



Publication Year	2016
Acceptance in OA	2020-07-22T11:22:34Z
Title	Optical components in harsh space environment
Authors	Pelizzo, Maria G., Corso, Alain Jody, Tassarolo, Enrico, Zuppella, P., Böttger, Roman, Huebner, Rene, DELLA CORTE, VINCENZO, PALUMBO, PASQUALE, Taglioni, G., Preti, G., Foggetta, Luca, Valente, Paolo, Rancoita, Piergiorgio, Martucci, Alessandro, Napolitani, Enrico
Publisher's version (DOI)	10.1117/12.2237966
Handle	http://hdl.handle.net/20.500.12386/26576
Serie	PROCEEDINGS OF SPIE
Volume	9981

PROCEEDINGS OF SPIE

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SPIE.

Event: SPIE Optical Engineering + Applications, 2016, San Diego, California, United States

Optical components in harsh space environment

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ABSTRACT

Space exploration is linked to the development of increasingly innovative instrumentation, able to withstand the operation environment, rich in ion particles and characterized by high temperatures. Future space missions such as JUICE and SOLAR ORBITER will operate in a very harsh and extreme environments. Electrons and ions are considered among the causes of potential damage of the optical instrumentation and components. Development of hard coatings capable to preserve their optical properties is pivotal. Different coating materials have been exposed to ion irradiation in particle accelerators. Change in optical performances has been observed in the extreme ultraviolet and visible spectral region and structural properties have been analyzed by different techniques. The knowledge of the damage mechanisms and thresholds allows the selection of more promising candidate materials to realize the optical components for the new frontiers space missions.

Keywords: optics, coatings, ions, electrons, irradiation, space

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1. INTRODUCTION

Begin Space components need to withstand extreme operational environments, rich of ions, characterized by high thermal excursion and UV irradiation. Accelerators are commonly used to simulate the particle irradiation on space components. By selecting ion energies and mission-lifetime-equivalent fluences, it is in principle possible to replicate the effects induced in space, even though flux rates in laboratory are orders of magnitudes higher with respect to real space conditions. This aspect has been addressed in the present work, by performing ion irradiation at different flux rates. However, the knowledge of the environment characteristics is usually limited, and thus the particles abundances are recovered starting from the available in-situ measurement and relying on scaling models. Moreover, the impact on the optical components needs to be calculated taking into account the physical path inside an instrument, the shielding and the spacecraft orientation. It is clear that such type of testing requires the contribution of different research and technological fields of competence, including particle and matter physics, which are necessary to understand the damage mechanism processes.

Although valuable experiments on the interaction of ions with coatings have been carried out [1-5], these are not always systematic: in fact, such studies are limited to specific values of energy and fluence of selected ions species and they generally have more the character of a qualification of a specific component with respect to its operation environment. A systematic study should take into account the penetration damage of the ions in the coatings, which depends on the species masses and energies, the type of the coating (single or multilayer) and the materials. For example, in the case of 1 keV protons (associated to the “quiet” solar wind), the ions are not so energetic, but they highly concentrate in the top of the surface (Fig.1). In case of 40 keV, they are more energetic and they are spread into the whole film. Such simulation are performed using SRIM/TRIM software, as discusses in the next section. Depending on the coating characteristics, in these two cases different potential damages can be expected, such as changes of the optical properties of the materials, inter-diffusion at interfaces due to elastic scattering interactions between the incident ions and the target atoms, delamination of layers or detachment from the substrate. With the intent of starting a systematic research on this topic, we carried out a first experiment with 1 keV protons to test the performance degradation of multilayer coatings. A detachment of the top layers for such nanoscale multilayer coatings has been proven at doses above 10^{16} H⁺/cm², equivalent to a 4 year Solar Orbiter space mission [6]. A second experiment with 4 keV He⁺ revealed a degradation of multilayer interfaces due to inter-diffusion with a consequent drop of extreme ultraviolet reflectance [7].

In the present paper we present the recent preliminary results of further experiments carried out on optical components considering the case of two major space missions of the European Space Agency (ESA): Solar Orbiter (SOLO) and JUperiter ICy moons Explorer (JUICE).

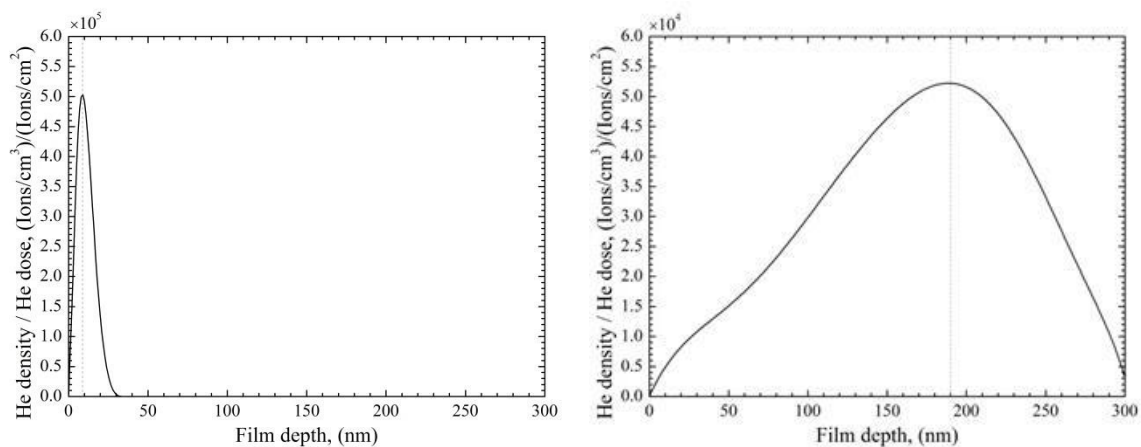


Figure.1 Left 1keV implanted proton distribution inside 300 nm gold layer. Right 40 keV implanted proton distribution inside 300 nm gold layer

2. IONS IRRADIATION OF COATINGS IN SUN CLOSE ENVIRONMENT

SOLO is a Sun-observing satellite which will approach the star at the closest distance ever reached (0.28 AU at the perihelion) providing observations with unprecedented temporal and spatial resolution [8]. The SOLO spacecraft will operate in a very harsh environment, which may cause severe degradation to space instrumentation. The “quiet” solar wind is considered a potential source of coatings degradation, due to its constant irradiation [9]. The solar wind is an outflow of completely ionized gas originating from the solar corona and expanding outwards the interplanetary regions, carrying the solar magnetic field along with it. It consists of protons and electrons with an admixture of alpha particles and of much less abundant heavy ions, such as O⁺⁶ and Fe⁺¹⁰. An implantation experiment with 4 keV He⁺ ions has been carried out on gold and platinum films deposited on a Si substrate coated by a 100 nm titanium layer, to simulate the effect of alpha particles.

Platinum and gold materials have been selected since they are widely used as mirror coatings for high reflectance in the vacuum ultraviolet (VUV) and visible (VIS) spectral range. The thickness of gold layer is about 100 nm, the platinum one is about 70 nm; such values have been defined in order to guarantee that all He⁺ ions stop inside the films. This has

been verified by simulations performed with TRIM/SRIM software [10] and later experimentally proved by Secondary Ion Mass Spectrometry (SIMS). TRIM/SRIM performs Monte Carlo simulations of elastic scattering interactions between the incident ions and the target atoms and provides data on implanted atoms and damage depth distributions as well as on surface sputtering. He+ ion energy of 4 keV has been specified and a statistics of total 99999 incident ions has been used. The simulation results reported in Fig.2 show the distribution of the incident ions inside the gold and platinum films.

The implantation parameters for the experiment have been selected in order to simulate the solar wind ions effect in the close sun environment during a space mission, such as the ESA Solar Orbiter, in particular considering four different fluences, which correspond to those accumulated during 1, 2, 4 and 6 years of mission operation. Samples have been implanted at the Low Energy Implanter (LEI) facility at the Ion Beam Center of the Helmholtz-Zentrum Dresden-Rossendorf (Germany). Experimental parameters of ion implantation sessions are reported in Table 1. Witness samples deposited in the same session haven't been implanted and kept as references. Different fluences have been realized by different flux rates varying the time of exposure.

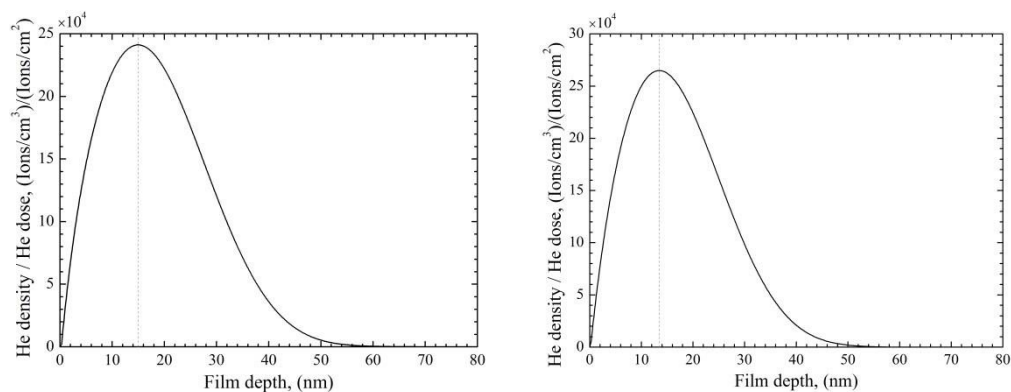


Figure.2 Distribution of He+ ions implanted in gold (left) and platinum (right) thin film as simulated by TRIM

Pt or Au Sample #	Fluence Alpha particles/cm ²	Flux Alpha particles/cm ² /s
1	A=2.6·10 ¹⁵	F1=1.5·10 ¹¹
2	A=2.6·10 ¹⁵	F2=3.0·10 ¹²
3	A=2.6·10 ¹⁵	F3=8.8·10 ¹²
4	B=5.2·10 ¹⁵	F1=1.5·10 ¹¹
5	B=5.2·10 ¹⁵	F2=3.0·10 ¹²
6	B=5.2·10 ¹⁵	F3=8.8·10 ¹²
7	C=10.4·10 ¹⁵	F1=1.5·10 ¹¹
8	C=10.4·10 ¹⁵	F2=3.0·10 ¹²
9	C=10.4·10 ¹⁵	F3=8.8·10 ¹²
10	D=15.6·10 ¹⁵	F1=1.5·10 ¹¹
11	D=15.6·10 ¹⁵	F2=3.0·10 ¹²
12	D=15.6·10 ¹⁵	F3=8.8·10 ¹²
Ref	-	-

Table.1 Experimental parameters for irradiation

Reflectance measurements have been performed in the visible (VIS) and in Lyman-α spectral region. The most significant results are those found in the UV range: for lower flux F1, the reflectance drops with the increment of fluence for both Pt (Fig.3) and Au samples. Such behavior was already observed in a previous experiment, and at that time attributed to a change in the optical properties of the films [11]. For example, proton implantation can lead to a decrease

of the layer density [12]. However, such huge degradation is not present if samples are irradiated at F2 and F3 fluxes (Fig.3). Vice versa, for each fluence value, a significant drop is present only in samples irradiated with F1, while for the other fluxes the reflectance is almost comparable with that of the reference sample. Such trends are consistently confirmed in all the measurement performed.

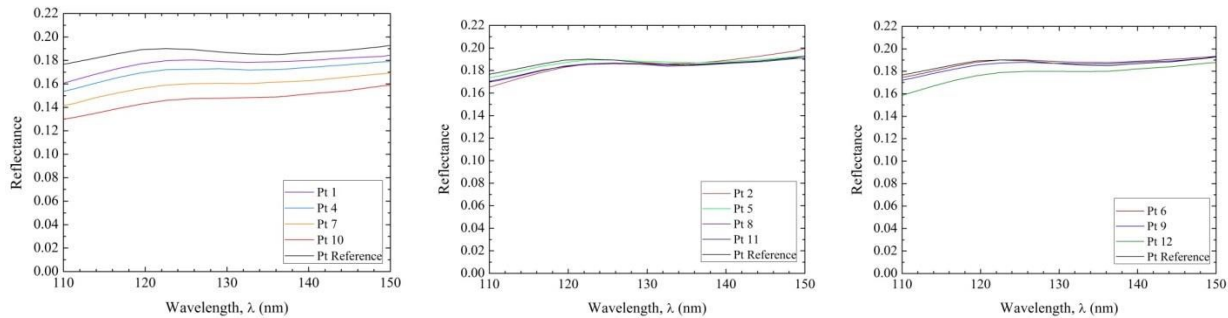


Figure.3 Reflectance of Pt sample irradiated with different flux and fluence parameters

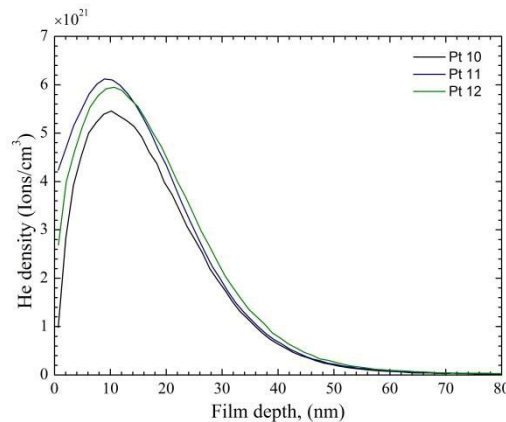


Figure.4 He⁺ implantation profile in sample Pt 10, 11 and 12 as measured by Secondary Ion Mass Spectrometry.

To verify that the ion implantation was performed successfully and the expected fluences are achieved regardless of the flux rate, Secondary Ion Mass Spectrometry (SIMS) has been carried out. The results show that the implantation profiles and fluences are comparable in all Pt samples treated with dose D, demonstrating that flux does not have any influence on the ion distribution inside the film. If compared with simulations reported in Fig.2, the implantation profile presents a small shift of its peak and an overall enlargement, which is compatible also with a lower density of the film with respect to values used in simulation. More in general, SIMS measurements demonstrate that the same implantation profile can be achieved regardless of the flux rate, thus suggesting the use of higher fluxes to reduce accelerator facilities occupation time. However, it is still unclear while only samples implanted with low flux rates show such a reflectance degradation. Our previous model was based only on the implantation profile and fluence, and given such experimental outcome is no longer valid on its own [11]. At the moment potential alternative/complementary explanations are mainly related to the presence of contamination due to longer exposure in chamber, including surface contamination; potential damage mechanisms or effects present at low flux (and not at higher ones) are also considered.

Further investigation are on-going, mostly devoted to search for structural modifications, i.e. X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) and chemical ones. Preliminary XRD measurements showed that the as deposited films are polycrystalline with a cubic structure, both in the case of Au and Pt films. After irradiation the grain size of both films are slightly affected, especially for the Au film. Further XRD analyses are in course. Atomic Force

Microscopy does not reveal any change of the local surface roughness, while Scanning Electron Microscopy (SEM) shows the presence of some defects on the gold surface (Fig.5), which are potential source of scattering effects.

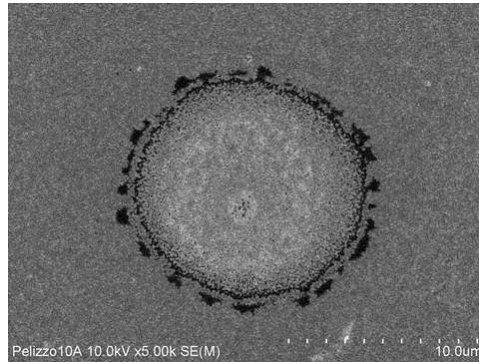


Fig.5 SEM revealing superficial defects on sample Au10.

3. ELECTRONS IRRADIATION ON OPTICAL COMPONENT ON BOARD OF JUICE

JUICE is the first large-class mission in ESA's Cosmic Vision 2015-2025 programme. It is planned to be launched in 2022. It will make observations of the planet Jupiter and three of its largest moons, Ganymede, Callisto and Europa [13]. The Jovian environment is predicted to be very harsh, rich of ions and in particular electrons, and optical and electronics components have to withstand such extreme conditions.

Jovis, Amorum ac Natorum Undique Scrutator (JANUS) is an optical camera on board of JUICE devoted to study global, regional and local morphology and processes on the moons, and to perform mapping of the clouds on Jupiter [14]. JANUS has an all-reflective optical configuration based on three mirrors (Fig.6). The selection of the different spectral bands of observation is made by a set of interferential filters mounted on a filter wheel placed in front of the detector. The filters are considered critical components in relation to their long-term stability when exposed to ions. In order to verify their long-term performances, a significant test has been carried out exposing one filter sample to electron irradiation.

Samples of interferential filters representative of JANUS optical components have been fabricated and provided by SELEX ES (now Leonardo Company). The filters were fully characterized for their optical transmission prior and after irradiation, both at Leonardo Company and at CNR-IFN using a double grating spectrophotometer. Electron bombardment has been carried out at Istituto Nazionale per la Fisica Nucleare – Laboratori Nazionali di Frascati (INFN-LNF, Italy) at the DAFNE Beam Test Facility (BTF).

A preliminary evaluation of electron fluxes and fluences on the filter has been carried out using the FASTRAD software, as provided by ESA. It allows to compute the particles intensity distribution over a selected optical component given the mechanical design of the instrument. The input related to the JUICE operation environment is provided by ESA. In Tab.2 the expected fluences for a three years mission are reported for different energies.

Simulations related to the penetration of electrons into the filter structure have been carried out using the software monte Carlo Simulation of electroNs in sOlids. Such software has been used improperly, since it's major use is related to the simulation of electron trajectories to represent the condition used to image structures in a scanning electron microscope (SEM). Such software practically allows only energies up to 1 MeV. Interferential filters based on TiO₂ and SiO₂ materials have been designed at CNR-IFN and optimized for the different spectral wavelengths according to JANUS requirements. Simulations show that below 1 MeV the minimum filter thickness d for which all electrons are collected is always lower than the filter coating total thickness (substrate not included), thus special care should be taken in testing lower energies.

The filter sample used in the irradiation experiment is 25 mm in diameter, the substrate is 3 mm thick fused silica and the spectral peak is centered at 865 nm. The selected energy was 50 MeV, which is the lower value compatible with the actual capability of the accelerator, and the total fluence released was about $2 \cdot 10^9 \text{ cm}^{-2}$. The electron beam distribution has been monitored during exposure.

After the irradiation, the filter transmission was measured again and compared with data obtained prior to electron irradiation. Two other reference filters were used as witnesses. No changes in transmittance have been detected (Fig.7).



Fig.6 Layout of Janus; the spectral filter position is marked in red.

Electron energy (MeV)	Fluence (e/cm^2)
10	$2.0 \cdot 10^{11}$
20	$2.5 \cdot 10^{10}$
50	$2.0 \cdot 10^9$
100	$3.0 \cdot 10^8$
200	$8.5 \cdot 10^7$

Tab.2 Expected electron fluences for a three years mission lifetime

4. CONCLUSIONS

The optical components and coatings degradation in space need to be investigated for applications to future space missions. Our results show that low energy ions (proton and alpha particles) can damage the structure of multilayer coatings in the nano scale range, affecting their optical response. Studies on single layer materials preliminary indicates that accelerated tests should be carried out at high flux rates to reduce contamination effects during irradiation, since according to our results flux rates does not affect the implantation profile in metals. Further studies are foreseen to

extend such investigations to other materials, type of coatings, ions species and energies. In particular, optical components for JUICE mission applications will be investigated. The results will be used to select the most promising candidate materials for hard coatings development and/or to adopt countermeasures to avoid potential degradation of the components. The results will also be important to address guidelines for the space qualification tests of optical coatings.

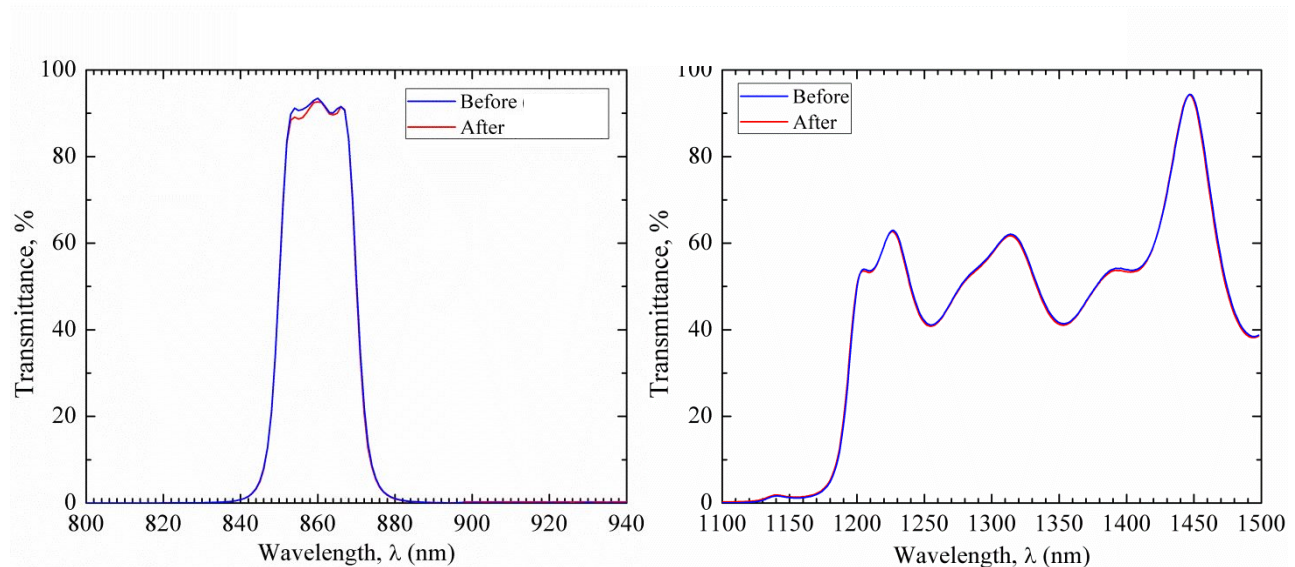


Fig.7: Filter transmittance before and after electrons irradiation.

ACKNOWLEDGMENTS

The authors thank Dr. A. Giglia and Prof. S. Nannarone for measurement at ELETTRA-BEAR beamline and Prof. Antonucci, METIS PI, Dr. Silvano Fineschi, G. Naletto and Marco Romoli. Parts of this research were carried out at IBC at the Helmholtz-Zentrum Dresden - Rossendorf e. V., a member of the Helmholtz Association. This work has been performed with the financial support of the Italian Space Agency (ASI/INAF/015/07/0, ASI/INAF/Solar Orbiter and ASI/INAF n. 2013-056-R.O).

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