THRESHOLD CONDITIONS TO INDUCE THE SUSTAINED ARC ON THE SOLAR ARRAY PANEL OF LEO SATELLITE

Jeongho Kim*, Seiji Aso, Satoshi Hosoda, Mengu Cho

Department of Electrical Engineering, Kyushu Institute of Technology

Hideshi Kagawa

JAXA

Abstract: Arcing on satellite solar array due to interaction with space plasma may cause permanent loss of satellite power, once the arc becomes permanent sustained arc. An arc on solar array becomes a secondary arc when solar array circuit is short-circuited and provides energy to the arc plasma. The permanent sustained arc, the final stage of the secondary arc, destroys a solar array string or the complete power circuits at the worst case. To investigate the threshold conditions for the secondary arc formation, laboratory tests are carried out in a xenon plasma chamber simulating LEO plasma environment with an external circuit simulating a spacecraft power system. Solar array coupon panels simulating the hot and return ends of a string circuit are tested for various combinations of string voltage and string current. Experimental results show that formation of secondary arc strongly depends on the string voltage and duration of secondary arc depends on the string current.

1. Introductions

Nowadays, satellites need power generations over 100 volts in Low Earth Orbit (LEO), therefore, they must endure that voltage without causing the sustained arc. In general, as the generation power of solar array grows larger, the risk to induce arcs on the solar array also becomes higher. These arcs on the solar array can cause the several problems such as electromagnetic interference, surface deterioration, or even destruction of spacecraft circuits[1]. It is known that arcing can occur once there is an opening in the insulator where the underlying conductor with a negative potential of -100 V or larger, typically, is exposed to space[2]. The arcing is triggered by charging of insulator material via plasma and field intensification at the conductor surface, especially at the junction with the insulator, which is called a triple junction, because three materials with different electrical conductivity (conductor, insulator, and vacuum) meet there. The example of triple junctions formed on the solar array is shown in figure 1. Spacecraft potential is determined by the balance between the current incidence and emission depending on the surrounding plasma environment, sunlight, and surface materials etc. Generally, conductive body of spacecraft is connected to the surrounding plasma, forming the ground state. And, the negative end of the solar array paddle connected to the spacecraft body becomes the ground state as well.

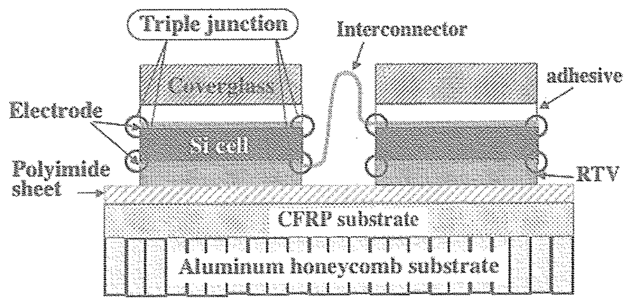


Figure 1. Solar array structure

If the voltage difference between coverglass of the solar array and the conductor grows above the threshold, arc can occur This is called the primary arc which carries the charge energy stored on the coverglass to the ambient plasma. In many cases, primary arc is called the trigger arc as well. It's not rare that a string of the solar array has a gap smaller than 1 mm between the positive and the negative ends because the solar array has to supply a necessary power from the limited space. If primary arcs occur between the gap with a large voltage difference, arc plasma may shorten it. Then, the current generated by the solar array itself can flow via the short circuit, providing the plasma with the generation energy to prevent arc from being extinguished. We call this secondary arc. If this secondary arc continues and carbonize the polyimide film insulator, permanent short circuit between the solar array and the conductive substrate can be formed. This will cause the permanent power loss of the string. This mechanism of destroying solar array was first proposed as the cause of the power loss of the Tempo-2 satellite by 15% in 1997 [3].

There are three types of secondary arcs as shown in figure 3. The first is the non-sustained arc which shortens the circuit only until the primary arc current flows via the gap. The second is the non-permanent sustained arc which continues after the primary arc is over, but is extinguished by itself. The last is the permanent sustained arc which is not extinguished until the power is turned off by force. I_{SC} is the generated current of a string whose value is almost the same as the current flowing via the short circuit. Because the definition of the arc current is not established yet, non-permanent and permanent sustained arc is frequently called secondary and sustained arc, respectively.

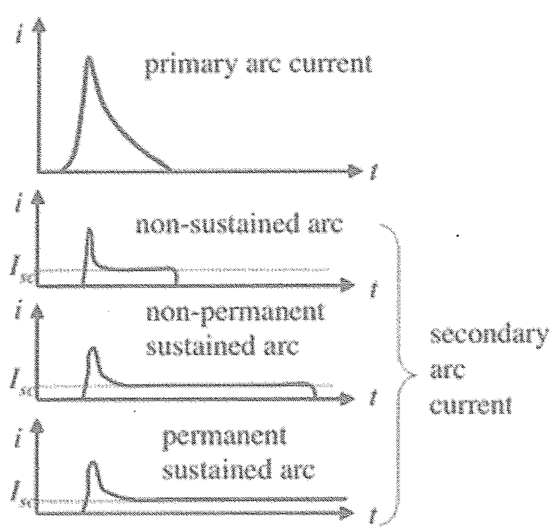


Figure 2. Definition of arc current

The condition to induce secondary arc may have the relation with the string voltage, string current, gap length between adjacent cells, etc. Unfortunately, the critical value of power generation to induce the secondary or permanent sustained arc was not yet established. In addition, there's no international standard to test the endurance against the secondary arc yet. Gaillot et al.[4] propose that it is needed to examine the influence of several parameter, such as the type of solar cell, gap length, and repeated number, on the primary or secondary arc by ground test. ECSS (European Corporation for Space Standardization) [5] published the draft of standard test about the spacecraft charging in Oct. 2004. The values of string voltage and current to be used without endurance test against secondary arc are determined in the text, but they did not mention the number of arc to be test.

In this study, we carried out the laboratory tests on charging and arcing of the solar arrays for satellites in a simulated LEO environment. The experiment was focused on the secondary and permanent-sustained arc occurrence, which could cause serious destruction on the power system. At first, we investigated the relationship between secondary arc occurrence and generated power of satellite. Finally, we searched for the threshold voltage and current to induce non-permanent or permanent sustained arc.

2. Experiment

2.1 Experimental system

Figure 3 shows the schematic of the experimental system. We mounted the coupon fabricated for the experiment in the cylindrical vacuum chamber with dimension of 1 m in diameter, 1.2 m in length. We exhausted the gas in the chamber by using rotary and turbo molecular pump. The pressure in the chamber could reach up to about 1×10^{-5} Torr. Average pressure during the experiment was maintained at about 1×10^{-4} Torr in order to make the plasma environment of LEO. We used an ECR plasma source of xenon gas. The conditions of the plasma environment measured by the langmuir probe were that the density and the electron temperature were 10^{12} m^{-3} and 1 eV, respectively. We connected external circuit via the fed-through mounted on the chamber, and applied negative bias to the solar array coupon in the chamber. The waveform of the arc current was measured using several probes. And, the measured data of the current and voltage is acquired by the high-speed AD converter board (National Instruments NI5102), and is stored directly to the PC. In addition, the video image of arc was acquired by the CCD camera and stored to the PC in real time. We analyzed the stored video data by using analysis program [6] to know the arc occurrence time and the arc position. After the video analysis, we matched the waveform data and the analyzed arc position data.

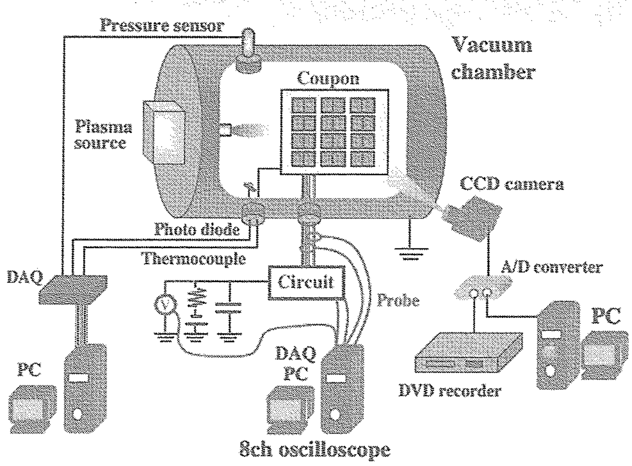


Figure 3. Experimental system

2.2 Solar Array Coupon

The picture of the solar array coupons used in the experiment is shown in figure 4. The coupon is composed of 12 sets of solar cells made of crystalline silicon, and each set is composed of two solar cells connected in series by the interconnector. I-V characteristic of each set shows the short circuit current of 1.1 ampere and the open circuit voltage of 1.2 volt. Cables are connected to both ends of each set, that is, p and n bus-bars. We connected four cables of adjacent two sets of solar cells, upper and lower sets, to the external circuit in order to simulate a solar array string. Therefore, we can use 9 combinations of string with this coupon. These extra string combinations are useful because we cannot use the destroyed string by the sustained arc. In addition, all of the bus-bars are covered with RTV silicone rubber. For the front face of the coupon, the Kapton film is mounted on a CFRP (Carbon Fiber-Reinforced Plastics) face sheet substrate on the top of aluminum honeycomb plate. And, for the back face, CFRP is exposed to the outer surface.

The purpose of this study is to acquire the conditions to make the primary arc occurring near the gap of adjacent two sets of solar cells transfer to the secondary arc. However, the primary arc could frequently occur on other triple junctions, such as interconnectors and edges of solar cells, instead of the gap. Therefore, we attached polyimide tape to all of the triple junctions except for the gap. Moreover, we also attached polyimide tape to the back face because the primary arc can occur on the exposed CFRP. Generally, one string of real solar array has a serpentine structure in which p bus-bar lies in opposite position to the adjacent p bus-bar. However, we laid the adjacent two p bus-bars at the parallel position because we wanted the voltage difference along the gap to be the same regardless of the voltage drop through the solar cells. We made another extra coupon which has the same structure, and the average gap distances of both coupons are 698 mm and 680 mm, respectively. We named these two coupons as #1 and #2.

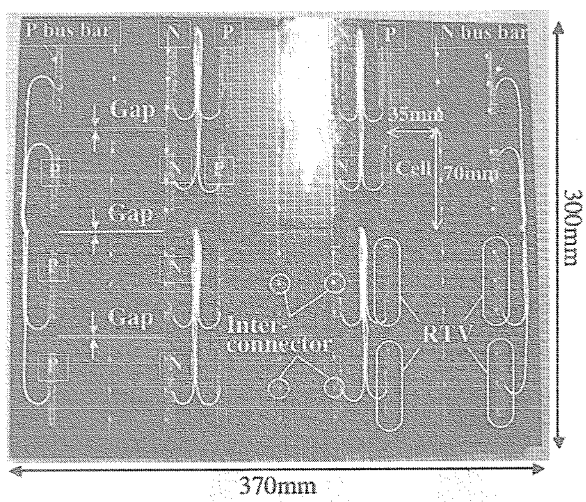


Figure 4. Solar array coupon

2.3 Experimental circuit

Figure 5 shows the experimental circuit. The circuit can be divided into two parts by node A according to the contents of simulation. One is the circuit below the node A, which simulates the floating voltage of the solar array. This circuit can cause the primary arc to occur. The other is the circuit above the node A, which simulates a string of the solar array connected to the load. This circuit is based on the published data by Payan et al. [7], which is designed to simulate the arc phenomena on the solar array during power generation.

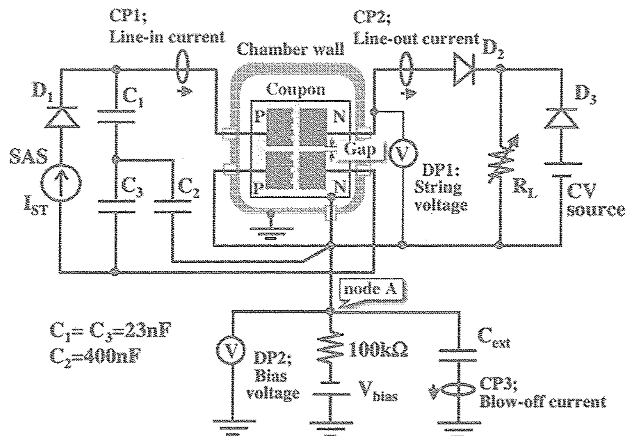


Figure 5. Experimental circuit

In the case of the circuit below node A, we applied the negative floating voltage by the power supply, V_{bias} (Takasago TMK 1.0-50), which simulates the body of the spacecraft. The limit resistor was used to protect the power supply from the over-current due to arcs. Generally, primary arcs can occur if -100 V or more negative floating voltage is applied at node A. But, we applied more negative bias voltage in order to increase the number of arcs without changing the primary arc energy by the reduced value of external capacitance. The external capacitor connected between the node A and the ground simulates the capacitance of the coverglasses of the solar cells. The charges stored in the external capacitor provide the energy to the primary arc by emitting electrons. Unfortunately, the critical value that how many charges are provided from the coverglasses to the primary arc plasma is not clarified yet. Therefore, the value of external capacitance is different among various research institutes, ranging from 100 pF to 10 ∝F. In this study, we selected the 10 nF and 6.5 nF in the case of bias voltage of -800 V and -1 kV, respectively in order to provide a constant energy of 3.2 mJ to the primary arc. This energy is the minimum value to identify the arc location by the intensity of the arc light in our system. And, the value is rather low than the average value applied in other research institutes.

In the case of circuit above node A, we applied the power supply to simulate the generation power of a string. We used Solar Array Simulator (SAS, Agilent E4351B) as the power supply in order to provide the constant current like the real solar array. Primary arc has the waveform of pulsed shape having duration from several ∝sec to several tens of ∝sec. The general power supplies show the response time of several mili-second orders because they have output capacitance ranging up to hundreds of ∝F. On the other hand, SAS is suitable as the power supply for simulating solar array because it has output capacitance lower than 50 nF, and shows the response time within 5 ∝sec. We used SAS as a current source whose output current is corresponding to the current value of a string. The maximum output current and voltage is 4 A and 120 V, respectively. In this experiment, we applied the power supply in the opposite direction of the real generation current because we carried out the experiment under the dark condition. Under the dark condition, a solar cell acts as a diode, and cannot flow current under the inverse bias. Despite the opposite direction of the current flow, it is thought that the simulation of the sustained arc phenomena is not affected because current flow via the arc plasma is not changed except that the direction is opposite.

The capacitors C_1, C_2 and C_3 simulate the capacitance of a string of solar cells. These values were calculated from the hypothesis that 200 solar cells made of crystalline silicon, one of whom generates 0.5 V, are connected in series. R_L is a variable resistor, and simulates the load of a spacecraft. The string voltage, the voltage between two adjacent sets of solar cells, can be adjusted by changing the value of variable resistor because the SAS is used as a current source. We call the positive power end of the solar cells as HOT, and the negative power end of the solar cells as RTN. The power supply of right side simulates the generated voltage by another string of solar cells.

In general, the current flows via the route of SAS-HOT-R_L-RTN-SAS, providing power to the load. These currents were measured by current probes (HIOKI 3274), labeled CP1 and CP2, which can measure the current of dc and ac up to 10 MHz. The current of primary arc flows via the closed path of ground-C_{ext}-primary arc position-ground by neutralizing the external capacitance. We call this current as blow-off current, and measure it by the current probe (HIOKI 9274) labeled CP3. The voltage of the node A was measure by a differential probe (Tektronix P5200) labeled DP2, which can measure the voltage of dc and ac up to 25 MHz. When the primary arc occurs, this voltage rises sharply up to the voltage near zero. Therefore, we used this voltage as the trigger source to record the overall arc waveforms. When the primary arc transfers to the secondary arc, the gap between adjacent two sets of solar cells become short-circuited, leading the current to flow through the gap instead of the load. In this case, we can distinguish the waveform of secondary arc because the current of CP1 flows as it was, but the current of CP2 drops to zero.

We found out that the secondary arc duration had a large variation. Therefore, we used an 8-channel oscilloscope in order to acquire both the detailed waveforms and the secondary arc duration without range over. 1-4 channels cover the range of short duration within dozens of micro-seconds, and 5-8 channels cover the range of long duration up to several hundred mili-seconds.

2.4 Experimental conditions

Table 1 shows the experimental conditions. These conditions are to simulate the LEO environment. The string voltage and current simulate the bus voltage and current of the solar array of the satellite, respectively.

Table 1. Experimental conditions

Back pressure, Torr	$1.1\times10^{-4} \sim 1.2\times10^{-4}$
Plasma density, m^{-3}	$9.1\times10^{11} \sim 4.3\times10^{12}$
Electron temperature, eV	$0.5 \sim 1.6$
Gap length, mm	$552 \sim 898$
String voltage, V	$20 \sim 120$
String current, A	$0.3 \sim 4.0$

3. Results and Discussions

3.1 Number of Arcs

Table 2 and 3 show the number of arcs on #1 and #2 coupons, respectively. N_{PR} means the number of primary arcs, N_{NS} means the number of secondary arcs (non-permanent sustained arc), and T_{EXP} means the experimental time. The number of primary arcs has a variation because when we continued the experiment at a certain gap, the frequency of the primary arc occurrence decreased with time. Therefore, some results were the cumulative numbers acquired from several gaps. We confirmed that 8 points of different voltages and currents among overall conditions showed the result of permanent sustained arc occurrence. In any case of permanent sustained arc, non-permanent sustained arc occurred only once or did not occur at all.

Table 2. Number of arcs (#01 coupon)

V_{ST}, V	I_{ST}, A	N_{PR}	N_{NS}	Sustained arc	T_{EXP}, h:m:s
50	0.5	204	0	No	1:23:55
50	1.0	137	0	No	0:06:59
60	1.0	108	0	No	0:08:53
50	1.5	144	0	No	0:44:36
60	1.5	134	0	No	1:10:17
55	2.0	129	0	No	0:41:55
50	2.5	194	1	No	0:18:31
55	2.5	45	0	No	2:05:55
55	2.7	24	0	No	1:10:57
55	3.0	45	1	No	2:15:00
50	3.5	52	0	No	1:34:18
55	4.0	25	0	Yes	0:08:56
100	0.5	331	182	No	0:30:29
110	0.5	46	8	No	0:20:03
100	1.0	190	139	No	1:54:56
120	1.0	10	2	No	1:03:16
100	1.5	2	1	Yes	0:01:05
100	2.0	5	1	Yes	0:01:05

Table 3. Number of arcs (#02 coupon)

V_{ST}, V	I_{ST}, A	N_{PR}	N_{NS}	Sustained arc	T_{EXP}, h:m:s
20	2.0	193	0	No	0:10:15
20	3.0	173	0	No	1:23:15
20	4.0	188	0	No	2:00:31
30	2.0	200	0	No	0:51:03
30	3.0	157	0	No	1:24:17
30	4.0	140	0	No	1:07:10
50	1.5	213	0	No	0:18:11
50	2.0	184	0	No	0:52:52
50	2.5	195	0	No	1:25:12
50	3.0	168	0	No	1:38:42
50	3.5	191	0	No	2:00:33
50	4.0	187	0	No	0:25:29
70	0.6	199	1	No	0:20:53
70	1.0	163	1	No	2:41:09
70	1.5	194	1	No	2:51:45
70	2.0	62	0	Yes	0:04:16

85	0.3	102	60	No	0:17:38
85	0.5	208	22	No	0:10:20
85	1.0	209	20	No	1:12:45
85	1.5	209	29	No	0:45:49
85	2.0	5	0	Yes	0:02:48
100	1.3	479	202	No	7:31:33

3.2 Feature of each arc

Figure 6 shows the typical waveforms of the primary arc and the bias voltage under the condition of V_{bias}=-800 V, C_{ext}=10 nF. In addition, the analyzed results of the waveforms of the primary arcs under the same condition are shown in table 4. The arc energy shown in table 4 is lower than the theoretical value of 3.2 mJ. This difference of energy seems to be resulted from the smaller bias voltage applied to the external capacitance. The reason for this is due to the voltage drop through the limit resistor of 100 kΩ. In this study, we examined the transfer to the secondary arc from the primary arc like this.

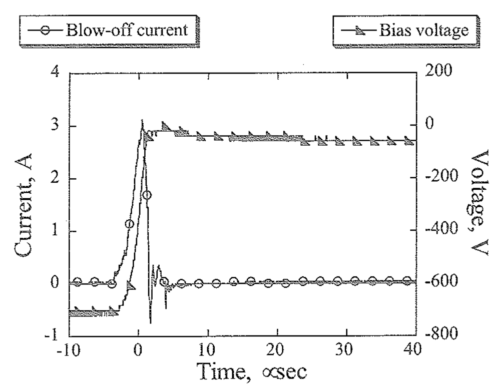


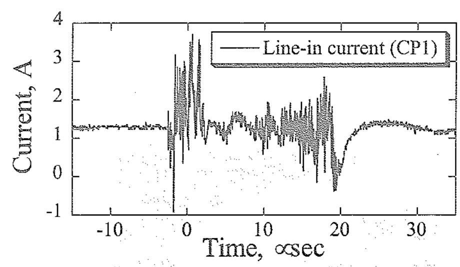
Figure 6. Typical waveform of the blow-off current and the bias voltage when a primary arc occurs

Table 4. Characteristic of blow-off current (V_{bias}=-800V, C_{ext}=10nF)

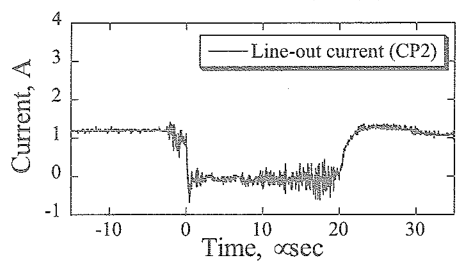
	Minimum	Maximum	Average	Standard deviation
Peak, A	2.81	4.96	3.58	0.473
Charge, ∝C	7.03	7.71	7.30	0.0244
Pulse width, ∝sec	4.25	6.35	4.97	0.482
Energy, mJ	2.46	2.70	2.57	0.00422

(Data point: 26)

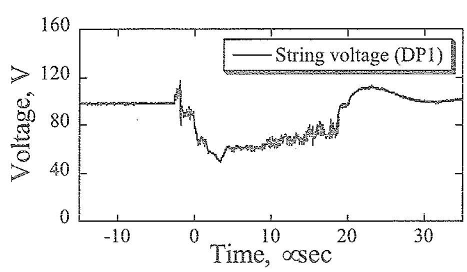
Figure 7 shows the typical waveforms of non-permanent sustained arc acquired by the oscilloscope channels covering shorter range under the condition of V_{ST}=100 V, I_{ST}=1.3 A. Initially, the string current set up at 1.3 A is confirmed to flow via CP1 and CP2. But, the line-out current component of the string current detected by CP2 falls to zero for certain duration. The value which subtracts current of CP2 from that of CP1 is called as the arc current, which flows via the arc plasma at the gap between the adjacent sets of solar cells. We defined whether the arc is secondary arc or not and how long is the secondary arc duration more in detail. At first, we defined the end time of blow-off current, T_{end}, as the time when the value of the blow-off current decreased to 10% of the peak value. If the arc current above 90% of the string current is still flowing after the time T_{end}, we call the current as the secondary arc and call the duration after the time T_{end} as the secondary arc duration. However, we excluded the arc from the secondary arc if the arc had the secondary arc duration within 2∝sec in order to avoid mistake caused by the noise. We distinguished the secondary arc from the primary arc by the program made on the basis of this definition. And, the non-sustained arc, shown in figure 2, cannot be counted as the secondary arc by this definition. The number of secondary arcs, N_{NS}, shown in table 2 and 3 is the result from this program. For example, the duration of non-permanent sustained arc shown in figure 7 was 16.3∝sec.



(a) CP1



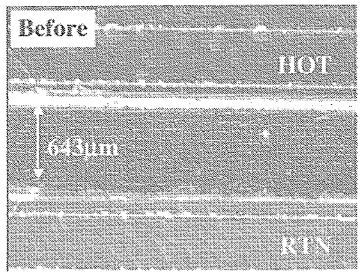
(b) CP2



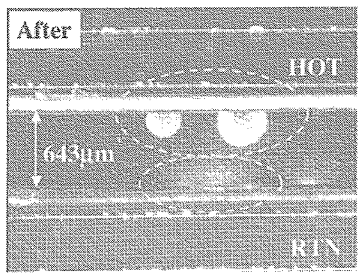
(c) DP1

Figure 7. Typical waveforms of non-permanent sustained arc

The microscopic images of the same position before and after the non-permanent sustained arc are shown in figure 8. The experimental condition is V_{ST}=100 V, I_{ST}=1.3 A. There are several arc tracks shown in the image after the experiment. The arc track in the RTN side seems much thinner than those in the HOT side. It is thought that arc tracks in both sides were created by the deposited materials once melted due to high temperature of the arc plasma. The arc tracks in each side represent the typical shape of them, that is, this image of arc tracks is fairly representative to respective HOT and RTN side.



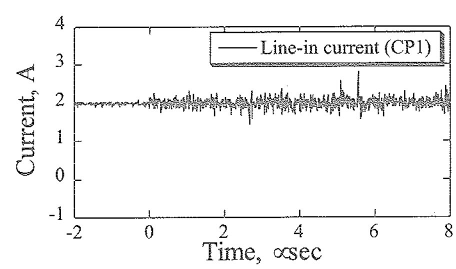
(a) Before arc



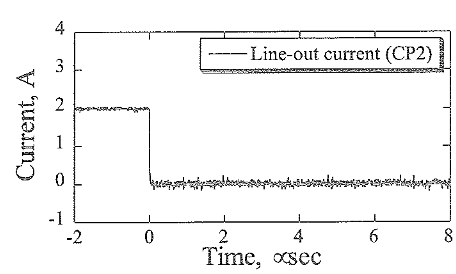
(b) After arc

Figure 8. Arc track by the non-permanent sustained arc

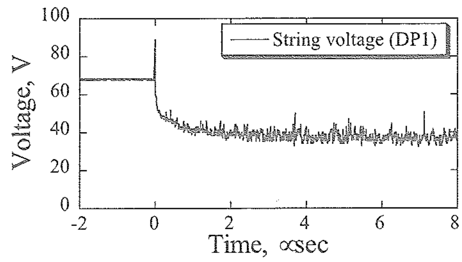
Figure 9 shows the waveforms of the permanent sustained arc acquired by each probe under the condition of V_{ST}=70 V, I_{ST}=2.0 A. In this case, the time range of the waveform was limited to 8 mili-seconds. However, the sustained arc was not extinguished until we turned off the power supply of the system by force in 120 seconds after the sustained arc occurred. The sustained arc started with the more intensive light emission than other type of arc. Then, the background pressure sharply increased from 1.10×10^{-4} Torr up to about 1.45×10^{-4} Torr. Figure 10 shows the image of the destroyed solar cell by this permanent sustained arc. It can be confirmed from this figure that the dielectric layer of polyimide between the solar cell and the conductive substrate is turned to black by carbonization. And, the solar cell is destroyed as well by the arc. The measured resistance value between electrode of solar cell and the conductive substrate decreased to 28.7 Ω.



(a) CP1 (Time, msec)



(b) CP2 (Time, msec)



(c) CP3 (Time, msec)

Figure 9. Typical waveforms of permanent sustained arc

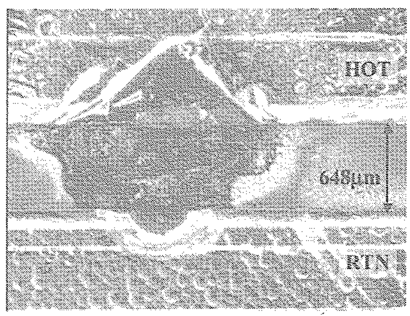


Figure 10. Destroyed gap by the permanent sustained arc

3.3 Threshold value of the secondary arc occurrence

Figure 11 shows the results of the secondary arc occurrence depending on the parameters of various string voltages and currents. The secondary arc shows the tendency to occur at the lower level of the string current as the string voltage increases. In the case of 100 V generating voltage, non-permanent sustained arc occurred at the string current of 0.5 A, and the permanent sustained arc occurred at the current of 1.5 A. For the condition of V_{ST}=100 V, I_{ST}=1.5 A, permanent sustained arc occurred at the fourth arc event as shown in table 2. On the other hand, for the condition of V_{ST}=100 V, I_{ST}=1.3 A, permanent sustained arc did not occur among 479 times of primary arcs as shown in table 3. This result means that the threshold current to induce permanent sustained arc for 100 V generating voltage of solar array can be about 1.5 A. Of course, this value can only be an indicator to alarm the possibility of sustained arc occurrence around it. And, the possibility is open to the different results in the case where one of the simulated environments, experimental conditions, gap length and so on will be different.

Figure 12 shows the ratios of the number of secondary arcs to that of primary arcs depending on the string voltage. These ratios are calculated by dividing the number of non-permanent sustained arcs, N_{NS}, by the number of primary arcs, N_{PR}, shown in table 2 and 3. We confirmed that the possibility of secondary arc occurrence increases with the string voltage. In addition, we can find out that the secondary arc occurrence for the lower string current of 0.3-0.6 A is high at the string voltage above 70 V. On the other hand, the relationship between the secondary arc occurrence and the string current is not so clear in this figure. Figure 13 shows the average secondary arc (non-permanent sustained arc) duration depending on the string current. The vertical axis indicating the secondary arc duration is in the log scale. The secondary arc duration increases rapidly with the increasing string current. Especially, for the string voltage above 70 V, the secondary arc duration exceeds 100-1000 ∝sec at the string current of 1.3-1.5 A. Above these conditions, the permanent sustained arc occurred. Therefore, we can consider that the longer duration may be the indicator of the permanent sustained arc occurrence. And, we confirmed that the string current has a good relationship with the duration of an arc as well.

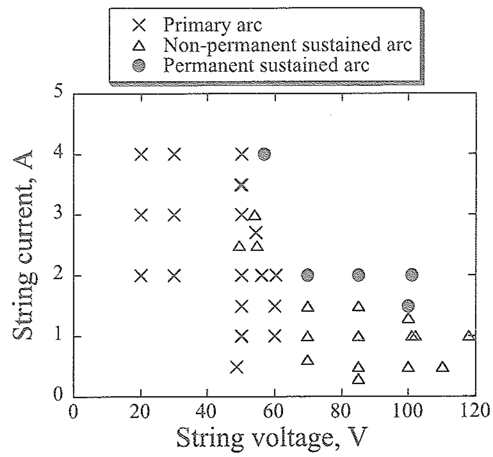


Figure 11. Mapping of the threshold voltage and current to induce secondary arc

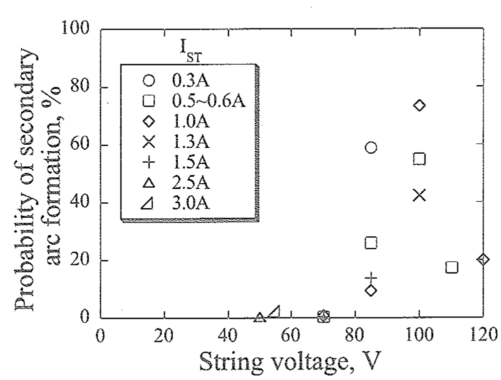


Figure 12. Change of non-permanent sustained arc occurrence according to the string voltage

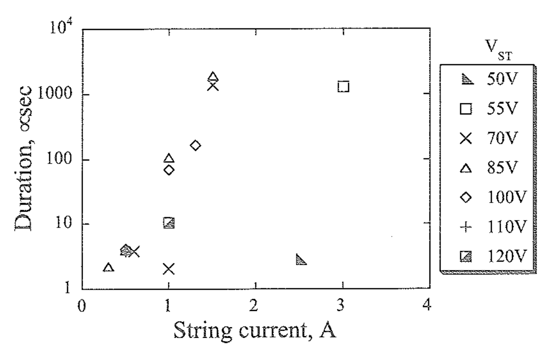


Figure 13. Change of non-permanent sustained arc duration according to the string current

4. Conclusions

We investigated the conditions of the secondary arc occurrence and measured the threshold conditions of string voltages and currents in the simulated LEO environment. From the results, we identified the specific conditions of string voltages and currents to induce the non-permanent sustained arc or the permanent sustained arc. In the case of 100 V generating voltage, non-permanent sustained arc can occur at the string current of 0.5 A, and the permanent sustained arc can occur at the current of 1.5 A. And, for the lower voltage, the string current to induce the secondary arc was higher. We found out that the possibility of secondary arc occurrence increases with the string voltage. And, the secondary arc duration increases drastically by a log scale as the string current increases. The increasing in this manner indicates that the permanent sustained arc occurs sooner. However, the permanent sustained arc suddenly occurs at the higher string voltage and current without the cumulative effect of non-permanent sustained arc. This result means that the voltage or the current is already beyond the limit which the solar array can endure. Therefore, we must avoid the worst case like this in designing the solar array. However, solar array shows relatively good performance under the condition right below the limit condition even if the secondary arc duration is longer than 100-1000 ∝sec. Finally, we confirmed that the arc track due to the secondary arc is created by the deposition of the melted materials, and has the shape of circular arc. It may be interesting to examine the relationship between the radius of arc track and the energy of secondary arc in the future.

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