a dilution factor and \( \tau_r \) is an effective exposure time. In experimental conditions the heat flux was \( q \approx 30–140 \text{ kW/cm}^2 \). More powerful heat fluxes led to a significant degradation of surface. For experimental estimation of degradation potential of quanta with different energies were fulfilled in air (\( \lambda > 200 \text{ nm} \)) and neon (\( \lambda > 60 \text{ nm} \)).

As shown above (see figure 5), the discharges structure in air and neon were different. Plasma flow in air was characterized by a complex structure that consisted in an irregular shock form (1), a presence of inner dense areas, etc. This was caused by an initiating of chemical and photo-chemical reactions in a mixture of air and PTFE vapors. The shock front (1) in neon was smooth. No significant inner features were recorded. The paramount features of interaction of the discharge radiation in neon with the substrate (3) consisted in a forming of a gas-dynamic response that moved from that. Similar phenomena were not recorded for the discharge in air. So evaporation of the coating was caused exactly by hard quanta with maximum energy of \( \approx 20 \text{ eV} \).

The coating surface was undergone by sufficient erosion during the radiation exposition in neon. Any visible erosion was not detected for discharge in air (figure 6).
Figure 5. Schlieren photos (at ≈ 12 μs) of generated plasma and gas-dynamic flows in air (left) and neon (right): 1 – shock wave front, 2 – surface evaporation front, 3 – substrate with coating and 4 – copper screen.

Figure 6. Photography of surface of HfO₂/SiO₂ antireflection coating irradiated in neon and air (single exposure).

4. Conclusion
As found experimentally, compressed plasma flow generated a high brightness radiation. It is possible to control its maximum quanta energy by selection of gas composition in the chamber. For neon the maximum energy is about ≈ 20 eV, for air this value is lower (≈ 6 eV). The hard quanta cause evaporation and erosion of the HfO₂/SiO₂ antireflection coating. In the case of air these phenomena are not detected.

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