TESTING OF FLEXIBLE Cu(In,Ga)Se_2 SOLAR CELLS FOR SPACE APPLICATIONS

K. Zajac[1], S. Fasoulas[1], S. Brunner[2], K. Seifart[2], K. Otte[3]

[1] Technische Universität Dresden, Institute for Aerospace Engineering, 01062 Dresden, Germany
[2] HTS GmbH Coswig, 01640 Coswig, Germany
[3] Solarion AG, Ostende 5, 04288 Leipzig, Germany

ABSTRACT

This paper describes the experimental investigations of flexible Cu(In,Ga)Se_2 (CIGS) thin film solar cells (TFSCs) on titanium (TI) and polyimide (PI) substrates to verify the possible use for space applications. The investigations include evaluation of mechanical properties, humidity exposure (HE), thermal vacuum cycling (CY) as well as high and low energy electron and proton irradiation. Details of the experimental procedures are provided and fundamental electrical parameters of these CIGS TFSCs are presented. The electrical analysis of tested samples shows a slight degradation of efficiency after the tests. These preliminary results revealed no show-stoppers for space applications of flexible CIGS solar cells.

1. INTRODUCTION

Thin film solar cells (TFSC) based on Cu(In,Ga)Se_2 (CIGS) as absorber material are an auspicious approach for the space and terrestrial photovoltaic industry. Different absorber compositions, a diversity of substrates and different techniques are usefull for CIGS production. TFSCs on flexible substrates for usage in space follow the main requirements of [1][2]:

- High power to mass ratio at array level (> 100W/kg)
- High power density (EOL > 100W/m²)
- Low mass and storage volume
- Low production costs

Flexible CIGS thin film solar cells are interesting candidates for space power due to low weight and high specific power potential. With the availability of these solar cells, new concepts for future space photovoltaic power systems could be offered [2][3].

CIGS thin film solar cells produced on glass substrates demonstrated confirmed AM1.5 (air mass, terrestrial solar spectrum) efficiencies of 18.8% (aperture area of 0.998 cm²) [4] and highest reported AM1.5 efficiency of 19.2% (total area of 0.408 cm²) [5].

Different companies and institutes fabricated CIGS thin film solar cells on light-weight and flexible substrates [6]. Efficiencies for solar cells on polyimide are 12.8% (AM1.5, 0.13 cm²) in the late 90's [7]. A new record for this substrate was reported in 2005 with an efficiency of 14.1% (AM1.5, 0.595 cm²) [8]. On other substrates, the best efficiencies are 10.4% (AM1.5, 0.43 cm²) or 8.84% (AM0 – solar spectrum outside the earth's atmosphere, 0.43 cm²) on flexible stainless steel foil [9] and 15.2% (AM0, 1.1 cm²) on flexible molybdenum foil [10].

This paper concentrates on flexible CIGS solar cells manufactured by Solarion AG. The general cross section is shown in figure 1. The flexible solar cells (SC) are produced on polyimide (PI) or titanium (TI) substrate in a roll-to-toll fabrication process. Molybdenum (Mo) is used as back-contact and fabricated using sputter techniques. The CIGS absorber layer is grown in a roll-to-roll web coater by co-evaporation of Cu, In and Ga, whereas Se is offered by an ion beam source. Na is supplied by co-evaporation during this process. The CdS buffer layer is fabricated by chemical bath deposition on top of the absorber layer. ITO (In_2O_3:Sn) is used as window layer and a thin intrinsic ZnO layer is deposited below the ITO layer. These layers are produced in a roll-to-roll web coater using sputter techniques. For space application, the CIGS thin film solar cells must be covered by a high emissivity (ε) layer for suitable thermal radiative properties. This flexible and lightweight layer is a combination of conductive oxide layers in the µm-range deposited by sputter techniques [1][11]. A typical flexible CIGS solar cell with contact grid is shown in figure 2.

2. EXPERIMENTS

Spacecrafts as well as the solar cells are affected by different environmental influences. These external influences occur during production, transport, storage, launch and operation, some of them even simultaneously. To ensure best performance and survivability of a spacecraft, the effects of the natural space environment on design, development and operation have to be considered. This natural space environment includes thermal and solar environment, radiation and other naturally occurring phenomena [12][13].

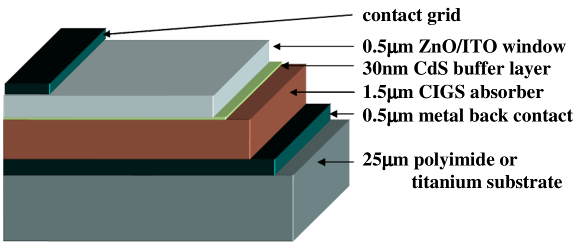

FIG 1. Flexible TFSC schematic drawing [1]

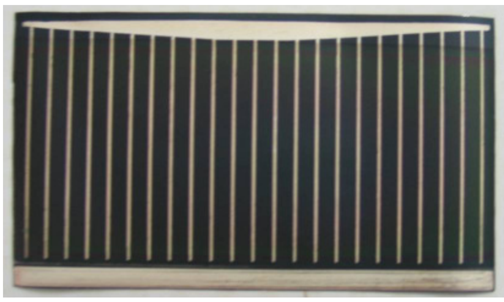

FIG 2. Flexible CIGS TFSC on polyimide substrate, size 40mm x 70mm, about 0.035 mm thick, contact grid with contact pads and grid fingers

	SC on PI substrate 40mm x 70mm	SC on PI substrate 32mm x 38mm	SC on TI substrate 32mm x 38mm
Humidity Exposure Test	3	-	3
Tensile Test	3	-	3
Characteristic Hysteresis Curve	3	-	3
Abrasion Test	4	-	4
Thermal Vacuum Cycling	3	-	3
Low Energy Electron Irradiation	-	3	3
High Energy Electron Irradiation	-	2	2
Low Energy Proton Irradiation	-	3	3
High Energy Proton Irradiation	-	2	2

TAB 1. Amount of solar cells used during the different experimental investigations

In order to verify the applicability of TFSCs for a spacecraft solar power source and to identify potential development and adaptation steps, different experimental investigations have been performed. The test methods and conditions have been chosen according to acceptance and qualification tests of generic bare solar cells [14]. An adjustment of the test methods and conditions has been made due to the fact that only the common Silicon and GaAs solar cells are mentioned in the standards.

The different experimental investigations, the number and kind of solar cells are summarised in table 1.

2.1. Humidity Exposure

In order to check the thin film solar cell stability and their contacts in a humid atmosphere and under higher temperature, a humidity exposure (HE) test has been performed. The primary effect on earth is the corrosion of contacts or an electrical degradation of the active layers of the solar cell during waiting periods for launch. For space application, the evaporation of trapped moisture during and after the launch is critical, a structural damage is possible.
The HE test has been performed with six bare TFSCs at the IKS Dresden (see table 1). One solar cell of each kind of substrate was additionally coated on the back side with a high-ε-coating labelled with CB. This test has been performed in a climate chamber under the following test conditions:

- Temperature: 75°C
- Relative humidity: 95%
- Duration: 96h

The solar cell samples were integrated in a special sample holder. The frame of this sample holder was made of plastic to avoid corrosion effects by the sample holder. The solar cells were clamped by an adjustable spring mechanism on the edges to lower the covered solar cell area. The sample holders were set up on one edge inside the chamber to avoid water accumulation on the surface of the solar cells.

2.2. Mechanical Tests

The handling of TFSCs during fabrication, functional testing, transportation and integration may cause mechanical damage. The launch and flight of a spacecraft as well as the solar cells are accompanied by a number of events that breed mechanical loads including acceleration, mechanical shock, vibration and acoustic field exposure. Due to these effects, interfacial friction of the stored solar cell during launch can occur. Interfacial friction of TFSCs is also possible during deployment or roll out of a thin film solar array.
The mechanical tests have been carried out to receive data of elastic modulus, stress-strain curves, characteristic hysteresis curves and data for estimation of abrasion resistance.
Six bare TFSCs have been used for a tensile test. Additionally, the characteristic hysteresis curves of six bare TFSCs have been recorded for determination of the strain-time curves. These tests have been carried out with a tensile test machine for thin films and qualified clamping jaw.
The abrasion tests have been performed with eight TFSCs. This test has been performed on an abrasion testing machine with different frictional resistances.

2.3. Thermal Vacuum Cycling

The thermal vacuum cycling (CY) test has been carried out to verify the ability of the TFSCs to withstand changes of ambient temperature under vacuum. The variation of temperature of a spacecraft is determined by the mission specification. A characteristic thermal cycling in space vacuum environment depends on this mission specification (spacecraft orbit, solar array orientation).
The CY test has been performed with six bare TFSCs at the DLR Berlin (see table 1). The solar cells were mounted in a special sample holder to keep them under tension of around 15 N/m for a flat surface during test [15]. After integration, the solar cells were placed inside the test chamber on a temperature support plate and insulated with MLI. The thermal vacuum cycling test was performed with a pressure less than 10^{-4} hPa. The maximum temperature was +100°C and the minimum temperature was -100°C with a dwell time of 10 min respectively [15]. The change of temperature was carried out with approx. 2.5±1K/min for heating and with approx. 13 ±1K/min for cooling.

2.4. Electron-/Proton-Irradiation

Commonly used solar cells are subjected to electrical degradation when exposed to particle radiation. The electron-/proton irradiation test shall show if the TFSCs efficiency depends on proton and electron irradiation. The space radiation environment is primarily characterized by electron and protons, so called particular radiation. The particles come from the solar wind and are trapped by the magnetic field of the earth to form radiation belts with widely varying intensities over a range from a few keV to many MeV. In lower earth orbits, electrons and protons are of significance, while at higher altitudes protons are the mainly damaging influence [12][13].

Previous investigations about defect generation in CIGS solar cells by high energy electron and proton irradiation showed in principle the very high radiation stability [16]. The CIGS solar cells can tolerate more high energy electrons as any other solar cell. The electron degradation is visible especially by the decrease of open circuit voltage decrease [17]. The high energy proton hardness is competitive to other solar cells. The proton degradation depends on short circuit current and open circuit voltage degradation [18]. Further on the investigations showed an annealing process at higher temperatures [19]. However, all this studies dealt with rigid CIGS solar cell on soda-lime glass. The main question to be answered with the tests performed in this study concerns the transfer of these results to flexible CIGS thin film solar cells.

The irradiation tests have been carried out with high and low energy electrons and protons to check the performance degradation of flexible TFSCs.
The low energy electron irradiation tests were performed at the DLR Berlin. The tests have been performed with six TFSCs. One solar cell of each kind of substrate was subjected to energy of (01) 25keV for 60 seconds, (02) 25keV for 120 second and (03) 100keV for 60 seconds respectively.
The high energy electron irradiation tests were performed at the BAM Berlin. These tests have been performed with four bare TFSCs. The solar cells were irradiated with a dose of 10^{15} electrons/cm² at electron energy of 1MeV.

The low energy proton irradiation tests were performed at the DLR Berlin. The tests have been performed with six TFSCs. One solar cell of each kind of substrate was subjected to energy of (01) 60keV for 60 seconds, (02) 60keV for 120 second and (03) 120keV for 60 seconds respectively.
The high energy proton irradiation tests were performed at the FZ Dresden-Rossendorf. These tests have been performed with four bare TFSCs. The solar cells were irradiated with a dose of 10^{13} protons/cm² at proton energy of 2MeV.

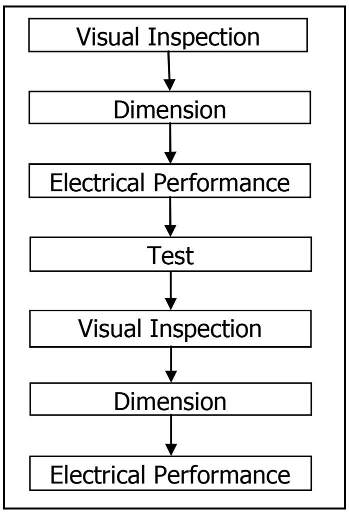

FIG 3. Test flow chart for TFSCs

3. RESULTS AND DISCUSSION

The preliminary results of the previous specified tests are presented in the following subsections. In order to find changes before and after each test the test sequence as depicted in figure 3 has been run through.

A Keithley 2425 sourcemeter, a HMI lamp with a spectrum close to AM1.5 and a calibrated reference cell serve to measure the solar cell parameters:

– Open circuit voltage V_{OC}
– Short circuit current density J_{SC}
– Fill factor FF
– Conversion efficiency η

The remaining factors $r_X = x(Test)/x(0)$, are defined as the ratio between the parameters x(Test) measured after the test and x(0) prior to test where x denotes the open circuit voltage V_{OC}, the short circuit current density J_{SC}, the fill factor FF and the conversion efficiency η, respectively.

3.1. Humidity Exposure

Table 2 summarises the remaining factors of the tested TFSCs after the humidity exposure test. Summarising, the main results of this test are:

- Inspection of dimensions shows no changes
- Visible inspection shows no changes, neither delamination of layers, nor interruption of grid fingers, contact pads, appearance of crease nor scratches
- Solar cells coated additionally on the back side with the high-ε-coating shows losses in excess of the standard TFSC
- Degradation of efficiency for flexible TFSCs on PI substrate is almost exclusively due to the decrease of short circuit current
- No degradation of efficiency for flexible TFSCs on TI substrate

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI				
PI-HE-01	101.2	99.1	103.9	104.3
PI-HE-02	98.1	88.8	102.8	89.6
PI-HE-03-CB	98.7	83.0	100.6	82.3
SC on TI				
TI-HE-01	97.9	98.6	104.1	100.5
TI-HE-02	100.0	96.0	104.4	100.2
TI-HE-03-CB	97.8	93.3	101.0	92.1

TAB 2. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after HE test

SC-ID	Young's modulus [N/mm²]	tensile strength [N/mm²]	Ultimate strain [%]
SC on PI			
PI-T-01	16913	221.3	5.1
PI-T-02	17068	232.2	6.5
PI-T-03	17730	273.7	14.3
SC on TI			
TI-T-01	27762	312.7	25.7
TI-T-02	27734	364.5	10.7
TI-T-03	29336	377.9	11.1

TAB 3. Mechanical data of TFSCs out of tensile test

3.2. Mechanical Tests

The results of the tensile test of TFSCs on PI substrate and TI substrate are summarised in table 3.

TFSCs on PI substrate exhibit a superior young's modulus (+70%), lower tensile strength (-22%) and lower ultimate strain (-28%) than uncoated polyimide foil. TFSCs on TI substrate exhibit a lower young's modulus (-16%), almost unchanged tensile strength (±4%) and lower ultimate strain (-35%) than uncoated titanium foil.

Caused by the nature of the evaluation procedure the average characteristic hysteresis curve of one solar cell configuration (PI or TI) was identified. The average characteristic hysteresis curve (tensile force of 30 N; dwell time of 3 min) for TFSCs on PI substrate is shown in figure 4 and for TFSCs on TI substrate is shown in figure 5. The flexible TFSCs on TI substrate show a strain hardening with ongoing test time in contrast to TFSC on PI substrate. The TFSCs on PI substrate show a superior strain level than TFSCs on TI substrate.

Table 4 summarises the remaining factors of the tested TFSCs after the abrasion test. The TFSCs PI-A-04 and TI-A-04 have been tested under rough conditions with a high frictional resistance. These tests revealed the following results:

- Inspection of dimensions shows no changes
- Visible inspection shows changes on PI based solar cells as delamination of layers
- Almost every TFSC shows a line impression on the surface
- TFSC PI-A-01 shows an interrupted contact pad
- TI-A-03 shows an interrupted grid finger

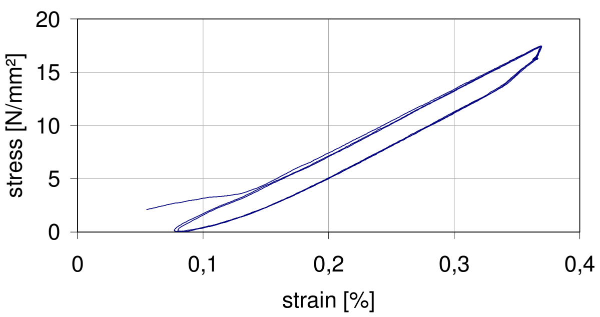

FIG 4. Average characteristic hysteresis curve for TFSCs on polyimide substrate

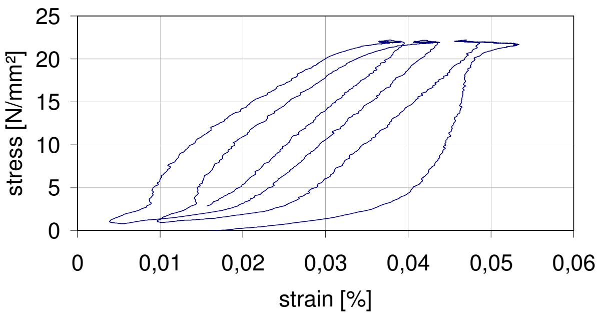

FIG 5. Average characteristic hysteresis curve for TFSCs on titanium substrate

- Degradation of efficiency for flexible TFSCs on PI substrate is affected by all parameters, for the most part by short circuit current losses
- Degradation of efficiency for flexible TFSCs on TI substrate is on the one hand due to the decrease of short circuit current and on the other hand due to the fill factor losses

3.3. Thermal Vacuum Cycling

Table 5 summarises the remaining factors of the tested TFSCs after the thermal vacuum cycling test. The main results of this test are:

- Inspection of dimensions shows no changes
- Visible inspection shows no changes with regard to delamination of layers, interruption of grid fingers or contact pads, appearance of crease or scratches
- Degradation of efficiency for flexible TFSCs on PI substrate is affected by all parameters, for the most part by short circuit current losses
- Degradation of efficiency for flexible TFSCs on TI substrate is on the one hand due to the decrease of short circuit current and on the other hand due to the fill factor losses

3.4. Electron-/Proton-Irradiation

Table 6 summarises the remaining factors of the tested TFSCs after the low energy electron irradiation test and table 7 after the high energy electron irradiation test. The given remaining factors include a 24 hours light soak test after the irradiation test. The results, in summary, are as follows:

- Inspection of dimensions shows no changes

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI				
PI-A-01	100.4	93.7	97.8	92.0
PI-A-02	101.4	85.8	91.8	79.9
PI-A-03	89.3	75.9	96.0	65.1
PI-A-04	81.6	65.8	93.1	50.0
SC on TI				
TI-A-01	101.3	83.3	91.8	77.5
TI-A-02	101.7	84.1	92.1	78.7
TI-A-03	102.4	89.7	98.0	90.0
TI-A-04	100.0	92.3	98.3	90.7

TAB 4. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after abrasion test

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI				
PI-CY-01	98.0	104.0	102.6	104.6
PI-CY-02	95	84.2	96.1	76.9
PI-CY-03	100.0	85.3	99.9	85.2
SC on TI				
TI-CY-01	100.6	100.4	93.6	94.6
TI-CY-02	100.5	87.3	97.1	85.2
TI-CY-03	101.1	96.9	96.7	94.7

TAB 5. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after CY test

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI				
PI-El-01	100.6	98.7	96.1	95.4
PI-El-02	100.0	98.4	97.7	96.1
PI-El-03	100.7	99.3	97.9	97.8
SC on TI				
TI-El-01	101.5	95.2	91.0	87.9
TI-El-02	100.6	100.5	88.9	89.9
TI-El-03	100.0	99.5	83.9	83.5

TAB 6. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after low energy El test, (01) 25keV for 60 seconds, (02) 25keV for 120 second and (03) 100keV for 60 seconds

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI	99.5	101.5	99.1	100.1
SC on TI	98.0	97.7	100.8	96.6

TAB 7. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after high energy El test, 10^{15} electrons/cm² at 1MeV

- Visible inspection shows no changes with regard to delamination of layers, interruption of grid fingers or contact pads, appearance of crease or scratches
- For the low energy electron irradiation the short circuit current losses contribute to the degradation of efficiency nearly as much as the fill factor loss for TFSCs on PI
- Degradation of efficiency for flexible TFSCs on TI is affected by fill factor losses
- Remaining factors for flexible TFSCs on TI substrate are lower than on PI substrate
- Degradation of efficiency after high energy electron irradiation is due to the open circuit voltage loss and fill factor loss for TFSCs on PI substrate
- Degradation of efficiency after high energy electron irradiation is due to the open circuit voltage loss and short circuit current loss for TFSCs on TI substrate

Table 8 summarises the remaining factors of the tested TFSCs after the low energy proton irradiation test and table 9 after the high energy proton irradiation test. The given remaining factors include a 24 hours light soak test after the irradiation test. These tests revealed the following results:

- Inspection of dimensions shows no changes
- Visible inspection shows almost no changes with regard to delamination of layers, interruption of grid fingers or contact pads, appearance of crease or scratches
- TFSCs PI-Pr-03 and TI-Pr-02 shows delamination of layers
- TFSC TI-Pr-03 shows an interruption of grid fingers and contact pad
- For the low energy proton irradiation the degradation of efficiency for TFSCs on PI is affected by all parameters, for the most part by short circuit current and fill factor loss
- Degradation of efficiency for flexible TFSCs on TI is affected by fill factor losses, partly with short circuit current losses
- Degradation of efficiency after high energy proton irradiation was not observed

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI				
PI-Pr-01	96.0	102.0	100.6	98.5
PI-Pr-02	98.2	94.6	94.8	88.2
PI-Pr-03	97.6	94.9	96.8	89.6
SC on TI				
TI-Pr-01	101.1	98.5	95.6	95.2
TI-Pr-02	100.6	100.8	95.8	97.1
TI-Pr-03	101.0	96.7	89.5	87.4

TAB 8. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after low energy Pr test, (01) 60keV for 60 seconds, (02) 60keV for 120 second and (03) 120keV for 60 seconds

SC-ID	r_{VOC} [%]	r_{JSC} [%]	r_{FF} [%]	r_η [%]
SC on PI	95.9	104.1	103.3	103.1
SC on TI	100.1	100.8	100.5	101.3

TAB 9. Remaining factors r_{VOC}, r_{JSC}, r_{FF} and r_η for CIGS TFSCs after high energy Pr test, 10^{13} protons/cm² at 2MeV

4. CONCLUSIONS

The mechanical test of flexible $Cu(In,Ga)Se_2$ TFSCs gives reliable data for simulation of flexible solar array structures. The abrasion test gives information about the effects of interfacial friction. The efficiency remaining factor after this test ranges between 92% and 50%. With further improvements of a flexible and lightweight high emissivity layer the efficiency remaining factor will increase.
The tests under different environmental conditions show the radiation hardness, the humidity resistance and the thermal stability of flexible TFSCs.
The results of this space application acceptance tests identified no showstoppers towards the use of flexible CIGS TFSC for space applications. However, there are still some necessary developments and adaptation steps before lightweight and flexible TFSCs could replace the current technologies for space power generation. For special applications a supplement to the traditional rigid panel technology might be the driver for an earlier use of the still young thin film technology.

5. ACKNOWLEDGMENTS

The authors would like to thank W. Haefker and S. Babben from the DLR Berlin for the collaboration concerning thermal vacuum cycling test, low electron and low proton irradiation. Further on we thank O. Haase from BAM Berlin and A. Kolitsch from FZ Dresden-Rossendorf for irradiating CIGS samples. We are grateful to R. Bentfeld from the IKS Dresden for collaboration with regard to humidity test. The support from U. Weiß (Technische Universität Dresden) as well as the team from HTS GmbH and Solarion AG is highly acknowledged. This work was supported by the European Space Agency under contract # 17537/02/NL/JA.

6. REFERENCES

[1] K. Otte, L. Makhova, A. Braun, I. Konovalov, Thin Solid Films 511–512 (2006) 613 – 622

[2] M.-L. Fille, R. Zwannenburg, S. Brunner, K. Otte, P. Greff, Proceedings of the 7th ESPC, Stresa, Italy, May 9 – 13, 2005, (ESA SP-589, May 2005)
[3] K. Seifart, T. Schmidt, W. Göhler, S. Langlois, Proceedings of the 7th ESPC, Stresa, Italy, May 9 – 13, 2005, (ESA SP-589, May 2005)
[4] M. A. Green, K. Emery, D. L. King, Y. Hishikawa, W. Warta, Prog. Photovolt: Res. Appl. Vol. 15 35–40 (2007)
[5] K. Ramanathan, M. A. Contreras, C. L. Perkins, S. Asher, F. S. Hasoon, J. Keane, D. Young, M. Romero, W. Metzger, R. Noufi, J. Ward, A. Duda, Prog. Photovolt: Res. Appl. Vol. 11 225–230 (2003)
[6] F. Kessler, D. Herrmann, M. Powalla, Thin Solid Films 480–481 (2005) 491– 498
[7] A. N. Tiwari, M. Krejci, F.-J. Haug, H. Zogg, Prog. Photovolt: Res. Appl. Vol. 7 393-397 (1999)
[8] D. Brémaud, D. Rudmann, G. Bilger, H. Zogg, A. N. Tiwari, 31rd IEEE Photovoltaic Specialists Conference. 2005, 223-226
[9] N. G. Dhere, S. R. Ghongadi1, M. B. Pandit, A. H. Jahagirdar, D. Scheiman, Prog. Photovolt: Res. Appl. Vol. 10 407–416 (2002)
[10] J. R. Tuttle, A. Szalaj, J. Keane, 28th IEEE Photovoltaic Specialists Conference, 2000, 1042-1045
[11] K. Otte, Proceedings of the 7th ESPC, Stresa, Italy, May 9 – 13, 2005, (ESA SP-589, May 2005)
[12] B. F. James, O.W. Norton, M. B. Alexander, NASA Reference Publication 1350
[13] ECSS-E-10-04A Space environment (21 January 2000)
[14] ECCS-E-20-08A Photovoltaic assemblies and components (30 November 2004)
[15] ECSS-Q-70-04A Thermal cycling test for the screening of space materials and processes (4 October 1999)
[16] A. Boden, D. Bräunig, J. Klaer, F.H. Karg, B. Hösselbarth, G. La Roche, 28th IEEE Photovoltaic Specialists Conference, 2000, 1038-1041
[17] A. Jasenek, U. Rau, T.Hahn, G. Hanna, M. Schmidt, M. Hartmann, H.W. Schock, J.H.Werner, B. Schattat, S. Kraft, K.-H. Schmid, W. Bolse, Appl. Phys. A 70 677–680 (2000)
[18] U. Rau, A. Jasenek, H. W. Schock, J. H. Werner, G. La Roche, A. Robben, K. Bogus, 28th IEEE Photovoltaic Specialists Conference, 2000, 1032-1037
[19] A. Jasenek, A. Boden, K. Weinert, M. R. Balboul, H. W. Schock, and U. Rau, Materials Research Society Symposium Proceedings Vol. 668 (2001) H3.2