FLEXIBLE $Cu(In,Ga)Se_2$ THIN FILM SOLAR CELLS FOR SPACE APPLICATIONS - RECENT RESULTS FROM A GERMAN JOINT PROJECT (PIPV2)

C. A. Kaufmann, D. Greiner, S. Harndt, R. Klenk, S. Brunken, R. Schlatmann, M. Nichterwitz, H.-W. Schock, T. Unold
PVcomB/Helmholtz-Zentrum Berlin für Materialien und Energie (HZB) , Hahn-Meitner-Platz 1, D-14109 Berlin
K. Zajac, S. Brunner
HTS GmbH, Am Glaswerk 6, D-01640 Coswig
F. Daume, C. Scheit, S. Puttnins, A. Braun, A. Rahm
Solarion AG, Pereser Höhe 1, D-04442 Zwenkau
R. Wuerz, F. Kessler
Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW), Industriestraße 6, D-70565 Stuttgart
M. Guenthner, M. Pscherer, S. Ihlow, G. Motz
Universität Bayreuth, Keramische Werkstoffe, Ludwig-Thoma-Straße 36b, D-95440 Bayreuth
H. Morgner
Fraunhofer-Institut für Elektronenstrahl- und Plasmatechnik (FEP), Winterbergstraße 28, D-01277 Dresden
R. G. Schmidt, A. Lambrecht
DuPont E&C – Circuit & Packaging Materials (DuPont), Hugenottenalle 175, D-63263 Neu Isenburg
J. T. Grundmann, P. Spietz
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Space Systems, Robert-Hooke-Straße 7, D-28359 Bremen
P. Schülke
DLR, Technik für Raumfahrtsysteme und Robotik, Königswinterer Straße 522-524, D-53227 Bonn
Corresponding author - C.A. Kaufmann, mail kaufmann@helmholtz-berlin.de, phone +49 30 8062 43241/18143

Since 2007 a German consortium of academic and industrial partners develops an extremely light and flexible $Cu(In,Ga)Se_2$ (CIGSe) thin film solar cell technology for space applications. The combination with a light support structure and an appropriate interconnection technology enables the construction of a solar generator with previously unmatched specific power (W/kg). This can be attractive as power supply for large platforms in space and is also compatible with alternative, flexible large area applications. The idea of the project is to utilize a solar cell technology, which - in comparison to the highly efficient, multi-junction III-V technology - is cheap and can be fabricated using manufacturing facilities for the terrestrial technology. Project activities encompass topics as fundamental as CIGSe thin film growth, individual aspects of single device components and also device interconnection, together with a corresponding support structure development. So far a maximum efficiency of 12.6% (57.8 cm²; AM1.5) could be demonstrated on an in-line roll-to-roll fabricated single device and a support structure prototype with a projected area density <1 kg/m² has been demonstrated. An earlier version of this constantly evolving technology was successfully tested on-orbit as part of the TET-1 mission.
Keywords: CIGSe, space application, flexible substrates, polyimide, thin film devices

1 INTRODUCTION

$Cu(In,Ga)Se_2$ (CIGSe) thin film solar cells on flexible polyimide (PI) foil carry the promise to offer a cheap and extremely light weight alternative to the established III-V based technologies for space applications. A major drawback is the comparably low efficiency of CIGSe devices. However, the polycrystalline thin film technology seems to show a remarkable tolerance to space radiation. The latter has been demonstrated in the lab for proton irradiation above 0.5 MeV [1] and for 1 MeV electron irradiation [2], but also by on-orbit experiments [3,4]. While the on-orbit trials were carried out on a lower earth orbit (LEO) in direct comparison to III-V technologies, the lab experiments did show, that proton irradiation with energies <0.5 MeV can lead to severe device degradation. However, an annealing process can recover much of the inflicted damage.

Table I shows an exemplary calculation for a 0.1 kW LEO mission, which demonstrates the potential for high specific powers to be reached, when using CIGSe thin film devices on flexible PI substrates of a thickness of 25 to 12.5 µm on a light weight support structure. It becomes clear, that only in combination with such a presumably flexible structure the full potential of this technology can unfold.

Table I: Comparative calculation of the specific power for a 0.1 kW LEO mission using established III-V or CIGSe on PI based photovoltaic devices (e.g. *10% PI (25µm)* - 10% efficient device on 25µm thick PI foil).

LEO 0.1 kW				specific power W/kg	
	type of device	area m²	P_{EOL} W/m²	1.5 kg/m²	0.5 kg/m²
GaAs	AZUR 3G28C	0.54	184.9	77.4	
	AZUR 3G30C	0.51	195.3	81.7	
	AZUR 3G30C-L	0.51	195.6	69.1	
CIGSe	10% PI (25µm)	1.54	65.1	40.7	114.0
	15% PI (25µm)	0.96	103.8	64.9	181.7
	15% PI (12.5µm)	0.96	103.8	65.6	187.8

PI was identified as the substrate of choice due to the fact, that it is cheaper and lighter than a metal substrate and also because it is electrically insulating, which simplifies the application of monolithic integration as a viable interconnection technology. Of course PI has the disadvantage, that it is thermally less stable than other substrate foils and also that it commonly has a large thermal expansion coefficient (typically < 20 $x10^{-6}$/K), which results in poor substrate handling properties. In addition, when stored in humid air, it has the tendency to absorb water, which can affect the stability and reproducibility of vacuum deposition technologies. In view of these characteristics DuPont took initiative to work on a new PI foil, which constitutes higher thermal stability and also a thermal expansion coefficient that is matched to that of CIGSe (7.9-11.4 x10^{-6}/K). It should also be noted that, with the achievement of 20.4% efficiency for a CIGSe thin film device on PI foil by Chirilă et al. [5], low temperature deposition routines for CIGSe fabrication on PI have been proven to also yield highly attractive efficiencies.

2 PROJECT OBJECTIVES AND PARTNERS

The currently ongoing joint activities (project acronym: PIPV2) are part of a follow-up project to the activities, which we previously reported here [6]. While the aim of the first PIPV project has been to demonstrate feasibility of the CIGSe technology on PI for space applications and to specify a national standard, the current project's main objectives are:

- an increased attractiveness of CIGSe for space applications by reaching a conversion efficiency >17.5% for lab scale single devices,
- an improved understanding of CIGSe growth at low temperatures for lab processes and know-how transfer to the industry,
- demonstration of a support structure with projected specific weight < 1kg/m²,
- further development of single device components, i.e. high-emissivity (high-ε) coating for optical cooling and a buffer layer with reduced optical absorption,
- device testing under simulated space conditions and technology demonstration.

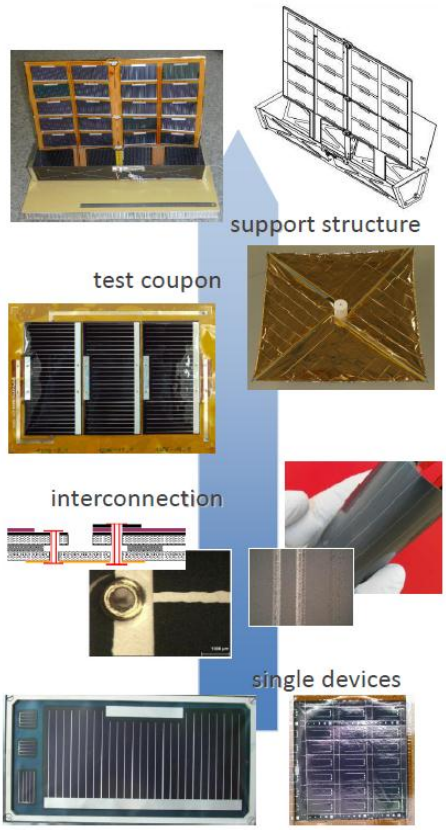

Figure 1: The project aims to encompass all stages of the development of a thin film solar cell technology for space applications.

For the follow-up project PIPV2, the initial consortium - made up of the industrial partners Solarion and HTS plus the research institutes HZB and ZSW - was joined by the Ceramic Materials Engineering group from the University of Bayreuth and the FEP, Dresden. HZB (batch-type multi-stage thermal coevaporation) and ZSW (roll-to-roll in-line multi-stage thermal coevaporation) both work on the more fundamental topic of CIGSe thin film growth. While the HZB has the task to identify critical growth parameters for achieving improved conversion efficiencies, the ZSW – with the help of the FEP – investigates CIGSe film growth using plasma activated species. The ZSW also works on monolithic integration for module fabrication on the PI substrate using solely laser scribing. Solarion has the responsibility to realize the technology transfer to the roll-to-roll (R2R) fabrication process and produces layer stacks for test devices. HTS is in charge of the development of module integration, device testing, technology demonstration and the development of a solar power generator support structure with a projected specific weight <1 kg/m². The Ceramic Materials Engineering workgroup of the University of Bayreuth, joined the team for the development of a high-ε coating technology that reduces the operation temperature of the illuminated solar cell in space by optical cooling. Furthermore the project's activities are supported by DuPont with the development of a new PI substrate foil and by the DLR, Bremen, who are consulting the project team in terms of a possible integration of the PIPV2 technology into the Gossamer I solar sail mission. As represented in Figure 1, the project hence encompasses virtually all the stages of the technology development, from single device fabrication to the design of a complete solar power generator.

3 RESULTS

3.1 Device Fabrication and Optimization

In order to be able to work on the development of interconnection technologies, to perform device tests relevant for space applications and to build demonstrators, a number of standardized single devices have to be available. Up to now a total of 430 complete 4x8cm² devices have been fabricated. While the layer stack (PI/back contact/CIGSe/CdS/TCO) for these devices has been deposited by Solarion, the front contact grid has been deposited by electron beam evaporation at HZB. Figure 2 shows that, while there are single devices

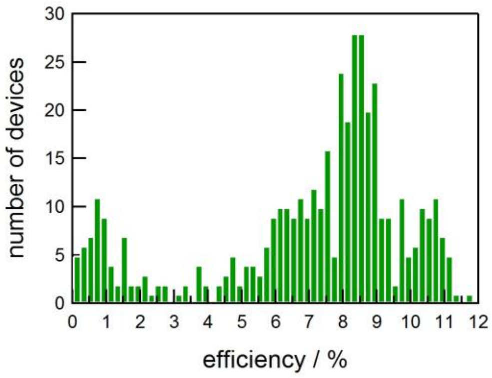

Figure 2: A total of 430 complete 4x8 cm² standardized single devices have been fabricated in the first 24 months of the project.

>11% efficiency, the largest number of samples was fabricated with efficiencies between 8 and 9%.

For investigation of the CIGSe thin film growth at low temperatures, the HZB performed real-time EDXRD growth analysis at the EDDIE beam-line of the BESSYII synchrotoron facility [7,8]. One main result from these investigations is that an increased amount of stacking faults [9] seems to be present at low growth temperatures in the CIGSe thin film during the early growth stages and that these are removed by Cu-rich recrystallization.

In an experiment, which looked at the influence of different in-depth Ga gradients on the device performance [10], the HZB found a correlation of the effective diffusion length and both, the V_{oc} deficit ($E_g/q-V_{oc}$) and the ratio $I_{sc}/I_{sc}^{max(AM1.5)}$, as shown in Figure 3. The effective diffusion length was determined by electron beam induced current imaging (EBIC) in cross-sectional SEM [11]. This implies that - for the low temperature CIGSe absorbers grown at the HZB - the effective diffusion length not only affects charge carrier collection, but also the open circuit voltage. A very simple extrapolation insinuates that, in order to reach a V_{oc} deficit of ~435 mV, as it is seen for world record efficient devices [12], an effective diffusion length of ~1.5µm may have to be achieved.

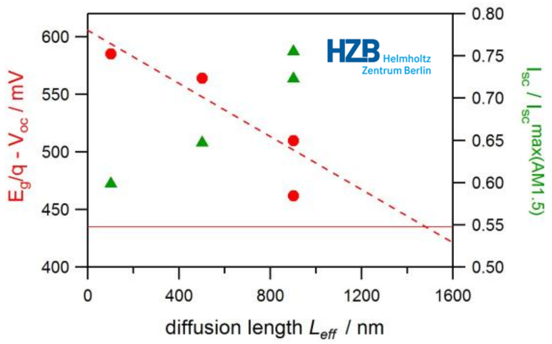

Figure 3: Correlation of V_{oc} and the effective diffusion length as measured by EBIC ($I_{sc}^{max(AM1.5)}$ - max attainable I_{sc} under AM1.5 illumination, considering EQE = 1 with E_g as determined by EQE).

In the joint activity of ZSW and FEP, a hollow cathode plasma source [13] was implemented in order to activate all the elements during low temperature growth in a multi-stage coevaporation process in an in-line R2R deposition system. Using a nominal substrate temperature of about 500° C for CIGSe growth. Figure 4 shows the

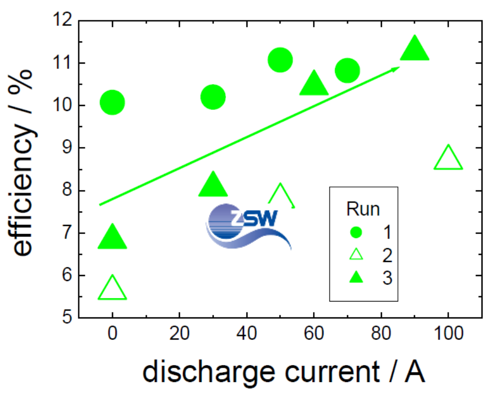

Figure 4: Effect of plasma activation (discharge current ~ plasma dose) on the efficiency of devices made from CIGSe thin films, deposited using activated species.

impact of plasma activation on the performance of devices made from CIGSe thin films that were deposited using different discharge currents, i.e. plasma dose. The data implicates, that plasma activation can indeed increase cell efficiency. A more detailed understanding of the activation process and its impact on the growth process is being developed.

In the course of achieving an efficient technology transfer, Solarion performed an in-depth analysis of the effect of the amount of Na supplied by coevaporation during R2R deposition [14]. It was shown that the optimum Na supply is determined by a trade-off between the beneficial effect of Na on V_{oc} and a deteriorating effect on FF and I_{sc}, mainly due to an electronic barrier that is thought to develop at the CIGSe/CdS interface.

3.2 Best Device Efficiencies

Tabel II and Figure 5 show the project's best devices, which have been fabricated so far. For a multi-stage thermal coevaporation process performed using a maximum deposition temperature of 430°C a conversion efficiency of 17.9% have been measured with the HZB in-house solar simulator under AM1.5 illumination using standard conditions. This deposition process so far only incorporates a NaF post-deposition process as the only alkaline supply to the CIGSe absorber material. It was also the aim of the project to implement an alternative buffer layer technology, in order to reduce optical losses inflicted by the commonly used CdS and particularly severe for AM0 illumination. While an indium sulfide based buffer does in principle show the potential to improve both, j_{sc} and V_{oc} of a CIGSe thin film solar cell in comparion to a CdS buffered reference [15], the In-S buffer layers by ILGAR and by PVD as used on PIPV2 CIGSe absorber layers, were both only able to demonstrate an increased current density. A simultaneous loss in V_{oc} could so far not be avoided. The best standardized 4x8cm² sized single device, which was fabricated jointly by Solarion and HZB shows an efficiency of 11.6%. However, an entirely R2R in-line fabricated device of double the size and a printed front contact grid has been seen to be up to 12.6% efficient. This clearly demonstrates the superiority of the industrial production environment in comparison to the batch-type fabrication in the lab, where dust and handling are a major limiting factor. Finally, the ZSW has also demonstrated a 9.2% total area efficient, monolithically integrated module on PI foil, which has been interconnected solely using laser scribing for the three interconnecting scribes. Figure 5 displays the corresponding dark and illuminated IV curves and lists the PV parameters.

Table II: The project's best single cell devices fabricated so far (AM1.5 illumination, AR – antireflective)

	HZB	HZB	ZSW	joint	Solarion
$area_{tot}$ /cm²	0.5	0.525	0.5	30.3*)	57.8*)
technology	batch	batch	R2R batch	R2R batch	R2R industry
buffer	CdS	In_2S_3 ILGAR	CdS	CdS	CdS
AR coating	yes	yes	yes	no	no
V_{oc} /mV	620	564	564	543	567
FF /%	72.9	68.9	70.7	74.8	70.0
j_{sc} /mA/cm²	39.7	38.9	33.7	28.6	31.8
η /%	17.9	14.9	13.5	11.6	12.6

*) total area, not considering back contact areas

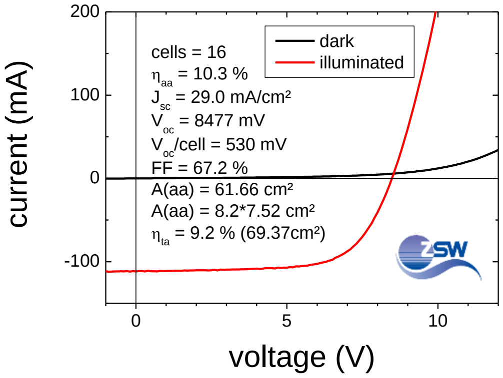

Figure 5: IV parameters of the project's best monolithically interconnected device, realized only using laser scribing on PI foil.

3.3 Additional Device Components

It should be mentioned at this point, that DuPont has supplied the project with a number of new PI substrates, which have been tested by all the CIGSe fabricating partners in the project. The final development is now available via DuPont under the name PV9202. It has a thermal expansion coefficient of 8 $x10^{-6}$/K in x and y direction, an increased thermal stability of up to ~450°C and currently a thickness of ~37µm. This product currently undergoes testing on a larger scale in our R2R deposition systems.

An important step towards a viable technology for space application of CIGSe thin film devices is the development of an efficient high-ε coating [16], which can be deposited at low temperatures. Figure 6 shows a cross-sectional SEM image of a CIGSe thin film solar cell device stack made by Solarion, which is covered by a high-ε coating processed from a HTTS precursor that has been cured in air at 200°C. The device retains full functionality and also remains flexible down to bending diameters of 20mm. With the HTTS precursor, SiO_x coatings with a resulting emissivity of 0.78 have been deposited. In addition a SiO_x/Alumina high-ε double layer system has been developed, which reaches similar emissivity [17].

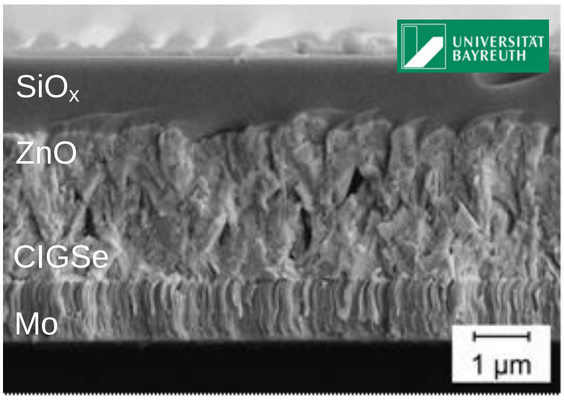

Figure 6: Cross-sectional SEM image of a CIGSe thin film solar cell, coated with a high-ε coating.

With respect to device testing the biggest draw back in the past has always been poor adhesion at different critical interfaces within the device. As a result after bending tests, thermal cycling tests, humidity tests and of course tape tests, delamination has always been a main issue for device degradation. Delamination mostly occurred at the Mo/CIGSe or at the CdS/ZnO interface and sometimes at the PI/back contact interface. Therefore it is particular important to also ensure good adhesion for high-ε coated devices. Figure 7 shows a CIGSe device stack coated with a high-ε thin film after a cross cut test has been performed. A figure of merit of 3 could be achieved. The standard scale for the cross cut test goes from 0 (excellent) to 5 (no adhesion).

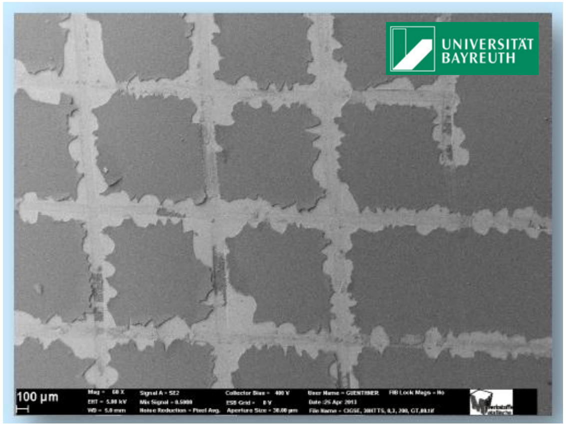

Figure 7: Top-view SEM image of a complete device with high-ε coating after a cross cut test.

3.4 Solar Generator and Technology Demonstration

Using rivet based device interconnection of standardized 4x8cm² CIGSe single devices, HTS designed and constructed a demonstrator of a complete solar power generator with a self-powered unfolding mechanism. While the demonstrator, which is shown in Figure 8, has a size of only 0.045m², a full size application of 1.2 m² in size has a projected specific weight of 0.78 kg/m². The demonstrator is currently in testing and has already successfully passed a sinus and random vibration test, thermal cycling in vacuum and at ambient pressure between -100° and +100°C.

On the 22nd July 2012 an early version of this project's technology has been launched into a lower earth orbit on board the TET-1 mission of the on orbit verification program of the DLR. Single cell devices, which were connected to the support structure via rivet based interconnection, showed no degradation over a test period of one year. [18]

4 SUMMARY AND OUTLOOK

Flexible CIGSe thin film solar cell devices for space applications show remarkable potential in terms of reducing weight, i.e. specific power, of solar power generators, and in terms of cost. Production cost <20 €/W on a device level is thought to be feasible. In comparison to the preceding project, our continued activities could further increase the efficiency of the devices produced within the consortium. 17.9% efficiency has been reached for a lab scale device. An in-line roll-to-roll fabricated single device with a total area of 57.8 cm² with an efficiency of 12.6% could be demonstrated. Individual components of the CIGSe device have been under

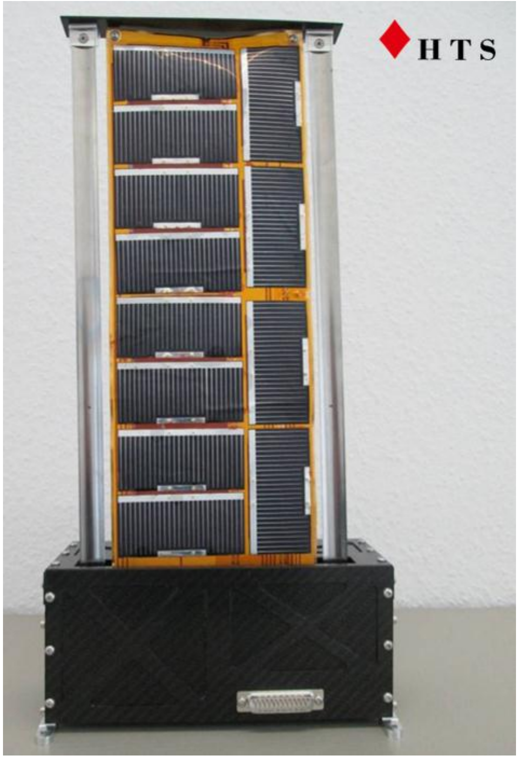

Figure 8: Complete Solar Generator; the projected specific weight for real size application is 0.78 kg/m².

investigation: the polyimide substrate, growth of the CIGSe absorber, an alternative buffer layer and a high epsilon coating for optical cooling. Also a monolithically integrated module (16 cells) only using laser scribing for the three interconnecting scribes with an efficiency of 9.2% has been fabricated on polyimide foil. A solar generator with a projected specific weight of 0.78 kg/m² is demonstrated. And finally it is reported that an earlier version of this project's technology has successfully been tested on-orbit within the TET-1 mission for the test period of 1 year.

The most important next step for the CIGSe growth optimization is the incorporation of a KF surface treatment, as it is currently performed on all the reported world record devices [5,12]. In terms of space verification the DLR Bremen is consulting the project consortium regarding a possible integration of CIGSe thin film devices into the solar sail of the Gossamer-I mission [19]. Launch is currently scheduled for 2016. Integration in the Gossamer-I mission could possibly be a decisive step towards the demonstration of live on-orbit power supply, realized by flexible CIGSe thin film solar cells on polyimide foil.

ACKNOWLEDGEMENTS

The authors would like to thank all the involved teams for their continuous support during the joint project. Financial support by the German Federal Ministry of Economy and Technology (BMWi), represented by the German Aerospace Center (DLR) under contracts 50RN1101, 50RN1102, 50RN1103, 50RN1104 and 50RN1105 is gratefully acknowledged.

REFERENCES

[1] A. Boden, D. Bräunig, J. Klaer et al.; 28th IEEE PVSC, Anchorage (2000) 1038
[2] U. Rau, A. Jasenek, H.W. Schock et al.; 28th IEEE PVSC, Anchorage (2000) 1032
[3] R.M. Burgess, W.E. Devaney and W.S. Chen; 23rd IEEE PVSC, Louisville (1993) 1465
[4] C. Morioka, K. Shimazaki, S. Kawakita et al.; Prog. Photovolt: Res. Appl. 19(7) (2011) 825
[5] A. Chirilă, P. Reinhard, F. Pianezzi et al.; Nature Materials 12 (2013) 1107
[6] C.A. Kaufmann, R. Caballero, R. Klenk et al.; 25th EU PVSEC/WCPEC-5, Valencia (2010) 2849
[7] C.A. Kaufmann, D. Greiner, H. Rodriguez-Alvarez et al.; 39th IEEE PVSC, Tampa (2013) 3058
[8] D. Greiner, R. Mainz, S. Brunken et al.; *Investigation of low temperature $Cu(In,Ga)Se_2$ multi-step co-evaporation growth on polyimide foil by real-time EDXRD: grain orientation and growth path*, E-MRS Spring Meeting, Lille (2014)
[9] H. Rodriguez-Alvarez, N. Barreau, C.A. Kaufmann et al.; Acta Materialia 61 (2013) 4347
[10] D. Greiner, C.A. Kaufmann, M. Nichterwitz et al.; *Adjusting the in-depth Ga gradient for low temperature grown $Cu(In,Ga)Se_2$ for flexible polyimide foil*, MRS Spring Meeting, San Francisco (2013)
[11] M. Nichterwitz and T. Unold; Journal of Applied Physics 114 (2013) 134504
[12] P. Jackson, D. Hariskos, R. Würz et al.; Physica Status Solidi rrl 8 (2014) 219
[13] F. Fietzke and B. Zimmermann; Surf. Coat. Technol. 2015 (2010) 1491
[14] S. Puttnins, M.S. Hammer, J. Neerken et al.; *Impact of sodium on the device characteristics of low temperature-deposited $Cu(In,Ga)Se_2$-solar cells*, Thin Solid Films (2014) in press
[15] R. Sáez-Araoz, H. Krammer, S. Harndt et al.; Prog. Photovolt: Res. Appl. 20 (2012) 855
[16] M. Guenthner, M. Pscherer, C.A. Kaufmann et al.; Solar Energy Materials and Solar Cells 123 (2014) 97
[17] M. Pscherer, M. Guenthner, C. A. Kaufmann et al.; *Thin-film silazane/alumina high emissivity doube layer coatings for flexible $Cu(In,Ga)Se_2$ solar cells*, Solar Energy Materials and Solar Cells (2014) accepted
[18] S. Brunner, K. Zajac, K. Seifart et al.; *In-flight results of the flexible solar cell Panel on TET-1*, 10th ESPC, Norwijkerhout (2014)
[19] U. Geppert, B. Biering, F. Lura et al.; Advances in Space Research 48 (2011) 1695