Optical spectral analysis of arc plasma on solar array in GEO plasma environment

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ABSTRACT

Preliminary spectroscopic measurement of electron temperature of arc plasma which strongly related to electrical conductivity was carried out to evaluate the range of proper amount of external capacitor. Using the solar array coupon with the flaw simulating debris impact on the face sheet beside one cell edge, we observed a lot of non-permanent sustained arcs between the cell and the substrate along with the primary arcs. Comparing the spectra of primary arc and non-permanent sustained arc, spectra of non-permanent sustained arc case contained many species compared with the case of primary arc only. Aluminum and ion atoms and silicon ion that included in substrate, electrode and cell were observed. These materials would be vaporized by joule heating of arc plasma. Also, time variations of electron temperature in each discharge mode using relative intensity ratio technique for C_2 Swan system spectra. Primary arc temperatures at peak current was about 5000 ~ 15000 K and were not much difference whether non-permanent sustained arc occurs or not. The temperatures of the non-permanent sustained arc were up to about 7000K and lower than that of primary arc.

1. Introduction

The power level of a geostationary satellite has increased dramatically to nearly 10 kW or even higher. To manage the large amount of power efficiently, nowadays many commercial telecommunication satellites employ solar array that generates the electricity at 100V. As the voltage of solar array increases to 100V, arcing during substorm has been recognized as serious hazard that sometimes threatens the stable supply of the solar array power. If an arc occurs at a gap of two solar array strings or near defect of the insulator layer between cells and conductive substrate, there is a risk of one primary arc growing to a catastrophic arc receiving energy from the array itself. The risk has increased recently as the power level of solar array has increased. When an arc occurs, the arc plasma may short-circuit two points on solar array panel with different potentials, that is called permanent sustained arc. The permanent sustained arc where the current is maintained by the solar array string circuit and keeps flowing until the solar array string circuit is disconnected. The permanent sustained arc gives excessive heat to underlying insulation substrate. Thermal breakdown of the insulation substrate leads to permanent short-circuit of solar array strings(see Fig. 1). Several satellites[2,3] lost a part of solar array output power due to the sustained arc. The risk of sustained arc increases as output voltage of solar array increases, because the potential difference between two points short-circuited by the arc plasma becomes higher. Also, the threat of such impacts increases with increase in the size of solar array paddle. When the insulative sheet on the substrate gets surface damage for some reason (e.g. hypervelocity impacts, mechanical stress, etc.), the permanent sustained arc phenomena are induced[4].

Therefore, there is more demand for careful ground test before launch as increasing size and price of GEO satellites. Ground tests are being carried out to confirm whether a given design of solar array can withstand the permanent sustained arc. When we carry out an ESD test of solar array, proper test conditions that simulate the conditions in orbit are necessary. Inadequate testing conditions lead to unexpected failure in space. Increasing the level of harshness beyond a reasonable limit is not always a good solution. There is not yet any standard on how we carry out the ESD test on solar array[1]. Especially, the value of external capacitance that feed energy to the trigger arc is very important. The external capacitance is corresponding to the absorbed electric charges on the insulator surface. A low capacitance value doesn't provide a sufficient current to trigger a secondary arc. While, we must avoid using excessive value capacitance that lead to degradation of cell electrical power output. The amount of external capacitor currently employed differs among research institutions.

We focused the relation between the electrical conductivity of the trigger arc plasma and the amount of external capacitor in order to evaluate the range of proper amount of external capacitor. Electrical conductivity is strongly related to plasma temperature. Thus, we measure the plasma temperature by the emission spectroscopy. Our objectives are to compare the spectra of primary arc and non-permanent sustained arc and the time variations of electron temperature in each discharge mode using relative intensity ratio technique.

2. Experimental apparatus

2-1. Test coupon

The picture of a solar array coupon used in the experiments is shown in Fig. 2. The size of the coupon is 220 mm x 240 mm. The coupon contains 3 strings and we call the strings as R, B, and G respectively. Each string consists of five Si cells (70 mm x 35 mm) with thickness of about 100 μm, therefore, the coupon has 15 cells as a whole. The cells are mounted on Kapton film with thickness of 50 μm by silicon RTV adhesive whose thickness is also 50 μm. The Kapton film is mounted on a CFRP face sheet substrate (0.1 mm thick) on the top of aluminum honeycomb plate (25 mm thick). On the face sheet beside one cell edge was made a flaw simulating debris impact. Figure 2 shows the microscope image of the flaw. The length of this flaw was about 2mm and width was >0.5mm. The entire surfaces without this cell edge are covered with Kapton sheet to prevent the arcing there.

2-2. Experimental set-up

The sketch of the experimental setup is shown in Fig. 3. The experiments were performed in a vacuum chamber, which has 600 mm of diameter and 900 mm of length. The pressure in the chamber could reach up to about 1.0×10^{-4} Pa. In order to generate the differential voltage, we biased the coupon to negative potential at –6kV using a high voltage power supply (Glassman; EW60kV), and irradiate the coupon by an electron beam gun (ULVAC; RHEED). The electron acceleration voltage and irradiation current were 8kV and 200μA, respectively. We measure the 2-D distribution of the surface potential of the coupon using a non-contacting surface potential probe (Trek probe; Model-341) attached to the X-Y stage (SIGMA KOKI; SGSP26-150_200). Coupon was connected the well-known circuit to investigate the non-permanent or permanent sustained arc occurrence[5]. The hot line and the return line connected to one cell string and the substrate, respectively. We applied the inter-string voltage of 105 V and the line currents of 1.9 A by a solar array simulator (Agilent, E4351B). The primary arc current was measured using AC current probe (Tektronix; P6022). And, we measured the arc current between string and substrate using DC current probe (HIOKI; 3274). Light emission from arc plasma was measured by spectrometer (Hamamatsu Photonics, PMA-11) with an image intensifier (I.I.). Figure 4 shows the optical measurement system and timing chart of spectroscopic measurement. This system consists of oscilloscope, dray pulse generator and spectrometer. When the Oscilloscope (LeCroy, WS424) measured a primary arc, a trigger pulse generated and drove the pulse delay generator. The pulse delay generator (Stanford, DG-535) can generate a gate pulse to drive the spectrometer with any delay time from primary arc initiation. Also, we can choose the exposure time of spectrometer by the pulse width of gate pulse.

3. Results and Discussion

First of all, we examined the relation between discharge state and the spectrum. Figure 5 shows the typical waveforms of primary arc. Pulse width and current peak of primary arc was about 10μs and 40A, respectively. Figure 6 shows the typical waveforms of non-permanent sustained arc. Although the pulse width and the current peak of primary arc are the same levels as shown in Fig. 5, arc current of non-permanent sustained arc began to flow after 5 ~ 10μs that primary arc current was falling, and it kept flowing for 30μs. Measured non-permanent sustained arc durations were about 10 ~ 50μs, sometimes it exceeded 50μs which the maximum measurement range of the oscilloscope. Hatched areas in the Fig. 5 and 6 indicate exposure time of the spectrometer. In these measurements, exposure time and delay time from the primary arc initiation to the exposure were 2μs and 6μs respectively. Measured spectrum shows in Fig. 7 and 8. Figure 7 shows the spectrum without non-permanent sustained arc. In this figure, strong peaks of single ionized silver (Ag II) emission lines were observed. Silver was included in the material of the interconnector. This silver would be vaporized and ionized by the heat of the arc spot. Also, we detected weaker emissions at 450 ~ 570 nm. These characteristic shape of band spectra corresponded to the C_2 molecule Swan system spectra. Carbon was included in many components of this coupon (e.g. adhesive, substrate, Kapton© and adsorption gas). It seems that any material near the interconnector would be vaporized by heating. Figure 8 shows the spectrum with non-permanent sustained arc. Comparing with Fig. 7, we can find a lot of strong lines beside Ag II lines. Aluminum and ion atoms and silicon ion that included in substrate, electrode and cell were observed. This result indicates the non-permanent sustained arc occurred between the substrate and the cell.

Figure 9~11 show the time variations of spectra of non-permanent sustained arc. Time delays from the primary arc initiation were 0μs, 5μs and 10μs. In this case, exposure time of spectrometer was 5μs. Mean intensity of emission lines were decreasing with increasing the elapsed time from primary arc initiation. Almost same lines were observed through the different time delay. Especially, the C_2 molecule Swan system spectra were measured with good repeatability. Thus, we deduced the electron temperature using the C_2 system spectra. The C_2 swan system consists from three parts. Each part of the band spectrum corresponds to a set of transitions between different vibrational levels (Δv=+1,0,-1) in different electronic states. The shape of these spectra was calculated numerically under the Boltzmann equilibrium condition with electron temperature and was distributed on the Internet[7]. Figure 12 shows the relation between the electron temperature and the calculated relative intensity ratio, which the integrated intensity from 450 ~ 475nm divided by that from 475~520 nm. These plots and line correspond the results of numerical calculation and fitting, respectively. The electron temperature is proportional to the exponential of relative intensity ratio. Figure 13 shows the time variations of the deduced electron temperatures using this fitting curve and measured spectra. Primary arc temperatures at peak current was about 5000 ~ 15000 K and were not much difference whether non-permanent sustained arc occurs or not. The temperatures of the non-permanent sustained arc were up to about 7000K and lower than that of primary arc.

4. Summary

Preliminary spectroscopic measurement of electron temperature of arc plasma which strongly related to electrical conductivity was carried out to evaluate the range of proper amount of external capacitor. Using the solar array coupon with the flaw simulating debris impact on the face sheet beside one cell edge, we observed a lot of non-permanent sustained arcs between the cell and the substrate along with the primary arcs. Comparing the spectra of primary arc and non-permanent sustained arc, spectra of non-permanent sustained arc case contained many species compared with the case of primary arc only. Aluminum and ion atoms and silicon ion that included in substrate, electrode and cell were observed. These materials would be vaporized by joule heating of arc plasma. Also, time variations of electron temperature in each discharge mode using relative intensity ratio technique for C_2 Swan system spectra. Primary arc temperatures at peak current was about 5000 ~ 15000 K and were not much difference whether non-permanent sustained arc occurs or not. The temperatures of the non-permanent sustained arc were up to about 7000K and lower than that of primary arc. In this measurements, we did not obtain enough data to discuss the temperature deference at 5 ~ 15μs corresponding to the transition from primary arc to the non-permanent sustained arc. Our future works are to obtain a lot of data with good time resolution and to clarify the relation between the capacitance value and the temperature.

References

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[6] Hornkohl, J. O. and Parigger, C.G., "Boltzmann Equilibrium Spectrum Program (BESP) Web page";http://view.utsi.edu/besp

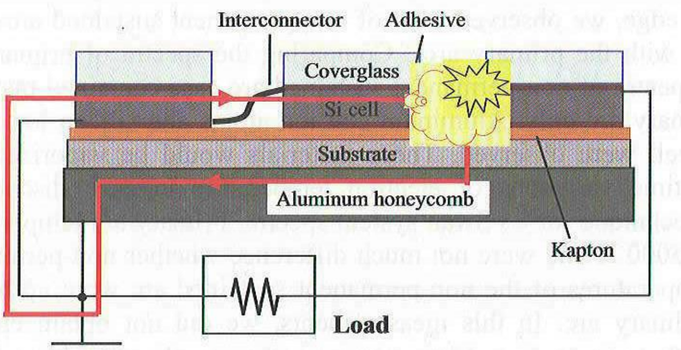

Figure 1. Sketch of the current flow of permanent sustained arc

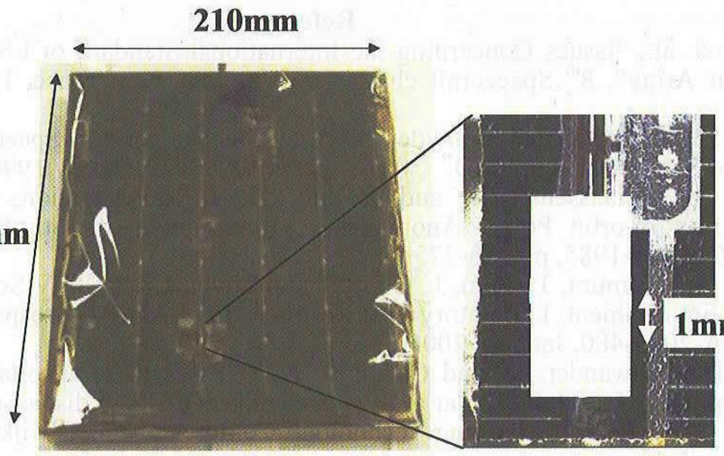

Figure 2. Picture and microscope image of test coupon

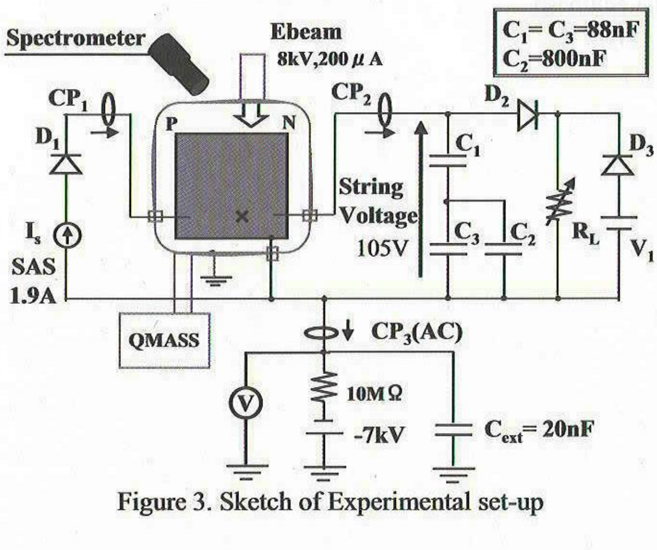

Figure 3. Sketch of Experimental set-up

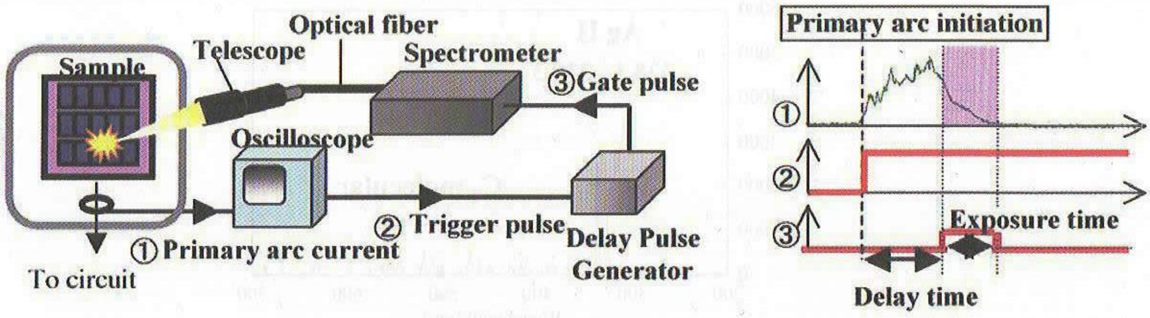

Figure 4. Optical measurement system and timing chart

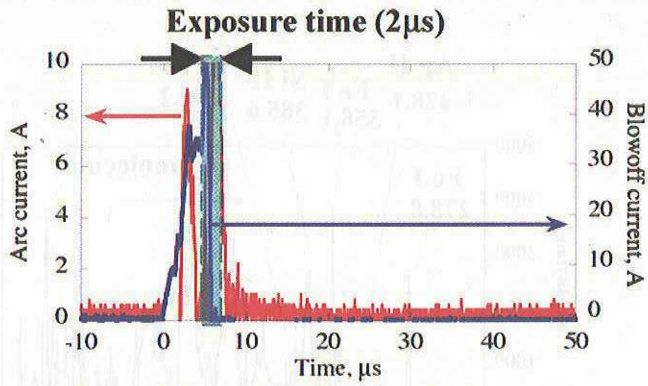

Figure 5. Typical waveforms of primary arc

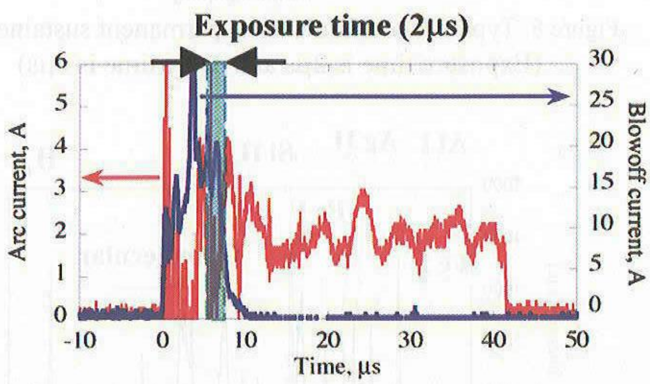

Figure 6. Typical waveforms of non-permanent sustained arc

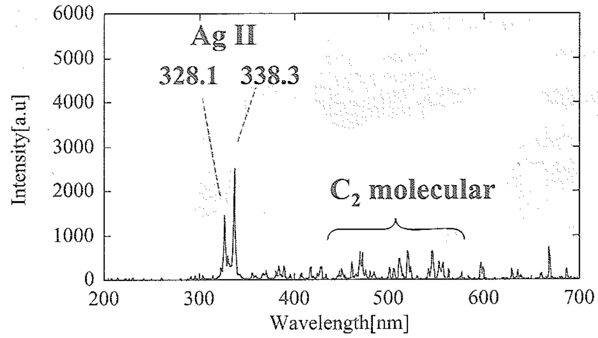

Figure 7. Typical spectrum of primary arc
(Exposure time is 2μs and delay time is 6μs)

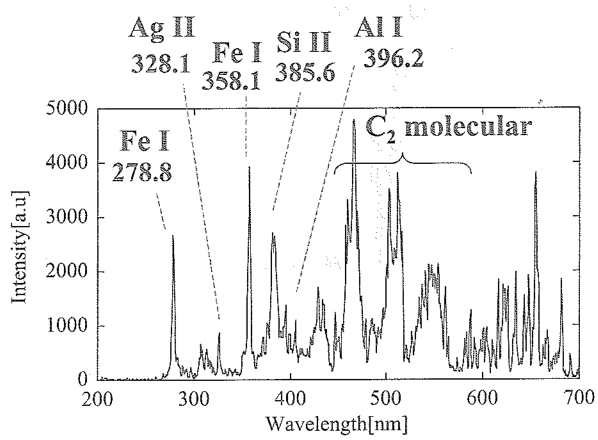

Figure 8. Typical spectrum of non-permanent sustained arc
(Exposure time is 2μs and delay time is 6μs)

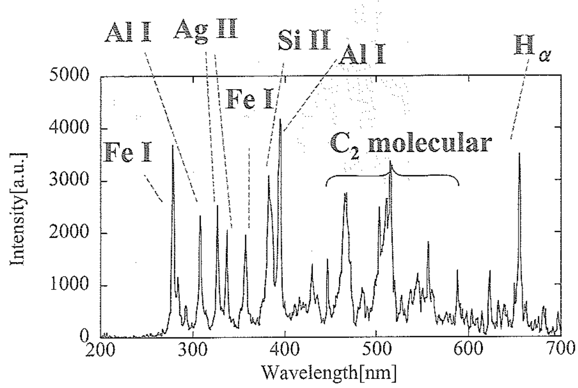

Figure 9. Typical spectrum of non-permanent sustained arc at 0μs delay.
(Exposure time is 5μs)

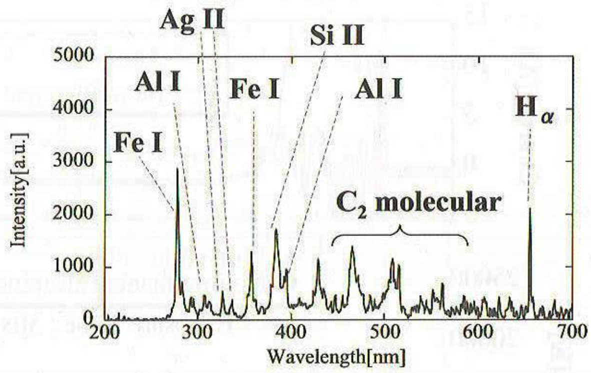

Figure 10. Typical spectrum of non-permanent sustained arc at 5μs delay. (Exposure time is 5μs)

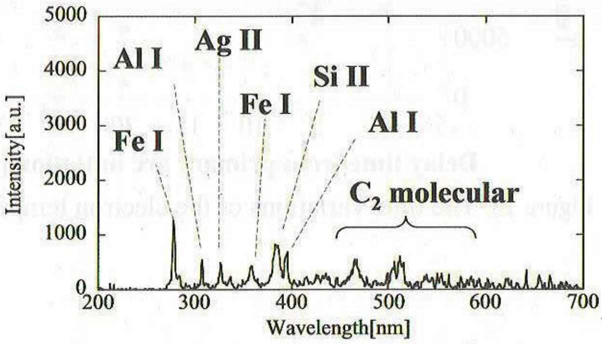

Figure 11. Typical spectrum of non-permanent sustained arc at 10μs delay. (Exposure time is 5μs)

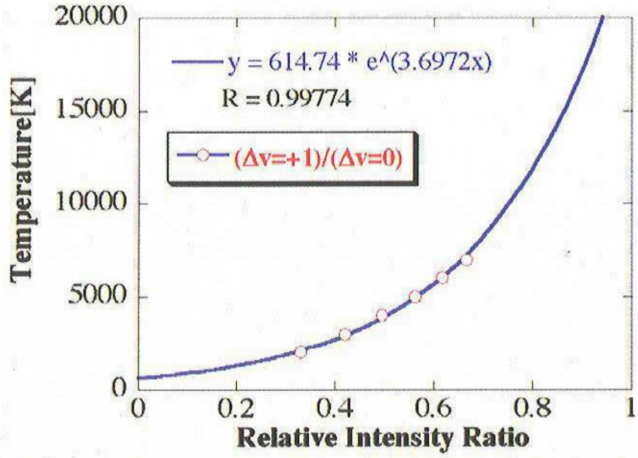

Figure 12. The relation between the electron temperature and the calculated relative intensity ratio

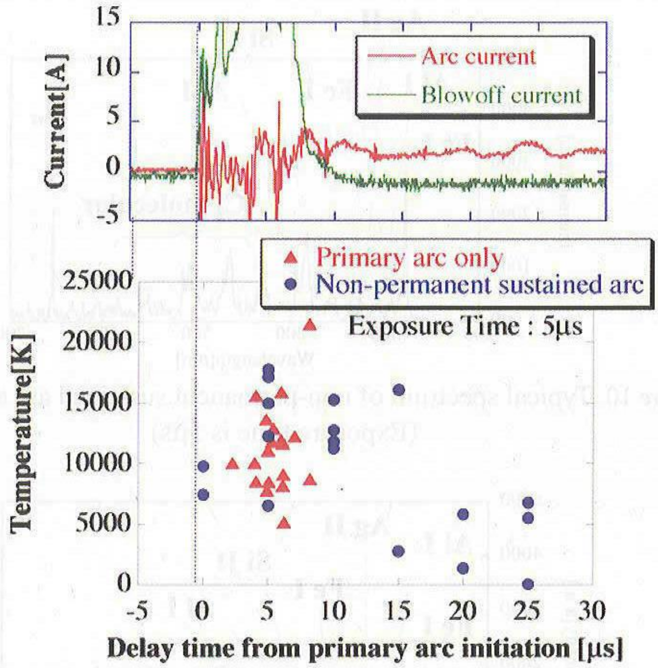

Figure 13. The time variations of the electron temperatures