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Ground Test for Spacecraft Charging and Discharging at NRIAG-Egypt

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Abstract:

National Space Plasma Interactions Unit (N-SPI-U) at NRIAG, EGYPT has been constructed five years ago to investigate the spacecraft charging/discharging phenomena under the effect of the ambient plasma environment in LEO. This is the first time to initiate such tests in Egypt which are very important for the ambitious Egyptian Space Program. Argon gas is used to generate plasma for simulating the plasma properties. The application of this plasma flowing gives the threshold in voltage and current at which potential the current is cut off in the connector. The effect of the plasma on different aluminum alloys (Al-6061, Al-7075, Al-2024) is considered, and results shown that the material deformation and surface degradation can be occurred due to discharge of the ambient plasma and the arc current. In addition we tested the arc and degradation occurred on solar array besides its electric performance after the effects of space plasma.The performance of Si solar cells as a consequence of exposure to LEO plasma environment are investigated. The operating point of the filament of the source is 13 A at 5 V. The potential difference between the filament and the surrounding anode is 450 V and the flowing current is 0.5 A. Diagnostic tools such as Longmuir probe, spectrophotometer and CCD camera are used to describe the plasma properties. Six square shaped Si cells samples of side length of 1cm are supported on a holder located inside the chamber. Three of them are back-connected to a power supply of -100 V, while the others are unbiased. Si solar cells (biased and unbiased) are exposed to the simulated plasma fluency for different times up to 14 h and their alternating current (AC) properties are measured. The results shown the shift of the junction profile toward the front surface and the decreasing in resistance of cell series. However, decreasing of a parasitic Schottky barrier between the front surface and metal grid indicate that,

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the exposure of the cells after simulated LEO plasma caused a structural change in the diffused donor layer, leading to an increase in the number of electrically active doping atoms.

1. Introduction

The environmental effects played an important role in determining the spacecraft's reliability and lifetime (NASA/SDIO 1989). Spacecraft surfaces are exposed to energetic and reactive particles, such as electrons, ions, protons and oxygen atoms and ultraviolet light, including particles exhausted from plasma thrusters, during space missions. Electrostatic interactions between the surface materials and the ambient plasma, such as negative or positive sheath creation, and charging and arcing phenomena, frequently occur (Tahara et al 1995, Zhang et al 1997, Abdel-Aziz et al 2013, and Afaf et al, 2015). Therefore, the environmental factors cause changes of chemical structures of spacecraft materials and their optical and electrical properties (Tribble et al 1996, and Tahara et al 1997). In LEO-plasma environment, neutral particles as well as charged particles around spacecraft played an important role in expansion of arc plasma causing the arcing characteristics. Large arcs may locally disrupt the surface, interrupt power for a short time, produce prompt contamination, and generate copious amounts of electromagnetic interference. Accordingly, high voltage operation of LEO spacecraft may cause degradation of spacecraft surfaces and structures by arcing depending on plasma condition and properties near spacecraft surface (Ferguson 1991, Takahisa et al 2003 and yehia et al 2013, and Afaf et al, 2015).

On the other hand, anodic oxide coatings on surface metallic alloys such as aluminum and aluminum alloys are the common used for space environment applications, which provide specific thermo-optical properties to spacecraft surface. Fragments of these coatings lead to generate the contamination in satellites and affect the mission life time (Danford 1994, Govindaraju et al, 2010, Charles and Thomas 1995, and Teichman et al, 1992). As in aluminum and aluminum alloys have many applications especially in aerospace industries because of their excellent properties such as high strength to weight ratios, low cost, high thermal conductivity and good corrosion resistance. Therefore the anodized coating for this material provides the

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required optical properties to minimize thermal cycling temperatures and prevent overheating and under-cooling in every part of equipment namely good temperature stability of onboard equipments (Julie A. Henkener 2003, Yann Goueffon et al 2009, Huong G Le et al 1993, and Tyler P. Black et al 2006). Moreover, the anodizing of metallic surface and alloy components are utilized in many key areas. The properties of anodic aluminum coatings however, may cause the designers to use it in high-voltage space power systems (Hillard and Ferguson 1995, Galofaro, et al 1998, Galofaro, et al 1999, and Hillard, and Vayner 2000). Dielectric breakdown and arc generation can lead to damage the anodized surface with the production of significant electromagnetic interference (Galofaro, et al 1998, Hillard, and Vayner 2000, and Black, et al 2006).

This study is focused on LEO plasma- induced discharging and electrical breakdown processes on some samples used in spacecraft surface structure and configuration. Ground-based simulations are performed to investigate the charging and arcing characteristics on these samples immersed in Ar-plasma environment. The physical characteristics and properties are analyzed before and after plasma exposure. The experimental results are discussed.

2. Experimental Setup

Ground-based vacuum facilities have been performed at National Space Plasma Interactions Unit (**N-SPI-U**) established at NRIAG Institute, to simulate LEO plasma environment. Cylindrical vacuum chamber is used and pumped to pressure of low as 10^{-5} torr. Argon gas flow through the chamber test is used to produce LEO plasma properties. Penning plasma source is used to generate plasma from the ionized Argon gas flowing through the vacuum chamber. The flowing gas pressure is fixed at about (P_{Ar} = 0.6 mbar), which produces plasma with considerably density value about 10^6 cm^{-2}. The operating point of the filament source is 16 A. The potential difference between the filament and the surrounding anode is 750 V. Test conditions and plasma parameters for the experiments are given in table (1). The sample is mounted on a holder, which is located inside and near the center point of the vessel chamber. Outside the chamber, the sample is connected with an electric circuit contains resistance and capacitor. Moreover, Different tools such as CCD camera connected with optical microscope, spectrophotometer, current probe, and oscilloscope are considered to investigate the plasma and sample characteristics. Bias voltage with various values is applied on the sample in order to test the charging and discharging processes. The test facilities and schematic of the experimental configuration is shown in Figures (1) and (2).

Table (1): Test conditions and plasma parameters

Test conditions	**Ar-plasma parameters**
Chamber pressure (P = 10^{-5} torrs)	**Electron density (n_e = 0.5 x 10^6 cm^{-3}**
Anode potential (750 V)	**Plasma temperature (T_e = 0.79 eV)**
	Ion temperature (T_i = 0.79 eV)
	Ion velocity = 700 m/S
Anode current (0.5 A)	**Debye length (λ = 0.7 mm)**
	Flowing gas pressure (P_{Ar} = 0.6 mbar)
Degree of ionization	**10^{-4}**

Fig. 1: Test facilities in (N-SPI-U) at NRIAG

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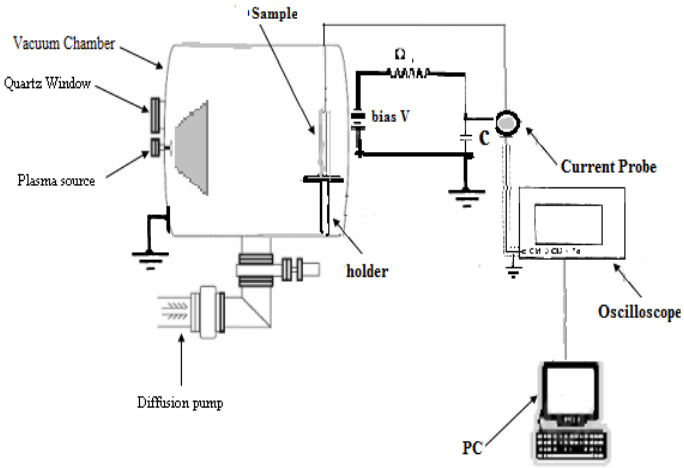


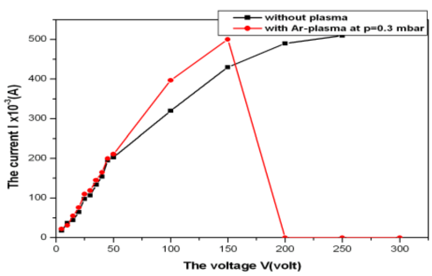
Fig. 2: Basic schematic of the experimental configuration

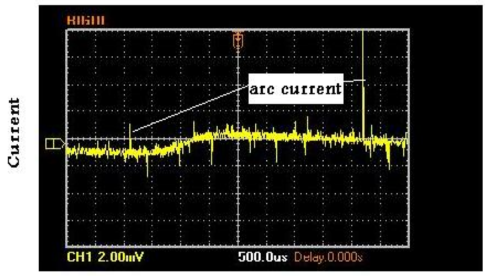
3. Experimental Results and Discussions

The Plasma is generated with specific properties in high vacuum plasma chamber. The experimental and simulated tests of this system confirm the plasma effect on different samples of materials used in spacecraft' structure and satellite' surfaces. This mechanism studies the charging/discharging processes on different samples, which leads the different surface potentials. Detailed of plasma effects and applications on some different samples are discussed and considered as follows;

3.1 Effects on Material interconnectors

Figures (3) and (4) show the arcs current on interconnector of the solar cell. The trace of charging and arc processes are measured and evaluated at different potential values up to 200V.





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Time (µs)

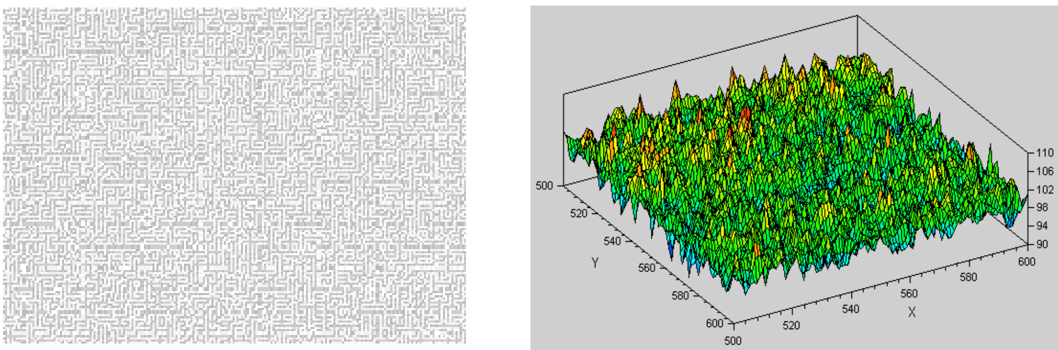
Fig3: Current versus the voltage on the interconnector material

Fig.4: Output oscilloscope signals for the current versus time at connector

It is seen here that, the current is continuously increase with plasma charging until it reaches to a maximum value (cut off value). This indicates that, the discharge and arc process is occurred. The figures show the current is reaching to the peak value at 150 V called (threshold voltage). After the threshold voltage value, the arcing process leads the current to decrease rapidly and becomes zero.

3.2 Effects on thin layer Aluminum sample

For spacecraft operates with a higher voltage, then, more intensive arcing is suspected to occur on the surface. The experiments are carried out to investigate the arcing phenomenon and examine the influences of the ambient space plasma on the arcing process on a thin metallic layer surface before plasma exposure as figures (6a, and 6b) and after plasma as seen in figures (7a and 7b). The results shown in figures (7a and 7b) clarify the disturbed surface with the deformation occurred on the material surfaces (Abdel-Aziz et al 2013). This is seen as a result of plasma discharge and arcing process. This causes the degradation of the surface. The test is very important for knowing what would be occur under the effect of plasma charging. This phenomenon is verified in the laboratory test.



(a) **(b)**

Fig 6: Thin Al-layer before plasma test

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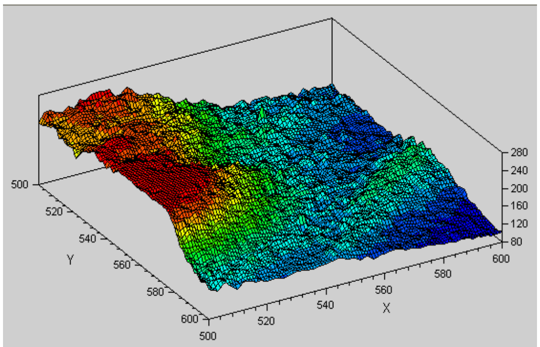

(a) **(b)**

Fig 7: Thin Al-layer after plasma test

From the results, it is shown that, the deformation of the material surface is observed. The surface also is degraded with the interruption occurred on the sample surface due to discharging process of the ambient plasma leading to the collected arc current.

3.3 Anodic coating formation for different samples of Al-Alloys

On the laboratory of plasma interactions and simulation at NRIAG, the anodic oxide film on different samples of aluminum alloys Al-6061, Al-7075, and Al-2024 are formed using electrochemical method (electrolyte solution). Experimental procedures are performed using sulfuric acid at different values of current density (1-2 A/dm^2). The influence of the parameters of anodic film formation on the coating characteristics and layer thickness of aluminum alloys has been investigated. Physical properties of the anodized aluminum alloy coatings are determined and found to be dependent on the alloying elements. Changes in anodic coating weight and film thickness of aluminium alloys with the process parameters as current density, temperature, acid concentration, and sealing system have been studied. Moreover, morphology and surface structural of the considered samples are carried out in attempt to understand the physical characteristics.

Table (2) gives the obtained results of the coating thickness for the considered alloys obtained at different parameters and anodizing conditions (Afaf et al, 2017).

Table (2): The thickness values of Al-alloys at different conditions

Temp (C°)	**Time (min)**	**Alloys**	**Coating thickness (μm)**	
			Current density=1A/dm^2	Current density=2A/dm^2
21	**30**	**7075**	**2**	**3.22**
		2024	**3.07**	**3.8**

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		6061	**5.85**	**6.55**
21	**60**	**7075**	**2.66**	**3.43**
		2024	**4.07**	**5.24**
		6061	**10.8**	**13.4**
35	**30**	**7075**	**1.8**	**3.12**
		2024	**2.18**	**2.7**
		6061	**5.3**	**5.65**

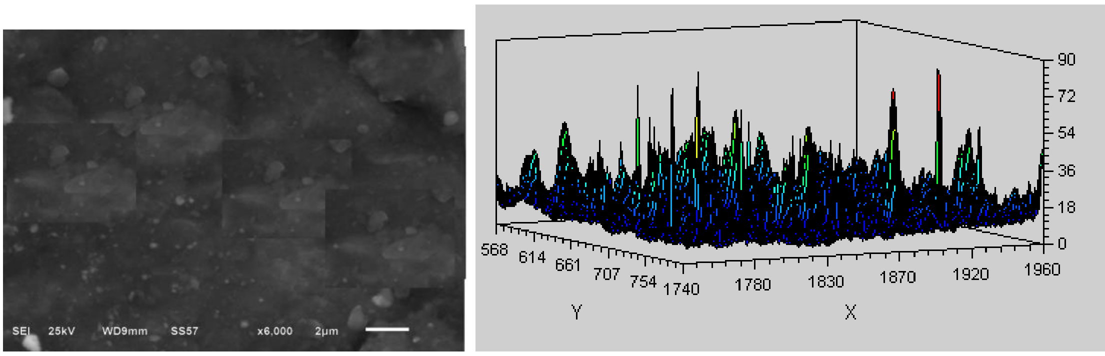
The table clarifies the increase in anodic thickness with time at the same other parameters and conditions of the experiment. These results are valid and correlated with that obtained from many studies (Sung Il Jeon, and Won Sub Chung 2014, Bensalah et al 2010, Mohammad Zaki Mubarok et al 2015, and Shanmuga Sigamani et al 2014).

3.4 Effects on Anodizing aluminum sample (AAS)

3.4.1 Before plasma exposure

In this case, the aluminum surface is anodized using the same procedures and electrochemical process considered above for different samples of aluminum alloys. The obtained film thickness is found to be about 0.05 mm. The results are carried out to investigate the morphology and physical characteristics for the oxide film coating on the metallic surface before and after plasma exposure.

Figure (8) shows the SEM image for the anodic aluminum surface (seen in (a)). The spatial distribution of the oxide formed film on the surface is seen in (b). The SEM image in figure (8a) reveals the morphology of anodic film surface of aluminum sample.



(a) **(b)**

Fig.8: SEM image of AAS surface before plasma exposure (a), and spatial distribution for the surface (b)

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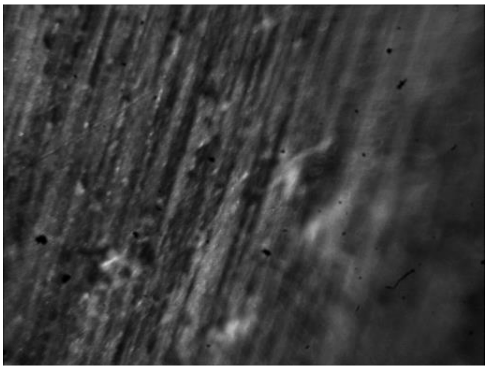
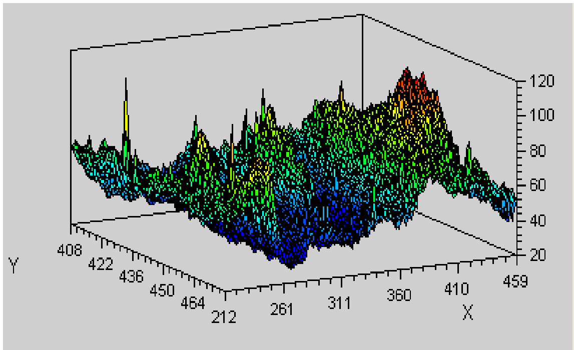
3.4.2 After Plasma Exposure

To understand the charging and discharging processes occurred on plate sample, many test variables are studied. The effect of plasma exposure on the anodic oxide film and the aluminum layer is shown in figures (9a) and (9b). The image in figure (9a) is taken with CCD-camera connected with optical microscope. The figures clarify the disturbed structures and deformation occurred on the film surface. This confirms the charging and discharge current flowing occurred in a selected section of the sample, and affecting on the film surface.





(a) (b)

Fig.9: CCD image of AAS surface after plasma exposure (a), and spatial distribution for the surface (b)

Anodized sample is tested for various time duration at a negatively biased voltage (-70V) to identify the threshold voltage of the occurrence of peak charging current. The data plotted in figure (10) are taken from the current probe connected with the circuit of the sample, and at resistance of (5Ω) and capacitor (2000 μf). The current reaches to a peak value before it tends to be lower due to the discharging process.

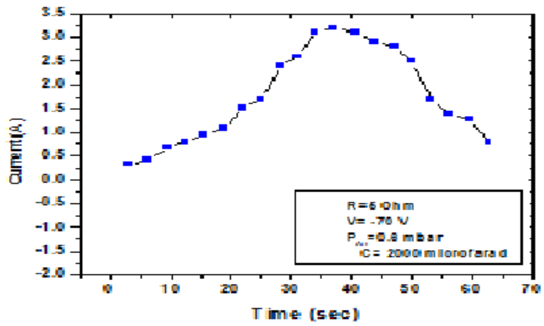


Fig. 10: Current-flow through the sample with selected values for time of plasma exposure (Bias voltage (-70 V))

Figure (11) shows the discharge current behavior on the sample and the voltage of the capacitor with time. In this case, the current probe is connected with the circuit of the sample, and the resistance is taken with a fixed value of (5Ω).The plotted data are taken from the oscilloscope. Moreover, these relations are also plotted from the data taken for the same capacitor but with the changeable of the connected resistance (500Ω). This is shown in figure (12). The two graphs are plotted at the same applied bias voltage (-70V). The voltage on the capacitor is measured as well

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as the current flow in the circuit. The voltage and current shown in figures 11 and 12 are corresponding to an arc initiating on an anodized plate connected to a 12 microfarad capacitor. Typical voltage and current traces during an arc event are shown in these figures. The obtained results are comparable with that obtained from the tests of (Todd A. Schneider et al, 2001, and Tahara H., and Masuyama T, 2006)

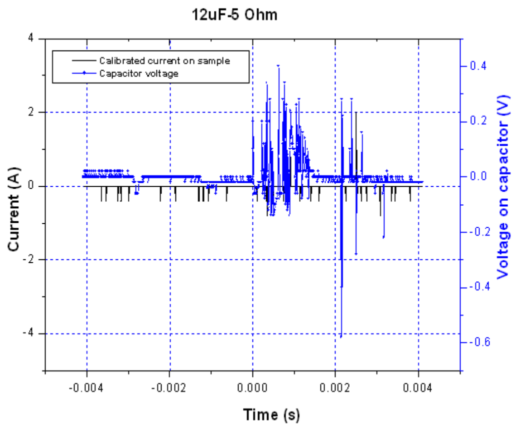

Fig. 11:Discharge current on the sample and the voltage of capacitor with time (Bias voltage (-70 V))

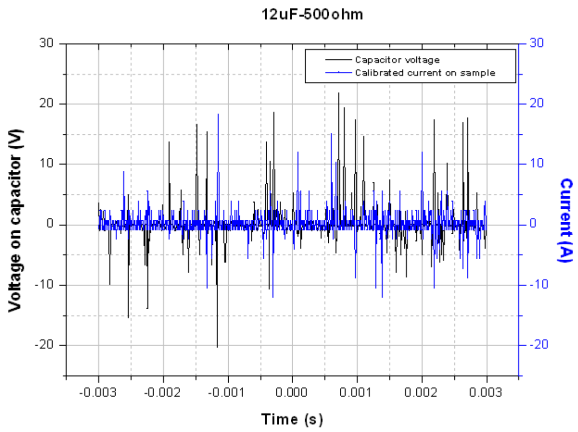

Fig. 12: Current on the sample and the voltage of capacitor with time (Bias voltage (-70 V))

3.5 Effects on the atomic structure of the silicon cell surface

Ground-based laboratory tests are performed to investigate the performance of biased and unbiased samples of solar cells with the exposure to the simulated LEO plasma generated from argon gas flowing. Silicon cells are used in these experiments. The results show the variation of the atomic structures of the cells, described in figures (from 13 to 15) under the effects of the plasma (Afaf et al, 2015).

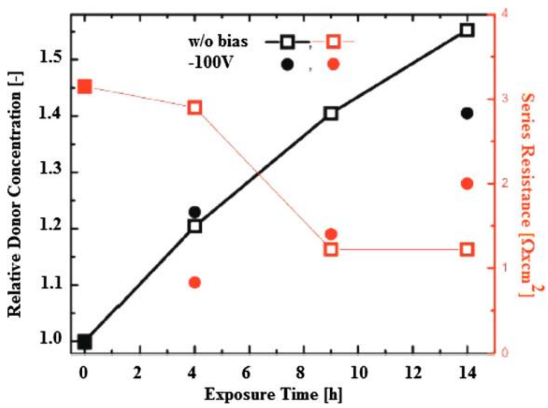

Fig. 13: Changes of electrically active donor concentration (left axis) and cell series resistance (right axis) as functions of exposure time.

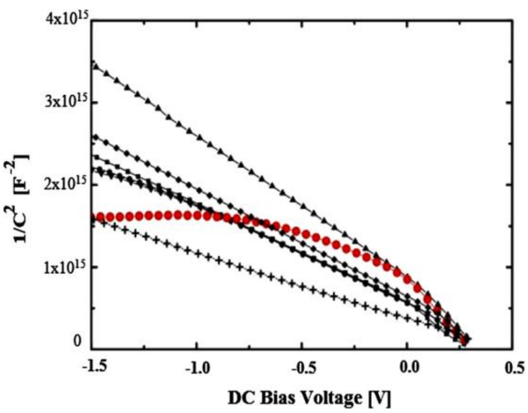

Fig. 14: Variation of measured capacitance with applied DC voltage. Negative voltage indicate the reverse bias condition.

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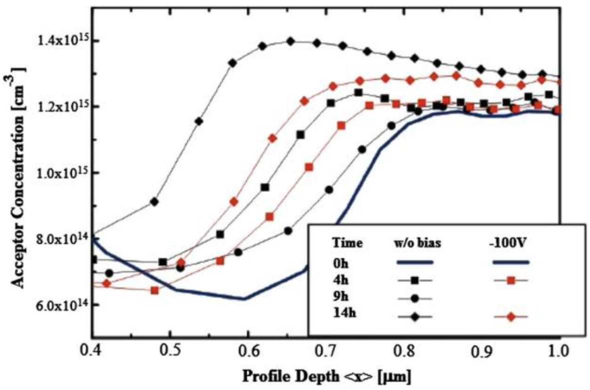

Fig. 15: Junction profile from small signal conductance experiments at 78.2 kHz

The results indicate that the exposure of the samples in the radiation chamber causes a structural change in the diffused donor layer leading to an increase of electrically active doping atoms:

- Shift of junction profile towards front surface
- Decrease of cell's series resistance
- Decrease of a parasitic Schottky barrier between front surface and metal grid.

3.6 Effects on the performance of silicon solar cells

Figure (16) shows the I-V characteristic curve (a) and the output power for a monocrystalline Si cell sample before and after plasma exposure. The electrical performance is acquired by means of measuring the output current-voltage relation (shown in figure b), and the output power (shown c). The data are obtained under the test conditions considered in table (3). The maximum power describes the electrical performance of the solar cell.

Table (3): Test conditions

Work gas	**Argon**
Gas pressure	**0.45 m bar**
Discharge voltage	**500 V**
Exposure time in plasma	**9 Hrs**
Cell temperature	**20 °C**
Cell area	**1cm^2**
Radiation intensity	**1000 W/m2**

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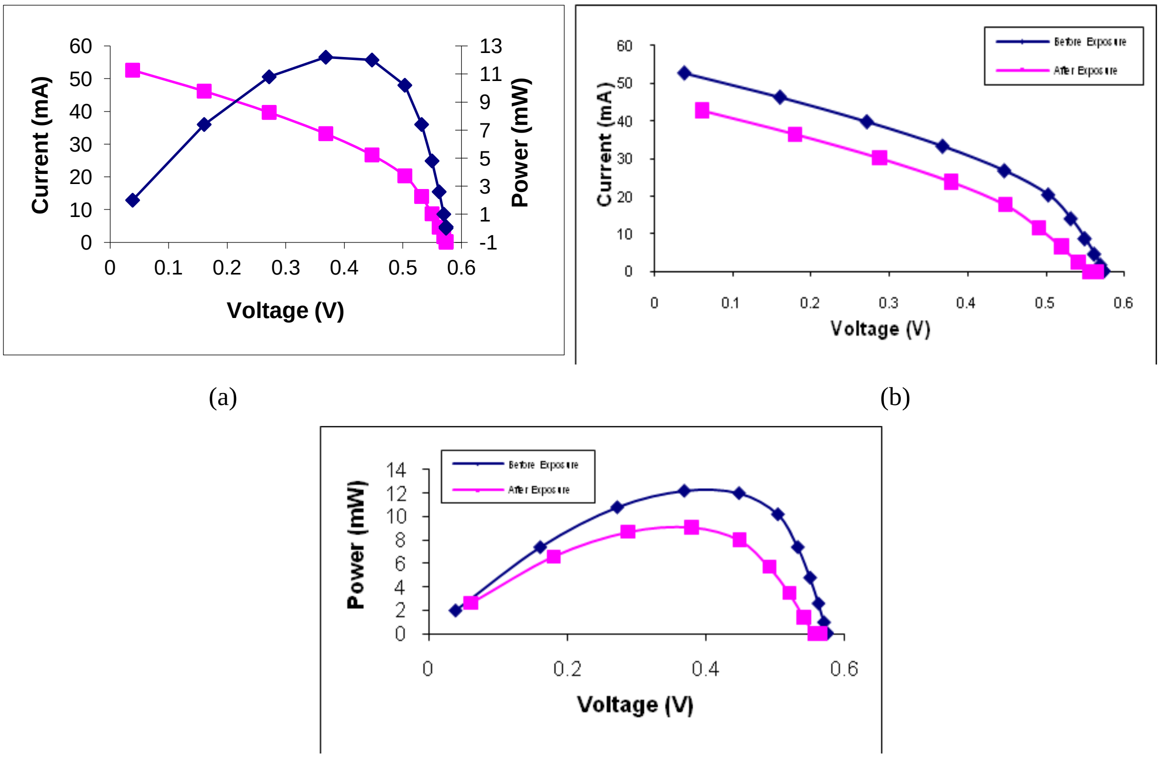

(a) (b)

(c)

Fig. 16: Electrical performance and output power of Si cell sample

From the above figures, it is clear here that, the cell electrical output is changed that is measured before plasma exposure. There is some of degradation in these observed data. Also, the maximum output power decreased to about (30 %) of the initial value under the effects of the discharge plasma processes (Abdel-Aziz et al 2013).

4. Conclusion

- Experimental ground tests for different samples with various properties and characteristics after exposure to simulated LEO-plasma in the vacuum chamber are investigated at (N-SPI-U), NRIAG. Negatively biased voltages are applied on the samples. Current and voltage waveforms associated with charging process are obtained and observed with the peak values. The obtained results show the behavior of current flow (voltage through the resistance) on the sample surfaces is affected with the used initial conditions as capacitance, resistance and plasma flowing conditions.

- Discharging and arcing occurred on the considered samples. These samples are aluminum Al-plate and anodized aluminum Al_2o_3 surface, used for spacecraft surface structures, interconnectors material used for solar cell and arrays, and different samples of silicon solar cells. The results show the discharging occurred on these samples with the deformation and degradation on surface structures. Moreover, arcing process is found and lead to the cut off on the interconnector materials. In solar cell samples, the decreasing on the performance and cell efficiencies under the effects of plasma exposure. In addition, the obtained results show the changeable of the electrical characteristics of the cell as a result of plasma effects on the internal surface and the atomic structures of the cell samples.

- This study is important in order to further understand the influence of spacecraft surface properties on the characteristics of the floating potential of low earth orbit spacecraft. Accordingly, this may be useful in attempt to limit the potential of spacecraft systems with respect to the plasma in order to prevent arcs, or to at least limit the amount of connected capacitance available to potential arc sites.

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