CHARGING MITIGATION BY USING SEMI-CONDUCTIVE COATING FOR HORYU IV SOLAR CELL COUPON ON GROUND TEST

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***ABSTRACT* —** In 2012, Laboratory of Spacecraft Environment INteraction Engineering (LaSEINE) has developed a charging mitigation method on solar cell using semi-conductive Antimony Tin oxide (ATO). One coated solar cell coupon was mounted on Horyu II satellite and launched to Low Earth Orbit. After experiments, the effectiveness of charging mitigation on coated solar cell coupon could be confirmed. However, the thick coating led to big decrease (35.5%) of power generation of solar cell[2]. Therefore, performance of the coating in both factors of mitigating charging and keeping efficiency of solar cell need to be improved. In this research, a new coating condition is applied on a similar triple-junction solar cell coupon on Horyu II satellite and mounted on Horyu IV satellite. After launching, discharge experiment on solar cell coupons will be conducted to investigate charging mitigation capability of ATO coating in space environment. On ground test results will be discussed in this paper.

Keywords— charging, electrostatic discharge, spacecraft charging mitigation, semi-conductive coating, space environments.

1. INTRODUCTION

Charging on spacecraft occur when charged particles from plasma or energetic particles environments collide and store in the spacecraft[1]. Charging can occur on surface or inside spacecraft, on every kind of material. Another source of spacecraft charging is due to secondary electrons generated by radiation of ions, electrons, or photons with sufficiently high energy. Charging on different materials is different due to material properties. When the cover glass's surface potential is higher than potential of the satellite chassis, an inverted potential gradient (IPG) shall be generated. At the IPG condition, electrostatic discharge (ESD) might occur at the triple junction, where the conductor, insulator and vacuum all meet. This phenomena if happen frequently might lead to failure of spacecraft solar array. To protect spacecraft from failure due to ESD, it is necessary to mitigate charging and arcing on solar array paddle.

At Laboratory of Spacecraft Environment INteraction Engineering, we have developed a charging mitigation method using semi-conductive coating applied on solar cell surface. On 2012, the Horyu II satellite with a coating solar cell coupon was launched to sun-synchronous orbit at 670km. On orbit discharge experiments were conducted to investigate the charging mitigation capability of ATO coating. During experiment, the solar cell coupon was biased to about -300V (provided by high voltage sphere solar cells). After experiment, we could confirm that ATO coating is able to mitigate charging on solar cell surface by conducting energetic particles through the path of coating to spacecraft's chassis. However, based on the ground tests, we could notice that there was a big decrease in power generation of solar cell due to the thick coating applied. In this research, we tried to improve the charging mitigation capability of ATO coating while keeping the efficiency of the solar cell as high as possible.

2. CHARGING MITIGATION MECHANISM

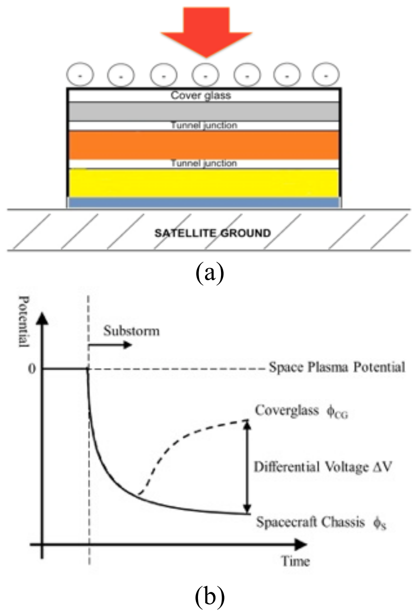
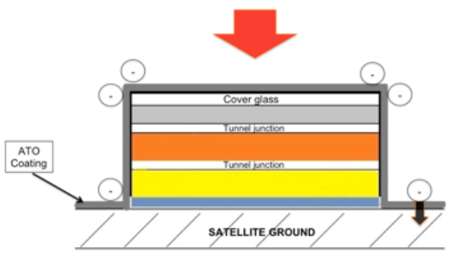


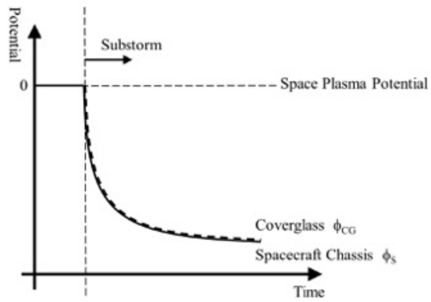
Figure 1. Charging and arcing mechanism on solar cell. (a) Cross sectional view of solar cell without coating. (b) Surface potential on solar cell without coating[3].

Fig. 1 shows the cross sectional view of solar array paddle. The spacecraft body potential becomes highly negative with respect to the ambient plasma due to encounters with substorms or aurora. Since the insulator (cover glass) has the different secondary electron emission coefficient with the substrate of solar array panel, the surface insulator has a positive potential with respect to the spacecraft chassis potential. The potential condition is called inverted potential gradient under which the arcing easily occurs.

To be able to mitigate charging on solar cell surface, we use Antimony Tin Oxide (ATO) Nanoparticles ($Sb2SnO5$) – a semi-conductive coating agent to cover entire surface of solar cell, which connect cover glass of solar cell to satellite ground as showed in Fig. 2 (a) so that it can prevent the IPG phenomena on solar cell (Fig. 2 (b)). The coating agent used in this research has a surface resistivity of 10^8 Ω/□, it is expected to be the optimal value to mitigate charging and keep high efficiency of solar cell[4].



(a)



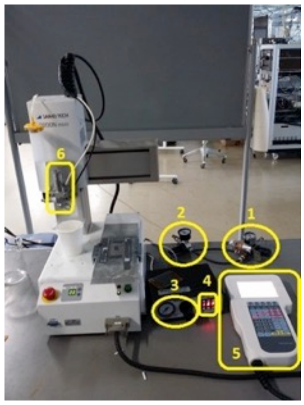
(b)

Figure 2. Charging and arcing mitigation mechanism due to ATO coating. (a) Cross sectional view of solar cell with coating. (b) Surface potential on solar cell with coating[3].

3. EXPERIMENTS

3.1 Coating method evaluation

Fig. 3 shows the coating machine used in this research. By controlling main pressure, pressure inside the syringe, droplet size and droplet amount, we can change the coating conditions. In previous research, two type of coating were tested which are single coating (one thick layer on entire solar cell) and multi layer (one thin layer on the surface and five layers on the edge of solar cell). On ground test results showed that the multi layer coating was not able to mitigate charging on solar cell while thick single layer coating caused a significant decrease of power generation of solar cell. So, this time we focus on developing a coating method of multi layer. Base on previous results, this time, we want to conduct experiment with multi-coated solar cell. At first, we tried some coating conditions for training purpose, to get familiar with the coating machine and coating process. After that, we change the coating condition and conduct the charging test in vacuum chamber under high-energy electron environment until achieve result that we believe is optimal coating condition to mitigate charging and arcing on solar cell.



1: Main valve regulator.
2: syringe pressure regulator.
3. Atomizing pressure regulator.
4: Timing controller.
5: Program controller.
6: Spraying nozzle.

Figure 3. Coating machine (2203N mini, San-Ei Tech)

Table 1. Coating condition applied on training solar cell sample.

Parameter	Value
Main valve pressure	500 kPa
Syringe pressure	70 kPa
Needle valve stroke indicator	3 Nm
Atomizing pressure	80 kPa
Scanning speed	20 mm/sec
Distance from nozzle to solar cell surface	5 cm

After making one layer of coating, solar cell sample was baked at 120°C in 30 minutes as recommended from manufacturer to achieve a good form of coating. This process is repeated after every layer of coating applied. Fig. 4 shows the non-coated and coated solar cell sample with the condition shows in Tab. 1. In this condition, we applied 2 layers on entire surface of solar cell.

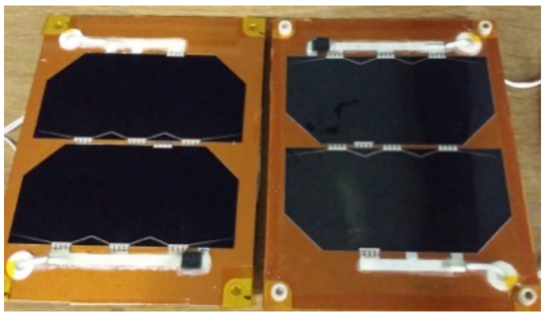


Figure 4. Coated (right) and non-coated (left) solar cell

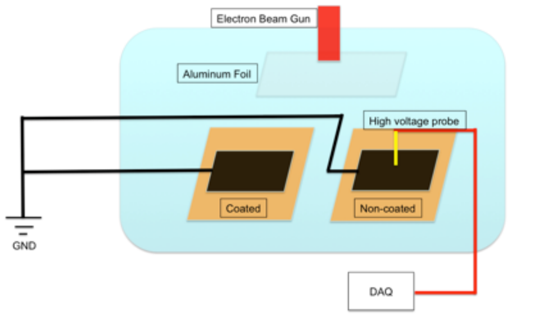


Figure 5. Charging test setup

Fig. 5 shows the setup of ATO coating solar cell charging test in vacuum chamber. Both coated and non-coated solar cell are placed inside vacuum chamber and connected to the ground. An electron beam gun is used to emit electron at controllable different level of energy. An aluminium foil is put right beneath the beam gun for two purposes of reducing current density and creating a uniform distribution of electron beam. After a certain time irradiated solar cell sample under electron beam, we use a non-contact high voltage probe (TREK 341B) to scan solar cells surface. Surface potential of solar cells shall be monitored by computer using a data acquisition system (DAQ).

Table 2. Charging test conditions

Parameters	Value
Chamber pressure	~10^{-4} Pa
Electron energy	8keV~12keV
Irradiation time	5 minutes
Surface potential scan interval	5 mm
Electron beam current	100µA

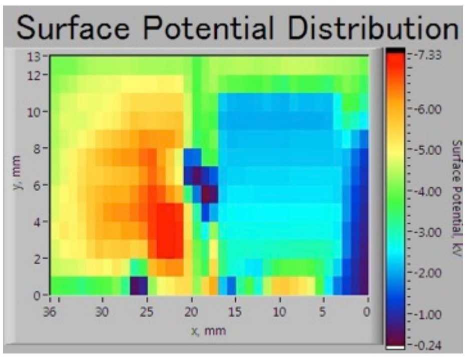


Figure 6. Charging test result at 10 keV

By looking at the color scale on the right side of the Fig. 6, we can see that the ATO coating can partly mitigate charging on solar cell surface. Surface potential of the coated solar cell is up to -3kV while it is up to -7kV on non-coated solar cell. So, we need to improve performance of the coating. We tried some other coating condition such as applying more layers, using combination of coating agent with different viscosity or using high viscosity coating agent only. After each time changing coating condition, we carried out the charging test in vacuum chamber to see the effect of coating. At the time of preparing the solar cell coupon for engineering model (EM) of Horyu IV satellite, after experiments with different coating conditions, we came up with a coating method that using high viscosity coating agent to apply on entire surface of the solar cell with multi layer. The coating condition is showed in Tab. 3 below.

Table 3. Coating condition applied on Horyu IV EM solar cell

Parameter	Value
Main valve pressure	500 kPa
Syringe pressure	60 kPa
Needle valve stroke indicator	3 Nm
Atomizing pressure	70 kPa
Scanning speed	20 mm/sec
Distance from nozzle to solar cell surface	10 cm

3.2 Horyu IV engineering model coating solar cell sample.

3.2.1 Charging test

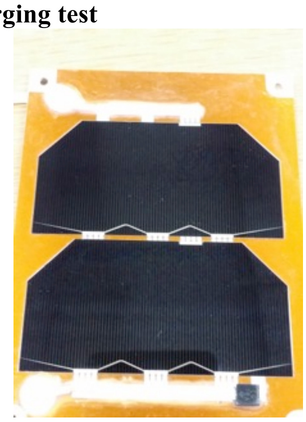


Figure 7. ATO coating solar cell sample (for Horyu IV EM)

Table 4. Comparision between Horyu II and Horyu IV solar cell sample

Parameters	Horyu II sample[3]	Horyu IV sample
Dimensions	10mmx13mm	9mmx12mm
AR coating	MgF2	TiOx/Al2O3
Cover glass	CMG 100	CMX 100
Cover glass thickness	100µm	100µm

In this coating condition, we reduce the presusre inside syringe and atomizing pressure, as well as increase the distance from the nozzle to solar cell surface. Purpose of these change is to create a lower pressure of coating stream to reach to solar cell, so that coating agent can be attached to solar cell surface but not separated by high pressure. After applying 3 layers of coating on entire surface of solar cell, we put the sample in vacuum chamber to conduct charging test. Testing condition is same with previous tests. Result of charging test for Horyu IV EM solar cell sample is showed in Fig. 8.

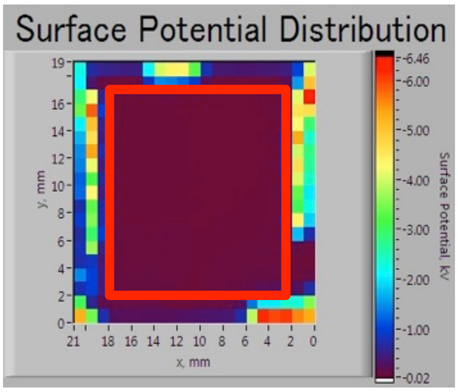


Figure 8. Charging test result on Horyu IV EM solar cell at 10 keV

Charging test result above clearly shows that there is almost no charge (-20V) on surface of coating solar cell (within red rectangular area) if compare to the other area (up to -6kV). During coating process, we let the nozzle of coating machine to scan whole surface of solar cell sample (including solar cell's cover glass, interconnectors, Kapton tape). However, ATO coating agent can difficult attach on the Kapton tape due to lower wettability than cover glass with anti reflection (AR) layer. Therefore, at the position where coating agent cannot fully cover material's surface, high energy electron might charge them up to several kV. From this testing result, we can conclude that ATO coating at the current condition has fully capability to mitigate charging on solar cell surface in high-energy electron environment.

3.2.2 Arcing test

After confirming effectiveness of ATO coating in charging test, we conducted arcing test to get further results. Fig. 9 shows the setup of arcing test in the same vacuum chamber in charging test before. However, in arcing test, coated and non-coated solar cell samples are biased at -5kV using high voltage power supply to simulate negative charge on solar cell. A 10MΩ resistor is used to protect power supply from short circuit current if discharge occurs. A 300pF capacitor is used to increase the discharge current so that it can easily be detected by current probe (Hioki 3272). Voltage drop due to discharge shall be monitor by oscilloscope. In this test, an IR camera (Sony XC-E150) is also equipped to detect location of discharge if it occurs. Tab. 5 shows conditions and results of arcing test. During the test, solar cell samples are irradiated in 60 minutes under each level of electron energy. When arcing occurred, IR camera will be triggered to identify position of discharge. Arcing was occurred at several positions on non-coated solar cell while no arcing observed on coated solar cell as shows in Fig. 10.

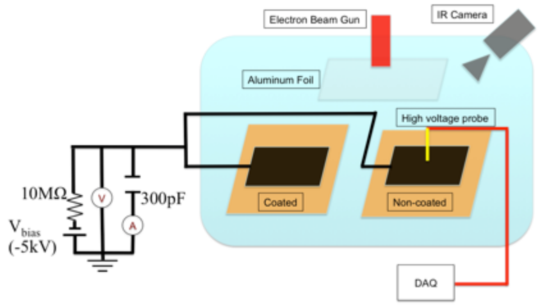


Figure 9. Arcing test setup

Table 5. Arcing test conditions and results

E-beam energy (KeV)	Number of discharge	
	Without coating	With coating
7	1	0
8	4	0
9	2	0
10	3	0
11	2	0

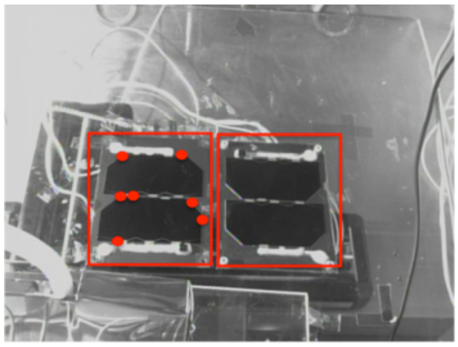
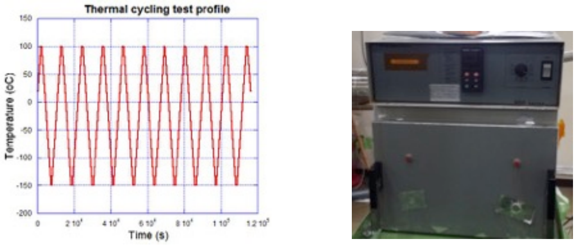


Figure 10. Arcing occurred on non-coated solar cell (left). No arcing occurred on coated solar cell (right)

3.2.3 Thermal cycling test

To investigate the strength of solar cell against temperature variation when satellite is operating in space, thermal cycling test is conducted by using thermal cycle testing machine (Despatch 900 series). Temperature range is from -150°C to 100°C as the typical limit of solar cell in space[3]. Solar cell sample temperature is monitored by a thermocouple. There is 10 minutes of soaking time at each upper and lower limit. Temperature changing rate during the test is kept at 3°C/min to avoid thermal shock. In this research, we conducted thermal cycling test with 10 cycles. Fig. 11 shows the temperature profile (a) for this test and Despatch 900 machine (b). After that, we performed charging test of solar cell sample with the same testing conditions as before to check the effect of thermal cycle on performance of ATO coating. The result of charging test for Horyu IV EM solar cell coupon after thermal cycling test is showed in Fig. 12, solar cell with coating is still effective to mitigate charging under high-energy electron environment.



(a) (b)

Figure 11. Thermal cycle temperature profile (a) and Depatch 900 machine (b).

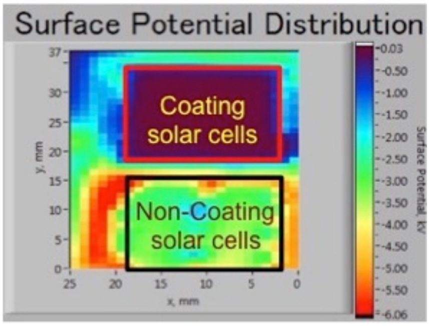


Figure 12. Charging test result on Horyu IV EM solar cell after thermal cycling at 10keV

3.2.4 Current-voltage characteristic

The current-voltage characteristic of solar cell coupon is measured using the system shown in Fig. 13. The sun light was simulated by using solar simulator in atmosphere condition. Light intensity is measured by a light intensity meter and set at 1310W/m^2.

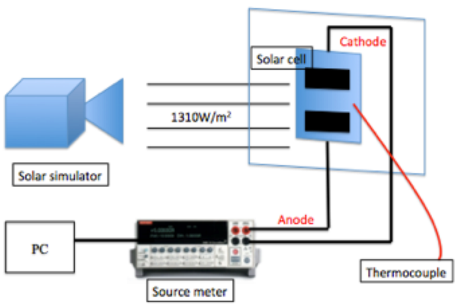
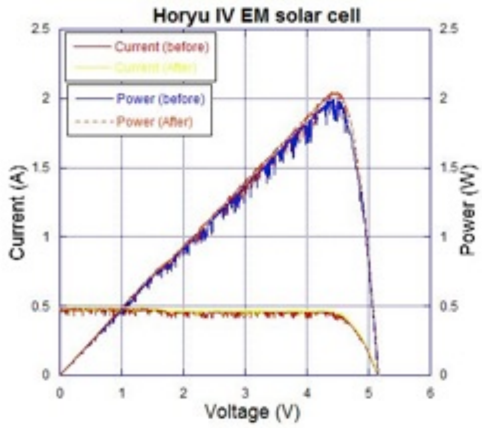


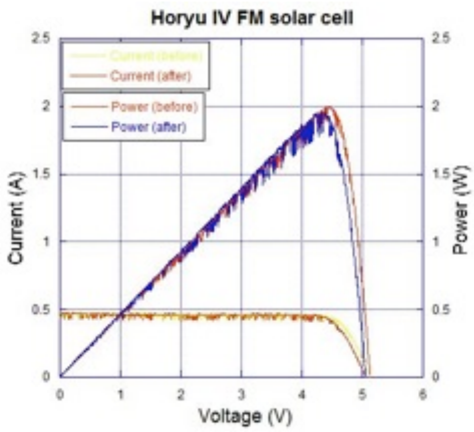
Figure 13. Setup of current-voltage charateristic measurement.

Since the temperature might affect to power generation characteristic of the solar cell, we tried to achieve the same temperature of the sample at beginning and the end of each time measurement. In this measurement, we measured current and voltage output of solar cell by a sweeping voltage supplied from a source meter (KETHLEY 2400).

As a measurement result showed in Fig. 14(a), power loss due to ATO coating on solar cell is 2.6% at peak power point. This is significant improvement when compare to 35.5% power loss on single coated solar cell coupon attached on Horyu II satellite[2].



(a)



(b)

Figure 14. Current-voltage characteristic of solar cell coupons before and after coating. (a) Horyu IV EM solar cell coupon. (b) Horyu IV FM solar cell coupon.

3.3 Horyu IV flight model (FM) coating solar cell sample

3.3.1 Charging test

When preparing Horyu IV FM solar cell coupon, we used the same coating condition as well as number of layer applied on Horyu IV EM solar cell coupon. After making the coating, we placed coated solar cell coupon with a cover glass in vacuum chamber, all connection and setting is the same as previous charging tests. The setup and result of charging test is showed in Fig. 15 and Fig. 16 respectively.

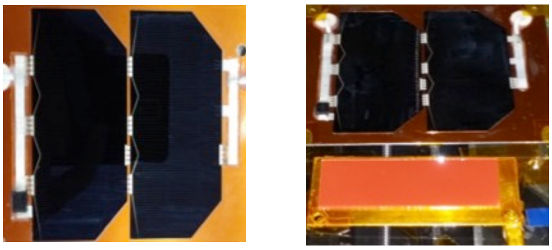


Figure 15. Horyu IV FM solar cell coupon (left) and charging test setup in vacuum chamber (right)

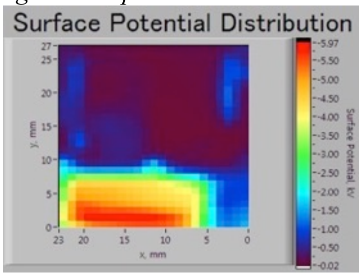


Figure 16. Charging test result on Horyu IV FM solar cell at 10 keV

Although we tried to use the same coating condition with Horyu IV EM solar cell coupon, there is small different, which is the coating is not fully uniform on the entire surface of solar cell. The reason is probably due to quality of coating machine, unstable pressure or bad mechanical connection between parts might produce an ununiformed stream of coating agent. However, by looking at the testing result, we can still say that the coating has mostly capability to mitigate charging on solar cell surface if compare to Horyu IV EM solar cell's result.

3.3.2 Current-voltage characteristic

Before and after applying ATO coating on Horyu IV FM solar cell coupon, we also did the current-voltage measurement with the same setup with Horyu IV EM solar cell current-voltage characteristic measurement. Results are showed in Fig. 14(b). By calculating value at peak power point, we can see that the power loss due to ATO coating is 2.4%. This result and EM solar cell coupon result are both significant improvement.

3.3.3 Horyu IV on-orbit experiment.

On Horyu IV satellite, which was launched successfully on February 17th, 2016, we have installed two type of charging mitigation solar cell coupons, which are ATO coating solar cell and Filmed solar cell. When satellite is operating on orbit, we will apply a bias voltage at about -350V produced by high voltage solar arrays to conduct arcing test. One on-board oscilloscope (OBO) and arc vision camera (AVC) are equipped to detect current waveform and image of arcing on solar cell coupon. When experiment is running, if OBO and AVC can observe discharge occurs on nominal solar cell, while there is no discharge on the ATO coating solar cell and filmed solar cell, mission will be success.

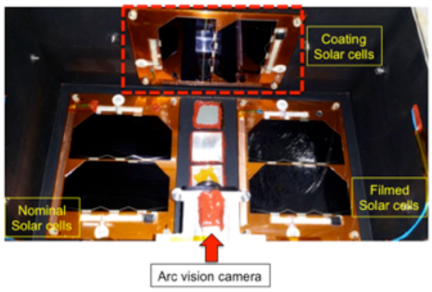


Figure 17. ATO coating solar cell coupon mounted on Horyu IV satellite (flight model)

4. 4. CONCLUSIONS AND DISCUSSIONS

Base on ground test results, we can conclude that multi layer ATO coating has capability to mitigate charging and arcing phenomena on solar cell surface in high-energy electron environment. Power loss due to coating is very low if compare to previous result on Horyu II satellite. We are going to conduct arcing experiment in the near future, after doing other main missions. We still need to conduct experiment under plasma and other conditions to ensure that ATO coating can withstand the harsh space environment. We wanted to use the same kind of solar cell for two satellite but there is different in anti reflection layer on solar cell cover glass (refer to Tab. 4). Either of it or change in coating condition can increase the wettability so that coating agent can easily attach to solar cell surface and charging and arcing mitigation capability are successfully achieved while keeping high power generation of solar cell. Therefore, we need to do more research to find exact reason affect to ATO coating performance in order to apply this charging mitigation method in other projects.

5. ACKNOWLEDGEMENT

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6. REFERENCES

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