RESEARCH ACTIVITY IN MITSUBISHI ELECTRIC ON SPACECRAFT CHARGING

Haruhisa Fujii and Alexander Palov*
Mitsubishi Electric Corporation, Advanced Technology R&D Center
8-1-1, Tsukaguchi-Honmachi, Amagasaki, Hyogo, 661-8661 JAPAN
TEL: +81-6-6497-7127, FAX: +81-6-6497-7288, E-mail: fujii@ele.crl.melco.co.jp
(* Present: University of Bristol, The School of Chemistry)

Toshio Abe
Mitsubishi Electric Corporation, Kamakura Works
325, Kami-Machiya, Kamakura, Kanagawa, 247-8520 JAPAN

Abstract

We started about fifteen years ago and continue until now the research on spacecraft charging from the viewpoint of improvement of reliability and mission lifetime of satellite in space environment. The followings are involved in the activity:

(1) Experimental investigation on the charging and discharge characteristics of satellite surface materials by electron-beam irradiation simulating hot plasma in space.
(2) Analytical simulation of electron-beam induced charge-up phenomenon of insulating materials.
(3) Development of the on-board surface potential monitor and measurement of the surface potentials of insulating materials in space environment.
(4) Development of the mitigation technology of spacecraft charging.
(5) Experimental investigation on the interactions of satellites with plasma simulating low Earth orbit environment.

1. INTRODUCTION

Many satellites such as communication satellites, broadcasting satellites and meteorological satellites are in Earth orbits. These satellites have the duties to work normally in a tenuous charged particle environment. However, the charged-particle environment happens to endanger to the performance of the spacecraft systems under certain conditions profoundly. Especially, low-energy plasma in the charged-particle environment causes "spacecraft charging" and is probable to induce ESD (electrostatic discharge) on the satellite. The ESD causes malfunctions or anomalies of the on-board electronics and/or the electric power systems, or degradation of the surface materials [1-3]. These influences must be minimized to achieve high reliability and long mission lifetime of the spacecraft systems.

Our company, Mitsubishi Electric Corporation, has started the research activity from the middle of 1980's in recognizing the importance of development of mitigation technology as the leading company for spacecraft manufacturing in Japan in cooperation with NASDA and so on.

The research on spacecraft charging has been carried out widely as follows:

(1) Experimental investigation on the charging and discharge characteristics of satellite surface materials by electron-beam irradiation simulating hot plasma in space.
(2) Analytical simulation of electron-beam induced charge-up phenomenon of insulating materials.
(3) Development of the on-board surface potential monitor and measurement of the surface potentials of insulating materials in space environment.
(4) Development of the mitigation technology of spacecraft charging.
(5) Experimental investigation on the interactions of satellites with plasma simulating low Earth orbit environment.

In this paper, we will review the outlines of our research.

2. EXPERIMENTAL INVESTIGATION ON SURFACE CHARGING DUE TO ELECTRON-BEAM IRRADIATION

Among the charged particles in space, electrons have large influence on the charging of spacecraft. Electron-beam irradiation method has been used to study the charging and discharge phenomena of the satellite's dielectric materials, especially under the simulated conditions of geomagnetic substorm [4]. The method has been useful for understanding the processes of differential charging phenomenon.

Satellite surface materials such as thermal control materials were irradiated with mono-energetic electron beam in the vacuum chamber evacuated to the pressure of $1x10^{-6}$ Torr. The electron beam was controlled at the ranges of the energy (E) between 15keV and 45keV and the current density (J_b) between 0.1nA/cm^2 and 16nA/cm^2. The electron-bombarded area of each sample was 19.6cm^2 (50mm in diameter).

By irradiating electron-beam, the currents flow through the sample (bulk current) and along the surface of the sample (surface current). The bulk current was measured by an electrometer (Advantest TR-84M) and the surface current was conducted to the grounded sample holder. The surface potential (V_s) of the sample was measured by a non-contact electrostatic voltmeter with an electrostatic probe (TREK 340HV and 5031S) [4-6].

Figure 1 shows the electron-beam current density dependences of surface potential of 25 μm thick Teflon FEP (fluorinated ethylene propylene co-polymer) film as a parameter of electron energy. In this experiment, the irradiation time (T_i) was 60min. In the case that discharge occurred during T_i, the surface potential at that time was plotted as black symbol. The surface potential is proportional to the beam current density in case of J_b lower than 0.1nA/cm^2. On the other hand, in case of J_b larger than 0.1nAcm^2, the surface potential gradually increases and saturates with J_b in E=15keV. In electron irradiation with energy larger than 15keV, it was controlled by discharge on the surface. Other surface materials show the different V_s – J_b characteristics. As one example, the characteristic of Kapton (polyimide) is shown in Fig.2. The slope of V_s to J_b is about 0.5 and surface discharge was not observed during T_i. Figure 3(a) shows the electron energy dependence of Vs in cases of Teflon and Mylar PET (polyethyleneterephthalate) and Fig.3(b) shows those in cases of Kapton films with different thickness. From Fig.3, the followings are obtained:

(1) Surface potential depends on electron energy.
(2) In low-energy region, surface potential increases with increase of electron energy. By contraries, in case of high-energy region, the surface potential decreases with electron energy. That is, the surface potential has the peak at some electron energy.
(3) The peak of the surface potential and its electron energy increase with the thickness of the film.
(4) Under the same condition, the order of three materials in surface potential is FEP>PET>PI.

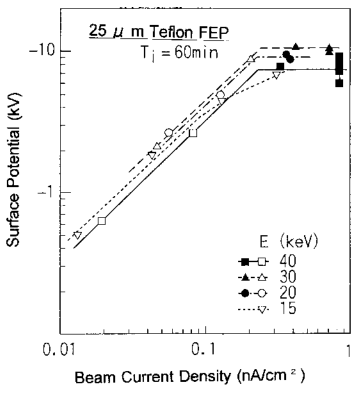


Fig.1 Beam current density dependence of surface potential on 25 μm Teflon. (●, ▲, ■: occurrence of discharge)

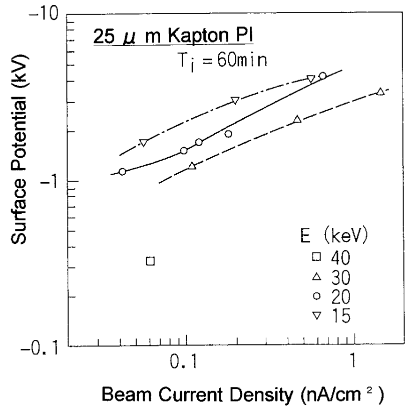
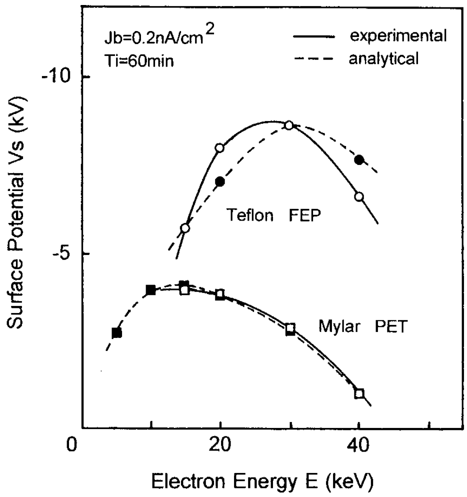
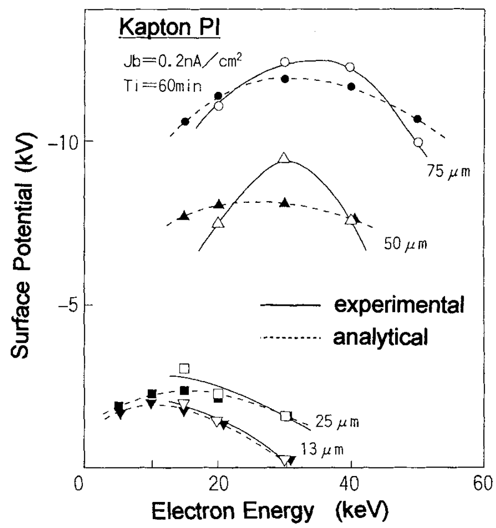


Fig.2 Beam current density dependence of surface potential on 25 μm Kapton.



(a) Teflon and Mylar



(b) Kapton

Fig.3 Electron energy dependences of surface potential.

3. ANALYTICAL SIMULATION OF ELECTRON-BEAM INDUCED CHARGE-UP

In order to analyze the charge-up characteristics of insulating films due to electron-beam irradiation, we used two-dimensional and axis-symmetric model shown in Fig.4. Flow chart is also shown in Fig.5. The analytical results are shown in Fig.3 in the broken lines.

Also we conducted the simulation of charge-up dynamics in Teflon film during electron-beam irradiation by Monte Carlo method [7]. The physical model of the ~1eV – 35keV electron scattering in that film has been used to calculate the average charge distribution inside Teflon films. The electric field and potential as a function of the injection time have been calculated from Poisson's equations. Figure 6 shows the distribution of electric charge inside Teflon film irradiated with 20keV electrons.

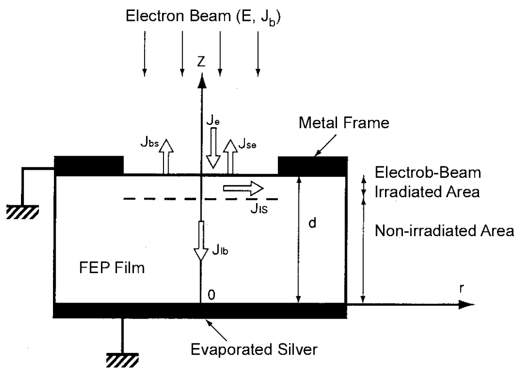


Fig.4 A two-dimensional model of electron-beam induced charging.

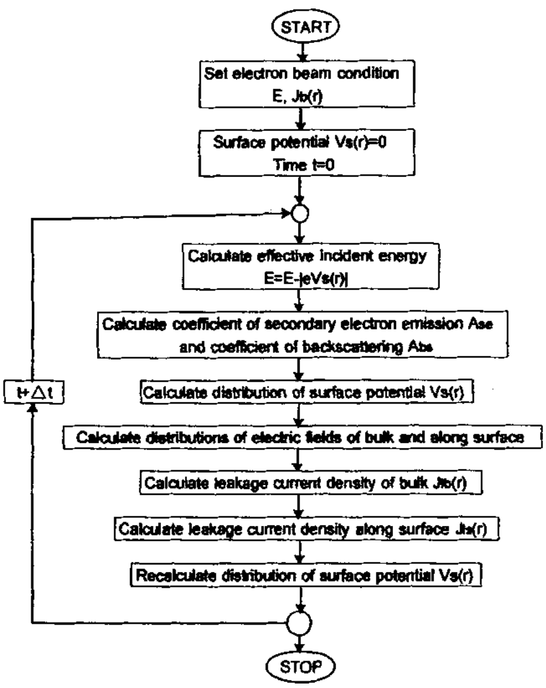


Fig.5 Flow chart of charging simulation.

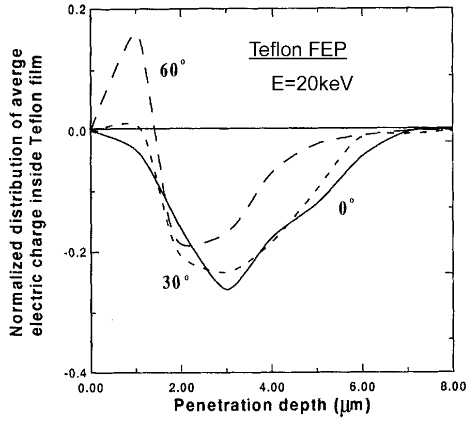


Fig.6 Distribution of electric charge inside Teflon film irradiated with 20keV electron.

4. MEASUREMENT OF ELECTROSTATIC CHARGING IN SPACE

We developed a potential monitor to measure the surface charging potential on the insulating material due to charged particles in space. The monitor was first installed on 3-axis-stabilized Engineering Test Satellite V (ETS-V) [8].

The block diagram of the monitor is shown in Fig.7. The monitor consists of sensing part (POM-S) and electronic circuits (POM-E). An electrostatic probe (Monroe 1017S) is used in a sensing part. A sample is set on the probe housing shown in Fig.7. The sample with metallized backing is pasted on the board with conductive adhesive. The electric field between the charged surface and the probe head is measured through the hole of a diameter of 1mm set in the board. The output voltage of the monitor is recorded as voltage. The relation between the output voltage and the surface potential is calibrated.

Figure 8 shows the profile of charging potential of the silvered Teflon on October 28, 1987 as one example of the data obtained on ETS-V. The negative increase of the surface potential was observed from 14UT (Universal Time) to 20UT. As the potential monitor was located on the south mission panel, the potential monitor was casted by sunlight on October 28. In spite of the sunlit condition that we can expect photo-electron emission from the surface, the negative increase of the surface potential was observed. This phenomenon is accounted for by taking into consideration the shadows caused due to the L-band antenna reflector and/or the solar array paddle.

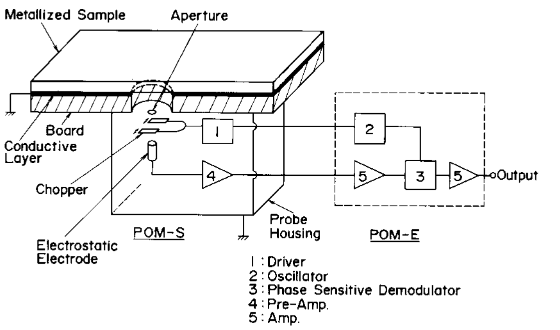


Fig.7 Block diagram of surface potential monitor.

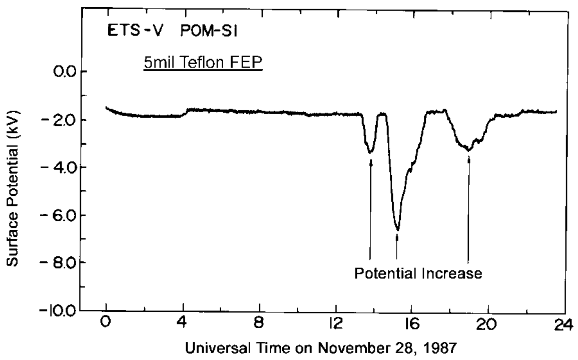


Fig. 8 One surface potential profile observed on ETS-V.

5. MITIGATION TECHNOLOGY OF SPACECRAFT CHARGING

From the results of the ground simulation experiments and the space experiments, we recognized the necessity of suppressing differential charging on a satellite to achieve high reliability and long lifetime for future spacecraft.

For this purpose, we have studied two methods to suppress surface charging on insulating materials for spacecraft.

One method is coating a conductive layer on insulating material. We confirmed that using ITO (Indium Tin oxide) as a conductive layer is effective on suppression of surface charging by means of electron-beam irradiation [4].

Another method is plasma ejection from satellite [9]. Figure 9 shows the schematic diagram of the experimental setup. In the experiment, a large space chamber of our Kamakura Works was used. The size is about 4m in diameter and about 9m in length. The cubic ($40x40x40cm^3$) metal case as a model of satellite body was equipped with an electron gun in the chamber. A neutralizer for ion thruster and the potential monitor as mentioned above were perpendicularly set on the two sides of the metal case. The neutralizer was a hollow-cathode type plasma source that was used to maintain the potential of satellite even during the operation of the ion thruster. A Kapton film with 5mil thickness was set on the potential monitor as the test sample. The length between the neutralizer and the Kapton film was about 50cm. The distance between the gun and the Kapton film was about 70cm. Electron beam was irradiated to the Kapton film at the pressure of $3x10^{-6}$Torr.

Figure 10 shows a typical example that the neutralizer eliminated the charges deposited on the Kapton film. In the beginning of the experiment, the Kapton film was irradiated with 3keV electron beam and the surface potential reached to –2kV. After the removal of irradiation, Xe gas was introduced to the neutralizer at the flow rate of 2.4sccm. The pressure in the chamber became about $5x10^{-5}$Torr. Then the neutralizer was operated and Xe plasma was generated from the neutralizer at 14.5min. The surface potential on the Kapton film became 0V without the occurrence of discharge on the sample. From the test, the neutralizer is considered to be one of the promising ways to eliminate surface charging on insulating materials.

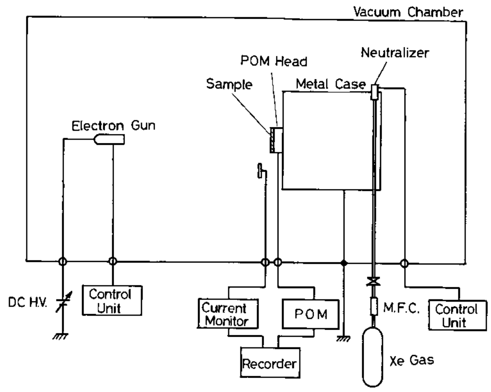


Fig.9 Experimental setup for mitigation of surface charging.

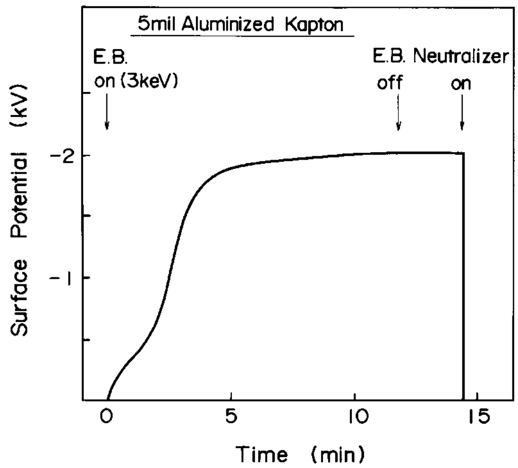


Fig.10 Elimination of surface charging of Kapton film due to plasma ejection.

6. EXPERIMENTAL INVESTIGATION ON LEO PLASMA INTERACTIONS

The power capability needed for space systems is increasing as big space programs such as space station, space platforms, space factories and solar power satellites are envisioned in low Earth orbit (LEO). The operating voltages higher than used to date (lower than 100V) are under consideration from the viewpoints of minimizing the weight of wire-harnesses and the electric power losses. It will also become necessary to supply higher voltages to high-voltage payloads such as microwave generators and electric propulsion system directly. However, power supply from high-voltage solar array arises the following problems originating from the interactions between the solar array and space plasma:

(1) Current leakage through the surrounding space plasma

(2) Arcing discharge.

These problems are serious, particularly in LEO, the altitudes around 400km where the plasma density is much higher than in GEO. These are important technical items to be overcome for the constructions of high-power space systems in the future.

From these viewpoints, we carried out the experiments of plasma interaction with coupon panels of solar array in the large space chamber [10]. Figure 11 shows the schematic diagram of the experimental setup. The plasma source was capable of generating plasma of densities from 10^4-10^6cm^{-3} by controlling the discharge current and the gas flow rate. This plasma source utilized Ar gas. The coupon panels consisted of twenty-five GaAs solar cells were used as samples. DC potential up to ±1000V was applied stepwise to the coupons. Figure 12(a) and (b) show the plasma-coupling currents as a function of DC potential for positive and negative polarities, respectively. The plasma density and plasma temperature measured with Langmuir probes were n_e=1x10^{5}cm^{-3} and kT_e=1.1eV. From these results, the followings are obtained:

(1) In positive bias to the test sample, the plasma coupling current increases with DC potential and at the bias larger than 100V it abruptly increased, that is "snapover".

(2) In negative bias, the discharge occurred at about –200V.

Therefore, it is important to prevent the occurrence of discharge in case of negative bias to space plasma and we proposed improved solar array structure as shown in Fig.13.

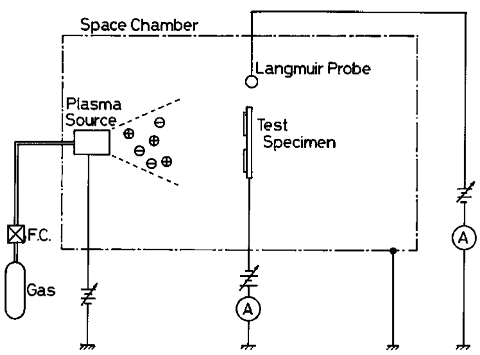
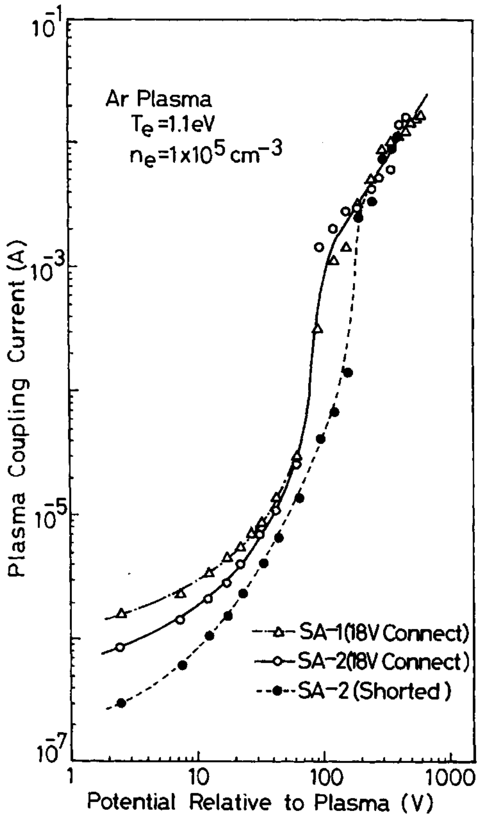
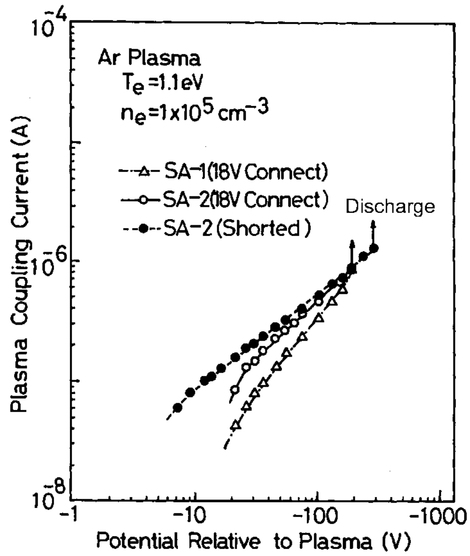


Fig.11 Experimental setup for LEO plasma interaction.



(a) Positive bias



(b) Negative bias

Fig.12 Plasma coupling current as function of DC potential.

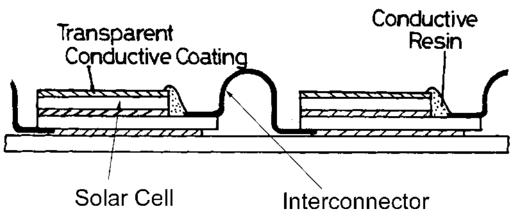


Fig.13 A proposed solar array structure.

Also it is considered that high-voltage systems are in the high-vacuum region in the wake of large spacecraft in LEO. However, in the wake low-energy electrons only inject from space plasma. Then we investigated the effect of low-energy electrons on high-voltage insulation [11]. Figure 14 shows the DC surface flashover voltage as a function of insulation distance. This figure shows that low-energy electron irradiation to the insulator surface lowers the flashover voltage. Then it is necessary to provide countermeasures to the surface flashover even in the wake space.

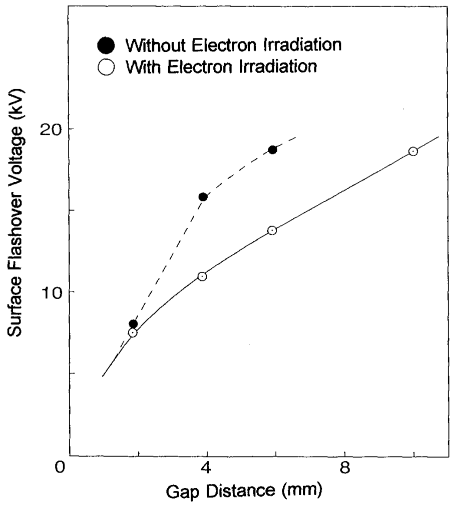


Fig.13 Gap distance dependence of surface flashover voltage.

7. SUMMARY

We have carried out the research related to "spacecraft charging" for about fifteen years. The achievement of the research has been applied to satellite manufacturing. We will also continue the research activity on spacecraft charging in order to contribute to high reliability and long mission lifetime of future spacecraft systems.

REFERENCES

[1] H. B. Garrett; Rev. Geophys. Space Phys., vol.19 (1981) p.577
[2] C. R. Francis; J. Electrostatics, vol.11 (1982) p.265
[3] R. J. L. Grard, K. Knott & A. Pedersen; Space Science Rev., vol.34 (1983) p.289
[4] H. Fujii, Y. Shibuya, T. Abe, R. Kasai & H. Nishimoto; J. Spacecrafts & Rockets, vol.25 (1988) p.156
[5] S. Hiro & H. Fujii; Trans. IEE of Japan, vol.117-A (1997) p.805 (in Japanese)
[6] S. Hiro, K. Tsuji & H. Fujii; Electrical Engineering in Japan, vol.129 (1999) p.10
[7] A. Palov, H. Fujii & S. Hiro; Jpn. J. Appl. Phys., vol.38 (1999) p.6777
[8] H.Nishimoto, H. Fujii & T. Abe; Proc. Spacecraft Charging Technology Conference, (1989) p.98
[9] H. Fujii, K. Nakanishi, T. Abe, T. Ohmura & H. Nishinoto; Proc. 16th Int. Symp. Space Technology and Science, (1988) p.1613
[10] H. Fujii, Y. Shibuya, T. Abe, K. Ijichi, R. Kasai & K. Kuriki; 15th Int. Symp. Space Technology and Science, (1988) p.825
[11] H. Fujii & S. Hiro; Proc. XVIIIth Int. Symp. Discharges and Electrical Insulation in Vacuum, (1998) p.808