Abstract book

ISOS 16

International Summit on Organic and Hybrid Photovoltaics Stability

MON. 29TH SEPT. →
WED. 1ST OCT. 2025

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9:00-9:30 **WELCOME**
BRAM DE WISPELAERE (GENERAL MANAGER, ENERGYVILLE)
IVAN GORDON (DEPARTMENT DIRECTOR IMOMEC, IMEC)
TOM AERNOUTS (GROUP MANAGER THIN FILM PV TECH, IMEC/UHASSELT/ENERGYVILLE)
ARANZAZU AGUIRRE (RELIABILITY LEAD AT THIN FILM PV, IMEC/UHASSELT/ENERGYVILLE)

SESSION 1 **Encapsulation and outdoor degradation** CHAIR: MARK KHENKIN

9:30-10:00 INVITED SPEAKER HAN XU
Toward Outdoor-Stable Organic Solar Cells: Revealing Device Stability Mechanisms from Material Photodegradation Pathways

10:00-10:15 ORAL PRESENTER ULAS ERDIL [ID 18]
Decoding Outdoor Degradation in Perovskite Solar Cells through Accelerated Aging Tests

10:15-10:30 ORAL PRESENTER JONATHAN PARION [ID 4]
A novel way of analyzing perovskite outdoor degradation: the S-Voc

10:30-11:00 **COFFEE BREAK AND EXHIBITION**

11:00-11:30 INVITED SPEAKER BUYI YAN
Lifetime Prediction model of Perovskite Solar Module using intensified ultra-violet and violet light

11:30-11:45 ORAL PRESENTER BEATRIZ ROMERO [ID 31]
Impact of Self-Assembled Monolayers on the Long-Term Stability of Perovskite Solar Cells: An Outdoor Degradation Study

11:45-12:00 ORAL PRESENTER ANUJ KUMAR SINGH [ID 22]
Accelerating the Discovery of Stable OPV Systems via a Portable Outdoor Testing Platform

12:00-12:30 INVITED SPEAKER EUGENE KATZ
New job of concentrated sunlight: is it reasonable with perovskites?

12:30-13:30 **LUNCH AND EXHIBITION**

13:30-13:45 ORAL PRESENTER FRANCESCA DE ROSSI [ID 48]
Radiation hardness of flexible perovskite solar cells employing PTAA-like hole transport material irradiated by atmospheric neutrons

13:45-14:00 ORAL PRESENTER BARTHÉLEMY HUGON [ID 30]
Development of an outdoor PV testing platform for comparison of energy production from various emerging solar technologies

14:00-14:15 ORAL PRESENTER HAIBING XIE [ID 52]
Cross-linked multifunctional bilayer polymer buffer for enhanced efficiency and stability in perovskite solar cells

14:15-14:45 INVITED SPEAKER LAURA SCHELHAS
Accelerated Stress Tests for Screening Early Field Failures in Metal Halide Perovskite Photovoltaic Modules

SESSION 2 **AI, Modeling and FAIR data** CHAIR: KRISTELLE BOUGOT

14:45-15:15 INVITED SPEAKER CHRISTOPH BRABEC
Unveiling Long-term Stability for Solution Processed High-Efficiency Tandem Solar Cells

15:15-15:45 INVITED SPEAKER JEAN-BAPTISTE PUEL
AI and modeling of PVK stability

15:45–16:15	COFFEE BREAK AND EXHIBITION
16:15–16:35	SPONSOR TALK FREDERIK C. KREBS (INFINITY PV) Perovskite roll-to-roll processing platforms
16:35–17:35	ROUND TABLE DISCUSSIONS 1 2 3
SESSION 3	Testing protocols CHAIR: KOEN VANDEWAL
17:35–17:50	ORAL PRESENTER PETER PASMANS [ID 51] Reliable inline IV characterization for commercial production of perovskite-based solar modules
17:50–18:05	ORAL PRESENTER EMILIO JUAREZ PEREZ [ID 3] Galvanostatic Power Tracking for Enhanced Long-Term Stability Assessment of High-Hysteresis Solar Cells Under Real-World Operating Conditions

ROUNDTABLES TOPICS

1. Low-power PV (IoT) indoor light
2. Encapsulation, Outdoor (also extreme, space, desert) degradation
3. OPV only

TUE.
↙ 30/09

SESSION 4 **Intrinsic stability** CHAIR: VIDA ENGMAN

9:00-9:30 INVITED SPEAKER JI-SEON KIM
Key Molecular Parameters for High Stability Organic Photovoltaics

9:30-9:45 ORAL PRESENTER QUN LUO [ID 29]
ZnO Interface Engineering Enabled the Promotion of Long-Term Stability of the Organic Solar Cells

9:45-10:00 ORAL PRESENTER ANTONIO CABAS VIDANI [ID 47]
Understanding Degradation and Recovery in Perovskite Solar Cells Under Reverse Bias

10:00-10:15 ORAL PRESENTER ELLEN MOONS [ID 24]
Photodegradation of organic solar cell materials

10:15-10:45 COFFEE BREAK AND EXHIBITION

10:45-11:15 INVITED SPEAKER YONGXI LI
Intrinsic Chemical Stability Limits of Non-Fullerene Acceptors for Long-Term Operation

11:15-11:30 ORAL PRESENTER JOEL LUKE [ID 11]
Don't fluorinate there! The Impact of Fluorination Position on Polymer Photostability and Its Effect on Photovoltaic Device Stability

11:30-11:45 ORAL PRESENTER YAKUN HE [ID 50]
Intrinsic Superior Stability of Single-Component Organic Solar Cells

11:45-12:00 ORAL PRESENTER ESWARAN JAYARAMAN [ID 44]
Intrinsic Thermal and Photodegradation Study of Slot-Die Coated, Air Processed High-Efficiency Organic Photovoltaics

12:00-12:15 ORAL PRESENTER ZAFAR IQBAL [ID 39]
Stability and Interfacial Energy Levels Alignment in Perovskite Solar Cells

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12:15-13:15 LUNCH AND EXHIBITION

13:15-13:30 ORAL PRESENTER SATOSHI USHIDA [ID 37]
Direct Measurement of Whole-device Capacitance in Perovskite Solar Cells Ensures Stable Performance

13:30-13:45 ORAL PRESENTER LUIGI ANGELO CASTRIOTTA [ID 40]
Tailored Ink Formulations for Scalable and Robust Perovskite Device Fabrication

SESSION 5 **Low power PV** CHAIR: RIIKKA SUHONEN

13:45 - 14:15 INVITED SPEAKER MORTEN MADSEN
Stability assessment of scalable organic photovoltaics for indoor and transparent application

14:15 - 14:45 INVITED SPEAKER THOMAS BROWN
Best Practices for Measuring Indoor Photovoltaic Devices

14:45 - 15:00 ORAL PRESENTER HIND LAMKAOUANE [ID 53]
Phosphorus-based electrode interfacial layer for application in organic solar cells

15:00 - 15:30	COFFEE BREAK AND EXHIBITION	
15:30-15:50	SPONSOR TALK CHEN YANG (PURI MATERIALS)	Evolving Tentacles of Innovation: Reaching Every Corner of Solar Cell Testing
15:50-16:50	ROUND TABLE DISCUSSIONS 4 5 6	
SESSION 6	Degradation experiments conducted outdoors	CHAIR: NIKOLETA KYRANAKI
16:50-17:20	INVITED SPEAKER STEPHANE CROS	Perovksite PV Stability challenge in CEA
17:20-17:35	ORAL PRESENTER MIRELLA AL KATRIB [ID 10]	Understanding Temperature-Dependent Metastability in Perovskite Modules Using Controlled Indoor Light/Dark Cycling
17:35-20:00	POSTER PRESENTATIONS AND WALKING DINNER	

ROUNDTABLES TOPICS

4. AI, modeling, FAIR
5. Greenification of the process OPV/perovskite
6. Testing protocols, Indoor degradation, Intrinsic stability

SESSION 6 **Degradation experiments conducted outdoors**
CHAIR: NIKOLETA KYRANAKI

9:00-9:30 INVITED SPEAKER QUENTIN JEANGROS
Microstructural changes in perovskite PV during stress testing: from known mechanisms to still elusive causes

9:30-9:45 ORAL PRESENTER SATISH BYKKAM [ID 13]
Enhanced Efficiency and Long-Term Stability of Semitransparent Perovskite Solar Cells and its Application in 4T Perovskite/Si Tandem Solar Cell

9:45-10:00 ORAL PRESENTER SUJITH VISHWANATHREDDY [ID 9]
Unraveling reverse bias induced degradation pathways in perovskite solar cells and modules

10:00-10:30 COFFEE BREAK AND EXHIBITION

10:30-11:00 INVITED SPEAKER SHENGZHONG LIU
Large-area scaleup preparation for perovskite solar cell production

11:00-11:15 ORAL PRESENTER KARA DUYGU [ID 12]
Interface Engineering Strategies for Enhancing the Performance of Flexible n-i-p Perovskite Solar Cells

11:15-11:30 ORAL PRESENTER DIMITRIS CHALKIAS [ID 6]
Unraveling depth-dependent photo-degradation of perovskite material in photovoltaics subjected to ISOS-L-1 and ISOS-L-2 accelerated aging: the influence of substrate, electron-transport-material and perovskite deposition method

11:30-12:00 CLOSING CEREMONY
- → Announcement of Award winners
- → Announcement of Stability Contest winner
- → Highlights from round tables
- → Announcement of next host for ISOS

12:00-13:00 LUNCH

13:00-16:45 VISIT TO THE ENERGYVILLE LABS

ISOS 16

International Summit on Organic and Hybrid Photovoltaics Stability

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Encapsulation and outdoor degradation (also under extreme conditions: space, desert, etc..)

Abstract 4: A novel way of analyzing perovskite outdoor degradation: the S-Voc

Jonathan Parion[1,2,3,4], Santhosh Ramesh[3,4,5], Elias Peraticos[6,7], Vasiliki Paraskeva[6,7], Matthew Norton[6,7], Maria Hadjipanayi[6,7], Aranzazu Aguirre[1,3,4], Tamara Merckx[1,3,4], Filip Duerinckx[1,3,4], Hariharsudan Sivaramakrishnan Radhakrishnan[1,3,4], Jef Poortmans[1,3,4,5], Johan Lauwaert[2], Bart Vermang[1,3,4]

[1]Hasselt University, Hasselt, Belgium. [2]Ghent University, Gent, Belgium. [3]imo-imomec, Genk, Belgium. [4]EnergyVille, Genk, Belgium. [5]KULeuven, Leuven, Belgium. [6]University of Cyprus, Nicosia, Cyprus. [7]Phaeton, Nicosia, Cyprus

Abstract

Today, many researchers use the IEC 61215 and ISOS protocols to unify and quantify reliability testing and to accelerate qualification. However, while accelerated tests can provide valuable insights, they are not adequate on their own to qualify modules for commercialization, which requires data from real-life outdoor deployment. This work tries to address this by comparing the performance evolution of two device architectures with different electron transport layers (ETL) over the course of more than three years. Perovskite mini-modules were manufactured with a process that is both reproducible and upscalable and placed outdoors on the island of Cyprus.

A key observation is that although the V_{oc} profile seems to be constant over time for both ETL compositions, this feature is, in the case of ETL1, directly resulting from the S-shape formation and is therefore not representative of the real module performance. This is a critical issue, since studies on outdoor data often rely solely on these figures of merit (FoMs) for their first-level analysis. To solve this, two new FoMs are introduced for the first time, namely S-V_{oc} and S-FF. They have the triple benefit of (a) being easy to extract even in the presence of a very large amount of IV curves (b) enabling the quantification of the S-shape formation over time and (c) constituting a closer representation of the real module. These FoMs could therefore constitute a new fast and reliable way of identifying and studying S-shapes in perovskite cells and modules.

Finally, in the last part of this work, an attempt is made at identifying the cause of degradation in ETL1 and ETL2 modules. Degradation in ETL1 samples is found to be related to a barrier formation at the perovskite/ETL interface, while in ETL2 samples it is likely caused by the partial delamination of the C_{60} layer.

Abstract 7: Outdoor stability analysis of perovskite modules after 1 to 4 years of field exposure in different climate zones

Ismail Kaaya[1,2,3], Aranzazu Aguirre[1,2,3], Tamara Merckx[1,2,3], Sujith Vishwanathredd[1,2,3], Jonathan Parion[1,2,3], Yinghuan Kuang[1,2,3], Anurag Krishna[1,2,3], Tom Aernouts[1,2,3], Jef Poortmans[1,2,3,4]

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Abstract

Perovskite solar cells (PSCs) have emerged as a highly promising photovoltaic technology, demonstrating power conversion efficiencies comparable to those of conventional silicon-based solar cells. Despite substantial advancements, the long-term operational stability of PSCs remains a critical challenge hindering their commercial deployment. Addressing this issue requires detailed investigation of their performance under realistic environmental conditions. This work presents insights from an extended outdoor performance monitoring campaign of large-area perovskite modules (ranging from 4 cm^2 to 800 cm^2) deployed across various climatic zones. This study aims to evaluate stability and degradation behaviors under actual operational settings.

We analyze temporal performance trends, highlighting phenomena such as partial recovery, seasonal variation, and other recurring degradation patterns. Through monitoring of key electrical parameters, we identify potential degradation pathways and attempt to clarify the underlying mechanisms. Particular attention is given to distinguishing whether observed degradation behaviors are intrinsic to the material properties or are influenced primarily by external operating conditions.

The findings contribute to the broader understanding of PSC degradation dynamics in outdoor environments, providing valuable guidance for improving device design and stability.

Abstract 22: Accelerating the Discovery of Stable OPV Systems via a Portable Outdoor Testing Platform

Anuj Kumar Singh, Han Xu, Marti G. Roca, Anirudh Sharma, Derya Baran

King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Abstract

Organic photovoltaics (OPVs) have recently surpassed 20% power conversion efficiency, marking a significant milestone toward commercialization. As efficiency improves, the field's attention is increasingly shifting toward long-term operational stability. Multiple studies report promising T_{80} (efficiency drop to 80% of initial PCE) lifetimes over 1000 hours through donor–acceptor engineering and interlayer optimization. Nonetheless, these are typically based on indoor thermal or light stability tests under controlled conditions. These fail to capture the complex and dynamic nature of real-world outdoor environments, where fluctuations in temperature, humidity, and irradiance can reveal additional degradation mechanisms. Recent efforts to assess OPV stability outdoors are valuable, yet existing setups are often bulky, costly, and geographically constrained, making them unsuitable for widespread or comparative studies across diverse climates.

Here, we introduce a compact, low-cost, and fully autonomous outdoor testing platform engineered to facilitate scalable field-based stability evaluation and enable high-throughput screening for the accelerated identification of robust OPV material systems. Our system combines reliable encapsulation, integrated performance measurement, and ambient sensing into a lightweight-portable design. It is built around a custom motherboard with an in-house designed micro-source measurement unit alongside an Arduino microcontroller, internal storage, and internet connectivity for wireless data transfer. All data are securely uploaded via HTTPS to a cloud server immediately after measurement, allowing remote access and streamlined analysis in real time. Using a cross-platform application (OMEGA App), advanced data analysis such as dataset comparison, diverse visualization methods, and statistical evaluation can be performed entirely offline. Finally, we demonstrate the platform's utility through a detailed analysis of 3-week outdoor stability data collected for various donor–acceptor systems. This platform enables scalable and real-world stability testing, opening new avenues for accelerated discovery and validation of stable OPV systems across diverse environments.

Abstract 26: Investigation of metastable behavior of perovskite samples using indoor light cycling techniques and outdoor assessment

Maria Hadjipanayi[1], Aranzazu Aguirre[2,3,4], Karim Medjoubi[5], Mirella Al-Katrib[5], Markus Kohlstädt[6], Matthew Norton[1], Elias Peraticos[1], Vasiliki Paraskeva[1], Tamara Merckx[2,3,4], Tom Aernouts[2,3,4]

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Abstract

Perovskite-based modules were tested outdoors and indoors using light-dark cycling at different temperatures to compare the evolution of electrical parameters of samples tested indoors and samples tested outdoors. The cycled metastable behavior was compared using the different cycling approaches indoors (fixed irradiance levels, high/low temperatures, varying irradiance) and then compared with the outdoor metastability of the samples at different locations (Germany, Cyprus). Voc bias load was applied to all samples under test indoors and outdoors for a reliable comparison between results. Comparison of power output in samples tested indoors with cycled testing at fixed irradiance and different temperatures showed more pronounced light soaking effects and minimum degradation at low temperatures compared to higher temperature testing in agreement with outdoor results. The same trend was obtained in Voc and FF in samples tested at low temperature cycling tests. Power output degradation and recovery during light/dark cycling were found to be statistically higher in samples tested at higher temperatures in agreement with past measurements. So far, results demonstrated similar cycled behavior of major electrical parameters in indoor tests at fixed irradiance levels and different temperatures especially during the last cycle. During the first cycles, larger impact of light soaking was found when testing at lower temperatures. Also, the strength of metastable behavior outdoors in samples tested in Cyprus exhibited differences compared to that obtained indoors at fixed irradiance levels. Furthermore, larger metastability in power output was obtained in Cyprus compared to Germany providing evidence that metastable behavior might be related to environmental conditions. More indoor and outdoor tests are underway for better understanding of metastability.

This work was financed by the European Union through the TESTARE project (Grant ID: 101079488) and by the European Regional Development Fund and the Republic of Cyprus through the DegradationLab project (Grant ID: INFRASTRUCTURES/1216/0043).

Abstract 27: Performance Metastability of Perovskite Solar Devices

Aimad-eddine Admane[1], Anne Migan Dubois[2], Anyssa Derj[1], Johan Parra[3], Marion Provost[1], Armelle Yaiche[4,1], Jordi Badosa[3], Jorge Posada[4,1], Jean Rousset[4,1], Karim Medjoubi[1]

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Abstract

Giving the actual energetic context, perovskite (PK) solar device is a potential candidate for a new solar technology, by being highly efficient with a low cost. The main obstacle is its high sensitivity to environmental factors [1]. Thus, enhancing the long-term stability is vital to reach commercial level.

Recent stability studies [2] of PK solar devices showed that in certain cases electrical performances vary during a day or day-night cycle. This variation as shown in Figure 1.(A), is commonly referred to as metastability, it raises many questions and require attention to comprehend operational phenomenon of devices. The aim of this study is to have a better understanding of this behaviour for PK solar devices using different cell architecture and devices configurations. Various indoor/outdoor stability tests were conducted: as ISOS-O, ISOS-LC, and others inspired by the protocols mentioned in the consensus statement, to spot this behaviour and reveal trends regarding environmental parameters.

Day Metastability (DM) is a parameter used to quantify metastability, it expresses the variation of performance during a day. Figure 1.(B) represents the DM of efficiency as a function of the date for an outdoor aging test. Through a polynomial fit, it can be clearly seen that the diurnal behaviour is oscillating between two stats: day degradation, and day recovery. To understand this, a 3000h modified ISOS-LC aging test was performed. Temperature was changed mid-test from 25°C to -5°C. A performance freeze was observed, as shown in Figure 1.(C).

Through results, metastability is qualified and quantified in both electrical performance, and material quality through opto-electronic characterization (luminescence and IV characterization), for various architecture, device size and aging environment.

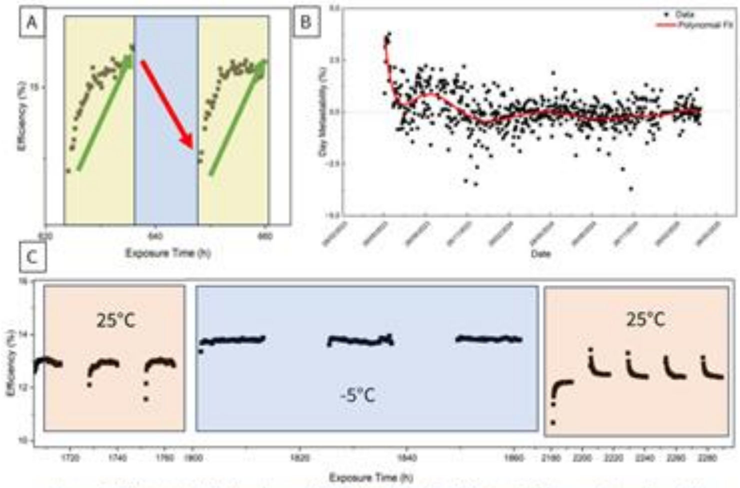

Figure 1, Metastable behaviour of efficiency (A). Day Metastability as a function of the date, and its polynomial fit (B). Efficiency as a function of exposure time in a modified ISOS-LC aging test (C).

[1] L. Meng, J. *et al.*, *Nat. Commun.*, doi: 10.1038/s41467-018-07255-1.

[2] V. Paraskeva *et al.*, *ACS Energy Lett,* doi: 10.1021/acsenergylett.4c01943.

Abstract 28: Large-area scaleup preparation for perovskite solar cell production

Shengzhong Liu

Dalian Institute of Chemical Physics, Dalian, China

Abstract

The ABX3-type perovskite structure appears to be a wonder for a wide spectrum of applications including piezo-, ferro-, antiferro-magnetism, antiferro-electricity, superconductivity, catalysis, etc. In particular, the organic-inorganic hybrid lead-halide-based perovskite has demonstrated amazing properties in photovoltaic, optoelectronic and photoelectronic applications. In only a few years since the thin-film type perovskite solar cell was reported in 2012, its solar cell efficiency has surpassed 27%, higher than all other thin film solar cells. In this conference, I'll cover research and developments in my groups on perovskite solar cells, membranes and their application in photovoltaics. In particular, I'll report our effort in scaling up fabrication. With support from industry, we have successfully designed and setup a pilot production line for square-meter size rigid panel and another for flexible roll-to-roll (R2R) deposition. Meanwhile, production line is getting ready for production. In summary, solar module efficiency for 1200x650 (mm^2) panel is about 20%. Figure 1 shows a kW-scale solar power plant installed with an assembly of 20 high-efficiency solar panels. We are pleasantly surprised by no detectable degradation observed over a period of about 18 months. Using the R2R continuous coating line, we are capable of depositing all functional films up to a hundred meter long, 350 mm in width. The unit area (175x175 mm^2) solar cell efficiency is as high as 19.2%, integrated 1050*350 mm^2 module efficiency as high as 17.75%, all among the highest in the field.

Abstract 30: Development of an outdoor PV testing platform for comparison of energy production from various emerging solar technologies.

Barthélemy Hugon[1], Martial Leyney[1], Marie-Estelle Gueunier-Farret[1], Anne Migan-Dubois[2], Frédéric Oswald[3], Guillaume Wantz[1]

[1]Université de Bordeaux, CNRS, Bordeaux INP, IMS, UMR 5218, Talence, France. [2]Université Paris-Saclay, CentraleSupélec, CNRS, Sorbonne Université, GeePs, Gif sur Yvette, France. [3]Université Paris-Saclay, CEA, CNRS, NIMBE, LICSEN, Gif sur Yvette, France

Abstract

In recent years, a growing interest in emerging photovoltaic solutions, such as organic (OSC) or perovskite (PSC) solar cells has emerged based on several successful breakthroughs on top of their distinctive advantages: light weight, printability, semi-transparency, low environmental impact and the use of non-strategic materials. These emerging solar technologies have recently reached impressive power conversion efficiencies in labs [1]. However, their industrial transfer is still facing important challenges mainly due to lower performances and stability for large area modules [2].

We report here on the design and development of an outdoor testing platform for solar modules located in Bordeaux. It allows their characterization in real time, under real conditions all year long, from the well-known hot and sunny days to the rainy and oceanic climate. A variety of emerging solar panels provided by international industrial and academic partners including PSC and OSC modules are studied versus mature crystalline silicon modules alongside with numerous environmental sensors. An acquisition card has been designed to monitor devices of various sizes and output power. It is light, portable, wireless and allows to choose the measurement conditions (MPP, open-circuit or short-circuit) for each module. The temperature of each module is also carefully monitored.

Besides the power conversion efficiency (PCE) consideration we will focus on the analysis of the integrated energy yield of each technology in order to gain a broader sense of the production capabilities of the devices under real outdoor illumination [3]. In addition to the Bordeaux location, a twin set of OSC and PSC modules have been implemented on the existing platform of SIRTA in the Paris region and the comparison between these two sites will be also discussed.

[1] www.nrel.gov

[2] Eva M. Herzig et Al, Joule, Volume 8, Issue 8, 2024

[3] Sarmad Feroze, et Al, Solar Energy, Volume 263, 2023

Abstract 31: Impact of Self-Assembled Monolayers on the Long-Term Stability of Perovskite Solar Cells: An Outdoor Degradation Study

Beatriz Romero Herrero[1], Silvia Delgado[1], Gonzalo Del pozo[1], Pedro Contreras[1], Belén Arredondo[1], Sujith Vishwanathreddy[2], Jonathan Parion[2], Santhosh Ramesh[2], Tom Aernouts[2], Aranzazu Aguirre[2]

[1]Universidad Rey Juan Carlos, Móstoles, Spain. [2]Imec, Genk, Belgium

Abstract

In this work we evaluate the impact of incorporating a self-assembled monolayer (SAM) into perovskite solar cells (PSCs) on device stability through an outdoor degradation experiment. Minimodules with seven series-connected cells were fabricated and subjected to degradation following the ISOS-O2 protocol for over 18 months. Results indicate that modules with SAM exhibit more pronounced long-term degradation compared to reference structures, with T_{80} values of approximately 21 days for SAM devices and 30 days for reference devices. The efficiency drop is primarily due to a significant decrease in short-circuit current, particularly during spring and summer. This degradation is attributed to the combination of high temperature and high irradiation.. Despite higher initial efficiencies, SAM modules show more significant degradation in short-circuit current, suggesting unbalanced charge transport due to SAM spacer degradation. Impedance measurements recorded indoors throughout the degradation experiment revealed a stronger decrease in high frequency capacitance (C_{HF}) for SAM modules, attributed to a proportional decrease in the dielectric constant. This confirms that SAM modules experience more significant active layer degradation, likely due to the deterioration of the SAM spacer group or diffusion of SAM into the perovskite layer. Further research is ongoing to optimize methodologies for accessing the degraded perovskite layer without inducing mechanical stress.

Abstract 32: Major degradation pathways of perovskite absorber materials and solar cells under simulated space conditions

Victoria Ozerova[1], Lyubov Frolova[1], Nikita Emelianov[1], Ivan Zhidkov[2,3], Sergey Aldoshin[1], Pavel TROSHIN[4,1]

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Abstract

Perovskite solar cells (PSCs) have achieved remarkable progress in power conversion efficiency, with certified values exceeding 27% for the best single-junction devices. The discovery of extreme radiation hardness of PSCs featured their significant potential for space applications, particularly considering impressive power-to-weight ratios demonstrated for these devices. However, the harsh operational conditions in Earth orbit – far more extreme than terrestrial environments - demand stringent stability requirements for PSCs.

In this presentation, we will summarize our systematic study of a panel of perovskite absorber materials and fully assembled PSC, focusing on their stability under simulated orbital conditions. Our study evaluates the effects of the key stress factors, including UV light exposure, different types of ionizing radiation and temperature cycling. The dominant degradation mechanisms will be discussed and potential mitigation strategies to enhance device resilience will be proposed.

This work was supported by Ministry of Science and Higher Education of Russian Federation (Project № 075-15-2024-532).

Abstract 33: Decoding Outdoor Degradation in Perovskite Solar Cells through Accelerated Aging Tests

Ulas Erdil[1,2], Lars Bergenholtz[3], Mark Khenkin[1,4], Marko Remec[1], Guillermo Farias Basulto[1], Quiterie Emery[1], Antonio Abate[1,2], Eugene A. Katz[5], Rutger Schlatmann[1,3], Carolin Ulbrich[1], Andreas Bartelt[3]

[1]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany. [2]Bielefeld University, Bielefeld, Germany. [3]Hochschule für Technik und Wirtschaft Berlin, Berlin, Germany. [4]University of Ljubljana, Ljubljana, Slovenia. [5]Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel

Abstract

Demonstrating long-term stability remains an important step toward the large-scale commercialization of perovskite solar cells (PSCs), making accelerated aging tests essential for rapidly uncovering their complex degradation pathways. In this work, we uncover three distinct spatially non-uniform degradation modes—electrode corrosion, edge patterns, and phase segregation—emerging following 20 months of outdoor exposure in Berlin, Germany. By varying light intensities (1 sun /2.3 suns) and electrical biases (OC/ MPP), we successfully reproduce these modes and also show how stressor interplay dictates the spatial extent and dominance of degradation modes. Phase segregation, manifesting most extensively across the device, is of particular interest due to its relevance for many perovskite compositions and its possible link to performance transients observed under real-world conditions. This study establishes a link between real-world degradation modes and accelerated aging, providing insight into both permanent losses and transient effects, and laying the groundwork for mechanism-specific accelerated aging protocols.

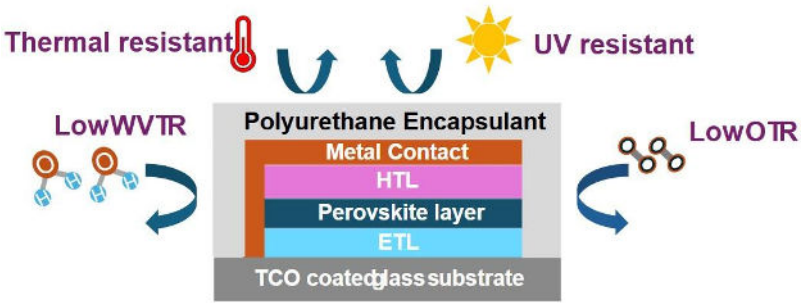
Abstract 42: Biobased Thermosetting Polyurethane Encapsulation for Perovskite Solar Cells

Divya Shaju, Seyede Maryam Mousavi, Hossein Baniasadi, Jaana Vapaavuori

Aalto University, Espoo, Finland

Abstract

The power conversion efficiency (PCE) of perovskite solar cells (PSCs) has skyrocketed from an initial 3.8% to an impressive 27% [1] within a relatively short span of time. However, their unstable nature adversely affects the performance and lifetime of PSCs, hindering their practical commercialization. The external detrimental factors such as ultraviolet radiation exposure, elevated temperature, moisture and oxygen diffusion into the solar cell can be controlled primarily by providing a suitable device encapsulation, thus enhancing the stability and durability of PSCs [2]. To address these challenges, we propose a facile, sustainable and solution-based encapsulation approach utilizing the biobased polyurethane that can be cured at ambient room temperature and applied through dip coating to provide barrier against the degrading environmental factors for perovskite solar cells. A series of biobased polyurethane is synthesized and the effect of stoichiometric ratio on the resulting encapsulant film properties is assessed. The characterization analysis on the polyurethane films imply that they block ultraviolet radiation to a great extend while maintaining approximately 90% transparency to the visible light. These flexible polyurethane films display hydrophobicity with a water contact angle of over 100^0 and excellent moisture and oxygen barrier properties. This flexible encapsulant material also exhibits good mechanical stability and thermal stability, deteriorating only after 300 ^{0}C. Thus, this study introduces a promising, ecofriendly encapsulant alternative to other conventional polymer coatings. The potential application of the proposed biobased polyurethane encapsulant is not only to the flexible perovskite solar cells but also extend to other optoelectronic devices such as other types of solar cells and light emitting diodes.



References

1. Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL. [Accessed: June 20, 2025].
2. S. M. Mousavi *et al.*, Materials Today Energy, Dec 2024, 46, p. 101707, doi: https://doi.org/10.1016/j.mtener.2024.101707

Abstract 45: Perovskite-Silicon Tandems in the Tropics: Outdoor Performance of Large (244 cm^2) Single-Cell Mini-Modules in a Wet and Warm Climate.

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Abstract

Perovskite-silicon tandem solar cells have demonstrated exceptional power conversion performance in the lab, and some have now achieved an early stage of commercialisation. However, long-term outdoor studies of their performance have been scarce, and research specifically on the performance of larger-area devices made with scalable techniques, as well as their performance in the tropical climate, is lacking in the literature.

This study investigates the performance of large-area (M2, 244.3 cm^2), encapsulated, 2-terminal single-cell perovskite-silicon tandem mini-modules over an extended period in a rainy tropical climate. Through real-time monitoring, diurnal behaviour of the devices is observed and analysed. Monthly current-voltage (I-V) measurements reveal the evolution of the tandem cell performance over time. Spectrometric characterisation was performed to give insight on the evolution of the top and bottom cells within the tandem device. Initial results show that moisture ingress is the most significant driver of performance loss and is expected to be a key challenge in deployment of perovskite-silicon tandem devices in tropical climates.

Abstract 48: Radiation hardness of flexible perovskite solar cells employing PTAA-like hole transport material irradiated by atmospheric neutrons.

Giulio Koch[1], Daniel Augusto Machado de Alencar[2], Cullen Choosy[3,4], Amanda Generosi[5], Flavia Righi Riva[5], Samyuktha Noola[2], Farshad Jafarzadeh[1], Kyle Frohna[3,4], Matteo Bonomo[2], Pierluigi Quagliotto[2], Paolo Rech[6], Carlo Cazzaniga[7], Marco Ottavi[8,9], Francesca De Rossi[1], Barbara Paci[5], Samuel D. Stranks[3,4], Claudia Barolo[10,11], Francesca Brunetti[1]

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Abstract

Flexible perovskite solar cells, with 25.05% record efficiency [1] and excellent power densities of 30 W/g [2], are promising candidates for space.

Our previous work revealed the positive impact of the insertion of benzothiadiazole unit on P3HT scaffold upon neutron irradiation [3]. Here, we synthesized a new HTM, co-polymerizing PTAA with a phenothiazine, and compared it to commercial PTAA.

Neutrons have been shown to induce degradation in traditional solar cells in space. However, the literature on PSC is still not as extensive. Studying potential damage sources selectively can help estimate PSC ageing in space more accurately. Therefore, we studied degradation induced by atmospheric-like neutrons (fluence $5 \bullet 10^9$ n/cm^2, equivalent to ~400 times the yearly fluence in LEO), which can represent the LEO environment [4]. The morphological and electronic properties of films and solar cells were probed before and after irradiation.

Both HTMs showed good resilience against neutron exposure: devices with our in-house-synthesized HTM experienced little-to-no loss in efficiency, while PTAA counterparts retained ~80% of their initial efficiency.

In all cases, V_{OC} remained stable, pointing to minimal non-radiative recombination losses induced by neutron irradiation. Such observation was corroborated by microscopic PL mapping on perovskite samples, showing minimal changes in spatial PL distribution. Morphological and crystallographic analysis showed that, while the perovskite crystallinity in general remains high, unbound PbI_2 defects in PTAA devices increase upon radiation, while the in-house alternative showed a consistently lower PbI_2 peak before and after the irradiation, suggesting the modified HTM can effectively passivate the perovskite interface and stabilize it against such defects formation.

1. Ren *et al*., *iEnergy*, vol. 3, no. 1, pp. 39-45, 2024
2. Wu *et al., Sci. China Mater.* 65, 2319–2324 (2022).
3. De Rossi et al, Nanoenergy 93, 2022, 106879
4. Frost et al. *Reliability Physics Symposium, 2009*, 952-955

Abstract 56: Inside Out: Correlating Indoor and Outdoor Degradation Experiments of Perovskite Photovoltaic Devices

Ceri Sophia Hommerich, Wilfried van Sark, Sara Mirbagheri Golroodbari

Utrecht University, Copernicus Institute of Sustainable Development, Utrecht, Netherlands

Abstract

Despite significant progress in developing standardized protocols for stability assessment of perovskite solar cells a key challenge remains: the predictive relationship between accelerated indoor stress tests and real-world outdoor degradation is not well established. Bridging this gap is considerably more complex than for established photovoltaic technologies such as silicon. This stems from the unique behaviors of perovskites – including pronounced responses to diurnal cycles and environmental fluctuations. These factors complicate the direct translation of laboratory results to field performance and hinder the development of universally reliable testing standards, which are especially important for successful industrial upscaling.

Our project within the national Dutch SolarNL photovoltaics research program is addressing this challenge through a coordinated study directly comparing combined-stressor accelerated indoor and parallel outdoor stability testing of perovskite solar cells and modules. By systematically analyzing degradation rates, failure modes, and performance metrics across both environments, we aim to identify which indoor stress tests most accurately predict outdoor stability, reveal degradation mechanisms unique to real-world operation and provide recommendations for refining accelerated testing procedures. The outcome of this research will contribute to the development of more predictive perovskite stability testing, adding to and/or refining the existing ISOS protocols.

Given the wide range of factors that leads to the degradation of perovskite solar cell performance, collaborative research is vital to enhance knowledge on degradation mechanisms. The correlated stability testing in this study will therefore partially build on the broad spectrum of perovskite stability projects within SolarNL, which collectively address key aspects such as fabrication methods and intrinsic stability mechanisms. Our approach establishes a connection between fundamental material and device stability and the long-term operational durability of perovskite devices.

This poster details our scientific rationale, key project objectives, and experimental framework, and invites collaboration to further advance stability testing methodologies within the perovskite research community.

Abstract 63: Lessons learned from outdoor and indoor assessment of perovskite single and tandem mini-modules in Germany, Cyprus and Israel.

Vasiliki Paraskeva[1], Markus Kohlstädt[2], Aranzazu Aguirre[3,4,5], Aregay Kiday[6], Eugene Katz[6], Matthew Norton[1], Elias Peraticos[1], Tom Aernouts[7,4,5], Maria Hadjipanayi[1]

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Genk, Belgium. [6]Ben Gurion University of the Negev (BGU), Sede Boker, Israel. [7]Imec, imo-imomec, Thin Film PV Technology, Genk, Belgium

Abstract

Poor operational stability and field reliability hinder the commercialization of perovskite photovoltaics. Outdoor inter-comparison campaigns of perovskite modules from different testing sites are still limited in literature. Furthermore, side-by-side outdoor testing of identical devices at different bias load conditions requires further investigation to compare the impact of different bias load conditions on the outdoor device stability.

In this work, a set of perovskite-based mini-modules (single-junction and 4T-tandem) has been distributed between testing partners in Cyprus, Israel and Germany to acquire performance measurements of the devices under long-term outdoor exposure at different bias load conditions (MPP and Voc) with the ultimate target to compare the impact of load, geographical location and device architecture (single junction vs tandem) on their long-term stability . Along with the MPP tracking by various algorithms, periodic scans of the full IV curves established the evolution of the major electrical characteristics over time.

The outdoor tests have been combined with thermal cycling and light soaking tests indoors to examine the impact of temperature and irradiance on both types of devices.

First outdoor results from Germany demonstrated no significant changes regarding the device stability at different bias load conditions (MPP and Voc) while all modules performance was quite stable after the initial burn-in period.

Preliminary outdoor tests at UCY established the criticality of some MPP input parameters on the reliable output of perovskite devices. More outdoor tests are underway and are expected to shed more light on the impact of bias load selection on the different device architecture at the three testing sites.

Testing protocols

Abstract 3: Galvanostatic Power Tracking for Enhanced Long-Term Stability Assessment of High-Hysteresis Perovskite Solar Cells Under Real-World Operating Conditions

Emilio J. Juarez-Perez[1,2], Roberto Casas[3], Marta Haro[2]

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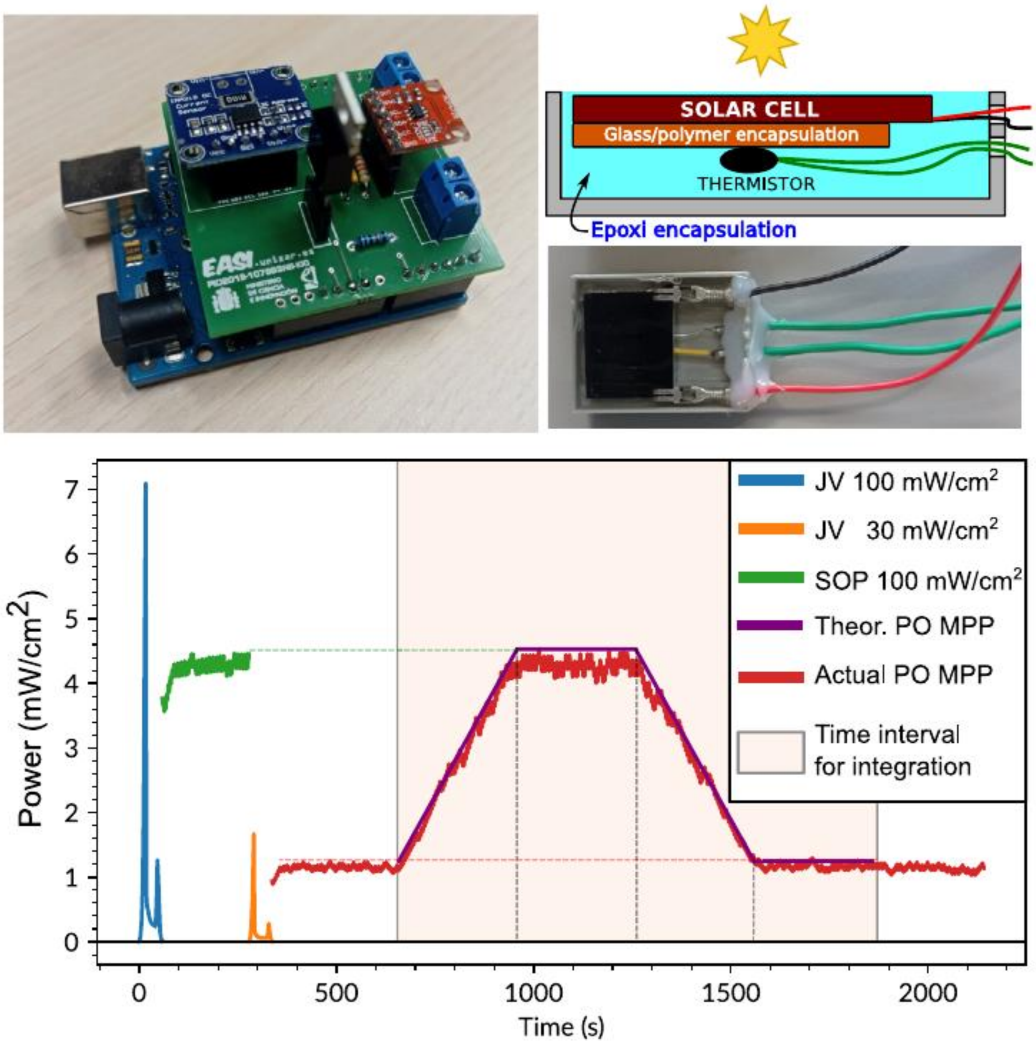
Abstract

The commercial viability of perovskite solar cells critically depends on addressing both efficiency and operational stability under real-world conditions. While triple-mesoscopic hole-transport-material-free architectures show promising operational stability, their inherent hysteresis challenges conventional maximum power point tracking algorithms, leading to inaccurate performance assessment. We present a galvanostatic power-tracking methodology and open-source hardware platform[1,2] designed for high-hysteresis perovskite devices, enabling precise long-term stability measurements under authentic operational conditions.

Our galvanostatic approach demonstrates significantly faster tracking response compared to traditional potentiostatic Perturb & Observe methods, particularly crucial for devices operating under rapidly changing irradiance levels. We validate this through extensive testing at our outdoor ParaSol platform in Zaragoza, Spain, where perovskite solar cells operate under real environmental conditions. We propose that ISOS protocols could incorporate EN-50530-like variable illumination testing standards to objectively evaluate MPPT algorithm effectiveness in perovskite devices with and without hysteresis, rather than simply assuming adequate tracking performance.



Our tracker's architecture can be extended to modules with V_{OC} exceeding 100V without voltage limitations inherent to potentiostatic methods. By providing open-source hardware and software, we enable standardized testing across research environments while delivering valuable insights into degradation dynamics under actual operational conditions—essential for bridging laboratory achievements with commercial deployment requirements.

References:

[1] E. J. Juarez-Perez; C. Momblona; R. Casas & M. Haro. Enhanced power-point tracking for high-hysteresis perovskite solar cells with a galvanostatic approach Cell Reports Physical Science, 2024, 5, 101885.

[2] A. Sanz-Marco; R. Jeronimo-Cruz; M. Haro & E. J. Juarez-Perez. Protocol Protocol for building and using a maximum power point output tracker for perovskite solar cells STAR Protocols, 2024, 5, 103394.

Acknowledgments:

Funding support from MCIN/AEI/10.13039/501100011033 and EU NextGeneration for grants PID2022-140516OB-I00, PID2019-107893RB-I00, PID2020-116011RB-C22, EIN2020-112315, PID2019-108247RA-I00, PID2022-142182OA-I00 and (RYC-2018-025222-I; M.H.). From the Aragon Regional Government T57_23R, E31_20R and T27_23R.

Abstract 8: Multi-biasing Characterization on Impedance Spectroscopy for Deeper Analysis of Perovskite Solar Cells' performance focused on the Ionic-electronic Transport and Recombination

Juan Pablo Medina Flechas[1], Dounya Barrit[1], Estelle Cariou[2], Marion Provost[2], Osbel Almora[3], Camille Bainier[1], Pilar Lopez-Varo[2], Philip Schulz[4]

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Abstract

The combined ionic and electronic conductivity in perovskite (PK) materials, along with concurrent degradation at the multiple layers and interfaces, complicates both the optoelectronic characterization and performance degradation analysis in perovskite solar cells (PSCs). Slow ion dynamics at PK interfaces with charge transport layers (CTLs) can modulate recombination and hinder charge extraction, inducing hysteresis and metastability during current-voltage (*JV*) characterization. Therefore, the evaluation of internal transport and recombination mechanisms limiting the response of the full device requires advanced characterization techniques, combined with enhanced physical interpretation via drift-diffusion simulations. Impedance spectroscopy (IS) is used to analyze in more detail the performance of the PSCs during *JV* scans. IS spectrum at a fixed bias enables decomposition into capacitive and resistive elements related to both electronic properties and slower interfacial dynamics at the PK/CTL interfaces.

In this work, a detailed optoelectronic characterization methodology for full PSCs is implemented through the coupling of (dark/light) *JV* curves, SunsVoc measurements and a multi-biasing IS analysis. As a case study, the proposed methodology is applied to analyze an inverted (p-i-n) PSC architecture developed at IPVF. By interpreting the experimental measurements along with drift-diffusion simulations at short-circuit conditions, parameters such as free carriers' mobility and ion concentration in the PK layer, along with the shunt resistance of the devices are estimated. At open-circuit conditions, focus is made on accounting for coupled effects on the performance loss of the device from mobile ions and energy band offsets at the PK/CTL interfaces. An analysis of dominant recombination is performed by comparing the ideality factor (n_{id}) obtained from dark *JV*/SunsVoc and the equivalent ones at high and low frequencies from IS. This methodology allows a consistent analysis, which is adapted to the characteristics of PSCs and that can be linked to changes in the constituent materials' properties.

Abstract 38: Intelligent Power Tracking and Stability Assessment of Perovskite Solar Cells under Dynamic Illumination Conditions

Viraj Jayaweera Piyankarage[1], Satoshi Uchida[2], Shoji Kaneko[1], Hiroshi Segawa[2]

[1]SPD Laboratory, Inc., Hamamatsu, Japan. [2]The University of Tokyo, Tokyo, Japan

Abstract

The dynamic nature of real-world operating environments presents a significant challenge for the long-term performance and stability of perovskite solar cells (PSCs). In particular, rapid changes in irradiance due to partial shading or passing clouds can lead to suboptimal energy harvesting. This work introduces an embedded predictive control approach for real-time maximum power point tracking (MPPT) and stability assessment of PSC modules under such transient conditions.

The control strategy employs a lightweight neural network-based inference model implemented directly on microcontroller hardware. It estimates the optimal operating point using voltage and current patterns from the PSC module. Designed for resource-constrained systems, the model runs efficiently on the same microcontroller that controls the DC-DC power conversion stage, eliminating the need for external processors or cloud-based computation. The system was trained and validated under diverse shading scenarios, enabling high-accuracy MPPT with minimal response time.

In addition to power tracking, the neural network model is also used to evaluate the stability of PSC modules over time. Trained on historical performance data—including trends in MPP, Voc, Isc, and energy output—the model identifies patterns associated with early signs of degradation. By analyzing recent operating behavior in the context of this learned performance history, the system can provide predictive insight into the long-term stability of each module without requiring external sensors.

Experimental validation demonstrates the capability of the proposed embedded system to enhance both power output and real-time stability diagnostics in outdoor PSC modules. The integration of a compact neural network with intelligent control and predictive analytics presents a promising direction for improving the reliability and energy yield of next-generation photovoltaic systems operating in dynamic environments.

Abstract 51: Reliable inline IV characterization for commercial production of perovskite-based solar modules

Peter Pasmans, Stefan Roest

Eternal Sun, The Hague, Netherlands

Abstract

Successful commercialization of perovskite-based solar modules requires ensuring long-term reliability and establishing accurate and reproducible characterization methods to measure stable module power. The inherent metastability and strong hysteresis of perovskites make accurate and stabilized performance measurements challenging. The diverse material compositions and device architectures further complicate the development of standardized testing methodologies.

Current industry standards are moving towards stabilization protocols that include maximum power point tracking and asymptotic IV measurements. However, these protocols are time-consuming, often requiring minutes up to many hours, which makes them impractical for inline characterization during manufacturing. Furthermore, accurately determining key IV

parameters beyond maximum power (Pmax), alongside accounting for pre-conditioning and temperature effects, significantly complicates efficient inline module characterization.

Given typical production line cycle times of 20-30 seconds, an effective inline quality control strategy requires a hybrid approach, similar to existing thin-film module practices. This involves 100% inline IV testing within the available time to assess module power and to verify basic functionality or identify gross defects. This inline testing would be complemented by offline stabilization tests on a representative sample of modules to determine the stabilized power output (SPO). An accurate and reliable nameplate Pmax rating for the module is then derived by correlating its inline Pmax measurements with comprehensive offline SPO data.

This work focuses on accelerating the performance assessment of perovskite-based modules. Through close collaboration with leading industry partners and research experts, and by leveraging standardization efforts within the IEC and related communities, we aim to establish best-practice recommendations for determining PV module power output. This presentation details our progress, integrating insights from a comprehensive literature review with experimental results. Our ultimate goal is to provide a consolidated framework for reliable and reproducible testing, thereby accelerating the commercialization of high-performance and reliable perovskite-based solar modules.

Abstract 57: Investigating the Oxygen Barrier Properties of Desiccated Edge Sealants for Protection of Perovskite Solar Modules

Paul Monroe, Lori Postak

Quanex, Akron, United States

Abstract

Conventional evaluation of Oxygen Transmission Rate (OTR) is done on thin polymer films according to ASTM D3985 using dry oxygen at different temperatures. Multiple challenges exist to obtaining reliable data from ASTM D3985 due to the high barrier properties and easily deformable nature of desiccated edge sealant. Data will be presented to show issues observed with testing that make even independent test lab results questionable without critical analysis.

Novel methods for monitoring oxygen ingress into mock-modules will be presented to characterize the relative barrier properties of different edge sealant widths or different sealant types. Oxygen indicator dots can be used to visually track the ingress of oxygen into a mock module. Additionally, a mock-module can be constructed in a way that allows for the quantitative measurement of oxygen content inside a module exposed to a high oxygen environment.

Intrinsic stability

Abstract 5: Enhanced Photostability in Organic Solar Cells Using a PEDOT:PSS/2PACz Hole Transport Bilayer

Julia Hönigsberger[1], Konrad Binter[1], Lakshmi Rajan[2], Egon Pavlica[2], Gregor Trimmel[1], Thomas Rath[1]

[1]Institute for Chemistry and Technology of Materials, Graz, Austria. [2]Laboratory for Organic Matter Physics, Nova Gorica, Slovenia

Abstract

With the power conversion efficiencies of organic solar cells (OSCs) already exceeding 20%, the improvement of long-term stability is receiving increasing attention. A significant performance loss in OSCs typically occurs in the initial operating hours, the so-called burn-in effect. We investigated the influence of various hole transport layers (HTLs) and found distinct differences in the photo-stability of PM6:Y6 bulk heterojunction OSCs. In particular, we tested several HTLs, including PEDOT:PSS 4083, PEDOT:PSS pH-neutral, 2PACz, and bilayer modifications. Even though the drawbacks of PEDOT:PSS regarding device stability are often discussed, the material is still the choice in highly efficient OSCs. In this regard, we investigated a pH-neutral PEDOT:PSS, but this alternative could not achieve comparable efficiencies and stabilities. Therefore, we focused our research on the self-assembling molecule 2PACz, which is known for its promising properties in interface engineering. While 2PACz as HTL is reported to suffer from photo-instability, the bilayer PEDOT:PSS 4083/2PACz led in our investigations to very promising shelf-life stability of solar cells under continuous illumination over 650 h without burn-in. While solar cells with a pristine PEDOT:PSS HTL show a significant burn-in and t_{80} times of 72 h, the solar cells with the combined PEDOT:PSS/2PACz HTL still show the initial performance after 650 h of continuous illumination. In addition to performing stability tests under various conditions, we studied the ongoing degradation mechanisms by investigating charge recombination kinetics, charge dissociation, collection efficiencies, and morphological changes before and after the stability tests.

Abstract 9: Unraveling reverse bias induced degradation pathways in perovskite solar cells and modules

Sujith Vishwanathreddy[1,2,3], Santhosh Ramesh[1,2,4], Aranzazu Aguirre[1,2,3], Michael Daenen[1,2,3], Tamara Merckx[1,2,3], Tom Aernouts[1,2,3], Jef Poortmans[1,2,3,4]

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Abstract

Perovskite solar cells (PSCs) have emerged as a promising candidate for next-generation photovoltaics due to their high efficiency and low fabrication costs. However, their long-term operational stability, particularly under reverse bias conditions, remains a key obstacle to commercial deployment. Reverse bias stress can occur in modules due to partial shading, causing shaded cells to operate in negative voltage and leading to irreversible degradation. Understanding and mitigating this behavior is essential for reliable outdoor performance and technology maturity.

At the cell level, reverse bias characteristics are evaluated using voltage sweeps at varying scan rates (2 V/s, 0.2 V/s, and 0.02 V/s), revealing pronounced rate dependence due to the material's ionic and electronic transport dynamics. Different electrode materials, silver, indium tin oxide (ITO), and silver fingers on ITO, are compared to assess their role in breakdown and degradation. Additionally, constant reverse current stress (~-J_{MPP}) is applied to simulate breakdown conditions in the cell. Also, the effect of light soaking and recovery of devices is monitored to understand the reversibility of the degradation.

In modules, degradation is studied in monolithically interconnected devices, focusing on the influence of laser scribing and electrode configurations. Laser scribing, necessary for series interconnection, may introduce microstructural defects that serve as preferential degradation sites under stress. Initial observations indicate that, as in CIGS technology, perovskite degradation frequently initiates at these scribe lines.

To complement the above tests, partial shading tests are conducted in a climate chamber with different shading geometries. Electroluminescence imaging is employed to visualize degradation patterns, while infrared thermography identifies thermal hotspots and weak points in the module. This comprehensive analysis aims to provide understanding of reverse bias effects in PSCs and highlights the need for standardized testing protocols to understand degradation pathways and cross-laboratory comparisons.

Abstract 11: Don’t fluorinate there! The Impact of Fluorination Position on Polymer Photostability and Its Effect on Photovoltaic Device Stability

Joel Luke[1,2], Shiyu Chen[2], Qiao He[2,3], Martina Rimmele[2], Adam Marsh[1], Martin Heeney[1,2], Ji-Seon Kim[2,4]

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Abstract

Despite the excellent progress in organic photovoltaic (OPV) efficiencies, they can still suffer from poor operational stability, especially in ambient conditions, with degradation frequently driven by intrinsic material instabilities. The design of more stable organic semiconductors (OSCs) requires an understanding of the intrinsic materials' stability in terms of molecular structure. Given the huge number of structural motifs and functional groups and the wide variety of degradation mechanisms present in a device, developing this understanding can be challenging. In this presentation, I will first outline some of my previous work in this area, using Raman spectroscopy as a molecular probe to understand the photodegradation of non-fullerene acceptors and high-performance donor polymers, and describe how this led us to propose molecular design rules for improved photostability in OSCs for photovoltaics. One of our recommendations for improved stability, and a commonly used approach applied in the literature, is fluorination. Fluorination deepens frontier orbitals and improves organic semiconducting packing, both of which can be beneficial for stability. I will present an investigation of fluorinated analogues of the high-performance workhorse polymer PBDB-T to explore the impact of fluorination. Device stability in both inert and ambient conditions is found to be critically dependent on intrinsic polymer photostability. Fluorination on the linker thiophene marginally improves stability, but fluorination of the benzodithiophene (BDT) unit is ruinous for stability, with the carbonyl group in BDT-fluorinated analogues becoming highly unstable towards illumination. We explore the origin of this instability, paying particular attention to the interfering non-covalent interactions along the polymer backbone, which seem to be critical for polymer photostability. Our results challenge the conventional belief that fluorination universally improves OPV stability and underscore the crucial role of non-covalent interactions in governing material stability.

Abstract 14: Elucidating the Photodegradation Pathways of Polymer Donors for Outdoor-Stable Organic Solar Cells

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Abstract

Organic solar cells (OSCs) have experienced significant breakthroughs in performance over the past decade. Driven by advancements in device and materials engineering, the power conversion efficiency of OSCs is approaching 21%. Many polymer donors have been designed and synthesized to achieve high efficiency. To accelerate the market readiness of OSCs, it is imperative to focus on device stability under real-world climates. However, the intrinsic photodegradation mechanisms of polymer donors remain poorly understood, and achieving stable OSCs under outdoor conditions has yet to be demonstrated.

Here, we investigate the impact of polymer donor building block selection on the in-lab photostability of OSCs and validate the outdoor stability of devices. Through tracking photochemical and morphological degradation behaviors, we elucidate the mechanisms of side-chain-induced photodegradation in polymer donors. We further examine the outdoor stability of 15 different OSCs to elucidate the relationship between polymer donor photostability and device stability in outdoor environments. By understanding performance losses induced by various photoactive layers, we demonstrate that encapsulated non-fullerene-based OSCs can preserve 91% of their initial efficiency after seven months of operation in the hot and sunny climate of Saudi Arabia. We anticipate that OSCs will offer significant potential for real-world applications in the future.

Abstract 15: An efficient passivation method of ETL/photoactive layer interface for high performance and stable inverted organic solar cells

Martina Smacchia[1], Fracncisco Bernal-Texca[1], Jordi Martorell[1,2]

[1]ICFO, Barcelona, Spain. [2]Universitat Politècnica de Catalunya, Tarrasa, Spain

Abstract

Inverted organic solar cells (OSCs) offer enhanced environmental stability and processing compatibility, making them a preferred architecture for scalable photovoltaics. The most commonly used electron transport layer (ETL) in this structure is zinc oxide (ZnO) due to its high electron mobility, optical transparency in the visible range, and chemical stability. However, its photoinduced catalytic activity remains a key limitation, as it accelerates interfacial degradation. To overcome this, effective surface passivation strategies are essential.

In this study, we introduce an ultra-thin lithium fluoride (LiF) layer onto the ZnO surface as a passivation layer to mitigate degradation effects. The LiF forms Li-O bonds with oxygen species on the ZnO surface, particularly targeting the oxygen vacancies that arise from incomplete sol-gel processing. Successful passivation is confirmed by X-ray photoelectron spectroscopy (XPS) showing a substantial reduction in surface oxygen content.

We demonstrate that the addition of the LiF layer at the ZnO/blend interface, in cells where the blend is either PM6:Y6 or PTB7-Th:IEICO-4F:$PC_{70}BM$, enhances the cell performance and stabilizes all key photovoltaic parameters such as power conversion efficiency (PCE), open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), and fill factor (FF), under continuous operation. In particular, in the time span considered, V_{oc} shows no degradation under thermal and illumination stress, a condition in which conventional ZnO-based devices typically exhibit pronounced voltage degradation.

Overall, this approach offers a simple, scalable, and effective route to improve both the operational stability and electronic performance of OSCs, making them more suitable for commercial implementation.

Abstract 17: Thermal Stability and Morphological Evolution of Polymer Donors in Organic Solar Cells

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Abstract

Recently, organic solar cells (OSCs) based on non-fullerene acceptors have achieved significant improvements in power conversion efficiency (PCE), however long-term operational stability remains a major challenge for their commercialization. Enhancing the photostability of polymer donors has been identified as a crucial strategy for improving the overall stability of OSC devices, highlighting that photodegradation behavior is primarily governed by the chemical degradation of the donor component[1]. Under continuous illumination, elevated operating temperatures typically impose thermal stress, which can accelerate detrimental morphological changes in the active layer. This metastable morphology is considered one of the main obstacles to achieving high-efficiency and stable OSCs[2]. In this study, we investigate the correlation between morphology and stability by examining the thermal degradation pathways of three representative donor polymers - D18, PM6, and PTQ10 - paired with a standard non-fullerene acceptor, L8BO, in binary and ternary systems. The morphological evolution of the active layers under thermal stress is monitored using ex-situ GIWAXS measurements. In PM6-based devices, the π–π stacking distance remains unchanged with heating, providing an enhanced molecular packing and domain sizes. In contrast, D18-based systems exhibit the emergence of recrystallized structures hence the disruption in stacking ordering. The temporal evolution of normalized solar cell parameters was monitored in devices aged in a dark and inert environment at 65 °C and 85 °C. Across all systems, the observed decrease in PCE is primarily driven by losses in open-circuit voltage (V_{OC}) and fill factor (FF), reflecting structural changes in the active layer, especially in vertical packing, detrimental to charge transport. These findings were correlated with the thermal properties (glass transitions) of the materials and first complementary FT-IR spectroscopic studies, provide a detailed analysis of phase distribution, structural and chemical bond stability within the active layer.

[1] Chem. Soc. Rev., 2024, 53, 7426-7454.

[2] Nat. Comm., 2023, 14, 2688.

Abstract 24: Photodegradation of organic solar cell materials

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Abstract

The operational lifetime of organic solar cells depends critically on the photochemical stability of the donor and acceptor molecules that make up the photoactive layer. Here we studied the evolution of optical properties, chemical composition and energy levels, during illumination in air of thin films of the small-molecule acceptors Y5 and Y6, their copolymer counterparts PF5-Y5 and PYT, as well as donor polymers PBDB-T, PM6 and PTQ10. We combined absorption spectroscopy, IR spectroscopy, X-ray and UV photoelectron spectroscopy and near-edge absorption fine structure spectroscopy. We found that under AM 1.5 illumination in air Y5 and Y6 film properties remain almost intact, that the copolymer PF5-Y5 undergoes rapid photooxidation, while the PYT film degrades much slower. [1] Films of the donor polymers PBDB-T and PM6 photo-oxidize rapidly, while PTQ10 is more resistant against photo-oxidation. The significantly faster photodegradation of PF5-Y5 compared to PYT could be assigned to the presence of the BDT moiety, which is also present in PBDB-T and PM6, and accelerates the photooxidation of these copolymers. We furthermore studied the effect of blending on the photostability of the films, and found that the degradation is accelerated compared to that of pure component films. Exposure of blend films to long wavelength light in air, which only the acceptor can absorb, yields new insights in the interplay of photooxidation processes by oxygen radical anions and singlet oxygen molecules.

References

[1]. Suraj Prasad, et al. *Materials Advances*, 2024, 5, 7708–7720.

Abstract 25: ZnO-free Organic Solar cells with Self-Assembled Monolayers as Electron Transport Layer for more stable Organic Solar Cells.

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Abstract

Albeit constant improvement of performances, stability remains limited for organic photovoltaics (OPV) solar cells. One of the restricting factors is the degradation happening at the interface between metal oxide transport layers and organic active layer. In particular, well-known zinc oxide (ZnO) used in inverted architecture (n-i-p) as electron transport layer (ETL) presents photocatalytic activity that degrades organic materials, ultimately affecting the performances upon operation. As a mean to address this issue, the use of self-assembled monolayers (SAM) in replacement of ZnO is investigated. Here we designed and synthesized a phtalimide based (2PAP-SAM) and a naphtalimide based (2PAN-SAM) molecules with a phosphonic acid as anchoring group, insuring a favorable molecular dipole. This resulted in a suitable shift of work function from 5.16 eV for pristine cleaned ITO to 4.28eV and 4.18 after 2PAP-SAM and 2PAN-SAM deposition respectively, that ultimately contributed to a better energy level alignment between the cathode and the LUMO level of the acceptor molecule. Solar cells with PTQ10:Y6 as active layer were then fabricated with 2PAP-SAM and 2PAN-SAM as ETL, and compared to a reference device with ZnO which presented mean power conversion efficiency (PCE) of 11.6%. As a comparison, devices with 2PAP-SAM reached up to 10% PCE with Voc around 0.78V while devices with 2PAN-SAM equaled standard ZnO cells with 11.3% PCE and V_{oc} of 0.81V. In comparison, devices without any ETL showed only poor performances with maximum of 7% PCE and 0.6V V_{OC}. Furthermore, ageing studies under continuous light illumination following ISOS-L1 protocol was performed and showed that devices with SAMs presented an overall improved stability maintaining 70% of the initial PCE after 100h. Whereas devices with ZnO lost 60% of performance under the same conditions. This work thus demonstrates that replacing ZnO with SAMs can be a promising alternative for more stable organic solar cells.

Abstract 29: ZnO Interface Engineering Enabled the Promotion of Long-Term Stability of the Organic Solar Cells

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Abstract

Currently, the efficiency of organic solar cells has developed rapidly. The stability issue became the most critical factor determining their practical application. For inverted-structure organic solar cells, photostability presents a particularly significant challenge. One of the main problems is caused by the ZnO electron-transporting layer. The surface defects on zinc oxide lead to interfacial recombination and causes serious light-induced degradation. Therefore, passivating or eliminating the defects of zinc oxide is a key issue that needs to be addressed. In recent years, we have developed a series of solution strategies, including organic interfacial passivation strategies using organic acids[1], alcohol solvent [2], and glucose [3], as well as in-situ conversion of inorganic passivation layers strategy[4]. Based on this, both efficiency and stability were significantly improved. In addition, we have extended the above strategies to in-situ passivation on the surface of particles[5, 6], which not only solves the defect problem, but also effectively regulate the surface energy of the materials and the stability of the printing inks. As a result, the organic solar cells exhibited a lifetime of T_{80} over 20000 h under ISOS-L-1 aging conditions, thus promoting the development of large-area printed organic photovoltaic cells.

References

[1] Han, Y., et al., *.ACS Appl Mater Interfaces*, 2021. **13**, 17869-17881.

[2] Liu, B., et al., Sol. RRL 2021. **5**, 2000638.

[3] Liu, B., et al., Adv Sci, 2022, e2104588.

[4] Liu, B., et al., Nat. Photonics, 2025. **19**, 195-203.

[5] Wei, J.F., et al., ACS Nano, 2018. **12**, 5518-5529.

[6] Ismail, I., et al., Sol. RRL, 2020. **4**, 2000289.

Abstract 34: Hydrophobic Organic Cation Incorporation for Long-Term Stability and High Efficiency in Mixed-Dimensional PSCs

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Abstract

In recent years, perovskite materials have shown tremendous potential for future solar cell applications. However, one major challenge that remains is their stability, which continues to hinder their practical use. To address the stability issues, various strategies are being actively explored, including surface passivation, compositional engineering, and optimization of the charge transport layers. To enhance stability without compromising efficiency, we propose the incorporation of a hydrophobic sulfoxonium cation into mixed-dimensional perovskite solar cells (MxD-PSCs). In our study, we utilize an innovative triple organic cation system consisting of methylammonium iodide (MAI), formamidinium iodide (FAI), and trimethylsulfoxonium chloride (TMSCl) to synthesize $MAFA(TMS)_XPbI_{3-X}Cl_X$ perovskite. The addition of TMSCl improves moisture resistance owing to its strong hydrophobic nature, while also enhancing charge transport and minimizing non-radiative recombination, as evidenced by optical, morphological, and electrical analyses. The optimized MxD-PSCs achieve a remarkable power conversion efficiency (PCE) of 21.43%, V_{OC} of 1.10 V, and J_{SC} of 24.82 mA cm^{-2}, with FF being enhanced to 78.5% under one-sun illumination (AM 1.5G). Furthermore, MxD-PSCs also perform remarkably with a PCE of 34.18% under indoor lighting (1000 lux). Moreover, the devices exhibit outstanding stability, retaining 85% of their initial efficiency after 90 days in an inert environment and 84% after 1000 hours under ambient conditions. These results underscore the effectiveness of the TMSCl cation in boosting both the stability and power conversion efficiency of MxD-PSCs, presenting a promising strategy for advancing durable and high-performance PSCs.

Abstract 35: Ion motion in perovskite solar cells

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Abstract

The presence of mobile ions in metal halide perovskite materials and charge transport layers have been shown to adversely affect the efficiency, hysteresis and stability of perovskite solar cells (PSCs). Li-TFSI doped Spiro-OMeTAD is the most used hole transport material in n-i-p perovskite solar cells. In the process of device preparation, Li^+ ions diffuse on the surface of metal electrode, which promotes the oxidation of Spiro-OMeTAD, improves the conductivity of Spiro-OMeTAD. Meanwhile, it is accompanied by the migration of Li^+ into the cells and enrichment at the perovskite/SnO_2 interface, which promote the extraction efficiency of electrons. However, during the operation of the device, the migration of Li^+ in SnO_2 will cause hysteresis and "burn-in" degradation. By introducing a thin layer of cross-linked fullerene (CL-PCBM) at the SnO_2/perovskite interface, the "burn-in" degradation can be suppressed. It was revealed that CL-PCBM can fix Li^+ ions in the SnO_2/perovskite interface, and the introduction of CL-PCBM can increase the built-in potential of the device and improve the electron extraction efficiency. Finally, the power conversion efficiency of 24.19% was achieved, and the "burn-in" degradation process was also eliminated.

Abstract 36: Intrinsic Chemical Stability Limits of Non-Fullerene Acceptors for Long-Term Operation

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Abstract

For organic photovoltaic (OPV) devices to achieve consistent performance and long operational lifetimes, organic semiconductors must be processed with precise control over their purity, composition and structure. This is particularly important for high volume solar cell manufacturing where control of materials quality has a direct impact on yield and cost. Acceptor-donor-acceptor (A-D-A)-type non-fullerene acceptors (NFAs) have proven to be an effective strategy for improving solar spectral coverage and reducing energy losses, leading to power conversion efficiencies exceeding 20%. However, we show that such materials have an intrinsic chemical instability issue, may influence both on device reproducibility and long-term reliability. We confirmed that the vinyl groups between the D and A in A-D-A type NFAs are vulnerable to dissociate even under the thermal energy of room temperature during the device fabrication, resulting in new chemical components by exchanging the end-capping groups between two NFAs. These new components can participate in charge transfer processes, resulting in the charge-transfer states change and affecting the device performance. Additionally, these asymmetric, dipolar molecules cause the heterojunction more disordered, leading to a less stable morphology that is more vulnerable to the photoaging. As a consequence, the efficiency of OPV falls to less than 40% of their initial values within 100 h when exposed to light intensity up to 10 suns illumination. Importantly, we find that the appropriate design of NFA molecules can prevent this end-capping exchange reaction, which will be critical to enhance the reproductivity as well as lifetime of NFAs based OPVs.

Abstract 37: Direct Measurement of Whole-device Capacitance in Perovskite Solar Cells Ensures Stable Performance

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Abstract

Organic–inorganic halide perovskite solar cells (PSCs) have attracted significant attention due to their high performance, simple fabrication processes, and compatibility with a wide range of substrates and processing methods.

One of the critical challenges in PSCs is the current–voltage (I–V) hysteresis, which is widely reported and closely related to interfacial phenomena. Our previous research revealed that internal capacitance, caused by charge accumulation within the PSC, plays a key role in the origin of this hysteresis.

The most commonly used technique to measure capacitance in PSCs is impedance spectroscopy, which applies a small AC voltage over a range of frequencies and analyzes the resulting current response to extract impedance. Although this method offers detailed frequency-dependent information, it relies on an equivalent circuit model and is time-consuming due to the required frequency sweeps.

To address these limitations, here in this work, we developed a new linear voltage ramp charge/discharge method with a specific algorithm, enabling direct measurement of total device capacitance in c perovskite solar cells for improved performance stability. Further chemical and physical properties of these solar cells will also be discussed in relation to crystallographic changes.

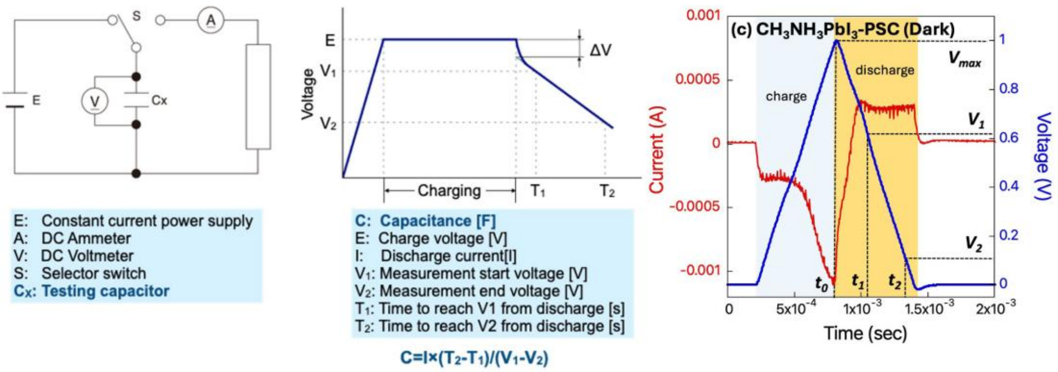

Fig. 1 Linear voltage ramp voltage charge/discharge testing protocol and capacitance measurement of perovskite.

Abstract 39: Stability and Interfacial Energy Levels Alignment in Perovskite Solar Cells

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Abstract

The stability of perovskite solar cells under working conditions is the main challenge to their practical application. Defects passivation in the bulk and at the surface of perovskite films has been applied as the state-of-the-art strategy in enhancing stability in perovskite solar cells. The interfacial energy alignment is well known to maximise efficiency but not stability. No direct experimental evidence provides insight into stability and energy alignment. The misunderstanding may have originated from the abundant literature on surface treatments and the impact of those on stability. However, the surface treatments so far reported in the literature simultaneously modify the defect density and the energy alignment of the perovskite. We disentangled the defect density by the energy alignment, providing direct evidence for stability and energy alignment. In this talk, we shall summarise that an optimal energy level alignment and consequent selective charge extraction at the interface with the contacts are equally necessary for stability, on top of passivating the defects within the perovskite.

Abstract 40: Tailored Ink Formulations for Scalable and Robust Perovskite Device Fabrication

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Abstract

As perovskite photovoltaics move closer to commercialization, one of the most critical challenges lies in the formulation of stable, scalable, and reproducible precursor inks. While significant progress has been made in achieving high efficiencies at the lab scale, the leap toward industrial manufacturing requires a rethinking of ink chemistry, with particular attention to long-term stability, environmental tolerance, and manufacturing reproducibility. This work highlights key design principles for next-generation perovskite inks, emphasizing the central role of solvent coordination, additive functionality, and intermediate phase control. Coordinating solvents, complexing agents, reducing additives, and humidity-tolerant formulations can collectively stabilize precursor solutions, reduce variability in film formation, and extend ink shelf life under realistic fabrication and storage conditions. Strategies such as halide migration suppression, solubility enhancement for multi-cation systems (e.g., cesium), and controlled nucleation through high-coordination additives offer promising routes to mitigate degradation pathways and crystallization defects. These formulations enable better grain uniformity, improved charge transport, and higher reproducibility in large-area devices. A major focus is the compatibility of such ink systems with scalable deposition techniques, including slot-die coating, blade coating, and roll-to-roll printing under ambient conditions. Ink robustness against humidity and temperature fluctuations is essential not only for long-term storage but also for outdoor manufacturing environments and high-throughput fabrication lines. Looking ahead, the development of universal inks, chemically robust, compositionally tunable, and tolerant to processing fluctuations will be essential to bridge the gap between high-performance lab devices and durable, mass-manufactured perovskite modules. Integrating these ink design strategies with in-line quality control, automated formulation optimization, and AI-driven feedback loops may significantly accelerate the reliable, cost-effective deployment of perovskite photovoltaics in real-world environments.[1]

Bibliography

1. L.A.Castriotta et al.; *Nature Energy*, in preparation.

Abstract 44: Intrinsic Thermal and Photodegradation Study of Slot-Die Coated, Air Processed High-Efficiency Organic Photovoltaics

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Abstract

In recent years, the state-of-the-art performance of organic photovoltaics (OPVs) has reached 20% with reasonable device reliability in a research laboratory using a spin-coating technique. However, this is not applicable for an industry-scale-up process. Therefore, it is essential to achieve high efficiency and more stable devices using industry-scale-up techniques, such as the slot-die coating method. In this study, we investigated device stability according to ISOS protocols and the scaled-up performance of two commonly employed OPV device architectures: inverted and conventional stacks processed in air. We explored two different strategies for forming photoactive layers: the bulk heterojunction (BHJ) method and the layer-by-layer (LBL) method. All solution-processable layers were fabricated from green solvents in air and optimized using the scalable slot-die coating technique, with PM6 as the electron donor and Y7-12 as the non-fullerene electron acceptor. Additionally, we studied the degradation of the devices under thermal (ISOS-T-1) and light stress, placing particular emphasis on identifying thermal degradation pathways for the different device architectures. Our findings suggest that, irrespective of the device architecture, the scalable slot-die coating method can be employed to achieve high-efficiency devices with a PCE of 15.24% for the best device. The partial stack device investigation indicates that minor thermal degradation occurs predominantly at the transport layer and electrode interface. Notably, inverted BHJ devices demonstrated impressive light stability (ISOS-L-1), maintaining initial high performance for over 800 hours. Additionally, a mini-module was fabricated, achieving a performance of 13.06%, which is comparable to that of small-scale devices. This work demonstrates the potential of slot-die coating at ambient conditions for producing high-efficiency OPV cells and modules, paving the way for the development of more stable organic photovoltaics.

Abstract 46: Engineering Efficient and Durable OPVs with PDIN-A Electron transport layer

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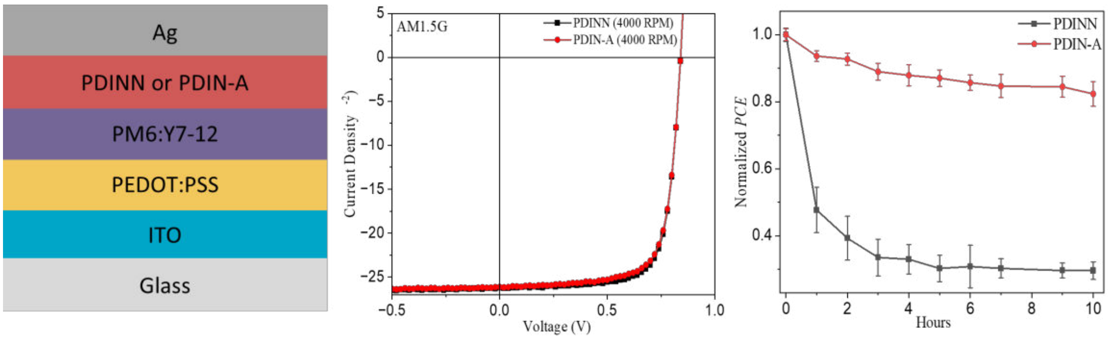
Abstract



Electron transport layers (ETL) in organic photovoltaics (OPV have attracted considerable interest due to their crucial role in improving charge extraction and transport while minimizing recombination losses at the interface. Out of a vast variety of ETL materials used for OPV, derivatives of perylene diimide (PDI) have demonstrated to exhibit very promising properties [1]. Here we demonstrate a new material, PDIN-A, that integrates the key characteristics shared by the high-performance electron-transport materials PDINN and PFN-Br and uses those for the fabrication of OPV devices [2]. We demonstrate promising performance and stability compared to reference PDINN material, which is a widely adopted highly effective ETL material in OPVs [3]. In this work, we developed OPV devices using a conventional device architecture of Glass/ITO/PEDOT: PSS/PM6: Y7-12 /PDINN or PDIN-A/Ag, as shown in Figure 1, and tested those under one sun AM 1.5 conditions. The photoactive layer consisted of the commonly employed donor PM6, and all the blends were processed from O-xylene solvent. As a reference ETL, the commonly employed PDINN material was chosen and compared against the newly synthesized PDIN-A, with both materials processed from methanol.

The optimized PDIN-A based OPV devices showed comparable performance to those fabricated with the reference PDINN. The solar cells achieved 16.17 % and 16.47 % for PDIN-A and PDINN materials respectively, under one sun AM1.5G illumination. To investigate the thermal degradation behavior, the OPV devices were subjected to thermal stress at 85 °C in a nitrogen atmosphere, corresponding to the ISOS-D2 protocol. PDIN-A ETL based OPV devices demonstrated remarkable stability under thermal stress, as compared to the reference PDINN.

Abstract 49: Fluorinated 2D Capping Layers for Stable and Efficient Perovskite Solar Cells: From Grain-Boundary Passivation to Tandem Integration

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Abstract

Perovskite solar cells (PSCs) hold immense promise for next-generation photovoltaics, thanks to their high-power conversion efficiencies, tunable optoelectronic properties, and compatibility with perovskite/silicon tandem architectures. However, their commercial potential remains constrained by long-term instability under ambient and operational conditions. Two-dimensional (2D) perovskite capping/passivation layers have emerged as a compelling solution, offering environmental resilience and interfacial passivation.

This work investigates the implementation of 4-fluoro-phenylethylammonium (FPEA)-based 2D capping layers atop three-dimensional (3D) perovskite absorbers. Two fabrication strategies were explored: direct deposition and solvent-washed formation at multiple spacer cation concentrations. The latter approach enabled superior film uniformity and orientation control, as confirmed by grazing-incidence wide-angle X-ray scattering (GIWAXS). Solvent-washed layers exhibited a horizontal alignment, which was optimal for moisture resistance and minimized perovskite ion transport barriers across interfaces. The fluorine substitution-induced dipole field at the interface reduces recombination and aids charge separation, confirmed via recombination dynamics using time-resolved photoluminescence and diode quality factor extraction using Suns-V_{OC} measurement. Conductive atomic force microscopy (c-AFM) highlighted enhanced conductivity pathways at grain boundaries, where FPEA cations passivate the trap sites and recombination centres, and suppress the non-radiative losses. These effects contributed to significant gains in the perovskite solar cell's open-circuit voltage and fill factor.

Critical optoelectronic parameters, carrier mobility, trap density, and energy levels were experimentally extracted and integrated into charge carrier drift-diffusion simulations in a solar cell for tandem solar cell optimizations. These simulations accurately simulated internal fields, recombination dynamics, and charge transport. In 2-terminal PIN perovskite/silicon tandem configurations, coupling optical modelling with electrical simulations mitigated parasitic absorption losses and theoretical efficiencies exceeding 39% and open-circuit voltages above 2 V were projected. This comprehensive study demonstrates the multifaceted benefits of engineered 2D perovskite capping layers and provides a validated pathway toward high-performance, stable PSCs and perovskite-silicon tandem devices.

Abstract 50: Intrinsic Superior Stability of Single-Component Organic Solar Cells

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Abstract

Organic photovoltaics (OPV) has emerged as a promising candidate among 3rd generation photovoltaic technologies with advantages of flexibility, transparency, roll-to-roll processing, low-cost, low-weight, and so on. As organic solar cells (OSCs) approach efficiencies of 20%, stability has become the primary barrier to their industrial application. Most state-of-the-art OSCs, typically constructed with bulk-heterojunction (BHJ) architectures, often experience morphological instability due to phase separation between donor and acceptor materials. Single-component organic solar cells (SCOSCs), where donor and acceptor functionalities are covalently integrated into a single molecule or polymer, offer a promising solution by minimizing phase separation and enhancing stability. Recent advancements in SCOSCs have led to efficiency improvements from 2% to 14%. Despite these gains, a comprehensive understanding of their photophysical properties and long-term operational stability remains limited.

In this presentation, I will discuss the evolution and classifications of single-component materials, including both molecular Dyads and polymers with in-chain and side-chain pendents (Double-cable polymers). We will explore how the design of spacer linkers influences both efficiency and stability. Notably, SCOSCs have demonstrated exceptional stability under continuous light exposure and elevated temperatures. The state-of-the-art molecular Dyads, though with a moderate efficiency of around 5%, exhibit excellent light stability without apparent degradation under the illumination of light intensity equivalent to 1 sun, concentrated light 7.5 suns, and 30 suns. A series of double-cable polymers with gradually elongated space linkers exhibits moderate efficiencies of 6-7%, while demonstrating impressive thermal stability at 90 °C without apparent degradation for over 1000 hours. Furthermore, single-component organic solar cells generally exhibit higher values of the industrial figure of merit than their BHJ counterparts, considering efficiency, stability, and synthetic complexity. Looking ahead, SCOSCs are promising to achieve efficiencies of around 10% while maintaining operational lifespans of up to 20 years.

Abstract 52: Cross-linked multifunctional bilayer polymer buffer for enhanced efficiency and stability in perovskite solar cells

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Abstract

Addressing the stability challenges induced by the chemical interactions between metal electrodes and perovskite components is essential for high-performance perovskite solar cells (PSCs). Herein, we design a bilayer multifunctional polymer buffer composed of polyethyleneimine (PEI) and 2-((2-methyl-3-(2-((2-methylbutanoyl)oxy)ethoxy)-3-oxopropyl)thio)-3-(methylthio)succinic acid (PDMEA), inserting into the interface of metal electrode/transporting layer. This buffer mitigates metal atom diffusion by forming thioether-metal-carboxyl chelation rings between the metal layer and PDMEA. Additionally, it facilitates efficient electron transport and suppresses interfacial recombination through an in-situ cross-linking between the carboxyl groups of PDMEA and the amine groups of PEI based on Lewis acid-base reaction. Consequently, this design effectively reduces undesirable metal/ion interdiffusion during device fabrication and operation. The resulting PSCs with the PEI/PDMEA buffer achieve certified power conversion efficiencies (PCEs) of 26.46% (0.1 cm2) and 24.70% (1.01 cm2). These devices maintain over 90% of their initial efficiency after 2000 h at 85 °C and retain 95.5% of their original efficiency after maximum power point tracking (MPPT) for 1010 h under one-sun illumination at 65 °C. We anticipate that this buffer design strategy, which forms bilayer polymer buffers via cross-linking of polymers with distinct functionalities, will inspire the rational design of robust buffers for highly efficient and stable PSCs and other electronic devices.

Abstract 55: Dual-Functional Interface Engineering with Fluorescein Disodium Salt for High-Efficiency Perovskite Solar Cells

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Abstract

Interfacial defects and charge recombination significantly hinder the efficiency and stability of perovskite solar cells (PSCs). These defects, particularly at the interfaces between the perovskite absorber and charge transport layers, lead to deep trap states that promote non-radiative recombination and limit device performance. To overcome these challenges, we developed a dual-functional interfacial engineering strategy using fluorescein disodium salt ($FLNa_2$), a Lewis base-rich molecule. $FLNa_2$ contains oxygen-rich functional groups capable of coordinating with under-coordinated Pb^{2+} ions in the perovskite and sodium ion interacting with the PEDOT:PSS hole transport layer (HTL). This dual role enables simultaneous passivation of defects at both interfaces.

$FLNa_2$ effectively neutralizes antisite defects and suppresses deep trap states in the perovskite layer, thereby minimizing recombination losses and enhancing charge extraction. It also improves perovskite film morphology by promoting better crystallinity and reducing pinhole formation. Additionally, the modified PEDOT:PSS interface leads to improved energy level alignment and interfacial contact. As a result, devices incorporating $FLNa_2$ exhibit a ~13.24% increase in power conversion efficiency. Trap density measurements confirm a substantial reduction in defect states in $FLNa_2$-5 treated devices, highlighting the molecule's strong passivation capability. Overall, this work underscores the pivotal role of molecular level interface engineering via oxygen lead coordination. The multifunctionality of $FLNa_2$ makes it a promising additive for advancing both efficiency and operational stability in next-generation perovskite photovoltaics.

Abstract 59: Boosting reverse bias stability of inverted perovskite solar cells: Suppression of filamentary conduction by SiOxNy modification

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Abstract

Metal halide perovskite solar cells (PSCs) have reached 27% photovoltaic convert efficiency and 19% efficiency for large-area modules. However, the run-time stability of PSCs does not satisfy their commercial needs. Nowadays , more efforts are being directed to stability, with cells maintaining >90% PCE after thousands of hours ageing at different International Summit on Organic Photovoltaic Stability conditions. However, the low reverse bias stability of perovskite solar cells, which has not been overcome so far, is a big threat to all.

Reverse Bias Causes: During the actual operation of the device, the presence of dark spots is unavoidable, and a global reverse bias is generated inside the device, which results in a rapid degradation of the device performance. The reverse breakdown voltage (VBD) of silicon cells usually exceeds 15 V. In contrast, PSCs have a very low VBD due to more mobile ions and capacitive effects. David S. Ginger et al. found that optimizing HTLs is essential to prevent reverse bias-driven degradation of PSCs, where the reverse breakdown voltage VBD of NiOx or SAM is much smaller than that of polymers such as PTAA. Therefore how to improve the reverse bias stability of NiOx/SAM structured PSCs needs to be urged to be investigated in order to apply them in a Real-World scene.

Here, we modified SAM by using fully hydrogenated polysilazanes. its hydrolysis under UV light converts it to a compact SiNxOy barrier layer, which prevents silver filamentary conductance from running through the device and improves the stability of PSCs under reverse bias. The final device was modified by using PHPS with a slight increase in efficiency. After 500 hours of continuous testing at -1.2V reverse bias, 80% device efficiency was maintained; while the standard device was reduced to 52% of the initial efficiency.

Abstract 61: The Influence of SAMs on the Performance and Stability of Perovskite Solar Cells

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Abstract

Self-Assembled Monolayers (SAMs) are promising materials to replace traditional Hole-Transport Layers (HTLs) in perovskite solar cells. However, the fundamental reasons governing how these SAMs affect the growth of perovskite crystals and device stability are still not clear. In this project, two different SAMs (F-4PACz and Me-4PACz) with different functional groups are studied. It is observed that perovskite wets well on F-4PACz, but the devices show a lower Fill Factor (FF). On the other hand, Me-4PACz exhibits poorer wetting (which can be mitigated introducing SiOx nanoparticles (NPs)) but a higher FF. To combine the advantages of both materials, a series of mixtures of the two SAMs is tested with the goal of overcoming wettability while maintaining well-functioned devices. The perovskite layer is analysed using different techniques such as Kelvin Probe Force Microscopy (KPFM), Atomic Force Microscopy (AFM), X-Ray Diffraction (XRD), Grazing-Incidence Wide-Angle X-ray Scattering (GIWAXS), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Photoluminescence (PL) mapping. Finally, several stability tests are performed to determine how the different SAMs and their effect on the crystal structure influence device degradation. Preliminary results indicate that mixed SAM devices perform similarly to Me-4PACz devices, while eliminating the need for NPs.

Abstract 64: Suppressing light-induced phase segregation in wide bandgap perovskite solar cells by incorporating lead thiocyanate

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Abstract

One key advantage of perovskites is their compositional tunability combined with consistent opto-electronic quality, offering the potential for high performance across a wide bandgap range. This property makes them perfect candidates for tandem and multijunction (perovskite/silicon or all-perovskite based tandems) solar cells capable of achieving efficiencies beyond the ~33% limit valid for single junction solar cells. Wide bandgap perovskite solar cells (1.77 - 1.8 eV) are essential in all-perovskite based tandem applications, providing spectral complementarity with the low bandgap perovskite solar cells (1.2 - 1.25 eV). However, the development of wide bandgap (WBG) perovskites is limited by light-induced phase segregation which reduces the performance and the stability of wide bandgap perovskite solar cells. This phenomenon known as the "Hoke effect" is driven by halide ion migration. In this work, we present an effective strategy of suppressing light-induced phase segregation in wide bandgap perovskite solar cells by incorporating lead thiocyanate () into the perovskite precursor solution. Steady-state photoluminescence (PL) is performed on wide bandgap perovskite devices to monitor the spectral shift under continuous illumination providing insight into the dynamics of halide ion migration. Compared to control devices, incorporated devices exhibited suppressed PL peak shifts with a significant stability improvement, confirming the effective suppression of light-induced phase segregation. Furthermore, we achieve impressive efficiency above 19 % for the wide bandgap perovskite solar cell treated with ,which we attribute to the additives. These results suggest that can passivate the halide vacancies and form alloyed phases by reducing halide migration in wide bandgap perovskite.

Low-power PV

Abstract 2: Mesoscopic carbon-based perovskite solar cells using methylamine vapor MAPbI3 precursor solution

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Abstract

A novel preparation method for $MAPbI_3$ perovskite precursor solution was developed for fabricating carbon-based mesoscopic perovskite solar cells (PSCs) in an air environment. The process involves dissolving $MAPbI_3$ powder via methylamine vapor treatment (3 h for 0.1 g) followed by dilution with acetonitrile (250 µL) to achieve an optimal precursor concentration. The solution was deposited on a TiO_2 porous layer (m-TiO_2), with annealing at 130 °C for 20 minutes yielding films with superior crystallinity and light absorption. Carbon electrodes were screen-printed to complete the FTO/c-TiO_2/m-TiO_2/$MAPbI_3$/carbon device structure. The optimized solar cell exhibited a power conversion efficiency (PCE) of 10.74%, with an open-circuit voltage (Voc) of 0.98 V, short-circuit current density (Jsc) of 18.75 mA cm^{-2}, and fill factor (FF) of 0.582. This work presents a facile, air-compatible approach for efficient carbon-based PSCs.

Abstract 19: Enhancing Efficiency in Semitransparent Perovskite Solar Cells via Down-Conversion Coatings

Damian Glowienka

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Abstract

Perovskite solar cells (PSCs) have demonstrated exceptional efficiency, yet surpassing theoretical performance limits requires innovative methodologies. Among these, down-conversion techniques are pivotal in reducing optical losses and enhancing energy conversion efficiency [1].

In this study [2], optical modeling, including a generalized transfer-matrix optical model, was employed to meticulously assess optical losses in semitransparent PSCs illuminated from front and rear sides of the device. To reduce these losses, two down-conversion layers, made of N,N-diphenyl-4-(1,2,2-triphenylethenyl)-benzenamine (TPETPA) and 4-(N,N-Diphenylamino)benzaldehyde (DPABA) mixed with polymeric binder, were developed, showcasing initial photoluminescence quantum yields of 60% and 50% as films, respectively. The materials luminescence relies on the effect of aggregation-induced emission, which enhance the fluorescence of the dyes within the binder, providing their films with a unique behavior beneficial for photovoltaic applications. An optimization of these layers was performed, which aimed at reducing UV optical losses by adjusting the film thickness atop the PSCs. The refined down-conversion layers yielded a notable increase in the power conversion efficiency by approximately 0.4% for both the front and rear sides of the PSCs, demonstrating their significant potential in pushing the boundaries of solar cell performance.

[1] Y. Zheng, Y. Li, R. Zhuang, X. Wu, C. Tian, A. Sun, C. Chen, Y. Guo, Y. Hua, K. Meng, K. Wu, and C.-C. Chen, *Energy & Environmental Science* 17 (2024), 1153–1162.

[2] D. Glowienka, C.-M. Tsai, A. Sbai, D. Luo, P.-H. Lee, S.-H. Huang, C.-F. Li, H.-W. Wang, G.-S. Liou, J. Guthmuller, and W.-F. Su, *ACS Applied Materials & Interfaces* 16 (46) (2024**)** 63528-6353

Acknowledgement:

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Abstract 53: Phosphorus-based electrode interfacial layer for application in organic solar cells

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Abstract

The rapid growth of the organic electronics field drives the rapid development in the discovery and synthesis of new stable molecules with different physico-chemical properties to meet various requirements to be incorporated into a device. Organic Photovoltaic (PV) devices represent an important application for converting light into electricity. These devices consist of a photoabsorber layer, which is responsible for light absorption and carrier generation, and interface modification layers, including anode and cathode interfacial layers. These interfacial layers play a crucial role in device performance, as high-quality interfacial materials are essential for achieving high-efficiency OPV cells.

In this work, phosphorus-based organic molecules, known as organophosphorus materials, will be integrated as an anode interfacial layer to enhance the device performance. Herein, we present a synthesis of a composite layer comprising organophosphorus molecules and Nickel oxide, along with the growth method and optimization results. The deposition process of the thin layer is also described. Furthermore, characterizations have been carried out to investigate, for the first time, the role and effect of organophosphorus materials on optical, structural, and electrical properties of the new composite interfacial layer prior to its incorporation into organic PV devices.

Degradation experiments conducted indoors

Abstract 6: Unraveling depth-dependent photo-degradation of perovskite material in photovoltaics subjected to ISOS-L-1 and ISOS-L-2 accelerated aging: the influence of substrate, electron-transport-material and perovskite deposition method

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Abstract

The light-induced degradation of perovskite solar cells remains an important challenge to be tackled before their entry into the photovoltaic market. Despite the progress in the field, the damage routes and heterogeneity in light-induced decomposition of the perovskite material during light-to-electricity conversion remain unresolved. The present investigation presents a direct comparison of depth-dependent photo-degradation of ambient-air-processed perovskite materials fabricated via one/two-step deposition methods on glass/plastic substrates and mesoporous/planar TiO_2/SnO_2-based electron-transport-materials for carbon-based hole-transport-material-free solar cells subjected to ISOS-L-1 and ISOS-L-2 accelerated aging. The gradient distribution of damage in the post-aged unencapsulated perovskite materials is mapped using grazing incidence X-ray crystallography, nanomechanical analysis and many other characterization methods. The findings indicated that light-induced perovskite damage initiates at both buried and top interfaces across all solar cell designs, and propagates through the bulk at different rates depending on the design of the multilayer and its aging conditions, impacting the quality and size of perovskite crystals. The nanomechanical behavior of the crystalline material transitions from elastic to viscoelastic, verifying the evidence of structural decomposition and suggesting a softening of the ionic lattice, which is known to impair charge transport and facilitate defect migration in the solar cell material. Consequently, the performance of the solar cells is reduced in terms of their light-harvesting efficiency, quantum efficiency and charge carrier dynamics. This study merits attention since it offers a thorough comparison of light-induced degradation of a series of photovoltaics with industry-compatible designs subjected to accelerated aging, thereby yielding valuable insights from multiscale and industrial viewpoints.

Acknowledgments: This work was carried out within the framework of the Action "Flagship Research Projects in challenging interdisciplinary sectors with practical applications in Greek Industry", implemented through the National Recovery and Resilience Plan Greece 2.0 and funded by the European Union–NextGenerationEU (project code: TAEDR-0537347).

Abstract 10: Understanding Temperature-Dependent Metastability in Perovskite Modules Using Controlled Indoor Light/Dark Cycling

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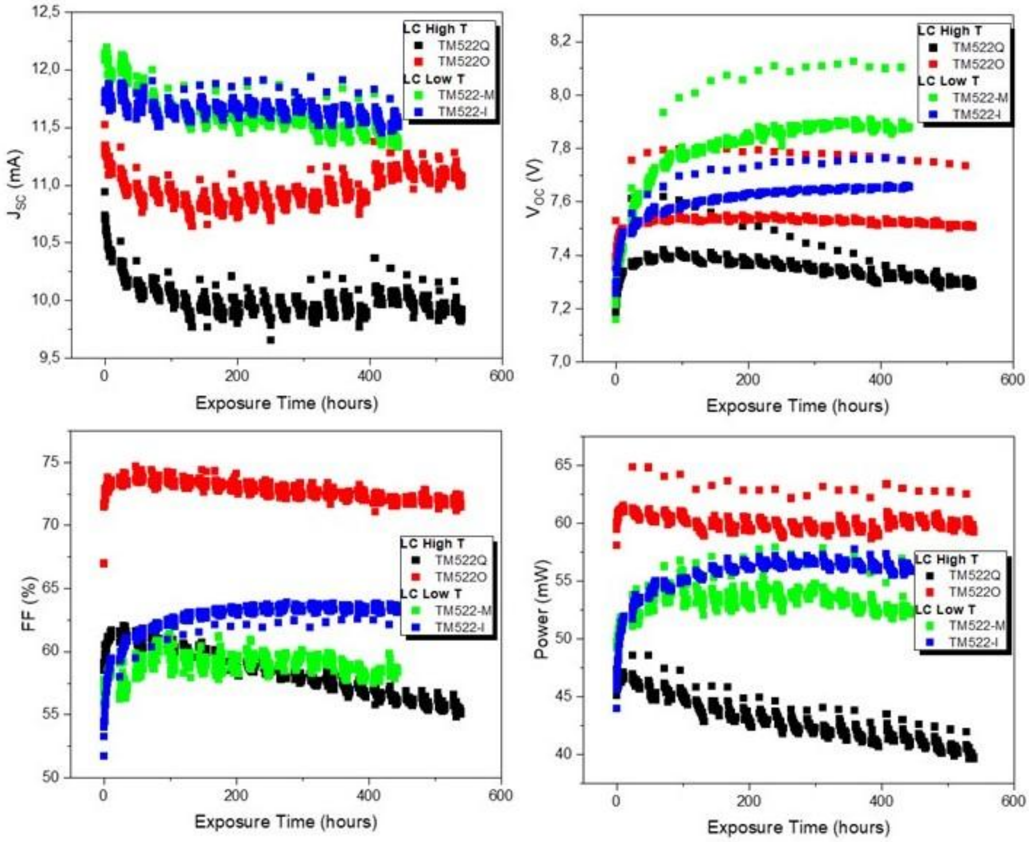
Abstract



Understanding the stability of perovskite solar modules under real outdoor conditions is essential for their future deployment. This collaborative study explores whether indoor light/dark cycling tests can replicate outdoor-induced effects by focusing on the metastable behavior of perovskite modules under different thermal conditions.

Modules were subjected to indoor light cycling (12 h light / 12 h dark) at three temperature regimes: low (23°C/7°C), moderate (45°C/23°C), and high (65–85°C/23°C). The evolution of key electrical parameters, including maximum power output (P_{max}), open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), and fill factor (FF), was monitored to assess light-induced degradation and recovery under varied temperatures.

Results show that modules tested at lower temperatures exhibited stronger light soaking effects with minimal degradation, particularly in P_{max} and V_{oc}. In contrast, samples tested at higher temperatures showed more pronounced degradation during light phases but also greater recovery during dark phases. FF recovery dynamics were similar across all temperature conditions, and J_{sc} showed comparable behavior at both low and high temperatures. Notably, power output was found to be strongly driven by FF behavior.

Hyperspectral imaging photoluminescence (HI PL) was also applied before and after aging to assess spatial homogeneity, PL shifts, and variations in bandgap (BG) and quasi-Fermi level splitting (QFLS), providing additional insights into material changes beyond electrical performance.

Overall, the results indicate that metastable behavior is present across all temperature regimes, but each regime affects electrical parameters differently. To validate these observations, the indoor tests were compared with outdoor stability data from test sites in Germany and Cyprus. Ongoing studies will continue to refine the correlation between indoor and outdoor degradation pathways and help optimize accelerated testing protocols for perovskite modules.

Work financed by the European Union's Horizon research and innovation program through the LAPERITIVO project (Grant ID: 101147311).

Abstract 12: Interface Engineering Strategies for Enhancing the Performance of Flexible n-i-p Perovskite Solar Cells

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Abstract

Flexible perovskite solar cells (PSCs) represent a promising solution for lightweight, portable, and wearable photovoltaic applications. However, their efficiency and operational stability are still limited by interfacial losses and surface defects. In this work, we focus on the optimization of the electron transport layer and surface passivation strategies in flexible n-i-p structured PSCs without altering the bulk perovskite composition.

We systematically investigate the effect of processing conditions and post-treatment methods on the SnO_2 electron transport layer to improve charge extraction and interface quality. Additionally, we employ surface engineering using various bulky organic ammonium halides — n-Octylammonium Iodide (nOAI), nbutylammonium Bromide (nBABr), and n-Octylammonium Bromide (nOABr) — to form quasi-2D passivation layers on top of the perovskite films. It is important to understand how molecular design — including chain length, functional groups, and hydrophobicity — affects the long-term operational stability and performance of perovskite devices.

The optimized devices fabricated on R2R patterned PET/ITO substrates exhibit improved power conversion efficiency and superior operational stability under ISOS-L1I protocol (inert atmosphere, constant illumination). The control device lost 10% of its initial efficiency after 500 hours. However, the passivated devices with nBABr, nOABr and nOAI, just lost 6.31%, 8.33% and 9.1% its first day PCE over 500hours, respectively. These molecules may allow denser packing at the interface, potentially improving mechanical stability and reducing defect sites, demonstrating the effectiveness of interface and surface engineering in advancing flexible perovskite solar cell technology.

Abstract 13: Enhanced Efficiency and Long-Term Stability of Semitransparent Perovskite Solar Cells and its Application in 4T Perovskite/Si Tandem Solar Cell

Satish Bykkam, Damian Glowienka

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Abstract

Semitransparent perovskite solar cells (ST-PSCs) are emerging as valuable components in advanced photovoltaic systems, including tandem and building-integrated photovoltaics [1-3]. This present study focuses on the development of ST-PSCs that enhance efficiency and exhibit long-term stability, crucial for their application in tandem solar cells. Despite their potential, the fabrication of ST-PSCs faces significant challenges, particularly regarding the protection of sensitive layers during the deposition of transparent conductive oxides (TCOs). To address this issue, we have developed an optimized fabrication approach that includes a tin oxide (SnO_2) buffer layer. This layer effectively protects sensitive layers from sputtering-related damage during the application of TCOs. Consequently, the ST-PSC achieves a power conversion efficiency (PCE) of 21.87%. When integrated with a commercial crystalline silicon (c-Si) bottom cell in a four-terminal tandem configuration, the overall efficiency of the device reaches 27.15%. In addition to high efficiency, these solar cells exhibit exceptional operational stability, achieving a T80 of 1600 hours under continuous light soaking conditions and maintaining performance for over 4000 hours in outdoor settings due to an efficient encapsulation technique.

Abstract 20: Inverted Perovskite Solar Cells Under Stress: Stability, Degradation Mechanisms, and Real-World Performance

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Abstract

Perovskite solar cells (PSCs) have gained significant attention due to their low fabrication cost and high power conversion efficiency, recently surpassing 27% [1]. However, their structural sensitivity to extrinsic factors such as oxygen, moisture, and airborne contaminants leads to reduced stability. To mitigate these effects, encapsulation strategies are actively explored, and device stability is typically assessed using standardized ISOS (International Summit on Organic Photovoltaic Stability) protocols [2].

In this study, inverted PSCs demonstrated promising stability under accelerated aging, retaining 80% of initial efficiency (T_{80}) for up to 600 hours under continuous illumination (ISOS-L) and 1000 hours under damp heat (ISOS-D). Despite employing a high-performance PIB encapsulant, degradation was mainly attributed to the deterioration of silver (Ag) electrodes. Post-aging analysis revealed two distinct failure modes linked to Ag instability, indicating that electrode integrity is a key limitation for long-term performance.

To investigate this further, we fabricated and evaluated several modified electrode architectures to decouple electrochemical and environmental degradation effects. Voltage-induced mechanisms, particularly under maximum power point (MPP) and open-circuit (V_{oc}) conditions, were emphasized. These tests identified ion migration and charge trapping as major contributors to performance decay [3]. Finally, outdoor ISOS-O testing was conducted in two climatically distinct regions in Gdańsk, Poland (maritime) and in Madrid, Spain (Mediterranean) to capture real-world degradation behavior. This dual-site comparison provided valuable insights into the interaction between device design and environmental stressors, including UV exposure, temperature, and humidity.

[1] National Renewable Energy Laboratory (NREL), Chart of Best Research-Cell Efficiencies

[2] M. V. Khenkin et al., Nature Energy. 5 (2020) 35-49

[3] M. Prete, M. V. Khenkin, D. Glowienka et al., Applied Energy Materials. 4 (2021) 6562-6573

Acknowledgement:

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Abstract 21: Stabilization of High-Performing PM6:Y7-12 Solar Cells using Naturally Occurring Antioxidants

Hsuan-yu Wang, Rovshen Atajanov, Sambathkumar Balasubramanian, Daniel Garcia Martos, Morten Madsen, Vida Engmann

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Abstract

Photostability of state-of-the-art polymer:non-fullerene acceptor based organic photovoltaics (OPVs) remains one of the roadblocks towards commercialization. Herein, we present a novel solution using naturally occurring antioxidant as a ternary component in PM6:Y7-12 bulk heterojunction blend. Without impeding the initial performance, the unencapsulated device saw a 10 % improvement in PCE after 80 h of degradation under ISOS-L-1 conditions. This stabilization originates form short circuit current density and fill factor. We discuss the results in light of different spectroscopic and microscopic techniques.

Abstract 23: Locally Resolved Thermally Induced Degradation on PM6:Y6-based Organic Solar Cells

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Abstract

The commercialization of new photovoltaic technology is impeded by the degradation of organic photovoltaic devices caused by thermal factors. Therefore, it is crucial to have an in-depth awareness of the underlying causes of thermal device instability and to develop effective approaches to reduce its negative impacts. This study examines the thermal degradation of PM6:Y6 bulk heterojunction solar cells, which are currently considered at the forefront of organic solar cell technology. The investigation focuses on the effects of varying temperatures on the performance and locally resolved thermally induced impact of these solar cells. We report a comprehensive study probing the influence of thermal annealing of solar cells by the use of several advanced optoelectrical and imaging characterization techniques.

Abstract 41: Enhancing the Stability of P3HT:PCBM Organic Solar Cells through BCF Doping: Experimental Investigation and Python-Based Curve Simulation

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Abstract

Organic solar cells (OSCs) offer attractive features like low-cost production, light weight, and semi-transparency, aligning well with the demand for clean, eco-friendly energy. Despite these advantages, their limited operational lifetime remains a significant barrier to widespread adoption. Their inherent nature as a clean energy source aligns strongly with ecological concerns, driving extensive research into the development of eco-friendly fabrication materials. The strategic application of additives has emerged as a promising approach to enhance device stability. This work investigates the impact of Tris(pentafluorophenyl)borane (BCF) as an additive on the lifetime of organic solar cells based on the well-established P3HT:PCBM blend. Unlike many studies focusing solely on the presence of BCF, our research delves into the specific mechanisms by which BCF influences the electrical parameters and, consequently, the device lifetime. Through comprehensive analysis of electrical parameters, including conductivity and carrier mobility, and an examination of potential barrier effects using Mott-Gurney and Richardson-Schottky analyses, we leverage Python-driven computational simulations and curve fitting to elucidate the underlying phenomena. Furthermore, absorbance spectroscopy is employed to track changes in the band gap over degradation time in conjunction with electrical performance. Our preliminary results demonstrate that BCF-doped blends exhibit superior maintenance of electrical parameters, leading to sustained power conversion efficiency (PCE) even after prolonged degradation in a controlled chamber. This study highlights that even slight improvements in electrical parameters can lead to substantial enhancements in the lifetime of organic solar cells, offering a valuable pathway for the development of more stable and durable devices.

References

[1] - Cui, Yu, et al. "Eliminating the imbalanced mobility bottlenecks via reshaping internal potential distribution in organic photovoltaics." Advanced Science 10.29 (2023): 2302880.

[2] - Pacheco, Kaike, et al. "Enhancing organic solar cell lifetime through humidity control using BCF in PM6: Y6 active layers." Sustainable Energy & Fuels 8.21 (2024): 4972-4979.

Abstract 43: Identifying Ultraviolet-Induced Degradation Mechanisms in Inverted Perovskite Solar Cells

Silvia Delgado-Rodríguez[1], Alexander Cuadrado[1], Gonzalo del Pozo[1], Satish Bykkam[2], Damian Głowienka[2]

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Abstract

UV-induced degradation is one of the most detrimental stability challenges in perovskite solar cells, as UV exposure is intrinsic to real sunlight conditions. UV radiation accelerates material decomposition, promoting ion migration and the breakdown of the perovskite into its precursors. This work aims to identify and understand the specific mechanisms driving UV-induced degradation.

A systematic degradation study was carried out using devices with the structure ITO/PTAA/CsFAPbIBr/PCBM/BCP/Ag. The samples were exposed to 385 nm UV LEDs at varying power densities (1.5–30 mW/cm²) and characterized periodically by J–V and impedance spectroscopy under a solar simulator. The entire experiment was performed inside a glovebox to isolate the effect of UV light.

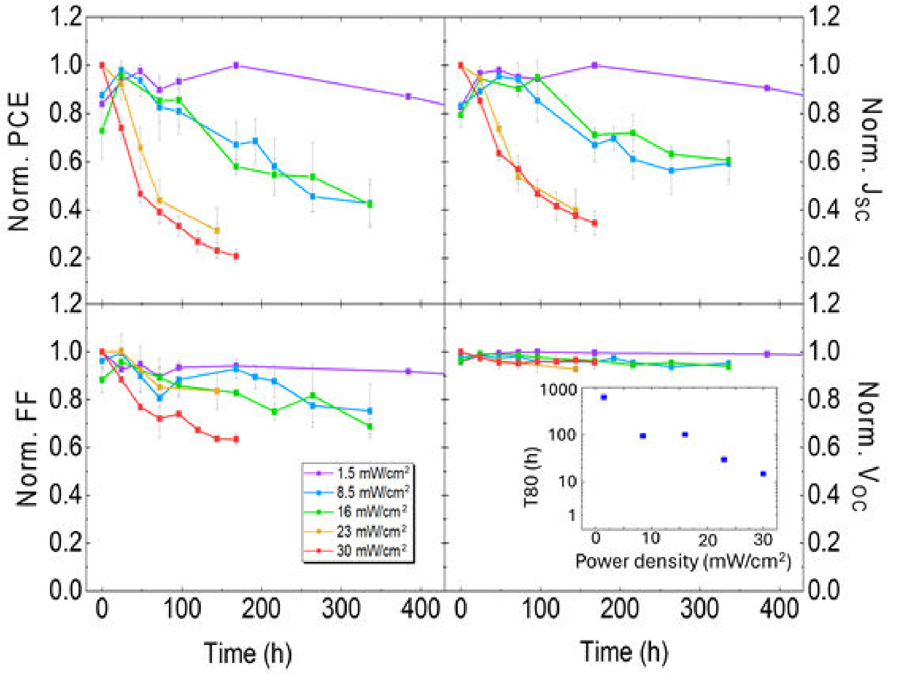

Figure 1 - Evolution of PCE, J_{SC}, FF and V_{OC} with UV exposure time. Inset shows the T80 as a function of power density.

Analysis of the J–V curves over time shows that UV exposure primarily affects the J_{SC} , while V_{OC} remains relatively stable. The observed loss in efficiency is mainly attributed to reduced charge extraction. The evolution of this characteristics different illumination intensities and degradation stages also reveals changes in recombination behavior due to UV.

Plotting the T80 values against the applied UV power density, a logarithmic trend is observed, indicating that the degradation rate increases with higher UV intensity but tends to stabilize at elevated power levels.

To complete the study, JV measurements at different scan rates (ranging from 0.01 to 100 V/s) and impedance spectroscopy analyses were carried out. These techniques provide information about ionic mobility in the perovskite layer and its increase upon exposure to UV light.

This study contributes to a better understanding of how the UV can influence the perovskite degradation pathways through limit charge transport, and increase ionic mobility, acknowledging the non-linear behavior of UV-induced degradation.

Abstract 47: Understanding Degradation and Recovery in Perovskite Solar Cells Under Reverse Bias

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Abstract

Metal-halide perovskite solar cells (PSCs) are promising candidates for next-generation photovoltaics due to their high efficiencies. However, their long-term operational stability remains a key challenge, particularly under reverse bias conditions arising from partial shading or current mismatch in tandem architectures.[1] Although previous studies have explored both reversible and irreversible degradation under reverse bias, the fundamental mechanisms driving these processes are still not fully understood.

This work presents a comprehensive investigation into the effects of reverse bias on PSCs, employing a novel combination of experimental techniques. While earlier research primarily focused on current-voltage (JV) analysis and, to a lesser extent, infrared thermography or electroluminescence / photoluminescence (EL / PL) imaging, our study integrates impedance spectroscopy (IS) and transient electrical measurements to directly monitor ionic charge transport. These are coupled with EL / PL mapping and dark lock-in thermography to spatially and temporally resolve degradation patterns across the device.

We observed the emergence of transient EL bright spots during reverse bias stressing, also detected during forward bias. We previously explained this phenomenon by local variation of ion densities using a combination of 1D drift-diffusion and 2D+1D FEM simulations.[2] Additionally, slow EL transients across the entire area, developing over seconds to hours, are consistent with ion migration influencing radiative recombination over time. We explore the impact of different relaxation conditions, such as light soaking and bias application, to evaluate partial recovery after reverse bias exposure. These findings highlight the dynamic interplay between ionic movement, defect formation, and recovery in PSCs.

By uncovering key mechanisms behind reverse bias-induced degradation and recovery, this study advances understanding of stability challenges in perovskite solar technology. The insights gained are relevant for improving the performance and reliability of scaled-up perovskite modules.

[1] U. Aeberhard et al., Solar RRL, 8, 2400492, 2024.

[2] E. L. Comi et al., Proceedings EU PVSEC, 2023.

Abstract 58: From Active Layer to Device to System: A Comprehensive Approach for Stable Organic Photovoltaics

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Abstract

Despite significant progress in power conversion efficiency, thermal instability remains a major challenge for organic photovoltaics (OPVs). Here, we present a holistic stabilization approach addressing both intrinsic and extrinsic degradation mechanisms. First, we introduce the UV-Vis absorption onset temperature (T_{onset}) as a key metric for rapid screening of thermally stable polymer blends. Second, we reveal that interfacial reactions at the polymer/MoO_3 interface drive extrinsic degradation and demonstrate that a thin C_{60} interlayer effectively suppresses this process. Finally, we develop a quantitative moisture diffusion model to optimize encapsulation. Combining these advances, our OPVs retain 94% of their initial efficiency after rigorous testing (1,032 hours at 85°C/85%RH and 200 thermal cycles between -40°C and 85°C), representing one of the highest stabilities reported for solution-processed OPVs under ISOS-D-3/ISOS-T-3 standards. This work provides critical insights for developing high-performance, stable OPVs.

Abstract 60: An example of a heat-regenerated P3HT:PCBM solar cell

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Abstract

Organic solar cells hold strong potential for flexible and lightweight energy applications. However, maintaining long-term stability under thermal stress remains a major challenge. High temperatures can distort the nanoscale morphology of the photoactive layer, leading to performance losses. Under specific conditions, this damage can be reversible. In this study, P3HT:PCBM-based devices recovered after exposure to temperatures as high as 250°C, which caused complete performance decay. Upon cooling, the devices recovered up to 97% of their original performance. Using photoluminescence spectroscopy, we were able to follow plausible changes in the scale of phase separation of the photoactive layer. Such a behavior can be understood considering the phase diagram of semicrystalline polymer fullerene blends.

Abstract 62: Long-Term Stability of Flexible Perovskite Solar Cells via Low-Temperature Encapsulation

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Abstract

Perovskite solar cells (PSCs) have rapidly progressed in power conversion efficiency, now exceeding 26%. However, their long-term stability, especially in flexible formats, remains a significant obstacle. Achieving stable lifetimes alongside economic and environmental sustainability remains a key challenge. Flexible PSCs, with mechanical resilience and R2R compatibility, show strong promise for large-scale deployment.

In this work, we fabricated flexible PSCs on flexible Al-based substrates using ambient compatible solvents and sheet-to-sheet (S2S) processing at a 15×15 cm^2 scale, achieving power conversion efficiencies exceeding 15% and high reproducibility. The initial interest of this study is the intrinsic and extrinsic stability of these devices. To evaluate intrinsic thermal stability, non encapsulated devices underwent thermal monostress testing. These devices, which initially had a PCE of 13.7%, retained a performance of 13.2% after more than 3000 hours, highlighting the robustness of the perovskite stack under prolonged thermal exposure.

Focusing on environmental stability, devices were encapsulated under mild conditions. The encapsulation employed front and back barrier sheets with high resistance to water vapor transmission—laminated at temperatures below 120°C. This approach is compatible with temperature-sensitive materials and upscalable to R2R manufacturing. The encapsulation scheme forms a hermetic seal without compromising mechanical flexibility or inducing thermal stress on the perovskite layer.

Mildly encapsulated devices exhibited excellent stability under damp heat conditions (85°C/85% RH) and during continuous light-soaking with applied heat, maintaining PCE above 10% and visual integrity for over 3000 hours. No signs of delamination, moisture ingress, or perovskite degradation were observed, demonstrating the effectiveness of the encapsulation strategy in mitigating common degradation pathways.

This study highlights the role of encapsulation engineering in enhancing flexible PSC stability, offering a scalable route to durable, lightweight devices suitable for real-world use. Future efforts will target outdoor testing and scaling to larger, reliable modules.