A Study on control of curvature of multilayer by sputter deposition

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Abstract

The solar power sail "IKAROS" and next solar power sail have the thin-film solar cells on the membrane. The thin-film solar cells have a curvature by the bimetal effect when a temperature changes shape changed of membrane by the thin-film curved solar cells has a bad influence on generating efficiency and accelerating performance by photon the sputter deposition is focused for solving this problem. The sputter deposition can make a new thin layer on the thin-film solar cell and internal stress of a new layer can reduce the curvature of the thin solar cell. On this study, unknown physical property of the thin-film solar cell will be identified from the theoretical formula and experimental. Value the curvature change of the thin solar cell with sputtering in the temperature change will be estimated.

スパッタリングによる多層膜の曲率管理に関する研究

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摘要

ソーラー電力セイル実証機 IKAROS や次期ソーラー電力セイルに搭載される薄膜太陽電池は多層膜構造体のバイメタル効果により温度変化によって曲率を持つことが確認されている. この曲率によって膜全体が変形し発電効率や光子加 s 速性能に悪影響を及ぼす. そこで薄膜太陽電池に新たな層を形成し, その薄膜がもつ内部応力によって曲率を低減するスパッタリング法に着目した．本研究では，温度変化に伴って変形する多層膜の曲率を管理することに焦点を置く．理論式と実験結果を用いて薄膜太陽電池の未知の物性値を同定し, その物性値を用いてスパッタリングを施した薄膜太陽電池の温度変化に対する挙動変化を予測する.

1. Introduction

In 2010, IKAROS, the first solar power sail shown as Fig.1.1., was demonstrated power generation. At the same time, IKAROS was also observed curvature of thin-film solar cell on IKAROS surface. Whole membrane shape is changed when thin-film solar cells are on membrane and shape change is bad influence on decreasing generating efficiency and accelerating by photon, so it needs to reduce curvature of thin-film solar cell. IKAROS tried to reduce curvature by attaching same solar cell on back surface, but various problems－mass, thickness and cost increased. This study focused on sputter deposition, one of the method of making thin film. This method can generate large internal stress in very thin film. This study is considered that large internal stress by sputter deposition, so purposes of this study are estimating internal stress and physical property of thin-film solar cell and control thin-film curvature in temperature range.

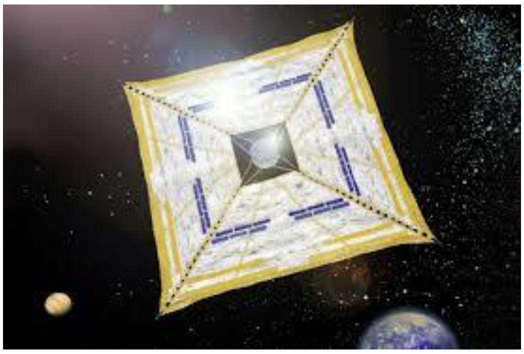

Fig. 1.1. IKAROS

2. Thin-film model

In order to use sputter deposition for curvature control, sputter material and internal stress by sputter condition are needed to arrange information. In this study, internal stress of sputtering is estimated by investigating deflection of sample. This study used two substrate samples 25μm and 50μm of UPILEX-S. These samples differ only thickness but sputter stress generated by sputtering is almost same when thickness of sputter layer is same if thickness of substrate is not same. It is proved validity of formula used by this characteristic.

First, it is considered about thin-film structure of two layer. Thermal stress σ_T is generated on cross section of thin-film by bimetal effect. It assumed that thermal stress generated on cross section is simplified, thermal stress σ_T is

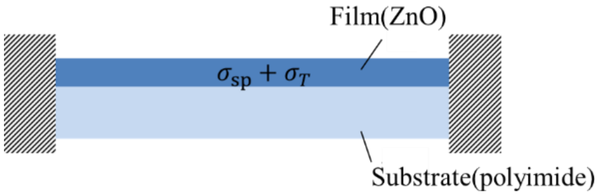

Fig. 2.1. The condition of the true stress and the thermal stress.

$$\sigma_T = -E_f\left(\alpha_f - \alpha_s\right)\Delta T \tag{1}$$

Where E_f, α_f, α_s and ΔT mean Young's modulus of sputter layer, coefficient of thermal expansion of sputter layer, coefficient of thermal expansion of substrate layer and difference between sputter temperature and observing temperature. Next, when it is changed to cantilever from double supported, sample is like Fig. 2.2 with radius curvature R.

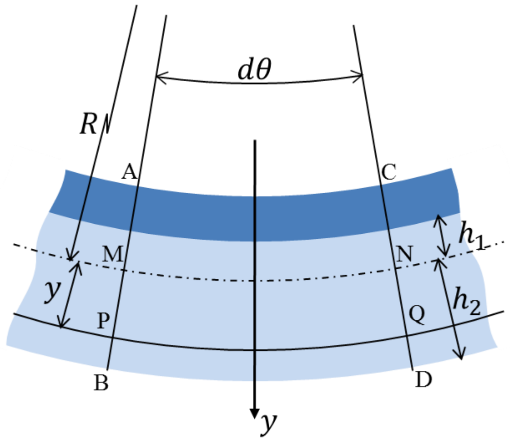

Fig. 2.2. The bending state of the film and the substrate.

Physical properties are defined shown as Fig. 2.2. bending strain ε and bending stress σ generated in PQ layer show formula (2) and (3).

$$\varepsilon = \frac{PQ - MN}{MN} = \frac{(R+y)d\theta - Rd\theta}{Rd\theta} = \frac{y}{R} \tag{2}$$

$$\sigma = E\varepsilon = E\frac{y}{R}\begin{cases} E_f\dfrac{y}{R} \\ E_s\dfrac{y}{R} \end{cases} \tag{3}$$

Then, bending stress can show linear expression, so stress worked on substrate and thin-film σ_s and σ_{sp} is

$$\sigma_s = E_s\frac{y}{R} \tag{5}$$

$$\sigma_f = E_f\frac{y}{R} + \sigma_{sp} + \sigma_{Tf} \tag{6}$$

Poison ratio is defined zero because behavior of samples is measured as one dimensional behavior. In addition, (7)~(9) expression are shown from bending moment and geometric balance.

$$\int_{-h_1}^{h_2}\sigma_f\,dy + \int_{-h_1-D_f}^{-h_1}\sigma_s\,dy = 0 \tag{7}$$

$$\int_{-h_1}^{h_2}\sigma_f\,y\,dy + \int_{-h_1-D_f}^{-h_1}\sigma_s\,y\,dy = 0 \tag{8}$$

$$h_1 + h_2 = D_s \tag{9}$$

Furthermore, (10) and (11) are calculated from (7)~(9).

$$h_1 = \frac{E_s\left(4D_s^3D_f + 3D_s^2D_f^2\right) + E_fD_f^4}{6E_s\left(D_s^2D_f + D_sD_f^2\right)} \tag{10}$$

$$\sigma_{sp} = \left(\frac{E_s\left(2D_sh_1 - D_s^2\right) + E_f\left(2D_fh_1 + D_f^2\right)}{2D_fR} - \sigma_T\right) \tag{11}$$

From these expression, internal stress of sputter layer can calculate if radius curvature R is observed when samples are two layer.

Moreover, (12) expression is shown in the temperature change.

$$\frac{\Delta(1/R)}{\Delta(\Delta T)} = \frac{2E_f\left(\alpha_f - \alpha_s\right)D_f}{E_s\left(2D_sh_1 - D_s^2\right) + E_f\left(2D_fh_1 + D_f^2\right)} \tag{12}$$

Next, it is considered expression about multi-layer samples. In case of layer above three, thermal stress cannot assume same value in whole layer, so thermal stress which is generated in 'i' layer is

$$\sigma_{Ti} = -E_i \alpha_i \Delta T \qquad (13)$$

When True stress by sputter Stress is defined σ_{spi}, a 'i' layer is

$$\sigma_i = E_i \frac{y}{R} + \sigma_{spi} + \sigma_{Ti} \qquad (14)$$

Balance of bending moment and axis force hold in multi-layer, so expression is shown

$$\int_{-h_1}^{h_2} \sigma_s dy + \int_{-h_1-\sum_{k=1}^{i} D_k}^{-h_1-\sum_{k=1}^{n-1} D_k} \sigma_i dy = 0 \qquad (15)$$

$$\int_{-h_1}^{h_2} \sigma_s y dy + \int_{-h_1-\sum_{k=1}^{i} D_k}^{-h_1-\sum_{k=1}^{n-1} D_k} \sigma_i y dy = 0 \qquad (16)$$

Using these expression and radius curvature R from experiment, internal stress of thin-film is estimated, after that, unknown parameter of thin-film solar cell(a-Si) are estimated used internal stress. Usually, thin-film solar cell is consisted of multi-layer structure, so unknown parameters increase if unknown layer increase. In this study, multi-layer structure regard as single layer like Fig. 2.2., so dummy physical property is estimated.

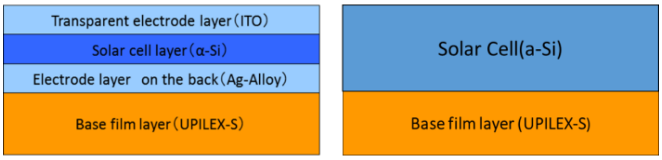

Fig. 2.2. The details of each layer of the solar cell.

3. Thermal vacuum experiment

3.1 Experiment method

Thermal vacuum experiment was done in order to observe relationship between temperature and radius curvature of samples in high temperature condition. There are two kind of substrates of samples, that is 25μm and 50μm of UPILEX-S. In addition, ZnO is used for sputter material and it is ready 4 thicknesses, 0, 100, 200, 400nm. In thin-film solar cell, ZnO thickness is ready 0, 100, 400nm. Temperature is measured with thermocouple attached to polyimide(UPILEX-S) not to sputter. Configuration of experiment is shown Fig. 3.1.

Experiment data is got 10 degree each between 20 degree and 130 degree. Calibration seat is set to same position of samples and compensated as Fig. 3.2. in this result, distortion is generated max 3.74%. radius curvature is observed two pixel points which are edges of samples like Fig. 3.3. From these data distance of pixel converted distance of meter.

In addition, samples are confirmed whether there is influence of gravity or not because direction of deflection is same direction to gravity shown as Fig. 3.4. From this result (Table. 3.1.), all value are almost same, so influence of gravity can be ignored in this experiment.

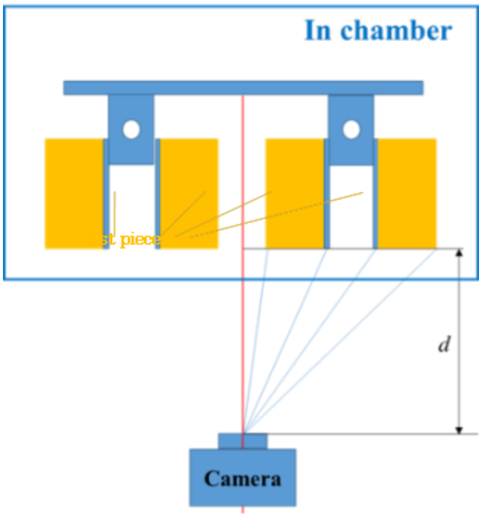

Fig. 3.1. The configuration of the experiment.

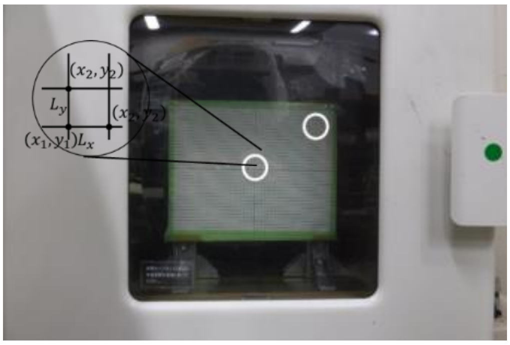

Fig. 3.2. A calibration seat in a chamber.

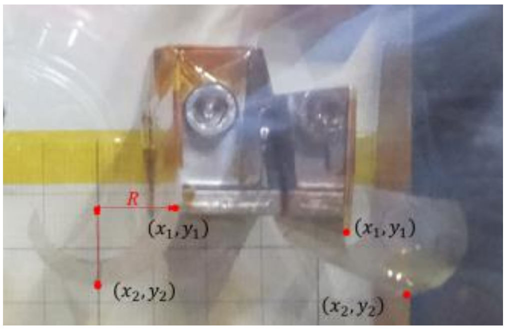

Fig. 3.3. The method of measuring radius curvature.

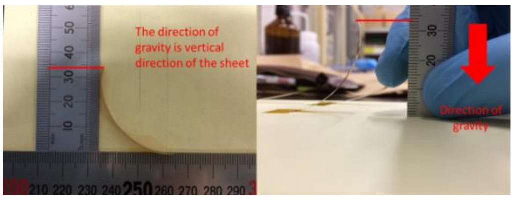

Fig. 3.4. Comparison between two direction.

Table. 3.1. A radius curvature between gravity and no-gravity.

	1st	2nd	3rd	4th	Average
Gravity	20.8	21.7	21.8	22.0	21.57133
No-gravity	21.5	21.7	21.7	20.6	21.36566

3.2 result of experiment

First, two layer results are shown from Fig3.5. to Fig3.7.

Internal stress is almost corresponding, so there is validity of logical calculation. When physical properties of thin-film solar cell are estimated, value of stress is used of 25µm because thickness of thin-film solar cell is about 30µm. Fig. 3.9. and Fig. 3.10. are shown result of thin-film solar cell. Dummy physical properties are shown as Table. 3.4. when values of these result are applied to logical calculation.

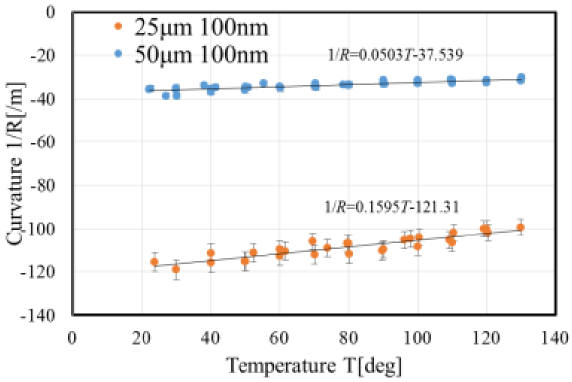

Fig. 3.5. The relationship between the curvature and the temperature at 100nm

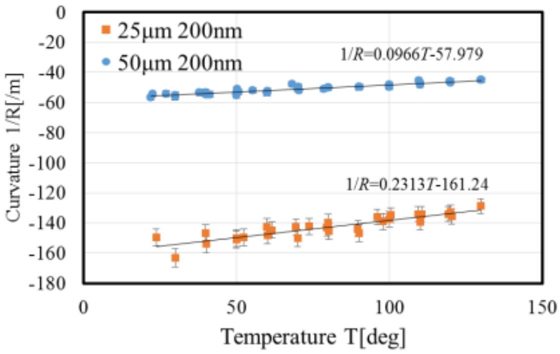

Fig. 3.6. The relationship between the curvature and the temperature at 200nm

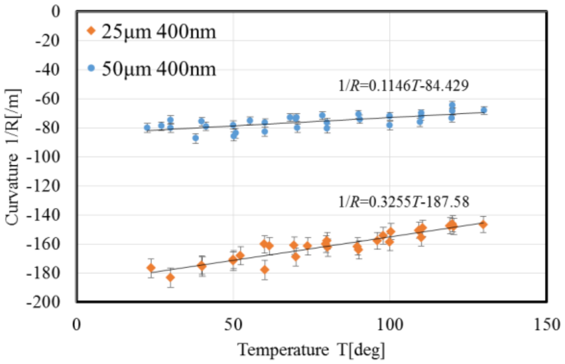

Fig. 3.7. The relationship between the curvature and the temperature at 400nm

From this result, internal stress of sputter layer (ZnO) is shown at Table. 3.3. and Fig. 3.8.

Table. 3.3. The internal stress at each thickness of the film.

	100nm [Pa]	200nm[Pa]	400nm[Pa]
25µm	-1.41E+09	-1.17E+09	-0.866E+09
50µm	-1.38E+09	-1.31E+09	-1.24E+09

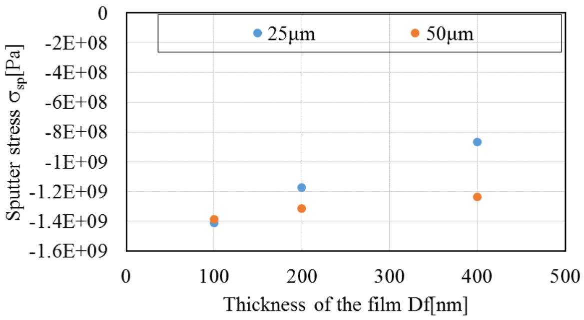

Fig. 3.8. The relationship between temperature and sputter stress.

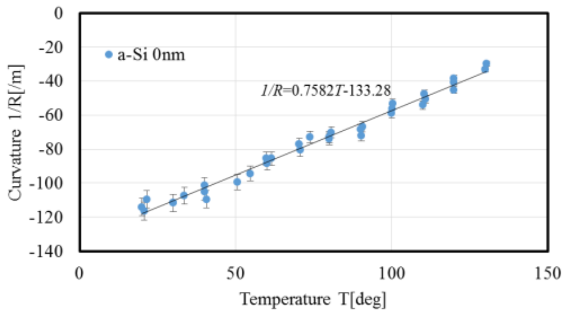

Fig. 3.9. Relationship between curvature and temperature at 0nm.

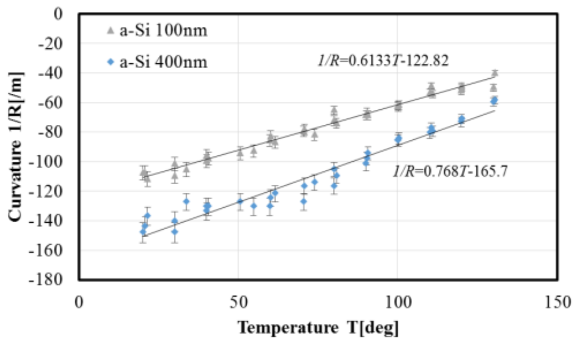

Fig. 3.10. Relationship between curvature and temperature at 100nm and 400nm.

Table. 3.4. The physical property of a-Si.

	Internal stress σ_{sp}	Young's modulus	CTE
100nm	3.22E+08	2.24E+11	1.36E-10
400nm	3.47E+08	2.10E+11	1.36E-10

4. examination

When sputter stress of substrate thickness 25μm and 50μm are compared, in sputter thickness 100nm, sputter stress is almost corresponding but gap widen if thickness of sputter is increased. The factor is considered that value of linear approximation is used. In this experiment, there are 30 observation points. Linear approximation makes from these data so error is big when inclination of least squares method. Sputter stress decrease when thickness of sputter increase between 100nm to 400nm shown as Fig. 3.8. Compared between samples of 100nm and 200nm, atomic position of 200nm is steadier than that of 100nm.

Physical properties estimated from experiment of 100nm sputter and 400nm sputter are almost corresponding, so these value is reliable.

Difference of internal stress caused on error of linear approximation.

From result of 100nm and 400nm, dummy physical properties of a-Si can anticipate near value of Table. 3.4.

Relationship between thickness of sputter and internal stress is needed to get more data. This study is got result as Fig. 3.8. but number of plot is only three. Validity needs to be considered to get data between 100nm to 400nm.

5. Conclusion

- Be confirmed validity by constructing logical model to use to get radius curvature of multi-layer structure and experiment.
- Observed behavior of film and curvature change in large range of temperature by using thermal vacuum chamber.
- estimated dummy physical property of a-Si by logical model

6. Future works

(1) Design of curvature of thin-film solar cell by getting more data.

(2) appreciated CIGS thin-film solar cell used to next solar power sail.

(3) analysis of film in two division surface.

Reference

(1) 白澤洋次，JAXA，宇宙構造材料シンポジウム

(2) 寺元祐貴，東京大学大学院，「スパッタリングによる多層膜の曲率管理に関する研究」