Nuclear Instruments and Methods in Physics Research B 348 (2015) 251–254

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Hypervelocity dust impact craters on photovoltaic devices imaged by ion beam induced charge

Changyi Yang [a], Yiyong Wu [b], Gang Lv [b], Sergey Rubanov [c], David N. Jamieson [a],*

[a] School of Physics, University of Melbourne, Parkville, VIC 3010, Australia
[b] National Key Laboratory of Materials Behavior and Evaluation Technology in Space Environments, Harbin Institute of Technology, Harbin, China
[c] Bio21 Molecular Science and Biotechnology Institute, University of Melbourne, Parkville, VIC 3010, Australia

ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form 16 December 2014
Accepted 19 December 2014
Available online 20 January 2015

Keywords:
IBIC
Nuclear microprobe
Photovoltaics
Ion beam induced charge

ABSTRACT

Hypervelocity dust has a speed of greater than 5 km/s and is a significant problem for equipment deployed in space such as satellites because of impacts that damage vulnerable components. Photovoltaic (PV) arrays are especially vulnerable because of their large surface area and the performance can be degraded owing to the disruption of the structure of the junction in the cells making up the array. Satellite PV arrays returned to Earth after service in orbit reveal a large number of craters larger than 5 μm in diameter arising from hypervelocity dust impacts. Extensive prior work has been done on the analysis of the morphology of craters in PV cells to understand the origin of the micrometeoroid that caused the crater and to study the corresponding mechanical damage to the structure of the cell. Generally, about half the craters arise from natural micrometeoroids, about one third from artificial Al-rich debris, probably from solid rocket exhausts, and the remainder from miscellaneous sources both known and unknown. However to date there has not been a microscopic study of the degradation of the electrical characteristics of PV cells exposed to hypervelocity dust impacts. Here we present an ion beam induced charge (IBIC) pilot study by a 2 MeV He microbeam of craters induced on a Hamamatsu PIN diode exposed to artificial hypervelocity Al dust from a dust accelerator. Numerous 5–30 μm diameter craters were identified and the charge collection efficiency of the crater and surrounds mapped with IBIC with bias voltages between 0 and 20 V. At highest bias, it was found the efficiency of the crater had been degraded by about 20% compared to the surrounding material. The speed distribution achieved in the Al dust accelerator was peaked at about 4 km/s compared to 11–68 km/s for dust encountered in low Earth orbit. We are able to extrapolate the charge collection efficiency degradation rate of unbiased cells in space based on our current measurements and the differences in the structure of the targets.

1. Introduction

The impact of ubiquitous space debris encountered by spacecraft in low Earth orbit results in numerous impact craters and holes in solar arrays from micrometres to several millimeters in size [1,2]. In the case of the Hubble Space Telescope (HST), extensive studies have been performed on solar arrays returned to Earth after service in low Earth orbit. The cells in these arrays are based on silicon and comprise a 150 μm thick cover glass bonded with a 40 μm thick adhesive layer to a 250 μm thick silicon photovoltaic (PV) layer and a ∼250 μm backing layer of complex structure [2]. Thin tracks of Al spaced 1.25 mm apart form the front contacts to the PV layer with the back contacts forming part of the backing layer. Damage is observed from debris impacts with both the front and back surfaces and a number of impacts penetrate completely through the front or back layers to reach the PV layer, or blast a hole completely through the whole multilayer structure. From a combination of theory and experiment [2], the cumulative flux of impact craters of diameter d (i.e. the flux of the specified diameter or larger) ranges from around 4000 impacts/m^2/year for $d = 1$ μm, ∼1000 impacts/m^2/year for $d = 10$ μm, 130 impacts/m^2/year for $d = 100$ μm, 3 impacts/m^2/year for $d = 1$ mm and less than 1 impact/m^2/100 year for d greater than 5 mm. Here d is defined to be the diameter of the conchoidal spallation which is roughly correlated with the diameter of the damage to the cover glass visible in an optical microscope. Degradation of the solar array can occur because of mechanical damage to the structure of the cell including electrical contacts or from occultation of the PV layer from spallation of the cover glass. The depth of a crater is typically

---

* Corresponding author.
E-mail address: d.jamieson@unimelb.edu.au (D.N. Jamieson).

http://dx.doi.org/10.1016/j.nimb.2014.12.069

4 or 5 times less than d [3], however cracks from the crater may extend into the PV layer from both front and back impacts even if the crater does not reach the PV layer itself.

Analysis of the HST projectile residue alloyed with molten glass in a thin surface layer within the melt pit in the centre of the crater by analytical electron microscopy has identified the likely origins of the projectiles [3,4]. Important elements are C, Cl, S, P, Ca, Mg, Cr, Ni, Fe and Al. The smaller craters ($d < 50$ μm) that have an identifiable trace elemental signature consist of about 30% from micrometeoroids and 70% from solid rocket combustion products (Al rich). Larger craters are mainly from micrometeoroids. About 25% of all craters have unknown origin and would probably benefit from more sensitive trace element analysis by proton induced X-ray emission in a nuclear microprobe.

Further studies have led to the development of detailed theoretical models for the degradation of the panel performance as a function of the crater diameter, projectile diameter and speed [5]. This study shows that the overall degradation of a panel in Low Earth Orbit (LEO) will be between 0.2 and 0.25% per year, but that the degradation is highly heterogeneous with 5 to 10% power loss possible for 10–20 large impacts. In adverse environments, such as those experienced by the Vega comet probe, more than 50% power loss occurred as a result of passage through the comet dust cloud [5]. In addition to the permanent mechanical disruption to the cell, transients associated with electrostatic effects can also be observed [6] and precautions have to be taken to ensure that accumulated charge can be dissipated to avoid exceeding the electrical stress limits of spacecraft structures.

Our model system in the present paper examines craters in the Class III category of impacts where the crater penetrates into the PV layer using the European Space Agency classification scheme [7].

2. Experiment

Measuring the degradation at the micrometre scale of the actual PV systems deployed in space is difficult because of the large capacitance of the cells which causes instrumentation difficulties associated with the controlled injection and measurement of charge. We have therefore elected to use a model system to examine the first order effects associated with projectile impact that is easier to manage but provides insights into the expected phenomena. Some previous studies with model systems have been done on crater residues produced by projectiles of known composition from light-gas-guns [8] accelerated to ~5 km/s. That prior work confirmed that the resulting impact morphologies were very similar to those from low-earth-orbit residues (11–68 km/s). However that prior work was not extended to examination of electrical degradation.

Electrostatic dust accelerators are available to simulate hypervelocity micrometeorite impacts. These accelerators employ similar technology to ion beam accelerators [9]. In our experiments (see Fig. 1) Hamamatsu p-i-n diodes type S1223 were exposed to hypervelocity dust from the Harbin space dust simulator system. This system employs an electrostatic accelerator of micrometre-sized particles in the National Key Laboratory of Materials Behavior and Evaluation Technology in Space Environments, Harbin Institute of Technology, China. In the particle accelerator Al particles of diameter ~5 μm were first charged by a specially designed charging tip and then accelerated using electric fields. The velocity distribution of the particles has a peak at 4 km/s. Particle charging, acceleration and target impact is done in vacuum and a single burst of particles constituted the exposure of the sample with a fluence of ~10 impacts over the 3×3 mm^2 area of the sample. During the exposure to particle impact the p-i-n diodes were grounded.

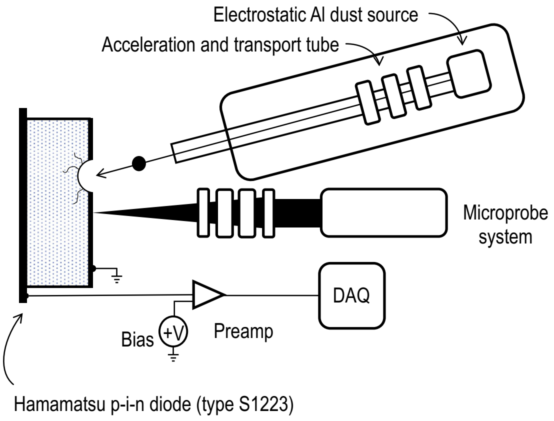

Fig. 1. Schematic of the experimental arrangements used to expose the p-i-n diodes to hypervelocity dust impacts in Harbin followed by IBIC imaging in Melbourne.

The p-i-n diodes have a nominal 120 nm thick SiO_2 passive surface layer covering the 300 μm thick active p-i-n structure. Although the peak of the present dust velocity distribution is lower than LEO, the p-i-n diodes do not have the thick surface layers protecting the active regions of the device typical of PV systems used in space. Hence in our experiments the thin SiO_2 surface layer is readily penetrated by the dust impacts. Therefore, as expected following exposure to the dust impacts the p-i-n diodes exhibited craters that extended into the active p-i-n layer when examined with optical and scanning electron microscopy. Numerous impact craters were identified along with unidentified particles of various sizes attached to the surface of the sample. Representative scanning electron microscope (SEM) images of the impact craters are shown in Fig. 2. It is evident that there is a variety of crater sizes and morphology which most likely results from the wide velocity and mass distribution of the hypervelocity Al dust particles. The features observed are broadly similar to those reported from LEO impacts [7]. Cross sectional images (not shown) were also taken of the craters and these revealed that the craters were very shallow with a large diameter to depth ratio greater than 20:1. Occultation

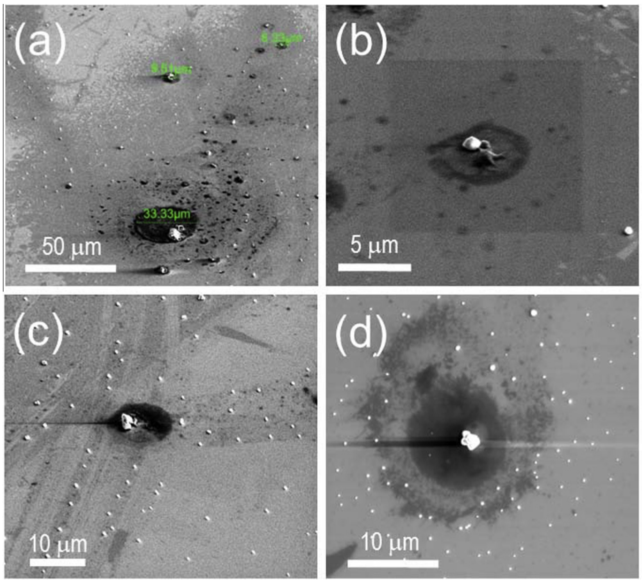

Fig. 2. SEM images of dust impact craters in different areas of a Hamamatsu p-i-n diode type S1223 from 5 μm diameter Al dust particles: (a) ~30 μm diameter crater, (b and c) representative ~5 μm diameter craters, (d) ~10 μm diameter crater.