Effect of Substrate on Sustained Arc between Electrodes

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EFFECT OF SUBSTRATE ON SUSTAINED ARC BETWEEN ELECTRODES

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Abstract

The high voltage generated by solar arrays can cause catastrophic damage such as that from short-circuit due to sustained arcs. Recently, many satellites suffered from sustained arc. The purpose of this paper is to develop the technique of mitigating the sustained arc. Three kinds of substrate were used to investigate the effect of substrate on sustained arc. The experiments were performed in vacuum chamber with an electron beam gun. The polyimide coupon had sustained arc in the condition of 60V and 2A. The ceramic coupon had also sustained arc in 60V and 2A. The coupon without substrate had no sustained arc up to 80V and 3A. We found that no sustained arc could occur without substrate between cells on this condition.

1 Introduction

The power level of Geosynchronous Orbit (GEO) satellite has increased dramatically to nearly 10 kW or even higher since ten years. To manage the large amount of power efficiently, the satellite bus voltage has increased to 100V. Nowadays many commercial telecommunication satellites employ solar arrays that generate the electricity at 100V.

As the voltage of solar array increases to 100V, the problems of arcing during the sub-storm condition have been recognized as serious hazard that sometimes threatens the stable supply of the solar array power. In GEO, when a satellite receives the sunlight, its charging is dominated by photoelectrons. As long as the satellite surface is well illuminated under the quiet condition, the photoelectrons keep the satellite potential within a few electron volts from the plasma potential. The insulator surface such as coverglass has similar potential. When a satellite encounters the substorm, the current due to high energy electrons increases and sometimes exceeds the current due to photoelectrons. Then the potentials of the satellite body and the insulator surface can become negative. Due to the difference of the secondary electron emission coefficients, the insulator potential may drop slower than the satellite body. During that process, the coverglass potential can be more positive than the nearby conductor, e.g. interconnector. This situation is called "inverted potential gradient". As the potential difference builds up between coverglass and interconnector, an arc may occur.

The inverted potential gradient is the nominal case in LEO, where an arc can occur once the potential difference reaches 100 or 200 V [1]. If an arc occurs as a single pulse, it is called a primary arc. The risk of one trigger arc growing to a catastrophic arc receiving energy from the array itself has increased recently as the power level of solar array has increased. TEMPO-2 satellite experienced the permanent loss of significant fraction of solar array out-put power when a severe substorm hit the satellite in 1997. The failure was attributed to an arc on solar array under the inverted potential gradient condition [2]. First, an arc occurred between adjacent array strings with different potential and short-circuited the two strings. Then the array output power of the two strings fed energy to the arc plasma. The arc current kept flowing and the underlying Kapton insulation layer was thermally broken leading to short-circuit between the array strings and the substrate. In the present paper, this type of sustained arc is called as "sustained arc".

All of primary arcs, however, do not cause always the sustained arc. Figure 1 shows the definition of arc current. If the arc between electrodes finishes flowing with some duration, this arc is called as "secondary arc". The secondary arc has much larger energy than primary arc. Therefore the secondary arc may cause the cell degradation. However, the sustained arc is most dangerous because it can destroy a string of solar array at least.

It is thought that the sustained arc occurred on ADEOS-II satellite even though this satellite generated the electricity only at 60V. In this case, the sustained arc might occur between power cables with cracks due to degradation caused by thermal cycle [3].

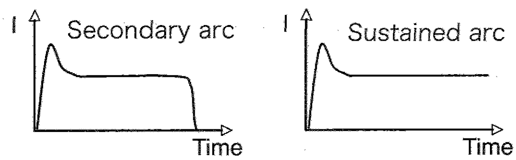

Fig. 1: Definition of arc current.

Several ESD ground tests as for sustained arc have been performed in our laboratory. These tests showed that the substrate melted and was carbonized due to sustained arc inception. After the sustained arc, the arc tracking is formed between electrodes. Therefore it is thought that the melting and arc tracking of substrate insulation can cause the sustained arc. If the insulation with high melting temperature is used, the arc tracking resulting in sustained arc may not be formed. In this paper, ESD tests were performed using three types of test sample for the purpose of developing the mitigation techniques of sustained arc inception.

2 ESD test

2.1 Test samples

The test samples used in this paper are shown in Figs. 2, 3, and 4, respectively. These samples simulate solar array. In these samples, copper tapes were used as electrodes and mounted on substrate insulation. These copper tapes simulated the solar cells. The SSM Teflon tapes were attached on the copper tapes to simulate the coverglasses on solar cells. To cause ESD on samples, the electric field due to potential difference between electrodes and dielectrics is necessary. In these test samples, the dielectric is the SSM Teflon, electrodes is the copper tapes.

Figure 2 shows the polyimide sample. In this sample, the polyimide film was utilized as a substrate insulation. This film was installed on a stainless steel plate. In the real solar array, this film was glued on a CFRP on an aluminum honeycomb as insulation film. Hence this polyimide coupon simulates the conventional solar array.

The test sample, whose substrate insulation was ceramic sheet, is shown in Fig. 3. This sample is called as ceramic sample. The ceramic sheet was mounted on the stainless steel plate. The SSM Teflon and copper tapes are the same as the polyimide sample. This ceramic sheet was used as high melting point material.

Figure 4 shows the floating sample. In this sample, no substrate existed between copper tapes. Two copper tapes were set with distance of 3mm from the substrate insulation. The adhesive sheet was formed at the backside of copper tapes.

In all samples, the distance between copper tapes was 0.4 mm. The cables were soldered on each copper tape.

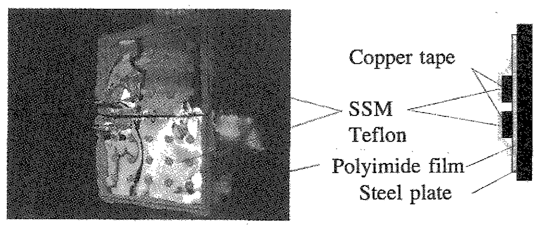

Fig. 2: Polyimide substrate sample.

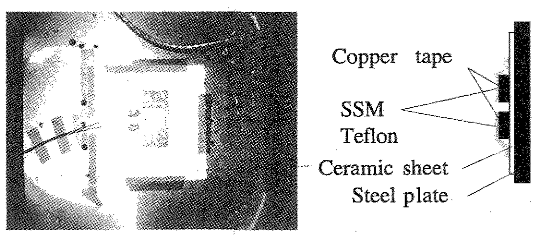

Fig. 3: Ceramic substrate sample

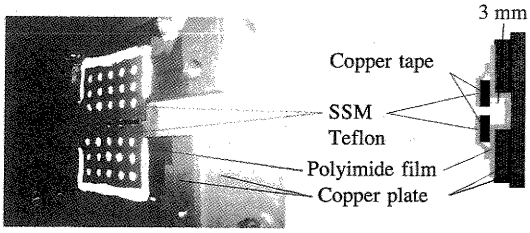

Fig. 4: Floating sample.

2.2 Experimental system

The photograph of experimental system is shown in Fig. 5. All tests were performed in a vacuum chamber possessed by ONERA. The test sample was fixed on a plate which was vertical to floor. The metal plate, which was used as substrate, was electrically connected to the vacuum chamber. The vacuum chamber was also connected to the circuit ground. The vacuum tank was evacuated using an oil diffusion pump. The pressure in the chamber was 10^{-4} Pa before tests, and around 5×10^{-3} Pa during tests. An electron beam gun was attached on the side of the chamber wall. The center of electron beam was set to the center of the sample. This electron beam gun could irradiate the electron beam energy of 40 keV. The beam current of electron beam was $10\mu A/m^2$ in 23 keV at the center of sample.

A surface potential probe was installed in the chamber and could measure the surface potential of sample along an axis.

A CCD camera was also installed in the chamber. The arc positions on sample were identified by means of recoding video image of the CCD camera during tests.

2.3 Test circuit

Figure 6 shows the test circuit used in this research. This circuit is generally utilized in the sustained arc test and consists of two power supplies, three diodes, and a variable resistance. One of the power supplies is a constant current (CC) power supply. During tests, this CC power supply flows a constant current into the variable resistance. The potential difference between electrodes on samples is decided by means of varying the value of this resistance. Another power supply is a constant voltage (CV) power supply. The voltage of CV power supply was set less a few volts than that between electrodes. This prevents the current from flowing into

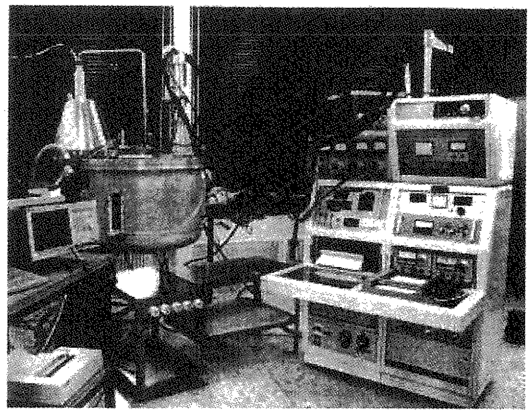

Fig. 5: Photograph of test system.

the variable resistance except to flow between electrodes at the moment that two electrodes are short-circuited. This current path simulates that of secondary or sustained arc on solar array. The negative side of the circuit was electrically connected to ground.

A CC power supply, which has been developed as a power supply suitable for sustained arc test, was used. The current regulative diode (CRD) was adopted in this power supply. The CRD is a electric device that can flow constant current even if the potential difference between CRD is not constant. Though one CRD can flow only 50mA, many CRDs connected in parallel can flow the current over 1A. The leading characteristic of this power supply is small surge current.

In Fig. 6, CP1, CP2, CP3 show current probes, respectively. At these points, current waveforms were measured. All current probes can measure the current waveforms with from DC to AC frequency. The potential between electrodes was measured using a voltage probe. These probes were connected to two oscilloscopes. The waveforms were recorded with different time scales using two oscilloscopes.

3 Test results and discussions

In this research, the sample surface is charged to negative because the electrodes potential is near 0V. After the irradiation of electron beam, the surface potential measurement showed that the sample surface had negative potential over 10 kV. Figure 7 shows an example of current waveforms of sec-

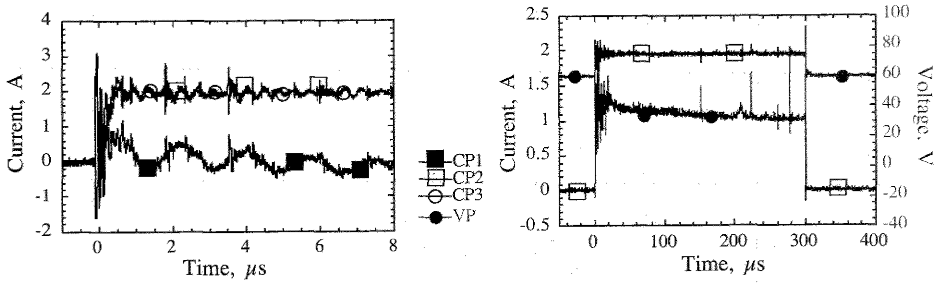

Fig. 7: Example of current waveform of secondary arc.

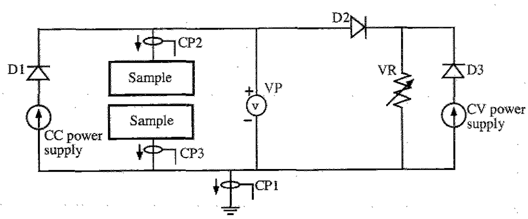

Fig. 6: Test circuit.

ondary arc measured in tests. These figures have different time scales. It is shown in the left figure that the current of CP2 and CP3 increased just after the primary arc inception of CP1 and had stable current value around 2 A. In the right figure, the secondary arc kept flowing for 300μs with decreasing slightly. Almost secondary arc measured in tests had such a waveform.

3.1 Polyimide sample test

Table 1 lists the number of arc in polyimide sample test. The potential difference between electrodes was set to 60 V. The test was started from 0.94 A. Secondary arcs occurred from 0.94A. At the current value of 1.94 A, 5th secondary arc shifted to sustained arc. The time duration of secondary arcs except for the sustained arc was under 1 ms.

Table 1: Number of secondary arc in polyimide sample test.

V, V	I, A	Number of secondary arc
60	0.94	5
60	1.44	9
60	1.94	5

Figure 8 shows a photograph of the gap between electrodes damaged by sustained arc. It is shown in this photograph that the polyimide film between electrodes melted completely and was carbonized. After the sustained arc inception, the insulation between electrodes, between electrode and metal plate under polyimide film was destroyed. It is thought that the arc tracking formed by secondary arc caused the sustained arc.

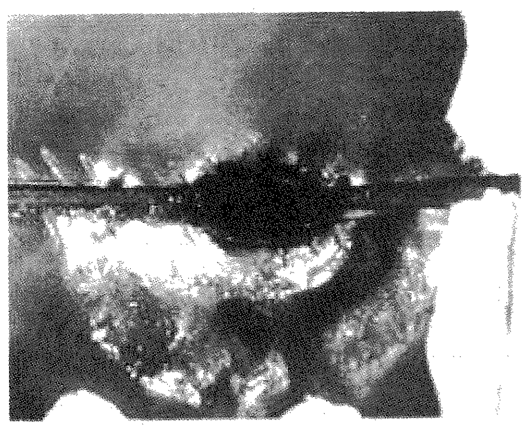

Fig. 8: Photograph of arc site in polyimide sample tst.

3.2 Ceramic sample test

The test for ceramic sample was started from 60V 1.94A. The sustained arc did not occur while 20 secondary arcs occurred although two secondary arcs had time duration over 1 ms. 36th secondary arc, however, caused a sustained arc. The arc lasted over 3ms and caused arc site between electrodes as shown in Fig. 9. After the sustained arc inception, the insulation between electrodes was destroyed. On the other hand, the insulation between electrodes and metal plate was safe. The substrate with high melting point could prevent sustained arc between electrodes and metal substrate. However the arc tracking was formed so that copper tapes, adhesive, SSM Teflon could melt and form arc tracking itself on ceramic sheet even if the substrate did not melt. In the real solar array, silver electrode used in solar cells can melt and form the path of discharge on insulation film.

Fig. 9: Photograph of arc site in ceramic sample.

3.3 Floating sample test

The number of secondary arc in floating sample test is listed in Table. 2. This test was started from the value of 60V and 1.9A which caused sustained arc in both polyimide and ceramic sample test. At 60V and 1.9A, the secondary arc over 1ms did not occur though 25 secondary arcs occurred. No sustained arc occurred in floating sample test though voltage and current increased up to 80V and 3.35A and caused more than ten secondary arcs with duration over 1 ms. After this test, this sample had no damage on its surface.

Figure 10 shows the discharge voltage between electrodes during secondary arc. In this figure, the current and the voltage between electrodes were 1.9A and 60V, respectively. The error bars mean the maximum and minimum value. The average values are plotted in this figure. The voltage is the value just

Table 2: Number of secondary arc in floating sample test.

V, V	I, A	Number of secondary arc
60	1.9	25
70	1.9	9
80	1.9	32
80	2.1	8
80	2.8	22
80	3.35	28

before secondary arc finishes. The discharge voltage of floating sample was higher than other samples. The polyimide sample had the smallest values of voltage. This small value of voltage means small resistance because of constant current. It is thought that the vaporization of polyimide raised local pressure between electrodes and reduced the resistance, resulting in sustained arc. In floating sample, on the other hand, it is thought that local pressure was hard to increase because the volume around gap was open. To verify these assumptions, more test should be performed.

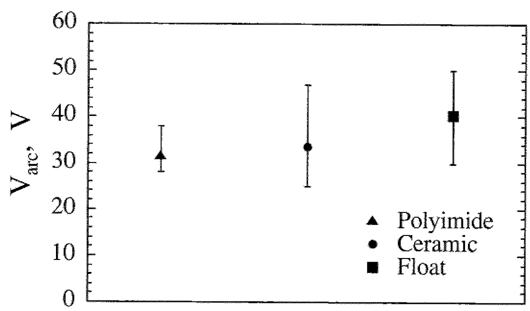

Fig. 10: Discharge voltage between electrodes during secondary arc.

4 Summary

It was verified experimentally whether sustained arc occurred using samples simulating solar array. Three types of substrate insulation were used. The sustained arc was not prevented on substrate insulation because the melting sample formed the arc tracing on substrate even if the ceramic sheet with high melting point was utilized as substrate insulation.

In using floating sample, no sustained arc occurred in spite of large current up to 3.4A. As the result, we found that sustained arc needed the substrate between electrodes. Therefore we propose the solar array design consisting of cells set with a distance from substrate or cells without substrate between cells.

Acknowledgement

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