1. Janusz RYBAK, 2. Konstanty MARSZAŁEK[1]

AGH University of Krakow (1)
ORCID: 1. 0000-0003-1924-7970; 2. 0000-0002-0564-5743

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Investigation of the cosmic radiation effects on the components of a thin-film electrochromic system

***Abstract**. In the this study, the investigations of the effects of cosmic radiation on the components of a thin-film electrochromic system were carried out. Using spectroscopic ellipsometry, the thickness and optical properties of five layers before and after cosmic radiation exposure was characterized.. The analysis revealed minimal changes in thickness homogeneity and optical parameters, such as the refractive index and extinction coefficient. Transmittance measurements across the visible spectrum showed only minor differences within the measurement error range. These results suggest that cosmic radiation has a limited impact on the stability and performance of electrochromic components in space environments.*

***Streszczenie.** W badaniu oceniono wpływ promieniowania kosmicznego na komponenty cienkowarstwowego systemu elektrochromowego. Wykorzystując elipsometrię spektroskopową, scharakteryzowano grubość i właściwości optyczne pięciu warstw przed i po ekspozycji na promieniowanie kosmiczne. Analiza ujawniła minimalne zmiany w jednorodności grubości i parametrach optycznych, takich jak współczynnik załamania światła i ekstynkcji. Pomiar transmitancji w pełnym zakresie widzialnego spektrum wykazał drobne różnice w granicach błędu pomiarowego. Wyniki sugerują ograniczony wpływ promieniowania kosmicznego na stabilność i wydajność komponentów elektrochromowych w środowiskach kosmicznych. (**Badanie wpływu promieniowania kosmicznego na komponenty cienkowarstwowego systemu elektrochromowego**)*

Keywords: electrochromism, cosmic radiation, magnetron sputtering, optical properties
Słowa kluczowe: elektrochromizm, promieniowanie kosmiczne, rozpylanie magnetronowe, właściwości optyczne

Introduction

The rapid advancement of aerospace technologies and the increasing need for durable, energy-efficient materials have driven significant interest in studying the effects of cosmic radiation on advanced functional systems [1]. Among these systems, electrochromic materials, which can dynamically modulate their optical properties in response to an applied voltage, have attracted attention for their potential applications in space environments. Thin-film electrochromic systems, due to their lightweight structure and versatility, are particularly appealing for use in space missions, where weight and power efficiency are critical.

Cosmic radiation, comprising high-energy particles such as protons, neutrons, and heavy ions, presents a significant challenge to the durability and performance of materials in extraterrestrial environments. The interaction of these particles with matter can lead to ionization, displacement damage, and other forms of degradation at the atomic level, potentially affecting the long-term functionality of electrochromic systems. Electrochromic materials have promising applications in various fields, such as smart windows for energy-efficient buildings [2,3], adaptive spacecraft surfaces to regulate thermal control [4,5], and dynamic display technologies [6,7]. In space, they can also be used in optical filters or protective coatings, helping to manage light and heat exposure for satellites and other space structures. Understanding the specific effects of cosmic radiation on the optical properties of these thin-film electrochromic components is therefore essential for developing materials that can withstand prolonged exposure in space. A typical multilayer electrochromic system is composed of six layers [8,9]: S / TCO / EL / FIC / ISL / TCO, where: S means substrate, TCO - transparent conducting oxide, EF – electrochromic layer, FIC – fast ionic conductor and ISF – ion storage layer.

By analyzing the effects of cosmic radiation on these systems, this study aims to provide valuable insights that can support the development of more resilient electrochromic technologies capable of long-term operation in space environments. The research includes ellipsometric and spectrophotometric results of proton-irradiated layers, which are key components of the electrochromic system, allowing for an assessment of changes in their structure and optical properties i.e. refractive index (n) and extinction coefficient (k) under proton radiation exposure.

Materials and Methods

The layers used in the study were obtained by the three different techniques: WO_3 layer (electrochromic layer) and NiO layer (ion storage layer) – DC reactive magnetron sputtering, LiF layer (fast ionic conductor layer) - RF magnetron sputtering, ZnO:Al (transparent conductive oxide) - ALD process by Beneq P400A reactor. Before each sputtering process, a pre-sputtering process was carried out. In ALD process, the precursors diethylzine and trimethylaluminum were then alternated with distilled water over a period of 2 h. The opening times of the valves supplying the precursors and distilled water were 0.3 and 0.5 s, respectively. The substrate with applied indium tin oxide layer (ITO) was purchased from Kamami.

The magnetron sputtering processes parameters are shown in Table 1 and the ALD process parameters in Table 2.

Table 1. Magnetron sputtering process parameters

Layer	Time [min]	p [mbar] x 10^{-2}	Ar flow [sccm]	O_2 flow [sccm]	Temp [°C]	Power supply [W]
WO_3	30	2,06	16	4	400	100
LiF	60	1,17	35	-	200	100
			Ar:O_2 ratio			
NiO	2,5	4	1:1		RT	240

Table 2. ALD process parameters

Layer	Time [min]	p [mbar]	opening of the water valve [s]	opening of the precursor valve [s]	Temp [°C]
ZnO:Al	120	1	0,5	0,3	200

A J.A. Woollam M-2000 spectral ellipsometer equipped with light beam focusing collimators and COMPLETEEASE dedicated computer software was used for ellipsometry studies. The data acquired enabled the mapping of thickness homogeneity and optical parameters such as refractive index (n) and extinction coefficient (k). The ellipsometer used for the study is shown in Figure 1.

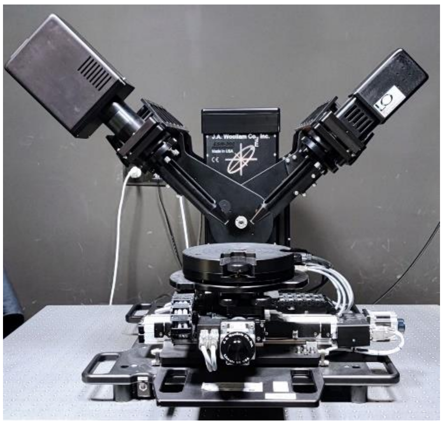

Fig. 1. J.A. Woollam spectroscopic ellipsometer used in studies.

Transmittance studies were carried out on an AVANTES spectrophotometer consisting of an AvaSpec-ULS-RS-TEC detector, an AvaLight-DH-S-BAL light source and dedicated computer software. Layer thickness measurements were carried out on a Taylor Hobson contact profilometer.

The irradiation of the layers with high-energy protons with an energy of 226.5 MeV and a fluence of $1x10^{15}m^{-2}$ was carried out at the Cyclotron Centre Bronowice at the Institute of Nuclear Physics Polish Academy of Sciences in Kraków. This dose corresponds to the exposure experienced over several hundred years in low Earth orbit.

Results

The thickness of each sample was measured using two independent methods - contact profilometry and spectroscopic ellipsometry. The thickness of the irradiated samples was measured by spectroscopic ellipsometry. The results of the measurements are shown in Table 3.

Table 3. Comparison of sample thicknesses

	ITO [nm]	WO_3 [nm]	LiF [nm]	NiO [nm]	ZnO:Al. [nm]
Contact profilometer	200	220	160	30	100
Average layer thickness from ellipsometric studies	189	215	155	30	104
Average layer thickness from ellipsometric studies after irradiation	189	216	157	31	103

Spectroscopic ellipsometry is an advanced analytical technique widely used to investigate the optical properties of thin films and surfaces [10,11]. This method relies on a two-step process: measuring the PSI and DELTA angles and fitting a theoretical model.

In the first step of spectroscopic ellipsometry, the PSI and DELTA angles are measured. These angles describe changes in the polarization of light reflected from the sample. The PSI angle relates to the amplitude of polarization, while the DELTA angle is associated with the phase. Accurate measurement of these angles requires precise equipment calibration and alignment, which is crucial for obtaining reliable results.

The second step involves fitting a theoretical model to the obtained data. During this phase, various optical models are applied to describe the properties of the material being studied, such as its thickness and optical parameters. Modern software enables sophisticated analysis and optimization of the model fitting, allowing for precise determination of material properties.

The recent advancements in ellipsometry systems include the use of collimators that focus the optical beam down to 140 microns. These collimators enable the concentration of the light beam onto a very small area, which is essential for thin film and surface studies. This enhancement allows for the generation of thickness homogeneity maps and precise determination of optical parameters, such as the refractive index and extinction coefficient.

In the study, thickness and optical homogeneity maps were created for each of the five layers both before and after irradiation. These maps provided detailed insights into the uniformity of the film thickness and the optical parameters, such as refractive index and extinction coefficient, across the surface of each layer.

The measurement process involved first characterizing the layers using spectroscopic ellipsometry to obtain baseline data on the thickness and optical properties. Subsequently, the samples were subjected to irradiation, and the measurements were repeated to assess any changes induced by this process.

Figures 2 and 3 show representative thickness homogeneity maps for the WO_3 layer before and after irradiation. The analysis of these maps indicates that there are no significant differences in thickness homogeneity between the pre- and post-irradiation states. Any visible differences are likely due to variations in the positioning of the sample on the measurement apparatus rather than actual changes in the layer thickness.

Similar results were observed for the other layers, suggesting that irradiation did not significantly affect the thickness homogeneity of the tested layers. The mentioned observations confirm the stability of the layer thickness and the effectiveness of the measurement method in monitoring potential changes in the material's structure.

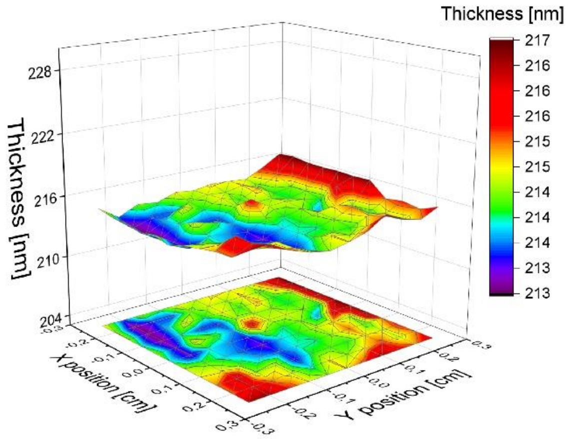

Fig. 2. WO_3 layer thickness homogeneity map before irradiation.

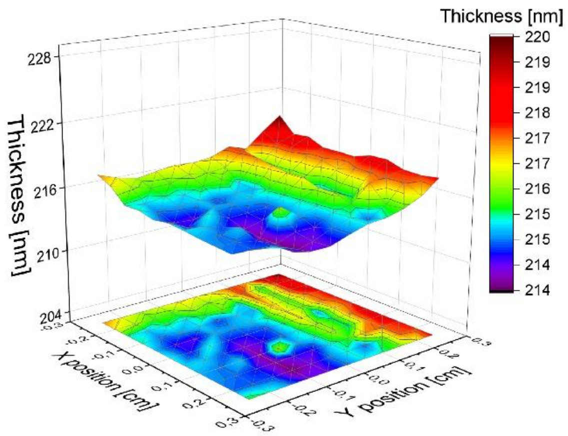

Fig. 3. WO_3 layer thickness homogeneity map after irradiation.

For all layers, homogeneity maps of the refractive index (n) and the extinction coefficient (k) were also created. Figures 4 and 5 present such maps of the refractive index for the ion conductor layer before and after irradiation. As with the thickness maps, no significant differences were observed between the pre- and post-irradiation states.

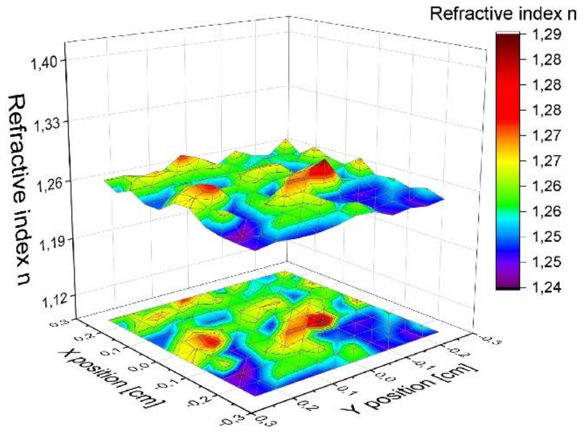

Fig. 4. LiF layer refractive index homogeneity map before irradiation.

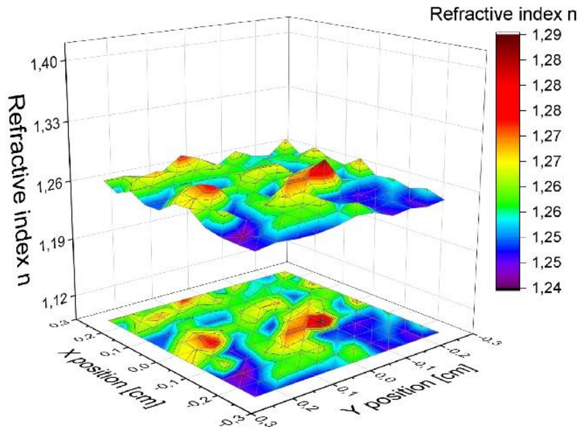

Fig. 5. LiF layer refractive index homogeneity map after irradiation.

Additionally, the maps demonstrate excellent uniformity of these optical parameters, indicating high homogeneity across the analyzed surfaces. This confirms the stability of the material's optical properties, even after the irradiation process.

Transmittance measurements for each layer were conducted using a spectrophotometer over the full visible light spectrum (380nm-780nm), both before and after irradiation. Each transmittance measurement was preceded by the collection of the dark signal to eliminate instrumental noise and a reference signal for accurate system calibration [12]. The reference sample used was the same substrate on which the investigated layer was deposited, ensuring that the influence of the substrate on the measured transmittance spectra was excluded. This measurement protocol provided high precision and allowed for reliable comparison of the transmittance of the layers before and after irradiation.

Figures 6 and 7 present the transmittance measurement results for the WO_3 and ZnO:Al layers, both before and after irradiation. The analysis of the mentioned results indicates minor differences in transmittance between the layers before and after irradiation; however, these differences fall within the measurement error range. This suggests that the effect of irradiation on the optical properties of these layers, in terms of transmittance, is minimal and does not lead to significant changes in the material structure in this regard.

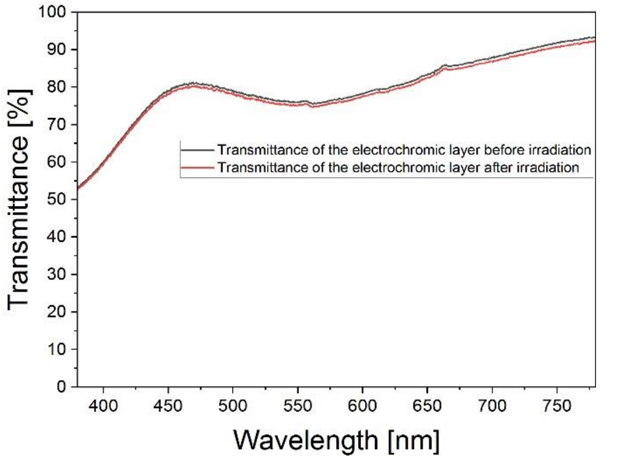

Fig. 6. Transmittance wavelength dependence diagrams for WO_3 before and after irradiation.

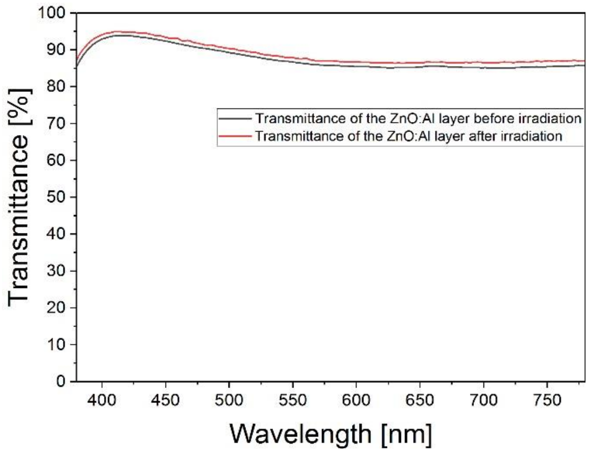

Fig. 7. Transmittance wavelength dependence diagrams for ZnO:Al before and after irradiation.

Similar conclusions can be drawn from the analysis of the optical spectra of the other investigated layers. In each case, the observed changes were minor and within the acceptable range of measurement error, confirming the optical stability of the materials studied. Thus, it can be concluded that irradiation did not significantly affect the transmittance properties of any of the tested layers.

Conclusions

This study demonstrated that cosmic radiation has a minimal impact on the structural and optical properties of the components in a thin-film electrochromic system. Both ellipsometric and transmittance measurements indicate that the layers retain their thickness uniformity and stability in optical parameters, such as the refractive index and extinction coefficient, after exposure to radiation. The observed differences were minor and fell within the measurement error range, suggesting that the layers are resistant to radiation and do not undergo significant changes as a result of exposure.

These findings confirm the high stability and resistance of thin-film electrochromic materials under conditions simulating space environments, making them promising candidates for aerospace and space technology applications. Their durability against cosmic radiation enhances their potential for use in environments where material stability is crucial to the reliability of devices. Future research should focus on long-term radiation exposure and the effects of varying radiation doses, providing deeper insights into the durability and performance of these materials in extreme space conditions.

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***Authors**: mgr inż. Janusz Rybak, Electronics Institute, AGH University of Science and Technology, Mickiewicza 30 Ave., 30-059 Kraków, Poland, E-mail: rybak@agh.edu.pl; dr hab. inż. Konstanty Marszalek prof. AGH, Electronics Institute, AGH University of Science and Technology, Mickiewicza 30 Ave., 30-059 Kraków, Poland, E-mail: marszale@agh.edu.pl*

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