Ion sheath structure and material degradation due to ion bombardment around high voltage solar arrays – ground simulation -

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Abstract. At Osaka University, a ground facility was developed for simulation of material and space plasma interaction. In order to understand the interaction between plasma flow and a solar array applied a negatively biased voltage, i.e. the ion sheath structure, a sample plate, which of the one side is an electrode collecting ions and of the other side is a dielectric side, was exposed to oxygen plasma flows generated using the facility. The collected ion current and the spatial plasma potential were measured for variations in the biased voltage and the attack angle of the plate to the plasma flow. The ion current and the plasma potential distribution were found to be intensively changed by the biased voltage and the attack angle, particularly a scaling parameter derived from the one-dimensional ion sheath theory. Furthermore, Kapton films, located on the center of the negatively biased plate, were exposed to oxygen plasma flows. The x-ray photoelectron spectroscopic analysis showed that an addition reaction and a desorption of structural components occurred on the films by ion bombardment.

1. Introduction

In general, an ion sheath is created around a metal plate applied a negatively biased voltage in a plasma flow. This phenomenon can be observed around a high voltage solar array of spacecraft on an Earth orbit[1]. In space satellites the current generated by a solar array is leaked by impact of ions, and furthermore the solar array is degraded by sputtering and arcing due to the collected ions. Therefore, it is important to understand the interaction between plasma flow and a metal plate, i.e. the ion sheath structure.

At Osaka University, a ground facility was developed for simulation of material and space plasma interaction and for study of spacecraft charging and discharge phenomena[2]. The space plasma simulator consisted of a large vacuum tank, molecular pumps with high pumping speed and an electron cyclotron resonance plasma source of a magnetic-field-expansion plasma accelerator. Oxygen plasma properties of plasma density, electron temperature, ion incident energy and ion freestream velocity were measured. Using the simulator, the structure of an ion sheath created around a high voltage solar array and degradation of spacecraft surface materials near the array due to high energy ion bombardment were investigated.

A metal plate applied a negatively biased voltage was exposed to oxygen plasma flow in order to examine the characteristics of ion sheath. The collected ion current was measured for variations in the biased voltage and the attack angle of the plate to the plasma flow. The plasma potential around the plate was also measured with an emissive probe. The shape and thickness of ion sheath are discussed. Spacecraft polymer films of polyimide BPDA-PDA Kapton, located on plates biased to minus 0.1-1.0 kV, were exposed to oxygen plasma flow. The x-ray photoelectron spectroscopic analysis was carried out to examine the change of chemical structure of the film surface[3][4].

2. Experimental Apparatus and Conditions

The space plasma simulator developed at Osaka University, as shown in Fig.1, consists of a vacuum tank, vacuum pumps and a plasma accelerator. The electron cyclotron resonance (ECR) plasma accelerator is set on the flange of a large stainless vacuum tank 0.7 m in diameter x 1.5 m long. The main vacuum pumps are two oil-free turbo-molecular pumps (OSAKA VACUUM: TH5000VA and TH3000VA) with high pumping speeds 5 and 3 m^3/s, respectively, each of which is connected to a rotary pump (ANELVA: T2033A). It takes about 90 minutes to achieve some 10^{-4} Pa of tank pressure using this pumping system.

The ECR plasma accelerator, as shown in Fig.2, is a type of magnetic-field-expansion plasma accelerators. Plasma is generated by ECR heating of the interaction between microwaves and divergent magnetic fields induced by a solenoidal coil around a discharge chamber and is electrostatically accelerated by micro electric fields induced by charge separation in the magnetic fields. Since the ECR plasma accelerator has negligible contamination because of no electrodes, clean and reactive plasma flows are expected to be generated in the space plasma simulator. Microwaves of maximum 1 kW and 2.45 GHz are introduced into the discharge chamber 125 mm in inner diameter x 100 mm long through a quartz glass window 150 mm in diameter x 12 mm in width. As shown in Fig.3, there exists an ECR layer with 87.5 mT about 20 mm downstream of the quartz window at a solenoidal coil current of 95 A. Oxygen is used as the working gas. After the mass flow rate is controlled with a commercially available thermal-conductivity-type mass flow controller, the gas is radially injected from four ports just downstream of the quartz window into the discharge chamber.

Plasma parameters of electron temperature, plasma density and ion velocity are controlled by varying microwave input power, magnetic field shape and strength, and oxygen mass flow rate. They were measured with a Langmuir probe and an electrostatic energy analyzer, ranging from 2 to 8 eV, from $3x10^{15}$ to $1x10^{16}$ m^{-3} and 2 to 3.5 km/s, respectively.

Square plates 50 mm x 50 mm or 25 mm x 25 mm, made of carbon, are located at 700 mm downstream from the plasma source. The sample plate, which of the one side is an electrode collecting ions and of the other side is a dielectric side, is exposed to oxygen plasma flow. The ion current is measured for variations in the biased voltage and the attack angle of the plate to the plasma flow. The biased voltage is -100 to -2000 V. The plasma potential around the plate is measured with an emissive probe.

In the case of collecting ions, charge limiting occurs. When the electron density is assumed to be determined by Boltzmann distribution, the one-dimensional governing equations of Poisson and the ion kinetic equations derive a scaling law (named P parameter) just like Perveance:

$$P=(L^2eN_pU/\varepsilon\square V\square^{3/2})x(m_i/2e)^{1/2} \qquad (1)$$

where L is characteristic length of metal plates, N_p plasma density, U plasma velocity, V absolute biased voltage, e electron charge, m_i ion mass and ε dielectric constant.

Spacecraft polymer films of polyimide BPDA-PDA Kapton, as shown in Fig.4, are also exposed to oxygen plasma flow. The square films 5 mm x 5 mm are located on the center of carbon plates 25 mm x 25 mm biased to minus 0.1-1.0 kV. Surface chemical structure of polyimide films before and after exposure is examined by means of x-ray photoelectron spectroscopy.

3. Results and Discussion

3.1 Ion Sheath Structure

The collected ion current dependent on the attack angle of plasma flow to the metal side at 1.9 P parameter is shown in Fig.5. The ion current is the largest at ram condition, and it decreases with decreasing attack angle. Figure 6 shows the plasma potential distributions at ram, airplane and wake conditions at 1.9 P parameter. The ion sheath and its presheath are expected to widely spread in front of the metal plate at every condition with the same P parameter. The equipotential lines at ram condition are intensively compressed in front of the metal plate compared with those at wake condition. The profile at airplane condition extends outward downstream. As a result, plasma flow is expected to influence the motion of ion and the ion sheath structure. Furthermore, the effective area collecting ions is found to spread behind the metal side, i.e. near the insulating surface, resulting in the larger ion current, as shown in Fig.5, than the current which is the absolute metal area multiplied by the ion flux of the plasma freestream. Figure 7 shows the thickness of ion sheath, inferred from the measured plasma potential distributions, dependent on the P parameter. The sheath thickness decreases with increasing P parameter, as predicted from the one-dimensional sheath theory. The sheath thickness at ram condition is smaller than that at wake condition at a same P parameter although the ion current was larger. This result shows that plasma flow influences sheath thickness.

3.2 Degradation of Polyimide Films by Ion Bombardment

Polyimide Kapton films, which were located on the center of carbon plates biased to –400 V, were exposed to oxygen plasma flow. The P parameter was set to 5.3. The exposure time is 15 min, which corresponds to about 1 month in LEO.

Figures 8 and 9 show the XPS O1s spectra of Kapton films before exposure and after exposure at ram and wake conditions, respectively. The profile before exposure is deconvoluted into two Gaussian profiles of >C=O and C-O-C. After exposure, the relative intensity of >C=O decreases, and the feature of O-C-O is created only at ram condition. Accordingly, the structural feature of >C=O in imide groups is expected to be destroyed by ion bombardment. At ram condition, an addition reaction of oxygen ions or atoms intensively occur just after the destroy of >C=O bonds, resulting in the creation of the structural feature of O-C-O. The addition reaction at wake condition is expected to be negligible compared with that at ram condition because of a smaller ion flux. Consequently, it was found that the addition reaction and a desorption of structural components occurred on polyimide films by ion bombardment. They are expected to cause the decrease in the performance of spacecraft thermal control.

4. Conclusions

At Osaka University, a ground facility was developed for simulation of material and space plasma interaction and for study of spacecraft charging and discharge phenomena. The plasma simulator consisted of a vacuum tank, two turbo-molecular pumps and an electron cyclotron resonance plasma source of a magnetic-field-expansion plasma accelerator. Oxygen plasma properties of plasma density, electron temperature, ion incident energy and ion freestream velocity were measured. The simulator was found to have a high potential for ground tests. Using the simulator, the structure of an ion sheath created around a high voltage solar array and degradation of surface materials near the array due to high energy ion bombardment were investigated. A sample plate was exposed to oxygen plasma flow. The ion current was measured for variations in the biased voltage and the attack angle of the plate to the plasma flow. The plasma potential around the plate was measured with an emissive probe. The collected ion current and the plasma potential distribution were found to be intensively changed by the biased voltage and the attack angle, particularly a scaling parameter derived from the one-dimensional ion sheath theory. Furthermore, in order to examine the influences of ion bombardment on chemical structures of spacecraft surface materials, polymer films of polyimide BPDA-PDA Kapton, located on the negatively biased plate, were exposed to oxygen plasma flow. The XPS analysis showed that an addition reaction of oxygen atoms or ions at wake condition was negligible compared with that at ram condition because of a smaller ion flux. Consequently, the addition reaction and a desorption of structural components were found to occur by ion bombardment. They are expected to cause the decrease in the performance of spacecraft thermal control.

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Running Heads
TAHARA et al.: ION SHEATH STRUCTURE AND MATERIAL DEGRADATION DUE TO ION BOMBARDMENT AROUND HIGH VOLTAGE SOLAR ARRAYS

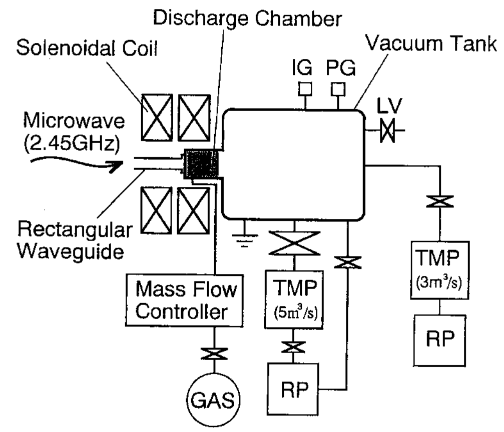


Figure 1. Schematic diagram of space plasma simulator with electron cyclotron resonance plasma accelerator.

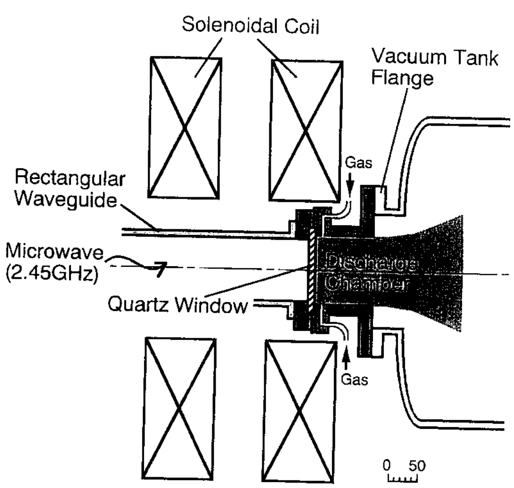


Figure 2. Cross section of electron cyclotron resonance plasma accelerator.

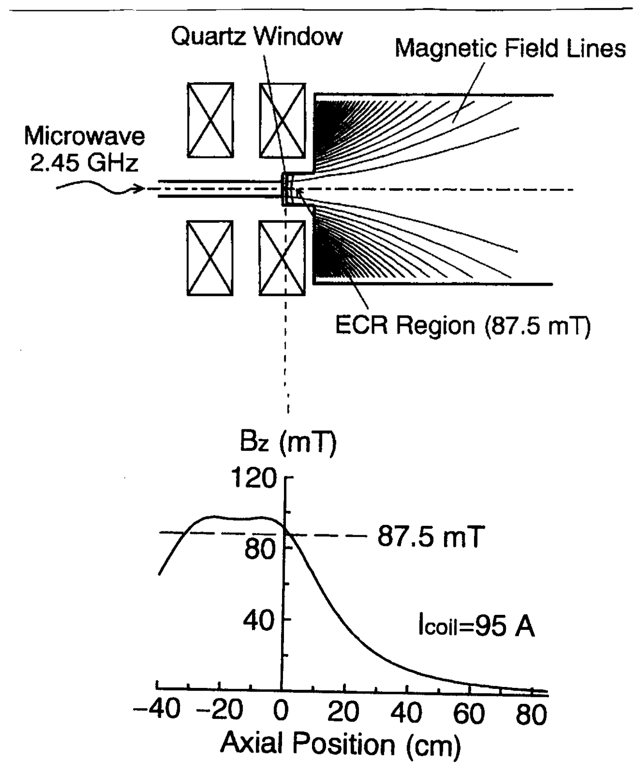


Figure 3. Calculated applied magnetic field lines and its strength on central axis.

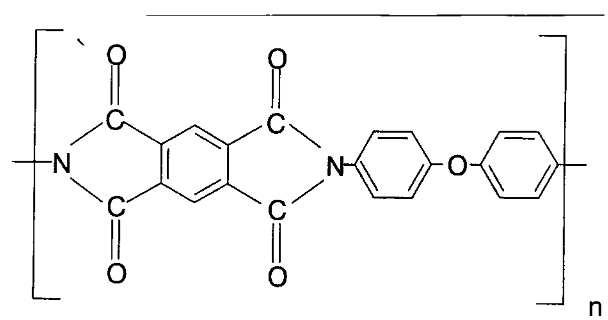


Figure 4. Chemical structure of polyimide Kapton.

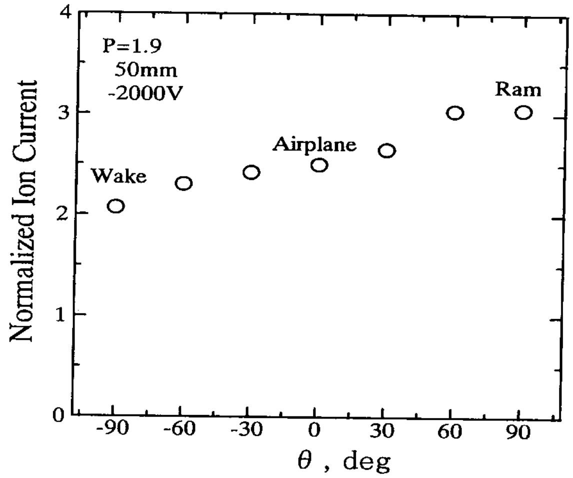
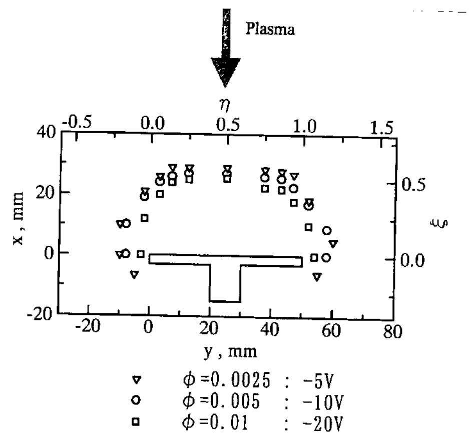
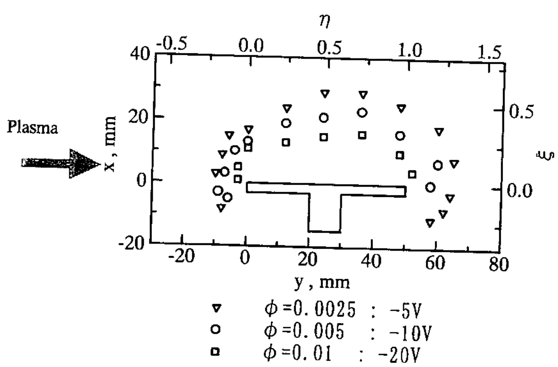


Figure 5. Collected ion current dependent on attack angle of plasma flow to metal plate at 1.9 P parameter.





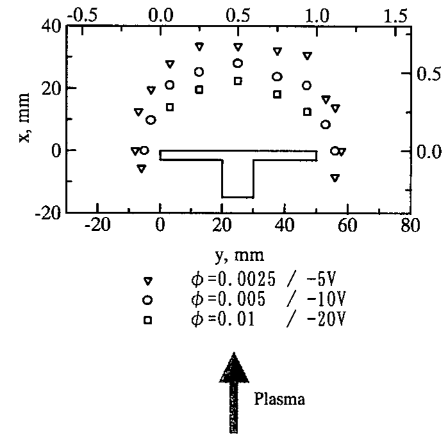


Figure 6. Plasma potential distributions at ram, airplane and wake conditions at 1.9 P parameter. (a) Ram condition. (b) Airplane condition. (c) Wake condition.

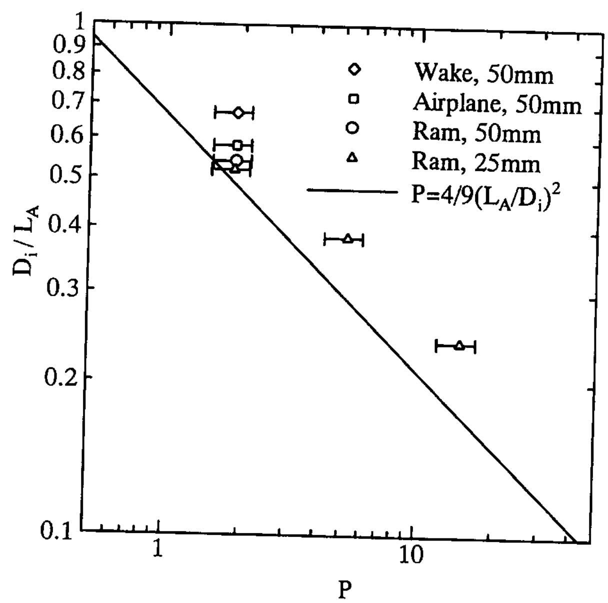
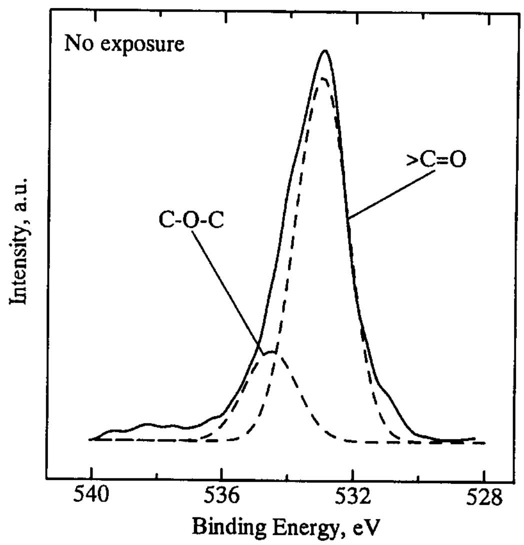


Figure 7. Thickness of ion sheath dependent on P parameter.



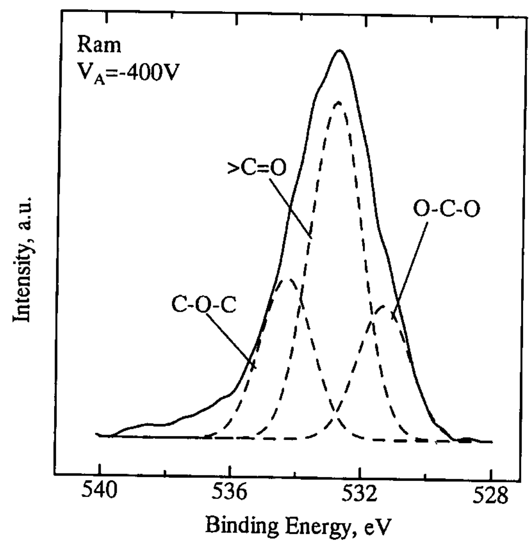


Figure 8. XPS O1s spectrum of Kapton films before exposure.

Figure 9. XPS O1s spectra of Kapton films after exposure at ram and wake conditions. (a) Ram condition. (b) Wake condition.