Flight Data of a Cu(In,Ga)Se₂ Thin-Film Solar Cell Module without a Coverglass by a Nano Satellite

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A CIGS solar cell module without a coverglass was demonstrated by a small satellite since October 2005. A coverglass is normally used to protect the cell performance from low-energy (<3MeV) protons in space. This mission evaluates the model to assess the cell performance of CIGS solar cells, which thus far exhibited no degradation by thermal annealing effect in space. Flight data indicates that the performance has showed no degradation for about 900 days.

Key Words: Solar Cell, Radiation, Cu(In,Ga)Se₂, Flight Demonstration

1. Introduction

A copper indium gallium di-selenide (CIGS) thin-film solar cell is a promising candidate for future thin-film space solar cells because it has shown conversion efficiencies greater than 19%¹⁾, which is considerably higher than other thin-film solar cells. Excellent radiation tolerance of CIGS thin-film cells has also been reported²⁾. The CIGS thin-film solar cells exhibit superior performance compared to conventional Si and GaAs space solar cells. They are low-cost, lightweight, and flexibility since the cells can be formed on polyimide³⁾ or metal sheet⁴⁾ substrates. These solar cells can be developed on flexible solar panels. However, solar cells require coverglasses to protect the cell performance from low-energy protons in space.

Radiation damage studies using CIGS thin-film solar cells have revealed that electrical properties of the cells are not degraded by high-energy electron irradiation. However, cell performance is degraded by high-energy proton irradiation similar to other types of solar cells²⁾. Radiation damage to the cells caused by proton irradiation gradually recovers when irradiated cells are kept at room temperature⁵⁾. In fact, the cell's recovery rate depends on the temperature⁶⁾. Predictions of on-orbit performance of CIGS solar cells must address their ability to recover well from radiation damage by thermal annealing.

We demonstrated CIGS solar cells on the MDS-1 satellite for 600 days starting in February 2002⁷⁾. The short-circuit current (I_{SC}) of the CIGS cells did not degrade, the open-circuit voltage (V_{OC}) of the cells degraded only about 1%. In contrast, the performance of other solar cells on the satellite, including Si and GaAs space solar cells, deteriorated significantly. The CIGS solar cells' superior recovery rate from radiation damage by thermal annealing was established through ground tests.

We predicted the degradation of the CIGS solar cells in space using the relative damage coefficient, the annealing rates of V_{OC} and I_{SC} for protons irradiating the cells, and the radiation response of the cells without thermal annealing. The results were in good agreement with observed data of the CIGS solar cells on the satellite. These results enabled us to predict that the electrical performance of the CIGS solar cells without a coverglass will not degrade in space. Therefore, flexible solar paddles with thin-film solar cell modules are considered achievable. We have been studying the new type of solar paddles with thin-film solar cells⁸⁾.

Electrical components are rarely demonstrated in space by satellites. Solar cell electrical performance has been verified using JAXA satellites only three times in the past 15 years. Small satellites weighting less than 100 kg have severe resource limitations. Small satellites are suitable for demonstrating solar cells in space because their measurement systems are simple and lightweight. For those reasons, these small satellites are very useful for quickly demonstrating new technologies in space. Universities worldwide have been developing miniature small satellites known as nano-satellites. A CIGS solar cell module without a coverglass has demonstrated by a nano-satellite in Low Earth Orbit (LEO). This paper presents discussion of the flight data of the module on the satellite.

2. Experiments

2.1 Cu(In,Ga)Se₂ Thin-Film Solar Cell Module

A CIGS thin-film solar cell module was fabricated using a selenization/sulfurization method⁹⁾. An overview

Fig. 1. Overview of the CIGS module.

Fig. 2. Current-voltage characteristics of the CIGS solar cell module on the Cubesat XI-V satellite.

of the module is presented in Fig.1. The structure of the cells is $\text{ZnO}/\text{Zn}(\text{O},\text{S},\text{OH})_x/\text{Cu}(\text{In},\text{Ga})\text{Se}_2/\text{Mo}/\text{Glass}$. The module was comprised 14 series-connected solar cells on the glass substrate. With efficiency of 11.0%, the solar cell module has V_{OC} of 8.6 V and I_{SC} of 162mA, as measured under AM0, 1-sun conditions. Figure 2 portrays the module's electrical performance.

Thermal cycle tests were carried out for CIGS modules. The temperature range was 90°C to -40 °C, for 3000 cycles. The cell performance degradation was less than 1%.

2.2 Nano-satellite Cubesat XI-V

University students are developing 10cm cubic satellites in the Cubesat project. The satellites will be launched into LEO. This project was originally adopted in the University Space Systems Symposium, and has been promoted primarily by Japanese and American universities community. More than 60 organizations are now developing Cubesats.

The University of Tokyo has been developing a nano satellite called Cubesat XI. The satellite is 10 cm

Fig. 3. Overview of Cubesat XI-V.

× 10cm × 10cm and weights 1 kg.

On October 27, 2005, Cubesat XI-V was launched on by a Russian rocket¹⁰⁾. The satellite was placed in Sun-synchronous orbit with an altitude of 688 km. An overview of the satellite is presented in Fig. 3.

The satellite has six solar cell modules to generate electric power. The modules comprise two space Si solar modules (+X, +Z) with 100 μm coverglass, three InGaP/GaAs dual junction (DJ) solar modules (+Y, -Y, -Z) with 100 μm coverglass and one CIGS solar module (-X) without coverglass. The average power of the satellite is 1.1 W.

The Si solar modules comprise 10 series-connected space Si solar cells. The DJ solar modules comprise two series-connected dual junction solar cells. All solar modules are parallel-connected to the load and the battery component. Table 1 presents the cell performance data of the solar modules mounted on XI-V.

Table 1. Electrical performance of the solar cells on Cubesat XI-V

	Type	Conversion Efficiency (%)
+X	Space Si Solar Cell	16
-X	CIGS Solar Cell Module	11
+Y	Space DJ* Cell	16
-Y	Space DJ * Cell	16
+Z	Space Si Solar Cell	16
-Z	Space DJ *Cell	16

*DJ: Double Junction

The CIGS module temperature sensor is located on the front side on the plate; other modules have sensors on the back side. The temperatures are monitored simultaneously when the electrical performance of the module is assessed.

3. Results and Discussion

We analyzed changes in the currents for about 900 days following the launch thereby evaluating our predictions.

Two observation modes were used. One mode, the detailed mode, is monitored every two seconds. The other mode, the rough mode, is monitored every 248 seconds. The satellite has been operated in either mode.

Figure 4 presents the flight data in the detailed mode 30 days after launch. Changes in the generating currents of each solar module are caused by the satellite rotation. The spin rate was determined from Fig.4 to be about 0.1rpm.

Figure 4 depicts that the maximum current of the Si module (+X) was 120.1mA, whereas the maximum value of the CIGS module was 114.3mA. The duration between the monitored currents of the Si module and the CIGS module was 374 seconds. Therefore, the change in the solar angle to the satellite was about 16 degree, and the solar light intensity decreased about 4%. The current of the Si module was estimated at 115.5 mA, based on the measurement time of the CIGS module. The difference between the corrected current of the Si and the maximum current of the CIGS was about 1 mA. In contrast, the respective I_{SC} of the Si and CIGS module were 164 mA and 163 mA in the ground test under AM0 solar light. The difference in the current from the flight data agreed well with that from the ground test. This result indicates that the Si and CIGS module generated the electrical power normally in space. Furthermore, the cell performance of the Si solar modules was not degraded from the predictions using a coverglass, indicating that CIGS modules do not degrade in space.

We analyzed the long-term trend data of the cell performance of the CIGS solar module. The solar light intensity was corrected using a comparison of the current of the CIGS module with that of the Si module, which was placed on the opposite side. The trend data were additionally estimated from the data of the rough mode, which monitors the data for more than one day. The flight data of the currents and temperatures of each module 35 days after launch are presented in Fig. 5.

The respective maximum and minimum temperatures of the CIGS module were 44°C and -16°C. In contrast, the maximum temperature of the other modules was 39°C. The maximum temperature was higher than that of the other modules. The thermal emissivity of the CIGS module is 0.25 since the module do not have a coverglass. The emissivity of the other modules is 0.8. Therefore, the emission rate of the heat from the CIGS module is lower compared with that of the other modules.

Fig. 4. Changes in the generating current of each solar modules 30 days after launch.

(a) Temperature

(b) Current

Fig. 5. Flight data of the solar modules on the satellite 35 days after launch.

The maximum current of the CIGS and Si (+X) module were 161.9 mA and 160.8 mA, as indicated in Fig. 5. The difference in the current between the CIGS and Si module from the ground measurements was the same as in the flight data, which indicates that the trend data are

obtained by comparing the maximum currents of the CIGS and Si module.

High radiation damage recovery of CIGS solar cells attributable to high temperature annealing was noted in ground testing. The results indicated that the electrical performance of CIGS solar cells without coverglass will be unaffected by radiation damage in space. The temperature of the CIGS module on the satellite was 30°C. Figure 6 illustrates predictions of the cell performances with and without thermal annealing effect for CIGS solar cells without coverglass. This result suggests that degradation of the current without the effect would be about 3% annually. In contrast, the current with the effect exhibited no degradation.

Fig. 6. Remaining factor of the cell performance for the CIGS solar cell in LEO. Full triangles and full blocks indicate I_{sc} and V_{oc} concerning without thermal annealing. Open triangles and open blocks indicate I_{sc} and V_{oc} with thermal annealing.

A previous analysis of Si solar cell degradation in LEO indicated that the degradation of electrical power was less than 0.5 % for three years¹¹⁾. The predicted equivalent 1MeV electron fluence for the Cubesat XI satellite mission is less than $5 \times 10^{13} \text{ cm}^{-2}$. The Si solar cells are not believed to be degraded by the amount of 1MeV electrons, based on the ground test results. Therefore, the solar light intensity can be corrected by comparing the current of the CIGS module with that of the Si module.

The current trend data of the CIGS and Si (+X side) solar cell module is depicted in Fig.7. This value is the maximum current on each day. The currents showed no degradation. The prediction of cell performance of Si solar cells with 100 μm in LEO indicates that current degradation is less than 1% for one year. This analysis agrees with the flight data of the Si cells. The current of the CIGS was corrected from the current of Si. The trend data of the current in the CIGS are presented in Fig. 8.

The first flight data (MET=7 days after launch) were used as the initial values. Figure 8 depicts that the current

is not degraded, which agrees well with our prediction.

(a) CIGS

(b) Si

Fig. 7. Current of the CIGS solar cell module (-X) and the Si solar cell module (+X) on the satellite.

Fig. 8. Remaining factor of corrected current of the CIGS solar cell module on the satellite.

4. Summary

The MDS-1 satellite demonstrated that the electrical performance of CIGS solar cells was not degraded in space, which implies that the CIGS cells require no coverglass to block low-energy protons. A CIGS module without coverglass was used on the Cubesat XI-V satellite to verify this prediction. The flight data confirmed that there was no degradation of the cell performance occurred, which verifies CIGS solar cells availability use in space.

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