LABORATORY TESTS ON PLASMA INTERACTION OF ETS -VIII SOLAR ARRAYS.

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Abstract: High voltage solar arrays in LEO and GEO are shown to be subject to arcing. Ground based experiments on the interaction between solar arrays of the ETS-VIII (Engineering Test Satellite-VIII) and ion thruster plasma are carried out in a large volume plasma chamber. The measured values of collected electron current due to the snapover mechanism have been reported.The power loss of the spacecraft due to the snapover mechanism is negligible compared to the total power of the satellite. We carried out experiments with two different types of solar arrays and the results are compared. Failure of the ion thruster neutralizer has been simulated and we have observed the sustained arc at the gap between the adjacent cells with 55 volts potential difference with current capability of 2.64 amperes. We have proposed a best solar array design to reduce the effect of arcing on solar array.

1.Introduction:

In the past, satellite solar arrays have operated at voltages of less than 100 volts. However, as systems become larger and more complex, such as the International Space Station the power needed to run them has increased. It is necessary to design the solar arrays which operate at higher voltages and lower currents [1], in order to reduce the transmission cable mass and the loss due to joule heating. Any spacecraft interacts with the space plasma. A wide range of these interactions has been studied for years [2]. For instance, it is known that solar arrays with a negative potential of several hundred volts exhibit destructive arcing [2].

Alternatively, arrays biased positively above a critical voltage (~ 100 volts) can undergo a phenomenon called snapover. During snapover the electron current collected by the exposed conducting interconnector with a positive potential exhibits a sharp increase at a critical potential. Snapover is a sudden and rather dramatic increase in the current collection in and around positive conductors that are surrounded by a dielectric. Having a positive potential above a certain value can only bring about such jumps. The exact mechanisms of the snapover phenomena is found in Ref.3 Primary electrons in the plasma surrounding the solar arrays are accelerated towards the positively biased conductor. As the primary electrons strike the dielectric, one or more secondaries can be liberated. As the sheath area grows, the surface of the dielectric quickly charges to positive potential. Secondary electrons, suffering collisions with the outgassed species, are responsible for excitation and ionization and result in gas-induced glow discharge. This results in substantial power loss for spacecraft.

NASDA (National Space Development Agency of Japan) is developing Engineering Test Satellite VIII (ETS-VIII). It has high voltage solar arrays operating at 110 V and Xe ion thruster system, expected tooperate continuously for five hours for north-south station keeping. Due to the operation of ion thruster neutralizer, the neutralizer will act as a plasma contactor. The solar array has a positive potential with respective to the plasma and the spacecraft potential is nearly zero. The increase of electron current to the solar array, however, may drop the solar array potential. If the collected electron current exceeds the amount of current emitted by the neutralizer, it is possible that the spacecraft potential drops to a negative potential of -110V. If the neutralizer fails to operate then the potential may drop to -1kV and this potential drop leads to the destructive arcing. Therefore, careful considerations about the interaction between the solar arrays and the low energy ion thruster plasma are necessary in the development and designing of ETS-VIII solar arrays.

Diagnostic tests on the plasma produced from the ion thruster revealed that the low energy plasma density around the thruster is approximately 5×10^{13} m^{-3}. The plasma density near solar array is simulated by the particle-in-cell method based on the above mentioned value. From the results of the analysis, the plasma density near solar array is approximately 5×10^{10} m^{-3} [4]. In the ground based plasma interaction studies, we have chosen the plasma density in the range of $2 \sim 5 \times 10^{11}$ m^{-3}. The solar array near the ion thruster may have the neutral density of about $10^{16} \sim 10^{17}$ m^{-3}. In our experiment the neutral density is $10^{18} \sim 10^{19}$ m^{-3} which is regarded as the worst of worst cases.

In the present work, we reported the collected electron current due to snapover and the threshold voltage for the gas-induced glow discharges. We also simulate the failure of the ion thruster neutralizer and we examine, whether that situation will lead to the sustained arc or not. We carryout experiments with two different designs of solar arrays, one with RTV (Room Temperature Vulcanization silicon rubber) between the solar cells and another without RTV.

2. Experiment:

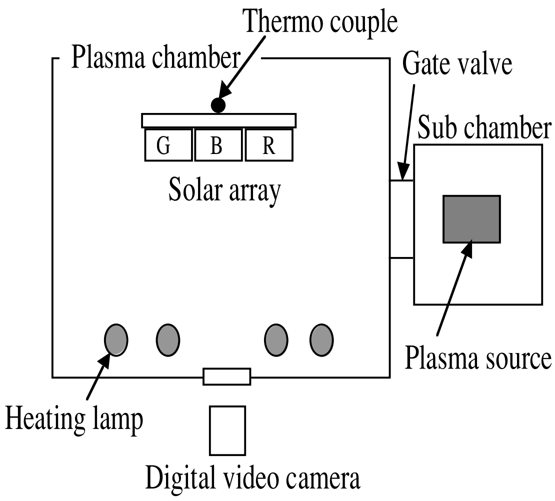

Fig.1.Schematic of experimental set-up

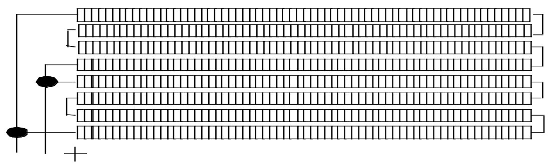

Fig.2.Layout of ETS-VIII solar array

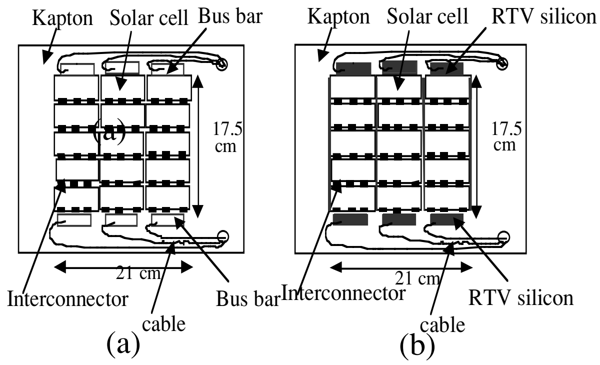

Fig.3.Schematic of the solar array (a).Array without RTV (b).Array with RTV.

Figure.1 shows the schematic diagram of the experimental setup. The length and diameter of the vacuum chamber are 1.2 m and 1 m respectively. The sub-chamber has a plasma source, the main chamber and the sub chamber are connected through a gate valve. Xenon Plasma is created using the plasma source in the sub-chamber that generates the plasma temperature of 1.6 eV and density of $2 - 5 \times 10^{11}$ m^{-3} . In order to simulate the operational temperature of 40° C at GEO, we use IR lamps inside the chamber. The solar array is placed inside the chamber so that its face is parallel to the chamber axis.

ETS-VIII solar array string layout is shown in Fig.2. It consist of 88 strings (two wings), each with 262 Si-IBF (Integrated Bypass Function) solar cells. Each string produces the bus voltage of 110V and placed as four rows of 66 cells, Two strings are connected together in the harness. The gaps between adjacent cells are potted with nonconductive adhesive. Each string produces approximately 1.32 A current. The ETS-VIII array has adjacent cells with 55 volts potential difference with the current capability of 2.64 amperes (worst case). The cover glass is made of BRR/s-0213. The schematic diagram of the solar arrays, which we have used for the study are shown in Figs.3a and b. The solar array contains 3 strings, we call the strings as R, B and G respectively. Each string consists of five cells (3.5cm × 7 cm each). We use two different designs of solar arrays, one with RTV (Fig.3a) between the cells, we call this as W/RTVthroughout this paper. Another one is without RTV between the cells (Fig.3.b), and the solar array string terminals are connect to the connecting cables through the bus bars, which is made of conducting material. We call this as W/O/RTV throughout this paper. In the case of W/RTV, the bus bars are covered with RTV. A digital video camera is used to record the arcs on solar array during the experiment.

We studied the snapover mechanism and measured the collected electron current and identified the threshold voltage for the glow discharge induced by the snapover. All the three strings are positively biased at same potential using the power supply, which is grounded through the 1kΩ resistance. The collected current was measured across the resistance using a passive probe (10:1) (Tektronix - P6112) connected to a 4-channel oscilloscope (Tektronix TDS 224).

The experimental circuit for the measurement of sustained arc phenomena is shown in Fig.4. To simulate the potential difference between the adjacent strings, we applied the potential difference (V_a) of 55V between the strings R and B using a floating power supply at the external circuit. The maximum current to flow is limited to

2.64 A. We bias the solar array strings at -500V (V_d). The currents flowing through the strings (I_R ,I_B , I_G) are measured using current probes (Tektronix-P6022), and the array potential (ϕ_a) is monitored using a HV probe (Tektronix- P5100) .

Before we start each experiment, we bake the solar array at a constant temperature of 70 °C for two hours to evacuate the gas and water molecules from the surface of the solar array. The array temperature during the experiment is kept to 40° C ± 1° C unless noted otherwise.

3.Results and discussions:

3.1.Collected current

Measured electron currents at different neutral densities for W/ RTV and W/O/RTV are given in Fig.5. In the orbital conditions, the neutral density around the solar array is very low (10^{15} ~10^{17} m^{-3}) when compared to the present study (10^{18} ~10^{19} m^{-3}). We have simulated the worst case because once we know the threshold of the snapover at the worst condition, then we can come to the conclusion in the real case. The collected current increases with increase in neutral density and the bias voltage for both the cases, and the same is higher for W/O/RTV than W/RTV. Higher electron current collection with W/O/RTV is due to the reason that the area for the current collection is larger compared to W/RTV. In the case of W/O/RTV, the bus bars collect more electrons, which is made of conductive material, thus the conducting area exposed to the outer plasma is larger in this case. However, in the case of W/RTV, the bus bars are covered with RTV and less conductive area (only interconnectors) of the array is exposed to the plasma. From the results it is clear that the bus bars covered with RTV reduces the electron current collection.

Figure 6 shows the threshold voltage for the gas-induced glow discharge due to the snapover at various neutral gas densities for solar array W/RTV and W/O/RTV. It is noted that the threshold voltage decreases with increase in neutral density. The threshold voltage for the glow discharge inception is higher between 320 and 370 V for solar array W/RTV and the same is lower between 95 and 290V for W/O/RTV. The current measured during the glow discharge at different neutral gas densities increases with increase in neutral density. The amount of current collected is 3 or 4 times larger than that of the current collected just before the glow inception. For an

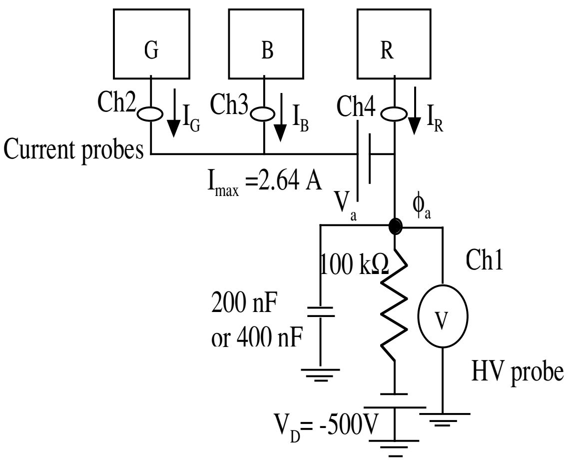

Fig.4.Circuit set-up for sustained arc experiment.

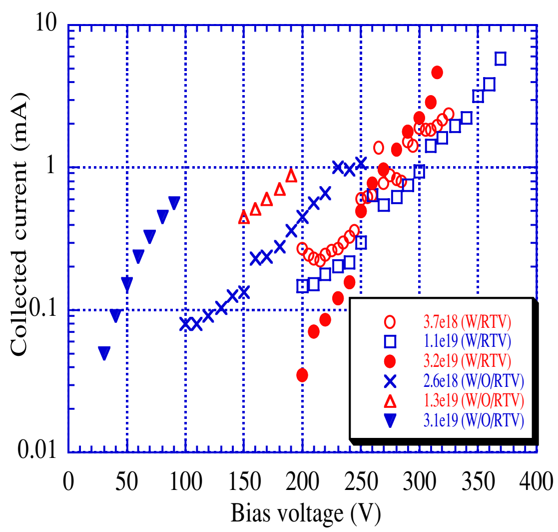

Fig.5. Collected electron current measured at different neutral densities for solar arrays W/RTV and W/O/RTV. X-axis is in logarithmic scale.

example the maximum current collected at the neutral density of 3. ×10^{19} m^{-3} at 95V for W/O/RTV is about 2.2 mA, whereas the same just before the glow inception is only 0.7 mA. For W/O/RTV, the glow was observed at bus bars which were the largest conductor exposed to the plasma. For W/RTV the glow was observed not only at bus bars but also at interconnectors, because the area of exposed bus barwas as small as the exposed interconnector. In real spacecraft, a huge amount of electron current will be collected by the solar array during the glow discharge, and the power loss is substantial.

Fig.7.shows the collected electron current at different bias voltages for different number of the array strings biased at the same time for solar array W/O/RTV. From the graph it is clear that the collected electron current depends on the collected area, but not linearly proportional. This can be explained as follows; before the snapover, the conductor/dielectric of the solar array maintains the equilibrium with the plasma primarily through an approximately hemispherical sheath above the positively biased conductor. Ambient electrons enter into the sheath

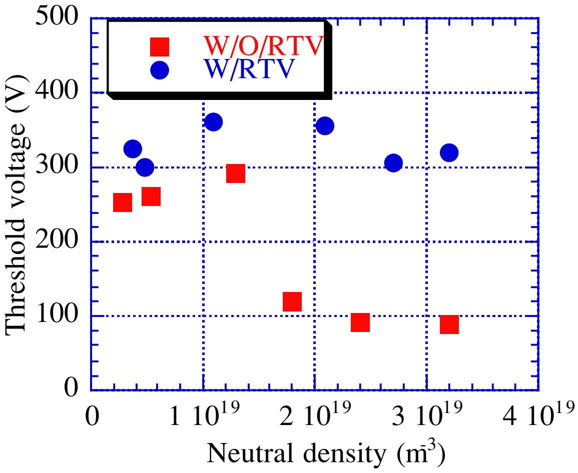

Fig.6.Threshold voltages for gas-induced glow discharge at different neutral densities for solar arrays W/RTV and W/O/RTV. X-axis is in logarithmic scale.

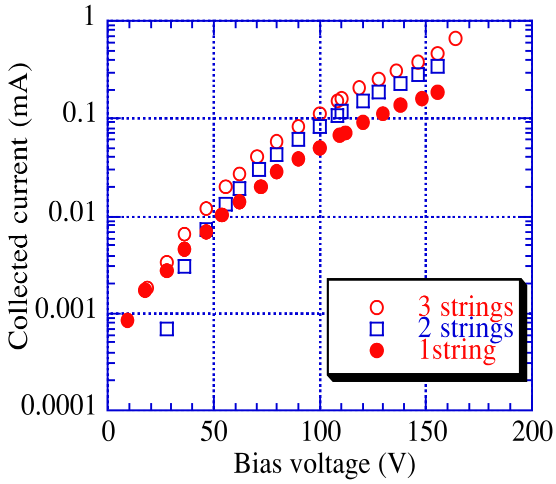

Fig.7.Collected electron current measured at different bias combinations of the solar array strings of W/O/RTV. Neutral density is 1.8×10^{19} m^{-3}

by their own thermal energies, and once inside they are accelerated radially inward towards the conductor. For the case of positive bias of only one string, more electrons per unit area will reach the sheath from all the directions. But for the bias of three strings the electron reaching the sheath from all the directions is limited. This may be the reason that the collected electron current is not linearly proportional to the area of the solar array. In real spacecraft conditions, the area available for the current collection is much larger, If the collected current is proportional to the area, then solar arrays collect more current, eventually it leads to the power loss of the spacecraft. In the ETS-VIII satellite, we have totally 23056 cells and each string (262 cells) will supply 110 volts and 1.32 amperes of current. The total power generated by the solar array is 12.66 kW maximum. The solar array that we have used for our experiment contains 15 solar cells. By extrapolating the data, the expected collected current for the ETS-VIII solar array which has RTV is about 228.4 mA at 110V. The expected power loss of the spacecraft is about 25.1 Watts. This power loss is negligible when compared to the total power generated from the solar power system of the satellite.

If the neutral density around the array increases accidentally to 10^{18} or 10^{19} m^{-3}, the gas-inducedglow discharge might occur then the potential of the array will drop to negative value. The maximum expected negative potential for that case is about -110V. The Ion thruster will operates for five hours. We simulated the same conditions in our experiments and we did not observed any arc for five hours at bias voltage of -110V for the both designs of the array.

3.2.Sustained arc:

In the case of failure of the neutralizer the potential of the solar array will drops instantaneously to -1kV negative and there is a chance for the sustained arc formation. In the present investigation, we have increased the negative bias voltage to -500V. A short duration electrical discharge between adjacent solar cells with highest potential difference can lead to the sustained arc. In this case the plasma as a result of an initial arc can provide a conductive path through which solar array power can flow. The strings of the solar arrays are short-circuited by the

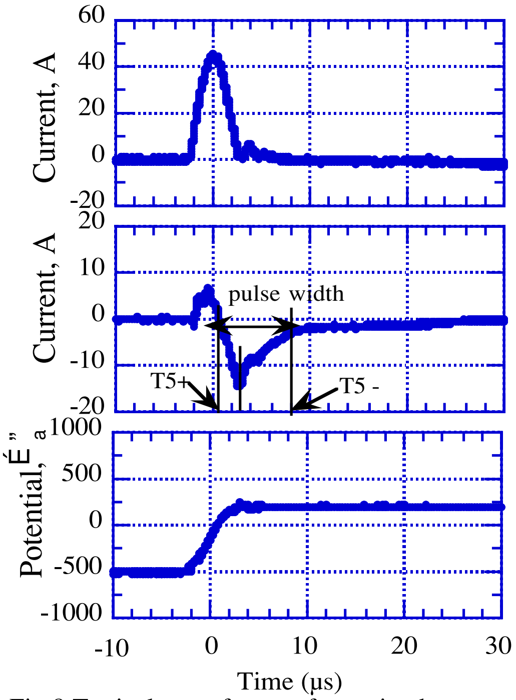

Fig.8.Typical waveforms of sustained arc experiment. Discharge current, I_R, at the top of the figure, neutralization current, I_B, at middle and array potential, ϕ_a, at the bottom of the figure.

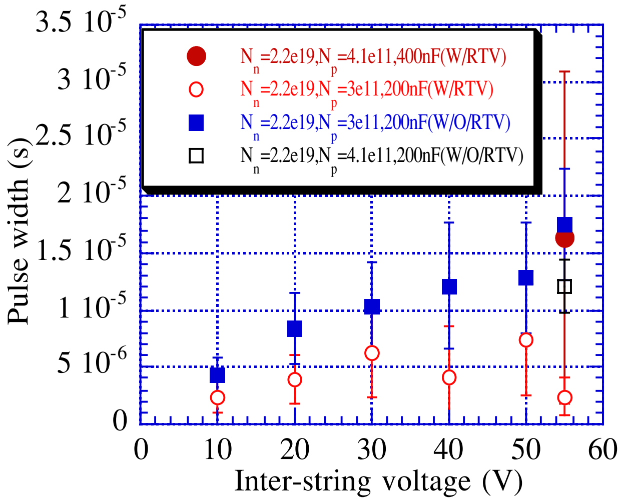

Fig.9.Measured pulse width at various inter-string voltage between the strings R and B for the solar arrays W/RTV and W/O/RTV. Error bars indicate the standard deviation. Each point is an average of at least 3 measurements., and maximum of 24 measurements

plasma. This solar array power may be sufficient to sustain the arc and the current keeps flowing until the array is broken [5].

Typical waveforms measured in the sustained arc experiment are given in Fig.8. The purpose of this experiment is whether an arc occurs at the string R leads to the sustained arc or not. Once an arc occurs at the string R, a positive current will flow from the same, which we call as the discharge current. The energy for the discharge current is supplied by the charges stored in a coverglass of string B and G. The current flowing through the string B and G is called as the neutralization current. In figure T5+ denotes the time at which the peak has 5% of its peak value in the neutralization current waveform and T5- denotes the time at which the neutralization current waveform has 5% of its peak current value at the other end of the waveform. Pulse width is defined as the time difference between T5- and T5+.

In Fig.9 we plot the pulse width of the neutralization current at different applied potential between the strings R and B for the solar array W/RTV and W/O/RTV. From the figure it is seen that the pulse width is smaller for the case of solar arrays with RTV. The pulse width increases with increase in inter-string voltage for both cases. To check whether the sustained arc occurs at higher plasma density or not, we have increased the plasma density to 4.1×10^{11} m^{-3}. To simulate the worst case we have increased the external capacitance in the circuit from 200 nF to 400 nF. The capacitance value of the coverglass in one string of ETS-VII solar array is about 180nF. Even at the worst case (neutral density: 2.2×10^{19} m^{-3}, plasma density: 4.1×10^{11} m^{-3}, and capacitance: 400nF) we did not observe sustained arc at the solar array W/RTV. But for the case of solar array W/O/RTV, we observed the sustained arc between the R and B strings of the solar array at neutral density of 2.2×10^{19} m^{-3}, plasma density of 4.1×10^{11} m^{-3}, and capacitance of 200nF. Figure 10 shows the charge from the coverglass of the string B at different values of inter-string voltage between the strings R and B. The charge released increases with increase in inter-string voltage, but the same is higher for the solar arrays W/O/RTV. It should be noted that coverglass of B string has a capacitance of 3.5nF, which can supply only 1.7×10^{-6} C to the arc. The fact that the charge more than that value is supplied by B string to the arc, indicates that the power supply between the strings R and B contributes to supply the additional charge to the arc plasma. When the amount of charge is limited to a finite value, the arc ends as a single pulse. But when it becomes infinite, it means that the power supply keeps supplying the current between the strings. From figure it is found that at higher plasma densities the charge is higher implying that the chance of sustained arc is higher at higher plasma densities. From the above figures (Figs.9 and 10) it is found that RTV between the strings of the solar array prevents the sustained arc formation between them.

Figure 11 show a model of the formation mechanism of sustained arc between the adjacent cells of the solar array. Once an arc occurs at the interconnector of the solar cell, the arc current will flow through the capacitance connected in the external circuit to the chamber wall and close the current path.

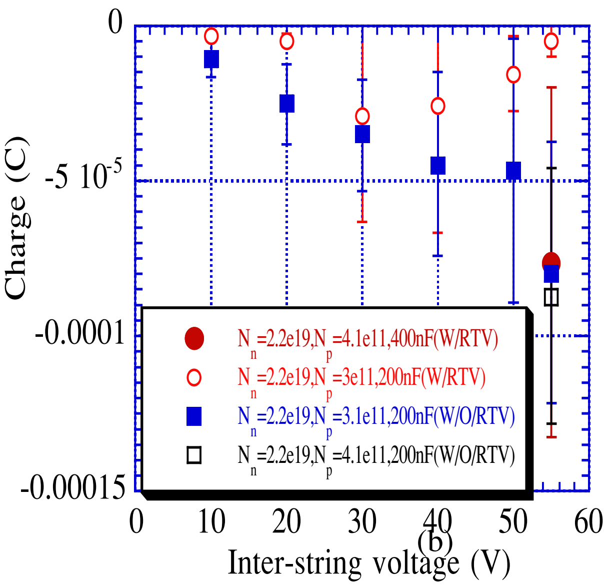

Fig.10.Charge released from the coverglass of B string at various inter-string voltage between the strings R and B for the solar arrays W/RTV and W/O/RTV. Error bars indicate the standard deviation. Each point is an average of at least 3 measurements., and maximum of 24 measurements

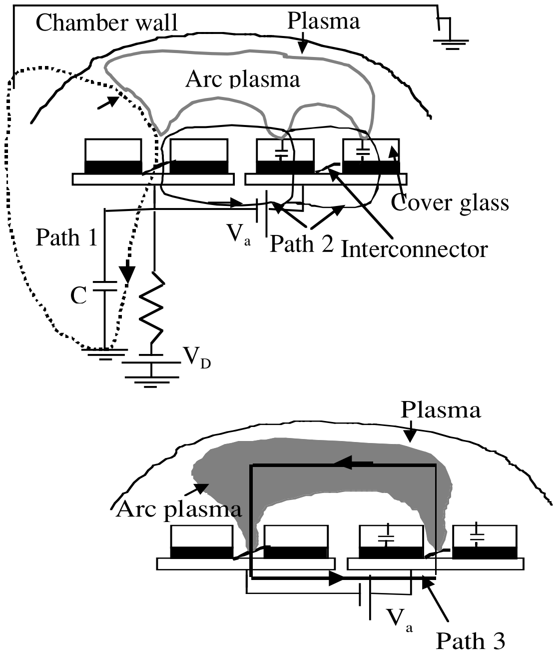

Fig.11.Model of formation mechanism of sustained arc between the adjacent cells of the solar array. Path 1 is a current path between the arc spot and the chamber wall through the external capacitance. Path 2 is a connection of arc spot with the coverglass of nearby solar array and the path 3 is the current path between the interconnectors of the adjacent cells through the external power supply.

This path is denoted as path 1. If the arc plasma makes the coupling with the coverglass of the nearby solar cells, then it supplies energy to the arc plasma (path 2) and that will grow and makes connection with the interconnector of the nearby solar cell. Then the current path (path 3) will be formed between the interconnectors of the adjacent cells through the external power supply (V_a). The arc will be sustained by the power supply and develops the short circuit between positive and negative end of the power supply leading to destruction of the solar array circuit.

(a) (b)

Fig.12.Microscopic pictures of the sustained arc point between the strings R and B of the solar array W/O/RTV. (a). before arc (b).after arc.

The microscopic picture of the sustained arc point between the R and B strings is given in Fig.12. We took microscopic pictures before and after the experiments. From the pictures it is seen that arc damages the strings and kapton film (50μm) on a aluminum substrate on which the cells are mounted. The inspection after the experiment revealed that the two strings and substrate were completely shortened.

Conclusions:

A ground-based large volume plasma chamber experiment was carried out to study the interaction between the ion thruster plasma and the solar arrays of ETS-VIII satellite. Results of the electron current measurements for two different designs of solar arrays at elevated neutral densities ($10^{18} \sim 10^{19}$ m^{-3}) revealed that the solar array with RTV filled between the cells and on the bus bars (W/RTV) collected the less amount of electron current compared to the solar array without RTV (W/O/RTV). The threshold voltage for the gas-induced glow discharge was lower for the case of solar arrays W/O/RTV. The power loss of the spacecraft will be negligible compared to the total power of the satellite as long as RTV is used.The potential drop of the solar array due to the snapover was simulated and we did not observed any arc at bias voltage of -110V for five hours. The failure of the ion thruster neutralizer was simulated and we observed the sustained arc between the adjacent cells of the solar array W/O/RTV. The RTV between the adjacent cells prevented the sustained arc formation. This sustained arc made the short circuit between the positive and negative ends of the solar array and lead to destruction of solar array circuit. From the results of the experiment, it is concluded that, the solar array with RTV filled around the cells and the bus bars are the best design for the ETS-VIII satellite.

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