Current Status and Future Plan for Material Property Measurements Related to Engineering Design Optimization Guidelines and Spacecraft Charging at JAXA

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ABSTRACT

This paper describes the study framework for material property measurements related to spacecraft charging, methods, and measurement results. The key parameters in modeling spacecraft charging are the secondary electron emission (SEE) coefficient, the photoelectron emission (PE) coefficient, the surface resistivity, the volume resistivity, and the dielectric constant.

This review is based on joint experimental studies conducted for the Japan Aerospace Exploration Agency (JAXA) at the High Energy Accelerator Research Organization (KEK), at the Tokyo City University, and at the Saitama University to investigate the relation to spacecraft charging. We also commissioned a study of the dielectric constant by Sumitomo Metal Technology Inc. This report introduces a summary of some typical measurement results following a brief explanation of the measurement project. A review is presented of methods to measure SEE—including the use of SEM with short-pulsed electrons for accelerating voltages of 600 eV-5 keV, a vacuum chamber with a low energy electron beam for accelerating voltages of 200 eV-10 keV, a system for measuring PE by vacuum ultraviolet light (VUV), the surface resistivity, the volume resistivity, and the dielectric constant. This report summarizes some typical measurement results after briefly explaining the measurement project.

1. INTRODUCTION

Recently, some accidents in spacecraft due to charging have been reported. A quantitative analysis from the viewpoint of charging-arcing issues from the early stage of the satellite design phase has thus become necessary. Electric potential of a satellite body with respect to ambient plasma and differential voltage of each surface component with respect to the satellite body potential are the most important elements to consider in charging-arcing problems. A spacecraft potential analysis tool that is available from the satellite design phase is necessary to support the satellite operations [1].

The Japan Aerospace Exploration Agency (JAXA) and Kyushu Institute of Technology (KIT) started the development as a joint project in November 2004, and the final version of the Multi-utility Spacecraft Charging Analysis Tool (MUSCAT) was released in March 2007 [2]. The simulation code can be used not only for polar satellites but also for GEO satellites or a low inclination LEO satellite. The aim of the simulation code is to give satellite designers the ability to identify the charging hazard in the satellite design phase with a user-friendly interface.

The most influential electrical properties of materials related to the electrostatic charge phenomena and the measurement means used for characterizing them have been extensively explained. The main properties to be taken into account are secondary emission under electron flow, secondary emission under proton flow, photoemission, surface resistivity, volume resistivity, radiation-induced conductivity, atomic number and the dielectric constant [3].

We describe the current status and the future plan for the study framework for material property measurements related to spacecraft charging, methods and measurement results. This work addresses the analyses and measurements of the secondary emissions under electron flow (SEE), the photoelectron emissions (PE), the surface resistivity, the volume resistivity and the dielectric constant.

This review is based on joint experimental studies. We conducted joint studies for JAXA at the High Energy Accelerator Research Organization (KEK), at the Tokyo City University, and at the Saitama University to investigate relations among spacecraft charging parameters of solid state properties. We also commissioned a
study of the dielectric constant by Sumitomo Metal Technology Inc.

This report introduces a summary of some typical measurement results following a brief explanation of the measurement project.

2. MEASUREMENT PROJECT

2.1 Framework for the measurements
We measured SEE using an SEM with short-pulsed electrons and an accelerating voltage of 600 eV – 5 keV at KEK. We also measured SEE using low-energy electron emission and PE current at the Tokyo City University and the surface resistivity, volume resistivity, and measurements of photoelectron emission images at the Saitama University. The dielectric constant was obtained from Sumitomo Metal Technology Inc. We began work in December 2005. The framework is summarized in table 1. Measurements were carried out under vacuum conditions. We also examined the measurement method with changing temperature in vacuum.

2.2 Irradiated condition
The measured materials are commonly used in space applications, e.g. on spacecraft surfaces; they include thermal control materials, adhesives, thin-film structure materials, paint, cover glass and electric wires and cables etc. We measured many materials, among which some selected ones were irradiated with electron beams, ultraviolet rays, atomic oxygen in order to simulate the space environment. Table 2 shows the irradiated condition. EB and UV irradiation is assumed to simulate 1, 3, and 5 years in GEO.

The Combined Space Effects Test Facility, placed at Tsukuba Space Center, JAXA, has a vacuum chamber and three beam sources, i.e., Atomic Oxygen (AO), Electron Beam (EB) and Vacuum UltraViolet ray (VUV), generating a simulated space environment on the ground [4].

We also conducted joint studies for the JAXA at the Kobe University to investigate relations among spacecraft charging parameters of atomic oxygen irradiated materials.

3. SECONDARY ELECTRON EMISSION

The energy of electrons from space, depending on the type of orbit, ranges from several electron volts to several kilo electron volts or even several mega electron volts in geostationary orbit. The energy transfer of the incident electrons in the material results, among other things, in the emission of secondary electrons. The energy density and distribution of this electron radiation depend on the energy and direction of the primary electrons and on the intrinsic properties and the conditioning of the bombarded materials. Several magnitudes characterize the secondary emission [3].

3.1 Beam Blanking Scanning Electron Microscopy
We measured SEE yields by using Beam Blanking Scanning Electron Microscopy (BBSEM) with a Faraday cup in order to observe secondary electrons at KEK. The pulse-beam method was adopted to measure the SEE yields to
avoid charging the surface of the insulation materials [5]. The pulse duration was 1 ms, and the pulse current was 100 pA. The SEE yield is calculated as the ratio of the primary electron current \( I_p \) to the secondary electron current \( I_s \). Primary electrons are accelerated to above 0.6 keV. Fig. 1 illustrates the SEE measurement system.

Fig. 2 illustrates the dependency of the cover glass of SEE yields on the primary electron energy compared with quartz, Au and Ag. We measured SEE yields at the same electron energy five times; the plotted line connects the average values.

We already measured all surface materials for the spacecraft as much as the traffic will bear in case of accelerated voltage above 0.6 keV. We also considered the influence of irradiated materials and measured the relevant conditions.

3.2 Vacuum chamber with low energy electron beam

We developed a low energy electron beam for detecting SEE. The new SEE measurement system can measure SEE within an energy range of 0.2 – 10 keV. The schematic diagram of the developed system is shown in Fig. 3. The base construction of this system is the same as that of the conventional system described in the above section. The Faraday cup can capture SEE current from the samples.

Fig. 4 illustrates the dependency of the Au of SEE yields on the primary electron energy compared with the measurement by BBSEM. The energy of maxmam SEE yield is equal and SEE yields are very close to the value that was obtained by BBSEM. We confirmed that our developed system can measure the SEE yields.

4. PHOTOEMISSION

Due to the action of solar radiation, in particular ultra-violet radiation, the surface of materials, whether they are conducting or insulating, emits a quantity of electrons, which varies according to the nature of the material. The energy of the emitted electrons varies between 0 and some tens of electron volts, and the densities are of the order of 0.1 nA/cm² to nA/cm² [7]. Based on these photoemission characteristics we deduce that the risk of the electrostatic discharge for a satellite in the daylight position is lower than in the night position.

The experimental setup is shown in Fig. 5. The deuterium lamp of 200 W (Hamamatsu Photonics K.K.:L1835) and band pass filters (BPF) are used for a source of VUV (vacuum ultraviolet) ray. The VUV ray is reflected by an aluminum vapor deposition mirror made by the vacuum evaporation method on the optical flat glass and is irradiated on the sample. An irradiated area is \( 1.6 \times 10^{-3} \) m². Photoelectrons are collected by the semi-spherical electrode and are measured at the electrode placed on the sample. Here, the
radiation wavelength range of the deuterium lamp is 115-400 nm. Negative bias voltage around 7 V is applied to the sample side, to prevent the pull back electrons that were emitted from the sample and the electrons emitted at the surface of chamber. Additionally, irradiated flux of VUV ray is measured by using a photomultiplier (Hamamatsu Photonics K.K.:R6836) for each wavelength to evaluate the quantum efficiency for the photoemission. Because VUV should be avoid absorption by the gas molecule, the measurement is performed by using a pressure lower than 10⁻² Pa.

The Fowler method is used for the photoelectric determination of the work function and the photoelectric yield is based on incoming photons. Fig. 6 illustrates the dependency of cover glass of quantum efficiency on the photoelectron emission energy. We translated to photoemission current for solar total emission from the quantum efficiency coefficient.

5. SURFACE AND VOLUME RESISTIVITY MEASUREMENTS

Resistivity tests were conducted in accordance with JEC-6148, which is the same as the standard ASTM D257-99 “capacitor method” using the Resistivity Test Fixture (R8252 Digital Electrometer, Advantest Corporation) [8]. Figure 7(a) depicts the test electrodes, which are comprised of a silver-coated circular electrode part and a toroidal part. The initial tests were conducted in air (no formal pre-exposure, and designated as Time “0”), followed by measurements in a vacuum of < 10⁻² Pa. All samples were initially exposed to a standard 100 V source voltage.

Results confirmed that the surface resistivity for almost all insulator materials under vacuum condition was higher than that under atmospheric conditions. Desorption of moisture vapor from the insulator surface is the main cause of the increase of the surface resistivity in vacuum. In contrast, their volume resistivity, except for the paints, had no difference between vacuum and atmospheric conditions. Paints under vacuum conditions showed higher volume resistivity than that of atmospheric conditions. Table 3 show examples of surface and volume resistivity in vacuum and with 100 V applied voltage.

We examined the effects of in-vessel vacuum on volume resistivity. The chamber is back to atmospheric pressure. After drawing a vacuum of
Table 3 Results of surface and volume resistivity
(a) Surface resistivity in air and vacuum

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Air (Ω)</th>
<th>Vacuum (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black paint</td>
<td>4×10^{14}</td>
<td>5×10^{16}</td>
</tr>
<tr>
<td>White paint</td>
<td>1×10^{10}</td>
<td>9×10^{12}</td>
</tr>
<tr>
<td>Cover Glass</td>
<td>&gt;2×10^{17}</td>
<td>&gt;2×10^{17}</td>
</tr>
</tbody>
</table>

(b) Volume resistivity in air and vacuum

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Air (Ωm)</th>
<th>Vacuum (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black paint</td>
<td>1×10^{10}</td>
<td>1×10^{12}</td>
</tr>
<tr>
<td>White paint</td>
<td>7×10^{7}</td>
<td>3×10^{10}</td>
</tr>
<tr>
<td>Cover Glass</td>
<td>6×10^{13}</td>
<td>5×10^{13}</td>
</tr>
</tbody>
</table>

Figure 8 White paint dependency of volume resistivity on the pressure

< 10\(^{-5}\) Pa, the in-vessel is exposed to the atmosphere again.

Figure 8 portrays the white paint dependency of volume resistivity on the pressure. The surface resistivity increases with decreasing pressure of the in-vessel when we decrease to the vacuum of 10\(^{-4}\) Pa from atmospheric pressure. However, for pressures in the chamber less than 10\(^{-5}\) Pa, the volume resistivity does not increase and maintains a stable value. Furthermore, we introduce air into the chamber and confirm that the volume resistivity decreases to the initial value. For the reasons described above, we conclude volume resistivities change under the influence of the moisture vapor and the adsorption amount of pressure for the paints.

6. DIELECTRIC CONSTANT

The dielectrics were measured by using an LF impedance analyzer (HP4192A; Agilent Technologies Inc.) for frequencies of 5 Hz–1 MHz. The electrodes on the paint samples consisted of silver paste coated similarly to those for measurements of resistivity. We dried out the paint samples for one day using a drying apparatus at atmospheric pressure after applying the paint. For the glass and film samples, the electrodes were made of gold evaporation. All samples were kept in a desiccator to prevent absorption of moisture. The initial tests were conducted in atmospheric pressure followed by measurements in vacuum of 0.1 Pa. We also changed the temperatures in vacuum when we measured some samples

Through 1 kHz – 1 MHz, we scan frequencies from 1 kHz to 10 kHz in steps of 1 kHz, from 10 kHz to 100 kHz in steps of 10 kHz, and from 100 kHz to 1 MHz in steps of 100 kHz. For frequencies less than or equal to 1 kHz, we averaged 21 values because frequency measurement accuracy is lower at a low frequency.

Figure 9 shows sample results of the dielectric constant \(\varepsilon_r\) of the cover glass and the black paint under changing temperature. In this study, the value of the dielectric constant \(\varepsilon_r\) of the
test environments was measured.

(a) Dielectric constant \(\varepsilon_r\) of cover glass

(b) Dielectric constant \(\varepsilon_r\) of black paint

Fig. 9 Dielectric constant \(\varepsilon_r\) to the frequency

RT: Room Temperature
LT: Low temperature -25°C
Black paint changed. According to our prior research [9], the effect of the temperature change on the value of the dielectric constant $\varepsilon_r$ is only 5%. But, as the condition of the combination in low temperature and vacuum, the value of the dielectric constant $\varepsilon_r$ changed by about 50%. We think that we should measure some samples which are subject to the influence of moisture vapor in this condition.

7. DATABASE

Figure 10 show the current status of the material property measurements. We already prepared and measured 22 films, 3 AO irradiated (6 conditions) films, 3 UV irradiated (3 conditions) films, 3 EB irradiated (3 conditions) films, 7 glasses, 3 AO irradiated (6 conditions) glasses, 3 UV irradiated (3 conditions) glasses, 3 EB irradiated (3 conditions) glasses, 13 paints, 9 metals and 6 other materials SEE using an SEM with short-pulsed electrons at an accelerating voltage of 600 eV - 5 keV at KEK, also surface and volume resistivity and so on. We started to design new spacecraft using those material properties.

![Fig. 10 Current status of the material property measurements](image)

8. CONCLUSION

- We introduced a project for measuring material parameters for MUSCAT.
- We found the SEE yield of the surface materials for the spacecraft with an accelerating voltage of 600eV-5KeV.
- We superposed two SEE measurement results and demonstrated a potential measurement range of 0.2 to 10keV.
- We measured PE and calculated the quantum efficiency coefficient of cover glass.
- Results confirmed that the surface resistivity for almost all insulator materials under vacuum condition was higher than that under atmospheric conditions.
- The volume resistivities of paints are influenced by moisture vapor and its adsorption in these conditions.
- At atmospheric pressure, the capacitance $C$ and dielectric constant $\varepsilon_r$ of glasses, which show high resistivity, are fairly constant over many frequencies.
- Some samples for those dielectric constant $\varepsilon_r$ are influenced by temperature changes in vacuum.

9. REFERENCES