ELECTRON-BEAM-INDUCED ESD TRIGGERING DISCHARGE TESTS OF SOLAR ARRAYS FOR SPACE USE

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Abstract

This paper deals with the electron-beam irradiation experiments concerning the arcing discharge on the solar array. It is very important to investigate this discharge phenomenon and offer a guideline to design solar arrays with high reliability. We used a pair of real GaAs solar cells on a substrate as a sample. The sample was biased to -9kV and the electron beam of the energy of 10keV was irradiated to the sample. On that condition, the voltage from DC battery was applied to the gap between the cells. The detrimental arcing did not occur even at the gap voltage of about 80V, although a few hundreds of ESD took place.

Therefore, the high voltage use of solar array, for example 100V, 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 reasonable distance.

Introduction

Spacecraft charging problems appeared about 30 years ago [1]. After that, researches and developments for the spacecraft charging technology was conducted extensively [2, 3, 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 satellites was the main subject. However, in 1997 TEMPO-2 satellite was troubled on the geostationary orbit [5]. The electric power of the satellite was supplied in 100V. From the investigation of the accident, the possibility 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 satellites clear [7]. However, it seems that the mechanism and the condition to cause arcing discharge are not yet clear.

From these viewpoints, 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 satellites. As a first step of our investigation, a pair of real GaAs cells for space use was used as a sample. Inverted potential gradient as one condition causing discharges was formed on the sample by negatively biasing the sample and by irradiating electron beam to it. By measuring transient currents and observing discharge lights induced at the time of the occurrence of electrostatic discharge (ESD) we carried out the experiments.

This paper describes the experimental results and the discussion.

Experimental Procedure

Figure 1 shows the sample configuration of a pair of real GaAs cells. The size of a GaAs cell was 76x37mm^2. The cells with cover glasses were bonded onto the 1mm-thick 100x100mm^2 aluminum plate (substrate) covered with 0.025mm-thick Kapton film. The long sides of the cells were opposed each other with the gap distance of d (mm). The three sides of the cell except for the gap side were covered with silicone 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. And 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 to suppress the influence of the capacitance of DC power supply was applied between the cell's gap to simulate the potential difference between cell strings on solar array.

Two current monitors (Pearson 411 and 4100) 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 ground. 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, a capacitance C_a (=2x30.9nF) 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.

Experimental Results

We carried out the experiments according to the procedure described above under the several conditions as parameters of the cell's gap voltage V_a, the gap distance d between the cells, and the existence of the scratched part in the cell's gap.

We first describe the results on the influence of the cell's gap voltage V_a in the case of the gap distance d=0.8mm. Figure 3 (a) shows an example of the waveforms of the transient currents, I_c and I_s, observed in the case of a discharge occurred at V_a=77V. And Fig.3 (b) shows the photograph of the light emission during about 2 minutes including the instant of the discharge occurrence. I_c in Fig.3 (a) continues for 25 microseconds after being triggered by ESD. I_s started to increase after the ESD, and at about 7 microseconds 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 as seen in Fig.3 (b). Also, straight and weak light emissions seen in this photograph continued until the occurrence of the main discharge. Although the discharges like this occurred about 100 times, arcing discharge sustaining longer than 30 microseconds did not occur in this sample. Therefore there was no detrimental damage on the cell's gap.

Next, an example of the waveform of the cell current I_c and the photograph of the discharge light occurred on the sample of d=0.8mm and V_a=30V are shown in Fig.4. This is the 67th discharge shown in Fig.5. The waveform of I_c shows that it continued for about 18 microseconds. Weak light emission at the gap apart from the discharge point was also observed as shown in Fig.4 (a). Although the sustaining time of the cell current changed with each discharge, as a whole, it had a tendency to become long with the applied voltage V_a. From Fig.5 we can also see that the time-to-discharge gradually became long with the number of discharge.

As the possibility, that the existence of the scratched part of the insulating film in the cell gap might cause the sustained arc, has been pointed out, we next investigated the influence by scratching the Kapton film in the cell gap. Figure 6 shows the photograph of the scratched part. This sample was subjected to the experiment under the condition of d=0.8mm and V_a=30V. In this sample discharges occurred 190 times. Figure 7 shows a typical example of the waveforms of I_c and I_s and the photograph of the light emissions including the instant of a discharge. In this sample most of discharges occurred at the scratched part. The waveforms of the transient currents at the discharge were similar to those of the other samples without the scratched part as shown in Fig.3 (a) and 4 (a). That is, each waveform of the cell current has the two parts, the initial current triggered by ESD and the following secondary arc current. The peak of the secondary arc current is thought to be larger than the non-scratched samples.

We also carried out the experiment using the sample with the gap distance d=0.5mm at V_a=30V. In this case, discharges occurred about 300 times in the cell gap. Figure 8 shows a typical waveform of I_c and the photograph of the discharge light. The value of the plateau of the secondary arc current is thought to be similar to the other cases. No weak light emission before the discharge was, however, observed as shown in Fig.8 (b).

We measured the resistance of the cell gap on the sample after each experiment in the vacuum chamber. The resistances in all samples were beyond 10Mohm.

Discussions

From the waveforms of I_c and I_s we speculate the discharge mechanism on solar array where the inverted potential gradient is formed.

Figure 9 shows the potential distribution in the neighborhood of the cell gap. In this calculation, we assume that the surface potential of about +800V on the cover glass against the substrate [8] 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 expands 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 where the equi-potential lines concentrate. 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 cell sample. By the diffusing plasma the current through the sample substrate, substrate current I_s, increases gradually after the ESD. This transient current is supplied from the capacitance C_a 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 the capacitor are almost lost 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 to sustain as secondary arc until the plasma declines to the chamber wall. The plasma density generated near the cell gap and the voltage V_a below about 80V are not enough to drive the secondary arc to sustained arc.

By the way, as seen in the photographs of the discharge light, Fig.3 (b), 4 (b) and 7 (b), straight and weak light emissions continuing for a few minutes on the cover glass were observed before the instant of discharge. The light is assumed to be cathode-luminescence due to the impact of electrons emitted from the cell gap. This weak light emission could not be always seen from the early stage of the experiment. We could see such lights after the discharges occurred frequently. Figure 10 shows the examples of the charts recording the pressures in the chamber during the experiments. Figure 10 (a) is the pressure change near the time of the discharge shown in Fig.4. In this Fig.10 (a) the pressure gradually increased before the discharge. This shows that the gas was released by the continuous impact of electrons. Therefore the cathode-luminescent light is seemed to be due to the impact of electrons emitted from some emission site generated by frequent discharges. Because the discharge at the comparatively early stage was not accompanied with pre-discharge light as shown in Fig.8 (b), the gradual increase of the pressure was not recorded as seen in Fig.10 (b). These emitted low-energy electrons move along the line of the electric force generated by the potential distribution near the cell gap shown in Fig.9.

At last we discuss the influence of the damaged Kapton film between the cell gap. We gave the Kapton film damage by scratching as shown in Fig.6. In the sample, discharges were occurred well at the cell gap near the scratched part. However, sustained arc did not occur similarly to the samples with the insulatingly sound cell gaps. Therefore it is thought that the secondary arc mainly flowed over the cell gap. The value of the plateau of the secondary arc in the scratched sample was about twice larger than that in the non-scratched samples as shown Fig.7. It is the reason why the cell current I_c is enhanced by the electron emission from the substrate through the scratched part.

Although the possibility of occurrence of the detrimental arcing discharges, sustained arcs, cannot be completely denied, it is thought to be very small from our experimental results.

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 model experiment using real GaAs solar cell samples by means of electron-beam irradiation. Obtained experimental results are as follows.

(1) In the cases of the cell gap distances of 0.5mm and 0.8mm, the voltage of the gap below 80V did not cause sustained arcing discharge, although the ESD-induced secondary arcs occurred a few hundreds times at the cell gap.
(2) The sustained arc did not occur even though there was scratched part in the Kapton film at the cell gap.

In the present study, the experimental parameters were not so many. So, we will continue the experiments by changing parameters such as the capacitances or the cell gap.

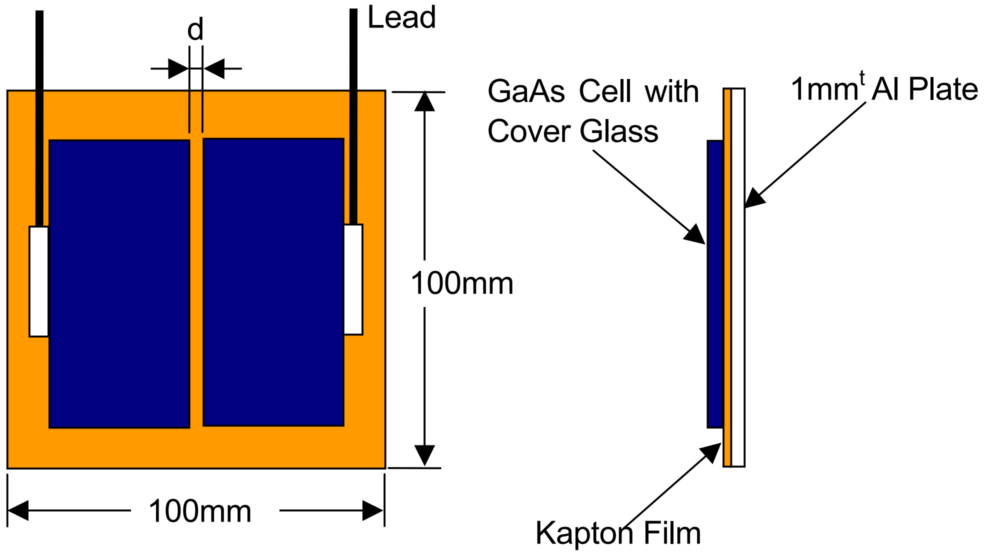


Figure 1. Sample configuration

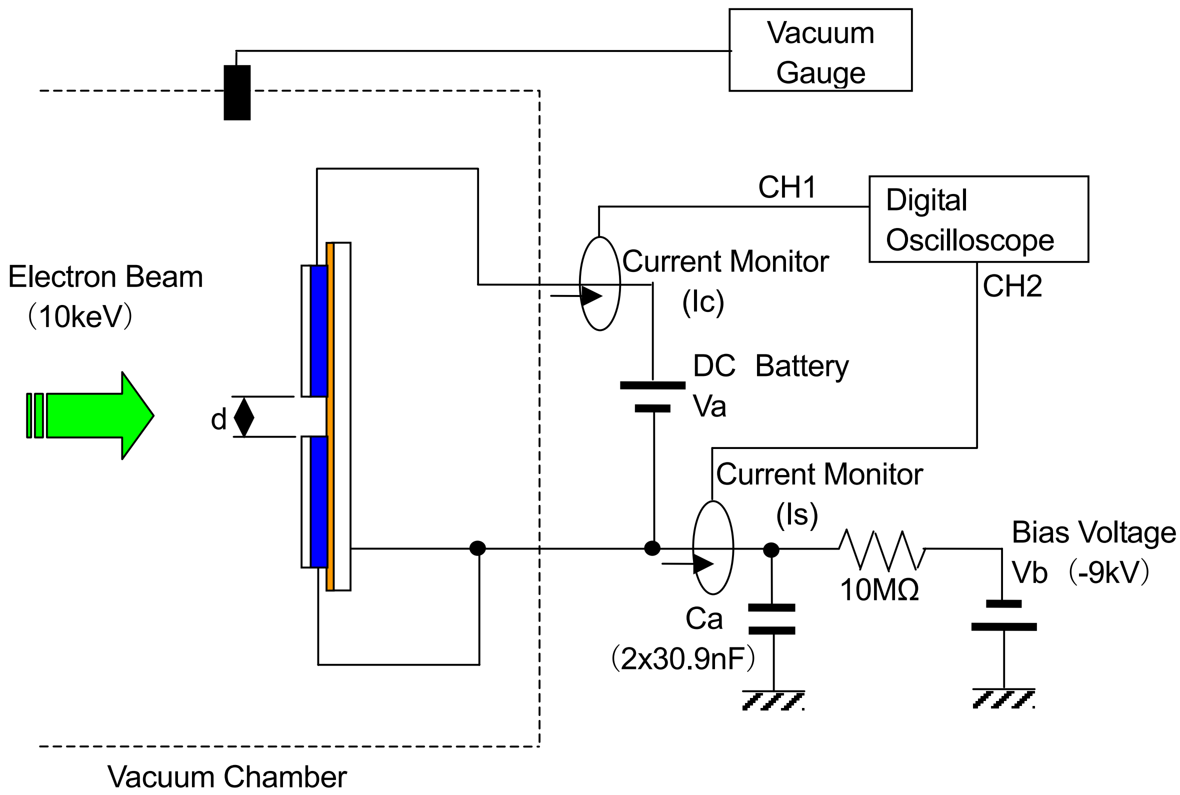
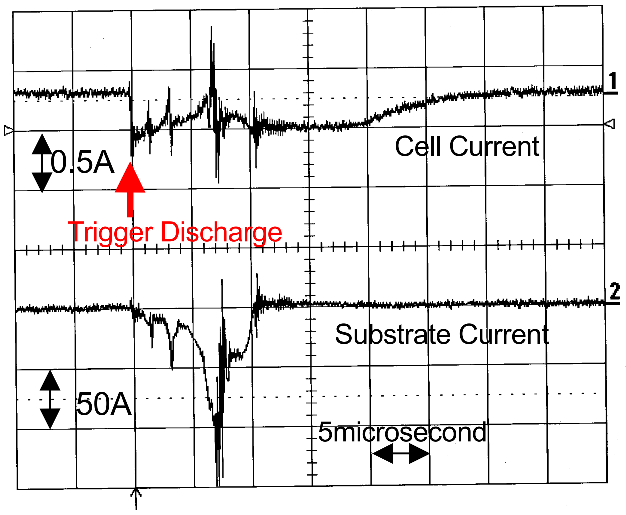
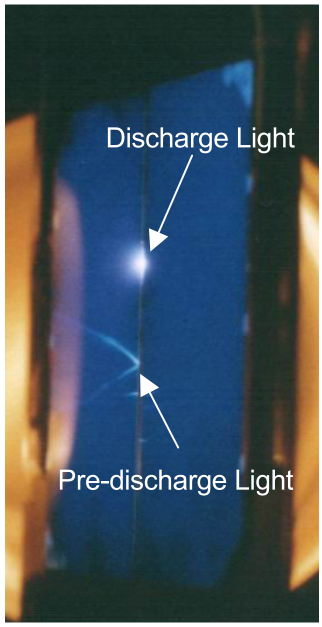


Figure 2. Experimental setup

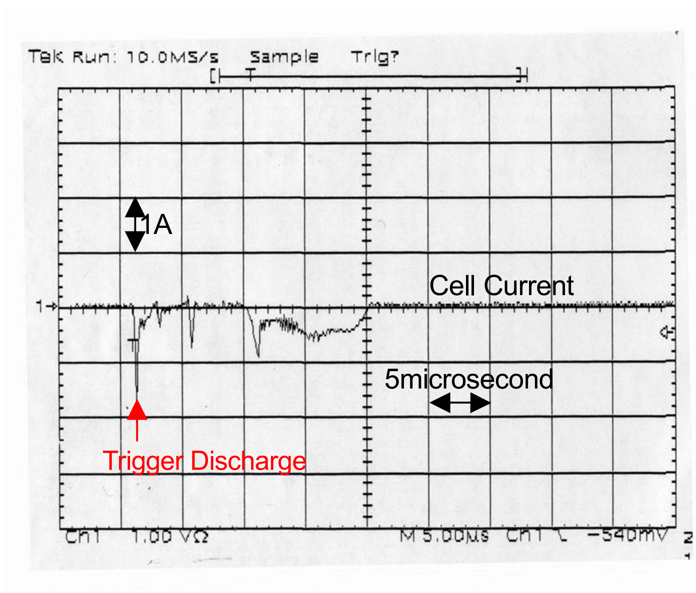


(a) Waveforms of transient currents

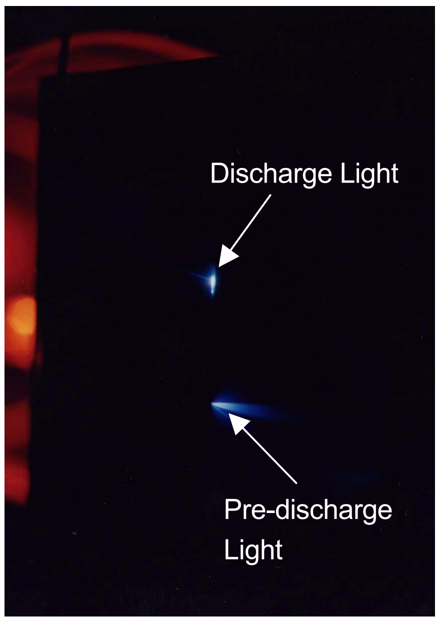


(b) Photograph of light

Figure 3. Example of the waveforms of transient currents and the discharge light in the case of d=0.8mm and V_a=77V.



(a) Waveform of transient current



(b) Photograph of light

Figure 4. Example of the waveform of transient current and the discharge light in the case of d=0.8mm and V_a=30V.

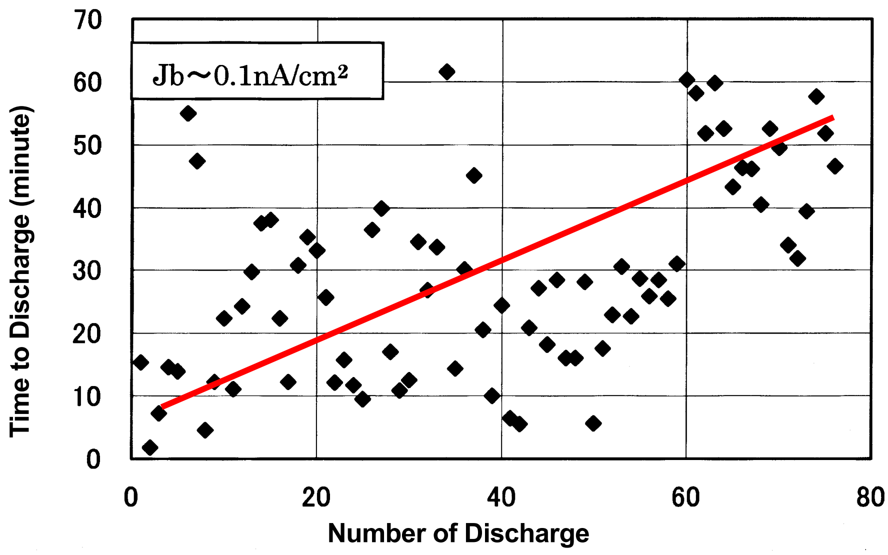


Figure 5. **Dependence of the time-to-discharge on the number of discharge in the case of d=0.8mm and V_a=30V.**

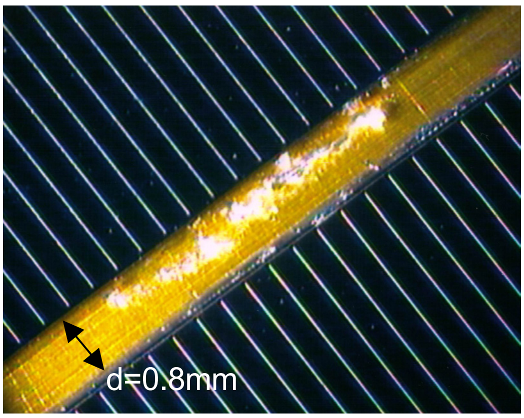
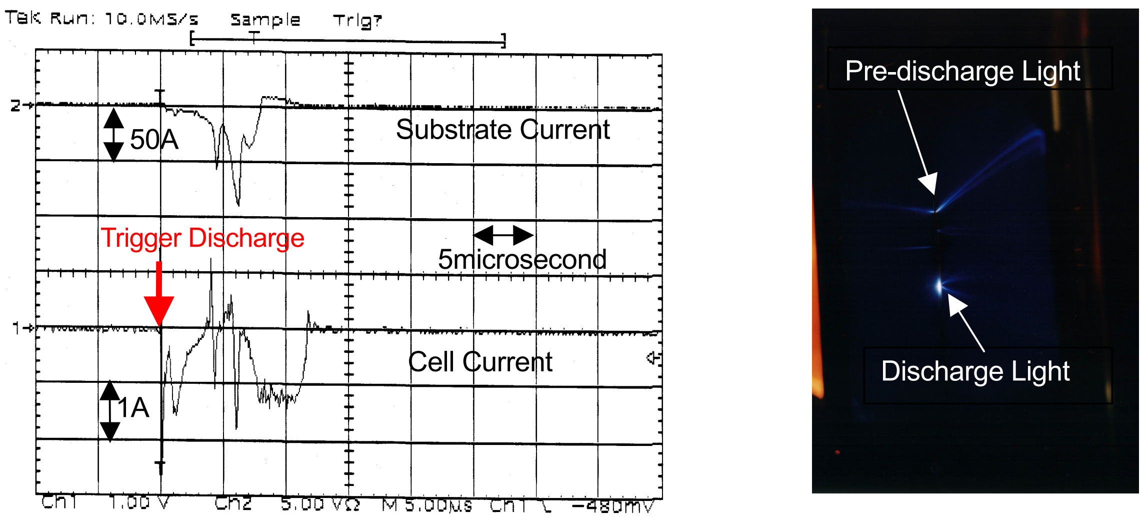
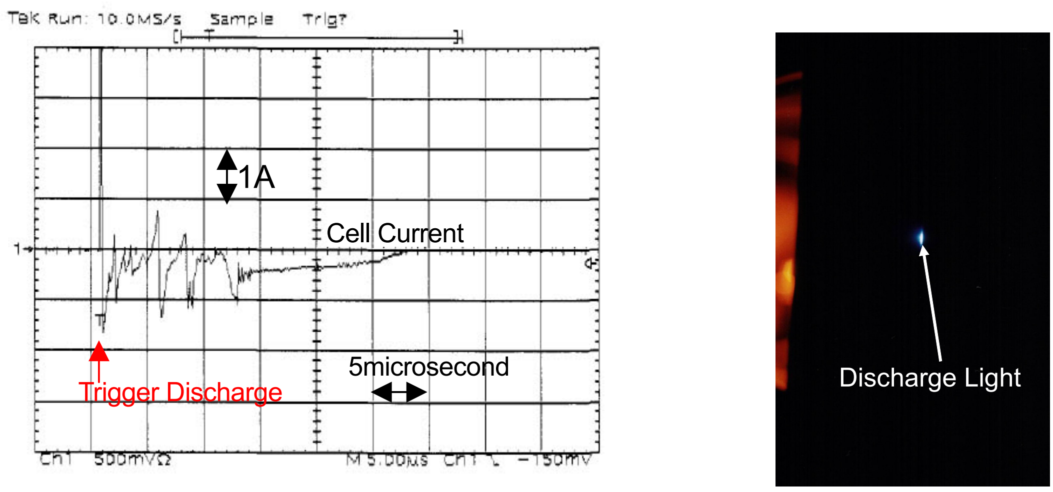


Figure 6. **Photograph of scratched part of the cell gap.**



(a) Waveforms of transient currents (b) Photograph of discharge light

Figure 7. **Example of the waveforms of transient currents and the discharge light of the scratched sample at d=0.8mm and V_a=30V.**



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

Figure 8. Example of the waveform of the cell current and the discharge light in the case of d=0.5mm and Va=30V

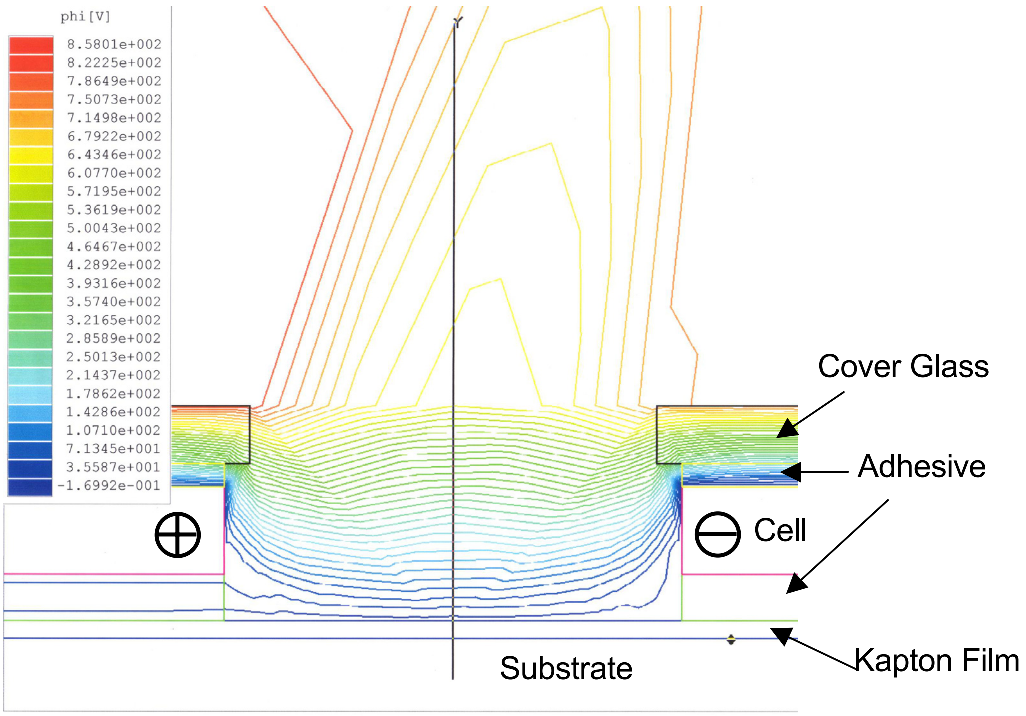
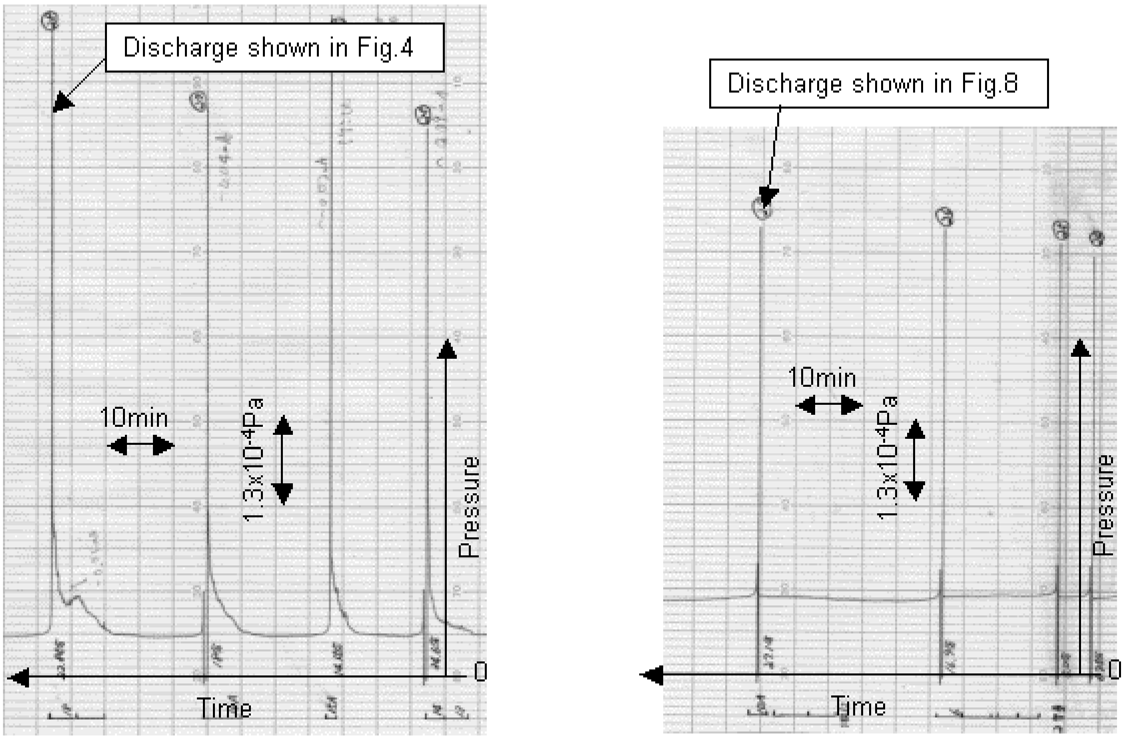


Figure 9. Potential distribution near the cell gap.



(a) d=0.8mm, V_a=30V

(b) d=0.5mm, V_a=30V

Figure 10. Example of the pressure change during experiment

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