Shape Maintaining of Ultra-lightweight Thin-Film Power Generation System

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A spacecraft requires lightweight power generation system. We are developing a lightweight flexible power generation system that uses thin film photovoltaic cells for a planetary exploration spacecraft. Because thin film solar cell on polyimide film has asymmetric and multi-layer structure, it will bend with changes in temperature in the space environment. To make ultra-lightweight flat thin film solar array which can be used in a space environment, we study about shape control by surface coating utilizing oxide materials on the solar array and durability against space environment. We describe experimental results in order to calculate the internal stress of the coating layer, predict the shape of the coated films and confirm the durability against space environment of the coated thin film solar cells.

Key Words: Solar Array, Lightweight, Flexible, Thin Film, Shape Prediction

Nomenclature

\[ R \] : the radius of curvature
\[ \delta \] : the deflection
\[ \theta \] : the rotation angle
\[ E \] : the Young’s modulus
\[ \varepsilon \] : the strain
\[ \sigma \] : the internal stress
\[ M \] : the bending moment
\[ A \] : the length of the chord.
\[ D \] : the thickness of glass substrate
\[ S \] : the cross sectional area of applied the internal stress
\[ h \] : the thickness of oxide layer
\[ L \] : the length of glass substrate

Subscripts

1 : the case of sputtering to glass substrate
2 : the case of sputtering to solar cell

1. Introduction

In planetary exploration of beyond Jupiter, nuclear energy has been used. For example, in the past, the spacecraft such as Voyager 2 and Cassini-Huygens have succeeded to reach beyond Jupiter by using nuclear batteries. And now, as the spacecraft to explore beyond Jupiter, for the first time, Juno using solar panels instead of a nuclear battery was developed by NASA, and it was launched in 2011.

On the other hand, because it is difficult to use a nuclear energy for the space applications in Japan, the spacecraft to investigate beyond Jupiter which utilizes large scale lightweight thin-film power generation system has been being developed by JAXA. It is referred to the solar power sail. It has the hybrid propulsion system which utilizes the electric propulsion and the propulsion by the sun light pressure. JAXA launched IKAROS in 2010 and was successful in demonstrating the solar sail for the world’s first time. The image of the solar power sail toward Jupiter is shown in Fig. 1.

![Fig. 1. The image of the solar power sail.](image_url)

An important parameter that determines the performance of the solar power sail is power generation per unit mass [kW/kg]. In particular, the target value is 2 [kW/kg] for the solar power sail. Lightweight is necessary in order to improve this parameter. Also, flexibility is required for the solar power sail in order to store the large solar array in the payload fairing of the launch vehicle. Therefore, we are developing a very lightweight flexible solar array utilizing thin film solar cell on the polyimide film. However, because the thin film solar cells on polyimide film have asymmetric and multi-layer structure, it will bend with changes in temperature. It is needed to suppress curvature of the solar array which is mounted on the spacecraft. To control the shape of the sail, it is important to minimize the required resources and the effect on the power...
generation. To suppress curvature, we study about shape control by surface coating aimed to make ultra-lightweight flat thin film solar cell which can be used in a space environment.

We carried out the experiment to evaluate the internal stress generated by the surface coating of the oxide materials on the films and to confirm the durability against the space environmental factors.

In this paper, we describe the results of the experiments and prediction of the shape of the solar array by the surface coating.

2. Internal stress by sputtering for the coating layer

This section describes the experiments about the measurement of the internal stress generated by the coating layer of the oxide materials.

2.1. Experimental methods

We used thin glass substrates to get the internal stress that was calculated using the radius of the curvature of the coated glass substrate.

2.1.1. Measurement of the radius of the curvature

We measured the radius of curvature of the coated glass substrate. We used zinc oxide (ZnO) and cerium oxide (CeO₂) for the coating materials. Figure 2 shows the measurement of the radius of curvature of the coated glass substrate.

\[ \frac{1}{R} = \frac{(1 - \cos \theta)}{\delta} \]  
(1)

where \( R \) is the radius, \( \delta \) is the deflection and \( \theta \) is the angle of the deflection.

We measured the deflection of the coated glass and calculated the radius of the curvature by Eq. (1).

2.1.2. Measurement of the stress on the cross sectional area

The glass substrate is assumed to be a beam. We calculated the stress on the cross sectional area of coating layer to predict shape by using a beam model. If the thickness of coating layer is assumed to be thinner than glass thickness, the internal stress is given by

\[ \sigma_1 = \frac{ED^2 \delta}{3L^2 h} \]  
(2)

where \( \sigma_1 \) is the internal stress, \( E \) is the Young’s modulus, \( D \) is the thickness of glass substrate, \( L \) is the length of the glass substrate, and \( h \) is the thickness of oxide layer.

We measured the deflection of the coated glass and the stress on the cross sectional area by Eq. (2).

2.2. Experimental set up

We have prepared metal oxide layer by RF magnetron sputtering for the surface coating layer. We have used ZnO and CeO₂ as metal oxide layer. The thickness of layers of ZnO are 20~700 [nm]. The thickness layers of CeO₂ are 20~400 [nm]. We used borosilicate glass as the substrate with the size of 50×3 [mm] and the thickness of 50 [μm].

2.3. Results and discussions

2.3.1. Results of measurement the radius of the curvature

The measured results of the radius of the curvature in the case of ZnO and CeO₂ are shown in Fig. 3.

In Fig.3, The curvature increases linearly. The curvature in the case of ZnO is larger than in the case of CeO₂. We can calculate the internal stress by using the measured values in Fig.3.

2.3.2. Results of measurement the stress on the cross sectional area

The stresses on the cross sectional area in the case of ZnO and CeO₂ are calculated by Eq. (2) as shown in Figs. 4 and 5.

The stress on the cross sectional area increases linearly. The stress in the case of ZnO layer is larger than in the case of layer of CeO₂. We have used a value obtained by linearly approximating for the shape prediction.
3. Experiment of shape prediction

This section describes the experiment of shape prediction. The experiments are calculation the radius of the curvature of a-Si solar array films and coated the a-Si solar cells.

3.1. Experimental methods

3.1.1. Calculation the radius of curvature of coated a-Si solar array films

We estimated the radius of curvature of coated a-Si solar array films. Relationship between the strain and the deflection is given by

\[ \varepsilon + \frac{\sigma_1}{E_1} = \frac{D\delta}{L^2} \]  \hspace{1cm} (3)

where \( \varepsilon \) is the strain. And the internal stress in the case of sputtering to solar cell is given by

\[ \sigma_z = \varepsilon E_2 \]  \hspace{1cm} (4)

We calculated the strain and the internal stress generated by sputtered to solar cell by Eqs. (2), (3) and (4). These results are used in Eqs. (5) and (6).

The each layer is assumed to be as the Bernoulli-Euler beam. The position of a neutral plane from each layer is given by

\[ \int \sigma dS = 0 \]  \hspace{1cm} (5)

where \( S \) is the cross sectional area of applied the internal stress.

The bending moment is given by

\[ \sum M = 0 \]  \hspace{1cm} (6)

where \( M \) is the bending moment.

We calculated the strain of solar cell which is described \( \varepsilon' \) by Eqs. (5) and (6). Relationship between the radius of curvature and the strain of solar cell are as Eq. (7).

\[ R = \frac{D}{2} \left( 1 + \varepsilon' \right) \frac{1}{\varepsilon' + \varepsilon} \]  \hspace{1cm} (7)

We calculated the radius of curvature of a-Si solar array films and predict shape of the coated the a-Si solar array films.

3.1.2. Shape control of a-Si solar array film

We sputtered ZnO as metal oxide layer on the a-Si solar array films. We examined the suppression of the curvature and made a comparison between predicted the radius of curvature of the coated a-Si solar array films and measured radius of the curvature of that.

3.2. Experimental set up

We prepared the sputtered a-Si solar array films with ZnO by RF magnetron sputtering. Details of experimental samples are shown in Table 1. The thickness of coating layer on both sides as shown in Table 1 is calculated under the condition that the radius of curvature of a-Si solar array films is less than about 10 [1/m].

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Size [mm]</th>
<th>Front side coating layer [nm]</th>
<th>Reverse side coating layer [nm]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>290×516</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>293×733</td>
<td>500</td>
<td>450</td>
</tr>
<tr>
<td>3</td>
<td>293×420</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

3.3. Results and discussion

3.3.1. Result of calculation of the radius of curvature of coated a-Si solar array films

The radius of curvature of the non-coated a-Si solar array film is 44.02 [1/m]. By using this result and the measured values in Fig. 4, we predicted the shape of coated a-Si solar array film as shown in Fig. 6.
In Fig. 6, we predict that the non-coated a-Si solar array films are suppressed the approximately 80 percent of the curvature by ZnO coating.

3.3.2. Result of shape control of a-Si solar Array Film

Figure 7 shows the coated a-Si solar array film. The coating layer is ZnO. The thickness of coated layer on front side is 500 [nm]. The thickness of coated layer on reverse side is 400 [nm].

We can flatten the a-Si solar array films by the oxide coating as shown in Fig. 7. We can also flatten other samples. We have succeeded in suppression of the curvature.

4. Experiment of durability against space environment

4.1. Experimental methods and set up

4.1.1. Experiment of ultraviolet irradiation

We measured degradation of non-coated CIGS solar cell and coated CIGS solar cell due to ultraviolet light. The coating material was CeO$_2$. Figure 8 shows the solar simulator with AM spectrum conditions. The thickness of layers of CeO$_2$ was 100 [nm].

We conducted the experiment of ultraviolet irradiation for one year. We used the solar simulator with the light intensity of 5 sun which is 5 times greater than the flux density of the sunlight at the distance of 1 AU from the Sun in order to carry out the acceleration test. We measured the short circuit current (Isc) and evaluated durability against ultraviolet light.

4.1.2. Experiment of proton irradiation and electron irradiation

We measured degradation due to proton and electron by experiment of proton irradiation and electron irradiation.

In experiment of proton irradiation, non-coated CIGS solar cell and coated CIGS solar cell were used. The coating materials were ZnO and CeO$_2$. As the experiment condition, the electron density is about 10$^{12}$ [/cm$^3$]. The thickness of layers of ZnO and CeO$_2$ were 500 [nm] and 100 [nm], respectively.

In experiment of electron irradiation, non-coated CIGS solar cell and coated CIGS solar cell were used. The coating material was ZnO. The thickness of layers of ZnO was 500 [nm].

We measured I-V characteristics and evaluated durability against electron and proton irradiation.

4.2. Results and discussion

4.2.1. Result of experiment of ultraviolet irradiation

The results are shown in Figs. 9 and 10. Non-coated CIGS solar cell and coated CIGS solar cell are not observed tendency of degradation due to ultraviolet light in Figs. 9 and 10. We found from this result that it is possible to prevent degradation due to ultraviolet light by coated CeO$_2$. But CIGS solar cell is observed decrease of the Isc by coated CeO$_2$. It is considered to be caused by the influence of the transmittance.
4.2.2. Result of experiment of proton irradiation and electron irradiation

The results of proton irradiation experiment are shown in Figs. 11 and 12.

In Figs. 11 and 12, CIGS solar cell is observed decrease of the I_{sc} by coated CeO\textsubscript{2}. As with the result of experiment of ultraviolet irradiation, it is considered to be caused by the influence of the transmittance. Coated CIGS solar cell is not observed tendency of degradation by proton irradiation. We found from this result that CIGS solar cell and oxide layers have durability against degradation by proton irradiation.

The results of electron irradiation experiment are shown in Figs. 13 and 14.

In Fig. 13, CIGS solar cell is not observed degradation by electron irradiation. In Fig. 14, CIGS solar cell is observed decrease of the I_{sc} by coated ZnO. Coated CIGS solar cell is not observed tendency of electron degradation. It is considered to be caused by the influence of the transmittance. We found from this result that CIGS solar cell and oxide layers have durability against degradation by electron irradiation.
5. Conclusion

We evaluated shape prediction of the thin film solar array by metal oxide coating and durability against space environment by experiments of ultraviolet irradiation, proton irradiation and electron irradiation. We confirmed that we could control the shape of the multi-layer films such as the solar array films by the surface coating using oxide materials experimentally. We figured out durability against space environment of the solar cell and the surface coating.

From now on, we examine the optimal thickness of the curvature suppression in consideration of the reduction of the conversion efficiency by film coating. We carry out tests of infrared spectroscopy to investigate whether or not the Isc is reduced by the influence of the transmittance.

References

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