Development of 400V solar array technology for LEO spacecraft

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ABSTRACT

In order to realize 400 volts operation in LEO, arcing caused by interaction between spacecraft and surrounding LEO plasma must be overcome. We have been investigating designs of high voltage solar array. This paper is the summary report for all the tests. The coupon with ion barrier film made from ETFE (called " film coupon") never suffered any arc. We carried out the tests under realistic orbit environment for the film coupon. It was confirmed that the covered film performed successfully in all the situations. This coupon has never arced for more than 25 hours that was equivalent to 1% power degradation in 30 yeas operation. No film contamination and degradation were observed after 90°C baking. No primary arc occurred at all vacuum pressure and no frictional charging occurred by contact. With respect to debris impact, the covered film had little damage even if the film support was hit directly. Also, film attachments were well supported after the heat cycle of –90 ~ +90°C by reducing tension of film. Conductive substrate, however, suffered many arcs at –400V. Also, a sustained arc phenomenon between cells and substrate was induced by simulated debris impact. Therefore, use of flexible substrate is adequate for 400V solar array in LEO environment.

1. Introduction

The use of high power in future space missions calls for high voltage power generation and transmission to minimize the energy loss during power transmission and the cable mass. In order to promote industrial use of Low Earth Orbit (LEO), such as manufacturing, sightseeing, or power generation, the power of a large LEO platform after the International Space Station (ISS) will soon reach the level of MW. In principle, the transmission voltage scales to the square root of the power to be delivered. Therefore, in order to realize a MW-class space platform, the power must be delivered at 400 volts, at least. In order to realize 400 volts operation in LEO, arcing caused by interaction between the spacecraft and the surrounding LEO plasma must overcome[1]. The development of 400V solar array benefits not only a large space platform but also a satellite with a hall thruster, because the voltage is high enough to directly drive the electric propulsion system without raising the voltage via a DC/DC converter[2].

When a solar array generates electricity in LEO, most of the voltage becomes negative with respect to the surrounding plasma due to mass difference between ions and electrons. Ions charge insulator surface positively. Then the electric field near triple junction, where interconnector (conductor), adhesive (dielectric) and vacuum meet together is enhanced and an arc occurs[1]. There have been numerous studies on arcing on high voltage solar array in LEO condition. It is now known that an arc occurs once an array has a negative potential as low as100V with respect to plasma. An arc on solar array surface is usually a pulse of current whose energy is supplied by the electrostatic energy stored on the coverglass surface due to charging via positive ions. Such an arc is often called primary arc, primary src or primary ESD (electrostatic discharge). Repeated arcs lead to surface degradation and electromagnetic interference. Destruction of solar cell PN junction due to intense arc current is another concern. Moreover, a single arc might shorten momentary the array circuit and the current flows for a much longer time than a primary arc, called secondary arc. A secondary arc might lead to permanent short-circuit in the array circuit and the arc current keeps flowing until thermal breakdown of insulative layer occurs. Such an arc is called sustained arc and believed to be the cause of the failure of Tempo-2[3].

We have been investigating designs of high voltage solar array for the last several years. We carried out many laboratory experiments to develop solar array capable of generating electricity at 400V in LEO plasma environment. The development effort is carried out to suppress the inception of arcing completely. Two important processes of arcing are enhanced electric field at triple junction by ambient ions and secondary electron emission from dielectric material. Thus, coupons were designed along following strategies;

(1) Using an ion barrier on the coverglass (to prevent the charging via ambient ions.)
(2) Changing the coverglass design (to prevent the charging via ambient ions or to decrease the electric field at triple junction.)
(3) Coating the surface of coverglass with conductive material (to decrease the electric field at triple junction.)

With respect to the first point mentioned above, ETFE film was utilized as the ion barrier. With respect to the second point, we used the overhanging coverglass, thick coverglass, the coverglass with slit on the side surface and large coverglass covering multiple cells. With respect to the third point, we used Indium Tin-Oxide coating connected to interconnector of each cell. We examined an arc mitigation performance in LEO plasma environment. All coupons raised the arc threshold voltage. Especially, the coupon with ion barrier film (called "film coupon") made remarkable achievement. This coupon never suffered any arc at any operation condition. We carried out the tests under realistic orbit environment for the film coupon. The performed tests are as follows; endurance test for 30 years operation, debris impact, heat cycle, film contamination, electro-static charging by contact, ambient pressure variation and arcing on substrate. This paper is a summary report for all the tests.

2. Solar array coupon samples

Figures 1 and 2 show the film coupons. Figure 1 shows the old version, and Fig. 2 shows the new version which achieved perfect performance for arc mitigation. These coupons use 7x3.5cm silicon cell with IBF (integrated bypass function) on the aluminum honeycomb / CFRP substrate with Kapton® sheet. Four cells are connected in series and three strings are placed in parallel. These coupons have a transparent Teflon film covering over all the strings. The Teflon film made of ETFE (Ethylene-Tetra Fluoro Ethylene copolymer) whose thickness is 12μm. It has a transmittance of about 95% between 400nm to 1μm wavelength. ETFE has the characteristic of radiation resistance. Because it is hard to adhere the film to substrate, the film is attached to adhesive supports at film edges.

Figure 3 shows the number of arcs observed in the plasma experiment. The chamber condition is the same as described later. A negative bias voltage of-100V ~ -800V is applied to all the cells. Each bias voltage was applied for 90 minutes considering the orbital period in LEO. Although the old version film coupon suppressed arcing well, it could not suppress arcing on the bus bars at high voltages. The reason of arcing on the bus bars was due to existence of the gap by cables between the film and substrate. To reduce this gaps as small as possible, doubled size of film and substrate were used for the new version coupon. All the bus bars were coated by RTV-Si rubber.

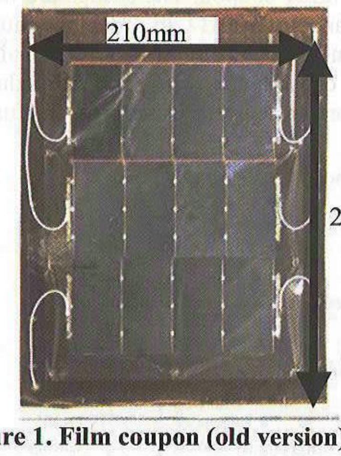
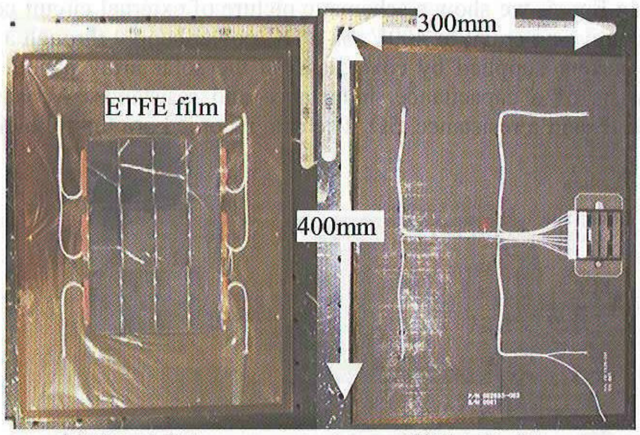


Figure 1. Film coupon (old version).



(a) front side **(b) back side**

Figure. 2 Advanced film coupon

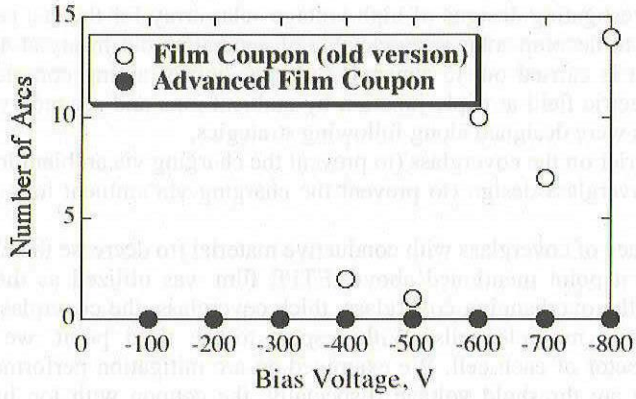


Fig. 3 Number of arcs in 90 minutes at each bias voltage for film coupons

Realistic orbit environment tests

A. Arc mitigation characteristics

Assuming 30 years operation in orbit, the allowed number of arcing which limit the degradation of cell electrical performance due to primary arcs below 1% is estimated as follows: According to the result of conventional silicon solar array coupon test[4], the probability of electrical performance degradation was 0.7% (1 for 150 primary arcs). Once an arc occurs, the arc plasma propagates and neutralizes the positive charge on the coverglass within 4 meter radius[5]. This area includes approximately 5000 cells for the cell size of *7cm*x*3.5cm*. Thus the permissible arc number under the condition of 1% degradation is about 7300 arcs (=5000x0.01/ 0.007). Assuming 30 years operation in LEO, total time of power generation is about 180 thousand hours. Therefore, we should suppress arcing at least as little as one in 25 hours (=180000/7300) at –400V.

Figure 4 shows a schematic of experimental setup. The experiments of arc mitigation characteristics were carried out with this setup. The vacuum chamber is 1*m* in length and 1.2*m* in diameter. The chamber can be pumped to a pressure as low as below $1x10^{-5}$ *Torr*. In order to simulate the LEO plasma environment, an ECR plasma source generated Xenon plasma with a density of $2x10^{12}$ m^{-3} at 3 ~ 7 *eV*. The plasma source operated at a flow rate of 0.2 *sccm* and the chamber pressure during the operation was 8 ~ $9x10^{-5}$ *Torr*. In order to keep the coupon temperature constant at 40 °C, halogen IR lamps were utilized. The chamber is also equipped with a metal-halide lamp to simulate the sum light. Using the lamp, we can monitor the cell electrical output without opening the chamber door.

In Fig. 5, we show a schematic picture of external circuit connected to an array coupon. The strings are biased to a negative potential of 400V via a DC power supply through a limiting resistance of 100*k*Ω. In order to simulate the arc current supplied by coverglass on the solar array panel[5], we connect an external circuit. The external circuit consists of a capacitance, inductance and resistance. We have attached a capacitance, 5*μF*, and an inductance, 270*μH*, and a resistance, 5Ω. The data recorded are the following; Arc position, arc current waveform, fluctuation of

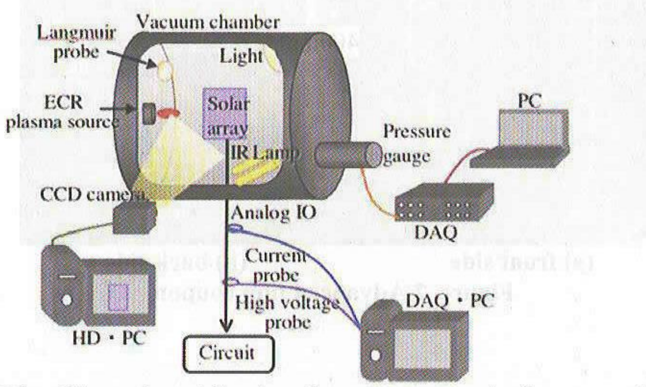


Fig. 4 Experimental set-up for measurement of arc mitigation performance

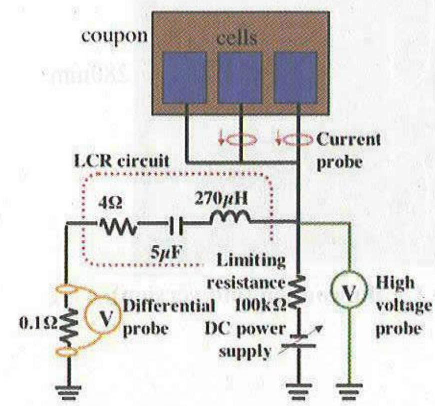


Fig. 5 External circuit used for measurement of arc mitigation performance at a bias voltage below –400V

the background plasma condition and increase of background pressure. We developed an experimental system that can record all the arc events including waveforms and locations[4].

Considering the load for plasma source and vacuum pumps, operation was carried out every 5hours with intermission of 2 hours. It was confirmed that the film coupon never suffered any arc for more than 25 hours at –400V. Therefore, this coupon has the perfect performance for arc mitigation.

B. Debris and micrometeoroids impact

Micrometeoroids or space debris impact becomes a problem in LEO. In order to evaluate the resistance film against hyper velocity particle impact, we carried out a test of simulated debris impact using the Two-Stage Light Gas Gun (TSLGG) of the Computational Mechanics Laboratory at Kyushu Institute of Technology. We carried out two shots. The test projectiles simulating debris were made of polycarbonate with weight of 1.03 *gram* and 10mm in diameter. This size corresponds to the smallest size that cannot be defended by a bumper. The projectile velocities were 3.4 *km/s* and 3.5 *km/s*. The coupon was set in the vacuum chamber attached to the TSLGG. Furthermore, the external circuit shown in Fig. 6 was connected to the coupon to examine the possibility of sustained arc induced by the dense plasma produced by debris impact.

Figure 7 shows the front side of the coupon after the two shots. The first projectile was aimed at the left center from the front to the back. This projectile hit the film support material directly, and the covered film around this support was broken off. But the other supports and film had little damage. The second projectile was aimed at the lower right form the back to the front. We were interested in seeing whether the broken pieces of substrate would fly in all the directions and cause damage on the covered film. On the contrary there was almost no damage except the area around the impact position. The film coupon has sufficient resistance against hyper velocity impact.

During the test with the first shot, light emission on the coupon was observed on the coupon. Figure 8 shows the measured arc current and inter-string voltage. Horizontal axis corresponds to the elapsed time from the impact. About 500μs after the impact, arc current flew until we turned off the power supply. It was confirmed as sustained arc. This resulted in short circuit between the cells and the substrate. From this result, it is possible that string-substrate sustained arc may be induced by debris impact regardless whether debris hit the inter-cell region or not. Therefore, from the viewpoint of sustained arc mitigation, the use of flexible substrate without any conductive layer connected to satellite body is the most desirable solar array design.

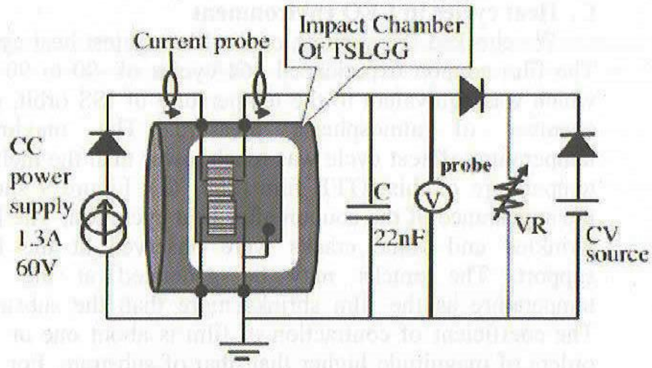


Fig. 6 Experimental set-up to verify sustained arc phenomena under hyper velocity impact

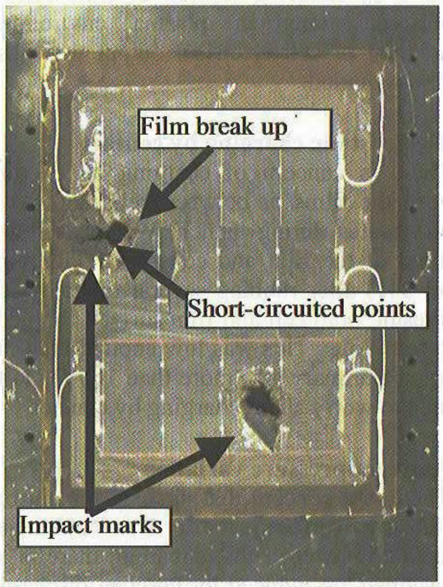


Fig. 7 Photograph of test coupon after debris impacts

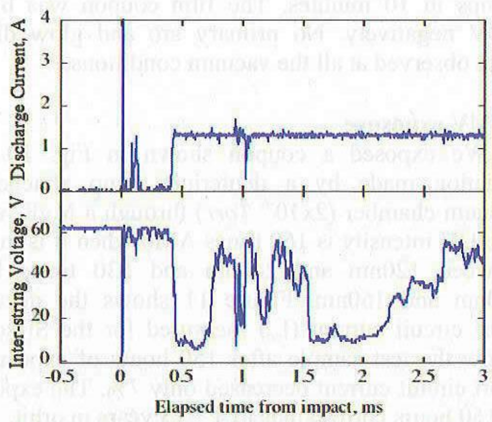


Fig. 8 Waveform of sustained arc induced simulated debris impact

C. Heat cycles in LEO environment

We checked the strength of the film against heat cycle. The film coupon experienced 164 cycles of -90 to 90 ℃, which was equivalent to the temperature of ISS orbit, in a chamber of atmospheric pressure. The maximum temperature of heat cycle was much lower than the melting temperature of this ETFE film (260 ℃). Figure 9 shows the appearance of the coupon after heat cycle test. The film wrinkled and some cracks were observed at the film support. The cracks may be generated at the low temperature as the film shrinks more than the substrate. The coefficient of contraction of film is about one or two orders of magnitude higher than that of substrate. For this reason, excessive stress occurred at the film support. We improved the film fixation method. The result was that the film attachments passed the two hundred heat cycles of -90 ~ +90℃ by reducing tension of film. Also, this coupon suppressed arcing in plasma environment and no degradation of cell electrical output was observed after the film wrinkled.

Fig. 9 Photograph of film coupon after 164 heat cycles

D. Electrostatic charging by contact

There is concern of charging by frictional contact between the films or between cells and the film as the panel vibrates during launch. We measured the surface potential of the film and cells by a TREK probe (Trek model 341) after rubbing several times by another film. As a result, both cell and film surface charged negatively up to tens volts. This was low enough than the threshold voltage of primary arc (more than 100V), so that there is no need to worry about charging by contact.

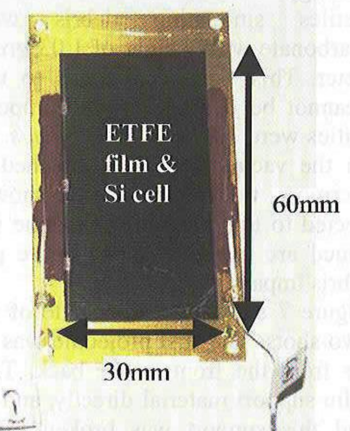


Fig. 10 Si film coupon for UV and AO exposure tests

E. Ambient pressure variation

There is a concern that air may remain between film and the array surface just after launch. If the array begins to generate power in this situation, there is a possibility of sustained arc induced by Paschen discharge under the film. We checked for arcing by changing the ambient pressure from atmosphere to 3×10^{-2} *Torr* using vacuum pumps in 10 minutes. The film coupon was biased at 400V negatively. No primary arc and glow discharge were observed at all the vacuum conditions.

F. UV exposure

We exposed a coupon shown in Fig. 10 to UV radiation made by a deuterium lamp attached to a vacuum chamber (2×10^{-6} *Torr*) through a MgF_2 window. The UV intensity is 160 times AM0 when it is integrated between 120nm and 240nm and 530 times between 120nm and 160nm. Figure 11 shows the decrease of short circuit current (I_{sc}) measured for the Si solar cell below the test sample after 150 hours of exposure. The short circuit current decreased only 7%. The expose time of 150 hours corresponds to 4 ~ 13 years in orbit.

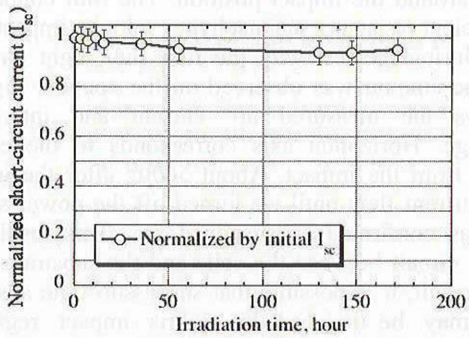


Fig. 11 Decrease of short circuit current (I_{sc}) measured for the Si solar cell below the film exposed to UV radiation

G. AO exposure

A coupon similar to the one shown in Fig. 10 was exposed to combined environment of atomic oxygen

(AO) and UV radiation. Using a test facility at Tsukuba Space Center, the coupon was exposed to AO for an equivalent time to 1 month in orbit and UV for an equivalent time to 1week in orbit. The result showed no degradation for cell electrical performance.

H. Arcing on the back surface of rigid substrate

All the coupons we tested so far use rigid substrate made of aluminum honeycomb and CFRP. The back surface is covered by CFRP that is partially conductive. When 400V power generation is carried out in LEO, the potential of the entire satellite conductive surface becomes –400V with respect to the plasma potential. The CFRP surface has many triple junctions because it consists of conductive carbon fiber and insulative plastics. In the test of film coupon mentioned in the first of this paper, the panel structure was not biased to avoid unnecessary arcs on CFRP surface. To study arcing on the biased back surface, we biased the entire panel to -400V in the plasma chamber. Figure 12 shows the arc positions observed on the CFRP surface. There are mostly two types of arc positions observed in this test. One is at the CFRP surface and another is at the boundary between CFRP and Kapton® tape used for covering frame edge. More than 400 arcs occurred for 5 minute. Because of this high-frequency discharge, the external capacitor was charged only to approximately -200V although the DC power supply was set to -400V. This result shows that a traditional rigid substrate is not adequate for 400V solar array in LEO environment.

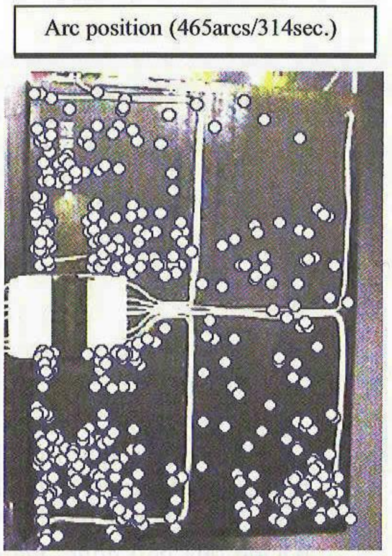


Fig. 12 Arc positions on CFRP surface of the substrate

3. Conclusion

We have developed solar array technology that is capable of generating power at 400V in LEO plasma environment. Covering solar array surface with ETFE film is the most effective method that suppress arc inception up to 800V. Even if it is used for 30 years in space, the damage caused by arcs can be kept below 1% of the total electrical output. The strengths of the film design against, debris impact, heat cycle, contamination, frictional charging, residual gas, UV exposure, and AO exposure were verified in the laboratory tests. Traditional rigid solar panel structure made of aluminum honeycomb and CFRP, however, is not suited for the high voltage operation. Short circuit due to sustained arc induced by debris impact and frequent arcs on partially conductive CFRP surface are the reasons. Flexible solar panel made of insulative substrate is suitable to avoid those problems.

Basic development of 400V solar array in laboratory has been completed now. In near future we will seek an opportunity of space experiment.

Acknowledgments

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