THRESHOLD MEASUREMENT OF SECONDARY ARC ON SOLAR ARRAYS FOR JAPANESE SPACECRAFT CHARGING GUIDELINE

Kazuhiro Toyoda, Takayuki Ose, Hirokazu Masui, and Mengu Cho

Laboratory of Space Environment Interaction Engineering, Kyushu Institute of Technology

1-1Sensui Tobata-ku Kitakyushu 804-8550, Japan

ABSTRACT : *In this paper, we report about the test results on coupons made for Working Group 1(WG1), which was established to make a Japanese guideline for spacecraft charging design. Laboratory tests were carried out with an external circuit simulating a spacecraft power system. The solar array coupon panels simulating the hot and return ends of a string circuit were tested under various combinations of string voltage and string current. We revealed that the threshold conditions for sustained arc were different in string voltage.*

1 - INTRODUCTION

Recently, the discharge phenomenon on solar array has become problem. The satellite potential depends on a surrounding plasma environment, the sunshine condition, and the surface physical properties. In GEO, when a satellite encounters substorm environment, its potential can become extremely negative due to high-energy electrons flowing into the satellite. The potential difference appears between the spacecraft ground and insulator structures like coverglass due to the difference of secondary emission yield. This cover glass potential can be higher than that of the interconnector that is close to the spacecraft ground. This is called inverted potential gradient. The cross-sectional view of spacecraft solar array is shown in figure 1.

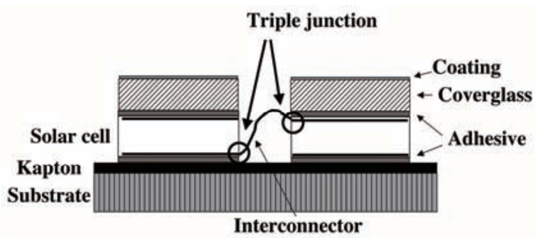

Figure 1 - Schematic of solar cell

An electric field is generated between the coverglass and the conductor, and the electric field is enhanced near the triple junction, which is the boundary of conductor, dielectric and plasma. The field enhancement at the triple junction induces an discharge. The single discharge called the primary arc causes considerable problems, such as electromagnetic interference and destruction of solar array circuit. The primary arc can cause short-circuit between adjacent cells having high voltage potential. This phenomenon is called the secondary arc. The short-circuit current of secondary arc is supplied by solar cells generating electric power. When the secondary arc occurs, the output power of the circuit is lost. This can cause the destruction of the solar array circuit at the worst case. The troubles of destruction of the solar array circuit due to secondary arc are reported[1,2].

The secondary arc is classified into several steps whether short circuit phenomenon is temporary or not. Figure 2 shows the definition of the discharge current waveform. The time that first falls to below 10% of peak value (I_{peak}) on the trailing edge of the primary arc waveform is defined as T_{end}. The time duration, which the current over 90% of peak current value flows from T_{end}, is defined as time duration of the arc. We defined that the secondary arc with time duration less than and more than 2µs were Non Sustained Arc (NSA) and Temporary Sustained Arc (TSA), respectively. If the arc current flows permanently, the secondary arc is defined as Permanent Sustained Arc (PSA). It is suggested that the occurrence of the secondary arc depends on the voltage between adjacent cells in the solar array (V_{ST}), the power generation current (I_{ST}), the gap length between adjacent cells, and the energy of the primary arc[3-5].

The Working Group 1 was organized to prepare a Japanese spacecraft charging guideline in order to mitigate spacecraft failure due to charging and discharging. In the guideline, the threshold measurement of secondary arc inception was needed to understand the voltage, the current, and the gap length that cause the secondary arcs. We have performed the secondary arc threshold measurement so far[4-5]. In this paper, the test results of secondary arc are reported mainly for the Triple-Junction solar array coupon.

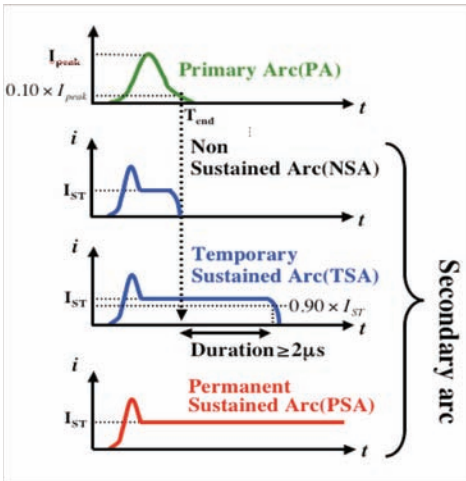

Figure 2 - Definition of primary arc and secondary arc.

2 - EXPERIMENT

9 Triple-Junction (TJ) cell coupons and a Silicone (Si) cell coupon were prepared for the threshold measurement. The gap lengths of TJ coupons were 0.5mm, 0.8mm, 1.0mm, and 2.0mm. The coupons with and without RTV grouting in gap were prepared for the gaps of 0.5mm and 1.0mm. The Si coupon had 0.5mm gap length. Figure 3 shows a example photograph of the coupon used in the experiment. The substrate was made of aluminum honeycomb covered with Carbon Fiber Reinforced Plastic (CFRP). The top of the substrate was covered with the Kapton® film. This solar array coupon consisted of 24 TJ solar cells (76mm×37mm). All solar cells were glued on the Kapton® film by RTV silicone adhesive. Two solar cells were connected in series via the inter-connectors. We used four cells formed two strings with two cells with facing as a treat sample. This coupon was composed of three strings named R, B, and G. The electrodes connected to both ends of the series connection are called bus bar. All bus bars are covered with RTV silicon in order to suppress arc inception there.

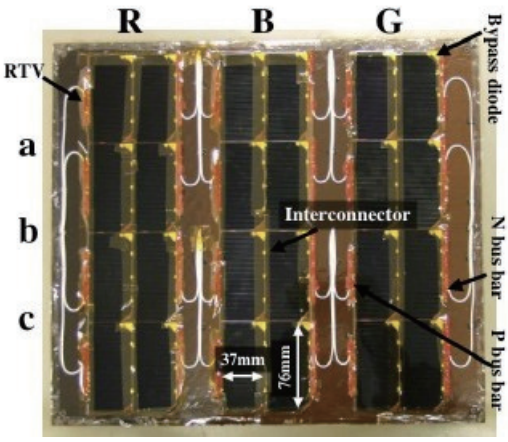

Figure 3 - Picture of solar array coupon.

The sketch of the measurement system is shown in figure 4. The experiments were performed in a vacuum chamber. The GEO environment was simulated by an electron beam gun. All waveforms of the array potential and the discharge current were acquired by a high-speed data acquisition system. During the experiments, the video image of the coupon was recorded in a hard disk drive connected to a PC as a digital video image.

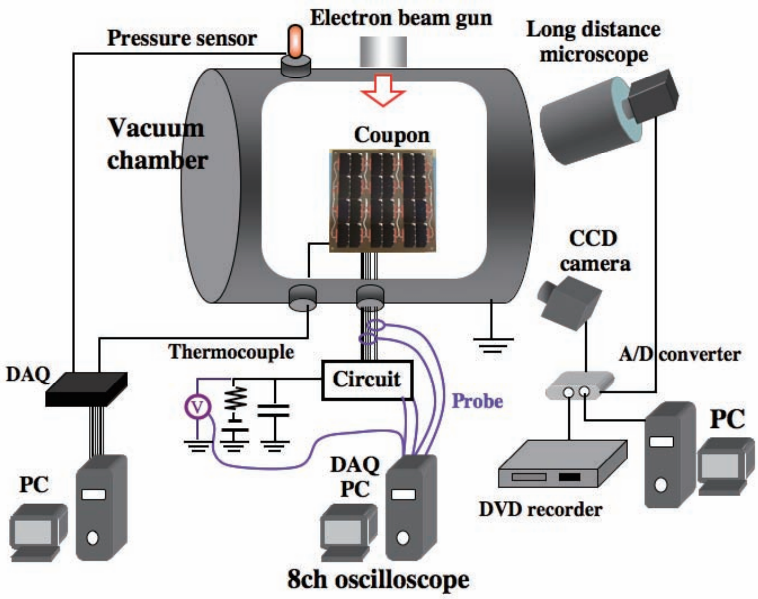

Figure 4 - Experimental setup

The external circuit used in the secondary arc experiments is shown in figure 5. Direct current source V1 is a power supply imitated output of solar array generating electricity. This power supply is demanded to follow the phenomenon of several microseconds like the primary arc[6]. Therefore, we used DC power supply composed of the current regulative diode parallel in this experiment. This power supply has the low output capacitance lower than 5nF and the recovery time of about 0.5μs. RL is pseudo-load.

The C1～C3 is corresponding to the capacitance of one series circuit which 50 TJ cells are connected on a substrate. V_{bias} and C_{ext} imitate the potential and capacitance of the satellite respectively. The primary arc energy is supplied by this capacitance. In the primary arc, the electron charged in C_{ext} flows from arc site to the chamber wall through plasma. This current is called a blow off current. We measured the blow off current with a current probe, CP3. Solar strings having higher potential only a due to RL potential is called HOT line and the other side is called RTN line.

At first, the current usually flow the route of V1-HOT-RL-RTN –V1 by V1 power supply. This route shows the current supplied by the electric power to the load. In normal operation, the V2 cannot usually output because the voltage of V2 is set less than voltage of RL. If arc plasma makes short-circuit between cells of HOT and RTN line, the voltage between strings decrease less than the voltage of V2. Here, all current flows from V1 to arc site. This is a current loop of the secondary arc. The secondary arc inception is judged by measuring the current with current probe (CP1, CP2). The difference between CP1 and CP2 is arc current that actually flows between cells as secondary arc. V_{ST} during steady-state is called string voltage. The bypass capacitance C_{BP} was also connected to simulate a bus capacitance. A LCR circuit controlled a primary arc waveform in order to simulate a flashover current.

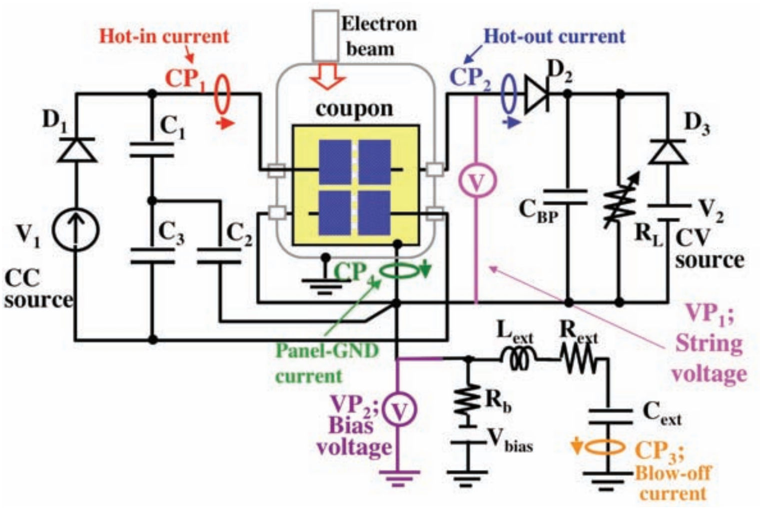

Figure 5 - Experimental circuit.

The test procedure is as follow;

1. Measure TSA threshold at a fixed V_{st} with L_{ext}= R_{ext} = 0 and C_{ext}= 5nF. If a TSA occurs, move to PSA test. If not within 20 arcs, increase current and continue TSA test.
2. Move to a virgin gap and measure PSA threshold from the current of TSA threshold. If a PSA does not occur within 10 TSA, increase current.

After every test case, microscopic pictures were taken by a long distance microscope to check the health of test gaps.

3 - RESULTS AND DISCUSSIONS

Figure 6 shows the threshold test results of secondary arc. The cells in figures were classified by color. The numbers in cells show the average of secondary arc durations except that PSA occurred as 1st secondary arc. The numbers in parentheses show the current value flowing during secondary arc actually.

In every coupon, no secondary arc occurred in the Vst of 30V. The TJ coupon with 2.0mm gap and Si coupon with 0.5mm gap showed higher threshold value of 50V. The threshold current for PSA was 1.5A except for 2.0A in TJ coupon with 2.0mm.

Figure 7 shows the relation between secondary arc duration and current. These durations were average values. As shown in this figure, the secondary arc duration increased with increasing current. The duration of 1ms corresponded to the current from 1A to 2A, resulting in PSA in all coupons. This means the secondary arc duration over 1ms can cause PSA.

V_{st}, V	I_{st}, A 0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50	7µs (0.7A)	28µs	4534µs (1.7A)	
70	4µs (0.6A)	250µs (1.2A)	7747µs (1.8A)	
90	54µs (0.5A)	231µs (1.2A)		
110	5µs (0.6A)	552µs (1.2A)	2750µs (1.6A)	

PA　NSA　TSA　PSA

(a) TJ 0.5mm

V_{st}, V	I_{st}, A 0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50		47µs	4086µs (1.7A)	
70	7µs (0.7A)	209µs (1.2A)		
90	4µs	41µs (1.2A)	4384µs (1.8A)	
110	3µs (0.6A)	179µs (1.2A)	7408µs (1.8A)	

PA　NSA　TSA　PSA

(b) TJ 0.8mm

V_{st}, V	I_{st}, A 0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50		12μs	1126μs	4433μs
70	3μs	25μs	1225μs	
90	3μs	7μs (0.9A)	415μs (1.3A)	
110	4μs	42μs	943μs	

PA NSA TSA PSA

(c) TJ 1.0mm

V_{st}, V	I_{st}, A 0.5	1.0	1.5	2.0
50	No secondary arc up to 4A			
70	7μs			
110	2μs	140μs	1400μs	3900μs
200	3μs (0.7A)	110μs (1.1A)	60μs (1.3A)	
300	5μs (0.6A)	25μs (1.3A)	370μs (1.4A)	

PA NSA TSA PSA

(d) TJ 2.0mm

V_{st}, V	I_{st}, A 0.5	1.0	1.5	2.0
30				
50	PA	PA	PA	PA
70	3μs (0.6A)	88μs (1.2A)	1098μs (1.7A)	
90				
110	4μs (0.6A)	233μs (1.2A)	727μs (1.7A)	

PA NSA TSA PSA

(e) Si 0.5mm

Figure 6 - Threshold measurement test results of secondary arc.

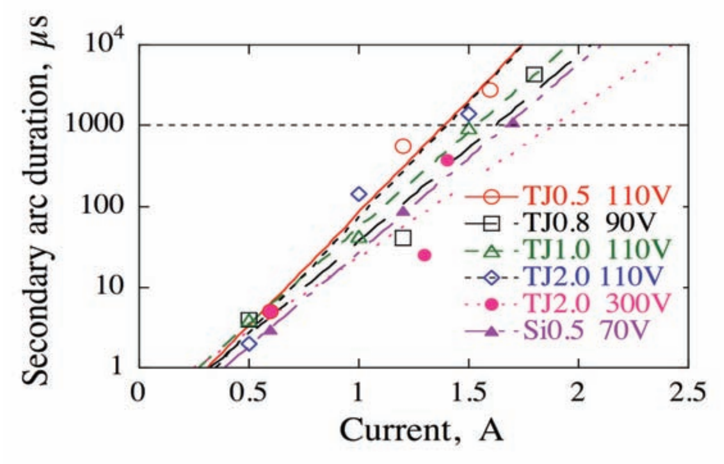

Figure 7 - Relation between secondary arc duration and current.

4 - SUMMARY

The threshold value of secondary arc was acquired for TJ cell and Si cell coupons. The ESD testing method for secondary arc was also established. The results were summarized in figure 8. The threshold value was different in gap and cell type. The safe condition was classified by 4 categories, as follows.

- Safe: no secondary arc can occur.
- Caution: TSA can occur, however PSA cannot occur.
- Danger: PSA may occur.
- Prohibition: PSA can occur.

In the case of TJ cell coupon with the gap length from 0.5mm to 1.0mm, the safe zone was below 30V. The secondary arc duration depended on current, and however showed the independent on voltage. The coupons with these gaps had PSA over 1.5A.

The TJ cell coupon with a 2.0mm gap had the safe zone below 50V. The prohibition zone was over 2.0A.

The Safe and prohibition zone of the Si 0.5mm coupon were below 50V and over 1.5A, respectively.

These test results were included in the Japanese spacecraft charging design guideline.

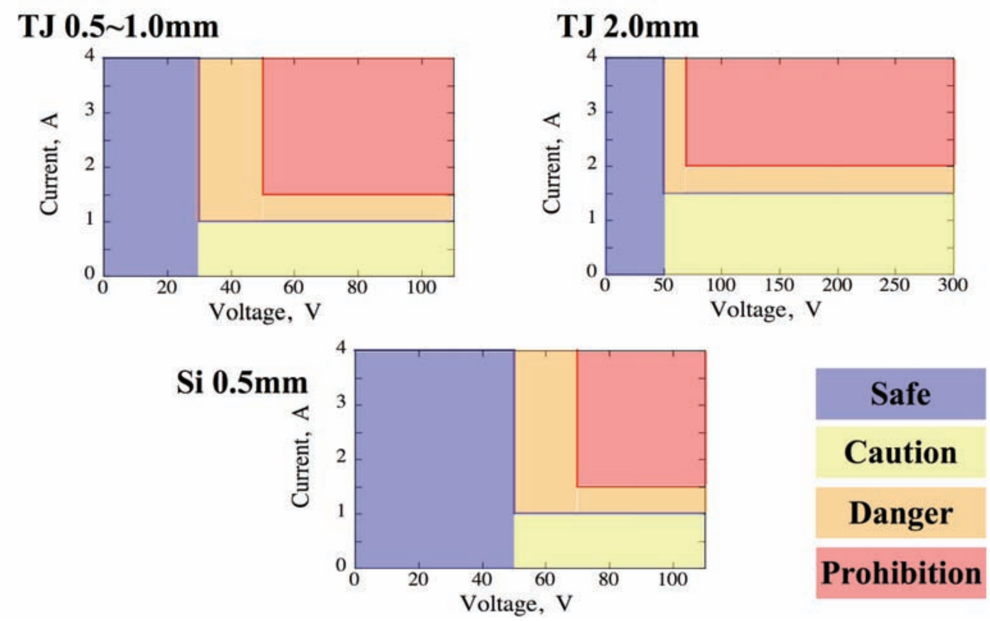

Figure 8 - Safe conditions for secondary arc.

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