Chapter 4

Ion Beams for Space Applications

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Additional information is available at the end of the chapter

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Abstract

This chapter uses an active space mission as well as current and ongoing research work to showcase the role of ion beams in the advancement of space science and technology. It uses the mission objectives of the ZACUBE-2 space mission developed at the Cape Peninsula University of Technology in Cape Town, South Africa, to predict the space environment it will encounter when in orbit. These predictions are then used to show how ion beam parameters for single event effect testing are selected, and how trade-offs are made to achieve a cost effective use of beam time. An experiment is detailed, showcasing the role of ion beams in the investigation of the shielding capabilities of coatings obtained from the pulsed laser ablation of W_2B_5/B_4C for solar panel applications in space. The results of this experiment show that indeed this is a potential shield capable of reducing solar panel degradation due to low energy protons. By using ZACUBE-2 and coatings made from W_2B_5/B_4C, this chapter takes a practical and current approach to demonstrate the central role played by ion beams in advancing space technology. More importantly, it eases the conversation between the satellite and the ion beam communities.

Keywords: ion beams, space applications, ZACUBE-2, W_2B_5/B_4C, radiation damage

1. Introduction

The objective of this chapter is to ease the conversation between satellite engineers, ion beam operators and contributors to fundamental science for whom ion beams are either a research tool or the very subject of their work.

Space is a very hostile environment for technology. Before sending any piece of technology to space, one must consider its likelihood to survive this environment made up of high energy ionising and non-ionising radiation. Spacecraft engineers consistently turn to ion beams to create environments similar to those in which their spacecraft are designed to dwell. The main reason for this is to ascertain the functionality of their technology in space. This can either mean testing existing/established technology for use under specific space conditions, or determining whether new technology can be space applicable.

Using a rather practical approach, this chapter brings to light the main aspects that are taken into account from a space science and technology point of view, when it comes to using ion beams to ensure the success of space missions and the advancement of space-related technology. It utilises an ongoing university space mission and related research and development to describe the role of ion beams in a typical space program.

The first step towards using ion beams for space related testing, is clarifying the space mission objectives. To describe this, the ZACUBE-2 satellite currently being tested prior to its launch scheduled for a June 2018 launch window, is used. This mission is designed by the French South African Institute of Technology (F'SATI) Space Program, which is housed at the Cape Peninsula University of Technology (CPUT) in Cape Town, South Africa [1].

The primary objective of ZACUBE-2 is the tracking of vessels within the South African continental shelf. The secondary objective is imaging applications such as ocean colour monitoring and fire tracking [1]. In order to meet these objectives, the satellite will have to be in a 550 km sun synchronous orbit with a 98° inclination for an estimated 2–4 years. ZACUBE-2 has an extremely important indirect objective, which is to demonstrate technology and serve as a precursor to a constellation of low earth orbit satellites whose mission will be continuous maritime vessel tracking and fire detection/monitoring. It is important to predict the space environment in which ZACUBE-2 will dwell in order to define appropriate test/experimental conditions for the future constellation satellites. This is because they will have similar orbit parameters, and each satellite is foreseen to carry at least one experimental/scientific payload. As will be mentioned further in this chapter, one of the future experimental payloads will be the in-orbit testing/measurement of the performance of novel and smart nanomaterials which have shown the potential to significantly increase functionality per unit mass in space. Knowing the space environment of ZACUBE-2 therefore informs the earth-based experiments carried out prior to the constellation design, one of which will be described in this chapter.

In space, a satellite is exposed to radiation from the Van Allen radiation belts (trapped particles), the sun (solar particles), and the galaxy (galactic cosmic radiation (GCR)). Thanks to in-orbit measured data it is now possible to model and predict the space environments that satellites are likely to encounter with relatively high levels of confidence. This can be done using software packages such as SPENVIS [2] or OMERE [3]. These models provide the individual contributions from each of the 3 main radiation sources for specified orbits. GCR are made up of particles ranging from protons to Uranium nuclei, with about 83.3% protons, 13.72% alpha particles, 2% electrons and 0.98% heavier nuclei. Their energies can vary from a few MeV/nucleon to a few GeV/nucleon [4, 5]. The sun emits mainly protons and electrons with energies ranging between about 100 eV to about 3.5 keV for protons [4]. Trapped particles consist of electrons of up to about 7 MeV, protons of up to about 600 MeV and heavier ions of less than about 50 MeV/nucleon [4]. It should be mentioned

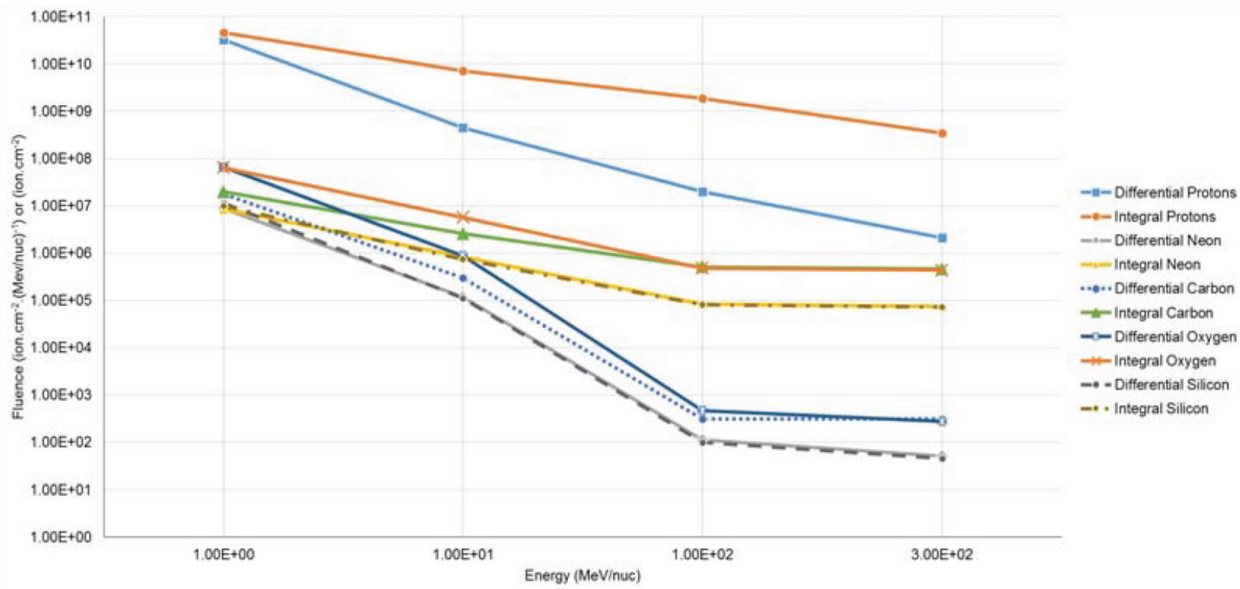

Figure 1. Expected proton, carbon, oxygen, neon and silicon total fluences as a function of energy for the ZACUBE-2 space mission for 4 years in orbit.

that sometimes considerable amounts of neutrons can be encountered in Low Earth Orbit (less than 1000 km altitude). When they occur, they are albedo neutrons coming from earth as a result of the interaction of GCR with the earth atmosphere [6].

In the case of ZACUBE-2, the predicted total fluence of protons, Carbon, Oxygen, Neon and Silicon from all radiation sources is shown in **Figure 1**. Although the range of ions present in the predicted environment for ZACUBE-2 includes more than only these ions, these are very likely to be used for testing purposes. Indeed, protons are the principal source of degradation in space due to ionising particle. This is either directly at low energies (direct ionisation of SRAM memory cells, or solar cell degradation for instance), or indirectly at high energies (by generating secondary heavier ions within devices, which in turn degrade the device functionality). A curve similar to **Figure 1** can be generated for any ion predicted to be present in the intended space mission. This can help define test conditions based on the capabilities of specific ion beam facilities.

2. Ion beams towards space radiation testing

With a clear prediction of the total fluence of protons and heavy ions of various energies that ZACUBE-2 will encounter during an estimated 4 years in orbit, one would seek out test facilities capable of providing protons and other test ions of the appropriate energy ranges. It is indeed after similar simulations and predictions that satellite engineers typically seek out and book time at selected ion beam (accelerator) facilities among the many that are available around the world. The radiation tests, which are in fact single event effect (SEE) tests when they involve damaging electronic devices, are then planned and prepared as a collaborative effort between ion beam operators and mission engineers (typically the radiation engineer or space radiation subject matter expert). This planning ensures the test hardware, software, and ion beam configuration are optimal to ensure the most cost effective use of the booked beam time.

While the dosimetry is generally carried out by the party providing the ion beam, engineers may or may not need to double check the dosimetry. A quick way to do this can be seen in [7]. That being said, for ions, a simple calculation can be performed to determine the particle flux as a function of the beam diameter and the beam current.

$$Flux(particles/s/cm^2) = \frac{IN}{\pi\left(\frac{d}{2}\right)^2} \tag{1}$$

where I is the beam current in Ampere (Coulomb/s), $N = 1/|particle\ charge|$ is the number of particles per Coulomb (ions/Coulomb) of charge in the beam, and d is the beam diameter in cm. If, for instance, the beam is a proton beam, then $N_{protons} = 1/1.6 \times 10^{-19} = 6.25 \times 10^{18}\, protons/Coulomb$.

Such an analytical particle flux can always be validated by using a thermoluminescent dosimeter (TLD) to measure the particle fluence (in particles/cm^2) for a specified duration.

Mission engineers can use Eq. (1) to work out specific requirements to be sent to beam operators in terms of determining the best trade-off between the flux and the time it takes to achieve the desired fluence, given the beam time available and the nature of the test to be carried out. To test for single event latch-up (SEL), for instance, it is important that the flux be low enough to characterise the SEL cross section, yet high enough to complete the experiments (achieve the desired total fluence) within a reasonable time frame [7].

Before 2013, SEE testing was mainly done at energies higher than 60 MeV, be it for protons or heavy ions. It was in October 2013 that standards for proton testing at energies below 5 MeV were first published in JEDEC's JESD234 release. At the time this chapter is written, there is no commonly accepted standard for heavy ion SEE testing at energies in the 5 MeV range. Be that as it may, when it comes to testing with heavy ions or with low energy protons, it is very important to know as much as possible about the materials that constitute the device being tested. This is because the devices to be tested must be delided (either by wet or dry etching), and this requires knowledge of the materials that constitute the device lid and overlayers. Furthermore, Monte Carlo based simulation packages such as SRIM [8] can be used to calculate the linear energy transfer (LET) of ions as they traverse different layers of materials. This is because even after etching, it is highly likely that there will still be a certain thickness of material left. In order to estimate the energy at which incident ions reach the actual device die, such simulation packages require prior knowledge of the stoichiometry of the traversed materials. Relatively precise knowledge of the chemistry of the layers of materials that are in the device can be acquired by the use of a combination of certain ion beam characterisation methods. This would require sacrificing a device by carefully cutting it in two to expose a vertical cross-section of the interior. A combination of micro-scale particle induced x-ray emission (micro-PIXE) and Rutherford backscattering (RBS), for instance, can provide a detailed knowledge of the elements present within each layer of material and their relative atomic percentages. This should be enough to run a meaningful SRIM simulation. Should there be a need for more precision, further material characterisation such as x-ray diffraction (XRD) and/or x-ray photoelectron spectroscopy (XPS) can be performed on the device cross-section.

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3. Space applicability of innovative technology solutions

CPUT, through F'SATI and the African space innovation (ASI), has a very strong innovation agenda when it comes to space science and technology. The research activities that result from this drive appropriately illustrate the role ion beams can play when it comes to advancing satellite technology.

With a focus on the space applicability of innovative technology solutions, there are ongoing collaborative research projects being carried out between CPUT/F'SATI/ASI and the National Research Foundation iThemba Laboratory for Accelerator Based Sciences (NRF/iThemba LABS). One of the experiments from this collaboration is detailed in this section to give a practical illustration of how central ion beams have been so far.

Scientific payloads are being designed to investigate the in-orbit performance of two coatings. These are vanadium dioxide (VO_2) coatings and coatings made from W_2B_5/B_4C ceramic composite. While VO_2 smart coatings can provide entirely passive thermal regulation (no power or circuitry is required), coatings made from W_2B_5/B_4C are promising potential nanoscale space radiation shields. Both materials will most likely be part of the scientific payloads in the constellation for which ZACUBE-2 is a precursor. It is therefore necessary to investigate how they are affected by radiation. This is done by irradiating the coatings with particles that are predicted to be encountered, and at the energies at which they are predicted to be encountered. The results of similar experiments can be seen in [9–14].

For this chapter, an experiment is described in which a coating obtained from the pulsed laser ablation of W_2B_5/B_4C was irradiated with 1 MeV protons. This energy is justified by its relatively large proton population predicted in **Figure 1**. Indeed, **Figure 1** indicates that ZACUBE-2 will be exposed to about 8×10^9 protons/cm^2 1 MeV protons (differential fluence over 4 years), and about 9×10^{10} protons/cm^2 of energies greater than 1 MeV (integral fluence over 4 years). One as-deposited sample was used as control sample and three were irradiated at fluences of 1×10^{15} protons/cm^2, 3×10^{15} protons/cm^2, and 5×10^{15} protons/cm^2. While these fluences are higher than those predicted in **Figure 1**, they are large enough to have a deeper understanding of the coating. The structural effects of the incident protons, and the optical transmission measurements in the Ultraviolet, Visible and near Infrared range were investigated. This was to find out whether this coating showed any indication that it could potentially shield solar panels from 1 MeV protons in space.

3.1. Experiment material and methods

The coating was synthesised using a technique called pulsed laser deposition (PLD). With PLD, a target material is ablated with a laser into a plasma plume which then grows as a film/coating onto a substrate. The target used for this deposition was the same B_4C/W_2B_5 pellet used in previous related experiments [9, 10]. The composition of this target was confirmed using XRD [9, 10], and its purity was investigated using yet another ion beam technique called heavy ion elastic recoil detection analysis (ERDA) [15]. The heavy ion ERDA revealed an oxygen contamination of about 10% in the target [9, 10].

The substrates were cut from soda lime corning glass and were approximately 1 × 1 cm in dimension. They were cleaned using a BRANSONIC ultrasonic cleaner (70 W, 42 kHz, ±6%). They were immersed in methanol, acetone, trichloroethylene, distilled water and methanol again for 5 minutes each in an ultrasound water bath. Although for the targeted applications the coatings are to be deposited directly on solar panels, glass was used as substrate for coating characterisation purposes.

The PLD was done using a Q-switched 3rd harmonic Nd − Y AG (Spectra Physics) laser with a wavelength of 355 nm and a frequency of 10 Hz. The laser fluence was $3.265 J/cm^2$. The deposition time was 5 minutes for four identical samples. The target was 3.7 cm away from the substrate in a vacuum chamber at 4×10^{-5} $mbar$. The deposition was carried out at room temperature.

The samples were irradiated with a focused proton beam emanating from the standard Van De Graaf accelerator based at the materials research department of iThemba LABS (this has been upgraded to a tandetron accelerator). The proton energy was set to 1 MeV, the beam diameter was 6 mm and the beam current was maintained at 10 nA. The proton flux was 2×10^{11} protons/cm^2/s and three samples were irradiated at fluences of 1×10^{15} protons/cm^2, 3×10^{15} protons/cm^2, and 5×10^{15} protons/cm^2 at room temperature in a vacuum chamber at 5×10^{-6} mbar. The fourth sample was not irradiated and was used as control sample.

Scanning electron microscopy (SEM) was used to study the structural effects of the proton irradiation on the coatings. This was done with a Zeiss Auriga field emission gun SEM (FEG-SEM) operated at 5 kV for secondary electron imaging, using an inlens detector and 20 kV for energy dispersive spectroscopy (EDS) analysis. The EDS spectra were collected using an Oxford Instruments X-Max solid-state silicon drift detector.

3.2. Results and discussion

The XRD characterisation of the synthesised coating was consistent with the coatings deposited in [9], where a good understanding of the coating (which do not have the same stoichiometry as the target) can be found.

Figure 2a–d shows the SEM images of the control sample and the samples irradiated at 1×10^{15} protons/cm^2, 3×10^{15} protons/cm^2, and 5×10^{15} protons/cm^2 respectively. One can notice the absence of the droplets that characterise PLD in all the samples. This means that during deposition, the laser beam energy was low enough that there was no sub-surface melting when the laser interacted with the target. Also noticeable are the cracks on the surface of the coatings. These cracks appear on all the samples, meaning they are not caused by irradiation.

Figure 2a shows a sample of the rods that are formed on the coating during deposition. These rods are, on average, about 10 μm long and about 1 μm wide, except for a few, like the rod in **Figure 2b**. On average, there are only about 2 rods in every 100 μm^2. One can suggest that the W content of the coating coupled with the high temperatures inherent to the PLD process might have favoured the formation of these rods [16–20]. However, their formation mechanism is not fully understood yet, mainly because of the way in which they melt under proton irradiation. Indeed, after a fluence of 1×10^{15} protons/cm^{2}as seen in **Figure 2b**, the surfaces of the rods appear to weaken, revealing a rough pattern from underneath. This is the first of

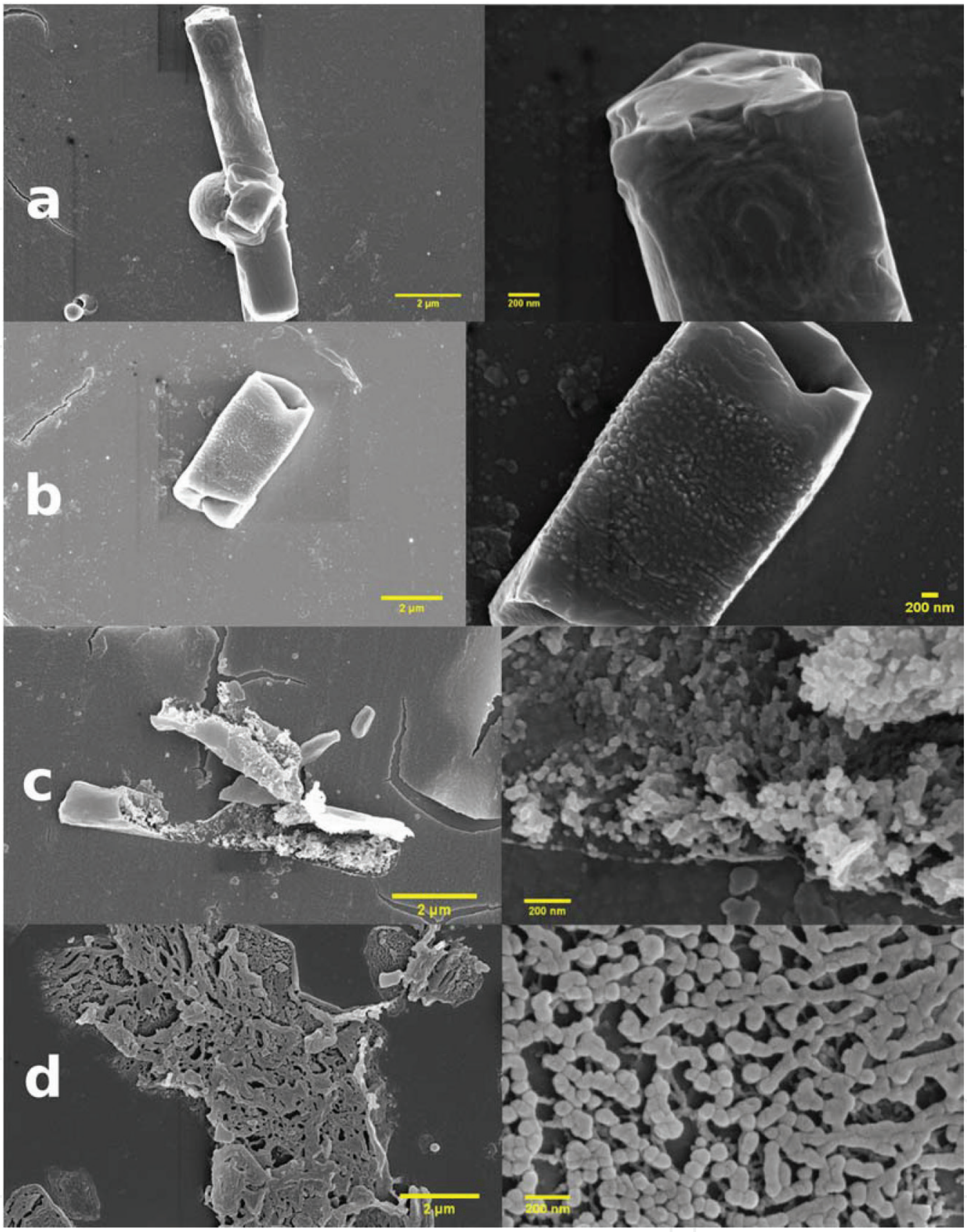

Figure 2. SEM images of non-irradiated and irradiated coatings. (a) as deposited, (b) at 1×10^{15} protons/cm^2, (c) at 3×10^{15} protons/cm^2, (d) at 5×10^{15} protons/cm^2.

three peculiar phenomena observed during the melting of these rods. **Figure 2c** shows the second phenomenon, which occurs after a fluence of 3×10^{15} protons/cm^2. The rod `skins' break open, exposing a very large amount of clustered nanospheres about 60 nm in diameter each. This observation suggests that the rods were in fact sealed enclosures containing nanospheres, analogous to coffee shop sugar sachets if they were completely full. It would be rather speculative to plausibly propose how such rods may have formed a this stage. The third phenomenon is the melting of the exposed nanospheres into the floor of the coating, as shown in **Figure 2d**. These nanospheres also appear to merge as they melt. As with a previous experiment involving 900 keV proton irradiation, these observations also show strong evidence of lateral diffusion of the energy lost to the coating by the incident protons [10]. It is, however, difficult to predict what would happen at higher proton fluences. Intuitively one may suggest that the nanospheres would completely melt and disappear into the coating, but it is not impossible that unexpected phenomena occur, similar to the rod growth described by Tadadjeu et al. [10].

The atomic percentages of, respectively, B, C, W and O, on top and beneath the cracked surface are approximately the same. This observation strongly suggests a layer-by-layer growth as proposed by Frank and Van der Merwe [21]. There is, however, an inconsistency in that Frank-Van der Merwe growth generally occurs in homoepitaxy, which is not the case of this coating since the substrate and the coating are made up of different materials. A Volmer-Weber growth [22], however, is consistent with heteroepitaxy but does not account for the observed layers. The latter observations and remarks are a very strong indication of a different growth mechanism, the reversed Stranski-Krastanov growth mode. In this mode, unlike in the Stranski-Krastanov growth mode [23], the early stages of the growth starts with nucleation, island formation and coalescence (consistent with heteroepitaxy and with the work

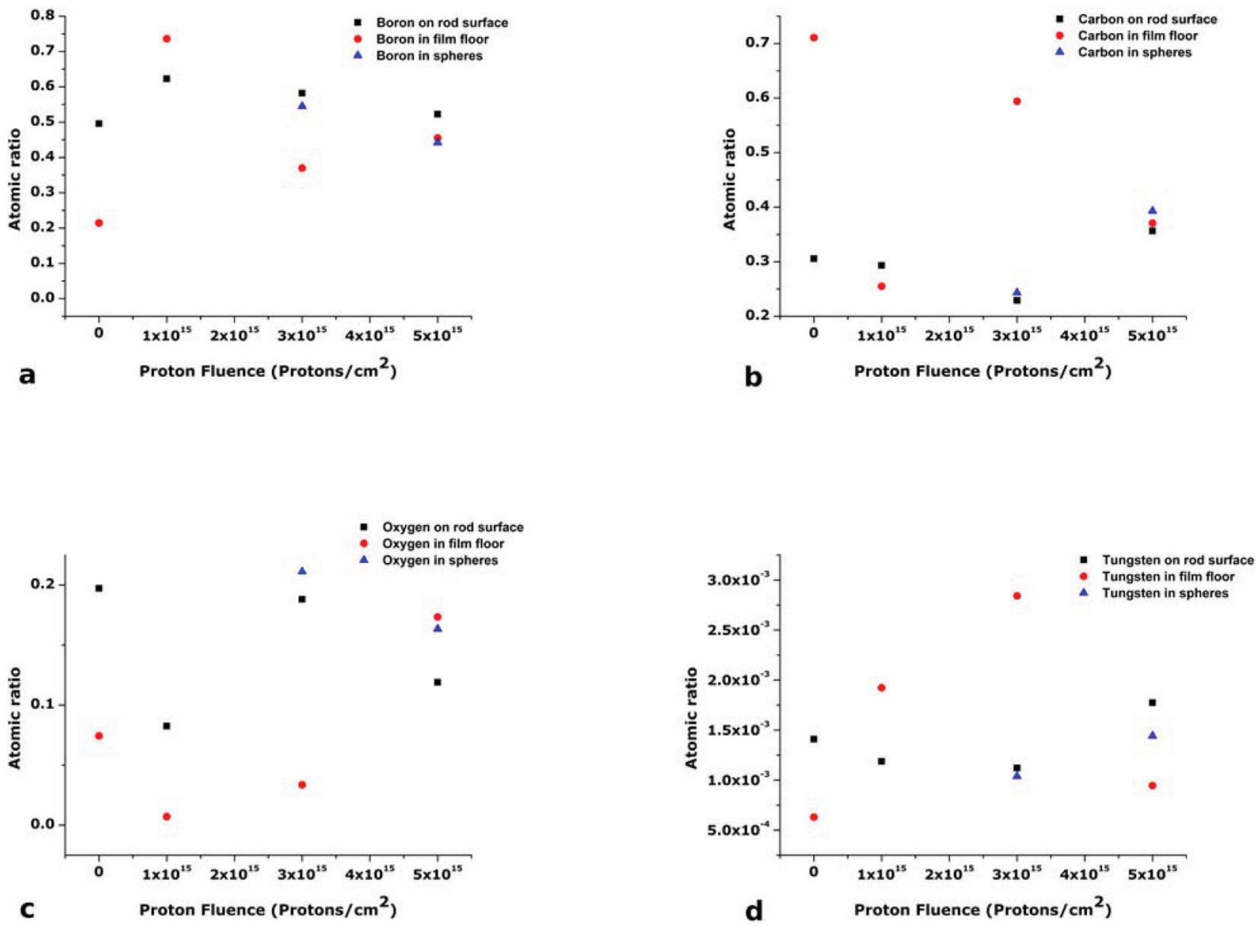

Figure 3. Atomic percentage distribution per element as a function of proton fluence. (a) B atomic percentage distribution, (b) C atomic percentage distribution, (c) O atomic percentage distribution, (d) W atomic percentage distribution.

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published by Tadadjeu et al. on the same coating [9]). After coalescence, the film surface becomes an apparent homoepitactic substrate, favouring a Frank-Van der Merwe growth. Chen et al. reported this mode to grow GaN films on Si(111), but he had to induce it through temperature ramping to 1050°C [24]. In this work, this growth mode occurs at room temperature under the specified deposition conditions.

Figure 3a–d shows the atomic percentages of B, C, O and W in the coatings as a function of proton fluence. It is difficult to explain the trends in atomic percentages before the rods break open. This is because the phenomenon in itself is not yet explained. Of particular interest, however, is what happens after the rods break open (at 3×10^{15} protons/cm^2). In **Figure 3a**, B is seen to steadily reduce in the rod surface and in the nanospheres, while at the same time increasing in the floor as the proton fluence increases. O follows the same trend as seen in **Figure 3c**. This trend is to be expected from melting nanostructures, and was previously observed [10]. In **Figure 3b**, C increases steadily in the rod surface and in the nanospheres as it decreases in the floor with an increase in proton fluence. W follows the same trend as seen in **Figure 3d**. These trends suggest that it is possible that nanostructures start forming at higher fluences, just like they did when the atomic percentage of W increased in the nanorods in Tadadjeu et al.'s observations [10]. Indeed, protons lose energy to matter through ionising processes, and non-ionising processes such as the thermal excitation of atoms [25]. Thermal excitation has been reported to favour the growth of nanorods in the presence of Zinc [26] and Tungsten [16] as catalysts. Furthermore, WC nanorods were reported to be synthesised in processes where WO_3 nanorods and thermal treatment played a key role [17–20].

In a broader observation, the melting and the evidence of potential nanostructure formation suggest that at least part of the energy lost by the protons to the coating is dissipated in its

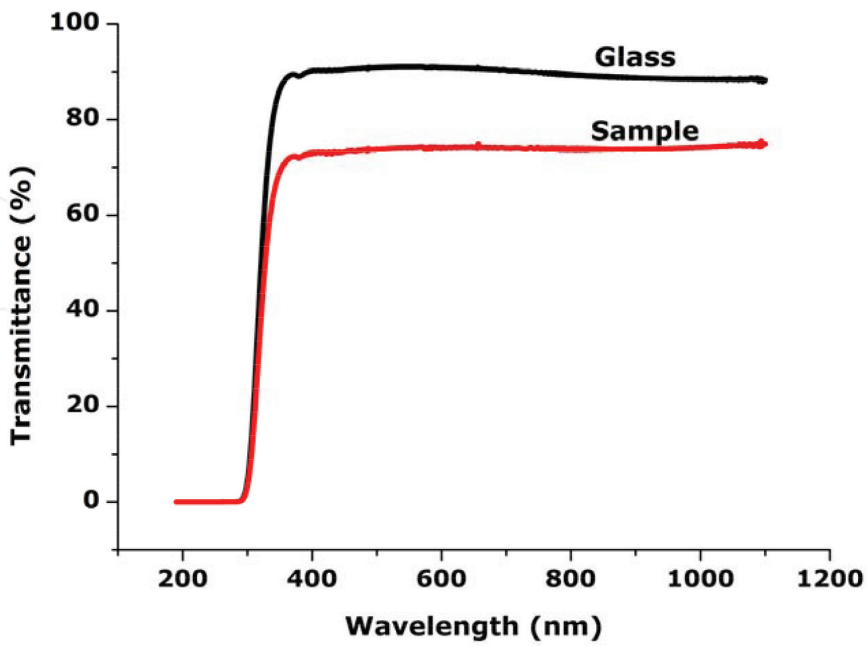

Figure 4. Percentage transmittance of the control sample relative to the glass substrate in the UV–visible and near-IR ranges.

surface rather than being transferred across itself. This makes the coating a promising shield against low energy protons in space.

Given that this experiment was geared towards solar panel shielding, it was necessary to investigate the transparency of the coating. This is to verify that the coating does not compromise the power yield of the panel it is meant to protect. **Figure 4** shows the percentage transmittance of the control sample relative to the glass substrate used at room temperature. While the substrate was about 90% transmitting across the near ultraviolet through the visible to the near infrared spectrum, the coating was about 73% transmitting in the same range. This is promising for solar panel applications in space, as it shows that this coating can be used as a shield to reduce the contribution of low energy protons to solar panel degradation, if its transmittance is deemed acceptable. The implementation of this application, however, would require further testing and optimisation, including the post-irradiation optical characterisation of the coating.

4. Conclusion

This chapter used a space mission and related research work, both active and ongoing at the time it was written, to showcase the role of ion beams in the advancement of space science and technology. The thought process and the factors that guide the specificity of beam parameters for space related testing were described using ZACUBE-2. An experiment that investigated the shielding capability of coatings made from W_2B_5/B_4C for solar panel applications in space was described in details. This experiment showed how a novel space applicable material can be investigated both at a fundamental level and at an application level with the help of ion beams. With a very practical, fresh and current approach, this chapter provides information that can help:

- Satellite engineers to better plan their SEE and related tests, and communicate their needs to ion beam facilities
- Ion beam facilities to better understand and serve the needs of the space community
- Satellite subsystems and device designers to understand how ion beams can contribute to the advancement of their technologies
- The satellite engineering and the ion beam communities to have a broader awareness of each other, which can enhance collaborative and innovative work

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Conflict of interest

We, the named authors of the paper titled "Ion Beams for Space Applications", confirm that the chapter contains nothing defamatory, and that it may be submitted to IntechOpen with a view to publication as a chapter in the book titled "Ion Beams".

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We wish to confirm that there are no known conflicts of interest associated with this publication.

There are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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