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Final report dated 7th December 2019

HESTPV

Skalierbare Messplattform zur Charakterisierung von hocheffizienten, stabilen Zinn-basierten Perovskit-Solarzellen

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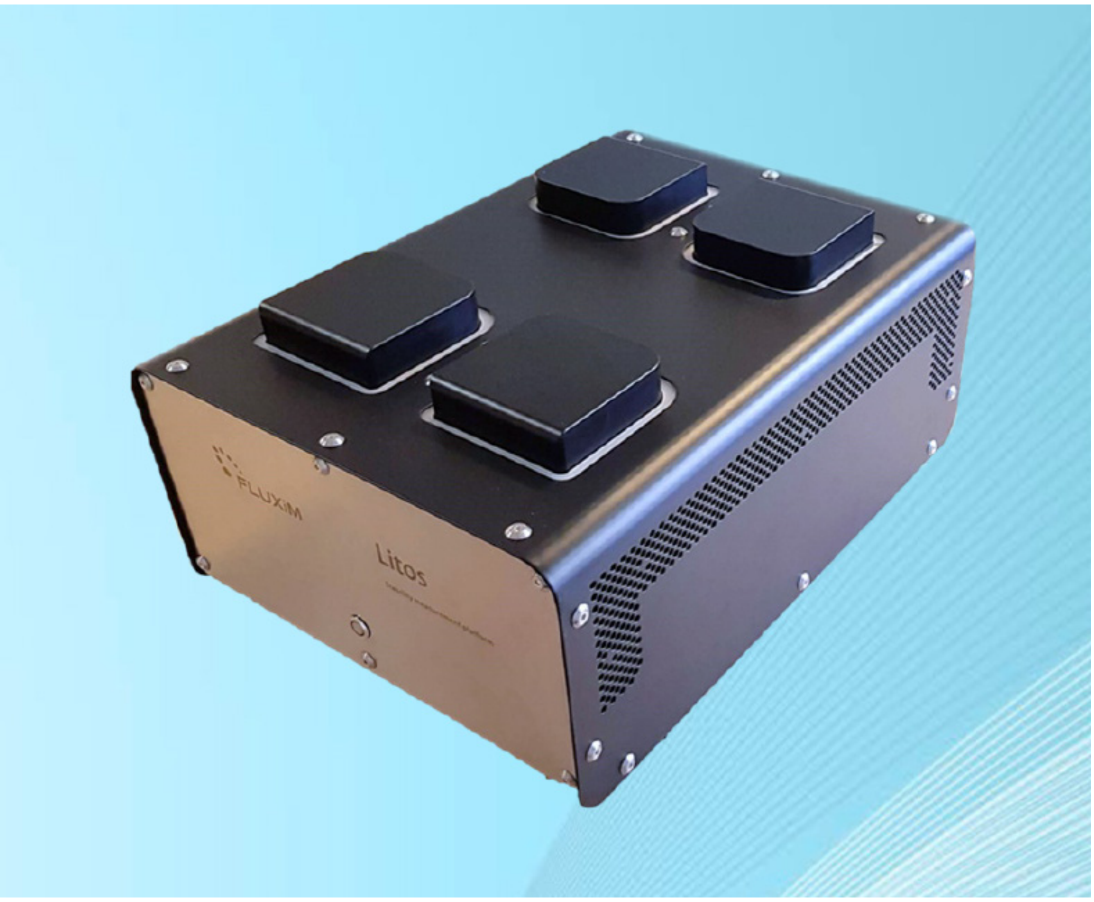

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Zusammenfassung

Innerhalb eines internationalen PV Forschungsprojekts (HESTPV) hat Fluxim AG mit diesem P+D Projekt eine skalierbare Erweiterung der PAIOS Messplattform für Belastungstests an zahlreichen Solarzellen entwickelt, aufgebaut und den erzielbaren Erkenntnisgewinn mit ersten Messreihen demonstriert. Mit diesem Ansatz kombiniert Fluxim das bestehende, äusserst vielseitige PAIOS Messsystem für DC, AC und transiente Experimente mit statistisch relevanten Stabilitätstests an vielen Solarzellen, und erzielen einen Mehrwert gegenüber herkömmlicher Testmethoden. Diese Erweiterung wurde als eigenständiges Messinstrument namens LITOS realisiert, lässt sich jedoch mit der gleichen Software (Characterization Suite, CS) ansteuern und auswerten.

Im HESTPV Projekt wurden vakuum-prozessierte Perovskitsolarzellen von der Universität Valencia, Spanien, mit Hilfe von der Messhardware und Simulationssoftware von Fluxim untersucht und wissenschaftliche Erkenntnisse publiziert.

Summary

As part of the international PV research project HESTPV, Fluxim AG used this P+D project to develop and build a scalable extension of the PAIOS measurement platform for load tests on numerous solar cells and demonstrated the achievable knowledge gain with first measurement series. With this approach, the existing, extremely versatile PAIOS measuring system for DC, AC and transient experiments is combined with statistically relevant stability tests on many solar cells, and value compared to conventional test methods is added. This scalable extension was realized as independent measurement instrument named LITOS, it however can be controlled and data analysed with the same characterization suite (CS) software.

In the HESTPV project framework vacuum-processed perovskite solar cells from the University of Valencia, Spain, were investigated with Fluxim’s measurement hardware and simulation software and corresponding scientific results were published.

Main findings

- 4 measurement chambers for one solar cell sample with up to 8 cells each are integrated in a compact, tabletop instrument called LITOS
- The chambers hosting the solar cells are temperature-controlled in the range from -20 C to +120 C, illuminated with up to approx. 10 sun intensity based on UV and white LEDs and maximum-power-point (MPP) tracking is implemented for accelerated lifetime testing (ALT)
- The LITOS instrument is not only an extension to PAIOS but can be operated as individual instrument for high-throughput stressing of solar cells at lab-scale thus providing early feedback on stability of the emerging PV technology under test.
- Control software is integrated in the characterization suite (CS) for seamless operation of stressing with LITOS and characterization with PAIOS.

Contents

Abbreviations

ALT	accelerated lifetime testing
CS	characterization suite software by Fluxim AG
MPP	maximum-power point
PSC	Perovskite solar cells
STU	stress test unit

1 Introduction

1.1 Background information and current situation

An extended stability testing and characterization platform like Litos is currently lacking and this pilot demonstration is thus addressing a clear market need for emerging PV technologies. Fluxim has already developed lab-scale all-in-one test equipment called PAIOS for PV (& OLED) research and the expansion into high throughput stress testing tools for more industrial fabrication is a logical expansion to its expertise and product portfolio. The existing challenge is the assessment of solar cell stability and degradation mechanisms early on in the development cycle.

1.2 Purpose of the project

In this project Fluxim aims at demonstrating a stress-test instrument Litos to be combined with the all-in-one characterization equipment Paios for improved understanding of operating and degradation mechanisms of novel solar cells.

2 Procedures and methodology

The existing all-in-one instrument Paios and the simulation software Setfos is complemented by the stress test system Litos developed in this project. This enables a methodology illustrated in Figure 1 where cyclic application of stressing with Litos and characterization with Paios is followed by detailed data analysis with the simulation software Setfos, which allows to fit the measured data with simulation data, thereby determining insightful material and cell parameters.

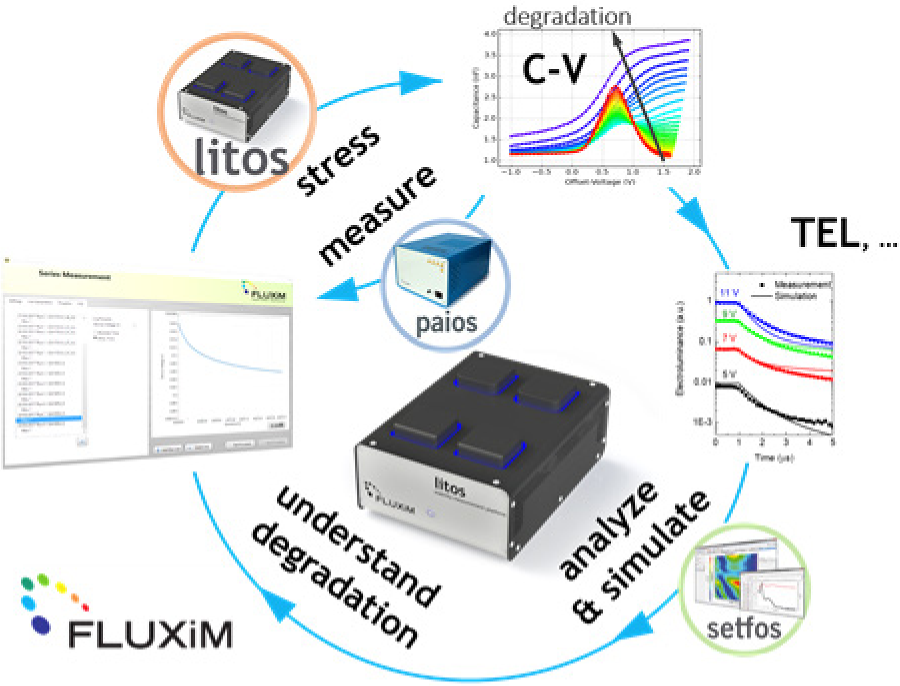

Figure 1: Illustration of methodology combining three R&D tools of Fluxim.

3 Results and discussion

3.1 Results with respect to project objectives

A critical examination of the findings/results w.r.t. goal definition in the project proposal document is provided below.

1. Realization of Stress-Test Units with 4 substrates (samples) of 4 solar cells each. For each substrate one illumination unit shall be integrated:

   The stress-test-unit was realized as a product named Litos with 4 measurement chambers, each hosting 1 sample and up to 8 pixels per sample, thus exceeding the original goal. A total of 32 channels is stressed simultaneously. Each sample is illuminated by its own LED unit.

2. Electrical power supply with maximum-power-point (MPP) tracking and constant current sourcing for each solar cell:

   MPP tracking and constant current sourcing was implemented for each solar cell channel and integrated with the Characterization Suite (CS) software that controls the measurent instrument.

3. Spectral quality of the illumination unit satisfies the solar simulator norm AAA within an area of 1 cm^2:

Even though we had a multi-LED illumination prototype with 16 LED channels available early on in the project, we decided not to integrate such solar simulator functionality into Litos. Instead the LED illumination of Litos unit was composed of UV and white LEDs to offer two spectral alternatives for stressing protocols. An additional red-emitting LED was also mounted to act as excitation source for the fast, time-resolved Paios measurements. The use of UV light for solar cell stability testing is already an extablished illumination source in IEC testing standards and was recently compared to the use of white LED illumination for testing perovskite solar cells [8]. Developing a high-quality, optically and thermally stable LED based sun simulator would be an endeavour on its own and competitive products are already on the market (Wavelabs, G2VOptics). Our multi-LED solar simulator prototype worked satisfactorily but had a drawback that due to light mixing the obtained illumination source was diffusive rather than collimated, which may not have satisfied end-user expectations. In order to still offer a solution to users that will have a separate solar simulator, we decided in the last project year (2019) to develop an additional instrument called «Litos Lite» which uses an external, third-party solar simulator but is based on similar hardware components as Litos but with a more limited range of temperature control. This new instrument will be finished in Q1 2020 and will not be integrated with CS software and Paios instrumentation, as no cell switching electronics is included.

4. Homogenous temperature for all cells of a stress-test unit (+/- 3 C):

   For each of the 4 measurement chambers of Litos we implemented a distinct temperature control unit based on Peltier elements for heating and cooling functionality. The PID feedback loop allowed to achieve a temperature accuracy of +/- 2 C.

5. Demonstration of a modular extension of the stress test units (STUs) to an array. Combining 4 STU's with 16 cells each to a system with a total of 64 individual solar cells:

   During an early stage of the project we decided to offer two Litos stress-test unit versions. One version of Litos would include control for 16 cells, one version would allow for control of 32 individual solar cells (on 4 substrate samples). Both versions are hosted in the same instrument chassis. Thus one version exceeds the original target. In order to achieve a total of 64 solar cells, one would either combine 2 or 4 Litos systems. The combination is enabled by daisy-chaining the Litos instruments with USB connectors and 4 coax cables that feed through the instrument to achieve a modular extension option.

   The high-throughput property of Litos is an important aspect that facilitates the quest to achieve statistically relevant data and is still compatible with intermittent Paios characterization measurements. Perovskite solar cells achieve their highest efficiency only after several minutes of operation, likely due to slow ionic motion in the perovskite crystal. Therefore, MPP tracking is commonly employed to get high efficiency numbers. Both Litos and Litos Lite allow for MPP tracking in all (32 or 64) parallel channels.

6. Interplay with the existing all-in-one instrument PAIOS (software integration and multiplexing), i.e. compatibilty of the stress-test units wiht the periodically executed PAIOS measurement methods:

   The CS software controls both the Litos instrument and the PAIOS instrument. PAIOS multiplexes 4 channels which correspond to the 4 chambers of LITOS. Multiplexing within the 4 or 8 cells on the sample of one LITOS chamber is performed within the electronics switching boards of LITOS. The CS software will store the data from extended stressing sessions in the .aio file format.

7. Continuous operation of the instrument for at least 1 month:

   A successful test was run for continuous operation of 3 weeks at 1 sun intensity. An important result is that the instrument does not overheat even when maximum electrical driving is provided to each of the 4 chambers. Thus the power dissipation and cooling concept works. Whenever the illumination is running at reduced intensity, the fans will throttle automatically, thus reducing power consumption. A large amount of data is acquired and handled.

8. Temperature control in the range of - 20 C to + 80 C shall be achieved and maintained in multi-day test operation regardless of ambient climate:

   The lowest temperature of -20 C and a highest temperature of +120 C was achieved.

9. Sensing: monitoring of air humidity:

   Each of the 4 chambers includes a humidity sensor whose signal is read out by the CS software and stored with the measurement data in addition to logging the temperature.

3.2 Demonstrator setup

In this section we provide detailed pictures of the developed Litos demonstrator for high-throughput stress testing. In Figure 2 the tabletop arrangement of the Litos demonstrator, the Paios instrument and a laptop is shown.

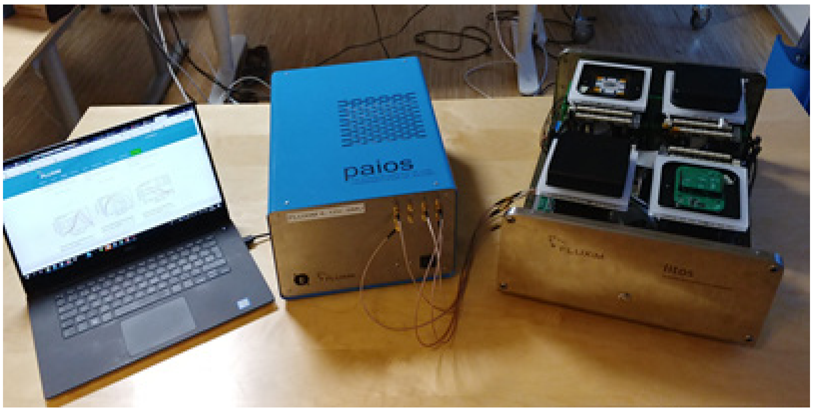

Figure 2: Picture of the tabletop setup including the laptop, the all-in-one characterization instrument Paios and the stress test platform Litos, the latter being developed in this P+D project. The black Litos chassis as well as 2 chamber covers are removed here.

A close-up view of the Litos stress-test unit is provided in Figure 3 and Figure 4. The latter shows the coax cable connectors for Paios as well as gas flow connectors for future extension of the Litos system with environmental control.

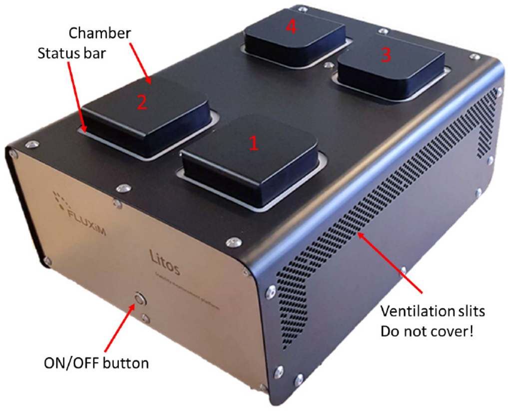

Figure 3: close-up view of Litos (front side).

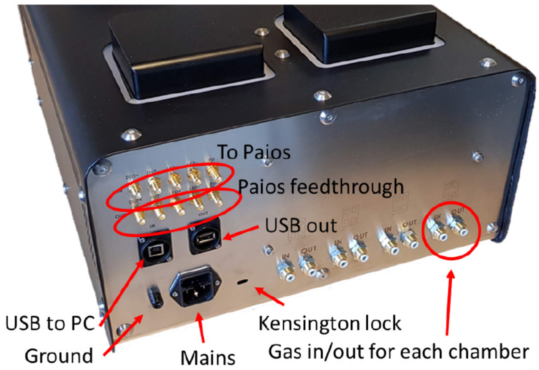

Figure 4: close-up view of Litos (back side) with all connectors.

The indicator lights of the Litos system in Figure 5 each show a distinct operating status of each chamber.

Figure 5: Litos instrument with color indicators around each measurement chamber showing the operating condition (green: setpoint reached, blue: measurement running, red: error or warning, magenta: trying to reach a setpoint).

3.3 Combination with CS Software and Paios Hardware

As illustrated in Figure 2 above, the stress-test unit Litos can be connected to Paios (see coax connectors at Litos rear side, shown in Figure 4), thus allowing to build a modular stress-test and degradation analysis system as illustrated in Figure 6. This approach combines a high-throughput stress test system (Litos), offering low cost per solar cell channel operated in parallel, and high-end, advanced cell characterization with the Paios instrument that is connected by HF switching electronics.

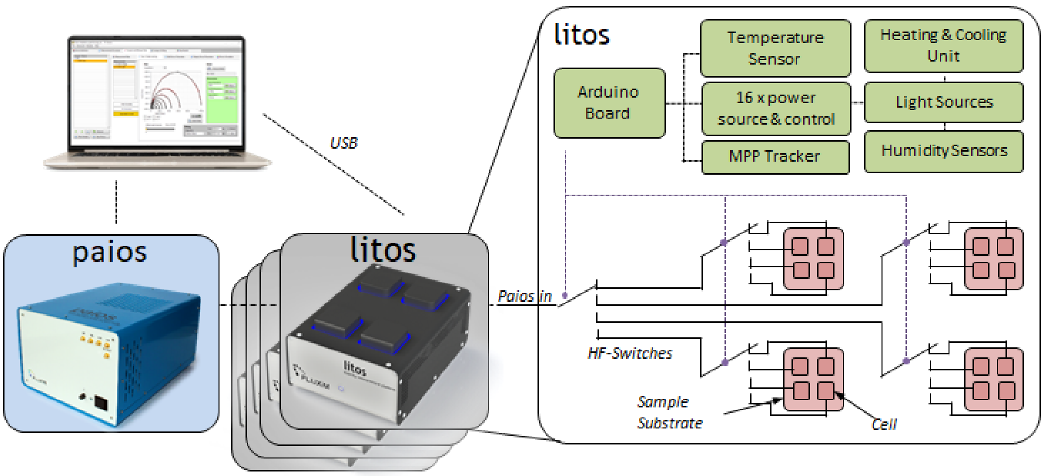

Figure 6: Conceptual overview of combining one Paios instrument with multiple Litos stress test units, each having 4 chambers holding one sample with 4 (or 8 in optional version) solar cells.

The Litos control software is integrated in the characterization suite (CS) for seamless operation of stressing with Litos and characterization with Paios. A screenshot example is shown in Figure 8. The CS software 4.2.2 integrates this functionality.

Figure 8 shows a screenshot of the control software's result section showing cell and environment data acquired live. The software handles data of all the cells in the four chambers and will also manage the control of the connected Paios instrument for advanced characterizations that occur during breaks of the stress testing protocol.

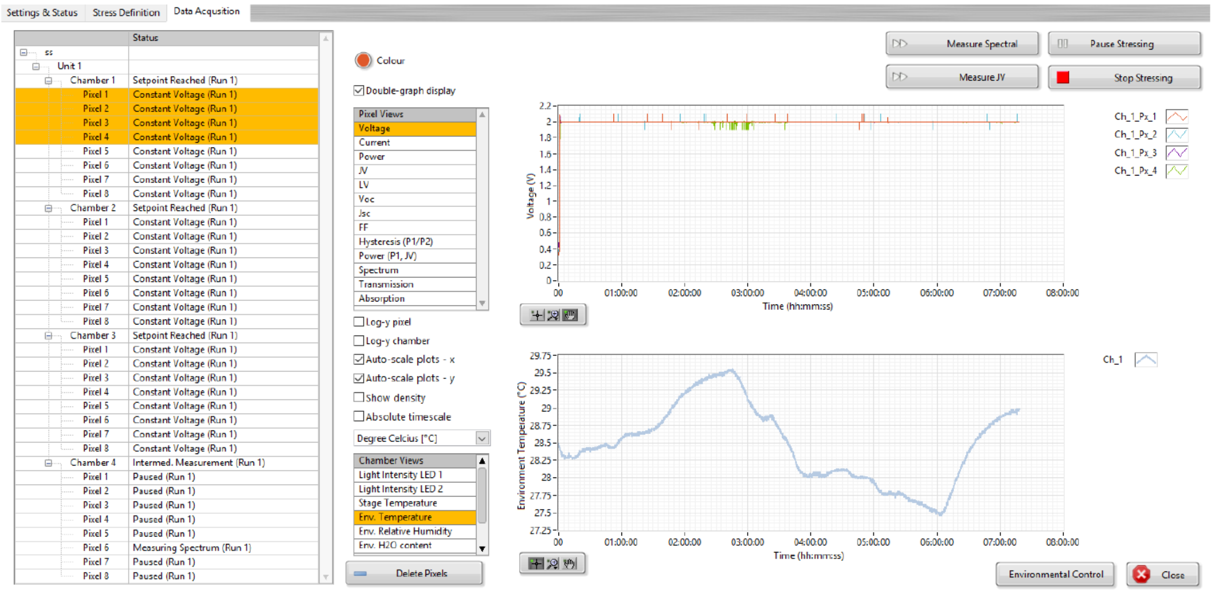

Figure 8: Screenshot of the Fluxim characterization suite (CS) showing 8 individual cells in each of the 4 measurement chambers (left panel) and the voltage (top panel) and environment temperature (bottom panel) vs. time.

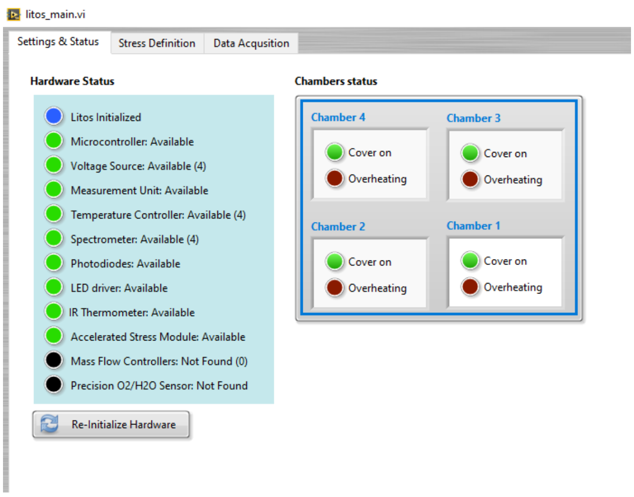

Figure 7: Litos instrument control showing the status of the connected hardware components.

3.4 Scientific results

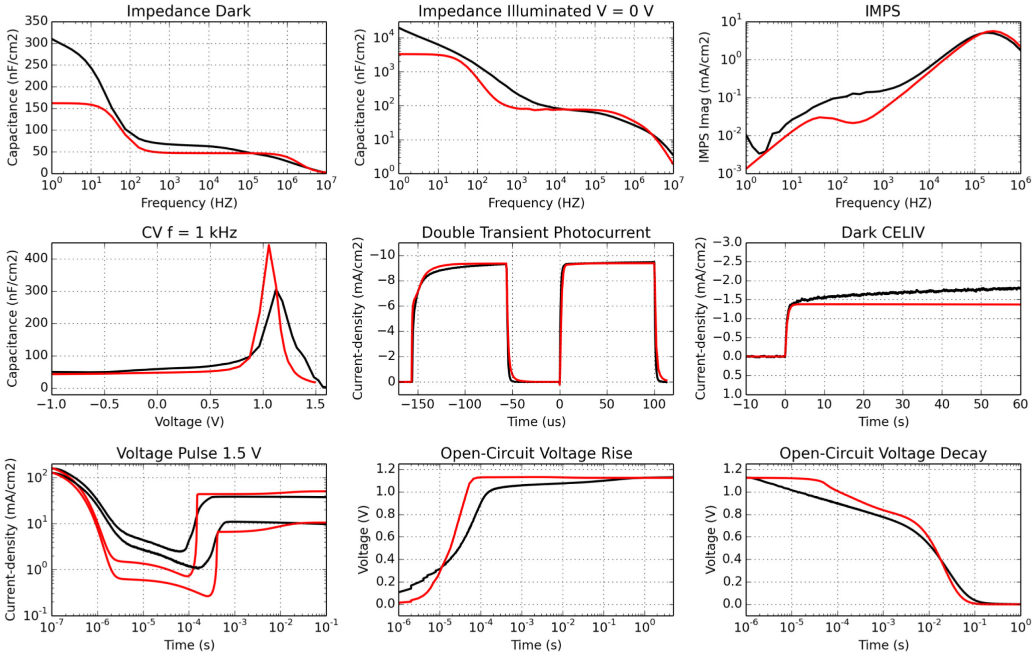

Figure 9: Successful global fit of the AC, transient and DC data obtained by Paios and Setfos for perovskite solar cells provided by the HESTPV project partner at University of Valencia. These results are published in [3]

The combination of characterization techniques provided by the all-in-one instrument Paios and the simulation software was exploited in Fluxim's scientific study on perovskite solar cell characterization by Neukom et al. [1] early on in this project. The follow-up study on characterization of third-generation solar cells by Neukom et al. [2] used the cell simulation by Setfos to explain how certain material and cell properties affect the cell performance and achieved a global fit with extensive data sets of an organic solar cell. A key result of this project is the successful simulation of the perovskite solar cells provided by the Spanish HESTPV project partner at Univ. of Valencia which was published before completion of this project by Neukom et al. [3]. Some examples of the obtained global fit on time-, frequency-dependent and steady-state data are shown in Figure 9.

With the updated model based on ionic-electronic charge transport in Fluxim's software Setfos, a global set of data measured by Paios was reproduced successfully, thus allowing for material parameter extraction.

In terms of scientific results of this study [3], some key conclusions were drawn from the comparison of simulated to measured data:

- The delayed current rise observed as a response to a step turn-on voltage (e.g. from 0 V to 1.5 V) is related to a retraction of ionic charges from the interface of the perovskite layer with the neighbouring transport layer.
- The steepness of the delayed current rise is directly linked to the passivation property of the perovskite/charge-extraction-layer: good passivation (low interface recombination) leads to a fast current rise, whereas bad contacts (high interface recombination) leads to slow current rise. On the one hand this was experimentally observed with a cell structure variation (fabricated in Valencia) where the perovskite was in direct contact with the doped transport

layers. This lead to slow rise of the delayed current and was reproduced in the simulation with interface recombination

- The ionic charges have characteristic dynamical behaviour that leads to a distinct shoulder in the IMPS (intensity modulated photocurrent spectroscopy), see Figure 9, at a characteristic AC frequency that itself scales with the inverse of the ionic charge carrier mobility.

Though the global fit shown in Figure 9 is good, there are some datasets that are not well understood and analysed yet. For instance the temperature dependent cell characteristics. Moreover, Figure 10 below shows a voltage step experiment that could not be reproduced satisfactorily by simulation. In this experiment the applied bias is switched from +3 V to – 3 V and the resulting transient current recorded. The data in the figure is displayed in a log-log plot that reveals a surprising current increase after 10 ms, that is absent in the simulation. Potential explanations are ion migration into neighboring layers or degradation phenomena (e.g. chemical reactions) taking place at internal or electrode interfaces.

Interestingly, our observation seems to be consistent with a recent publication from EPFL's PVLab that stressed the perovskite solar cell with reverse bias that can occur in partially shaded solar cells/modules. It was found that reverse bias stress leads to severe degradation in the solar cell layers and contacts [9].

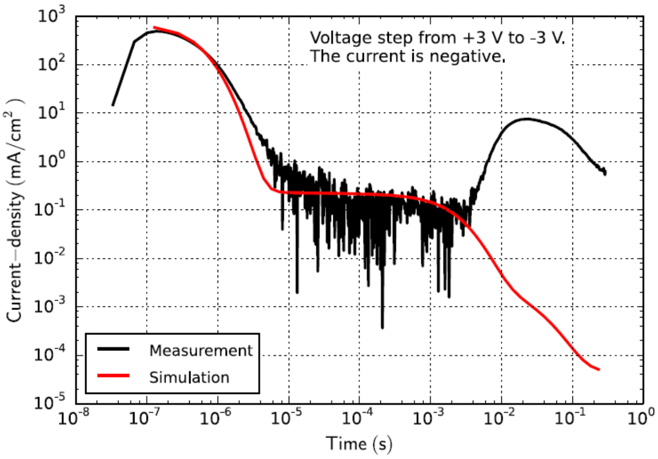

Figure 10 Measurement and simulation result of the MAPI perovskite solar cell [3] in double-logarithmic data representation. A voltage step to +3 V is applied for 300 ms. At t = 0, the voltage is switched to −3 V.

Repeating the advanced characterization methods of Paios during prolonged stressing experiments has lead to insights of how (organic) solar cells degrade, see the publications by Züfle et al. [4-7]. Publication [5] on photodegradation of (organic) solar cells was carried out together with HESTPV project partners in Sweden and Israel.

4 Conclusions

Four measurement chambers for one solar cell sample with up to 8 cells each are integrated in a compact, tabletop demonstrator and instrument called Litos. Fluxim has started to commercialize this demonstrator as stand-alone product. A first academic customer has purchased a Litos system for perovskite solar cell research and several prospects are evaluating this innovative stress-test platform.

The Litos chambers hosting the solar cells are temperature-controlled in the range from -20 C to +120 C, illuminated with up to approx. 10 sun intensity based on UV and white LEDs and maximum-power-point (MPP) tracking is implemented for accelerated lifetime testing (ALT).

The Litos instrument is not only an extension to Paios but can be operated as individual instrument for high-throughput stressing of solar cells at lab-scale thus providing early feedback on stability of the emerging PV technology under test. The seamless integration of the Litos control in Fluxim's CS software ensures a user-friendly operation. The CS software in turn also provides a link to the simulation software Setfos that is successfully used to analyse and fit the measured data.

Perovskite solar cells from the HESTPV consortium were received for advanced characterization and several key observations about solar cell operating mechasims were identified. These scientific results were published in the third year of the project [3].

5 Outlook and next steps

In a follow-up project, the tight measurement chambers will be flushed with a gas of controlled composition, having the desired humidity. Mass-flow controllers and software that achieve the desired oxygen or nitrogen content inside the measurement chambers as well as humidification will be employed. In terms of control and analysis software, realistic weather conditions as well as ALT scaling laws will be put to test.

A convincing scientific study that demonstrates the power of small-cell scale climate stress testing was published by Tress et al. [8] and will guide Fluxim's further development of the Litos stress test system with climate control.

6 National and international cooperation

Parallel to the present P+D project with focus on hardware platform development, Fluxim cooperated in a CTI project (PEROLEC) with the ZHAW and the EMPA Dübendorf (R. Hany and F. Nüesch) to model Organic-Light-Electrochemical Cells and Perovskite solar cells. Moreover, Fluxim was associated partner in the PV2050 SNF project lead by EPFL's PVLab in Neuchatel.

Fluxim has received perovskite solar cells from the CSEM PV Centre in Neuchatel for a joint stress-testing study employing Litos and the results are currently being collected.

The present P+D project was embedded in a European SolarEra.Net project "HESTPV" in cooperation with renowned academic PV research groups in Europe: Prof. H. Bolink, Univ. Valencia (Spain), Prof. E. Moons, Univ. Karlstad (Sweden), Prof. D. Cahen, Prof. G. Hodes, Weizmann Institute of Science (Israel), Prof. F. Gao, Univ. Linköping (Sweden). A couple of scientific publication resulted from this collaboration [Neukom et al [3], Züfle et al. [5]].

7 Publications

The following scientific publications were written by Fluxim staff during the HESTPV project period on the topic of solar cell characterization and degradation analysis, partially in direct collaboration with HESTPV project partners (e.g. references [3,5]).

[1] M.T. Neukom, S. Züfle, E. Knapp, M. Makha, R. Hany, B. Ruhstaller, “Why perovskite solar cells with high efficiency show small IV-curve hysteresis”, Solar Energy Materials and Solar Cells 169, 159 (2017)

[2] M. Neukom, S. Züfle, S. Jenatsch, B. Ruhstaller, “Opto-electronic characterization of third-generation solar cells”, Sci. Technol. Adv. Mater. 19, 291–316, (2019)

[3] M. Neukom, S. Züfle, A. Schiller, E. Knapp, J. Ávila, D. Pérez-del-Rey, C. Dreessen, K. Zanoni, M. Sessolo, H. Bolink, B. Ruhstaller, “Consistent device simulation model describing perovskite solar cells in steady-state, transient and frequency domain”, ACS Materials and Interfaces, 11, 26, (2019) https://doi.org/10.1021/acsami.9b04991

[4] S. Züfle, M.T. Neukom, S. Altazin, M. Zinggeler, M. Chrapa, T. Offermans, B. Ruhstaller, “An effective area approach to model lateral degradation in organic solar cells”, Advanced Energy Materials 5 (20), 1500835, (2015)

[5] S. Züfle, R. Hansson, E. A. Katz, E. Moons, “Initial photo-degradation of PCDTBT: PC70BM solar cells studied under various illumination conditions: Role of the hole transport layer”, Solar Energy 183, 234 (2019), https://doi.org/10.1016/j.solener.2019.03.020

[6] L. Ciammaruchi, S. Züfle, et al. “Stability of organic solar cells with PCDTBT donor polymer: An interlaboratory study”, J Materials Research 33, 13, 1909 ,(2018)

[7] D. Fluhr, S. Züfle, B. Muhsin, R. Öttking, M. Seeland, R. Rösch, U. Schubert, B. Ruhstaller, S. Krischok, H. Hoppe, “Aluminum electrode insulation dynamics via interface oxidation by reactant diffusion in organic layers”, physica status solidi (a), (2018)

8 References

[8] K. Domanski, E.A. Alharbi, A. Hagfeldt, M. Grätzel, W. Tress, “Systematic investigation of the impact of operation conditions on the degradation behaviour of perovskite solar cells”, Nature Energy 3 (1), 61, (2018)

[9] R. Razera, D. Jacobs, F. Fu, P. Fiala, M. Dussouillez, F. Sahli, T. C. Yang, L. Ding, A. Walter, A. F. Feil, H. I. Boudinov, S. Nicolay, C. Ballif and Q. Jeangros, “Instability of p-i-n perovskite solar cells under reverse bias”, J. Mater. Chem. A, (2019), DOI: 10.1039/C9TA12032G.

[10] W. Tress, K. Domanski et al. “Performance of perovskite solar cells under real weather conditions in the lab”, Nature Energy (2019)