ESD-TRIGGERED ARC DISCHARGES ON SOLAR ARRAY BY ELECTRON-BEAM IRRADIATION

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Abstract

We carried out electron-beam irradiation experiments concerning the arcing discharges on solar arrays for space use. It is very important to make the discharge mechanism clear and to reflect it to a guideline for designing the solar arrays in order to maintain the high reliability of the future large spacecraft systems. We used a pair of real GaAs solar cells on an aluminum substrate as a sample. The sample was biased to -9kV and irradiated by the electron beam of the energy of 10keV. The voltage from DC battery was applied to the gap between the cells under that condition. The discharge characteristics were obtained as parameters of the gap distance and the applied voltage between the cells. From the waveforms of transient discharge currents, the discharge time was analyzed to evaluate the harmfulness of arcing discharges to solar cells. As a result, the detrimental arcing did not occur even under several conditions of the cell gap distance and the cell gap voltage below 120V, although a few hundreds of ESD (electrostatic discharge) took place.

Therefore, the high voltage use of solar arrays is thought not to cause sustained arcing discharge to destroy the satellite system if arrays are designed to lower the maximum voltage between cell strings with an adequate distance.

1. Introduction

Spacecraft charging problems appeared about 30 years ago [1]. After that, researches and developments for the spacecraft charging technology were conducted extensively [2-4]. As the results, satellite systems reliable to the spacecraft charging have been developed and operated in space. In these R&D's for the spacecraft charging technology, the protection against the surface charging on satellite was the main subject. However, in 1997 TEMPO-2 satellite with 100V bus voltage was troubled on the geostationary orbit [5]. From the investigation of the accident, the possibility of the occurrence of arcing discharge at the high voltage terminal between the solar cell strings was pointed out [6]. Since then investigations have been conducted in order to make the arcing discharge mechanism leading to detrimental failure of a satellite clear [7]. However, it seems that the mechanism and the condition to cause the arcing discharge are not yet clear.

From these view points, we intended to make the mechanism clear by investigating discharge characteristics by means of the electron-beam irradiation method and to reflect the results to the solar array design for future high-power satellite. The results of a first step of our investigation were presented at last 8th Spacecraft Charging Technology Conference [8]. In this paper, we also used a pair of real GaAs cells for space use as a sample. Inverted potential gradient as one condition causing discharges was formed on the sample by biasing the sample negatively and by irradiating electron beam to it. We carried out the experiments by measuring transient currents after the occurrence of electrostatic discharge (ESD). And we discuss the results from the viewpoint of the discharge time.

2. Experimental Procedure

Figure 1 shows the sample configuration of a pair of real GaAs cells which is the same configuration as mentioned in the previous paper [8]. The size of a GaAs cell was 76x37mm^2. Two cells with cover glasses were bonded onto the 1mm-thick 100x100mm^2 aluminum plate (substrate) covered with 25μm thick Kapton film. The long sides of the cells were opposed each other with the gap distance of d. The three sides of the cell except for the gap side were covered with RTV adhesive in order to make discharges occur at the gap only.

Figure 2 shows the experimental setup to investigate the electron-beam induced discharge characteristics. After one sample was set in a vacuum chamber, the chamber was evacuated to the pressure of about 1.3x10^{-4}Pa by a rotary pump and a turbo-molecular pump.

The sample was biased to -9kV (V_b) by DC power supply. Then electron beam of the energy of 10keV was irradiated to the sample. The beam current density (J_b) was about 0.1-0.3nA/cm^2 at the sample position. Due to this method the surfaces of the cell's cover glasses were irradiated with electrons of the energy of 1keV. Therefore the surfaces were expected to charge up positively against the cells and the substrate due to the secondary electron emission yield characteristics of the cover glass, that is, the inverted potential gradient was formed on the cover glasses. DC voltage V_a by connecting 9V batteries in series was applied between the cell's gap to simulate the potential difference between cell strings on solar array.

Current monitors (Pearson 411, 4100 and 2877) were used to measure transient currents at the time of the occurrence of discharge. One transient current, cell current I_c, flows the loop current path including the cell gap and the other, substrate current I_s, is the current flow between the sample and the earthed chamber wall. The occurrence of the discharge was also detected from the abrupt change of the pressure which was always monitored by an ionization gauge in the chamber. Photographs were also taken out of the window of the chamber.

As shown in Fig.2, an external capacitance C_b was inserted in parallel with the DC power supply (V_b). This capacitance simulates that of all cover glasses on the solar array panel wing of a typical real satellite.

All experiments were done at room temperature.

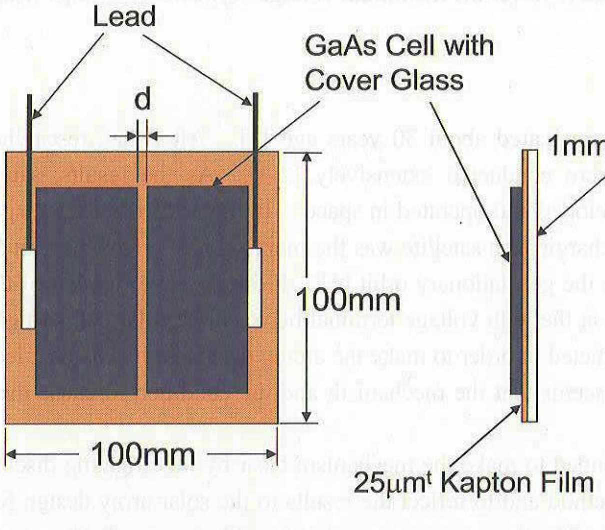


Figure 1 Sample configuration

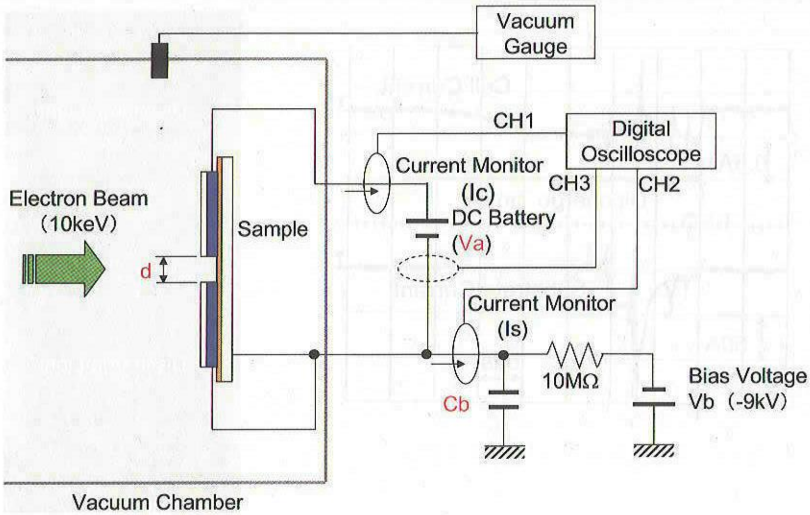
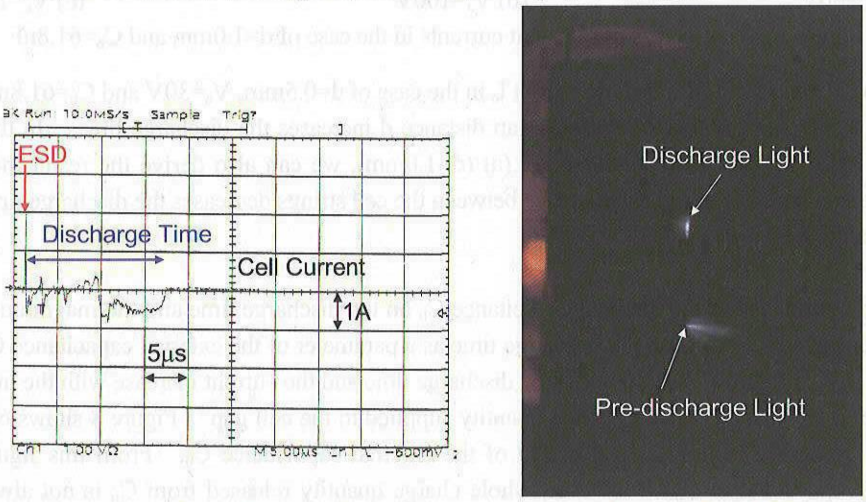


Figure 2 Experimental setup

3. Experimental Results

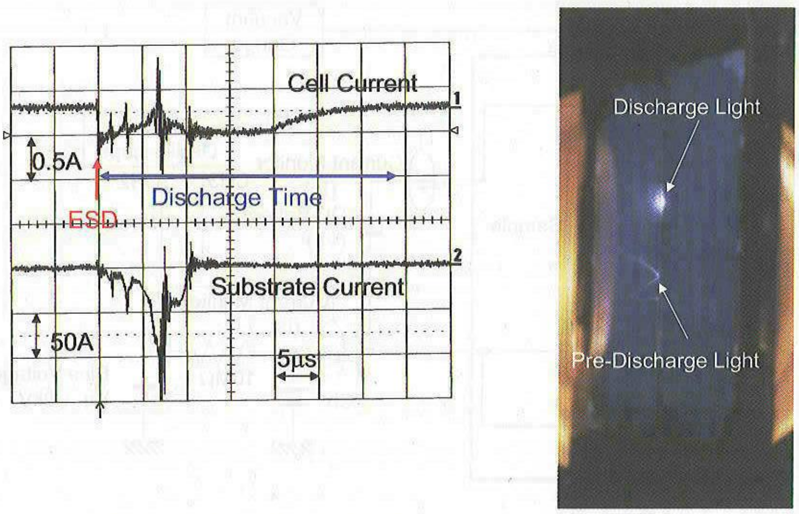
We carried out the experiments under the several conditions that include the gap distance d between the cells, the voltage V_a applied between the gap and the external capacitance C_b as parameters.

We firstly describe the influence of V_a in the case of the gap distance d=0.8mm. Figure 3 (a) shows an example of the waveform of the transient current I_c observed in the case of a discharge occurred at V_a=30V and C_b=61.8nF. And Fig.3 (b) shows the photograph of the light emission during about 2minutes including the instant of the discharge occurrence. I_c in Fig.3 (a) continued for 16μs after being triggered by ESD, although it had unstable period. This discharge occurred near the center of the gap as seen in Fig.3 (b). Also, a straight and weak light emission seen in this photograph continued until the main discharge occurred. This light seems to be cathode-luminescence stimulated by electrons which are emitted from the cell edges and impinge the surface of the cover glass [8]. Figure 4 shows typical waveforms of the transient currents, I_c and I_s, and the photograph of the light emission in the case of a discharge occurred at V_a=77V and C_b=61.8nF. I_c in Fig.4 (a) continued for about 35μs after being triggered by ESD. I_s started to increase after ESD, and at about 7μs the current I_s reached the peak. Although the current I_s abruptly decreased after that, the cell current I_c continued to flow. This discharge occurred near the center of the gap and the cathode-luminescence was also observed as seen in Fig.4 (b). We can see that the discharge time in the case of V_a=77V is longer than that in the case of V_a=30V.



(a) Waveform of transient current (b) Photograph of light

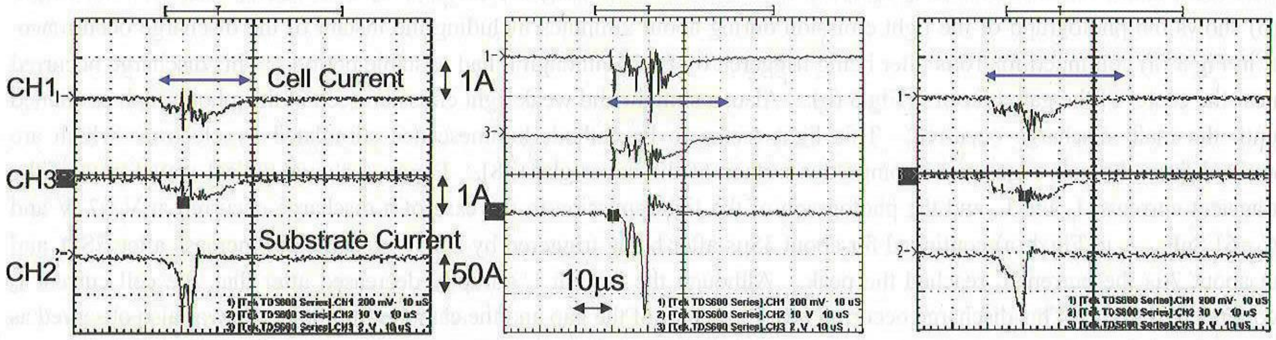
Figure 3 Example of waveform of transient current and the discharge light in the case of d=0.8mm, V_a=30V and C_b=61.8nF



(a) Waveforms of transient current (b) Photograph of light

Figure 4 Example of the waveforms of transient currents and the discharge light in the case of d=0.8mm, V_a=77V and C_b=61.8nF

Next, Figure 5 shows the typical waveforms of the transient currents, I_c and I_s, in the case of the gap distance of d=1.0mm varying the gap voltage V_a from 80V to 120V. We can see that the discharge time increased with the voltage V_a the same as in the case of d=0.8mm. However the discharge frequency in the case of d=1.0mm was lower than that in the case of d=0.8mm.



(a) V_a=80V (b) V_a=100V (c) V_a=120V

Figure 5 Waveforms of transient currents in the case of d=1.0mm and C_b=61.8nF

Figure 6 shows a typical waveform of transient current I_c in the case of d=0.5mm, V_a=30V and C_b=61.8nF. Comparing this figure with Fig.3 (a), we can see that decrease of gap distance d increases the discharge time. In the case of V_a of about 80V, comparing Fig.4 (a) (d=0.8mm) with Fig.5 (a) (d=1.0mm), we can also derive the result mentioned above. This result indicates that the increase of the gap distance between the cell strings decreases the discharge time in the case of the same voltage applied to the gap.

At last we describe the influence of the external capacitance C_b on the discharge time and the magnitude of cell current I_c. Figure 7 shows the dependence of I_c on the discharge time as a parameter of the external capacitance C_b in the case of d=1.0mm and V_a=80V. This figure shows that both the discharge time and the current increase with the increase of the C_b. That is to say, the increase of C_b increases the charge quantity supplied to the cell gap. Figure 8 shows charge quantities of I_c and I_s integrated by discharge time as a function of the external capacitance C_b. From this figure, both charge quantities are linearly proportional to C_b. However, whole charge quantity released from C_b is not always supplied to sustain the arcing discharge between the cells. The rate of two charge quantities is below 10%.

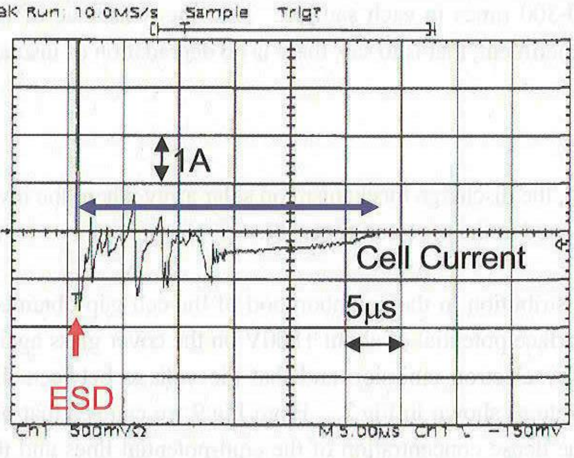


Figure 6 Waveform of transient current in the case of d=0.5mm, V_a=30V and C_b=61.8nF

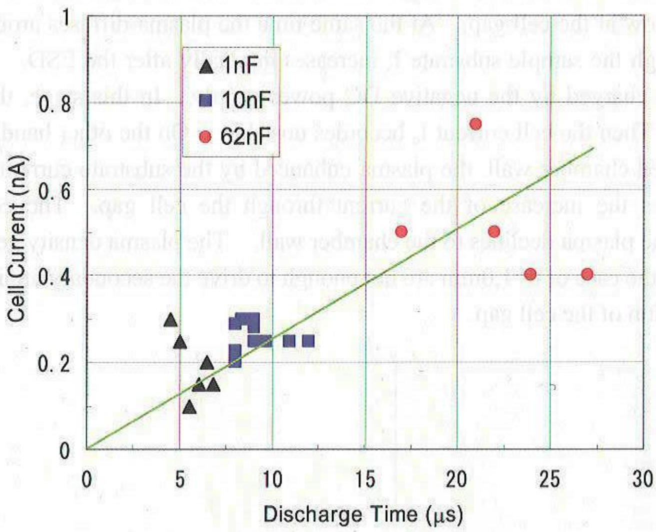


Figure 7 Relationship between the discharge time and the cell current as a parameter of the external capacitance C_b in the case of d=1.0mm and V_a=80V

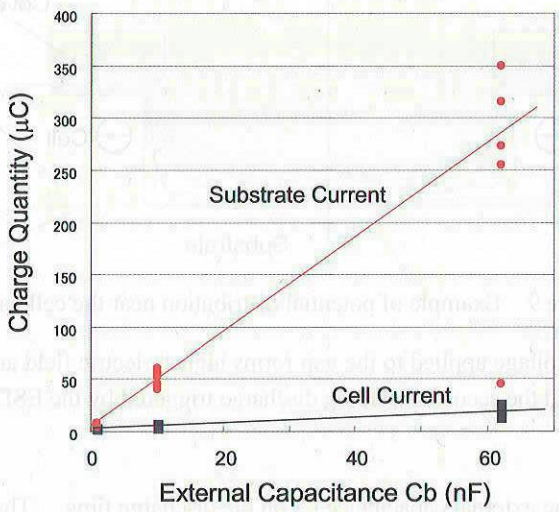


Figure 8 Relationship between the external capacitance C_b and the charge quantities of currents integrated by discharge time

We could not observe sustained arcing discharges causing detrimental damage to the sample, although discharges triggered by ESD's occurred 200-300 times in each sample. And the resistance of the cell gap for each sample was always beyond 10MΩ after the experiment, that is to say, there is no degradation of insulation of cell gap.

4. Discussions

From the waveforms of I_c and I_s, the discharge mechanism on solar array where the inverted potential gradient is formed is seemed to be the same as mentioned in the previous paper [8].

Figure 9 shows the potential distribution in the neighborhood of the cell gap obtained by Maxwell SV code. In this calculation, we assume that the surface potential of about +800V on the cover glass against the substrate [9] is formed by positive charging due to secondary electron emission and that the voltage between the cells is 50V and the negative terminal is grounded to the substrate as shown in Fig.2. From Fig.9 we can see that both upper edges of the cells have higher electric field because of the dense concentration of the equi-potential lines and that the potential distribution over the cell gap expand to free space and the potential gradient exists on the cover glass. Therefore the electron emission causing ESD starts at the triple junctions of the upper edges of the cells. The ESD generates locally dense plasma near the cell gap and induces current flow at the cell gap. At the same time the plasma diffuses around the sample. By the diffusing plasma the current through the sample substrate I_s increases gradually after the ESD. This transient current is supplied from the capacitance C_b charged by the negative DC power supply. In this stage, the main current channel changes to the substrate current. Then the cell current I_c becomes unstable. On the other hand, when the charges in C_b are almost released to the grounded chamber wall, the plasma enhanced by the substrate current also diffuses to the cell gap. The diffused plasma causes the increase of the current through the cell gap. The cell current continues as secondary arcing discharge until the plasma declines to the chamber wall. The plasma density generated near the cell gap and the voltage V_a below 120V in the case of d=1.0mm are not enough to drive the secondary arcing discharge to sustained arcing causing insulation degradation of the cell gap.

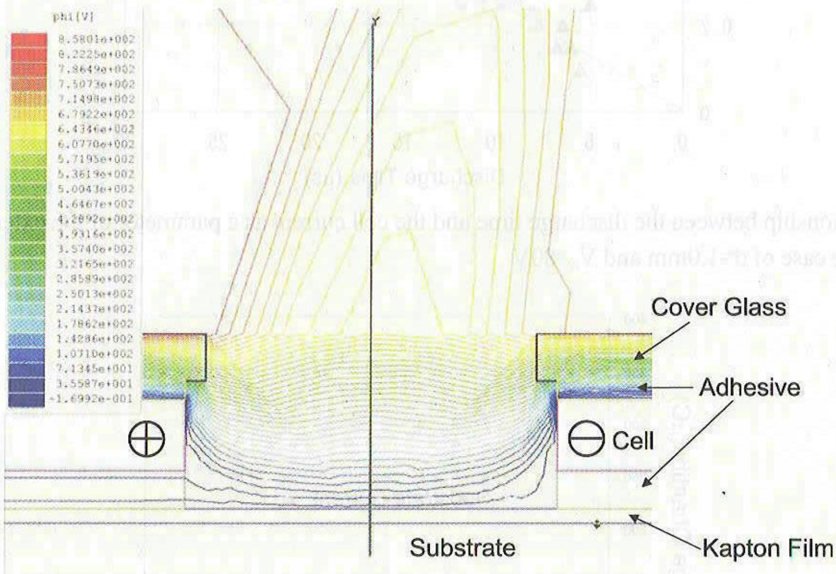


Figure 9 Example of potential distribution near the cell gap

In some cell gap distance, higher voltage applied to the gap forms higher electric field at the triple junction near the cell edge. Then ESD is easy to occur and the secondary arcing discharge triggered by the ESD continues for longer discharge time due to the higher voltage.

Next we discuss the influence of the external capacitance C_b on the discharge time. The substrate current I_s is supplied by the capacitance C_b after an ESD is triggered. If the capacitance C_b is large, the plasma density around the substrate becomes large and then the conductivity of the cell gap is increased by the plasma. Therefore in the case of larger C_b, the cell current I_c increases and the discharge time becomes longer.

At last we discuss the influence of the cell gap distance on the discharge time. If the same voltage is applied to the cell gap, the electric field at the triple junction of the cell edge with the longer gap becomes lower and is more difficult to start ESD. Even though the ESD is started, the secondary arcing discharge is difficult to sustain for long time due to lower average electric field (V_a/d). Then the discharge time becomes shorter in the case of the longer cell gap.

From these results and discussions, the high voltage use of solar arrays is thought not to cause sustained arcing discharges to destroy the satellite system if arrays are designed to lower the maximum voltage between cell strings with an adequate distance.

5. Conclusion

In order to verify the possibility of the occurrence of the detrimental arcing discharge on the solar array where inverted potential gradient is formed, we carried out the electron-beam irradiation experiments using real GaAs solar cell samples as parameters of the cell gap distance and the voltage applied to the gap. Obtained results are as follows.

(1) We confirmed that the discharge time is not so long as to give damage to cell gap under the current experimental conditions.
(2) We confirmed that no detrimental arcing discharge did occur even at 120V in the cell gap of 1.0mm. So it is valid to design solar arrays to lower the maximum voltage between cell strings with an adequate distance.
(3) We confirmed that the insulation resistance of cell gap didn't change in the existing measurement even though the secondary arcing discharges occurred 200-300 times.

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