Evaluation of electron-emitting film for spacecraft charging mitigation (ELFs charm)

著者	Tanaka Atomu, Mateo Velez Jean-Charles, Dadouch Sarah, Okumura Teppei, Sakamoto Kenji, Iwata Minoru, Toyoda Kazuhiro, Cho Mengu
year	2017-06
URL	http://hdl.handle.net/10228/00007882

Evaluation of electron-emitting film for spacecraft charging mitigation (ELFs charm)

By Atomu Tanaka,[1)] Jean-Charles Mateo Velez,[2)] Sarah Dadouch,[2)] Teppei Okumura,[3)]
Kenji Sakamoto,[1)] Minoru Iwata,[1)] Kazuhiro Toyoda[1)] and Mengu Cho[1)]

[1)]*Kyushu Institute of Technology (Kyutech), Kitakyushu, Japan*
[2)]*Office National d'Etudes et de Recherches Aérospatiales (ONERA), Toulouse, France*
[3)]*Japan Aerospace Exploration Agency (JAXA), Japan*

To protect the satellite from the accidents due to spacecraft charging, Kyushu Institute of Technology (Kyutech) is developing a device called ELFs-Charm, which stands for ELectron-emitting Film for Spacecraft CHARging Mitigation. ELFs-Charm was mounted on HORYU-II, which was launched to a Polar Earth Orbit in May 2012. From the orbital data, the emitter's soundness and working principles were confirmed. As a next step, we are considering the practical operation for mitigation of spacecraft charging. The present emission level was not enough to increase the satellite potential. Theoretically, if the emitter can emit more electrons than the incoming electrons, it can increase the satellite potential during the sub-storm. We focus our efforts on improving two parameters. One is the potential difference of the emitter surface. Another one is the threshold voltage of electron emission. A potential difference of the emitter surface depends on the insulator charging capacity due to the secondary electron emissions with each energy gap between the satellite potential and the primary electron energy. The threshold voltage depends on the shape of emitter. We can improve the ELFs-charm emission performance by measurement of these two parameters in ONERA Space Environment vacuum chamber and Kyutech Space Environment chamber. In this paper, we describe the two parameters of several samples and how the performance was improved.

Key Word: ELF, spacecraft charging, ESD, mitigation technology

Nomenclature

V	:	voltage
σ	:	secondary electrons yield
E	:	energy
E_f	:	Fermi level
Φ_S	:	Satellite potential

1. Research purpose and background

Spacecraft usually uses solar arrays as electric power source and once in orbit the spacecraft cannot be repaired. Thus, once a failure occurs affecting solar arrays, a spacecraft available power can be degraded or, in some cases, the spacecraft can be totally lost. One of the dangerous and common phenomenon leading to solar arrays failure are electro-static discharges. In this research, the authors aim at proposing a method to mitigate discharge accidents on the surface of a spacecraft including its solar arrays.

In space, spacecraft are flying in plasma and their potential is hence determined by inflow and outflow currents to or from the spacecraft (see Fig. 1). To ensure equilibrium, the amount of inflow currents to the spacecraft should be equal to the amount of outflow currents from the spacecraft. As a result, the spacecraft obtains a certain potential.

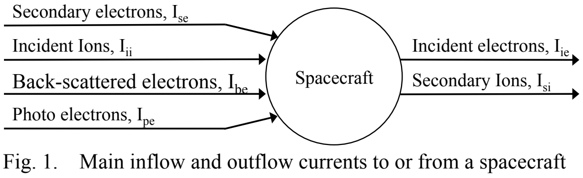

Fig. 1. Main inflow and outflow currents to or from a spacecraft

$$I_{se}(\phi_s) + I_{ii}(\phi_s) + I_{be}(\phi_s) + I_{pe}(\phi_s) = I_{ie}(\phi_s) + I_{si}(\phi_s) \tag{1}$$

The Earth and surrounding outer space are exposed to the flow of plasma particles also known as solar winds. Plasma particles from solar winds are driven by the electromagnetic field to the backside of the Earth in the opposite direction of the sun. The magnetospheric tail behind the Earth is thus a special area where high-energy electrons are injected from the plasma sheet onto the geosynchronous orbit. This leads to charging of geosynchronous spacecraft. This phenomenon is referred to as sub-storm, one of the factors that cause spacecraft charging. During a sub-storm, the amount of incident electrons increases and becomes the dominant inflow current. Then the spacecraft's potential becomes negative at a level of a few kilovolts. The state of a spacecraft during a sub-storm is shown in Fig. 2.

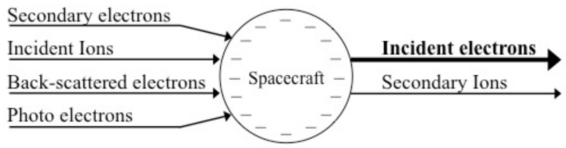

Fig. 2. Main inflow and outflow currents to or from a spacecraft during a sub-storm with "-" indicating the spacecraft's negative potential

In Fig. 2, the spacecraft is assumed to be uniformly charged. But in reality, spacecraft are made of conductive and insulating parts. Due to the presence of these different types of materials, there is a potential difference between the spacecraft ground point and the insulator on the spacecraft surface during a sub-storm, i.e. when the incident electrons current is the dominant inflow current. When this potential difference becomes too large, electro-static discharges can occur.

In chapter 2, the principle of electro-static discharges generation on solar array is explained and in chapter 3, the method to prevent electro-static discharges generation is detailed.

2. Principle of discharge on solar array

In this chapter, the principle of electro-static discharges generation on a spacecraft's solar array is described.

Solar cells are fixed to the spacecraft structure with an adhesive and cover glass (SiO_2) is attached onto the upper surface of solar cells to protect them from high-energy particles. In addition, solar cells on an array are connected by an electrode (see Fig. 3).

During a sub-storm, high energy electrons bombard the spacecraft and due to the inflow of this high energy electrons, the spacecraft's body becomes negatively charged up to a few kilovolts. As the spacecraft potential decreases, the energy difference between the high energy electrons and the spacecraft's body becomes smaller. This results in charges being accumulated onto the spacecraft's surface. This charging process during a sub-storm is presented in Fig. 4. As the spacecraft potential becomes bigger, secondary electrons are emitted from the spacecraft surface.

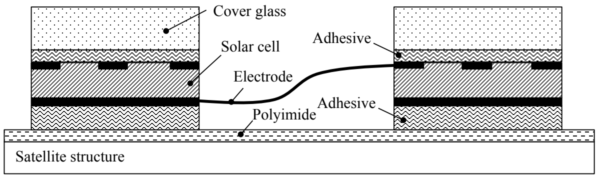

Fig. 3. Solar array structure

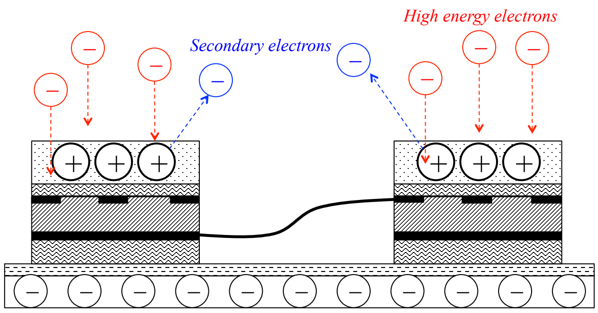

Fig. 4. Spacecraft charging due to secondary electrons emission

Due to the emission of secondary electrons, the cover glass on solar cell is charged positively compared to the satellite structure. This is called "inverted potential gradient". As more secondary electrons are emitted, the potential difference between the spacecraft ground and solar cells' cover-glass increases. Due to this potential difference, an electric field is formed on the solar cell, and sometimes electrostatic discharge (ESD) occurs. The ESD onset is greatly affected by the surrounding environment such as desorption gas and the microscopic conditions of the local surface area such as field enhancement factor. (see reference 1,2 and 3)

3. Electron-emitting film for spacecraft charging mitigation (ELFs-charm)

The purpose of this research is to propose a method for the mitigation of electro-static discharges that occur on solar array as it was described in chapter 2.

The mitigation technique proposed is called electron-emitting film (ELFs-charm) and its structure is shown in Fig. 5.

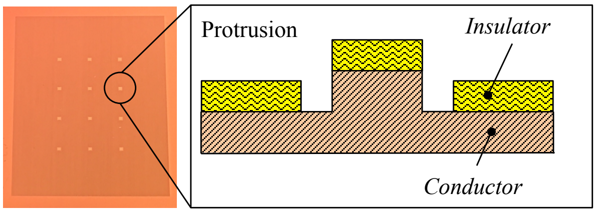

Fig. 5. Electron-emitting Film (ELFs-charm)

ELFs-charm is composed of a conductive base material as well as an insulator cover material and its charging process is the same as charging process described for solar arrays. At the time of high-energy electrons inflow, ELFs-charm is charged due to the difference in secondary electrons emission rate between the conductor part and the insulating part. This results in the generation of electric field at the interface between conductive and insulating part. Thus, electrons can be emitted through field emission process from ELFs-charm top side's triple junction points, which are points where insulator, conductor, and outer space cross each other. From this process, ELFs-charm can, hence, passively emit electrons. Potential diagram at a triple junction during field emission is presented in Fig. 6.

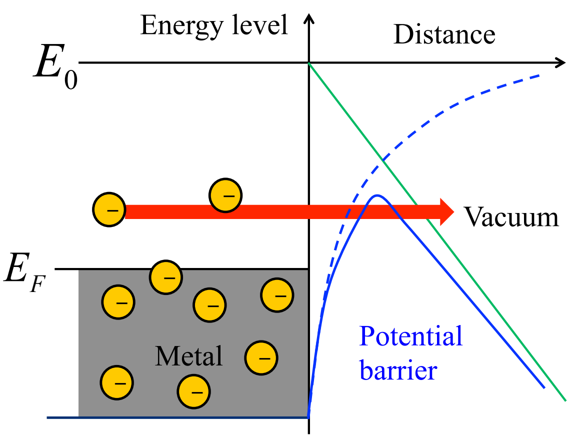

Fig. 6. Potential diagram at a triple junction during field emission with E_0 is vacuum potential level and E_f is Fermi level.

In Fig. 7, the potential evolution of a spacecraft and solar cell's cover glass with and without ELFs-charm is presented. When ELFs-charm is not operating, the spacecraft potential becomes negative to a level of several kilovolts. Thus, the potential of the cover glass floats from the spacecraft potential due to different secondary electrons emission coefficient and the spacecraft many suffer discharge. However, by using ELFs-charm, electrons in excess are emitted from the spacecraft's surface and the spacecraft potential rises. Then, as the spacecraft potential rises, the potential of the cover glass rises and eventually the spacecraft potential exceeds the potential of the cover glass. This state is called "normal potential gradient". During this state, it is considered that electro-static discharges do not occur because the potential threshold value for discharge to occur is about several kilovolts for forward potential gradient, whereas the threshold is only about 400V for inverted potential gradient. (see reference 11) Through this process, ELFs-charm is therefore capable to mitigate electro-static discharges on solar arrays and spacecraft.

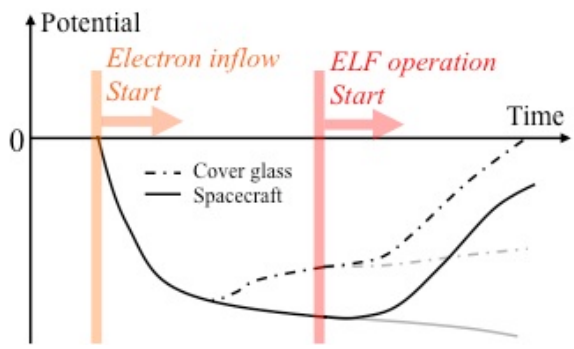

Fig. 7. Representation of spacecraft potential transition and spacecraft surface potential evolution with and without electrons emission.

4. Samples

ELFs-charm is being developed at Kyushu Institute of Technology. So far, 16 different types of samples have been manufactured and tested. In the following sub-sections, ELFs-charm samples used in this study are described.

4.1. ELFs-charm fifth generation

The 5th generation of ELFs-charm consists of samples where an etching process was performed on the copper base plate to design a part favorable to electric field concentration. Polyimide was printed on top of the copper base plate. The appearance and structure of the 5th generation of ELFs-charm are presented in Fig. 8.

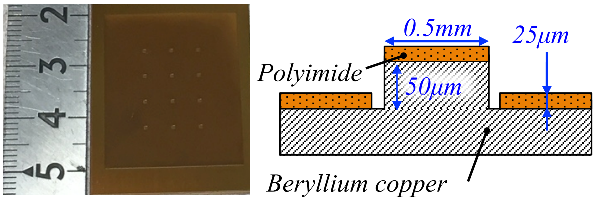

Fig. 8. ELFs-charm 5th generation sample

4.2. ELFs charm seventh Generation

The 7th generation of ELFs-charm consists of samples for which plating processing was applied to the copper base plate to design a part favorable to electric field concentration and then, polyimide was printed on top of the copper plate. The appearance and structure of the 7th generation of ELFs-charm are presented in Fig. 9.

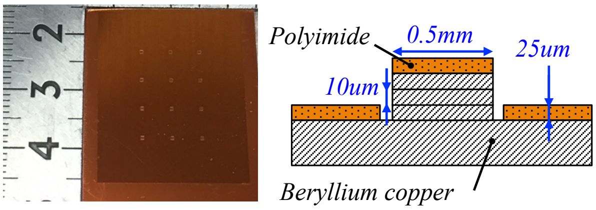

Fig. 9. ELFs-charm 7th generation sample

4.3. ELFs-charm fluorine resin coating

The fluorine resin coating sample is a sample for which an etching process was performed on the copper base plate to design a part favorable to electric field concentration. Fluorine resin was coated on top of the copper base plate. The appearance and structure of fluorine resin coating sample are presented in Fig. 10.

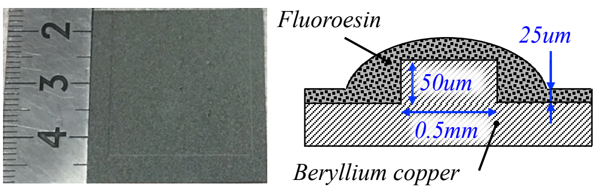

Fig.10. Fluorine resin coating sample

4.4. ELFs-charm silicon sample (prototype)

ELFs charm silicon sample (prototype) was made of silicon wafer to make the surface finer. In this sample, since it was a prototype to verify whether field emission could be performed using silicon, only the triple junction part was designed to favour electric field concentration. The appearance and structure of silicon sample (prototype) are presented in Fig. 11. SU-8 is one of photoresist.

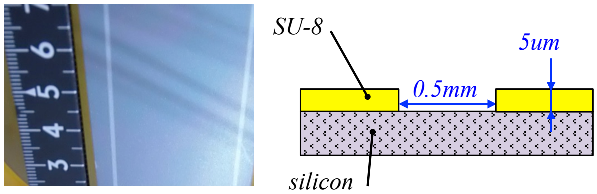

Fig.11. Silicon sample (prototype)

5. Evaluation of ELFs-charm charging capability

ELFs-charm must be capable of passively releasing electrons from its surface under the influence of sub-storms' high energy electrons. To evaluate how much the performance improve, an important point is to investigate the state of charging against the influx of high energy electrons. This section describes the result of evaluation.

ELFs-charm samples were exposed to vacuum and were irradiated by an electrons beam to verify the charging ability of the surface material (insulation part) of each ELFs-charm sample. From this experiment, the surface potential of ELFs-charm samples was measured. The experimental system diagram is described in Fig. 12.

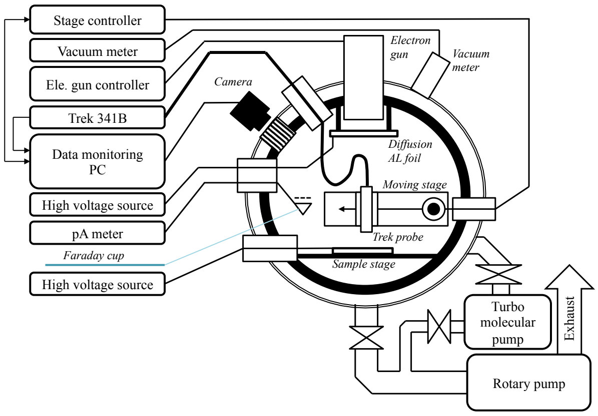

Fig. 12. Experimental system diagram of charging capacity measurement. The same setup was used at ONERA and Kyutech.

Tests were performed within two experimental facilities: ONERA and Kyutech, the vacuum inside the chamber was set to 10^{-6}mbar (10^{-4}Pa) or less using a turbo molecular pump. Then, an arbitrary voltage was applied to the sample under vacuum and the sample was irradiated by the electron beam. After five minutes of irradiation, the irradiation was stopped and the potential of the sample surface was measured with a surface potentiometer (Trek® probe). The results of the charging capability for each sample are shown in Figs. 13 and 14.

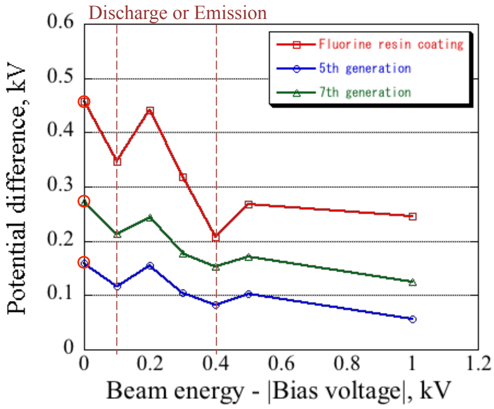

Fig. 13. Charging capacity of each sample (ONERA experiment)

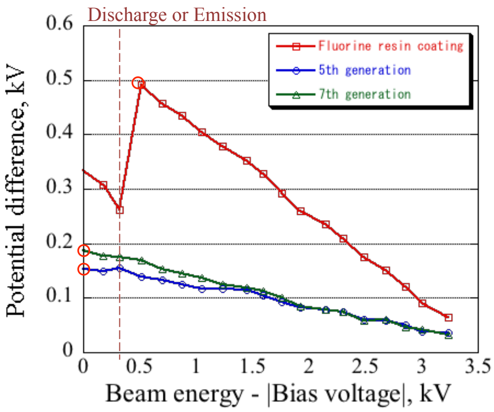

Fig. 14. Charging capacity of each sample (Kyutech experiment)

Figures 13 and 14 show the differential voltage when electron beams are irradiated to the samples (in the set-up shown in Fig. 12) at the different energies of incident electrons at the experimental facilities of ONERA and Kyutech respectively. The differential voltage is a potential difference between the insulator part and the conductor part of the samples (the potential of the insulation part - the electric potential of the conductor part). The circles in Figs. 13 and 14 show the maximum voltages measured during the experiment. And mitigation of potential on the surface of the sample was observed due to generation of discharge and electron emission during the experiment. Broken lines in these figures indicate points where discharge and electron emission are considered to have occurred.

During a sub-storm, the potential of a spacecraft gradually becomes negative with respect to the plasma. The difference between the spacecraft chassis potential (negative value) and the energy of electrons gradually decreases. The charging capacity of each sample is shown in Table 1.

Table 1. Charging capacity of each samples

Sample name	Max. energy gap, V	Incident electron environment		Measurement place
		Density, nA/cm^2	Energy, keV	
5th generation (Polyimide)	~160	~1	~4keV	ONERA
	~200	~5	~5keV	KIT
7th generation (Polyimide)	~273	~1	~4keV	ONERA
	~200	~5	~5keV	KIT
Teflon (t20um)	~458	~1	~4keV	ONERA
	~500	~5	~5keV	KIT

From the results, the differential voltage (potential difference) of each sample charged by electron irradiation of space-like environment could be measured. If this potential difference is larger than the voltage at which the sample starts field emission, the sample is considered to have electrons emission capability in space-like environment. Both the test results at Kyutech and ONERA were similar. It was found that the polyimide sample (5th generation and 7th generation samples) and fluorine resin coating sample were capable of being charged to approximately 200 V and 500 V , respectively during a sub-storm.

6. Evaluation of ELFs-charm electron emission capability

ELFs-charm must be able to emit electrons when surface is sufficiently charged. To evaluate ELFs–charm performance, the threshold differential voltage (the potential difference of the surface that can emit electrons) at which electrons emission starts is an important parameter. This section describes the evaluation of ELFs-charm electrons emission capability.

6.1. The experimental system and method using plasma

In this experiment, in order to verify the electrons emission capability of each ELFs-charm sample, arbitrary voltage was applied to the sample exposed under vacuum. The differential voltage was produced by a low-energy plasma (a few eV and the density of 10^{11} to 10^{12} m^{-3}). In the plasma environment, unlike the case where the sample is charged by keV electrons, the insulator surface potential is near the plasma potential, which we can approximate to zero compared to the bias voltage applied, of the order of 100V. The differential voltage is approximated by the bias voltage applied to the sample. The experimental system diagram is shown in Fig. 15.

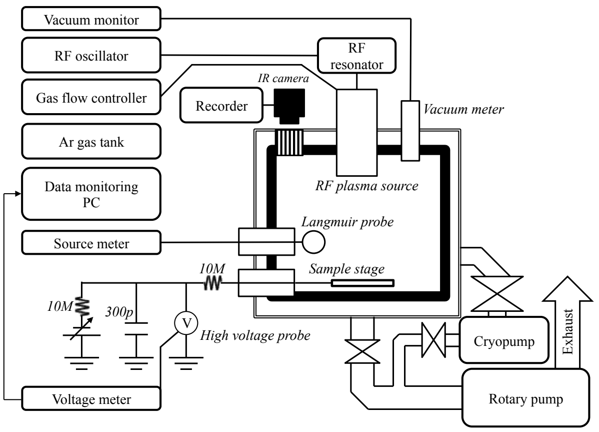

Fig. 15. Experimental system diagram of threshold measurement using plasma condition.

The sample was installed in a vacuum chamber and a cryopump was used to reduce the degree of vacuum inside the chamber to 10^{-6}mbar (10^{-4}Pa) or less. Thereafter, an arbitrary voltage was applied to the sample under vacuum and plasma was generated around the sample by the RF plasma source. The amount of electron emission current was measured from the sample using a 10 M resistor and a high voltage probe. When the current value rose, the voltage applied to the sample was taken as the threshold value of the sample field emission.

6.2. Test results and consideration of electrons emission capability of each sample

The test results of the electron emission capability are shown from Figs. 16, 17 and 18; and table 2 gives the threshold values of electrons emission as obtained from the test results.

Figure 16 shows the electron emission waveform when voltage of 600 V and 650 V is supplied to the conductive part of the 5th generation sample set in the plasma. When a voltage of 600 V was supplied, no waveform like the electron emission was confirmed, but when 650 V was supplied, the electron emission waveform was confirmed from about 5.5 minutes. From this, it is considered that the electron emission threshold voltage of the 5th generation sample is about 650 V. Similarly, in Figs. 17 and 18, the waveforms before and after the electron emission in the fluorine resin coating sample and the silicon sample are shown. It is considered that the electron emission threshold of the fluorine resin-coating sample is about 450 V and that of the silicon sample is about 300 V.

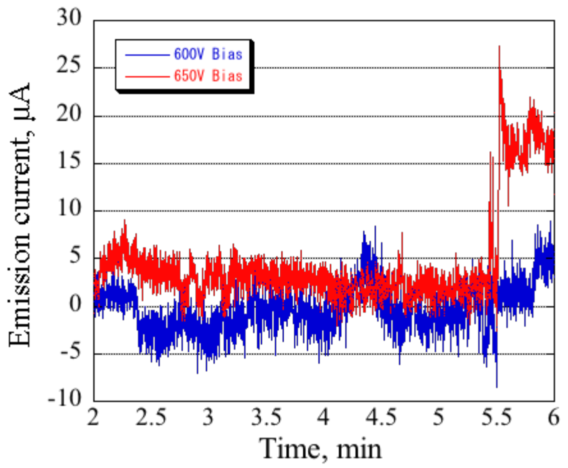

Fig. 16. Electrons emission capability of 5th generation sample. (due to the specifications of the measurement system, the bias voltage is large, so the resolution is lower than the measurement result of other samples)

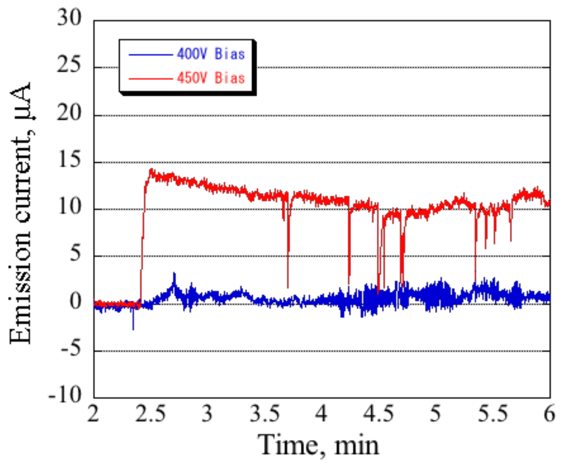

Fig. 17. Electrons emission capability of fluorine resin coating sample under plasma.

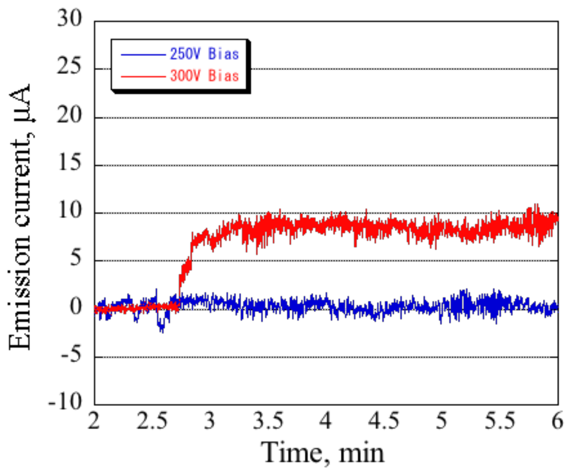

Fig. 18. Electron emission capability of silicon sample under plasma.

Table 2. Threshold voltage of each sample

Sample	Threshold, V
5th Generation sample	650
Fluorine resin coating sample	500
Silicon sample (Prototype)	300

The results confirm that electrons emission is started beyond a certain threshold value. Since the sample was placed in the plasma and the surface potential was near 0V, the bias value becomes the potential difference at which emission starts.

It is known from the previous experiment that Teflon sample had better electrons emission performance than polyimide sample. (see reference 10) From this threshold test, it was also found that the Teflon sample has the less threshold value than the Polyimide sample.

7. Conclusion

The development phase of ELFs-charm is at the stage of practical application and electrons emission performance in real space or space-like conditions must be improved. In previous experiments, we could not confirom electron emission from the samples made of copper plates and polyimide under conditions realistic in orbit. The electrons emission was confirmed in from the samples made of copper plate and fluorine resin coating even under conditions realistic in orbit.

In the present paper, to study the difference of the polyimide sample and the fluorine resin sample, two parameters, the charging characteritics and the differential voltage threshold for electron emission, were studied. The first parameter is how well the insulator surface is charged under realistic flux of energetic electrons. The second one is the voltage at the surface of the sample required to emit electrons (threshold).

While the polyimide sample was charged only up to about 200 V, the fluorine resin coating sample was charged to about 500 V. The fluorine resin coating can apply a higher electric filed to the electrons emission point. In addition, it was found that a voltage of 650 V or higher is required to be applied to the sample surface for the polyimide sample to emit electrons. As a conclusion, the polyimide sample is not suitable in space environment. On the other hand, the fluorine resin coating sample can operate in outer space considering because the surface can be charged to 500V and the threshold value is also 500V. In addition, the silicon sample under development is able to emit electrons at a lower voltage than the fluorine resin coating sample. In the future, we plan to improve ELFs-charm performances by applying high charging capacity coating to silicon sample.

Acknowledgment

I want to thank Iwaki Coating Ind. Ltd. and Center for Microelectronic System for their assist in manufacturing of ELF and SCM.

References

1) M. Cho, D. E. Hastings, "Computer particle simulation of high voltage solar array arcing onset", Journal of Spacecraft and Rockets, Vol. 30, No 2, pp. 189-201, 1993.
2) D. Payan, F. Séverin, J.-P. Catani, JF. Roussel, R. Reulet, D. Sarrail, "Electrostatic Discharges on Solar arrays. Physical Model of Inverted Potential Gradient Electrostatic Discharge," 7th Spacecraft Charging Technology Conference, Noordwijk, the Netherlands, 2001.
3) P. Sarrailh, J.-C. Matéo-Vélez, J.-F. Roussel, B. Dirassen, J. Forest, B. Thiébault, D. Rodgers, A. Hilgers, Comparison of numerical and experimental investigations on the ESD onset in the Inverted Potential Gradient situation in GEO, IEEE Trans. Plasma Sci., Vol 40, N°2, 2012
4) Daniel Hastings, Henry Garrett 'Spacecraft-Environment Interactions'
5) Rod Latham 'High Voltage Vacuum Insulation'
6) Naoki Matsumoto, Atomu Tanaka, Arifur R Khan, Minoru Iwata, Kazuhiro Toyoda and Mengu Cho. "In-orbit demonstration of spacecraft charging mitigation of passive electron-emitting film" International Symposium on Space Technology and Science
7) Minoru Iwata, Arifur R. Khan, Hideyuki Igawa, Kazuhiro Toyoda, and Mengu Cho, Tatsuhito Fujita, "Development of Electron-emitting Film for Spacecraft Charging Mitigation", J. Spacecraft and Rockets, vol. 49, no.3, (546-552), 2012
8) Arifur R. Khan, Takahiro Sumida, Minoru Iwata, Kazuhiro Toyoda, Mengu Cho, and Tatsuhito Fujita, 'Environment Exposure Tests of Electron-Emitting Film for Spacecraft Charging Mitigation.' IEEE Transactions on Plasma Science, Vol. 40, No. 2, February 2012.
9) Minoru Iwata, Arifur R. Khan, Hideyuki Igawa, Kazuhiro Toyoda, and Mengu Cho, Tatsuhito Fujita, "Development of Electron-emitting Film for Spacecraft Charging Mitigation", J. Spacecraft and Rockets, vol. 49, no.3, (546-552), 2012
10) A. R. Khan, M. Iwata, K. Toyoda, M. Cho and S. Tomonari, Y. Takaki."In-orbit Demonstration of Newly Developed Passive Electron-emitting Film for Spacecraft Charging Mitigation" Journal of Spacecraft and Rocket, Vol.50, No 4, pp. 853-859, 2013.
11) Mengu Cho: Laboratory Test on 110-Volt Solar Arrays in Simulated Geosynchronous Orbit Environment, Journal of Spacecraft and Rockets, Vol.40, No.2, March-April 2003