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Original Paper

Research on Mitigation Method against Secondary Arcing on Solar Array

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The recent trend of satellite manufacturing is to increase its communication capacity, multi-purpose mission payload, electric power and lifetime. A short-circuit due to discharge on the solar array of the satellite hampers its target by causing serious problems, such as, lowering of power generation that ultimately halts the operation of solar array. In this paper, we have investigated possible mitigation methods against short-circuit due to discharge on solar array by applying coating and by changing the shape of Room Temperature Vulcanization: Silicon adhesive (RTV). The electrostatic discharge is mitigated by obtaining the event of secondary arc generated on each condition.

Key Words: Secondary Arc, Sustained Arc, Coating

Nomenclature

C_{ext}	:	external capacitance
C_{BC}	:	bypass capacitance
C_1	:	string capacitance
C_2	:	string capacitance
C_3	:	string capacitance
CRD	:	current regulated diode source
I_{peak}	:	peak current
I_{sc}	:	short-circuit current of solar array
I_{ST}	:	string current
R_b	:	bias power supply protecting resistance
R_L	:	load resistance
T_{start}	:	start of blow-off current
T_{end}	:	end of blow-off current
t_{arc}	:	duration of TSA
V_1	:	constant power supply voltage
V_2	:	constant power supply voltage
V_{ST}	:	string voltage
V_{bias}	:	bias voltage
$O.F.$	:	over flow

1. Introduction

In recent years, the satellite is an essential part of modern life. Geostationary meteorological satellite “GMS-6” forecasts the weather information time to time. In addition, earth observation satellite “ALOS” can acquire topographical information accurately. As the time running, a satellite of multiple functions gets importance to reduce the effective cost. However, to run such a multifunctional satellite, high power, such as 10 kW or more is essential. When a satellite is operated by a high power efficiently, it needs a bus voltage about 100 V. However, with increasing the bus voltage of the satellite, a short-circuit discharge accident on the solar array is enhanced. A short-circuit discharge on the solar array of the satellite is causing serious problems, such as, lowering of power generation that ultimately halts the operation of the solar array. Therefore, it is necessary to investigate the mitigation method against a short-circuit discharge on solar array by ground experiment. The purpose of this research is to develop effective mitigation methods to stop short-circuit discharge on the solar array.

1.1. Discharge mechanism

The potential of spacecraft is resolved by the balance of electrons which enter and leave off the spacecraft. While the spacecraft is in sunlight, the potential of insulator on spacecraft is kept approximately several volts due to photoemission. In contrast, the spacecraft body potential terns to negative potential of several kV. Even under the magnetic storm (substorm), spacecraft potential turns to several kV. The coverglass potential and satellite potential deviate by the difference of the secondary electron emission coefficient. Inverted potential gradient is formed when the coverglass potential exceeds the satellite potential. Furthermore, the electron is emitted from the triple junction in the direction opposite to the electric field, collides with the adjacent coverglass causing secondary electron emission from adjacent area. In addition, the potential difference between the satellite and the coverglass enhances the electric field in the triple junction neighborhood and the field emission current increase by the effect of feedback. Hence, these electrons after hitting the adjacent coverglass increase the field emission current. Moreover the adhered gas is detached. As a result, ionizing occurs in the gas and the discharge is generated [1)]. Afterwards, the charge over coverglass is neutralized. This arc phenomenon is called primary arc (PA). The solar array is damaged when PA is generated which causes decreasing of output power [2)]. In addition, the solar array cells can be short-circuited through the gaps in between cells by the arc plasma formed by primary arc if the insulation sheet is deteriorated or damaged. This arc phenomenon is generally called secondary arc. When secondary arc occurs, the power cannot be supplied to the on board instrument of satellite due to loss of output power of the solar array circuit.

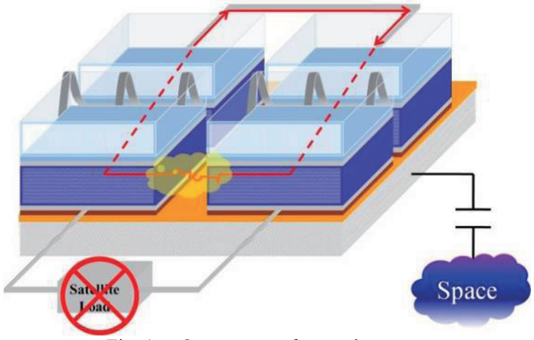

Fig. 1. Occurrence of secondary arc.

The arc is classified by the current waveforms flowing into the substrate as shown in Figure 2. Primary arc is an arc phenomenon when the stored charge on the cover glass flows into the arc spot through the arc plasma. This current flowing into electrode is called a blow-off current. If there is no secondary arc after a blow-off current, this is called the non-sustained arc (NSA). The temporary sustained arc (TSA) and the permanent sustained arc (PSA) are the current generated by solar cells flowing into the substrate through the arc plasma and is maintained even after the blow-off current stopped. This current flowing into the substrate is called an arc current.

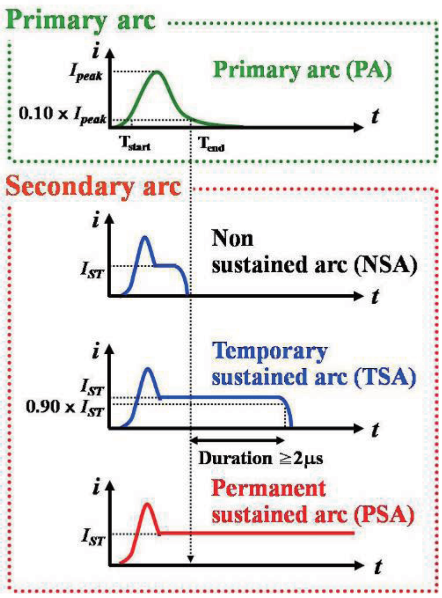

Fig. 2. Definitions of different arc current based on current waveforms.

1.2. Mitigation method of SA

One of the mitigation methods of SA is to add RTV barrier between cells (grouting). Figure 3 shows RTV barrier between cells. The effect of grouting is shown experimentally by Cristopher *et.al.* [3]. However, grouting has some faults, and it is hard to say that this method is sound and effective against SA. RTV evaporates by the discharge causing contamination adjacent to discharge point. Moreover, it is adhered to the coverglass followed by reduction of power generation. In addition, an enormous amount of RTV needed that increases the weight of satellite. Next, the voids and cracks on RTV between gaps might accelerate the discharge under the space environment. Therefore, it should be removed by manually or mechanically. However, large manpower or special mechanical system is necessary to remove the voids and cracks in all gaps and it needs cost. Finally, the surface temperature of satellite changes from 190K to 360K in the space environment. Therefore, it has yet to solve whether RTV can be endured at the heat cycle in the space environment. In the viewpoint of mitigation against the sustained arc, grouting is sufficient, but faults have not been solved yet. Hence, the investigation on the mitigation method against sustained arc should be continued.

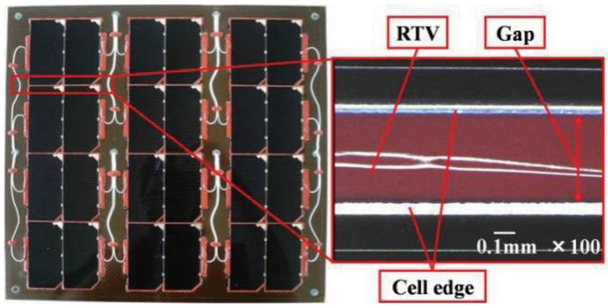

Fig. 3. RTV barrier between cells (grouting).

Therefore, we have investigated about two mitigation methods of the sustained arc. The first one is the painting of coated material in gaps based on the idea that it may hide triple junctions (TJ). The second one is to change the shape of RTV. We have changed the thickness and the depth of RTV. Therefore, this may not initiate the sustained arc route.

2. Experimental Setup

All experiments were performed in a vacuum chamber. The pressure in the chamber was less than $2x10^{-4}$Pa during experiment. Figure 4 shows the experimental circuit with equipments arrangement, such as, electron beam gun, plasma source, etc. The electron beam gun simulated the high energy electron that hit the satellite during the substorm. Acceleration voltage of the electron beam could be varied from 0 kV to 30 kV. Electron current density could be controlled from 0 to 200 μA. The ECR plasma source was attached on the chamber producing a plasma with a density ranging from $10^{11}m^{-3}$ to $10^{12}m^{-3}$. Moreover, high voltage power supply V_{bias} (0~60kV, 0~10mA) (Glassman: EW60R10) was used to simulate the potential of satellite sinking negatively during the substorm. In addition, a solar array simulator, SAS, (Agilent: E4351B) was used to simulate the power generation of solar array with a resistance R_L that simulated the load of the satellite. CRD speeded up the response to the load of low rush current [4]. The C_{ext} (20nF) is used to simulate the stored charge inside the cover glass because the solar array of an actual size is not possible to set in our chamber for experiment. String capacitance was parasitic capacitance of 30 cell in series, and it was calculated based on the distribution multiplier theory. C_1 and C_3 were 23 nF, and C_2 was 400nF.

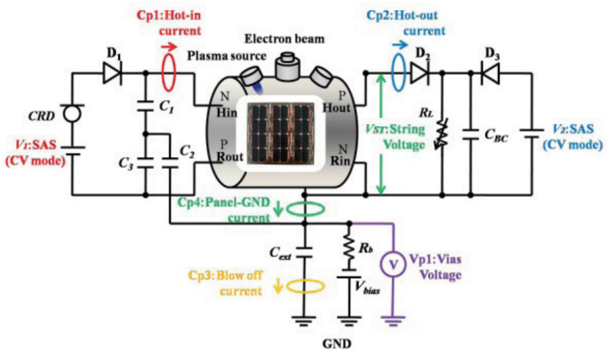

Fig. 4. Experimental circuitry.

2.1. Solar array coupon for coating (coating experiment)

Figure 5 shows solar array coupon for coating. Silicon (Si) cells were used for this coupon. The size of each Si cell was 70mm x 35mm. Four Si cells were connected in series and arranged in three lines (shown as ST1, ST2 and ST3). The bypass diode was installed in each cell. The substrate of the coupon was aluminum honeycomb/CFRP panel, and it was covered with Kapton phase sheet. P bus bar and N bus bar of the solar cell were covered with Kapton tape. The coating material was semi-conductive and it was painted with brush by one round trip between ST2 and ST3. This coated coupon was named as same as Si coupon.

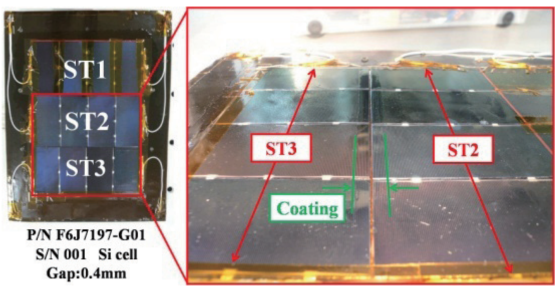

Fig. 5. Solar array coupon for coating (Si coupon).

2.2. Sample coupon for coating

Figure 6 shows Triple Junction (TJ) cells for coating. The size of the TJ cell was 76mm x 35mm. TJ cells edge of the gap was soaked for 30 minutes in semi-conductive coating material. The substrate was aluminum board and coupon was set on Kapton tape. This coated coupon was named as same as coating sample.

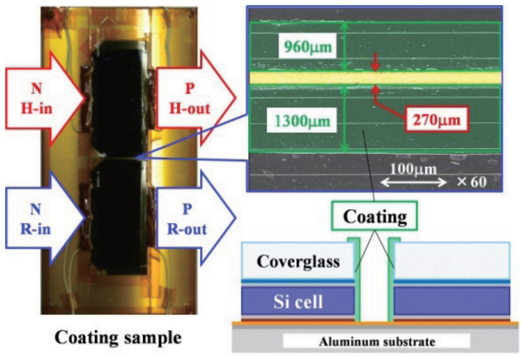

Fig. 6. Coating sample.

2.3. Imitation coupon for changing the shape of RTV

Figure 7 shows the imitation coupon for changing the shape of RTV. Kapton tape, copper tape and slide glass imitated the coverglass, electrode and RTV, respectively. Changing the shape of RTV could be imitated by changing the thickness and the depth of the slide glass of the part shown in figure 7. Table 1 shows different parameters of different samples.

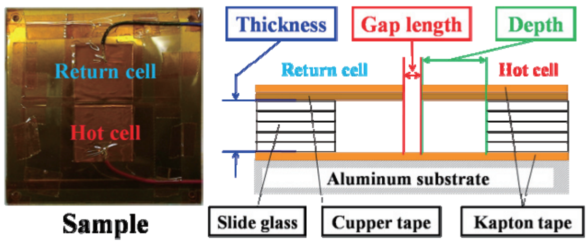

Fig. 7. Imitation coupon changed the position of glass slide.

Table 1. Imitation coupon samples parameter.

Name	Thickness (mm)	Depth (mm)	Gap length (µm)
samples base	0.1	0.0	267
sample 1	0.1	2.0	298
sample 2	0.5	0.0	278
sample 3	0.5	2.0	288
sample 4	0.5	4.0	208
sample 5	1.0	2.0	328

2.4. Sample coupon for changing the shape of RTV

Figure 8 shows TJ cells coupon after changing the shape of RTV. The substrate of coupon and the arrangement of cells were as similar as that of coating sample. TJ cells were floated 0.5 mm top from Kapton tape on aluminum substrate. This coupon was named as same as RTV sample (Thickness: 0.5 mm, Depth: unknown). In this RTV sample (Thickness: 0.5 mm, Depth: unknown) only thickness was adjusted.

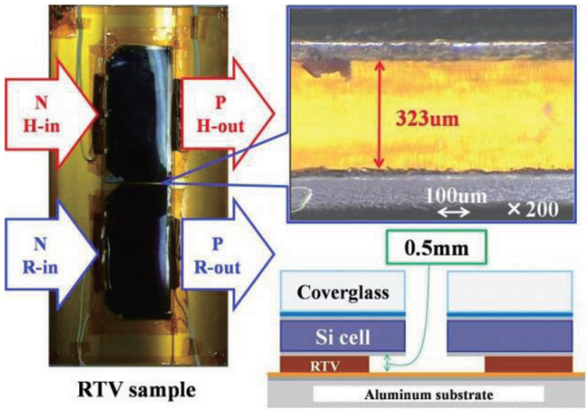

Fig. 8. RTV sample (Thickness: 0.5 mm, Depth: unknown) .

3. Experimental Result and Discussion

Table 2 shows parameter of coating experiment and table 3 shows parameters of the RTV shape changing experiment.

Table 2. Experimental parameters for coating.

Parameters		Si coupon		Coating sample
Background Pressure (Pa)		(2~3.6)x10^{-3}	(1~1.2)x10^{-3}	(1~2)x10^{-3}
V_{bias} (kV)		-0.4 ~ -0.6	-5	-5
C_{ext} (nF)		20	5	5
R_b (MΩ)		0.1	10	10
V_{ST} (V)		100	100	100
I_{sc} (A)		0.5, 1.0	0.5, 1.0	1.0
Plasma density (m^{-3})		5.09x10^{+12}	-	-
Electron beam	Energy (keV)	-	5.0	4.0~5.0
	Current (μA)	-	8~10	20~40

Table 3. Experimental parameters for changing the shape of RTV.

Parameters		Imitation coupon	RTV sample (Thickness: 0.5 mm, Depth: unknown)
Background Pressure (Pa)		(2~4)x10^{-3}	(2~3)x10^{-3}
V_{bias} (V)		-5	-5
C_{ext} (nF)		5	5
R_b (MΩ)		10	10
V_{ST} (V)		50	50
I_{sc} (A)		0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3,5	1.0 1.5 2.0
Electron beam	Energy (keV)	5.0 ~7.0	4.0 ~5.0
	Current (μA)	25 ~75	20 ~40

3.1. Coating effect against primary arcing

Table 4 shows the result of coating experiment. All discharges were occurred in gaps. SA was TSA and NSA. The probability of NSA and TSA, SA was given by following equations.

$$\text{Prbability of NSA}=\frac{\text{Number of NSA}}{\text{Number of arcs}}$$

$$\text{Prbability of TSA}=\frac{\text{Number of TSA}}{\text{Number of arcs}}$$

$$\text{Prbability of SA}=\frac{\text{Number of NSA+Number of TSA}}{\text{Number of arcs}}$$

Table 4. Result of coating experiment.

Coupon	Isc (A)	Number of arcs in gap			Probability		
		PA	NSA	TSA	NSA	TSA	SA
Si coupon	0.5	0	0	0	0 %	0 %	0 %
	1.0	8	0	0	0%	0 %	0 %
	0.5	8	0	0	0%	0 %	0 %
	1.0	13	0	1	0%	7 %	7 %
Coating sample	1.0	34	0	17	0	33%	33%

For the Si coupon, TSA was generated once, and PA was generated 8 times. TSA and PA were generated in the different location. Figure 9 shows an arc location of PA and figure 10 shows an arc location of TSA. Both PA and TSA were occured due to irregularity of the coating.

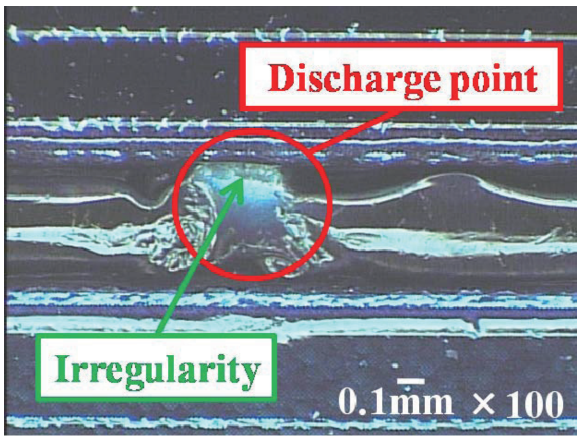

Fig. 9. Discharge point of PA.

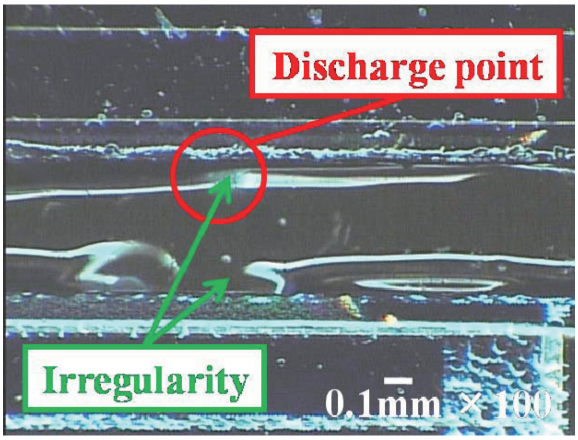

Fig. 10. Discharge point of TSA.

However, with the coating sample, PA was occured at the place where there was a crack at cell edge. In addition, the short-circuit route was formed due to peel off of semi conductive coating material and TSA was generated. Figure 11 shows the picture before TSA and figure 12 shows the picture after TSA.

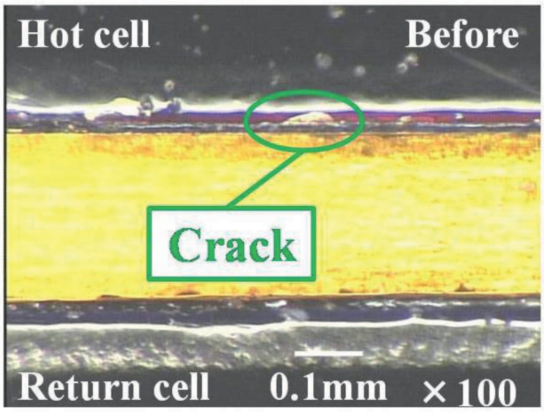

Fig. 11. Picture before the discharge (TSA) .

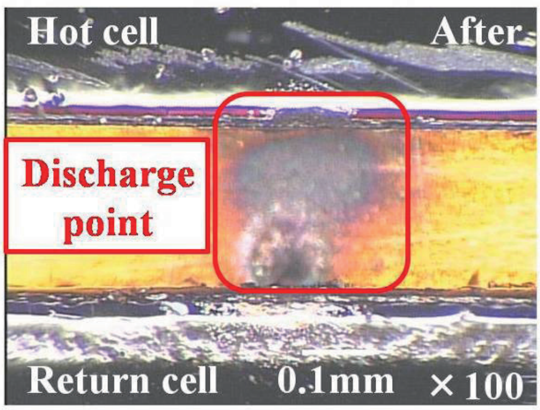

Fig. 12. Picture after the discharge (TSA) .

3.2. Mitigation effect against PSA on solar array for changing the shape of RTV

In the RTV shape changing experiment, sustained arc was not observed in the sample having the thickness of slide glass more than 0.5 mm. But, when the thickness of the slide glass was 0.1 mm, a sustained arc was generated. Figure 13 and 14 show TSA duration. There was no influence in duration of TSA after changing the thickness and the depth of slide glass. The error bars represent the standard deviation.

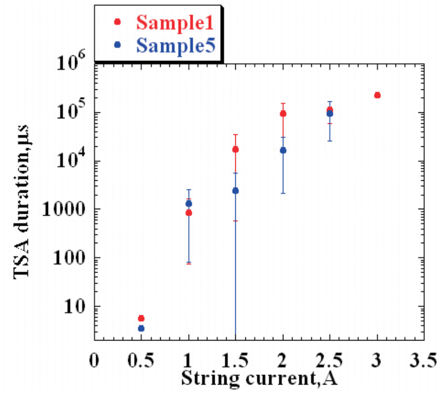

Fig. 13. TSA durations of Sample 1 and Sample 5.

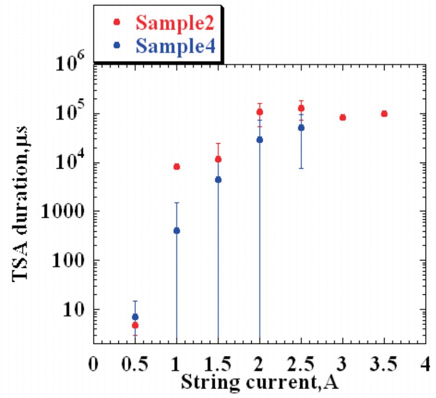

Fig. 14. TSA durations of Sample 2 and Sample 4.

Moreover, the resistance between panel ground, Return cell, and Hot cell of each sample was measured. Table 5 shows the resistances measured. The resistance decreased significantly in the sample where sustained arc was generated. However, resistance was hardly decreased in the sample with a thickness of 0.5mm or more.

Table 5. Resistance values of imitation coupon.

Sample name	Hot-GND	Return-GND	Gap
Sample base	2.4 kΩ	1000 MΩ	1 MΩ
sample 1	2.0 kΩ	38 kΩ	40 kΩ
sample 2	O.F.	O.F.	O.F.
sample 3	O.F.	1500 MΩ	O.F.
sample 4	O.F.	O.F.	O.F.
sample 5	O.F.	O.F.	O.F.

Table 6 shows the experimental result of RTV sample (Thickness: 0.5 mm, Depth: unknown) shown in figure 8. TSA was generated for each current value, but PSA was not noticed.

Table 6. Result of changing the shape of RTV.

Cell	Isc (A)	Number of arcs in gap			Probability		
		PA	NSA	TSA	NSA	TSA	SA
RTV sample	1.0	10	0	6	0%	38 %	38 %
	1.5	8	0	2	0%	20 %	20 %
	2.0	6	0	3	0%	33 %	33 %

TSA with a duration of more than 130ms was generated at RTV sample (Thickness: 0.5 mm, Depth: unknown) shown in figure 16. On the other hand, no PSA was observed. Resistance was measured after the end of experiment. The resistance in gap was decreased to only 105 kΩ. Moreover, resistance was decreased to 4.5 kΩ measured again after a few minutes. It was understood that resistance was decreased with time. Perhaps, when the long duration TSA was generated, the electrode and cell were dissolved by the arc heat and are scattered. This depended on duration. When TSA of long duration was generated, it seemed that a large amount of electroconductive materials were scattered. The electroconductive material might form the short-circuit route. Figure 15 shows the discharge point where the short-circuit route was formed.

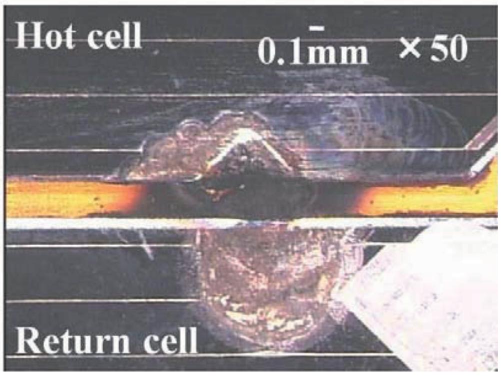

Fig. 15. Picture of gap where the resistance was decreased.

4. Conclusion

In the coating experiment, PA is mitigated in the place where coating is applied. An enormous amount of RTV is needed that increases the weight of satellite. On the other hand, the coating material used in gaps will not increase the weight of satellite. Furthermore, this coating mitigated the progress of TSA. In our experiment “Coating sample” was dipped in a semi-conductive material in order to coat the side of cells. However, due to irregularity in coating PA was generated in some places. This irregularity is due to hand made coating. To prevent the irregularity, it is necessary to develop other effective coating methods.

In the RTV shape changing experiment, the thickness of RTV that mitigated the sustained arc was studied. However, TSA with long duration was generated and the resistance between gaps were decreased. Therefore, it is possible to mitigate the sustained arc without grouting.

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