QUALIFICATION TEST RESULTS OF IMM TRIPLE-JUNCTION SOLAR CELLS, SPACE SOLAR SHEETS, AND LIGHTWEIGHT&COMPACT SOLAR PADDLE

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ABSTRACT

Development of a high specific power, low stowage volume and lightweight solar paddle utilizing high-efficiency, thin-film, InGaP/GaAs/InGaAs inverted metamorphic triple-junction solar cell has been completed. The cell exhibits the efficiency of as high as 32% with sufficient radiation resistance. Owing to the high efficiency of the cell, the paddle achieved the specific power of greater than 150 W/kg. Qualification and reliability tests for the cell and paddle were carried out. The results confirmed that both the cell and paddle have enough capability to use them in space. Space demonstration of the paddle is now in preparation.

1. INTRODUCTION

Solar paddles with high specific power (W/kg) and compact stowage volume have been demanded to meet the requirements of high electrical output power for spacecraft within limited launch volume [1-4]. We started the development of such solar paddles about a decade ago, and completed the development last year. To realize high specific power, high-efficiency, thin-film, InGaP/GaAs/InGaAs inverted metamorphic triple-junction (IMM-3J) solar cells have been developed to apply to the solar panels of the paddle. The cells are formed in a thin and flexible cell array structure which is called space solar sheet (SSS) [5]. We completed the development of SSS with InGaP/GaAs dual-junction thin-film (TF-2J) solar cell in 2011 [6]. However, since the efficiency of the TF-2J cell was as low as around 25%, the target specific power of 150 W/kg at paddle level was not realized.

In this paper, we introduce the performance of the high specific power solar paddle as well as the IMM-3J solar cells utilized in the paddles. The results of qualification and reliability tests for the cells and paddles are presented. Also, space demonstration test results on the SSS, which are proving high environmental resistance, are shown. In addition, we now have a plan to demonstrate the paddle in space. The details of the plan are explained.

2. IMM TRIPLE-JUNCTION SOLAR CELL

The IMM-3J thin film solar cells are fabricated by inverted growth of InGaP top-cell, GaAs middle-cell and InGaAs bottom-cell by metal-organic vapour phase epitaxy (MOVPE). The cell layers were mounted on a film with the thickness of 10-20 µm after the removal of GaAs substrates, and then the cell fabrication process was carried out. Figure 1 exhibits a photograph of the typical figure of completed IMM-3J bare cells.

Figure 1. Typical figure of bare IMM-3J solar cells after completion of the fabrication process.

Two types of IMM-3J space solar cells with different design have been developed. One is Type A which has rather radiation hard design in order the remaining factor of maximum power (*P*max) to be greater than 85% after irradiation of 1 MeV electrons with a fluence of 1×10^{15} e^-/cm^2. Meanwhile, the other, Type B, is designed for missions in which high radiation tolerance is not required. Therefore, beginning-of-life (BOL)

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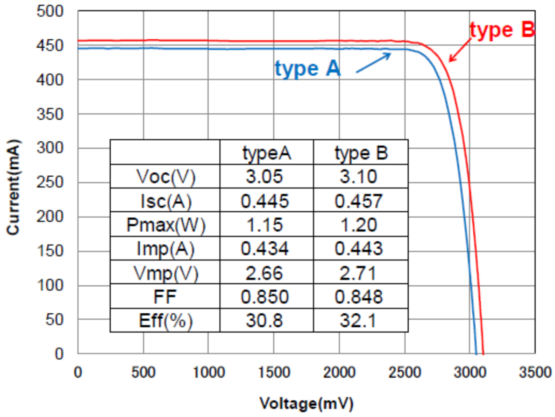
efficiency of Type B cell is higher than that of Type A



	typeA	type B
Voc(V)	3.05	3.10
Isc(A)	0.445	0.457
Pmax(W)	1.15	1.20
Imp(A)	0.434	0.443
Vmp(V)	2.66	2.71
FF	0.850	0.848
Eff(%)	30.8	32.1

Figure 2. Light I-V characteristics of two types of IMM-3J space solar cells (27.4cm^2, AM0, 25°C).

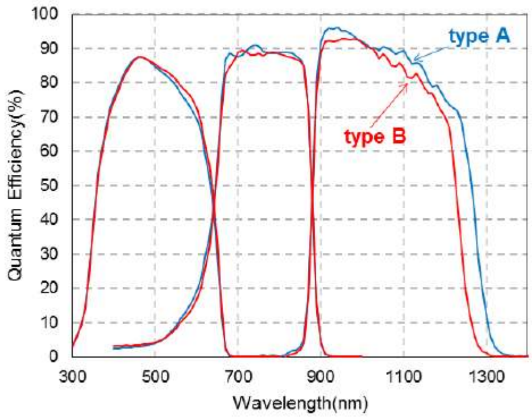


Figure 3. Comparison of external quantum efficiency (EQE) of Type A and B IMM-3J solar cells.

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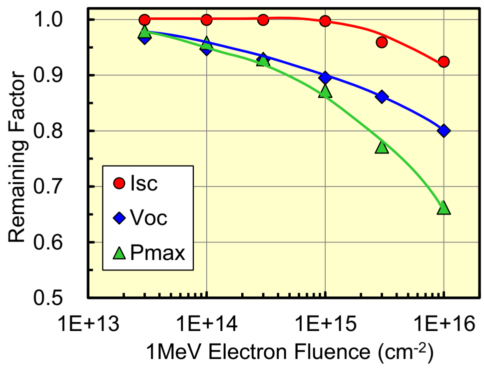
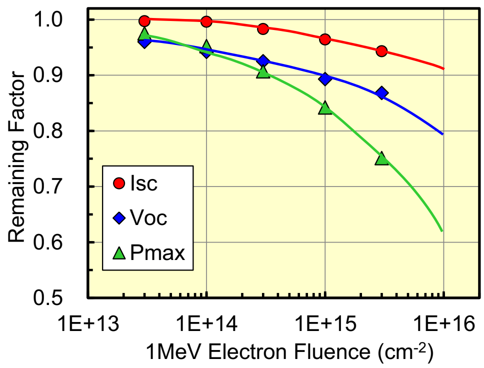
Fig. 2 presents light current-voltage (I-V) characteristics of the two types of IMM-3J cells. The cell area is 27.4 cm^2. The best efficiency of Type A is 30.8% and that of Type B is 32.1% under AM0, 1 sun (136.7 mW/cm^2) condition.

The external quantum efficiency (EQE) of the two types of IMM-3J cell is exhibited in Fig. 3. The generation current ratio of Type A cell was designed with taking account of the radiation condition (1 MeV electrons, fluence of 1×10^{15} e$^-$/cm^2). The deterioration of EQE of the InGaAs bottom cell due to the electron irradiation is found to be greater than that of the InGaP top and GaAs middle cells [7].

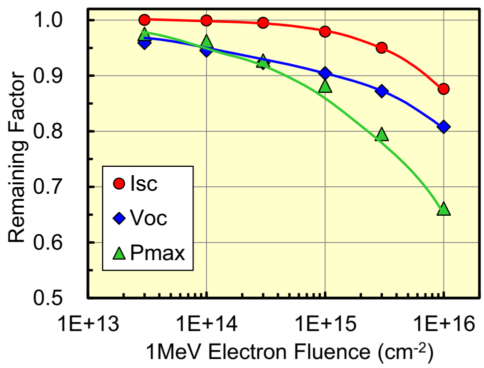
For Type B cell, we can adopt a current matching design since the current margin for radiation degradation is not required. Thus, Type B cell has an InGaAs bottom cell with wider band gap (lower indium content) compared to Type A cell. As a result, open-circuit voltage (*V*oc) of Type B cell is about 50 mV higher due to the wider bandgap of InGaAs. In addition,



(a) IMM-3J Type A cell



(b) IMM-3J Type B cell



(c) InGaP/GaAs/Ge space cell (SHARP 502)

Figure 4. Degradation characteristics of the IMM-3J Type A and B cells and a current InGaP/GaAs/Ge 3J cell obtained from 1 MeV electron irradiation.

the thickness of the InGaP top cell can be increased because of less current margin for the GaAs middle cell. This results in slightly higher EQE of InGaP top cell of Type B than that of Type A cell. Consequently, short-circuit current (*I*sc) of Type B cell increased by 2.7% from that of Type A cell.

The radiation resistance of Type A and B IMM-3J cells against 1 MeV electrons are compared in Fig. 4. For reference, the irradiation data of a current InGaP/GaAs/Ge 3J space solar cell (SHARP #502) are posted in the figure. All the radiation tests were carried

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out at the Takasaki Advanced Radiation Research Institute of National Institute for Quantum and Radiological Science and Technology (QST). From the comparison with #502 cell, equivalent radiation resistance is confirmed for Type A IMM-3J cell. Note that Type B IMM-3J cell also indicates sufficient radiation resistant properties.

3. QUALIFICATION OF SPACE SOLAR SHEET

Fig. 5 illustrates a schematic of cross-sectional view of the Space Solar Sheet (SSS). The SSS utilizes thin silicon bypass diodes and flat-type interconnectors, both of which were specially designed for SSS. An in-plane stress relief structure is applied to the interconnectors for thermal-cycle reliability. The thin-film IMM-3J cells described above are embedded in transparent silicone adhesive, and the cells and the bas-bar tubs as terminals at the ends of SSS are connected by the interconnectors, forming thin-film solar cell arrays (typically five or six cells in series). The thin silicon bypass diodes are located at the cropped corner of the IMM-3J cells, as seen in the current 3J cell panels, and connected by also specially designed flat-type interconnectors. The surfaces of the arrays are laminated with front and back sheet materials.

Two types of pairs of shielding materials are employed for SSSs. One uses transparent polymer films for both sides (film-type SSS), and the other uses thin coverglass (typically 50 μm thick) for the front side and a reinforced carbon fiber sheet for the back side (glass-type SSS). Both are shown in Fig. 6. Total thickness of the both SSSs is less than 0.2 mm and the specific power is approximately 0.6 W/g for both types of SSSs.

Reliability tests were performed for the SSSs to prove the space environment tolerance. The specimens for the reliability tests were sheets with a single string consisting of five IMM-3J cells connected in series. Three specimens were prepared for the respective tests. Tab. 1 depicts the test items and their conditions. The differences in the test condition for film-type and glass-type are based on difference of potential application in space. The acceptance criterion of all the tests is that the change or degradation of power output characteristic parameters, namely, *I*sc, *V*oc, maximum power (*P*max), fill factor (*FF*), voltage at maximum power (*V*mp), and current at maximum power (*I*mp), is within ±2.5%. The test results are also shown in the column next to the test condition in Tab. 1.

As indicated in Tab.1, no significant change in the parameters was observed. In addition no change in appearance, such as discoloration, deformation or crack propagation was confirmed. Therefore, the reliability tests results clearly confirmed that the both types of SSS have sufficient tolerance for space environment. Furthermore, we should mention that the dark lines observed in the electroluminescence (EL) image of the IMM-3J cells which were originally existed before the tests did not influence on output performance of the SSSs throughout the tests.

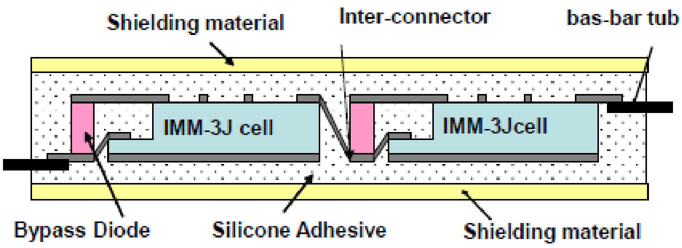
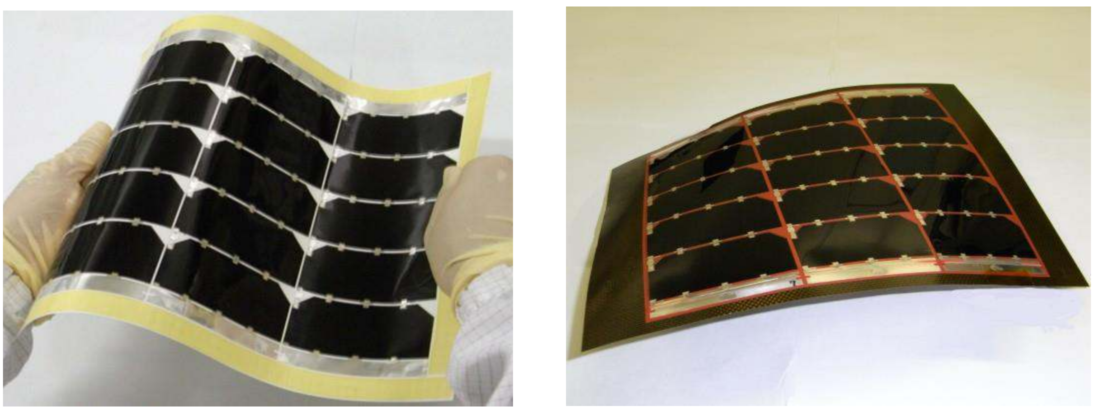


Figure 5. A schematic of cross-sectional view of Space Solar Sheet.



(a) Film type *(b) Glass type*

Figure 6. Photograph of two types of Space Solar Sheet.

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Table 1. Summary of reliability tests for two types of Space Solar Sheets

Test item	Film type sheet		Glass type sheet	
	condition	Result characteristic change	condition	Result characteristic change
Thermal cycling	temp. :-178 °C⇔+161 ° C 1200 cycles	< ±1%	temp. : -180 °C⇔+120 °C 1000 cycles	< ±1%
Humidity and temperature	temp.: 65 °C, humidity: 90% duration : 720 h	< ±1%	temp.: 65 °C, humidity: 90% duration :720 h	< ±1%
High temperature vacuum	pressure: <133.3×10^{-5} Pa temp.: 160 °C, duration : 168 h	< ±1%	pressure: <133.3×10^{-5} Pa temp.: 160 °C, duration : 168 h	< ±1%
High temperature	temp.: 161 °C duration :1000 h	< ±1%	temp.: 150 °C duration :1000 h	< ±1%
Reverse current	Reverse current : 500 mA temp. :161 °C, duration :1000 h	< ±1%	Reverse current : 500 mA temp.: 150 °C, duration :1000 h	< ±1%

Table 2. Summary of tests for lightweight and compact solar paddle

Test item	Target/condition	Result
Vibration	In plane: (swp rate: 2oct/min) 0-25 Hz: 15g 25-50 Hz: 12g 50-100 Hz: 8g Out of plane: (swp rate: 2oct/min) 0-50 Hz: 12g 50-100 Hz: 8g	**OK**
Deployment	Vertical (main) panels deployed Lateral (sub) panels deployed	**OK**
Acoustic	145.8 dB	**OK**
Thermal vacuum (coupon)	Temp. range: −125 °C ↔ +110 °C Cycle: 8	**OK**
Thermal cycle (coupon)	Temp. range: −173 °C ↔ +128 °C Cycle: 1370	**OK**

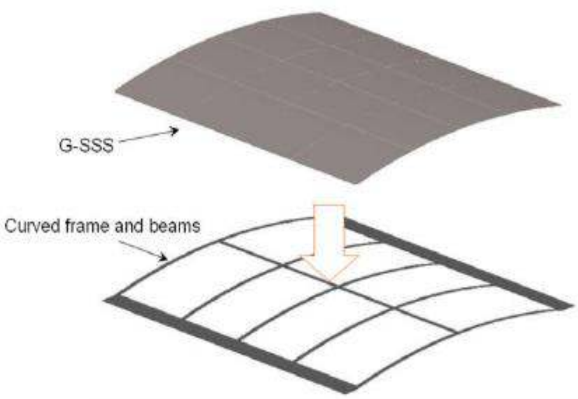


Figure 7. Schematic drawing of the lightweight panel structure utilizing the space solar sheets.

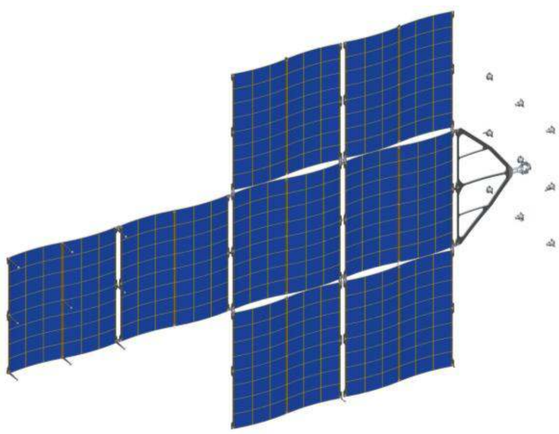


Figure 8. Schematic drawing of the engineering model of the lightweight and compact solar paddle.

4. LIGHTWEGHT AND COMPACT SOLAR PADDLE

The development of a new lightweight and compact solar paddle using lightweight solar panel with the glass-type SSSs has been completed [8] in 2015.
The lightweight solar panel employs a frame-type structure as shown in Fig. 7. The SSS is a thin sheet with thin coverglass, typically 50 µm thick, and they are attached on the frame structure like paper. We call this configuration "SHOJI structure" which is a Japanese traditional partition between rooms. The frame is made of a standard aluminium honeycomb but the thickness is as thin as 11 mm. To increase the out-of-plane stiffness of the thin panels, a curved structure is applied, and it prevents SSSs on the panels from cracks generated by vibration or other mechanical shocks. The SSSs are attached to the curved frame by Velcro fasteners. The influence of the curved shape on output power due to oblique incidence on the SSS surface is calculated to be 2 % decrease or less.
The engineering model (EM) of the lightweight and compact solar paddle was manufactured for environmental testing. Fig. 8 depicts a schematic of the EM solar paddle. It consists of eight panels, and the size of the panel is 1.75 m × 1.65 m. The weight of the paddle is 40.63 kg. The estimated output power calculated using a cell efficiency of 30% is about 6.5 kW, which results in the specific power of the paddle of about 160 W/kg. The architecture is inherently modular and scalable. For increased power requirements, just the number of the unit panel can be increased. New lightweight hinges, holding/releasing devices and synchronization mechanisms for deployment have been designed, developed and integrated in the EM solar paddle.

5. TEST RESULTS OF LIGHTWEGHT AND COMPACT SOLAR PADDLE

Various tests were performed for the EM solar paddle to qualify the new design and devices. Most of the panel surface was occupied with the glass-type SSSs without solar cells (dummy sheets), while the real ones with healthy IMM-3J cells were attached for some important areas of the panels. Tab. 2 summarizes the tests, their conditions and the obtained results. The EM solar paddle survived all the tests and the new structure and configuration have been qualified successfully. Fig. 9 posts a photograph of the setting for the vibration tests. Note the compactness of the folded eight panels. The height is around 2/3 compared with the current folding/stowing technology with eight of 25 mm-thick panels.

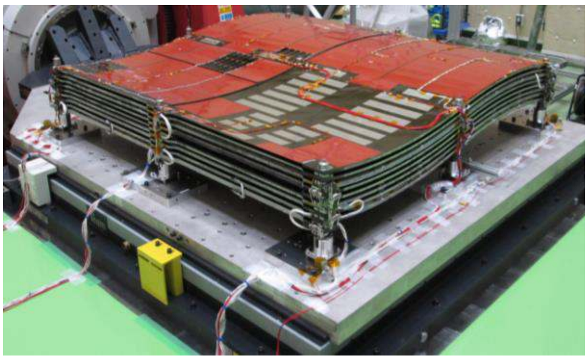
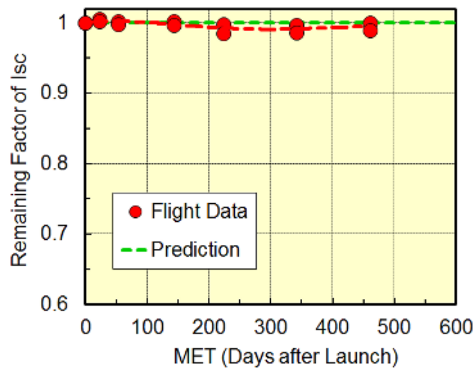


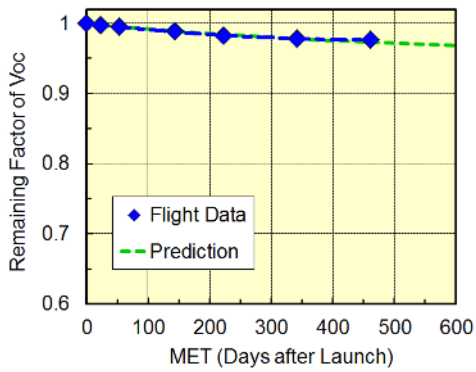
Figure 9. Setting of the EM solar paddle for the vibration tests.

6. FLIGHT DEMONSTRATIONS

Currently, the electrical output characteristics (*I*sc and *V*oc) of three prototype glass-type IMM-3J SSSs has been collected in orbit as the world–first demonstration of such thin solar panel structure. This demonstration is being performed on the scientific telescope satellite "HISAKI" launched in September, 2013. HISAKI was injected in an elliptical orbit at an altitude of 950×1150 km, at an inclination angle of 31°, and for an orbit period of 106 minutes. Two IMM-3J cells are connected in series and covered with 50 µm-thick coverglass. The trend data of remaining factors of the *I*sc and *V*oc are exhibited in Fig. 10. So far the SSSs show no degradation on *I*sc and about 2% degradation in *V*oc



(a) Short-circuit current



(b) Open-circuit voltage

Figure 10. Trend of remaining factors of (a) short-circuit current and (b) open-circuit voltage of the glass-type SSSs with IMM-3J cells on HISAKI.

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which meets our radiation degradation prediction, and no anomaly has been observed. These flight data prove good environmental durability and reliability of glass-type SSSs.

For film-type SSS, a space demonstration is now ready. A demonstration panel which consists of six film-type SSSs has been developed. For electrical connection between SSSs, the conductive thermo-compression bonding tape produced by Dexerials Corp. was employed [9]. The panel is mounted on JAXA's ISS transfer vehicle KONOTORI (HTV) No. 6 which is waiting to be launched in late 2016. The primary purpose of this demonstration is to confirm durability of film-type SSSs in launch/mechanical environment. Environmental tests for the flight panel shown in Fig. 11 have already completed successfully.

Furthermore, a demonstration test for the lightweight and compact solar paddle is now planned using a small, innovative technology demonstration satellite. A small-size solar paddle composed of five panels will be manufactured with using the same deployment mechanisms with practical size paddles. Thus, the prior purpose of this demonstration is to examine the function of the developed three-dimensional deployment system.

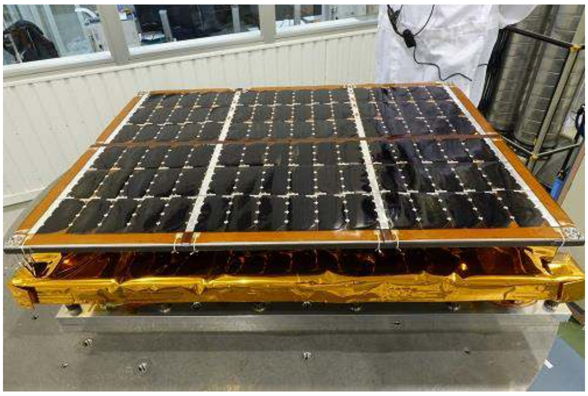

Figure 11. Lightweight solar panel flight demonstration unit "SFINKS".

7. SUMMARY

Development of a high specific power, low stowage volume and lightweight solar paddle utilizing high-efficiency, thin-film, InGaP/GaAs/InGaAs inverted metamorphic triple-junction solar cell has been completed. The cell exhibits the efficiency of as high as 32% with sufficient radiation resistance. Owing to the high efficiency of the cell, the paddle achieved specific power of greater than 150 W/kg. Qualification and reliability tests for the cell, SSSs, and paddle were carried out. The results confirmed that both the cell and paddle have enough capability to apply them in space. Space demonstration of the new paddle is now underway.

8. REFERENCES

1. R. Stribling, (2006) 'Boeing High Power Thin Film Solar Array', 4th International Energy Conversion Engineering Conference and Exhibit, AIAA No. 2006-4013.

2. M. Eskenazi, S. White, B. Spence, M. Douglas, M. Glick, A. Pavlick, D. Murphy, M. O'Neill, A. J. McDanal, and M. Piszczor, (2005) 'Promising Results from Three NASA SBIR Solar Array Technology Development Programs', NASA/CP-2005-213431.

3. K. Seifart, T. Schmidt, W. Göhler, and S. Langlois, (2005) 'Structural Design of Flexible Solar Generators', In Proc. 7th European Space Power Conference, ESA SP-589 (CD-ROM), European Space Agency, Noordwijk, The Netherlands.

4. Y. Combet, (2013) 'State of the Art and Future Challenges for Space Telecommunication Satellites Solar Generators' In Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition, 1BO.12.1, Paris, France, 30 Sep - 4 Oct.

5. T. Takamoto, T. Agui, A. Yoshida, K. Nakaido, H. Juso, K. Sasaki, K. Nakamura, H. Yamaguchi, T. Kodama, H. Washio, M. Imaizumi, and M. Takahashi, (2010) 'World's Highest Efficiency Triple-junction Solar Cells Fabricated by Inverted Layers Transfer Process', In Proc. 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii USA, pp.412-417.

6. M. Imaizumi, , K. Shimazaki, , Y. Kobayashi, M. Takahashi, K. Nakamura, T. Takamoto, S. Sato, T. Ohshima, (2011) 'Properties of a Qualified Space Solar Sheet with InGaP/GaAs Dual-Junction Solar Cells', In Proc. 9th European Space Power Conference, ESA SP-690 (CD-ROM), European Space Agency, Noordwijk, The Netherlands.

7. T. Takamoto, H. Washio, and H. Juso, (2014) 'Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic', In Proc. 40th. IEEE Photovoltaic Specialist Conference, Tampa, Florida, USA.

8. K. Shimazaki, M. Takahashi, M. Imaizumi, T. Takamoto, T. Ito, Y. Nozaki, H. Kusawake, (2014) 'Lightweight solar paddle with high specific power of 150 W/kg', In Proc. 10th European Space Power Conference, ESA SP-719 (CD-ROM), European Space Agency, Noordwijk, The Netherlands.

9. See http://www.dexerials.jp/en/