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TRIUMPH

Triple junction solar modules based on perovskites and silicon for high performance, low-cost and small environmental footprint



Deliverable report

D5.1 – Report on accurate measurement of IV and SR/QE of 2J/3J cells

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About TRIUMPH

TRIUMPH is aimed at developing the next generation PV technology to come after tandems, i.e., an advanced triple junction cell concept. The devices will be based on the cost-effective and highly-efficient perovskites for the middle and top cells and the robust and well-proven silicon for the bottom cell. The **4 objectives** of are:

1. Achieving highly-efficient triple junctions **>33%** with **high stability** on 1 cm² area
2. Demonstrating a cost-effective and scalable route for triple junctions on **large-area (≥ 100 cm²)** with minimal upscaling losses (efficiency **>90%**_{rel} to small-area devices) with **3J modules** passing accelerated reliability testing.
3. Designing triple junction cells and modules for **sustainability** by **reducing CRMs** such as In and Ag, and by introducing **circular concepts** that allow easy recycling at end-of-life of the 3J modules.
4. Establishing the **value chain within EU** for future multi-junction modules.

The project consortium, coordinated by IMEC in Belgium, consists of **15 complementary partners** from renowned research institutions, illustrious universities as well as strong industrial players from across the value chain.

TRIUMPH consortium members

No.	Participant Legal name	Acronym	Country
1 (Coord.)	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM	IMEC	BE
2	FRAUNHOFER GESELLSCHAFT ZUR FÖRDERUNG DER ANGEWANDTEN FORSCHUNG E.V	F-ISE	DE
3	L'INSTITUT PHOTOVOLTAÏQUE D'ÎLE-DE-FRANCE	IPVF	FR
3.1	ÉLECTRICITÉ DE FRANCE	EDF	FR
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13	VON ARDENNE GMBH	VA	DE
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Lead Author	M. C. Schubert
Co-Author(s)	A. J. Bett, S. Sedani
Reviewed by	José Alvarez (CNRS), Pilar López-Varo (IPVF), and Hari Sivaramakrishnan (imec)

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Publishable summary

Two-terminal perovskite based multi-junction solar cells have gained remarkable efficiencies in the past years and have overcome the efficiency limit of single junction solar cells. However, there are challenges for the correct measurements of these solar cells. One reason is the monolithic tandem architecture, which means that the individual sub-cell currents and voltages are not accessible individually. A second reason are mobile ions in the perovskite absorber leading to a dynamic behavior of the solar cells. In this work, mainly the first point is addressed.

For a correct current-voltage measurement from which the performance can be determined, the solar simulator spectrum needs to be adjusted in a way that all sub-cells generate the same current as they would do under the reference spectrum. This can be reached by using solar simulators with multiple, individually adjustable light sources as is known from the world of III-V multi-junction solar cells, often ignored in the perovskite community. In this work, the importance of this spectral adjustment for every individual solar cell is highlighted. Large errors of up to 5% - 10% in the current can occur when using the same spectrum for solar cells with different relative spectral responses, as shown by calculations. It has to be noted that even an A+ spectrum is by far not enough to fulfill the required current conditions for all sub-cells. A round robin has been carried out within the TRIUMPH project where stable III-V-on-silicon triple junction solar cells have been measured in different research laboratories. Strong deviations compared to measurements carried out in a calibration laboratory can be seen when the spectrum is not adjusted.

For the correct spectral adjustment, the relative spectral responses of the multi-junction solar are needed as input. Measured spectral responses are often considered as absolute and integrated to determine sub-cell currents and the current-matching situation of the multi-junction device. However, this can lead to large uncertainties and misinterpretations as the sub-cell voltages cannot be determined accurately and thus, the operational point of the sub-cell to be measured might differ from the short-circuit condition which might lead to measurement artifacts in case of non-ideal solar cells. Luminescent coupling can lead to such artifacts as well, which can in principle be corrected. However, inhomogeneities can lead to errors in the absolute intensity of even the corrected spectral response. Thus, measured spectral responses should never be considered as absolute which could experimentally be shown by the round robin. The relative spectral responses were in good agreement between all research laboratories. However, the absolute values differed up to ~10%. In the case of perovskite-based multi-junction solar cells, it gets even more critical because dynamic effects can make the absolute values dependent on measurement conditions.

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List of acronyms, abbreviations and definitions

Abbreviation	Definitions
AM1.5g	Air mass 1.5 global
$E_{AM1.5g}$	Air mass 1.5 global spectral irradiance
E_{sim}	Spectrum of the solar simulator
EQE	External quantum efficiency
FF	Fill factor
I_{sc}	Short-circuit current
IEC	International Electrotechnical Commission
IV	Current-voltage
j_{sc}	Short-circuit current density
m	Number of light sources
n	Number of junctions
P_{MPP}	Maximum power point
SR	Spectral Response
sr	Relative spectral response
$sr_{sub-cell}$	Relative spectral response of a sub-cell
V_{oc}	Open-circuit voltage

1 Introduction

The global transition towards sustainable energy necessitates the exploration and development of advanced photovoltaic technologies. Perovskite-silicon multi-junction solar cells have emerged as a particularly promising candidate, offering the potential to surpass the limit that constrains the efficiency of conventional single-junction silicon devices. As research and development in this field accelerates, the imperative for accurate, reliable, and standardized performance testing protocols becomes increasingly critical [1]. Such protocols are essential not only for benchmarking device performance and comparing results across research groups, but also for guiding further optimization and ultimately, facilitating the commercialization of this technology.

While significant effort has been directed towards enhancing the stability of perovskite solar cells, as reflected in the development of ISOS protocols [2], a corresponding emphasis on rigorous performance testing methodologies on metastable cells is equally vital. The ion migration and stability issues of perovskites can cause performance to change with different pre-conditioning such as light soaking and bias voltage which is out of scope of this report. This work addresses the critical need for a harmonized approach to performance evaluation, specifically tailored for monolithic two-terminal perovskite-silicon tandem and triple solar cells, differentiating it from degradation/stability testing, which focuses on long-term operational reliability. It is important to make a clear distinction between performance testing, which aims to characterize the instantaneous electrical behavior of a solar cell under controlled conditions, and degradation/stability studies, which assess the device's ability to maintain its performance over extended periods of operation under various stress factors [3].

Existing International Electrotechnical Commission (IEC) standards such as the IEC 60904 series provide a general framework for photovoltaic testing in the context of silicon wafer-based solar cells, but do not cover challenges of emerging photovoltaics such as instability in performance over time, unorthodox spectral responsivity, transient and non-linear response to irradiance. Standards such as IEC TR 63228 focused on the emerging challenges of organic photovoltaics, dye-sensitized solar cells and perovskite solar cells impose regulations on IV measurement steps and preconditioning. Nevertheless, these standards often remain lack the specificity required to address the unique challenges posed by perovskite materials integration into multi-junction architectures [1, 6]. The rapid evolution of perovskite technology necessitates a continuous refinement of testing methodologies to keep pace with advancements in device design and materials science. Wang et al. [6] highlight the difficulties in reliably measuring perovskite solar cells, which consequently creates difficulties for researchers to compare and reproduce published results. This is further complicated by factors inherent to the materials and as it is set in a perovskite/silicon multi-junction structure [4].

Calibration laboratories play a crucial role in ensuring the accuracy and traceability of solar cell measurements. [12] These laboratories employ sophisticated equipment and adhere to strict protocols to minimize measurement errors and provide reference standards for the broader research community. However, even within these highly controlled environments, subtle variations in procedures, equipment, and environmental conditions can introduce discrepancies in the results. Addressing the inconsistencies in measurements requires careful consideration of the factors that contribute to measurement variability, including temperature control, spectral mismatch correction, and accurate determination of cell area. The current-voltage characterization method is often employed to evaluate the performance of perovskite-silicon tandem solar cells, but it is fraught with challenges [1].

Dynamic effects within the perovskite material, such as ion migration, can significantly influence device performance and complicate accurate characterization [4, 5]. These effects can manifest as hysteresis in current-voltage curves, variations in efficiency depending on the measurement conditions, and challenges in achieving stable power output [6]. Considering these complexities, approaches to performance measurements, as noted by Dunbar et al. [1], can lead to unreliable assessments of cell performance and hinder progress in the field. The current-limiting behavior of the sub-cells, spectral mismatch, parasitic resistances, ion migration, metastability, and current-voltage (IV) hysteresis can all significantly affect the accuracy and reliability of measurements [4, 7].

A central challenge in performance testing of perovskite-silicon tandem cells stems from the current-limiting behavior of the sub-cells [8]. In a two-terminal tandem configuration, the sub-cell generating the lowest current dictates the overall current of the device. This constraint necessitates careful optimization of the performance of each sub-cell to ensure current matching and maximize overall efficiency. The spectral mismatch between the calibrated reference diode and the device under investigation can be difficult to precisely estimate for IV curves and steady-state efficiency, as we will discuss later. Furthermore, measuring the external quantum efficiency (EQE) of independent sub-cells is difficult, particularly when the absorption spectra of the active layers overlap. These difficulties, as well as appropriate measurement procedures, have previously been reported for III-V multi-junction devices [9] and organic thin-film photovoltaic tandem solar cells [10, 11], and standard test methods for non-concentrator multi-junction photovoltaics such as ASTM E2236-10(2019) have also been constructed. Here, we will address their consequences for perovskite/silicon multi-junction devices.

Existing research papers often lack sufficient detail regarding the specific measurement protocols employed, making it difficult to reproduce results or compare performance across different studies. A failure to account for these factors can lead to overestimation of device performance and hinder the identification of promising materials and device architectures [13]. Furthermore, many studies focus solely on power conversion efficiency

as the primary performance metric, neglecting other important parameters such as that the measurement itself, its speed and many other parameters could affect the device behavior and reach different results for the same cell [14]. Besides, reverse bias resilience of monolithic tandem cells has been overlooked and rarely reported which could even occur during the measurement of devices with two-terminal multi-junction structure. [15] A holistic approach to performance testing should encompass a comprehensive suite of measurements that capture the full range of device characteristics and provide a more complete picture of its potential for real-world applications [12, 16].

For IV measurements, an accurate calibration of the solar simulator is paramount to minimize spectral mismatch errors. Performing accurate IV measurements under standard test conditions is important. Therefore, it is crucial to precisely adapt the spectrum based on the relative EQE of the sub-cells in a way that all sub-cells generate the same current under the simulator spectrum as they would under the reference spectrum [8]. The spectral output of the simulator should be regularly calibrated against a reference standard. Appropriate masking of the solar cell area is crucial to avoid artificially inflated short-circuit current density (j_{sc}) values, as highlighted by Christians et al. [14]. Reproducible stabilization procedures [2, 17], such as controlled light soaking, should be implemented to minimize the influence of metastability on power output. Furthermore, comprehensive uncertainty analysis and reporting of all potential sources of uncertainty in the measurements is essential for establishing the reliability of the results.

The uniformity of illumination across the device area is another factor which should be checked and tuned primarily with the test device while the critical factor manifests itself as lateral inhomogeneity of multi-junction solar cells which can significantly impact performance measurements both in EQE and IV characterizations. Characterization and simulation work by Reichmuth et al. [18] shows that inhomogeneous cell features, such as low localized shunt resistances or non-uniformities in the cell absorber, might affect EQE measurements when combined with illumination and biasing circumstances.

Spectrometric characterization presents a sophisticated approach to probe the performance of multi-junction solar cells under systematically varied spectral conditions. By carefully manipulating the spectral content of the illumination source, researchers can gain valuable insights into the current matching characteristics of the tandem device and identify potential limitations within individual sub-cells [5, 8, 19]. The capability to calculate spectra in advance and apply them sequentially eliminates the need for intermediate reference measurements, streamlining the characterization process [20]. Spectrometric characterization enables accurate determination of current matching, offering advantages over traditional methods that rely on integrating EQE measurements [5]. This analysis can be further enhanced by considering the dependence of the fill factor on the illumination spectrum, which provides insights into sub-cell parallel resistance and hysteresis behavior [4, 5, 8].

In this work, the most critical points of IV and EQE measurements of multi-junction solar cells are addressed. In the first part, the importance of an accurate spectral adjustment for IV measurements for every solar cell is emphasized accompanied by theoretical calculations showing how large the errors can be when a standard A+ spectrum or a spectrum calculated for another solar cell is used. In the second chapter, it is highlighted why measured EQEs should never be considered as absolute and thus, integrated currents from measured EQEs might have strong uncertainties and thus, can lead to misinterpretations. In both cases, measured data from different laboratories obtained in the framework of a round robin carried out within the TRIUMPH project are shown and underline the importance of the discussed points. For that purpose, stable III-V on silicon triple-junction solar cells have been used to avoid degradation effects. For perovskite-based multi-junction solar cells more difficulties occur which are shortly discussed.

2 Reliable Current-Voltage Measurements

2.1 Spectral Adjustment Procedure for Solar Simulators

For a correct current-voltage (IV) measurement of a solar cell with n junctions it must be ensured that each of the n sub-cells generates the same current density as it would under the reference spectrum [8], which is usually the Air Mass 1.5 global (AM1.5g) spectrum $E_{AM1.5g}$, in the case of terrestrial perovskite based multi-junction solar cells. That means that all the following equations for the current density of each sub-cell i , $j_{sub-cell\ i}$, must be fulfilled simultaneously:

$$\begin{aligned} j_{sub-cell\ 1}^{simulator} &= j_{sub-cell\ 1}^{AM1.5g} \\ j_{sub-cell\ 2}^{simulator} &= j_{sub-cell\ 2}^{AM1.5g} \\ &\vdots \\ j_{sub-cell\ n}^{simulator} &= j_{sub-cell\ n}^{AM1.5g} \end{aligned}$$

It has to be noted that it is not enough to fulfill one equation for the limiting sub-cell for several reasons. First, the short-circuit current density (j_{sc}) of the multi-junction solar cell can be larger than the current generated by the limiting sub-cell when the limiting sub-cell has a low parallel resistance or a low breakthrough voltage. Second, even for ideal sub-cell IV curves, a wrong current in a non-limiting sub-cell would lead to fill factor (FF) errors. Anyway, determining the sub-cell currents and thus the limiting sub-cell is challenging, and the integration of measured EQE curves for that purpose should be avoided (see next chapter).

The conditions for the current densities of the sub-cells mentioned above leads to the following equation system:

$$\begin{aligned} \int sr_{sub-cell\ 1} E_{Sim} d\lambda &= \int sr_{sub-cell\ 1} E_{AM1.5g} d\lambda \\ \int sr_{sub-cell\ 2} E_{Sim} d\lambda &= \int sr_{sub-cell\ 2} E_{AM1.5g} d\lambda \\ &\vdots \\ \int sr_{sub-cell\ n} E_{Sim} d\lambda &= \int sr_{sub-cell\ n} E_{AM1.5g} d\lambda \end{aligned}$$

where the solar simulator spectrum E_{Sim} can be composed of the spectra of several (m) lamps, so that $E_{Sim} = \sum_{i=1}^m E_i$. Note that only the relative spectral responses of the sub-cells $sr_{sub-cell}$ appear in the equation. The absolute value is cancelled out.

Ideally, the solar simulator is composed of at least the same number of individually adjustable lamps as the number of junctions (n) in the device under test ($m=n$). For $m=n$, there is a unique solution when solving the equation system for the lamp intensities

(provided that the lamps are chosen in appropriate wavelength ranges) [8]. For a solar simulator with less lamps than junctions of the test device ($m < n$) there is no solution. A correct spectrum could still be found by filtering the light. For solar simulators consisting of more light sources than junctions of the device under test ($m > n$), such as for example LED-based simulators, there can be an infinite number of solutions of the equation system. In this case, further boundary conditions can be defined such as being close to the reference spectrum [20].

A spectral adjustment would not be necessary if the solar simulator spectrum would deliver a perfect AM1.5g spectrum ($E_{\text{Sim}} = E_{\text{AM1.5g}}$). The equation system would be fulfilled independently of the shape of the spectral responses of the sub-cells in this case. However, all spectra of commercially available solar simulators deviate from the reference spectrum. Even a class A+ spectrum is not close enough to the AM1.5g spectrum to avoid large measurement uncertainties without spectral adjustment. The A+ classification only assures a comparable irradiance in certain wavelength ranges compared to the irradiance in the AM1.5g spectrum, but not a similarity of the spectral shapes (IEC 60904-9 (2020)).

It is important to note that spectral adjustment is necessary for every individual solar cell for a correct measurement, not only for the calibration of solar cells but also in laboratory setups. For laboratory measurements, it might be enough to use the same spectral settings for solar cells with the same architecture where the relative spectral response (shape of the spectral response) is not expected to change significantly. However, as soon as optical properties change (e.g. change of perovskite bandgap, layer thickness adaptations, change of contact materials, etc.) the spectrum needs to be re-adjusted. Otherwise, measurement uncertainties between 5% and 10% can occur, which is in the range of 1 - 2 mA/cm² in the case of a dual-junction solar cell. This error is not a constant offset but will be different for each cell type, *i.e.*, when not adjusting the spectrum for each solar cell type, the comparison of different groups of solar cells can lead to misinterpretations.

An example is given in Figure 1. Figure 1a shows the normalized EQEs of three multi-junction solar cells, a III-V on silicon triple-junction solar cell (Cell 1), a perovskite on silicon triple-junction solar cell (Cell 2) and a III-V dual-junction solar cell (Cell 3). In Figure 1b the AM1.5g spectrum is represented together with a default simulator spectrum of an LED based solar simulator (Wavelabs, Sinus220) which fulfils the A+ criterion, and the adjusted spectra calculated to fulfill the above-mentioned condition for the three different solar cells. The ratio of the current density under the different simulator spectra to the current density under the AM1.5g spectrum is shown for all three sub-cells of Cell 1 in Figure 1c. It clearly shows that the A+ simulator spectrum would lead to significant measurement errors. While for the top cell, the current is around 4% too high, for the bottom cell it is almost 6% too low. Using the adjusted spectrum for Cell 1, the current density perfectly fulfills the above-mentioned condition, as the current ratios are 1.000 for all sub-cells.

Using the spectra calculated for Cell 2 and Cell 3, significant deviations of up to 7% can be observed. This example highlights the necessity of spectral adjustment for each solar cell.

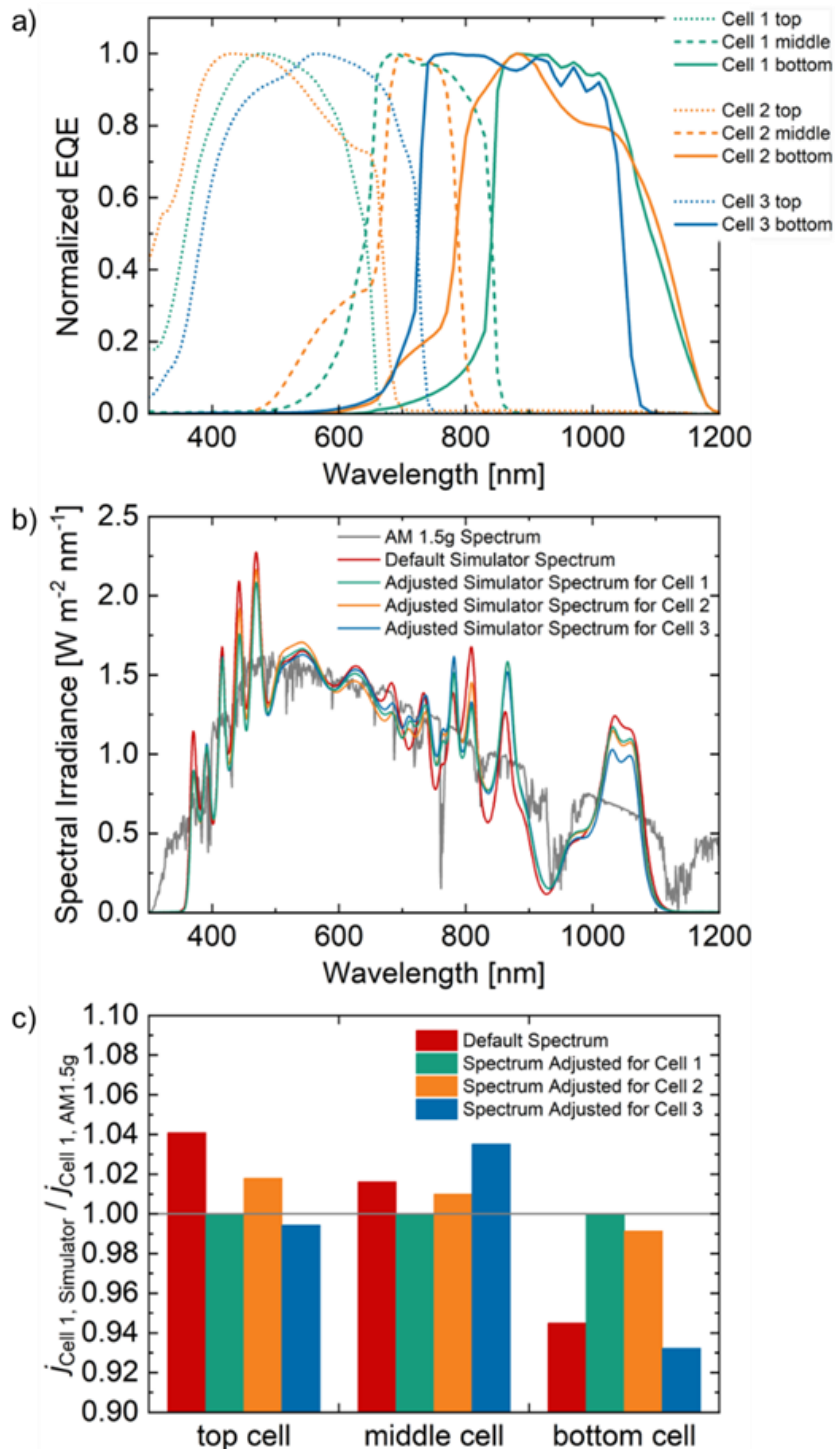


Figure 1: a) Normalized EQEs of three different multi-junction solar cells: a III-V on silicon triple-junction solar cell (Cell 1), a perovskite on silicon triple-junction solar cell (Cell 2) and a III-V dual-junction solar cell (Cell 3). b) AM1.5g spectrum, a default solar simulator spectrum fulfilling the A+ criterion and adjusted spectra based on the relative EQEs of the three solar cells shown in a). c) Current density ratios obtained for the simulator spectra to the AM1.5g spectrum for the three sub-cells of Cell 1. Only the adjusted spectrum for cell 1 gives the correct current densities in all three sub-cells. All other spectra would lead to significant measurement errors of several percent.

2.2 Results from the Round Robin Carried out in TRIUMPH

In the framework of the TRIUMPH project, a round robin has been carried out in which solar cells have been measured in different research laboratories. For multi-junction solar cells containing perovskite there is a high risk of degradation during a long experiment (shipping from lab to lab, repeated measurements) and the interpretation of the results is difficult afterwards, as it might be not clear whether changes in the solar cell performance are coming from differences in measurements in different set-ups at different laboratories or from a change in the solar cell itself. Therefore, two III-V on silicon triple-junction solar cells, which will not exhibit the aforementioned degradation, have been sent around and were measured in four laboratories. The first and the last measurements are nevertheless conducted at the Fraunhofer ISE CalLab.

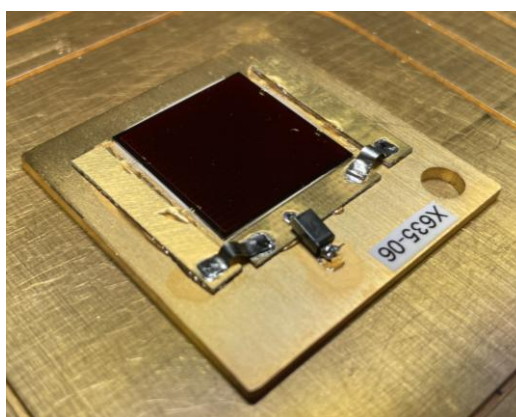


Figure 2: Picture of III/V-III/V-Si triple junction test solar cell. Solid contacting bars and a bypass diode were added to avoid cell damage during the round robin.

The results of the measurement round robin are shown in Figure 3 and the corresponding parameters are summarized in Table 1. Initially and afterwards, these solar cells were measured at Fraunhofer ISE CalLab PV Cells. Only a slight difference in the IV curves can be seen between these two measurements with more than one year between them. However, clear differences can be seen between the measurements at the four laboratories.

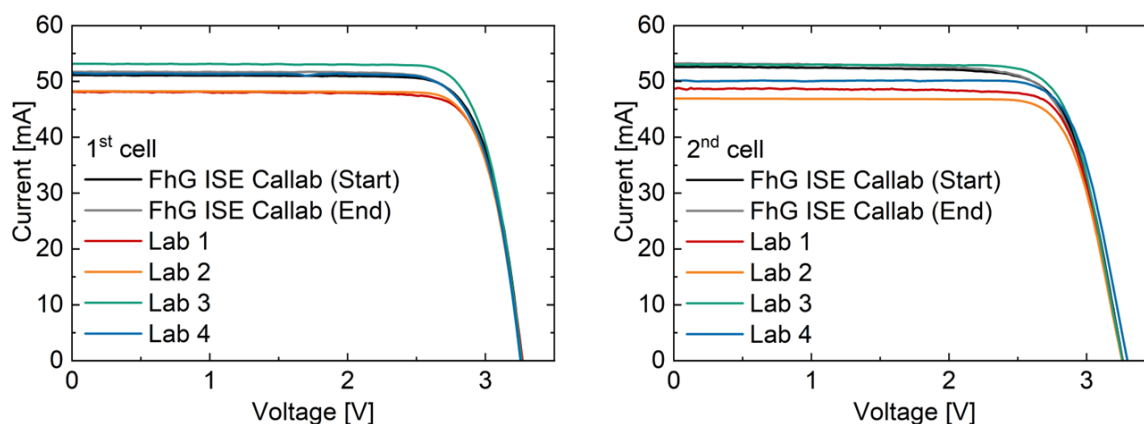


Figure 3: IV curves for two III-V on silicon triple-junction solar cells carried out in four different research laboratories within the round robin of the TRIUMPH project. Before and afterwards the solar cells have been measured at Fraunhofer ISE Callab PV Cells.

Table 1: IV parameters corresponding to the IV curves shown in Figure 3.

	FhG ISE Callab		Lab 1	Lab 2	Lab 3	Lab 4
	before	after				
1st cell						
I_{sc} [mA]	51.1	51.7	48.1	48.3	53.2	51.6
V_{oc} [mV]	3264	3260	3275	3260	3262	3253
FF	79.9	78.8	80.3	81.3	80.6	78.9
2nd cell						
I_{sc} [mA]	52.6	53.2	48.7	46.9	53.0	50.0
V_{oc} [mV]	3263	3258	3260	3260	3262	3293
FF	76.4	75.4	79.2	79.1	78.1	78.7

The open-circuit voltage (V_{oc}) is the only parameter which shows a very low deviation between the labs. The short-circuit current I_{sc} is the parameter which shows the largest spread (up to >7%). But also, the FF shows significant deviations. The most probable reason for these deviations is a poor spectral adjustment.

In Lab 1, the solar cells have been measured with a solar simulator consisting of only one lamp whose intensity has been adjusted using a silicon reference solar cell. This procedure generally does not lead to a condition where all three equations mentioned in the previous section are fulfilled and thus, it is not surprising that the obtained parameters show a large deviation compared to Fraunhofer ISE Callab PV Cells.

Lab 2 used an LED-based solar simulator and adjusted the intensity of the LEDs to achieve a spectral match similar to the AM1.5g spectrum across wavelength ranges. However, fulfilling an A+ condition is not enough for an accurate measurement, as has been discussed in the previous section, and therefore also large deviations can be seen between Lab 2 and Fraunhofer ISE Callab PV Cells.

Lab 3 used a solar simulator with two individual light sources. That means a spectral adjustment is possible, but not optimal for a triple-junction solar cell. However, the results are much closer to the Fraunhofer ISE CalLab PV Cells results compared to Lab 1 and Lab 2. For the second cell, the current could even be almost perfectly matched; however, there is still a discrepancy in FF .

In Lab 4, the spectrum was adjusted based on the relative spectral response of all sub-cells. A very good match with the IV curve from Fraunhofer ISE CalLab PV Cells can be seen for the first solar cell in all parameters. For the second solar cell, there are some deviations in I_{SC} and FF . One reason could be related to known uncertainties of the spectrometer in the infrared range, which is used in Lab 4. Also, the calculated mismatch factor of the bottom cell deviates by $\sim 3\%$ for the adjusted spectrum for the second solar cell.

This example of the TRIUMPH round robin shows again that an accurate spectral adjustment is crucial in order to obtain reliable measurement results. However, it is also difficult for triple-junction solar cells. Besides the hardware requirements (three individually adjustable light sources), the spectra of the lamps need to be accurately determined. This is challenging as a calibrated spectrometer is needed. Besides the spectral adjustment there are further sources of measurement uncertainties influencing the results: the temperature setting might not be perfectly precise, or the light sources might not be homogenous. Errors in the determination of the active solar cell area can impact the efficiency value. Every laboratory should try to minimize all uncertainties as much as possible. However, it is very clear that they will never vanish completely. Thus, it is important to check for uncertainties and consider them in the data evaluation and interpretation.

2.3 Additional Notes for Metastable Perovskite Solar Cells

Adjusting the spectrum to ensure that each sub-cell generates the same current under the simulator as under the reference spectrum is a necessary condition for a reliable IV measurement and accurate efficiency determination.

Adjusting the spectrum as accurately as possible is especially important if perovskite sub-cells are involved. While the non-limiting sub-cell operates always at a positive voltage close to its V_{OC} , the limiting sub-cell experiences a large voltage range up to negative voltages during an IV sweep. Due to the presence of mobile ions in the perovskite absorber, this can lead to a large hysteresis in case of even a slight perovskite limitation; while the hysteresis vanishes already for a slight silicon limitation [4]. Thus, a slightly incorrectly adjusted spectrum might lead to large effects in the measured hysteresis, when the tandem solar cell is optimized to be current matched under the AM1.5g spectrum.

Moreover, there are more difficulties for the measurement of perovskite-based multi-junction (as well as perovskite single-junction solar cells) due to mobile ions which lead to dynamic effects affecting the *IV* results. This needs to be considered when interpreting and reporting the data. The preconditioning and the scan speed of the *IV* sweep play an important role and can influence all *IV* parameters (j_{SC} , V_{OC} , FF , P_{MPP}) and the hysteresis [1, 4, 6, 12, 21].

It is difficult to define one standard recipe for the *IV* measurement of perovskite-based solar cells as the perovskite absorbers can differ significantly concerning composition and ion types, so that there can be time effects which are different by orders of magnitude between different perovskite solar cells. That means, it is questionable if measuring different perovskite solar cells with the same recipe leads to a fair comparison between the solar cells as they might be under different conditions, closer or further away from a steady state depending on the ion diffusion constants. A new standard measurement procedure might be defined for every new perovskite absorber and every cell architecture. This is time-consuming because a large range of parameters (scan speed, precondition) must be checked. This could be feasible in production lines, however, it is challenging in research labs, where materials and cell designs are often changed. Additionally, especially for solar cells in an early development stage, transient/reversible effects might overlap with degradation.

3 External Quantum Efficiency / Spectral Response Measurements

3.1 Results from the Round Robin Carried out in TRIUMPH

Within the round robin carried out in TRIUMPH, EQEs have been measured in different laboratories in addition to the IV curves shown in the previous chapter. Again, the same III-V on silicon triple-junction devices have been used for this. Figure 4 shows the results first as measured and second normalized to the highest measured value for each sub-cell.

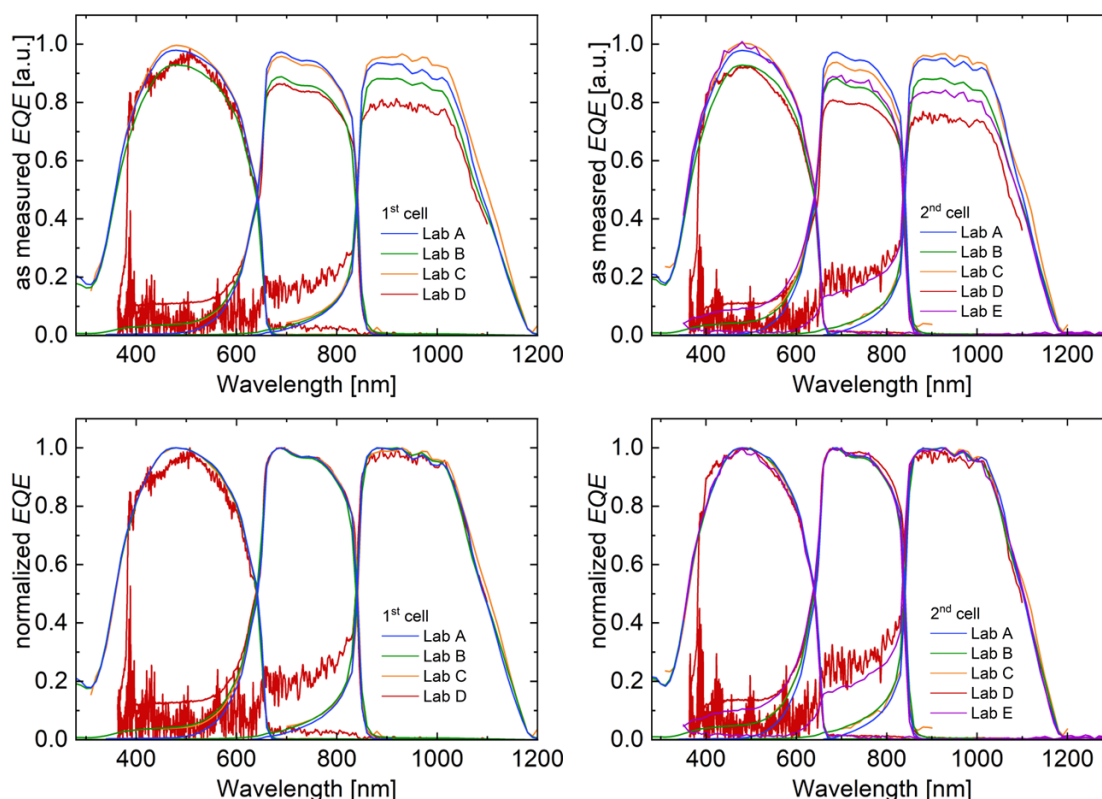


Figure 4: As-measured and normalized EQEs measured in different laboratories within the TRIUMPH round robin.

The as-measured EQEs differ significantly between the laboratories. The difference in height can be up to 10%. However, the normalized values show similar results, ignoring some noise in the data of Lab D. Thus, while the relative EQEs are in good agreement, the absolute EQEs do not match. This is a clear hint that measured EQEs are not absolute and should thus not be integrated to determine sub-cell current values or determine the current-matching situation. The reasons for that will be discussed in the next section. There are also some artifacts visible (EQE signals in a wavelength range where there should be no signal for the measured sub-cell) which can occur if a sub-cell has a low parallel resistance, an early reverse breakdown of the limiting sub-cell or when luminescent coupling is present [9, 22]. They can be mathematically corrected [23], which is exemplarily done for some of the curves in the next section.

3.2 Problems with Integration of Measured EQEs

Measured EQEs of perovskite/silicon multi-junction solar cells are often integrated to determine current density values of the different sub-cells. However, this would require absolute EQEs which are nearly impossible to measure for perovskite/silicon tandem solar cells due to several reasons.

Measuring an absolute EQE is already challenging for single junction solar cells [24]. For multi-junction solar cells, the sub-cell to be measured needs to be brought in short-circuit conditions, which is realized by a bias voltage. However, the sub-cell voltages cannot be determined individually in monolithic multi-junction devices, and the operational point can differ from the actual sub-cell short-circuit condition. This can lead to measurement artifacts and a wrong absolute value of the EQE if the measured sub-cell has a non-ideal behavior, as for example a low parallel resistance or a low reverse breakdown voltage [9], which is often the case in perovskite/silicon multi-junction solar cells. Luminescent coupling effects can lead to similar effects [22]. These artifacts can be mathematically corrected [22, 23]. However, also the correction factors have uncertainties, and the presence of multiple artifacts can complicate the procedure. Additionally, the sub-cell may exhibit a non-linear SR.

Additionally, inhomogeneity effects can affect the absolute value of the EQE. In laboratory setups, the measurement spot in the EQE is often smaller than the active solar cell area. The position where the EQE is measured on an inhomogeneous cell can also have an influence on the height of the EQE as could be shown experimentally and by simulation [18]. Furthermore, local shunts can lead to a different ratio between measured and artifact signal, so that the artifact correction can still lead to an incorrect height of the EQE [18].

Figure 5a shows again the measured EQE of a III-V/III-V//Si triple-junction solar cell (1st cell of the TRIUMPH round robin) measured in the three different laboratories Lab A, Lab B and Lab C). Significant artifacts can be seen in all measurements in the top and middle cell range (i.e., EQE signals in wavelengths where there should be no signal for the measured sub-cell). After an artifact correction according to [23], the EQEs have been integrated to determine the current densities of the sub-cells (Figure 5b). It can clearly be seen that there are strong deviations between the three measurements up to ~10% (comparing the integrated j_{sc} of the bottom cell between Lab B and Lab C). It can also be seen that the ratio between the current density values is not the same for the three laboratories. The EQE of Lab A is always between the two others, however for the top cell it is very close to the EQE of Lab C, while for the bottom cell it is closer to the one of Lab B. Thus, the assumption that measured EQEs are absolute is wrong and can lead to misinterpretations, even for a stable III-V on silicon multi-junction solar cell. However, the normalized EQEs show a good agreement (Figure 5c). An adjusted spectrum for a solar

simulator has been calculated based on the EQE of Lab A and the corresponding current ratios ($j_{SC, Simulator} / j_{SC, AM1.5g} = \int sr E_{Sim} d\lambda / \int sr E_{AM1.5g} d\lambda$) for all sub-cells are indicated in the graph. E_{Sim} and $E_{AM1.5g}$ are the simulator and the AM1.5g spectrum, respectively. Note again that only relative spectral responses denoted by sr are needed here, the absolute height is cancelled out. For Lab A, the mismatch factors are logically all 1.000 as this EQE was used for the calculation. But also, for Lab B and Lab C they are all clearly lower than 1%. Thus, all EQEs could be used for the spectral adjustment of a solar simulator and would fulfill the spectral requirement defined in the standard IEC 60904-1-1.

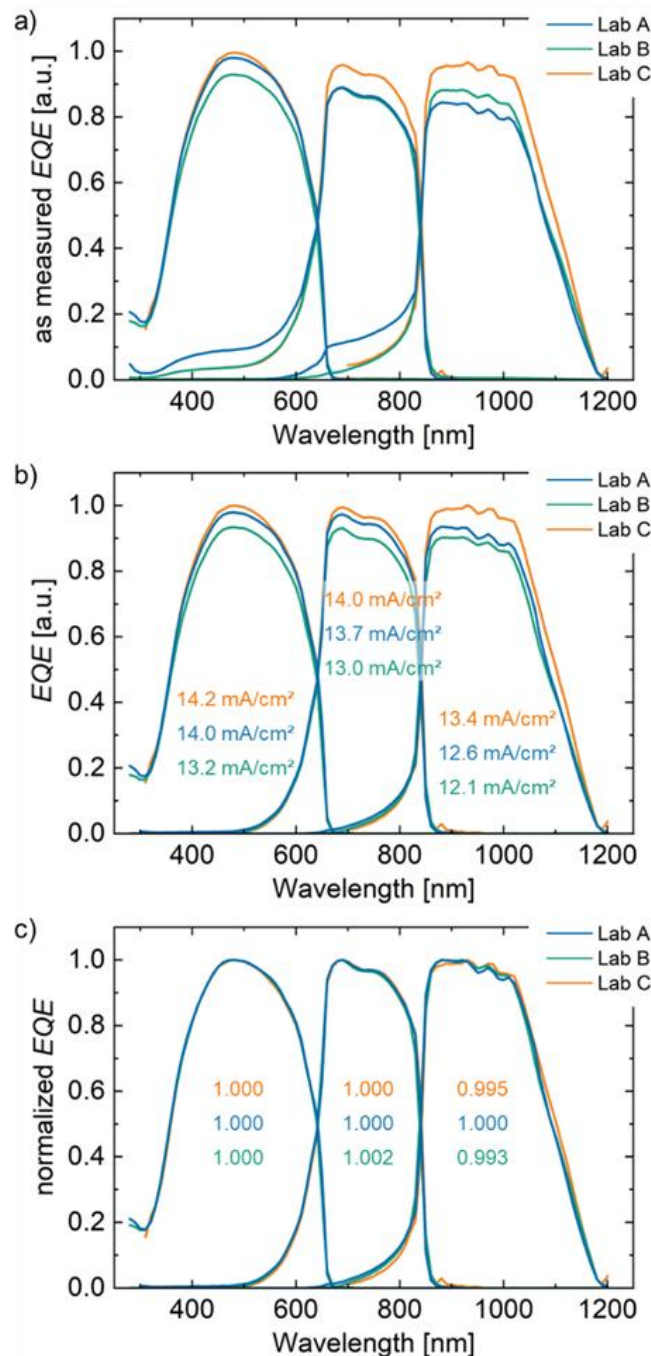


Figure 5 a) as measured EQEs in three different laboratories Lab A, Lab B and Lab C. Clear artifacts are visible in all measurements. b) EQEs after artifact correction. The integrated current density values show strong

deviations between the laboratories. c) Normalized EQEs after artifact correction. The relative EQE (shape of the EQE) is in good agreement between all labs. The current ratios (current under the simulator spectrum divided by current under the AM1.5g spectrum) calculated for a solar simulator spectrum determined based on the EQE from Lab A are <1% for all sub-cells for the measurements from all laboratories.

So far, the discussion has been focused on multi-junction solar cells in general. If perovskite is involved, additionally, dynamic effects can influence the EQE. A difference between j_{SC} determined from IV scans and from integrated EQEs has often been seen for perovskite single-junction solar cells [25]. There are several publications from different research groups which show that the height of the EQE of a perovskite solar cell can be dependent on measurement conditions, such as bias light intensity or chopper frequency [26–28]. Thus, for perovskite-based multi-junction solar cells an additional problem occurs. Measured EQEs from perovskite based multi-junction solar cells should never be integrated to determine sub-cell current density values or determine the current matching situation.

For that purpose, it is recommended to use spectrometric characterization as already mentioned in the introduction. IV curves are recorded for systematically varied spectral conditions calculated based on relative EQEs [5, 8]. However, the data recorded must be evaluated carefully for non-ideal solar cells, for example if a sub-cell has a low parallel resistance or a low breakthrough voltage [29].

4 Conclusions

In this work, two key aspects of global characterizations of multi-junction solar cells have been addressed: the proper spectral adjustment of a solar simulator to obtain a reliable IV curve, and the problems with assuming that measured EQEs are absolute. Although these aspects are well known in the III-V community, such errors still occur in the perovskite community, making it necessary to rediscuss and emphasize these points.

For an accurate IV measurement of a multi-junction solar cell, the solar simulator spectrum should be adjusted so that all sub-cells generate the same current under the simulator as they would do under a reference spectrum (mostly the AM1.5g spectrum for the terrestrial perovskite-based multi-junction solar cells). Generally, this condition is not fulfilled by a default A+ spectrum. If this requirement is not considered, large measurement uncertainties can occur as was shown in theoretical considerations and experimental results obtained from a round robin carried out within the TRIUMPH project.

Measuring an absolute EQE for multi-junction solar cells is nearly impossible, and current densities determined by integrating measured EQEs can lead to strong misinterpretations. The result of the round robin clearly shows that the relative EQE (shape of the EQE) could be well reproduced between different laboratories, but the absolute value strongly differs, even for stable III-V on silicon triple junction solar cells. For the investigation of the current matching situation, spectrometric characterization should be used, which is more time-consuming but more accurate.

For perovskite-based multi-junction solar cells, the situation in IV and EQE measurements becomes even more complex. The metastability of the perovskite leads to dynamic effects which can add further measurement uncertainties. Therefore, it is important to consider these uncertainties in data evaluation and interpretation.

5 References

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