Trans. JSASS Aerospace Tech. Japan
Vol. 12, No. ists29, pp. Pr_35-Pr_39, 2014

Original Paper

Discharge Propagation in Normal Potential Gradient on Spacecraft

By Kazuhiro TOYODA, Ryota NODA and Mengu CHO

Kyushu Institute of Technology, Kitakyushu, Japan

(Received June 24th, 2013)

The number of electrostatic discharge (ESD) accidents on solar arrays has been increasing. Such accidents can cause serious problems for power generation, such as halting the normal operations of a satellite. To prevent ESD, ground checks should be performed under a normal potential gradient, i.e., when the satellite surface potential is negative with respect to space plasma. In this study, we obtained ESD parameters to establish a method for ground testing. Experiments were performed in a vacuum chamber with an electron gun. Discharge images (propagation length and velocity) were captured by an IR camera. The charge flowing into the discharge point was captured by a current probe. A non-contact surface potential probe measured 2D-potential distributions on test samples. As a result, we found that the threshold voltage of the electrical discharge was −10 kV and the amount of electric charge depended on the propagation area of the discharge plasma. The propagation velocity in a normal gradient potential was 10^5 m/s.

Key Words: Discharge, Flashover, Normal Gradient

Nomenclature

Φ	:	potential
V	:	voltage
v_p	:	propagation velocity
L_p	:	propagation distance
T	:	pulse width
Q	:	quantity of the electric charge
R	:	ratio of the charge flowing into the discharge point
X, Y	:	position

1. Introduction

The latest satellites are both multifunctional and multipurpose, so they require power as high as 10 kW, and consequently, it involves an enormous investment. Efficient generation of high electric power from big solar panels requires high voltage, and recently, the bus voltage on satellites has increased to over 100 V. Since the late 1990s, electrostatic discharges (ESDs) in solar array panels have become a serious problem. For example, in 1997, the TEMPO-2 satellite experienced permanent loss of a significant fraction of its solar array output power. It is believed that the ESD current significantly influences deterioration of solar arrays.

Figure 1 shows a cross section of a conventional solar cell. When a satellite encounters a substorm, energetic electrons hit the coverglass. Discharge phenomena can be divided into a normal potential gradient and an inverted potential gradient. When the solar array is not exposed to sunlight, substorm electrons cause a normal potential gradient in the insulator (coverglass) that is negatively charged with respect to the conductor (spacecraft structure). The back side of the solar array paddle is negatively charged with respect to the spacecraft structure [1].

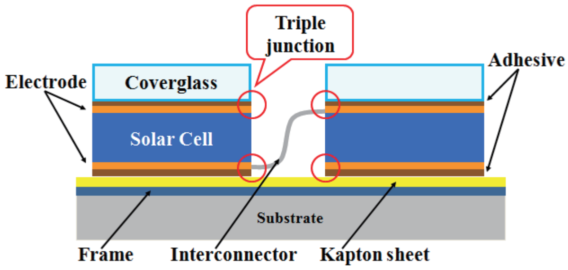


Fig. 1. Cross section of the solar array.

The ESD between the insulator and conductor triggers a discharge, which occurs between the conductor and space by discharging the charge stored between the floating satellite and space. The insulator surface, which has a negative potential with respect to conductors, such as interconnectors, is neutralized electrically by the electrons fed from the cathode of the blow-off discharge. This neutralization process propagates from an arc site at a certain speed and is known as a flashover discharge. The flashover current waveform mainly depends on the neutralized charge and area, the position of the arc, and propagation speed [2, 3].

To prevent total loss of a solar array from an ESD, an optimum design is needed, and ground examinations are required to verify the design. The test method used in this study is based on the inverted potential gradient. A ground check is done for the normal gradient potential by similar recognition[4], but discharge phenomena depend on the potential gradient. In fact, when the image is examined during an electrical discharge, the current seems to flow to not only the electrical discharge point but also the other interconnectors [4]. Hence, changing the gradient of the potential also changes the test method. However, discharge phenomena in space are not as well understood as those on the ground.

This study's purpose is to develop an experimental method based on the normal potential gradient. Therefore, to examine how the discharge truly acts in a normal gradient potential, the current flowing into the ESD point was measured by a current probe. The amount of charge was then determined from this measured current.

2. Experimental Setup

Figure 2(a) shows a typical sample used in this study. The size of the coupon was 400 × 400 mm^2. An aluminum board with a thickness of 0.8 mm was covered with polyimide adhesive tape. The tape was composed of a polyimide film and a silicone pressure-sensitive adhesive with thicknesses of 50 µm and 40 µm, respectively. A round electrode with diameter 10 mm and thickness 0.8 mm was connected to the center of the aluminum board by the adhesive tape. In addition to this sample, tests were conducted for several similar coupons (Table 1).

Table 1. Test coupons.

Coupon	Size	Material	Thickness	Number of Electrodes
#1	400 mm × 400 mm	Polyimide	Polyimide	1
#2	400 mm × 400 mm	Polyimide	80 µm	1
#3	400 mm × 400 mm	Teflon	260 µm	1
#4	400 mm × 400 mm	Polyimide	90 µm	2
#5	100 mm × 100 mm	Coverglass	100 µm	1

Figure 2(b) shows a schematic of the experimental coupon. Copper and polyimide tape in Fig. 2(b) corresponds to the place indicated in Fig. 2(a). Three current probes, CP1, CP2, and CP3, were mounted in the experimental circuit. They were connected to the electrode, the aluminum board, and the synthetic point, respectively, as shown in Fig. 2(b). The current probes measured discharge current waveforms.

The experiment was performed in a vacuum chamber (1.7–4.0 × 10^{-4} Pa) with an electron gun (12–18 keV) installed above, as illustrated in Fig. 3. A mechanical shutter was used to control the irradiation time. To measure the 2D-potential distribution on the test sample, a non-contact surface potential probe (TREK 341) was placed on a motor-controlled X-Y stage. ESD images were captured by an IR camera. From the acquired ESD images, we calculated the propagation distance of the electrical discharge plasma. Figure 4 is a flowchart of the experimental procedure.

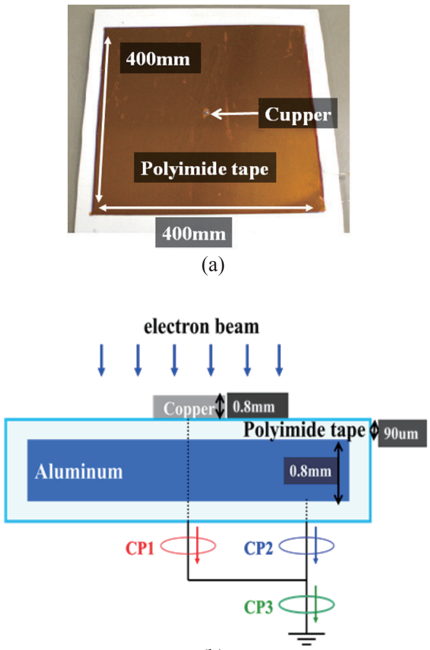


Fig. 2. Test coupon. (a) Photograph of the sample. (b) Schematic of the sample.

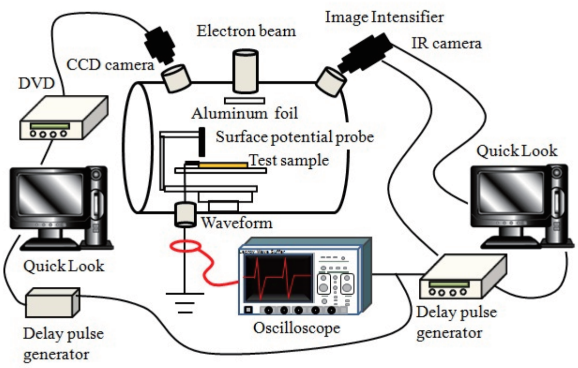


Fig. 3. General view of the experimental system.

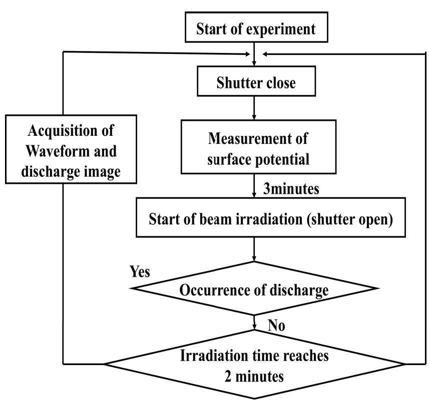


Fig. 4. Flowchart of the experimental procedure.

3. Experimental Results

Figures 5(a) and 5(b) show a test sample before the experiments and a discharge image captured by the IR camera, respectively. The propagation distance was calculated from the length of the branch of the current from Figure 5(b), which was 240 mm.

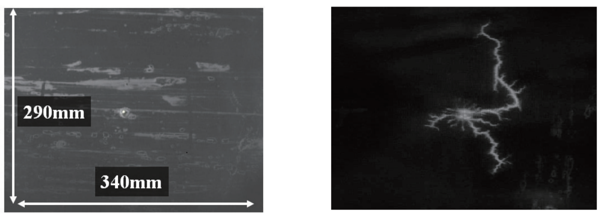
Typical current waveforms are shown in Fig. 6. During electron irradiation, the sample surface was negatively charged. During discharge, electrons stored on the insulator surface entered the electrode, and the current at electrode CP1 showed a negative current. The current at the aluminum board (CP2) showed a positive current because electrons on the insulator surface were discharged. In Fig. 6, the peak current that flowed to the electrode was −19.7 A with a pulse width of 2.27 μs, and the peak current that flowed to the aluminum board was 29.7 A with a pulse width of 2.67 μs. The amount of electric charge was calculated by

$$Q = \int I dt \tag{1}$$

The amount of electric charge into the electrode was -1.38×10^{-5} C and that into the aluminum board was 3.36×10^{-5} C. The ratio R [%] of the electric charge into the electrode (Q_1) to that into the aluminum board (Q_2) was calculated by

$$R = Q_1/Q_2. \tag{2}$$

The result was $R = 41.1\%$.



(a) (b)

Fig. 5. Typical discharge image for coupon #1. (a) Base image. (b) Discharge image. The surface potential was approximately −10 kV.

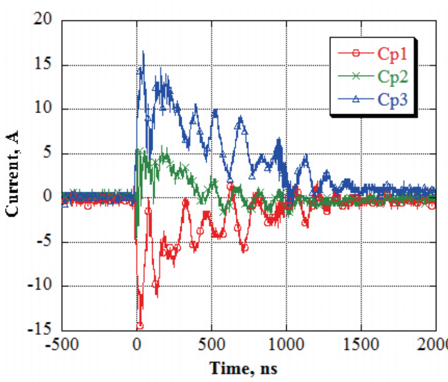


Fig. 6. Typical current waveform for coupon #1. The surface potential was approximately −10 kV.

From the discharge image, the propagation area and propagation distance were calculated. The propagation distance is the length from the electrode to the farthest end of the flash branch. The propagation area is the sum of discharge flash areas. From the current waveforms, the peak current, discharge duration, and electric charge into the discharge point were calculated. The electron beam energy was from 12 to 18 keV. Figure 7 shows the relationship between discharge duration and propagation length for coupon #1. In the figure, each point corresponds to one discharge. The figure shows that the propagation distance was proportional to duration of the current waveform. In addition, the propagation area was proportional to the peak current (Fig. 8) and charge into the discharge point (Fig. 9). Similar results were obtained regardless of the thickness and material of the sample (Fig. 10).

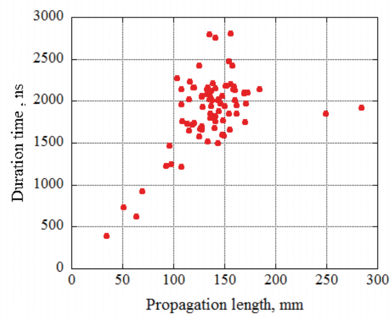


Fig. 7. Relationship between discharge duration and propagation length for coupon #1.

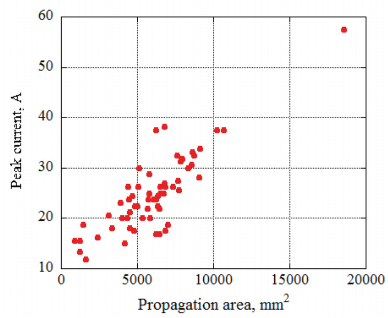


Fig. 8. Relationship between peak current and propagation area for coupon #1.

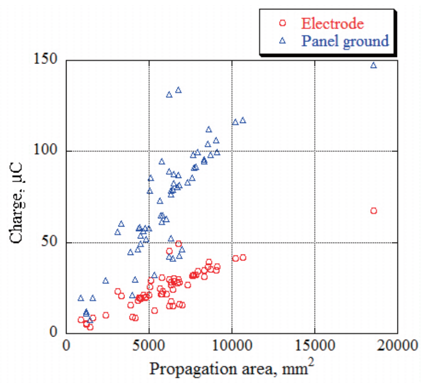


Fig. 9. Relationship between charge and propagation area for coupon #1. Electrode (red) and panel ground (blue) are for the copper electrode and aluminum panel, respectively.

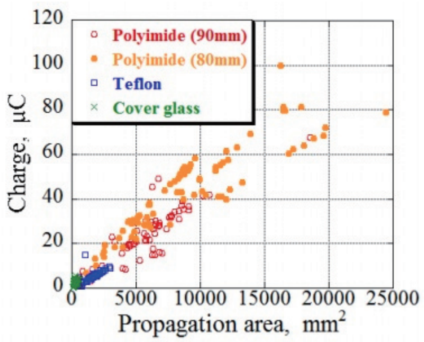
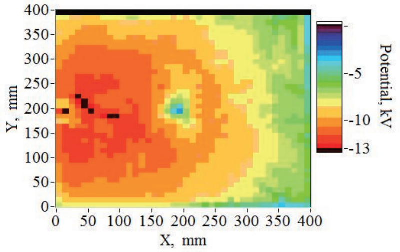
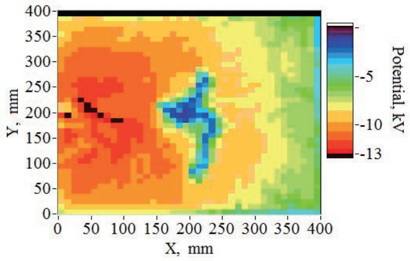


Fig. 10. Relationships between charge at electrode and propagation area for different coupon materials.

Figure 11 shows typical 2D surface potentials on the sample for case 1 before and after discharge. The surface potential measurement system scanned an area of 0.4 × 0.4 m^2 with a resolution of 0.01 m. Figure 11(a) shows the surface potential of the sample charged by the electron beam irradiation before the arc occurred. The position of the electrode was X = 200 mm and Y = 200 mm. The surface of the test sample was charged to approximately −10 kV around the electrode. Figure 11(b) shows the potential of the surface of the sample after arcing. Charges were neutralized around the discharge point. Figure 12 shows the potential difference across the sample before and after arcing.



(a)



(b)

Fig. 11. Typical surface potentials for coupon #1. (a) Before discharge. (b) After discharge.

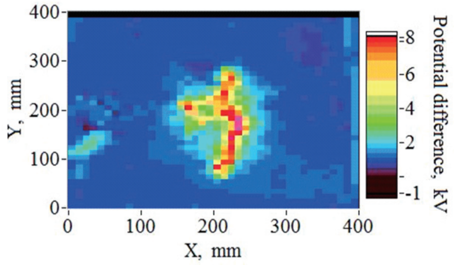


Fig. 12. Typical potential difference for coupon #1.

An image intensifier was used for measuring the propagation velocity of discharge. Discharge images were acquired by changing the timing of the shutter on the camera. Propagation lengths were measured from images acquired with different timings. Figure 13 shows the relationship between average discharge propagation length and time from the beginning of discharge. In Fig. 13, the *x*-axis is the time to close the shutter of the camera, and the *y*-axis is the propagation length from the discharge point. The error bars are standard deviations. The propagation distance increased linearly with time. From the slope of the line in Fig. 13, the propagation velocity of the plasma discharge was calculated to be 10^5 m/s.

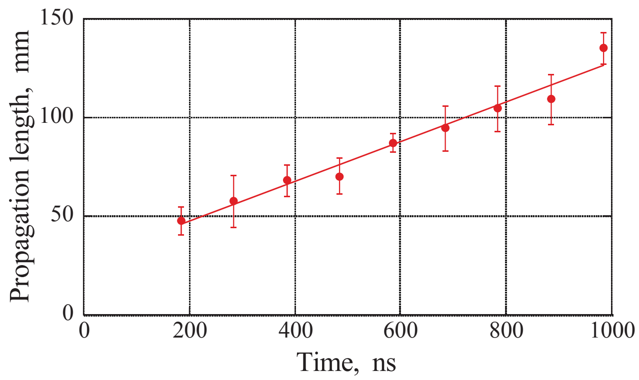
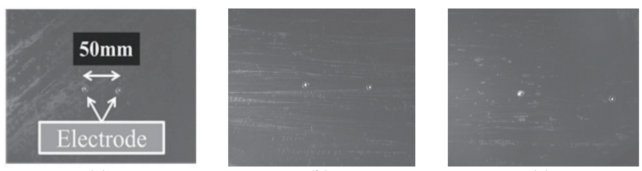


Fig. 13. Relationship between average propagation length and time from beginning of discharge. Electron beam energy was 15–16 keV.

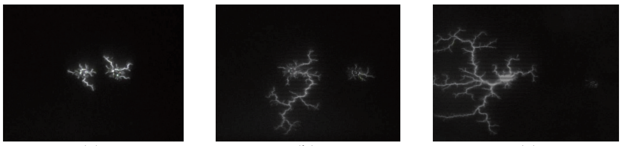
Figure 14 shows test samples before experiments and Fig. 15 shows discharge images during discharge. The discharge images show that when a discharge occurred in one place, a discharge on the other electrode was induced. Figure 16 shows the relationship between the distance between electrodes and charge into the discharge point. The *x*-axis is the energy of the electron beam, and the *y*-axis is the charge into the discharge point. The charge into the discharge point was largest when the distance between electrodes was 150 mm. In contrast, the charge was smallest when the distance between electrodes was 50 mm. Therefore, we conclude that the size of the discharge depends on the distance between electrodes and the number of electrodes.



(a) (b) (c)

Fig. 14. Test samples (coupon #4) before experiments. Distance between electrodes was (a) 50 mm, (b) 100 mm, and (c) 150 mm.

From experimental results using a plate with an insulator, flashover propagation area and velocity were investigated. This type of insulator is usually used on the backside of a solar array paddle. However, on the front side of the paddles, small coverglasses were mounted on each solar cell. To



(a) (b) (c)

Fig. 15. Discharge images. Distance between electrodes was (a) 50 mm, (b) 100 mm, and (c) 150 mm. Electron beam energy was 15–16 keV.

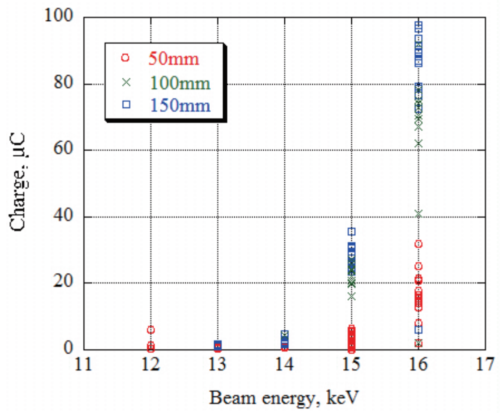


Fig. 16. Charge into discharge point for different distances between electrodes on coupon #4.

investigate flashover discharge on the front side of the solar array paddles, a solar array coupon was used for the ESD experiment. The coupon consisted of nine TJ cells (80 mm x 40 mm), as shown in Fig. 17. The electron beam was irradiated on the coupon in a vacuum chamber.

Figure 18 shows the flash image of discharge on the coupon. Discharge lighting starts from the side edge of the solar cell and ends in the cell. This means that a discharge cannot propagate from one cell to another. From the results of this electrode coupon, it was confirmed that the flash lightning of discharge corresponded to discharge current. Lightning cannot propagate to other cells on a solar array coupon. In other words, the discharge current was supplied to a discharge site from the charge stored on only one coverglass. From these experimental results, we conclude that the external capacitor used for a normal potential gradient does not need to undergo ESD testing for the front side of a solar array coupon.

4. Summary

Parameters of discharge images correlate with discharge waveforms.

- Propagation area correlates with the amount of charge and peak current.
- Propagation distance correlates with the duration of the current waveform.

The same results were obtained regardless of the thickness and material of the sample. The propagation velocity in the normal gradient potential was 10^5 m/s. If there is more than one electrode, a discharge is triggered by a discharge at a different electrode. The size of the discharge depends on the distances between electrodes and number of electrodes. For the normal potential gradient, a discharge cannot propagate from one solar cell to another.

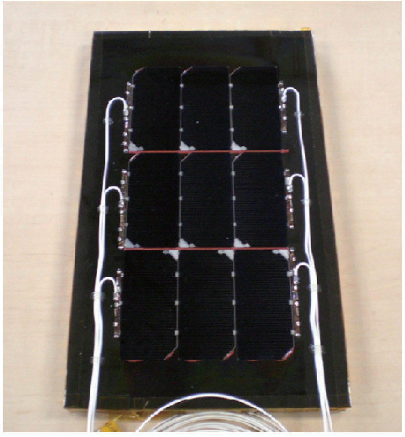


Fig. 17. Photograph of the solar array coupon containing nine TJ cells.

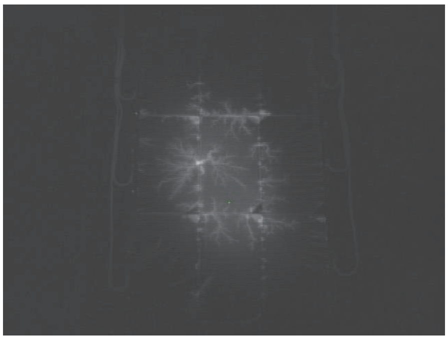


Fig. 18. Flash image of discharge on solar array coupon in Fig. 17.

References

1) Leung, P. and Bodeau, M.: Plasma Phenomena Associated with Solar Array Discharges and their Role in Scaling Coupon Test Results to a Full Panel, 8th Spacecraft Charging Technology Conference, Huntsville, Alabama, USA, October, 2003.

2) Suzuki, T.: Research on Flashover Discharge Generated on Solar Battery Array, Graduation thesis, Depart. Electr. Eng., Kyusyu Institute of Technology, Kitakyushu, Fukuoka, 2010.

3) Masui, H., Toyoda, K. and Cho, M.: Electrostatic Discharge Plasma Propagation Speed on Solar Panel in Simulated Geosynchronous Environment, *IEEE Trans. Plasma Sci.*, **36** (2008), pp. 2387-2394.

4) Masui, H., Toyoda, K. and Cho, M.: ESD Ground Test of Solar Array Coupons for a Greenhouse Gases Observing Satellite in PEO, *IEEE Trans. Plasma Sci.*, **36** (2008), pp. 2413-2423.