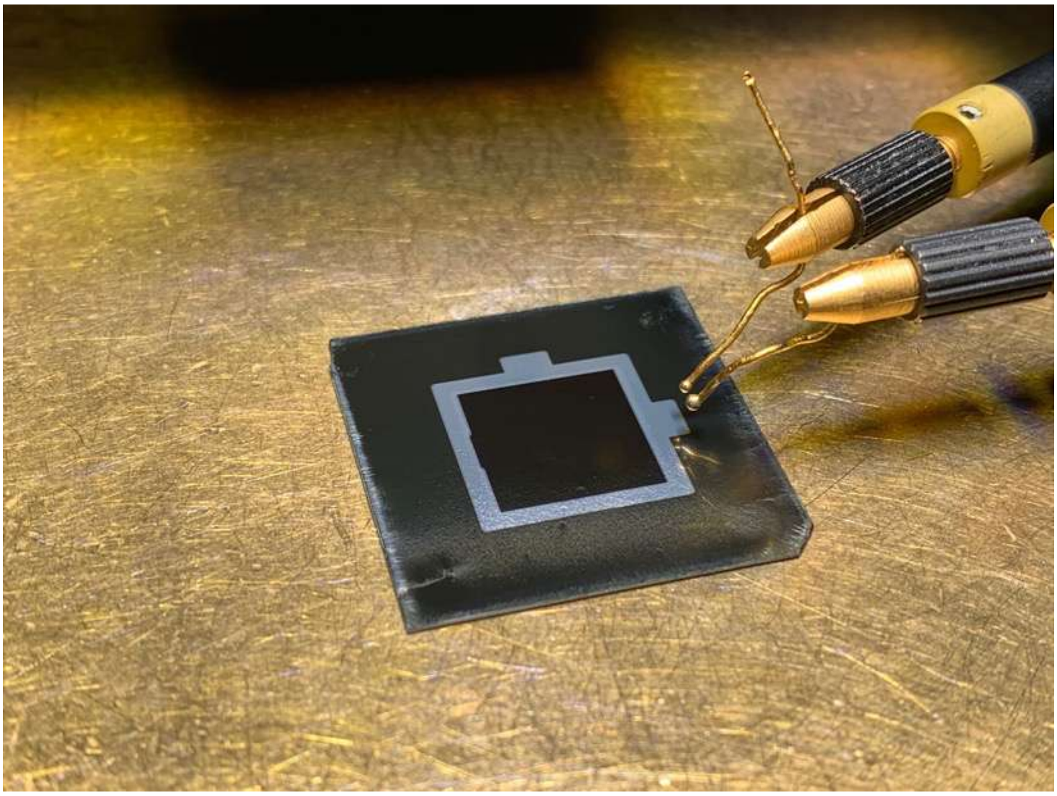
WHITEPAPER

# MEASUREMENT CHALLENGES
# FOR PEROVSKITE / SILICON TANDEM (PST) SOLAR CELLS

## How to scale PST cell production and characterization in R&D and commercial manufacturing



# TABLE OF CONTENT

## About this whitepaper

This whitepaper investigates what it means for solar cell producers to add Perovskite/Silicon Tandem (PST) cells to their portfolio. We examine the special characteristics of PST cells and discuss testing requirements.

Finally, we introduce an approach that provides all necessary characterization functions for pre-conditioning with a permanent and adjustable light source, EQE capability, Pmpp tracking and spectral characterization.

## Riding the energy transition with multi-junction PV

Who would have thought that a few decades after its grassroots beginnings, PV has become a $183 bn industry? By early 2022 already 1 TW[1] of PV installations were moving us into a zero-carbon world. Of course, the success of renewable energy boils down to its efficiency. Since commonly used single-junction crystalline silicon (c-Si) cells are limited to maximum efficiency of approximately 29 %[2], multi-junction cell designs have moved into focus to help us address the urgency of our climate crisis.

***With the reduction of the LCOE by another 30 %, PST tandem cells will be automatically cheaper than any other form of electricity generation available on earth.***

Dr. Kaining Ding, Head of Department "Silicon Heterojunction Solar Cells and Modules" at IEK5-Photovoltaics Forschungszentrum Jülich[3]

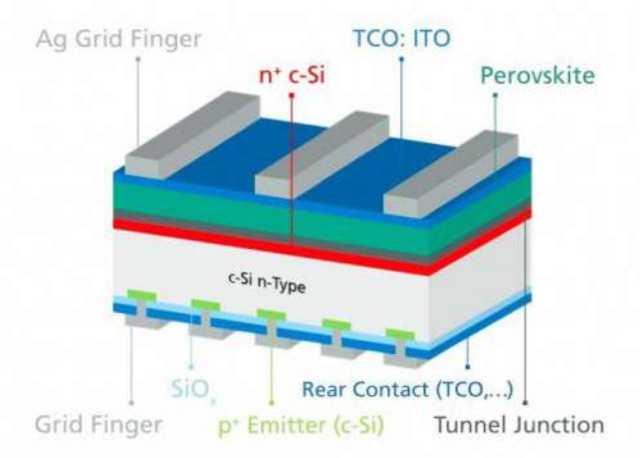
Multi-junction PV cells maximize energy conversion across the entire light spectrum and achieve a world record efficiency of currently up to 47.6 %[4]. Unfortunately, for decades industry-scale utilization of multi-junction PV has been out of question due to its high levelized cost of energy (LCOE). Typically, they were applied in space[5] to power satellites and the ISS. The progress achieved in the 2,000s and with it the reduction of the LCOE, opens the way for Perovskite Silicon Tandem (PST) cells to become commercially available[6]. After more than a decade of intensive research and development, PST cells will become an important industry-scale solution for tackling the climate crisis within the next years.

Namesake of the photo-active mineral perovskite: Lev Perovski
© Wikipedia

## Why PST cells could become the new mono

In contrast to typical c-Si designs, multi-junction PV cells are made up of different sub-cells. PST cells consist of a standard c-Si bottom sub-cell and a thin perovskite sub-cell on top (see fig. 1).

**Fig. 1: Classic 2-terminal design of a PST solar cell**

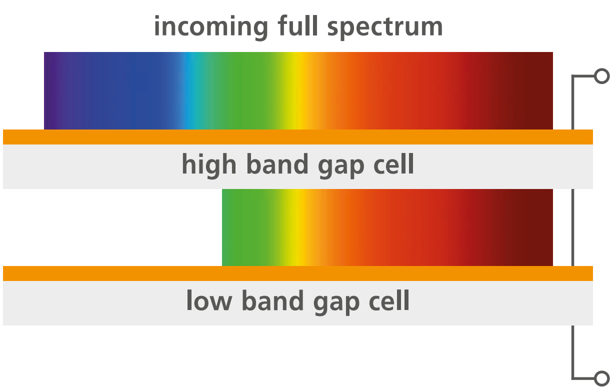



© Fraunhofer CSP

What makes the tandem design so promising is that it enables the improved utilization of the sun light spectrum. Pure c-Si cells lose part of the energy of the UV and visible spectrum as heat. The subcells of a PST have a better match of their bandgaps. This leads to a reduction of thermal losses of approx. 15 %. Therefore, the combination of c-Si as bottom cell and perovskite as top cell allows the stabilized and optimized utilization of sun light from UV to infrared[7] (see fig. 2).

**Fig. 2: Light utilization of combined high and low band gap cell**

The top cell absorbs the high energy photons.
The bottom cell absorbs the low energy photons.




© WAVELABS

These characteristics have led to remarkable progress in conversion efficiency from 3 % in 2006 to the current world record of 31.25 % (as of July 2022) by the EPFL and CSEM[8]. PST cell technology based on the established 2-terminal design is prognosed to have a potential of 45 % which would lead to module efficiencies 30% higher than currently available.

This is already good news despite the fact that the effective efficiency of 2-terminal cells is limited to the weakest link, i.e. the weakest sub-cell due to being serial-connected. Further efficiency leaps will be achieved with the development of industrially scalable 3-terminal and 4-terminal designs.

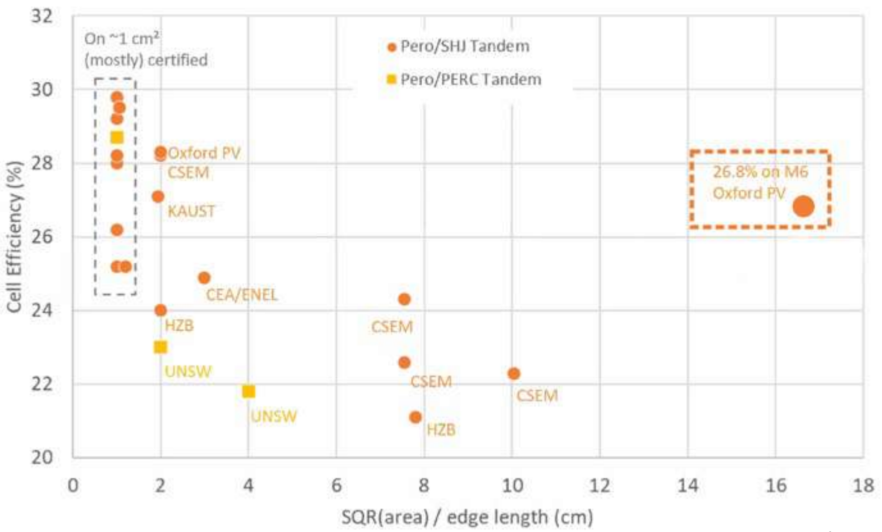
The 3-terminal design connects the sub-cells in parallel thus reducing the efficiency limitation that comes from the "weakest link" paradigm of serial-connected tandem cells. The paradigm even could be eliminated with 4-terminal cells where the sub-cells run completely independent from each other (see fig. 6)

***Our results [setting the current world record for PST cells] are the first to show that the 30 % barrier can be overcome using low-cost materials and processes, which should open new perspectives for the future of PV.[8]***

Christophe Ballif, Head of the EPFL Photovoltaics Laboratory and CSEM’s Sustainable Energy Center

While the HZB record was established with a 1 cm² cell, PST technology is not pure R&D at all. Companies like OxfordPV have already made the step to the industrialization of PST production (see fig. 3).

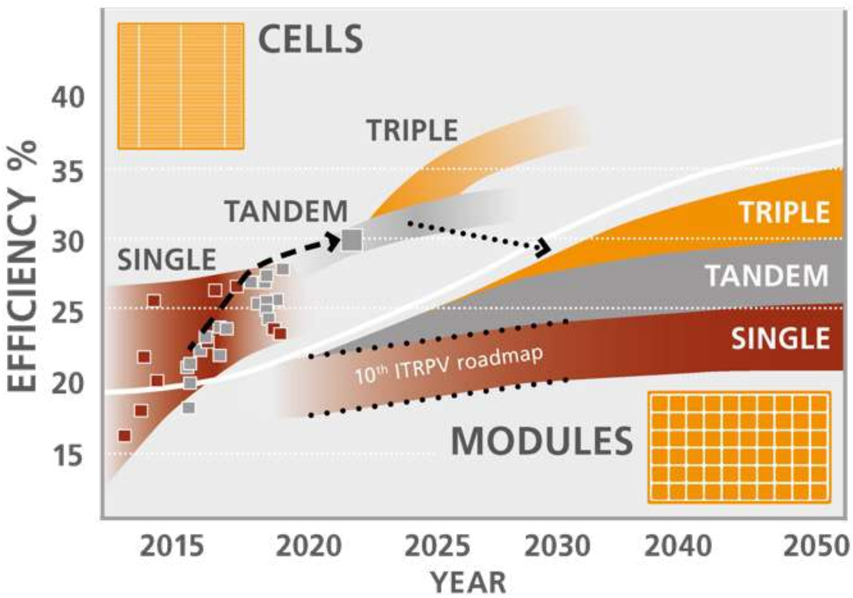
**Fig. 3: Current efficiency levels of PST cell technologies (as of April 2022)**




© Dr. Bernd Stannowski, HZB

Therefore, it's no surprise that PST modules are prognosed to become a profitable and efficient alternative to c-Si modules in the next years (see fig. 4).

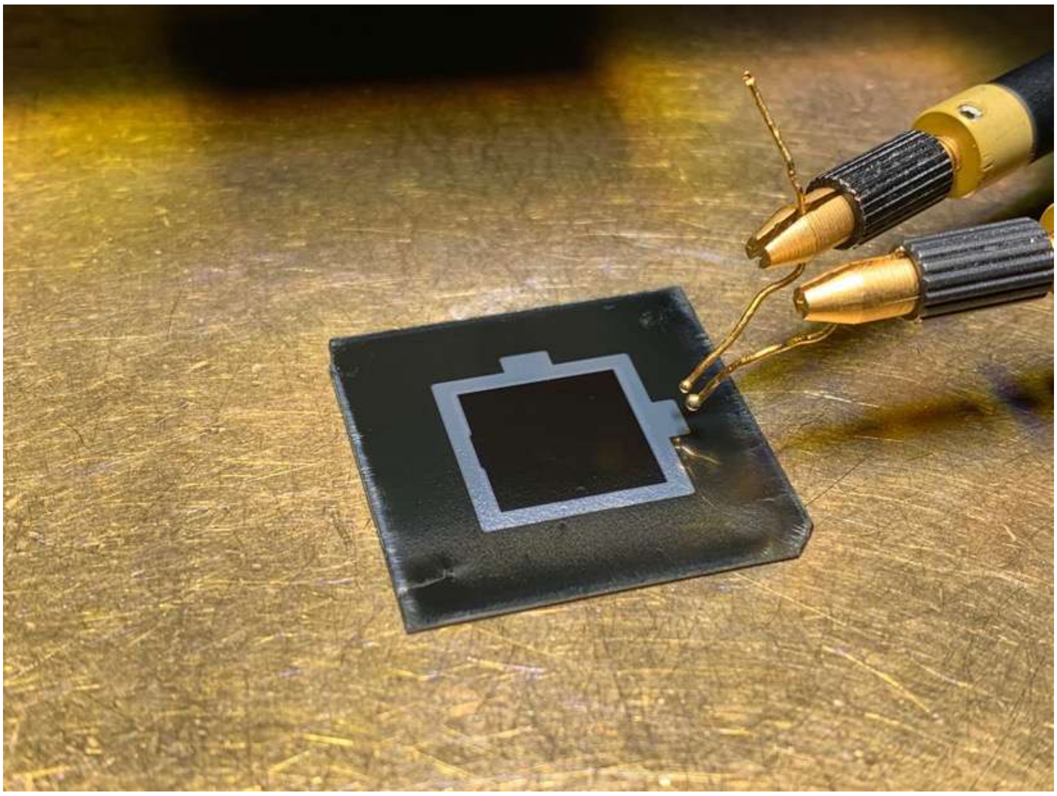
**Fig. 4: Roadmap: PST technology will boost the PV market**




© Dr. Bernd Stannowski, HZB

And the story does not end here! Even though there are still some uncertainties in regard to industry-scale production of perovskite/silicon tandem cells the basic principles of the manufacturing processes are well known in the semiconductor and photovoltaics production, including wet processes like slot die, spin coating, doctoral blade, atomic layer deposition (ALD) and physical vapor deposition (PVD).

Overall, those developments increase the energy yield and improve the value-for-money ratio for both PV manufacturers and PV users. PST cells truly offer a chance to boost the energy transition process and to achieve net zero carbon emissions faster.



Experimental PST cell design with contacting © Helmholtz-Zentrum Berlin für Materialien und Energie

WAVELABS

## Three reasons, PST cell measurement is special

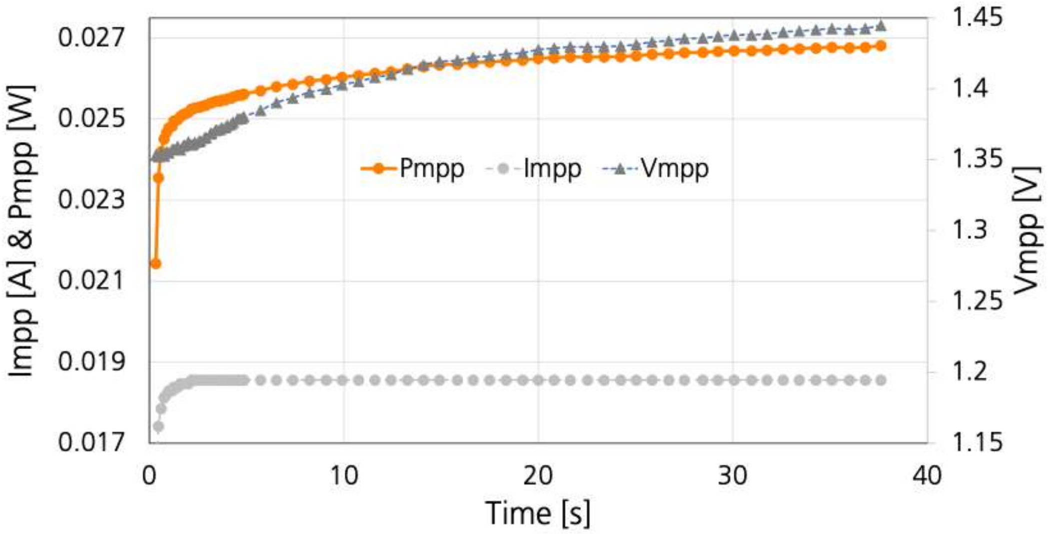
With two different sub-cells working together in tandem, part of the adjustments needed in PST cell production consists of some tweaks to cell testing and characterization. Let’s dig a little deeper into the specifics of PST behavior.

### 1. There’s no conditioning like pre-conditioning

Challenge: PST cells need more time to adjust to light exposure. To guarantee stable test outcomes, PST cells need light soaking before testing (see fig. 5). Different PST technology requires different soaking times. Too short light soaking may leave the cell not properly activated.

Requirement: To ensure precise timing irrespective of the tested PST technology, light soaking needs to become an integral part of cell testing capabilities. Moreover, the light soaking technology needs to provide the option to adjust soaking times fast, easy and in a stable manner.

**Fig. 5: Influence  of light soaking time on Pmpp and Impp stabilization**



## 2. It takes two!

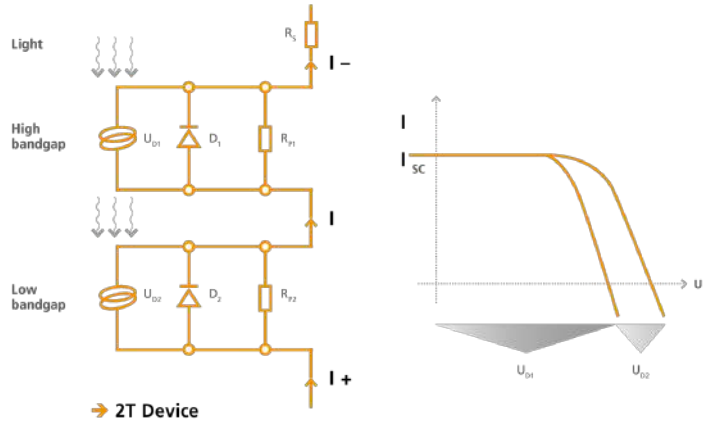
**Challenge:** Efficiency always depends on the weakest link. Due to the different properties of the c-Si and perovskite material, the overall cells' efficiency is sensitive to the current matching of both sub-cells. For example, different temperature coefficients can lead to a current mismatch of approximately 5 %[9] at field operating conditions. This is particularly relevant in 2-terminal designs where the sub-cells are connected in series. The problem of mismatching can be solved on cell-design level by applying 3-terminal or 4-terminal designs. The difference between 2-, 3- and 4-terminal is defined by the way the cells are connected to each other, thus determining how both sub-cells influence each other in terms of bandgap utilization and current matching (see fig. 6). In 2-terminal cells both sub-cells are connected in series. This results in a strong interdependency, i.e. the weakest sub-cell determines the resulting current. 3-terminal devices consist of a top cell optically in series with a modified interdigitated back contact (IBC) Si cell featuring a conductive top contact[10]. This design improves energy yield while still only requiring wiring on the front and back of the cell. 3-terminal designs have significant advantages under low light intensities as opposed to concentrated sunlight, which is the critical factor in designing tandem solar cells for low-cost terrestrial applications[11]. With the 4-terminal design both sub-cells are operating independent from each other. While this deletes the risk of current mismatch completely, it increases production costs and requires grid alignment to minimize shading.

**Requirement:** Irrespective of the applied design, it is useful to monitor the current match of multi-junction cells by measuring the external quantum efficiency (EQE) of both sub-cells more frequently as in standard c-Si production. Electric arc and gas discharged lamps based flashers (e.g. powered by Xenon) lack the flexibility to vary the spectrums accordingly. The complex interactions and interdependencies of multi-junction cells like PST cells require cell flasher and test systems to enable the detailed characterization of these cells to reduce effects that negatively influence Isc or Impp. Spectrometric characterization and spectrometric determination of current matching has been proven by the Fraunhofer ISE to be the get-go methodology[12]. Amongst others, this includes measuring the EQE of both sub-cells. Hence, PST cell flasher and testing systems need the flexibility to create varying spectra and light intensities according to the respective cell's optimum – and to do this at ease and with precision. This also includes being able to monitor the current mismatch between sub-cells during degradation tests to ensure the best match and optimal performance in the field.

WAVELABS

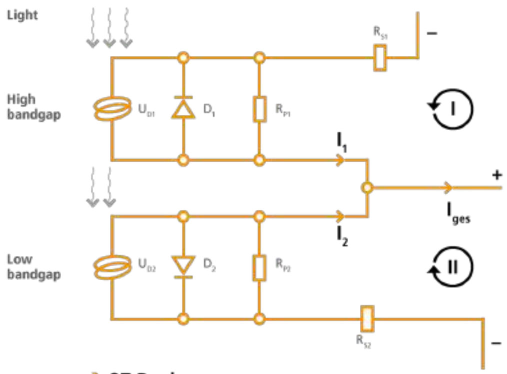
**Fig. 6: Different cell designs change the risk of mismatch**

## 2-terminal cell design circuit diagram



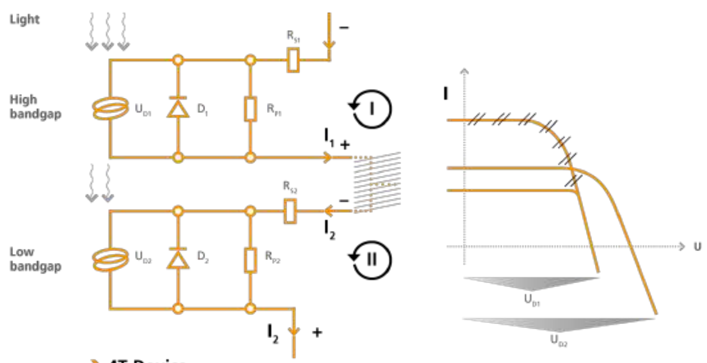

- ➔ 2T Device
- ➔ Single current

## 3-terminal cell design circuit diagram




- ➔ 3T Device
- ➔ I + II share same terminal
- ➔ Currents $I_{ges} = I_1 + I_2$

## 4-terminal cell design circuit diagram



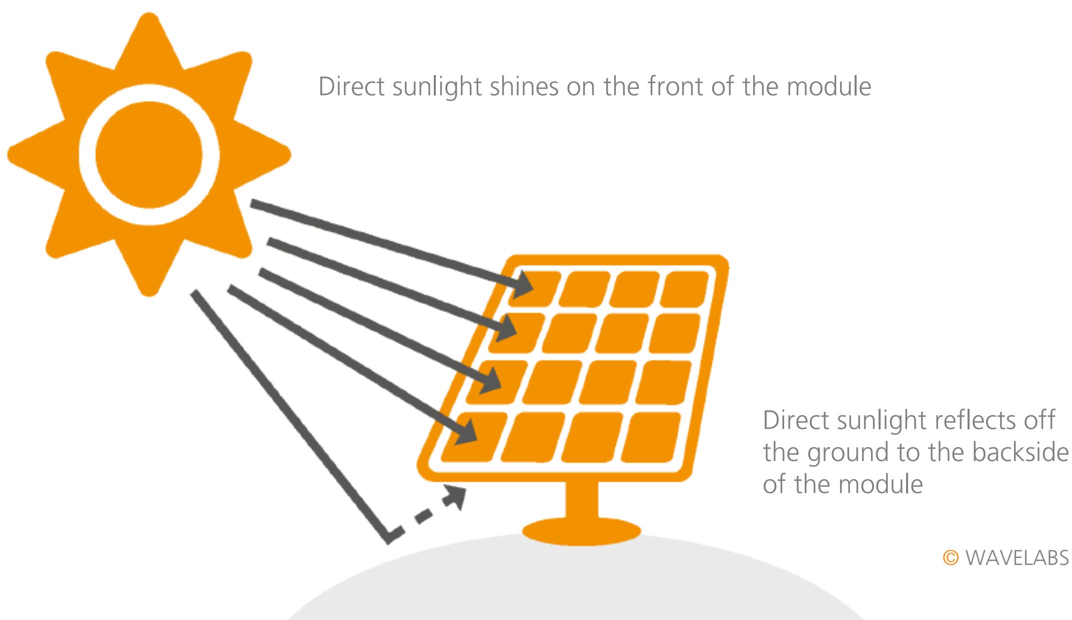

- ➔ 4T Device
- ➔ I + II separate circuits / different currents
- ➔ U / I independent

## 3. Two Sides of the Story

Challenge: The general efficiency promise of PST cells might already be more than enough for a boost in happiness. Nonetheless, it is worthwhile to think one step ahead because efficiency also differs from the applied module design. While mono-facial module designs where the solar cells only receive light from the front are the wide-spread standard, bifacial modules have entered the PV market as a promising design option to further increase efficiency. Bifacial solar modules allow the utilization of incident light on both sides of module increasing total energy generation. While the front side absorbs direct incident light, the backside utilizes light reflected from the underground (see fig. 7). Though, bifacial solar modules also require bifacial solar cells that differ from the common monofacial solar cells in terms of general design as well as measurement requirements: bifacial cells need to be flashed and tested on the front as well as on the rearside to correctly characterize the cell stack. Furthermore, it has to be taken into account during characterization that the reflected light on the rearside heavily differs from the AM1.5G spectrum in terms of available wavelenghts and incident light intensity (depending on background properties as well as daytime).

Requirement: R&D labs and production lines that specialize in bifacial PST cells or demand flexibility between mono- and bifacial cell testing need a flasher and cell testing system that can easily switch between frontside-only flashing and bifacial testing. Furthermore, the flasher needs to be able to flexibily adjust light conditions (spectra, intensities) to model cell and module efficiency under varying light incident conditions.

**Fig. 7: How bifacial modules work in the field**



PST cells require a different and slightly more complex testing regime – namely spectrometric characterization – to ensure reliable test and characterization data. Developers and manufacturers of PST cells (or any other multi-layered PV cell) rely on this level of precision to define and hold product performance warranties as well as to ensure satisfied customers.

Gas discharged bulbs-based flasher technology falls short of providing scalable and easy-to-implement ways to integrate the advanced functions in legacy production lines. But there is no need to panic. Where there is a challenge, a solution waits just one "Flash" around the corner.

**"Flash" is WAVELABS' Chief Motivation Manager (CMO)**
If you want to learn more about Flash: https://wavelabs.de/flash/

## Spectrometric Characterization of PST cells at a glimpse

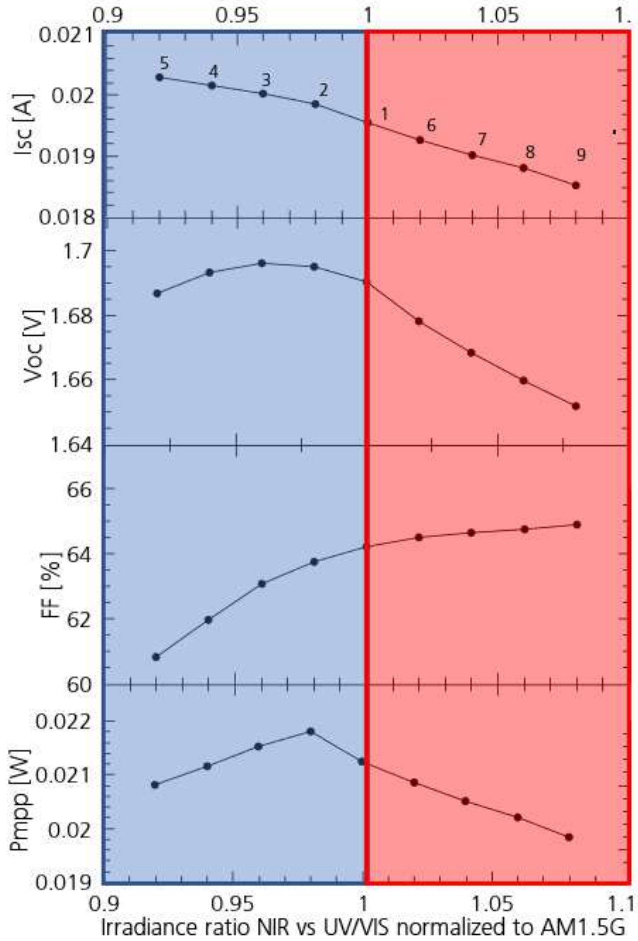
In perovskite/silicon tandem structures (and consequently in any multi-junction structures), it is necessary to study not just the overall I-V curve. Instead, every sub-cell needs to be monitored individually to subsequently determine the optimum current match and overall external quantum efficiency (EQE). The best practice methodology to apply is called spectrometric characterization[13].

A spectrometric characterization consists of a subsequent measurement of the solar cell characteristics for a series of spectral irradiation variations. The simulator spectrum is varied between a" blue-rich" spectrum to a "red rich" spectrum (see fig. 8). The total irradiation intensity (in Watt/m$^2$) of the light source is kept stable during this measurement. The "blue-rich" spectrum shifts the bottom sub-cell (c-Si) into current limit while keeping the top sub-cell (perovskite) saturated. Consequently, the "red-rich" spectrum shifts the top sub-cell to limit the overall current while the c-Si sub-cell is kept saturated. This technique allows to determine the current matching behavior at short circuit current (Isc) and MPP (Impp). Selecting suitable spectral irradiation also allows to maximize either STC efficiency or to optimize energy yield for specific sites and their specific environmental conditions.

While this methodology has been around for about 20 years, the right tooling was not always at hand. Spectrometric characterization requires a sun simulator that allows controlled spectral variations and long irradiation times. In the past this was achieved with complicated and cumbersome adjustments combination of Xenon and halogen light sources. While this might have been a somewhat sufficient auxiliary crutch in long-term monothematic research projects, it has no use in industry-scale production with varying conditions and cell types.

To establish spectrometric characterization in production lines and dynamic R&D environments, advanced solar simulators are a must-have. They need to feature flexible and stable light sources to enable the detailed measurement of a cell's behavior under different light conditions (fig. 8). They also need to allow for preconditioning, tracking of the maximum power point and accurate I-V measurements of perovskite/silicon tandem solar cells. All in one tool. And all easy as pie.

**Fig. 8: Exemplary data plotting from spectrometric characterization**




Results of the spectrometric characterization of a PST cell achieved in one measurement utilizing an LED-powered solar simulator. Isc, Voc, FF and Pmpp are plotted versus the ratio of used irradiance spectrum and the AM1.5g spectrum. Small spectra quotients (ratio < 1) indicate a "blue-rich" spectrum, while large values (ratio > 1) indicate a "red-rich "spectrum. The results show an optimized utilization of blue-rich light by the measured PST cell. This level of detail allows for a perfect matching of solar cells on module level.[14]

## LED’s move PST cell measurements to industry-scale level

LED technology is the best available choice for a stable and highly flexible light source. It is superior to old-generation flasher technology in significant ways:

- LEDs emit a highly stable light even over a long period of time.
- LEDs can be flexibly adjusted to any irradiation intensity
- LEDs are available for a wide range of wavelengths covering the spectrum from UV to IR.
- LEDs have long endurance of 20,000 hours and more.
- LEDs are 4 times more energy-efficient than gas discharging bulbs (incl. halogen & Xenon).
- LEDs are easy to integrate and maintain on an industrial scale.
- LEDs are cost-efficient.

The stability and flexibility of light source regulation are at the core of spectrometric characterization and test settings for multi-junction solar cells.

Let's flash to the advantages of LED flasher technology for perovskite / silicon tandem cells.

## PST cell characterization requires light soaking that can be individually adjusted.

LED flasher technology provides full flexibility to set light soaking times from milliseconds to hours. The fully automated adjustment process allows different recipes for different cell types or cell classes without having to change bulbs or any parts of the flasher.

## PST cell characterization requires highly stable and homogeneous light emission for light soaking cycles.

LED flasher technology uses a special WAVELABS lens system that enables a homogeneous light distribution across the entire cell surface. To ensure a stable spectrum over time, an integrated spectrometer and multiple photodiodes continuously measure the emitted light and trigger self-correction if necessary. This provides a highly precise and long-term stable light source with a deviation between the target and actual spectrum of less than 5 %. In comparison, Xenon light sources used in industrial cell flashers operate at a spectral match deviation to the AM1.5G spectrum of as high as +/- 12.5 %.

## PST cell characterization requires flexible spectra for determining current matching and EQE.

LED flasher technology provides full spectral flexibility to measure the different optima of sub-cells. WAVELABS LED solar cell flasher carry 20 and more LEDs of which each LED covers a different spectral range. Users can switch on and off every single LED channel as needed. This gives full freedom for creating any conceivable spectral mix. This high adaptability also builds the foundation for the highly efficient and successful R&D of PST cell designs for different applications and environments (e.g. designs for conditions that differ from the AM1.5G standard).

### PST cell characterization requires stability of total integrated irradiance while changing the spectrum.

LED flasher technology also allows adjusting the intensity of every single LED channel. This means, that if the irradiance of lower blue LEDs is reduced, the irradiance of red LEDs can be increased to maintain a stable total integrated irradiance as required by the international standard IEC 60904-1-1 “Measurement of current-voltage characteristics of multijunction photovoltaic devices”.

### PST cell characterization requires high stability even at lower light intensities.

LED flasher technology provides high stability for low irradiance flashes, which are typically used for backside flashing. Even light intensities as low as 150 W/m² can be run stable over a long period of time.

### PST cell characterization in R&D requires different sweeping modes to prevent hysteresis effects.

LED flasher technology offers two modes for Pmpp tracking: beyond the standard MPP tracking commonly used for perovskite cells there is a second method. WAVELABS refers to as Perturb & Observe (P&O). The latter enables a Pmpp tracking where the power output is first measured under a slowly increasing voltage followed by a slowly decreasing voltage. This prevents incongruent measurement data caused by the hysteresis effect of PST cells.

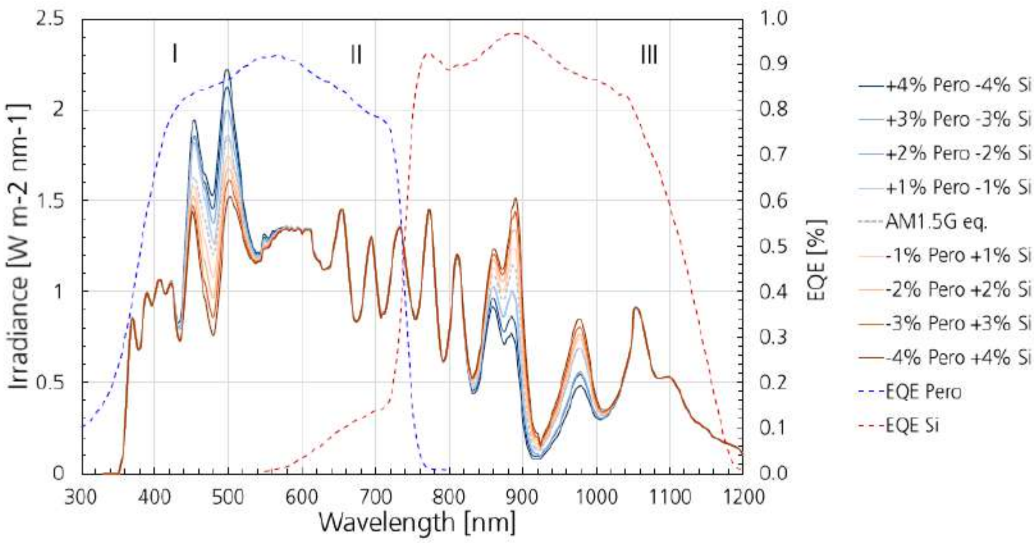
## PST cell characterization needs precise and reproducible measurement sequences to understand cell properties

LED flasher technology allows the precise control of the light source regarding its spectrum, intensity, spectral distribution, and duration (see fig. 9). Every setting is reproducible and even automatable. This also facilitates sound process analysis and the optimization of manufacturing parameters.

## PST cell characterization requires a setup that reduces complexity and risk for cells.

LED flasher technology provides all tools in one application needed for spectrometric characterization – from light soaking to different measurement cycles. This all-in-one approach minimizes the risk of cell degradation or change of cell properties due to time gaps and/or movement of cells during the individual conditioning and measurement steps. It also renders the perceived complexity of spectrometric characterization easy as pie.

**Fig. 9: EQE of PST cell and applied simulator spectra**




The graph showcases both, the flexibility and precision of the utilized LED flasher solution SINUS-300 by WAVELABS. The different simulator spectra applied to vary the spectral metric (thin lines) are overlaid by the EQE of an investigated PST cell at HZB (dashed lines). All spectra are designed to have the same total irradiation power[14].

## Bonus: 3-terminal and 4-terminal PST cells are best characterized by using a combined front-side and rear-side flasher.

Compact LED flasher technology provides the flexibility of adding a rear-side flasher to the basic front-side flasher. It also ensures that both flashers run stable and exact to ensure comparability and an effective combination of both measurements.

The development and progress of PST cells within the last decade create the great potential to push PV efficiency beyond the 29 % limit of c-Si cells. In the past, multi-junction high efficiency solar cells have been restricted to expensive special project applications like space exploration satellites. Though, further advances in scaling PST cell production processes offer a real opportunity for the PV industry to transfer high-efficiency cell designs to domestic use.

These advances include a measurement and testing regime that allows both to consider and understand the specifics of different PST cell designs, and to implement them on an industry-scale level. Leading PST cell research and production companies like Fraunhofer ISE and Hanwha use WAVELABS LED flasher solutions to profit from the combination of advanced technological capabilities and scalable implementation.

## How to achieve precise and flexible PST cell characterization today

### Meet the LED Solar Simulator SINUS-300

The SINUS-300 is the ideal solar simulator for production, research and certification. With its highly accurate and precise simulation of the sun spectrum, it suits solar cell efficiency measurement just as well as experiments in life and material science - just to name a few of the possible applications. The intelligent LED-based light source is what makes this exceptional accuracy possible.

Since 2011 WAVELABS have been revolutionizing the solar cell flasher market by utilizing the best available choice for a stable and highly flexible light source: LEDs. Today more than 40 % of cell flashers in cell production lines are made by WAVELABS. Our LED solar simulator SINUS-300 provides all capabilities to characterize PST cells precisely, flexibly and economically.

### The LED solar simulator WAVELABS SINUS-300:

- ✓ Provides stable and precise measurements through 20 LEDs that perfectly copy the sun.
- ✓ Allows full flexibility for individual measurement designs through free spectra definition of flashs between UV and IR.
- ✓ Ensures reliable, reproducible measurement results even for challenging cell designs through flexible light-soaking settings from milliseconds to hours.
- ✓ Enables throughput of more than 4,000 cells per hour since LED light engines do not require re-charging.
- ✓ Provides excellent spectral match, non-uniformity and temporal stability exceeding class AAA criteria (IEC 60904-9 Ed. 2, JIS C8912, ASTM E 927-10).
- ✓ Requires low maintenance with typical LED lifetime of 20,000 hours and more.
- ✓ Can be upgraded with EL and synchronized IR cameras for micro crack detection and IR imaging, respectively.
- ✓ Is ready for 3- & 4-terminal cells through rear side flasher for bifacial cell testing.
- ✓ Is ready for cut-cell designs through optional cut-cell measurement (CCM) for simultaneous measurement of up to 3 cut-cells in one cycle.
- ✓ Prevents hysteresis effects in measurement results as well as high throughput with RapidWAVE® technology (optional).

WAVELABS


[1] https://www.pv-magazine.com/2022/03/15/humans-have-installed-1-terawatt-of-solar-capacity/, last accessed, June 30, 2022

[2] Lucio Claudio Andreani, Angelo Bozzola, Piotr Kowalczewski, Marco Liscidini & Lisa Redorici (2019) Silicon solar cells: toward the efficiency limits, Advances in Physics: X, 4:1, 1548305, DOI: 10.1080/23746149.2018.1548305

[3] https://wavelabs.de/how-the-perovskite-solar-cells-will-shape-our-world/

[4] https://www.ise.fraunhofer.de/en/press-media/press-releases/2022/fraunhofer-ise-develops-the-worlds-most-efficient-solar-cell-with-47-comma-6-percent-efficiency.html, last accessed June 30, 2022

[5] https://www.cell.com/joule/fulltext/S2542-4351(20)30322-6#secsectitle0020

[6] https://cleantechnica.com/2021/02/07/4-billion-us-oil-company-banks-on-perovskite-solar-cell-of-the-future/

[7] Moritz H. Futscher and Bruno Ehrler (2016): Efficiency Limit of Perovskite/Si Tandem Solar Cells, ACS Energy Lett. 2016, 1, 4, 863–868

[8] https://www.csem.ch/page.aspx?pid=172296, last accessed July 2022

[9] E. Aydin et al., "Interplay between temperature and bandgap energies on the outdoor performance of perovskite/silicon tandem solar cells," Nat. Energy, vol. 5, no. 11, pp. 851–859, 2020

[10] Emily L. Warren et al.: Maximizing tandem solar cell power extraction using a three-terminal design, Sustainable Energy & Fuels, Issue 6, 2018

[11] Hiroyuki Kanda et al. (2022): Three-terminal perovskite/integrated back contact silicon tandem solar cells under low light intensity conditions, Interdiscplinary Materials, Vol. 1, issue 1, p. 148-156

[12] Seifert, H. et al. (2010): Spectrometric characterization of multi-junction organic solar cells, 25th European Photovoltaic Solar Energy Conference and Exhibition, EU PVSEC 2010. Proceedings

[13] M. Meusel, R. Adelhelm, F. Dimroth, A. W. Bett, and W. Warta, "Spectral mismatch correction and spectrometric characterization of monolithic III-V multi-junction solar cells," Prog. Photovoltaics Res. Appl., vol. 10, no. 4, pp. 243–255, 2002.

[14] B. Mette, E. Köhnen et al.: Advanced LED solar simulator: flexible and fast characterization tool for research and industrialization of perovskite/silicon tandem solar cells, 38th EUPVSEC proceedings, 2021, p. 490-495

# ABOUT WAVELABS

Dr. Torsten Brammer, Jörn Suthues and Dr. Thankmar Wagner founded WAVELABS Solar Metrology Systems GmbH in September 2011. In just over a decade, WAVELABS has grown from a start-up to a global market leader for LED solar simulators – with customers in more than 30 countries and a market share of around 30 percent. The 90 employees of the Leipzig-based technology company generated sales of approximately 29 million euros in 2021.

Today the innovative measurement systems for characterizing solar cells and modules are used globally for R&D, production, quality assurance and certification at major photovoltaic manufacturers as well as at renowned research institutes and universities. The company's vision is an energy supply that is 100 percent from renewable resources in order to leave the world in a better state than we found it. LED's COPY THE SUN!

**LED's get in touch!**

With a WAVELABS expert today to find out how we can help your research results or manufacturing processes shine brighter:
https://wavelabs.de/contact/

**WAVELABS Solar Metrology Systems GmbH**

Spinnereistr. 7

04179 Leipzig

+49 341 3375 560

+49 341 3375 5696

info@wavelabs.de