

Imperial College London
Department of Physics

New Techniques for the Measurement of Second and Third Generation Photovoltaics

Mauro Pravettoni

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The author hereby certifies that the work presented in this thesis is of his own and that everything else is appropriately referenced.

Abstract

New generations of photovoltaics (PV) have demonstrated a significant cost-reduction with respect to c-Si wafer-based modules. Though second (thin-film) and third generation PV (high-intensity, low-cost) are already in the PV market, the preparation of standard procedures for their characterization is still ongoing. This work was developed by the author in order to extend some of the existing characterization techniques to a set of three different emerging technologies: multi-junction thin-film modules, concentrator PV cells and luminescent solar concentrators.

An original method for the spectral response measurement of large area thin-film multijunction modules is presented in the first part: the method is validated with several examples. A basic theoretical approach is also presented to propose innovative explanations of measurement artefacts that are observed in the literature.

In the second part of the thesis, the setup, characterization and classification of a high intensity pulsed solar simulator for concentrator PV cells is illustrated. A new procedure for the preparation of a set of filtered reference cells for the irradiance detection at high intensities is also presented, providing an original tool for the verification of the linearity of these devices towards irradiance, which is usually assumed in the literature.

In the third part the performance characterization of high-efficiency luminescent solar concentrators is presented: a simple ray-tracing model and its experimental validation, the impact of backside diffusive reflector on the performance of this kind of devices are mainly highlighted.

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Dedication

To Luciana and Giuseppe

“CLAUDIUS: How is it that the clouds still hang on you?
HAMLET: Not so my lord; I am too much i' **the sun.** ”

W. Shakespeare, Hamlet, 1600

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Chapter 1

Introduction

1.1 Global Energy Perspectives for the 21st Century and the Role of Photovoltaics

In their several hundred thousand years of history, human beings have lived for long time in a kind of “ecological symbiosis” with the environment, getting from the sun all the energy they needed [1, 2]. In the very early stage, they had not yet discovered fire and had access only to the food they ate: their energy consumption has been estimated at around 2000 kcal per day [3].

Emancipation from this primitive conditions went on across centuries, from the Mesopotamian civilizations to the Roman Empire buildings, roads and aqueducts and through the 15th century’s technological developments. But it was the so-called Industrial Revolution (18th-19th Century, with the invention of steam engine) that saw a big improvement in the energy consumption pro capita, which raised above 50,000 kcal per day.

In 1859 E. L. Drake started drilling oil for energy production purposes in Titusville, Pa, USA. The wide consumption of oil and fossil fuels in the 20th century brought an impulsive improvement in living conditions. According to the historical data reported in the 2010 International Energy Outlook by the U.S. Department of Energy [4], each

American consumed in 2007 more than 230,000 kcal of energy per day (a hundred times more than that of the primitive man). The European in the same year performed on the average “more environmentally”, consuming less than half (105,000 kcal pro capita per day). Considering the entire world, including third-world and developing countries, the average daily consumption in 2007 decreases to about 51,000 kcal, approximately the same as in the UK and central Europe just after the invention of the steam engine.

It is well known that the expected parallel increase in world population and world energy consumption, especially those lead by the two giants China and India (or “Chindia”, according to J. Ramesh, [5]), is a serious challenge for the global energy production and the availability of appropriate energy solutions. Concerns about the global warming and oil depletion (see Ref. [6]) led the European Union (EU) on June 2009 to issue the new Directive on the “Promotion of the Use of Energy from Renewable Sources” [7]. According to this directive, each member state has a target calculated according to the share of energy from renewable sources in its gross final consumption for 2020. This is in line with the overall “20-20-20” goal for the Community:

“saving 20% of the EU’s primary energy consumption, a binding target of 20% reduction of greenhouse gas emissions and 20% renewable energies by 2020”,

according to the official Communication from the Commission [8]. Furthermore,

“both greenhouse gas emission reduction and the renewable targets trigger energy efficiency improvements and, conversely, ambitious action on energy efficiency will greatly help achieve the EU’s climate objective, notably under the effort sharing decision. If the saving objective of 20% is met, the EU would not only use about 400 Mtoe less primary energy but it would also avoid the construction of about 1000 coal power units or half a million wind turbines. CO₂ emissions reduction would be about 860 Mton”.

Photovoltaics (PV), the subject of this thesis, will be a key-technology option to realise the shift towards a decarbonised energy supply [9, 10].

The PV industry has emerged from the semiconductor industry which has transformed communications and computation and has the potential to transform electricity generation as well. It is among the fastest growing industries, having seen an increase in worldwide production since 2000 with annual growth rate between 40% and 80% [11]. In 2009, despite the world economy crisis, it increased again by more than 50%, reaching a volume production of 11.5 GWp of PV modules. Analysts forecast the market volume to reach 40 billion euros (35 billion pounds) in 2010 and prices for consumers are constantly decreasing, boosted by the thin-film PV market.

New technologies are also entering in the PV market, thus enabling further cost reduction [12, 13]. Concentrating PV (CPV) is an emerging market, with a still small market share, but an increasing number of companies that are focusing on it, attracted by the possible positive income in geographic areas of high direct normal irradiance (DNI), such as the Sun Belt in the US and the Mediterranean. In 2008 about 10 MW of CPV only were produced, but about 100 MW are expected by the end of 2010. In addition, potentially inexpensive PV devices (such as dye-sensitized solar cells, DSSC, and organic PV) are also entering the market.

Apart from an expansion of silicon production capacities to ensure the appropriate feed-stock, the following pathways have been recently pursued: (a) reducing material consumption (i.e. higher efficiencies, thinner c-Si wafers); (b) developing high-efficient multi-junction thin-film modules; (c) accelerating the CPV reliability, through higher efficiencies and improved solar tracking technologies; (d) developing novel low-cost semiconductive materials that do not require elaborate manufacturing apparatus.

These pathways retrace the historical development of PV, as discussed in the next sections.

1.2 Brief history of PV

The PV effect was first observed in 1839 by the French physicist Alexandre-Edmond Becquerel (the father of Henri Becquerel, Nobel laureate with Pierre and Marie Curie for the discovery of radioactivity). Forty years later Adams and Day observed the PV effect in a sample of selenium when contacted by two heated platinum contacts. The other milestones in the development of PV devices across the 19th and the 20th centuries are illustrated in Figure 1.1 and compared with a selection of major historical events.

In 1954 the first *mono-crystalline Silicon* (c-Si) PV cell was produced by Chapin, Fuller and Pearson with a significant record efficiency of 6%. During the energy crisis of the 1970s, the interest in PV grew, together with research and development both in c-Si and other materials. This rise in interest led to overcome the 20% efficiency barrier in 1985 [18] and to the search for new materials with either low-cost or higher efficiencies. How this latter aspect led to the development of the so-called “second” and “third generation PV” is discussed in section 1.4.

Since the 1950s however, what has been called later on the “first-generation PV” basically refers to c-Si, by far the most prevalent bulk material for solar cells. Currently the record of efficiency for a c-Si cell is the 25% cell developed by the University of New South Wales, Sydney, measured in 1999 at Sandia National Labs [19, 20].

c-Si has diamond-like structure based on sp^3 bonding, good electrical properties and it is easily dopable. The process developed by Czochralski in 1918 to grow cylindrical c-Si ingots is the most commonly used. A second procedure, called *float-zone growth*, can yield higher purities and therefore higher efficiencies. Starting from large blocks of molten silicon carefully cooled and solidified leads to the so-called *multi-crystalline Silicon* (mc-Si), also belonging to the “first generation PV” group: a material consisting of a number of small silicon crystals (grains) grown together to form multi-crystalline wafers.

In the next subsection the basic characteristics of a typical c-Si PV cell are summarized, together with important definitions of electrical parameters that are required tools for the

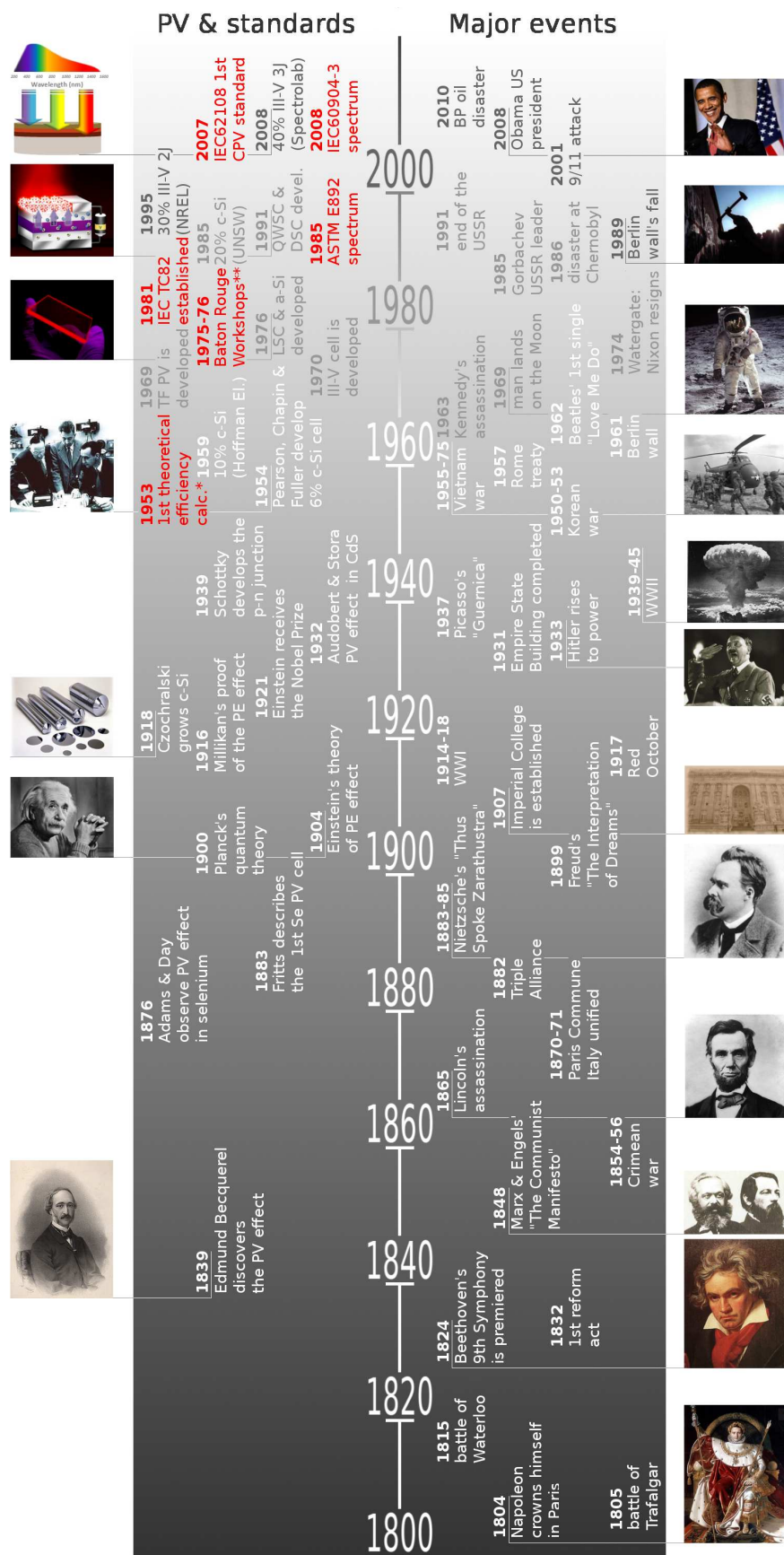


Figure 1.1: PV history timeline: comparison with major historical events (source: [14, 15]). In red developments in the standardization of PV are shown.

* See Trivich [16]. ** See the workshop report [17].

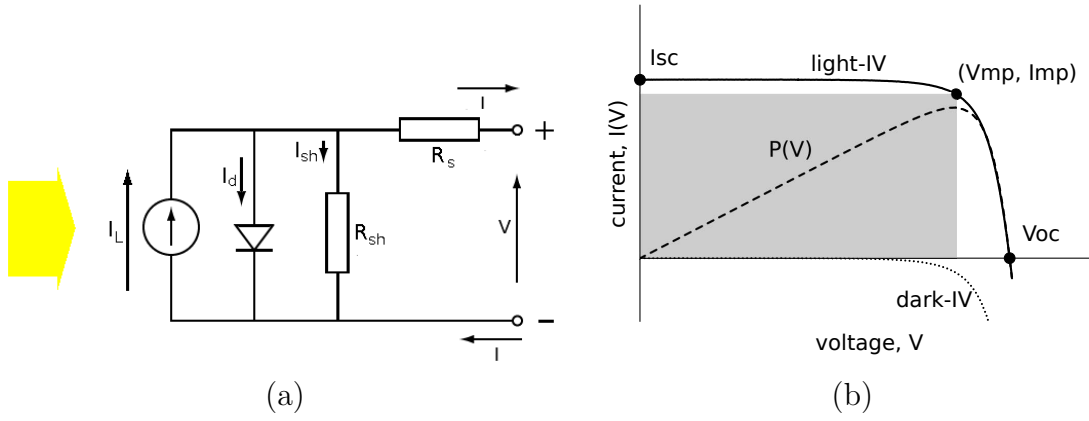


Figure 1.2: (a) Equivalent circuit of a PV cell (*single diode model*). (b) Current-voltage characteristics of a PV cell as an ideal diode in the light (*light-IV*), in the dark (*dark-IV*, dotted line) and power produced as a function of voltage $P(V)$ (dashed line).

analysis in the next chapters.

1.3 Characteristics of a PV cell

A PV cell is a two terminal device that conducts like a diode in the dark and generates a photovoltage when it is illuminated [21, 15]. The top surface is usually anti-reflection coated in order to reflect as little visible as possible, appearing black or dark blue.

When illuminated, depending from the bandgap of the material a single PV cell generates in open-circuit a certain DC voltage (*open-circuit voltage* V_{oc} : 0.7 V for c-Si, 1.0 V for GaAs) and, in short-circuit, a certain current (*short-circuit current*, I_{sc}) of several milliamperes per square-centimetres, depending on the material and its quality.

To a first approximation the PV cell behaves as a source of current in parallel with an ideal diode, plus two parasitic resistances (Figure 1.2a): a parallel resistance (*shunt resistance*, R_{sh}), taking into account the leakage of current through the depletion region of the *pn* junction, plus leakages around the cell edges and between contacts; and a *series resistance* R_s that arises from the cell material resistivity in its neutral *p* and *n* regions and from resistive contacts.

Consider first the *single diode model* when $R_s = 0$ (negligible series resistance). Via *Kirchhoff's Current Law*, the total output current $I(V)$ is given by

$$I(V) = I_L - I_{sh}(V) - I_d(V) \quad (1.1)$$

where I_L is the *photogenerated current* and is equal to the current when $V = 0$ (*short-circuit current*, I_{sc}); $I_{sh}(V)$ is the current flowing through the shunt-resistance and is given by *Ohm's law*

$$I_{sh}(V) = \frac{V}{R_{sh}}. \quad (1.2)$$

$I_d(V)$ is the *dark current*: in the dark, the PV cell as a diode admits a large current flow, opposite to the photogenerated current, when it is biased in one direction (also referred to as *forward bias*, $V > 0$) and a smaller or even negligible current flow in the opposite direction (*reversed bias*, $V < 0$). The dark current is given by the *Shockley's non-ideal diode equation*

$$I_d(V) = I_0 \left[\exp \left(\frac{qV}{nkT} \right) - 1 \right] \quad (1.3)$$

where I_0 is a constant (the *reversed saturation current*), q is the elementary charge, n is an *ideality factor* that quantifies any non-ideal diode behaviour, k is Boltzmann's constant and T is cell temperature.

In the general case where R_s is not negligible, the voltage V needs to take also into account the voltage drop across the series resistance: V is therefore replaced in eqs. (1.1-1.3) by $V + IR_s$. An efficient cell has negligible R_s and high R_{sh} .

For any intermediate load resistance R , the cell produces a voltage across the terminals between 0 V (short-circuit, zero load resistance) and V_{oc} (open-circuit, infinite load resistance) and produces therefore a current $I(V) = \frac{V}{R}$. I and V are determined both by the total incoming irradiance and by the load: the curve $I(V)$ characterizes the PV cell and is therefore referred to as the *current-voltage characteristics* (or *light IV curve*, see Figure 1.2b). If the IV curve is measured in the dark, then the dark current only is measured (plus the current flow across the shunt resistance) and it is referred to as the *dark IV*

curve.

In its operating regime between 0 V and V_{oc} the PV cell delivers a positive power $P(V) = I(V) \cdot V$ (dashed line in Figure 1.2b). $P(V)$ increases linearly with V for lower voltage biases, then reaches a maximum at the *maximum power point* (MPP) $P_{\max} = I_{mp} \cdot V_{mp}$.

For any real PV cell is $V_{mp} < V_{oc}$ and $I_{mp} < I_{sc}$: the *fill factor* FF , defined by

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}} \quad (1.4)$$

is a key parameter in evaluating the performance of solar cells and describes “how rectangular” is the IV curve. Commercial PV cells have typically $0.70 < FF < 0.90$.

The *cell efficiency* η is the ratio between the incident power P_{inp} and the power delivered by the cell and can thus be written as follows

$$\eta = \frac{I_{mp}V_{mp}}{P_{inp}} = \frac{I_{sc}V_{oc}FF}{P_{inp}}. \quad (1.5)$$

1.3.1 Standard test conditions

The quantities just introduced (I_{sc} , V_{oc} , $P_{\max}$ and η) illustrate the electrical characteristics of a PV cell. To be able to compare the performance of different PV products, it is important to refer to these quantities once they have been measured in some particular, internationally defined and recognized, standard conditions.

The *standard test conditions* (STC) define the commonly accepted conditions at which standard electrical characterization needs to be performed and referred to. For current-voltage characterization of 1st generation PV cells, these conditions are 1000 Wm^{-2} total irradiance, global air mass 1.5 spectral irradiance (AM1.5g) as defined in the international standard IEC 60904-3 [22] and $T = 25^\circ\text{C}$ cell temperature.

1.4 Towards New Generations of Photovoltaics

Single-crystal c-Si cells are expensive and their circular geometry may lead either to large losses of efficiency once assembled on a module, or loss of materials when cut in a square shape: commercialized c-Si modules have efficiencies between 14% and 19%. mc-Si modules are a little cheaper but also generally less efficient.

Figure 1.3 illustrates the efficiency of a selection of several modules on the market, as a function of the cost per area (spot prices in Germany, January 2010 [23, 24]). The blue area (cost per area higher than 150 \$m⁻² and efficiencies less than 20%) groups the modules that have been referred to as 1st generation PV [25].

The green area (cost per area less than 150 \$m⁻² and efficiencies less than 20%) represents the so-called 2nd generation PV, while the red area (cost per area less than 200 \$m⁻² and efficiencies higher than 20%) the 3rd generation PV.

1.4.1 Second generation PV

Second generation PV is a synonym of thin-film PV. Regardless the materials involved, thin-film PV offers a huge reduction in prices thanks to less material and the low-cost growing technique. These techniques allow to increase easily the size of the PV cell deposited, thus reducing the cost-per-area of the 2nd generation PV below 100 \$m⁻².

On the other hand, for example in amorphous silicon (see Figure 1.4), the lack of purity leading to intrinsic defects (*dangling bonds*) and an increase of recombination centres. As a consequence, several different aspects (shorter diffusion lengths, presence of defect states in the band gap, increased resistivity, Staebler-Wronski effect,...) arise, typically causing a reduction in the thin-film PV module performance (hence the lower efficiencies of 2nd generation products in Figure 1.3).

Thin-film PV cells and modules have been developed since the late 1960s: the best developed materials at present are *hydrogenated amorphous silicon* (a-Si:H, or simply *amor-*

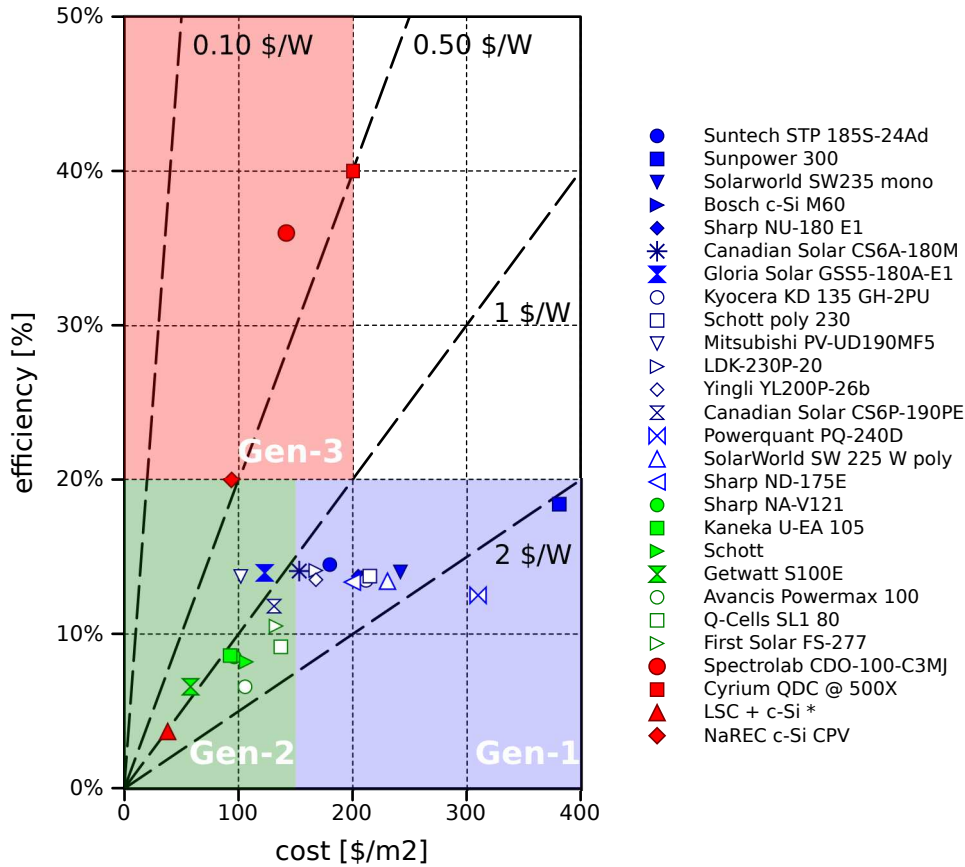


Figure 1.3: Efficiency of PV devices versus cost: module spot prices for selected models (Germany, January 2010, [23, 24, 26]). Full blue markers: c-Si; empty blue: mc-Si; full green: a-Si compounds (a-Si, a-Si/a-Si, a-Si/ μ c-Si); empty green: CIS, CIGS, CdTe, CSG; full red: concentrator PV (CPV) cells (source: [27, 28, 29]). Definition of the three generations of PV is provided according to Ref. [25]. CPV data include the cell cost only. * The cost of luminescent solar concentrator (LSC) includes the cost of the concentrator and has been estimated assuming geometric gain $G = 10$ and high efficiency c-Si cell spot price [30].

phous silicon, a-Si), *microcrystalline silicon* (μ c-Si: a mixed phase material of small crystallites of silicon, 10-100 nm size, embedded in an amorphous matrix), cadmium telluride (CdTe) and copper indium diselenide alloys (CIS and CIGS with the addition of gallium).

Multi-junction thin-film PV modules have also emerged as low-cost solutions with efficiencies well above 10%. Double (a-Si/a-Si and a-Si/ μ c-Si) and triple-junction (a-Si/a-Si/a-Si:Ge) thin film modules are already on the market, showing great interest from the consumer.

The record efficiency thin-film modules to date are listed in Table 1.1.

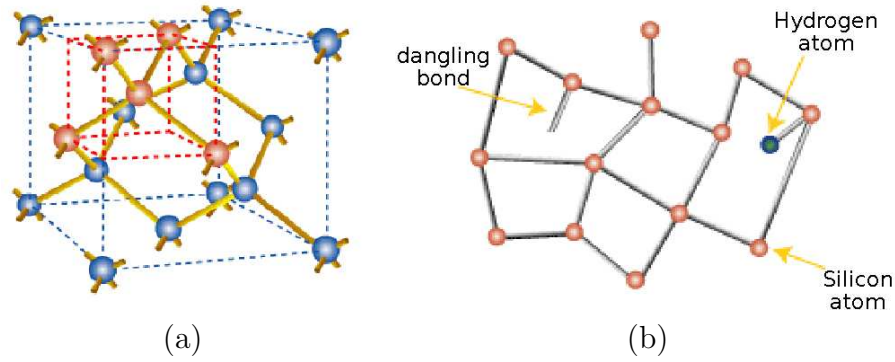


Figure 1.4: (a) The basic unit of a crystalline silicon (c-Si) solid; (b) The random structural characteristic of amorphous silicon (a-Si). Source: *The Encyclopedia of Alternative Energy and Sustainable Living*, [31].

material	efficiency	cell area [cm ²]	manufacturer	year	ref.
CSG	$(8.2 \pm 0.2)\%$	661	Pacific Solar	2002	[32]
CIGS	$(15.7 \pm 0.5)\%$	9703	Miasole	2010	[33]
CdTe	$(10.9 \pm 0.5)\%$	4874	BP Solarex	2000	[34]
a-Si/a-Si:Ge/a-Si:Ge	$(10.4 \pm 0.5)\%$	905	USSC	1994	[35]
a-Si/ μ c-Si	$(11.7 \pm 0.4)\%$	14.23	Kaneka	2003	[36]

Table 1.1: Thin film record efficiency modules [19].

1.4.2 Third generation PV: high concentration

Going towards 3rd generation PV (red area in Figure 1.3) means basically improve the efficiency above the 20-25% limit of c-Si.

As Figure 1.5 shows, concentrating the light [15] and increasing the number of junctions in a PV cell theoretically increase the limiting efficiency [25], towards the ultimate theoretical limit of about 85% for an infinite number of junctions and at maximum concentration under direct radiation [37].

Concentrating light has indeed a twofold advantage. Apart from increasing the cell efficiency on many crystalline materials, concentrating systems are also compulsory for these cells to be economically feasible, since multi-junction III-V group PV cells are extremely expensive (100,000 \$m⁻² at time of writing). Figure 1.6 shows the cost-efficiency trend of a commercially available cell, at various concentrating ratios.

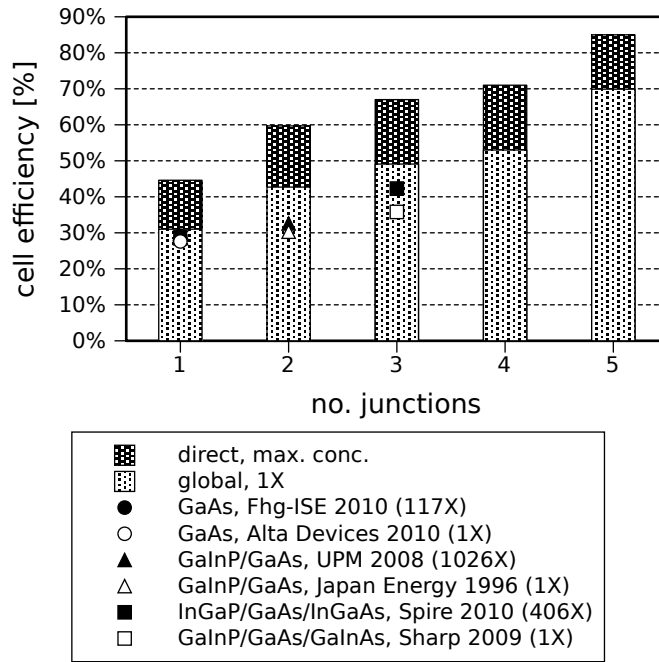


Figure 1.5: Theoretical limiting efficiencies and the most recent record cells. Theoretical limits are calculated in Ref. [37], assuming global normal irradiance at 1000 Wm^{-2} (1X). Record efficiencies are reported in Ref. [38] and refer to AM1.5g (1X) and AM1.5d (under concentration).

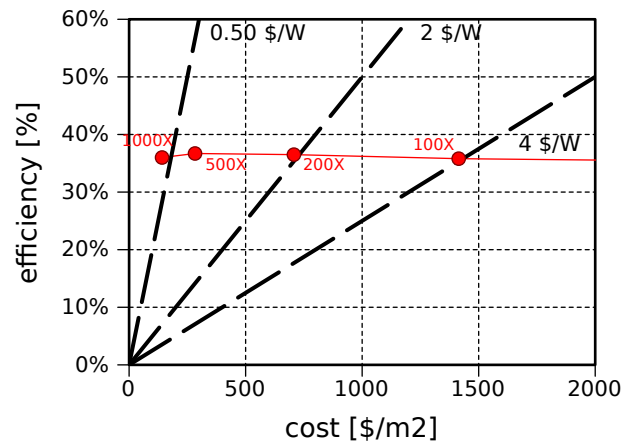


Figure 1.6: Efficiency versus cost of a CPV cell (Spectrolab CDO-100, cell area: 1 cm^2 ; cost: 14 \$ [27]): cost-per-watt dependance on concentration. Ref. [27].

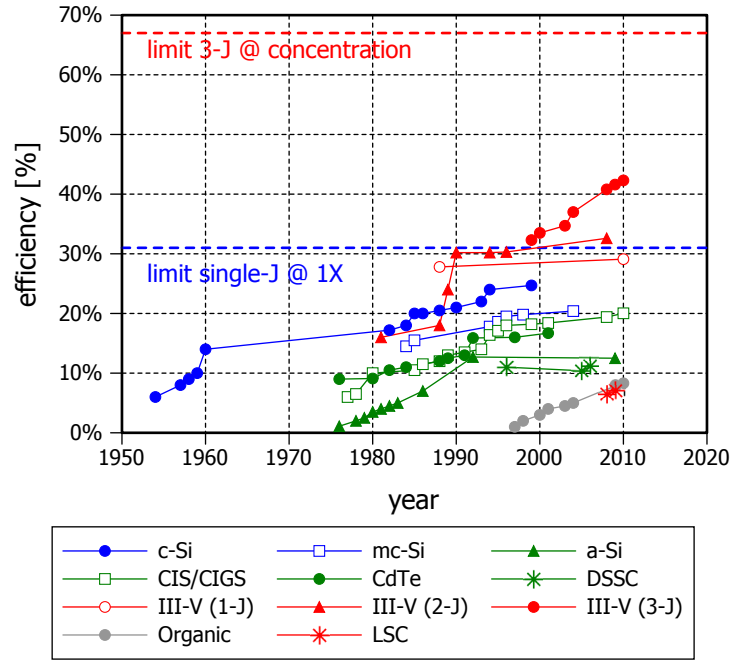


Figure 1.7: Timeline of solar cells. Data for the III-V group cells are generally measured under concentrated light. Theoretical efficiency limits for single-junction non-concentrator cells (in blue dashed line) and for 3-junction concentrators (in red dashed line) are shown [39, 40, 41, 38, 42, 43].

As Figure 1.7 shows, the highest efficiency cells available at present all belong to the III-V group materials. As a result of years of research on the first generation PV, the gap between the theoretical limit and the experimentally reached efficiency is small on single-junction PV cell at 1000 Wm^{-1} global irradiance (“one sun”, 1X), while a larger gap still needs to be step over on multi-junction cells.

To date, the most efficient PV cell at 1X is a monolithic 3-junction GaInP/GaAs/Ge by Sharp, with $(35.8 \pm 1.5)\%$ efficiency [44]. Spire Semiconductor holds the record of efficiency under direct concentrated light to date, with its bi-facial, 3-junction, $(42.3 \pm 2.5)\%$ efficient 2-terminal InGaP/GaAs/InGaAs cell at 406X [45]. 4-Junction, 5-junction and 6-junction PV cells are under development [46, 47, 48] and the trend of production of new CPV cells with higher and higher efficiencies looks promising¹ [49].

¹Such records have frequently been updated in last few years, as can be observed in Figure 1.7. At time of writing the new 43.5% world record has just been announced by Solar Junction, on a 3-junction CPV cell at 400X.

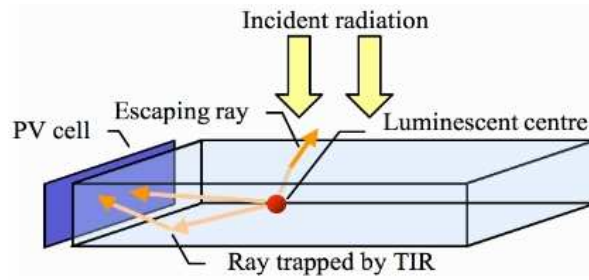


Figure 1.8: The luminescent solar concentrator.

1.4.3 Third generation PV: novel concepts

A group of novel devices can also be classified in the 3rd generation, all sharing the goal of further increasing the limiting efficiency: *intermediate band-gap* [50, 51], *quantum dot* [52] and *quantum well solar cells* [53, 54] are relevant examples.

Static concentrators have also been introduced to both reduce cost and enhance the efficiency of 1st or 2nd generation PV cells and thus should be considered as part of the 3rd generation PV group. As a first example, the *holographic planar concentrator* (HPC, [55]) is an extremely low-cost planar concentrator, increasing the energy seen by solar cells up to 3X, without mechanical tracking or the need for cooling systems. HPC consists of holographic imprinted film, placed in strips along side solar cells. The HPC film diffracts only wavelengths of sunlight that can be converted to energy by the solar cells. This energy is guided, via total internal reflection in the panel, to the cells. HPC technology improves solar module efficiency by: (a) collecting both direct, diffuse and reflected light; (b) keeping cells near their optimal temperature by allowing unusable wavelengths to pass through; and (c) generating more kilowatt hours while using less silicon.

Total internal reflection is also the driving force of *luminescent solar concentrators* (LSC, [56, 57, 58]). In LSCs a refractive material (typically glass or PMMA) is filled with fluorescent particles, either dyes or quantum dots, that absorb photons at certain wavelengths and re-emits photons at higher wavelengths (Figure 1.8). The re-emitted light (luminescent light) is transmitted to the PV cell at edge of the concentrator by total

internal reflection if emitted outside the escape cone, with a gain factor G given by the ratio between the PV cell area and the receiver area. In principle, the spectral range of the luminescent light can be controlled by selecting appropriate luminescent species and the efficiency may be enhanced by reflectors at the rear surface.

There has been renewed research interests in LSCs in last ten years, due to improved luminescent dye life-times and proposals for new luminescence species such as QDs [59].

LSCs are treated in detail in chapter 4 of this thesis, where probably the most relevant result of the author's research work is reported: the pre-normative characterization of a 7.1% efficient LSC module, representing the highest efficiency value among such devices to date [38].

1.5 Standardization in Photovoltaics

As discussed above, PV energy systems have the potential for meeting the world's objectives of sustainable energy supply. The practical, market-driven achievement of this potential depends also upon accurate and standard measurements of performance and degradation mechanisms of different devices and systems, in particular when technology advances rapidly as in PV.

The International Electrotechnical Commission (IEC) is the world's leading organization for the preparation and publication of international standard procedures for all electrical, electronic and related technologies. Founded in 1906, it counts 81 member countries and 174 Technical Committees (TC).

The red entries in Figure 1.1 (p. 29) indicate the historical milestones in the standardization of characterization procedures in PV. Though IEC TC82 ("Solar Photovoltaic Energy Systems", [60]) was established in 1981, the starting point is considered to be the Baton Rouge Workshops by the American National Aeronautics and Space Administration (NASA) in 1975-76, where the definition of standard spectrum and temperature (25°C)

TC82 Chairman: H. Ossenbrink (EU)		
Working Group	Topic	Convenor
WG1	Glossary	H. Shimizu (JP)
WG2	Modules (non-concentrating)	J. Wohlgemuth (US)
WG3	Systems	M. Cotterell (UK), T. Spooner (AU)
WG6	Balance-of-system components	G. Bell (US), V. Salas Merino (ES)
WG7	Concentrator modules	B. McConnell (US)

Table 1.2: IEC TC82 organization chart.

were stated in the Technical Report “Terrestrial Photovoltaic Measurement Procedures” [17].

TC82 is due to prepare international standards for the PV conversion of solar energy into electricity and for all elements in the entire PV energy system. Member countries are 46 (either participants or observers), with 211 experts. The organization chart of TC82 is shown in Table 1.2.

To date standard reference test conditions (STC) have been approved for non-concentrating 1st generation PV only. Dedicated standard methods for 2nd and 3rd generation PV are still on going. Nevertheless, the presence of both CPV and multi-junction thin-film products has already become important on the PV market and the request of new standards is stronger and stronger.

The primary objective of the European Solar Test Installation (ESTI) laboratories within the Directorate General Joint Research Centre (DG JRC) of the European Commission, where the author has spent his part-time doctoral research activity, is to provide the technological basis for a solid and credible assessment of all aspects of PV, assisting both policy-makers and industry, but also organisations for standards and national research agencies. The three-year activity of the author at ESTI has helped to build up excellent links with European universities, research centres and industries.

1.6 Motivations and Objectives

Testing and measuring new generation PV devices is needed to provide a means of assessing performance under controlled conditions and to serve as a research monitor to identify, investigate and support new concepts and technologies. Among a number of different topics where a standard for measurement of novel devices is missing, certain importance has recently grown in spectral response (SR) measurements of multi-junction devices. A method for this kind of measurements is known since the late 1980s [61] and several works in the literature have appeared since. The most important contributions to date are described in the state-of-the-art section of Chapter 2.

A dedicated experimental setup for SR measurement was missing at ESTI at time the author's research activity started: exploring the specific topics of this kind of measurement; investigating over the aspects and measurement artifacts where a full explanation is still missing in the PV community; developing a new setup both for small-size cells and large-area module SR measurements; validating the new setup and testing it with the widest variety of multi-junction CPV cells and thin-film modules; developing appropriate operating instructions for the routine activity at ESTI, in the absence of a dedicated international standard procedure were the main motivations of this first sector of the research activity. The main objectives have been achieved and are part of the thesis: most importantly, new insights on the SR dependence of multi-junction devices with low shunt resistance are given. Part of the activity presented on this research sector has been developed within the Framework VI Integrated Projects (IP) PERFORMANCE [62] of the European Commission.

A second topic where the absence of a dedicated standard sets the need of explorative research at ESTI was indoor IV characterization of CPV cells at high intensities. The Framework VII IP APOLLON [63] funded this second sector of the research, where the main motivation was to set up a high intensity solar simulator, to characterize it and to test it, with a number of CPV cells. The setup, characterization and classification according to the available standards of the first ESTI's high intensity solar simulator are

presented and discussed.

Linearity of the short-circuit current of the testing device with irradiance is usually assumed in the IV characterization of CPV cells. An important objective reached in this second sector is the development of a procedure to test the linearity of CPV cells.

The third and last sector of the research activity is specifically focused on LSCs. ESTI and Imperial College were both partners of the Framework VI IP FULLSPECTRUM [64]. While Imperial College was involved in work package (WP) 4, mainly dedicated to LSC development and modelling, ESTI, being part of WP5 (“Pre-normative work”), was involved in all WPs, providing indications and support to the electrical characterization of products in various WPs. Modelling and indoor/outdoor characterization of LSCs were therefore the motivations of this research sector.

LSCs present several challenges in IV characterization and Monte Carlo modelling has been widely used in the literature since the 1980s for better understanding light dynamics in the device and optimizing the LSC geometry. Thin-film luminescent layer deposition has also been investigated recently as a mean to reduce particle re-absorption: differences between thin-film composite LSCs and homogeneously doped ones has therefore been an objective of study with Monte Carlo modelling technique and experimental verification.

The non-conventional static concentrating configuration set also a series of problems to be solved when trying to apply standard methods of IV characterization. The impact of a backside diffusive reflector on the performance of LSCs and their performance dependence on the incoming light direction were additional motivations for indoor/outdoor measurement campaign. The main objective reached in this sector has been the pre-normative characterization of the most efficient LSC module to date, that has been performed together with partners of the FULLSPECTRUM project.

The final objective in common to all the three sectors was the dissemination of appropriate information to the PV community. Meeting this objective completes also the ultimate goal of ESTI laboratories within the DG JRC: to serve as a European Reference Centre

for PV Solar Energy.

1.7 Structure of the Thesis

There are five chapters in the thesis: after this Introduction, each of the following three chapters presents results and discussion on one of the three research sectors presented above.

In Chapter 1 the three generations of PV are introduced. Motivations and objectives of the thesis are then discussed.

In Chapter 2, which discusses thin-film multi-junction modules, a method for spectral response measurements of multi-junction devices is presented. The chapter includes the description of the new ESTI's experimental setup for spectral response measurements of multi-junction cells and mini-modules. In addition, the proposal of an original technique for the spectral response measurement of multi-junction large-area modules is presented.

In Chapter 3 (CPV) the setup and the characterization of a high intensity pulsed solar simulator is discussed. The classification of the new simulator is presented in detail, via adapting the available standards. The uncertainty analysis and results of the characterization of several CPV cells of various technologies are reported at the end of the chapter and in the appendix.

In Chapter 4 the indoor/outdoor pre-normative characterization of LSCs is presented, paying particular attention to the importance of ray-trace modelling and to the comparison between computational results and experimental data (IV characterization, outdoor performance, cosine response and spectral response, acceptance area definition).

Chapter 5 contains the Conclusions, with the summary of thesis achievements, possible applications and future work.

The state of the art in each of the three main research sectors opens all chapters. The

complete list of all the author's publications in each sector is displayed in Appendix A, at the end of the book together with the other appendices and the bibliography.

Chapter 2

Spectral Response Measurement of Multi-junction Thin Film Solar Cells and Modules

2.1 Introduction

In a multi-junction PV cell, junctions with different band gaps are stacked in optical series. This structure allows the wider band gap material at the top to efficiently collect the higher energy photons; less energetic photons pass through to the smaller band gap materials below (see the simple scheme in Fig. 2.1, where for simplicity each a-Si junction is treated as a 0.8 V battery). As a general result, even if the current is reduced in multi-junction devices, the open-circuit voltage increases, the energy loss by thermal recombination is reduced and thus the cell efficiency is increased.

A common configuration for the electrical connection of the junctions in a multi-junction cell is the “two-terminal monolithic” one: the junctions are grown epitaxially on top of each other and the interconnection is provided by tunnelling junctions between each pair of sub-cells.

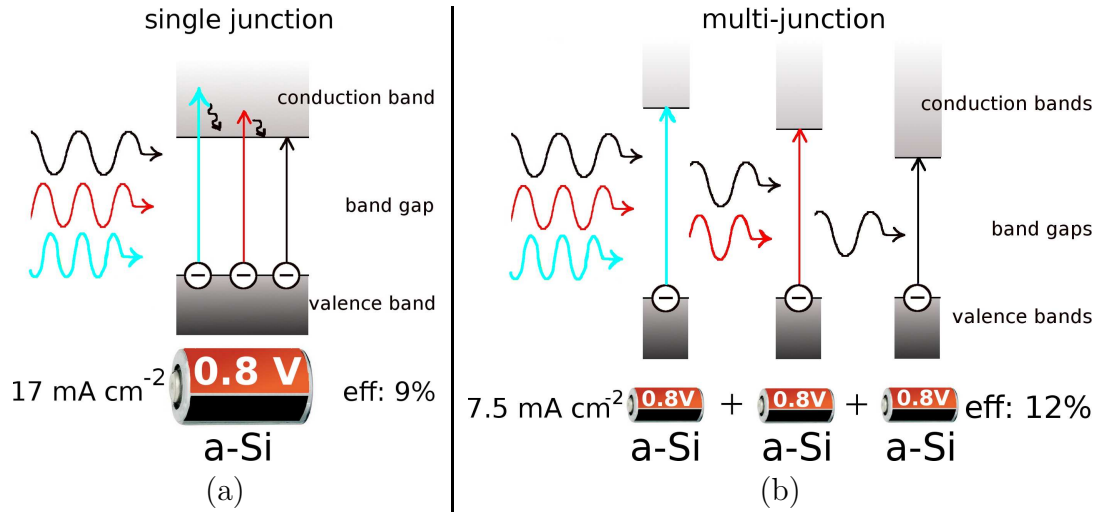


Figure 2.1: Single and a multi-junction PV cells compared with conventional batteries: (a) a single-junction behaves like a single battery, where a significant fraction of the incident power is lost by thermal recombination of high-energy photogenerated carriers; (b) a multi-junction behaves like a series of optimized batteries, producing less current than an equivalent single-junction device, but with higher voltage and better efficiency, due to the reduced thermal recombination. Example data refer to the best recorded efficiencies of a-Si and a-Si/a-Si/a-Si:Ge cells respectively [65].

Multi-junction PV devices were first introduced by E. D. Jackson in 1955 [66] as a means to increase the power conversion efficiency. The most efficient cells currently¹ are the triple-junction cells of the III-V group for CPV (42.3% at 406X on a bi-facial InGaP/GaAs/InGaAs 0.9756 cm² cell by Spire, measured at NREL in 2010 [45]).

Multi-junction structures have helped to increase the efficiencies of non-concentrator thin-film cells and modules as well [19]. The world record 12.5% efficiency of a stabilized 3-junction a-Si cell has been reported by United Solar (measured at NREL in 2007 [67]). The other record efficiency thin-film modules are reported in Chapter 1 (Table 1.1).

This chapter discusses the measurement technique for spectral response (SR) measurements of multi-junction devices. The SR of a PV device is required to calculate the spectral mismatch between the standard reference spectrum and the actual spectral irradiance of the light source in use: this correction can be particularly important for indoor measurements of multi-junction devices on single lamp solar simulators.

¹See the note at p. 37.

Thin-film PV devices only are considered in this chapter: the same measurement technique was applied to multi-junction CPV cells as well, but results are discussed in Appendix E.

2.1.1 Definition and units

The *spectral response* $SR(\lambda)$ (in A W^{-1}) of a PV device is defined as the following ratio

$$SR(\lambda) = \frac{\delta J_{sc}}{E(\lambda)d\lambda} \quad (2.1)$$

where²: δJ_{sc} (in A m^{-2}) is the short-circuit photogenerated current density of the test device, under spectral irradiance $E(\lambda)$ (in $\text{W m}^{-2} \text{ nm}^{-1}$) and in the wavelength band between λ and $\lambda + d\lambda$ (in nm).

If N_e is the total number of electron-hole pairs produced and moving in the external circuit, then

$$\delta J_{sc} = \frac{N_e q}{A dt} \quad (2.2)$$

where $q = 1.602 \times 10^{-19}$ C is the electron charge, A (in m^2) is cell area and dt (in s) is the time interval in which the current-density δJ_{sc} flows. If N_λ is the total number of incident photons at wavelength λ , then

$$E(\lambda) = \frac{N_\lambda h c}{\lambda A dt} \quad (2.3)$$

where $h = 6.625 \times 10^{-34}$ J s is Planck's constant and $c = 2.998 \times 10^8$ m s⁻¹ is the speed of light. From equations (2.1-2.3) the following relation follows

$$SR(\lambda) = \frac{q\lambda}{hc} EQE(\lambda) \quad (2.4)$$

giving SR as a function of the *external quantum efficiency*, $EQE(\lambda) = \frac{N_e}{N_\lambda}$ (in normalized units), i.e. the probability that an incident photon at wavelength λ will deliver an electron-

²Notice the *inexact differential* symbol δ to distinguish between δJ_{sc} (which is just a “small quantity of current density” and not the differential of a function) and for example the *exact differential* $d\lambda$.

hole pair to the external circuit which is collected at the contacts.

Conservation laws require $EQE(\lambda) \leq 1$: in terms of SR this limit gives the following restriction to possible SR values

$$SR(\lambda) \leq \frac{q}{hc} \lambda. \quad (2.5)$$

By inverting eq. (2.1) and integrating over wavelengths, the following useful relation for the short-circuit current, I_{sc} , results

$$I_{sc} = A \int_{\lambda_{\min}}^{\lambda_{\max}} SR(\lambda) E(\lambda) d\lambda \quad (2.6)$$

where the integral is performed in the wavelength band where $SR(\lambda)$ is non-zero. The value of $\lambda_{\max}$ is the absorption cut-off of the PV device under examination and is determined by its band-gap E_g : typical values are 1200 nm for c-Si ($E_g = 1.1$ eV at 300 K), 900 nm for GaAs ($E_g = 1.42$ eV) and 1700 nm for Ge ($E_g = 0.74$ eV).

2.1.2 State of the art

The procedure for measuring the SR of a single-junction PV cell is described in the international standard IEC 60904-8 “Measurement of Spectral Response of a Photovoltaic (PV) Device” [68] and in the ASTM standard E 1021 [69]. The two procedures are based on the *differential spectral responsivity* method (Metzdorf et al. [61]) and shown schematically in Figure 2.2. The total energy of the monochromatic chopped beam is measured by means of a reference cell of known absolute SR. The SR of the test device is then obtained from eq. (2.1). Possible sources of uncertainties in determining the absolute SR of a test device are well described in the cited standards and in Ref. [70]. Temperature and bias light dependence of single-junction SR measurements have been analysed by Müllejans et al. [71].

In a two-terminal multi-junction PV device, due to the series connection of the component junctions, the total incoming spectral irradiance determines which junction limits the total

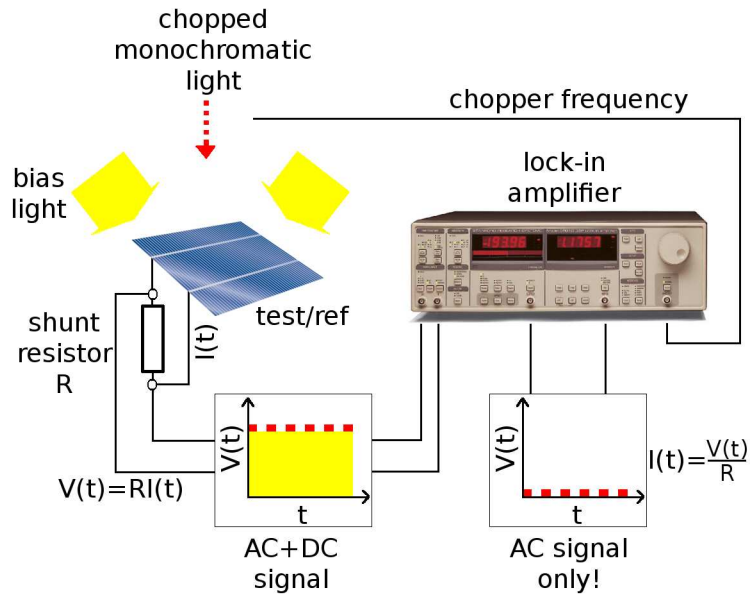


Figure 2.2: SR measurement of single-junction devices. The total current from the chopped monochromatic light and bias light is converted to an AC+DC voltage signal via the shunt resistance R . A lock-in amplifier tuned to the chopper frequency filters out the DC component, giving the AC component only.

photogenerated current. The method of measuring the SR of a single-junction PV cell described in Sec. 2.1.1 can be used in principle to determine the SR of the current-limiting junction, but requires the bias light to “saturate” the junction(s) not under examination, as has been first proposed by Burdick and Glatfelter in 1986 [72] on 2-junction a-Si alloy solar cells. The authors there suggest to use an appropriate bias light, which is absorbed mainly by the junction(s) not under examination so that the current of the entire device is limited and determined by the current-limiting junction. An increase in the intensity of this bias light would not produce an increase in the overall current, hence the term “saturation”.

In 1988 Emery et al. [73] reported for the first time the SR measurements of two-terminal 3-junction PV device (an a-Si/a-Si/a-Si:Ge solar cells).

No international standard procedure currently exists for SR measurement of multi-junction CPV cells, but the ASTM standard test method E2236-05 [74] describes the procedure for SR measurement of nonconcentrator multi-junction devices and discusses the current balance problem, giving indications on how to perform an appropriate spectral mismatch

correction on IV measurements with both a spectrally adjustable and a non-spectrally adjustable solar simulator.

SR measurements of III-V multi-junction CPV devices together with related measurement artifacts have been described by Meusel et al. (providing detailed measurement procedure in an appendix [75]). The same authors have also presented a procedure for spectral mismatch correction [76]. Several improvements have followed these two papers [77, 78], the most recent being the work by Siefert et al. [79], which proposes a new procedure for correcting observed measurement artifacts in the bottom junction SR measurement that may occur in 3-junction GaInP/GaInAs/Ge CPV cells. All these papers underline the importance of applying bias voltage when measuring the SR of the Ge junction in such a device. The same result has also been shown recently by Lim et al. [80], while Li et al. [81] have investigated the possible additional effects of radiative recombination from the junctions above to the junctions underneath. SR dependence on bias voltage of multi-junction thin-film devices has been recently analysed also by Hibberd et al. [82].

The dependence on temperature of the SR of CPV multi-junction cells has been discussed by Kinsey and Edmonson in 2009 [83]: the results have been combined with annual spectral irradiance data, showing that a higher performance may be obtained in CPV if multi-junction cells were designed for an effective air mass, higher than standard AM1.5.

The spectral effects on PV device rating are strictly correlated to SR measurements of PV devices and have been presented in several papers [84, 85, 86, 87]. Effects of poor shunt resistances on dark SRs have been also observed [88, 89, 90].

The SR measurement of a multi-junction large-area thin-film PV module involves additional challenges, since multiple cells are series or parallel connected in one device [91]. An experimental method has been recently proposed by Hishikawa et al. [92, 93], which is similar to the setup developed independently by the author [94, 95, 96].

Section	Page	Content
2.1	45	- Introduction - Definition and units - State of the art - Structure of the chapter
2.2	52	- SR measurements of multi-junction cells - Current limitation - Effect of low shunt resistance - Experimental setup for cells - Results
2.3	72	- SR measurements of multi-junction modules - Experimental setup for modules - Validation of the new setup - Comparison with the state of the art
2.4	89	- Spectral mismatch correction - Results and discussion
2.5	95	- Conclusions
App. B	183	- ESTI's procedure for SR measurements of multi-junction devices
App. C	193	- Uncertainty calculation

Table 2.1: The structure of Chapter 2.

2.1.3 Structure of the chapter

This chapter is divided in five sections (see Table 2.1). Following this introduction, section 2.2 deals with the main multi-junction SR measurement topics: current limitation and the requirement of coloured bias light; effect of shunt resistances; dark SR and the effect of shunt resistance on dark SR. The experimental setup developed by the author for SR measurements of multi-junction cells and small-size modules is presented in subsection 2.2.4. Results and discussion follow at the end.

Section 2.3 describes a modification of the setup described in the previous section to SR measurements of large-area multi-junction modules. The effect of non-uniformity of monochromatic light onto the testing module is analysed in subsection 2.3.1. Validation of the new measurement procedure is provided and discussed (subsections 2.3.4-2.3.5). At the end of the section, advantages and disadvantages of the novel setup with respect to the state of the art are highlighted (subsection 2.3.6).

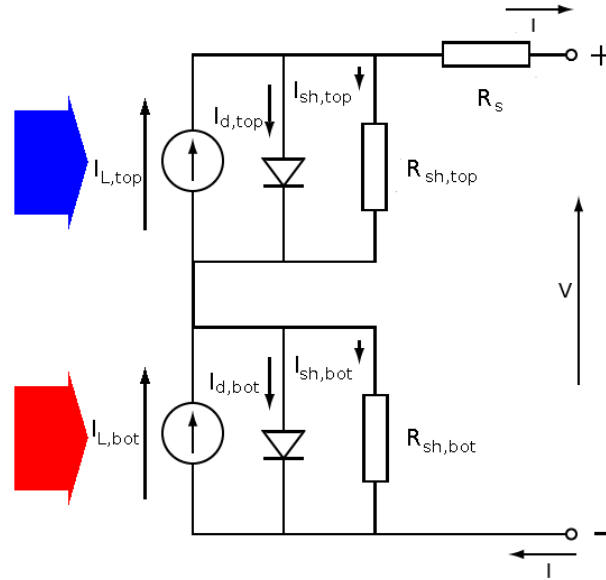


Figure 2.3: Equivalent circuit of a 2-junction PV cell.

Finally a procedure for spectral mismatch correction of the short-circuit current of multi-junction modules is presented in section 2.4. This procedure is applied to several modules; results of indoor characterization are spectrally corrected and compared to outdoor measurements and further improvements to the methods proposed.

2.2 Spectral Response Measurement of Multi-junction Devices

2.2.1 Current limitation in multi-junction PV devices

Consider the electrical equivalent circuit of a N -junction PV cell (see the $N = 2$ example in Figure 2.3). This is a generalization of the diode model for a single-junction PV cell described in section 1.3.

Via *Kirchhoff's Current Law*, the total output current $I(V)$ is equal to the total current

flowing through the i -th sub-cell, i.e.

$$I(V) = I_i(V) \equiv I_{L,i} - I_{sh,i}(V_i) - I_{d,i}(V_i), \quad (2.7)$$

where $I_i(V)$, $I_{L,i}$, $I_{sh,i}(V_i)$ and $I_{d,i}(V_i)$ are the total current flowing through the i -th subcell, its photogenerated current, the current flowing through its shunt resistance and its dark current respectively. The latter two terms depend on the voltage drop across that sub-cell V_i , which is governed by *Kirchhoff's Loop Rule*, giving

$$V_i = V - \sum_{j \neq i} V_j + I(V)R_s. \quad (2.8)$$

Combining the terms gives the following characteristic equation for a multi-junction device

$$I = I_{L,i} - I_{0,i} \left\{ \exp \left[\frac{q(V - \sum_{j \neq i} V_j + IR_s)}{nkT} \right] - 1 \right\} - \frac{V - \sum_{j \neq i} V_j + IR_s}{R_{sh}}, \quad (2.9)$$

which is the generalization to N junctions of eq. (1.1).

In the experimental setups for SR measurement using bias light, chopped monochromatic light and the lock-in technique as described in section 2.1.2, the photogenerated term is $I_{L,i} = I_{bias,i} + \delta I$, where $I_{bias,i}$ is the DC component from bias light and δI is the AC component from the chopped monochromatic beam.

The simplest case $N = 2$ will be considered. Furthermore, in all the following charts the current across the i -th junction is normalized to its photogenerated contribution $I_{L,i}$ and the voltage to the open-circuit voltage $V_{oc,i}$. The shunt resistance is also normalized accordingly, as $\tilde{R}_{sh,i} = \frac{I_{L,i}}{V_{oc,i}} R_{sh,i}$.

Without loss of generality, bias light absorbed by the top junction will be simply referred to as “blue bias light”, while that absorbed by the bottom junction as “red bias light”.

2.2.1.1 Top junction current limiting: infinite shunt resistance approximation

In order to understand the behaviour of a dual-junction cell when a chopped monochromatic beam is superimposed on a steady state coloured bias light, let us first assume the shunt resistances to be high enough to neglect the last term on the right hand side in eq. (2.9) (i.e., $R_{sh,i} = \infty$). The general case where a finite shunt resistance is introduced is studied in two dedicated sections below.

Consider Figure 2.4, where a steady red bias light is an order of magnitude more intense than the chopped monochromatic light. For simplicity, assume the red bias light is absorbed by the bottom junction only.

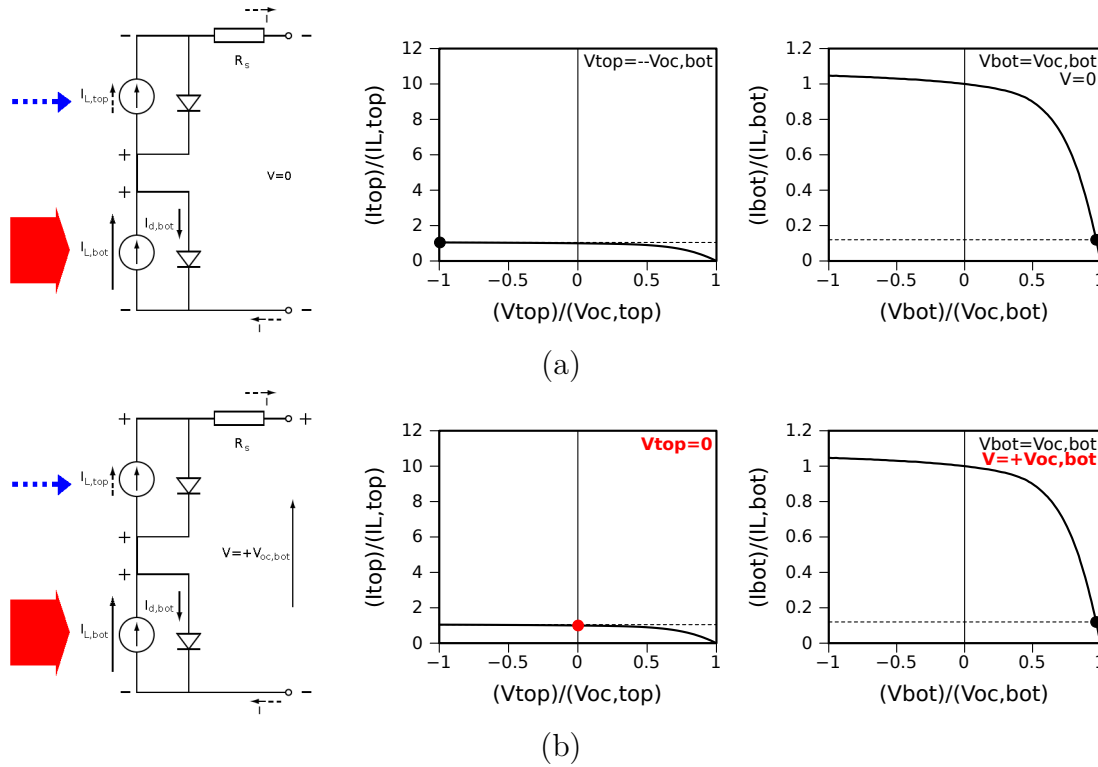


Figure 2.4: Top junction current limiting (red bias light an order of magnitude more intense than the monochromatic chopped beam): (a) no voltage bias ($V = 0$); (b) with voltage bias $V = +V_{oc,bot}$. For simplicity $V_{oc,top} = V_{oc,bot}$ is assumed.

When the chopped monochromatic light is tuned to wavelengths where only the top junction responds (short wavelengths), the small photocurrent produced by the top subcell $I_{L,top} = \delta I$ limits the current flow into the circuit. As a consequence, when the entire cell is in short-circuit (no voltage bias: $V = 0$, Figure 2.4a), the bottom junction is forward

biased approximately to its open-circuit voltage ($V_{bot} \approx V_{oc,bot}$) and its dark current nearly cancels the photogenerated current ($I_{L,bot} = I_{bias,bot} \approx I_{d,bot}$).

The top junction is reverse biased instead at $V_{top} \approx -V_{oc,bot}$. Small variations of the chopped monochromatic light intensity lead in principle to variations to the forward voltage bias across the bottom junction (and therefore to the reverse voltage bias across the top one). However, since near $V_{oc,bot}$ the voltage varies as the logarithm of $I_{L,bot}$, we can assume the voltage drop across both junctions to be constant.

At 25°C, $\frac{kT}{q} \approx 0.026$ V and, for typical cell parameters, the exponential term in eq. (2.9) is negligible when the top junction is reverse biased and the saturation current $I_{0,top}$ flows through the depletion region in the same direction as the photogenerated current, giving a small contribution to the total current ($I(V=0) = I_{L,top} + I_{0,top} = \delta I + I_{0,top}$).

The term $I_{0,top}$ (the reverse bias saturation current of the top junction) is independent of the bias light and therefore represents a DC contribution to the total current. If a lock-in technique is used to detect the AC signal component, that term is filtered out and only the “monochromatic term” δI is detected.

However, the dark current contribution equals zero when the top junction is in short-circuit: therefore when a forward bias $V \approx +V_{oc,bot}$ (also simply referred to as the *voltage bias*) is externally applied to the 2-junction cell (see Figure 2.4b), the total current is $I(V) = \delta I = I_{sc,top}$.

The calculation of the exact value of the voltage bias V to apply is not straightforward. Nevertheless, if $I_{L,top}$ is within an order of magnitude smaller than $I_{L,bot}$, one may conclude that the open-circuit voltages of the two junctions are of the same order of magnitude and the total open-circuit voltage of the cell is $V_{oc} \approx V_{oc,top} + V_{oc,bot}$. Therefore the assumption made in Figure 2.4a that at $V = 0$ V the top junction is reversed bias by a quantity $V_{top} = -V_{oc,bot} \approx -V_{oc,top}$ is reasonable.

2.2.1.2 Bottom junction current limiting: infinite shunt resistance approximation

The same argument of the previous section holds for the bottom junction, when a blue bias light is applied an order of magnitude more intense than the monochromatic chopped light at wavelengths where the bottom junction responds (Figure 2.5).

Similarly, when the top junction is saturated, a forward bias $V = +V_{oc,top}$ may be applied to drive the bottom junction to short-circuit (Figure 2.5b) and in this case the total current is $I(V) = I_{L,bot} = \delta I \approx I_{sc,bot}$.

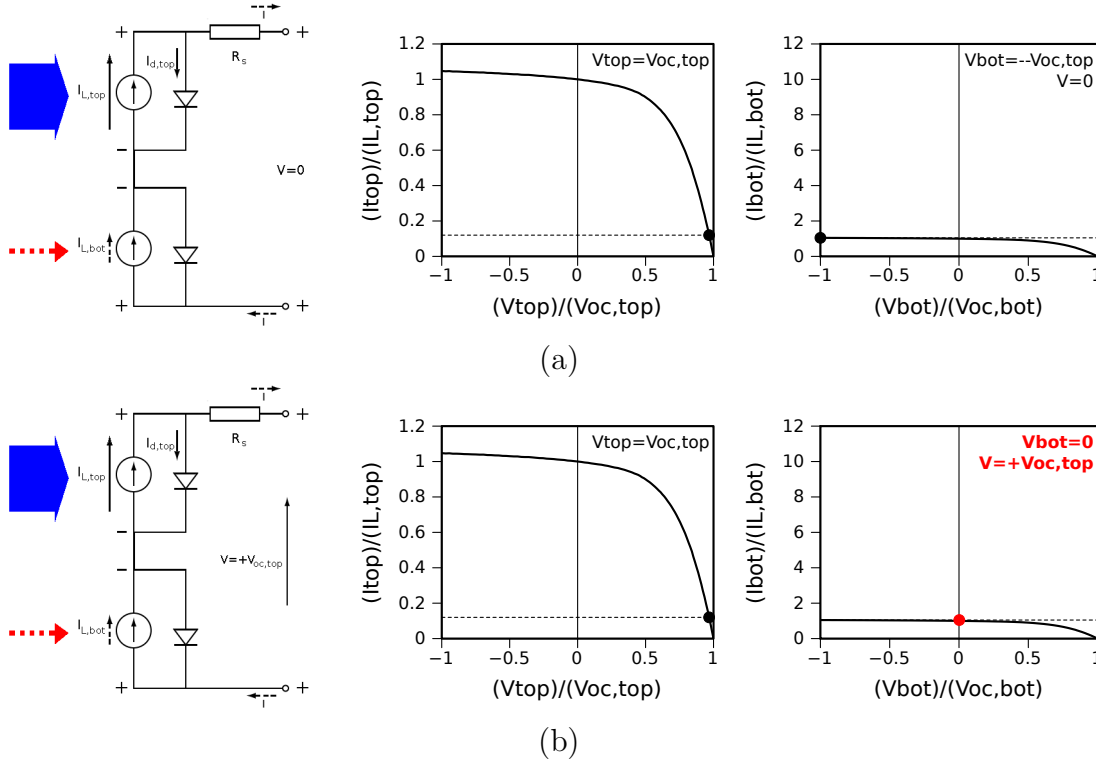


Figure 2.5: Bottom junction current limiting (blue bias light an order of magnitude more intense than the monochromatic chopped beam): (a) no voltage bias ($V = 0$); (b) $V = +V_{oc,top}$. For simplicity $V_{oc,top} = V_{oc,bot}$ is assumed.

In conclusion, when the multi-junction device is in short-circuit conditions, a selected coloured bias light of appropriate intensity may drive the saturated junction to operate near its open-circuit voltage. Thus the current-limiting junction operates in reversed bias, rather than at short-circuit. An additional forward bias voltage should be applied

to the terminals of the multi-junction device to drive the junction under examination to short-circuit.

A reasonable choice for the bias voltage in a 2-junction device is $V = \frac{1}{2}V_{oc}$, where V_{oc} is the open-circuit voltage of the cell under the given bias light system in use. In the general case of a N -junction PV cell, the voltage bias choice should be

$$V = \frac{N-1}{N}V_{oc}. \quad (2.10)$$

2.2.2 The effect of finite shunt resistances

Consider the 2-junction cell described above in the general case when a finite shunt resistance term is added to the top junction and the bias light to the bottom junction is slightly more intense than that to the top junction ($I_{bias,top} < I_{bias,bot}$). In this section the effect caused by the shunt resistance is quantified analytically. For simplicity only the top junction current-limiting case will be treated, $R_s = 0$ and $R_{sh,bot} = \infty$.

The IV characteristic is given by eq. (2.7), which is applied here to the top junction. When a chopped monochromatic “blue” light is added, the current flowing to the external circuit at $V = 0$ is $I(0) = I_{bias,top} + \delta I - I_{d,top}(V_{top}) - I_{sh,top}(V_{top})$. Assume $\delta I \ll I_{bias,bot} - I_{bias,top}$ (see Figure 2.6a).

The chopped blue monochromatic light drives the bottom junction to forward bias $V_{bot}(I + \delta I) = V_{bot}(I) - \delta V$ and at $V = 0$, the top junction is reverse biased at $V_{top}(I + \delta I) = -V_{bot}(I + \delta I) = -V_{bot}(I) + \delta V$. The AC term δV can thus be calculated from the IV equation for the bottom junction giving

$$\begin{aligned} V_{bot}(I + \delta I) &= \frac{nkT}{q} \ln \left[\frac{I_{bias,bot} - I_{bias,top} + I_{0,bot}}{I_{0,bot}} \right] + \\ &+ \frac{nkT}{q} \ln \left[1 - \frac{\delta I}{I_{bias,bot} - I_{bias,top} + I_{0,bot}} \right] = \\ &= V_{bot}(I) - \delta V, \end{aligned} \quad (2.11)$$

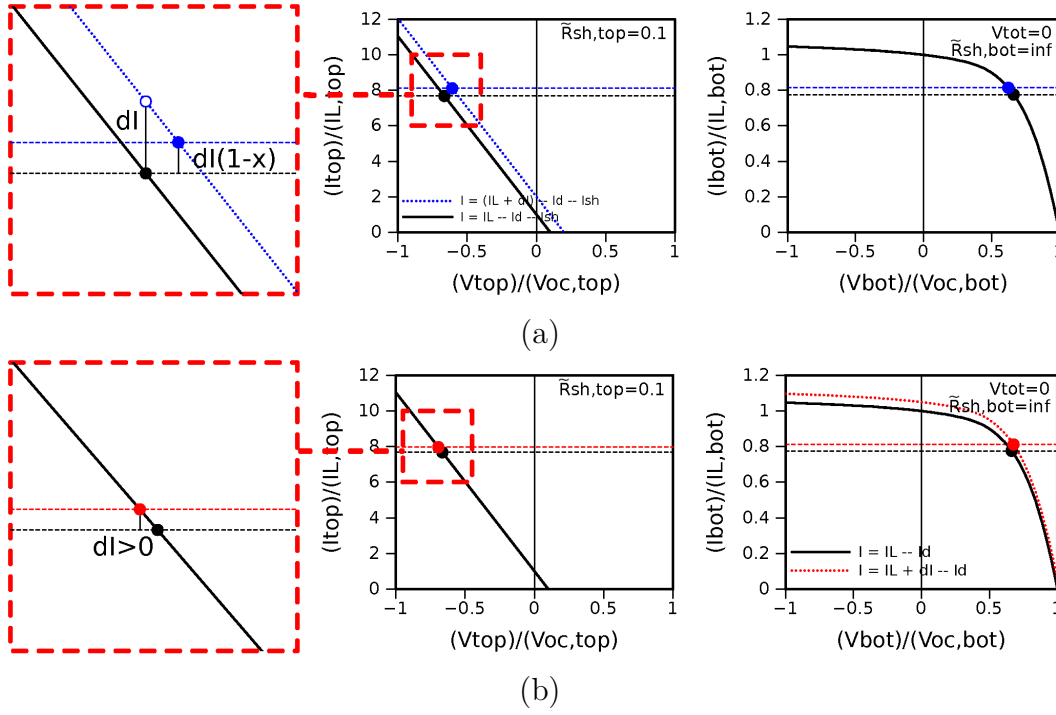


Figure 2.6: Top junction current limiting: (a) effect of low shunt resistance of the top cell ($R_{sh,top} = 0.1 \frac{V_{oc,top}}{I_{L,top}}$) on its SR at short wavelengths (“blue” chopped monochromatic light); (b) effect on the top junction SR at long wavelengths (“red” chopped monochromatic light). The details show the decrease in the measured signal at short wavelengths ($\delta I (1 - x)$ is the second term on the right hand side of eq. (2.14)) and the non-zero signal at long wavelengths (also referred to as the “SR measurement artefact” in Ref. [75, 79]).

where

$$\delta V = -\frac{nkT}{q} \ln \left[1 - \frac{\delta I}{I_{bias,bot} - I_{bias,top} + I_{0,bot}} \right] = \frac{nkT}{q} \frac{\delta I}{I_{bias,bot} - I_{bias,top} + I_{0,bot}} + O(\delta I)^2. \quad (2.12)$$

Substituting eq. (2.11) into the IV equation for the top junction and neglecting terms smaller than δI , gives finally

$$\begin{aligned} I(0) = & I_{bias,top} - I_{0,top} \left[\exp \left(-\frac{qV_{bot}}{nkT} \right) - 1 \right] + \frac{V_{bot}}{R_{sh,top}} + \\ & + \delta I \left[1 - \frac{I_{0,top}}{I_{bias,bot} - I_{bias,top} + I_{0,bot}} \exp \left(-\frac{qV_{bot}}{nkT} \right) - \right. \\ & \left. - \frac{nkT}{q} \frac{1}{R_{sh,top} (I_{bias,bot} - I_{bias,top} + I_{0,bot})} \right]. \end{aligned} \quad (2.13)$$

At room temperature the exponential terms can be neglected. Assume also $I_{0,bot} \ll I_{bias,bot}$

and thus

$$I(0) \approx \left(I_{bias,top} + I_{0,top} + \frac{V_{bot}}{R_{sh,top}} \right) + \delta I \left[1 - \frac{nkT}{q} \frac{1}{R_{sh,top} (I_{bias,bot} - I_{bias,top})} \right]. \quad (2.14)$$

The lock-in technique filters out the constant term $\left(I_{bias,top} + I_{0,top} + \frac{V_{bot}}{R_{sh,top}} \right)$ and gives the second term, in which the effect due to $R_{sh,top}$ is shown. This term may give rise to a decrease in the current signal measured by the lock-in at short wavelengths (where the top junction is expected to respond, Figure 2.6a) and a non-zero signal at long wavelengths (where it is expected not to respond, Figure 2.6b), giving the measurement artefacts described in Ref. [75, 79].

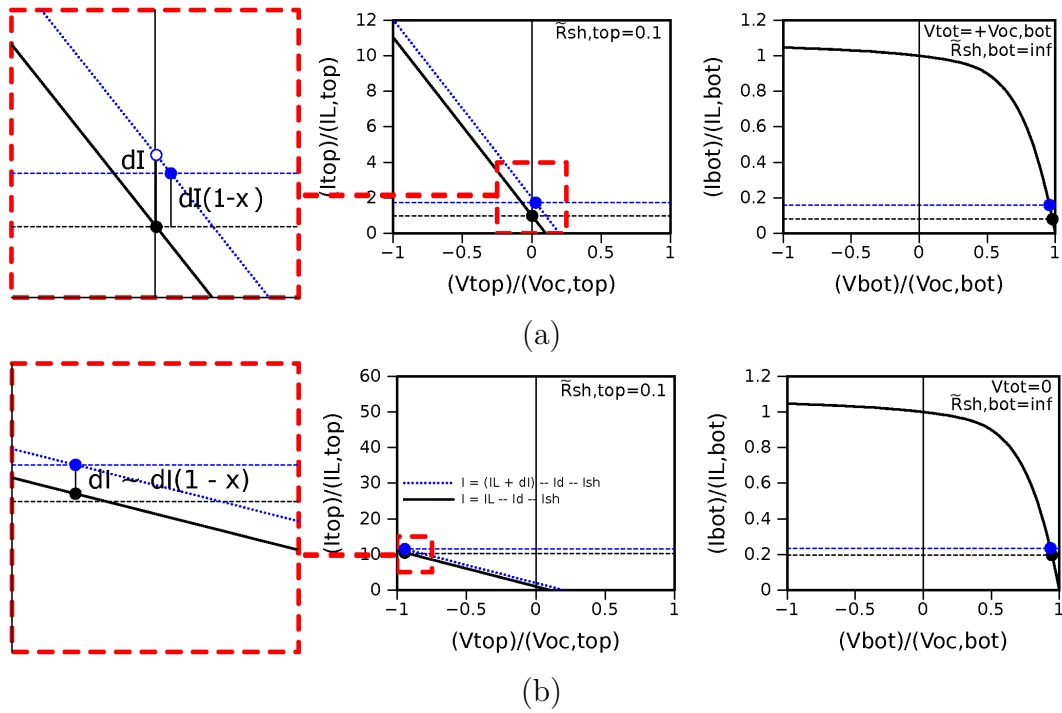


Figure 2.7: Strategies to avoid the SR measurement artefacts: (a) apply a forward voltage bias and (b) increase the red bias light intensity.

These artefacts may be reduced with the following two possible strategies:

- **Apply forward voltage bias** - as discussed in the previous case, this would shift the operating voltage of the top junction near its open-circuit point. However this may be not enough, as Figure 2.7a highlights, if the following additional strategy is not also applied at the same time:

- **Increase red bias intensity** - this would increase the quantity $(I_{bias,bot} - I_{bias,top})$ in eq. (2.14), thus reducing the measurement artefact (see Figure 2.7b, where red bias has been increased to five times its previous value and without application of voltage bias).

Results in Refs. [75, 79] suggest that measurement artefacts that are common for example in the SR measurement of the 3-junction GaInP/GaInAs/Ge cell arise from low shunt resistance of the Ge junction. In these works only the first of the approaches above is stressed.

Shunt resistances are an important determining factor in thin film multi-junction devices. In the next section the peculiar effect of a low shunt resistance on the SR in the absence of bias light (*dark spectral response*) is investigated.

2.2.3 The “dark spectral response” and the effect of shunt resistances

From the analysis of the previous sections, the importance of bias light can be summarised in the following main aspects:

- Bias light drives the test device close to its normal operating conditions.
- Bias light contribution to the total intensity may increase the total photogenerated current to levels where the shunt resistance is high enough to neglect the last term in eq. (2.9). Therefore, at short-circuit, the device responds linearly with increasing irradiance and the absolute spectral response can be obtained by filtering and detecting the additional chopped monochromatic beam.
- In SR measurements of multi-junction devices, bias light is also a tool to “saturate” the junctions not being measured, so that only the SR of the current-limiting junction is detected.

In this section the special case where bias light is not applied is analysed, here also referred to³ as the “dark SR”. Before focusing on the real case of a finite shunt resistance, consider again the ideal case where shunt resistances of all component junctions are high enough that no current leakage occurs through the junctions. For simplicity, the simplest case of two junctions only is considered and no bias voltage is applied. The saturation current contributions $I_{0,i}$ is also neglected.

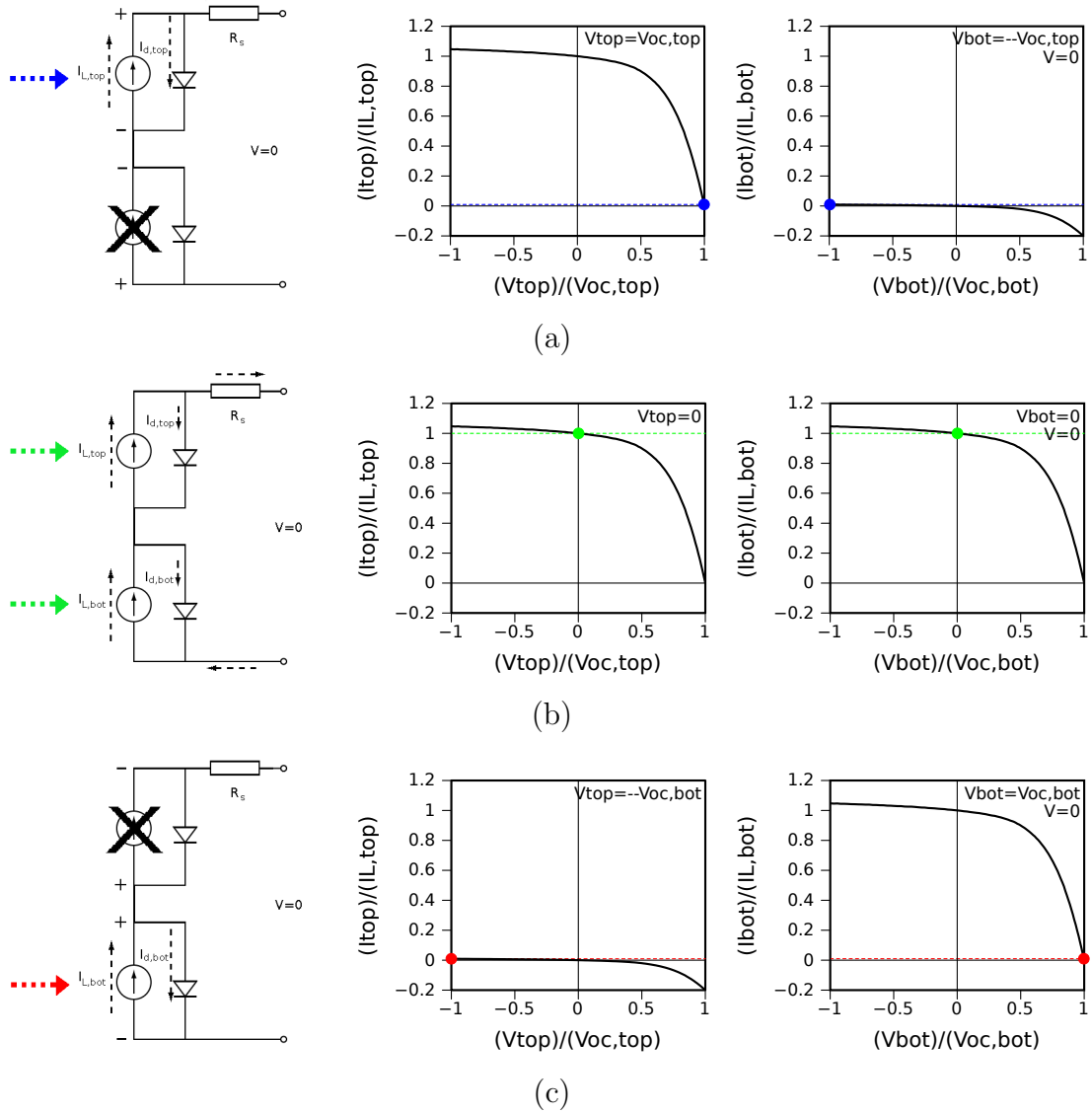


Figure 2.8: Dark spectral response. Equivalent circuit (no bias voltage, $V = 0$): (a) short, (b) middle and (c) long wavelength monochromatic light. Ideal case where $R_{sh,top} = R_{sh,bot} = \infty$.

³Note that unlike the so-called “dark IV curve”, in the “dark SR” light is indeed applied, but only as chopped monochromatic signal.

Figure 2.8 shows the equivalent circuit and the current-voltage analysis of top and bottom junctions in the following three typical situations that may occur:

Short wavelengths: photons are completely absorbed in the top junction only and the bottom junction is in the dark at reverse bias $V_{bot} = -V_{oc,top}$. The top junction is in open-circuit: its dark current $I_{d,top}$ equals the photogenerated current $I_{L,top}$ and no net current flows (Figure 2.8a).

Middle wavelengths: photons are absorbed either in the top junction or in the bottom one. In the particular case where the same fraction of light is absorbed by the two junctions, both of them are in short-circuit and contribute equally to the total current (Figure 2.8b).

Long wavelengths: similarly to the short wavelength case, here photons are absorbed by the bottom junction only; the top junction is in the dark at $V_{top} = -V_{oc,bot}$; the bottom junction is in open-circuit and no net current flows (Figure 2.8c).

When the approximations made above hold, the expected dark SR equals point-by-point the minima of the SRs of the component junctions.

Figure 2.9a shows the current-limiting behaviour in dark SR measurements of an hypothetical 2-junction cell, where top and bottom junctions have a wide overlap in the visible (400-700 nm, e.g. an a-Si/a-Si thin-film device). Both top and bottom junctions have infinite shunt resistances. In this simple scheme, the monochromatic chopped signal is produced at seven different wavelengths: violet (Vi, 400 nm), blue (B, 475 nm), green (G, 550 nm), yellow (Y, 575 nm), orange (O, 600 nm), red (R, 675 nm) and near infrared (NIR, 750 nm). As wavelength increases from Vi to Y, the photogenerated current in the top junction decreases, while in the bottom junction it increases. In the simulation, Y monochromatic light is equally absorbed by both junctions, while the top junction has maximum absorption in the Vi (where the bottom junction is in the dark) and the bottom junction has maximum absorption in the NIR (where the top junction is in the dark). Measurement points are indicated by dots of the appropriate colour and the dashed

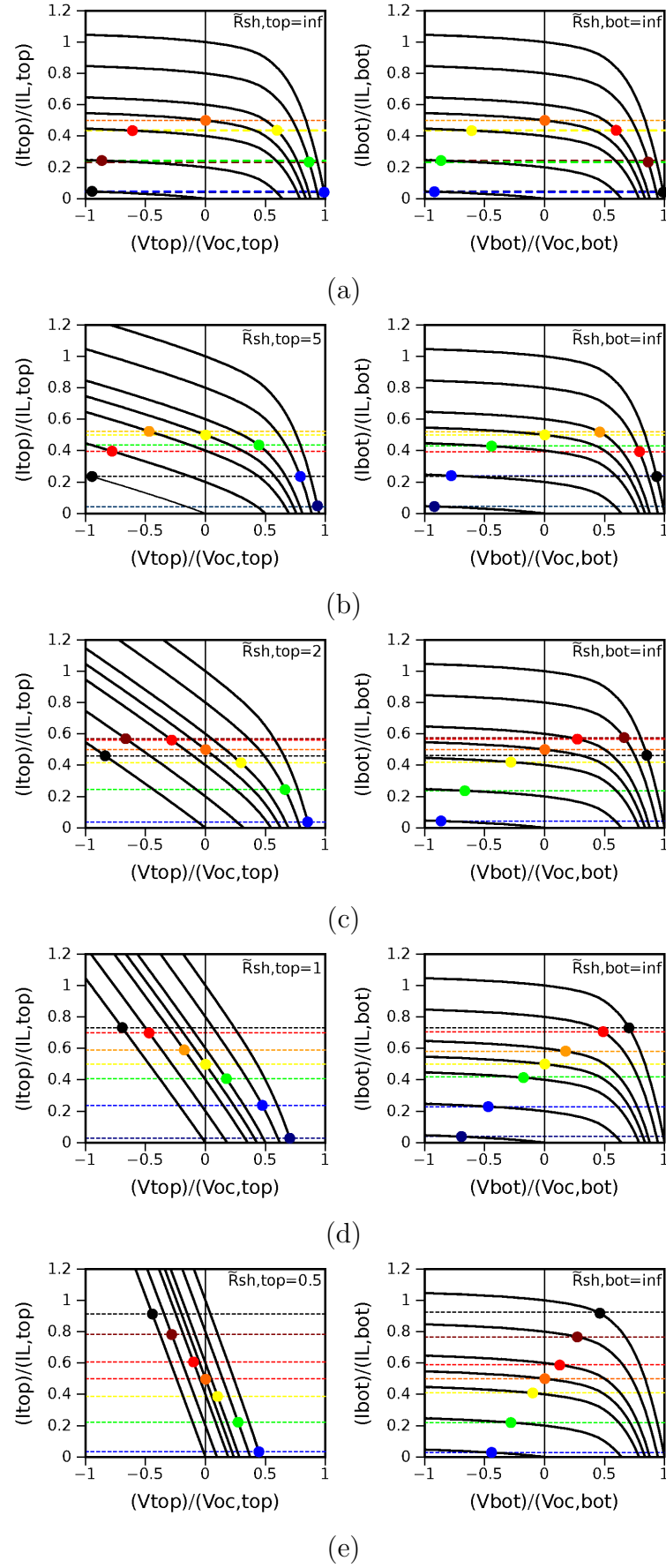


Figure 2.9: Dark spectral response measurement: effect of a different shunt resistances for the top junction ($R_{sh,bot} = \infty$).

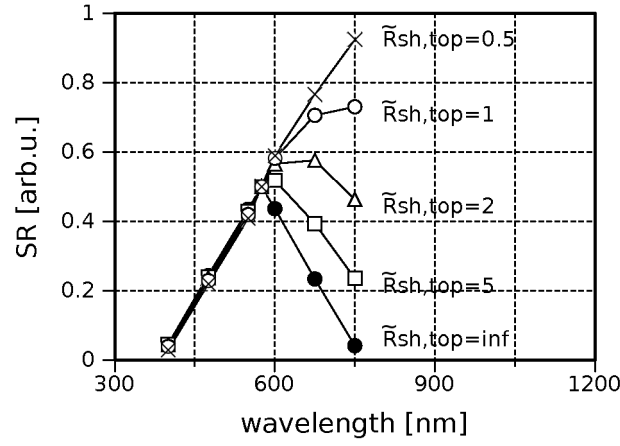


Figure 2.10: Dark spectral response (in arbitrary units) as a result the two-diode model simulation with a finite shunt resistance in the top junction.

coloured lines show the current limitation at each wavelength.

The current values obtained may be plotted as a function of wavelength. Assuming arbitrarily the same power intensity at each wavelength, the plot represents the simulated dark SR (in arbitrary units). The solid dots in Figure 2.10 show the expected triangular shape corresponding to the short-wavelength tail of the simulated bottom junction and the long-wavelength tail of the top one.

The effect of a finite shunt resistance in the top junction has then been modelled in four further simulations (Figures 2.9b-e) where the normalized shunt resistance is $\tilde{R}_{sh,top} = 5, 2, 1$ and 0.5 , respectively.

As the shunt resistance value decreases, the simulated current value at a given wavelength moves from the open-circuit towards the short-circuit point. Furthermore, the simulated current at longer wavelengths increases as shunt resistance decreases, providing evidence of the expected current leakage through the top junction.

The modelled dark SRs of Figure 2.10 show the effect of finite shunt resistances in the top junction as an increasing SR in the long wavelength region. At $\tilde{R}_{sh,top} = 0.5$, the top junction is almost short-circuited and the dark SR nearly equals the expected SR of the bottom junction: in the extreme case where $\tilde{R}_{sh,top} \approx 0$ the device behaves as a filtered

single-junction cell.

Measurements of the dark SR, results of which are presented in section 2.2.5, show similar behaviours to the modelled curves. Deviations from the expected triangular shape have also been described theoretically in the literature [90] and modelled by the presence of thin defective regions perpendicular to the charge transport direction inside the intrinsic layers. These defects are common in a-Si/ μ c-Si thin-film devices (see Ref. [97]).

2.2.4 Experimental setup for cells and small-size modules

Fig. 2.11 shows the scheme of the experimental setup developed by the author for absolute SR measurements of multi-junction cells and small size modules (also referred to as “Oriel setup”, since the light source is obtained from an Oriel small-area continuous solar simulator).

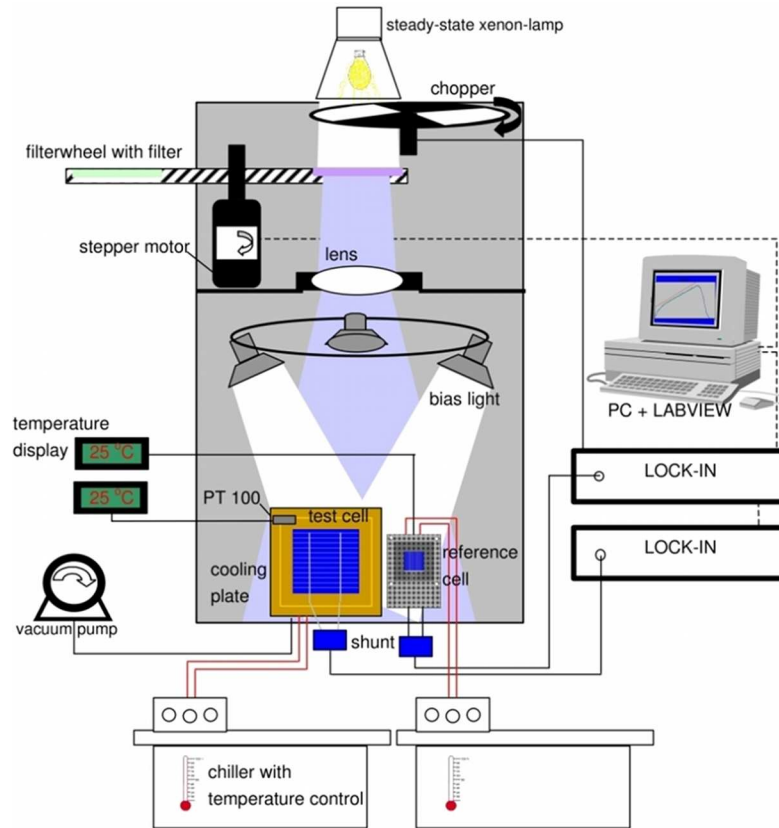


Figure 2.11: Experimental setup SR measurements of cells and mini-modules (also referred to as “Oriel setup”).

A 300 W steady-state xenon lamp provides the source light that is filtered by up to 80 bandpass filters (8 to 20 nm band width; wavelength range: 300 to 1650 nm). Filters are mounted on five filter-wheels to produce the monochromatic light, which is then chopped at a given frequency (typically 70 Hz), superimposed to the continuous bias light and measured by a digital lock-in amplifier (1 mHz to 102.4 kHz frequency range, 2 nV to 1 V sensitivity).

Monochromatic light with $\pm 5\%$ uniformity over a $30 \times 30 \text{ cm}^2$ target area is provided by a lens system and allows simultaneous measurement of a small-size test device and of a reference cell of known absolute SR. The test device and the reference cell are kept at $(25 \pm 2)^\circ\text{C}$ temperature by a cooling plate.

Device currents are measured across a shunt resistor. The resistance value is set in order to maintain the test device in short-circuit. Voltage bias may also be applied and SR measurement is performed as described in section 2.2.1.

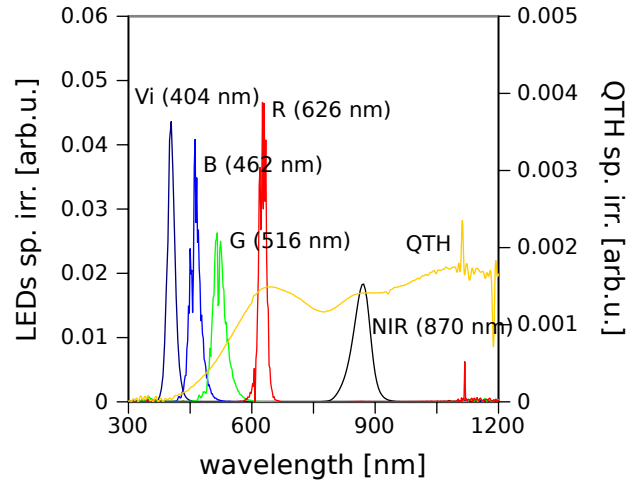


Figure 2.12: Oriel setup: spectral irradiances of bias light lamps used. Spectra have been normalized to the same total irradiance in the range 300 to 1200 nm. A different scale has been chosen for QTH spectrum for comparison, highlighting its large IR content.

Bias light is provided by up to 24 quartz-tungsten-halogen (QTH) lamps and a set of coloured LEDs. Bias light spectra are shown in fig. 2.12. Tab. 2.2 shows the possible choice of bias light system for the saturation of given junctions of several multi-junction PV devices.

junction	wavelength band [nm]	bias light
GaInP (top)	300-600	Vi, B or G
GaInAs (mid.)	600-900	R or NIR
GaAs (top)	300-900	Vi, B, G or R
Ge (bot.)	900-1650	QTH
a-Si (top)	300-700	Vi, B, G or R
a-Si (mid.)	400-700	G
a-Si:Ge (bot.)	500-900	NIR or QTH
μ c-Si (bot.)	600-1200	NIR or QTH

Table 2.2: Bias light: examples of lamp choice for the saturation of typical junctions in multi-junction PV devices.

ESTI code	Num. of junctions	Cell type	Cell area [cm ²]	Module area [m ²]	Cells in series	Cells in parallel
DU06	2	a-Si/ μ c-Si	3.50	0.0014	4	1
	V_{oc} [V]	I_{sc} [mA]	V_{mp} [V]	I_{mp} [mA]	FF [%]	η [%]
	5.194	39.5	4.093	34.5	68.9	9.92

Table 2.3: SR measurement of multi-junction small-size modules: test device specification.

2.2.5 Results

2.2.5.1 Spectral response dependence on bias light spectrum and intensity: current limitation

The SR of several multi-junction small-size modules was measured for the calibration of the experimental setup described above. As an example, results from an a-Si/ μ c-Si small-size module (ESTI code: DU06, tab. 2.3) are presented here.

Fig. 2.13 shows the SR of DU06 measured with six different bias light sources: B, G and R LEDs, QTH and no bias, showing the SR dependence on bias light spectrum.

Fig. 2.14 shows the dependence of the SR of DU06 on bias light intensity. Top (Fig. 2.14a) and bottom (Fig. 2.14b) SRs have been measured at fixed voltage bias and several light bias intensities, varying from the dark SR to the maximum intensity available (approximately 100 Wm^{-2}). While varying the bias light intensity, the junction not being measured is driven to current saturation, when the SR at a given wavelength reaches the plateau shown in Fig. 2.14c-d.

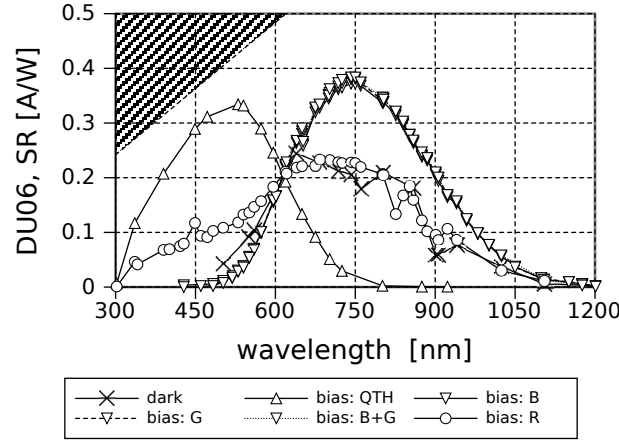


Figure 2.13: Spectral response of DU06 (a-Si/ μ c-Si) with various bias light sources.

2.2.5.2 Spectral response dependence on voltage bias

With fixed coloured bias setup, the SR of both top and bottom junction of DU06 were measured while varying the bias voltage value from 0 to 4 V.

According to eq. (2.10), in order to short-circuit the junction in examination, the bias voltage should be chosen to be close to half the open-circuit voltage of the device, i.e. $V_{bias} = \frac{1}{2}V_{oc} \approx 2.6$ V. Fig. 2.15a-b illustrates SR dependence of DU06 with voltage bias. Fig. 2.15c-d show the SR of the top junction at 530 nm and of the bottom junction at 802 nm respectively, i.e. near the SR maxima, as a function of voltage bias.

2.2.6 Discussion of results

In the measurements described above investigating the effect of bias light and bias voltage intensity, ASTM standard E2236-05 [74] was applied.

The bottom μ c-Si junction of DU06 was saturated by the IR-rich QTH bias light, while the top a-Si junction was saturated by any combination of B and G LEDs. The R LED peak wavelength (626 nm) falls between the two wavelength bands where each junction individually responds: as a result, when R bias light only is applied, the SR almost equals the dark SR.

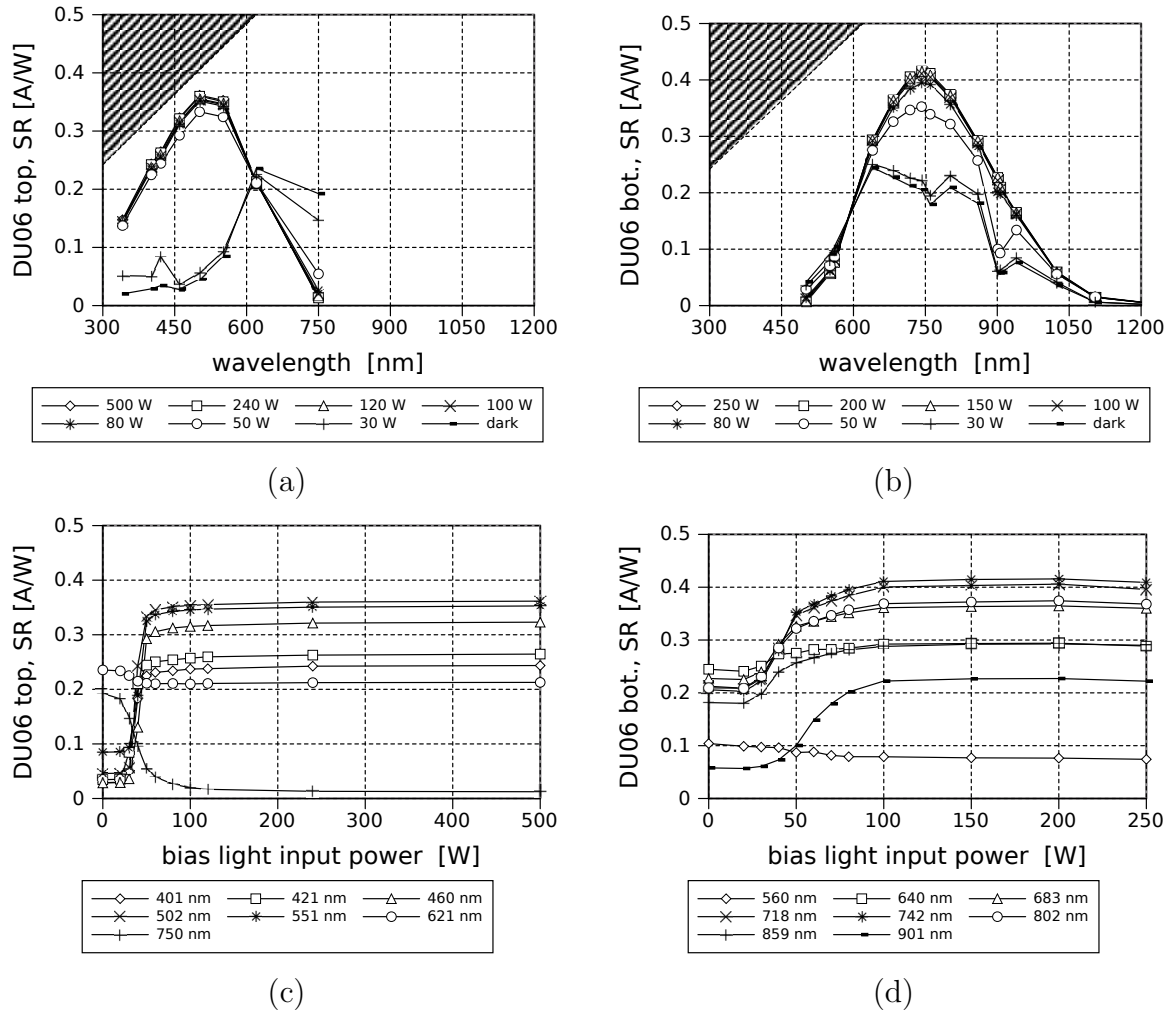


Figure 2.14: Spectral response of multijunction devices: dependence on bias light intensity. (a) top and (b) bottom junction of DU06 (a-Si/ μ c-Si) as a function of wavelength at given bias light intensity; (c) top and (d) bottom junction as a function of bias light input power at given wavelength.

Variation of the intensity of bias light at a given wavelength allows the selection of the minimum intensity where the junction in examination starts to respond linearly. This value sets a minimum requirement for the bias light intensity that should be applied.

The dark SR of DU06 showed a current leakage across the depletion region of the top junction: as discussed in section 2.2.1, this result is caused by a low shunt resistance in the top a-Si junction. From a comparison between Figures 2.10 and 2.13, the shunt resistance of the top junction could be quantitatively calculated (see Ref. [98]).

In the experimental setup described in section 2.2.4, QTH bias light (“red” bias light in

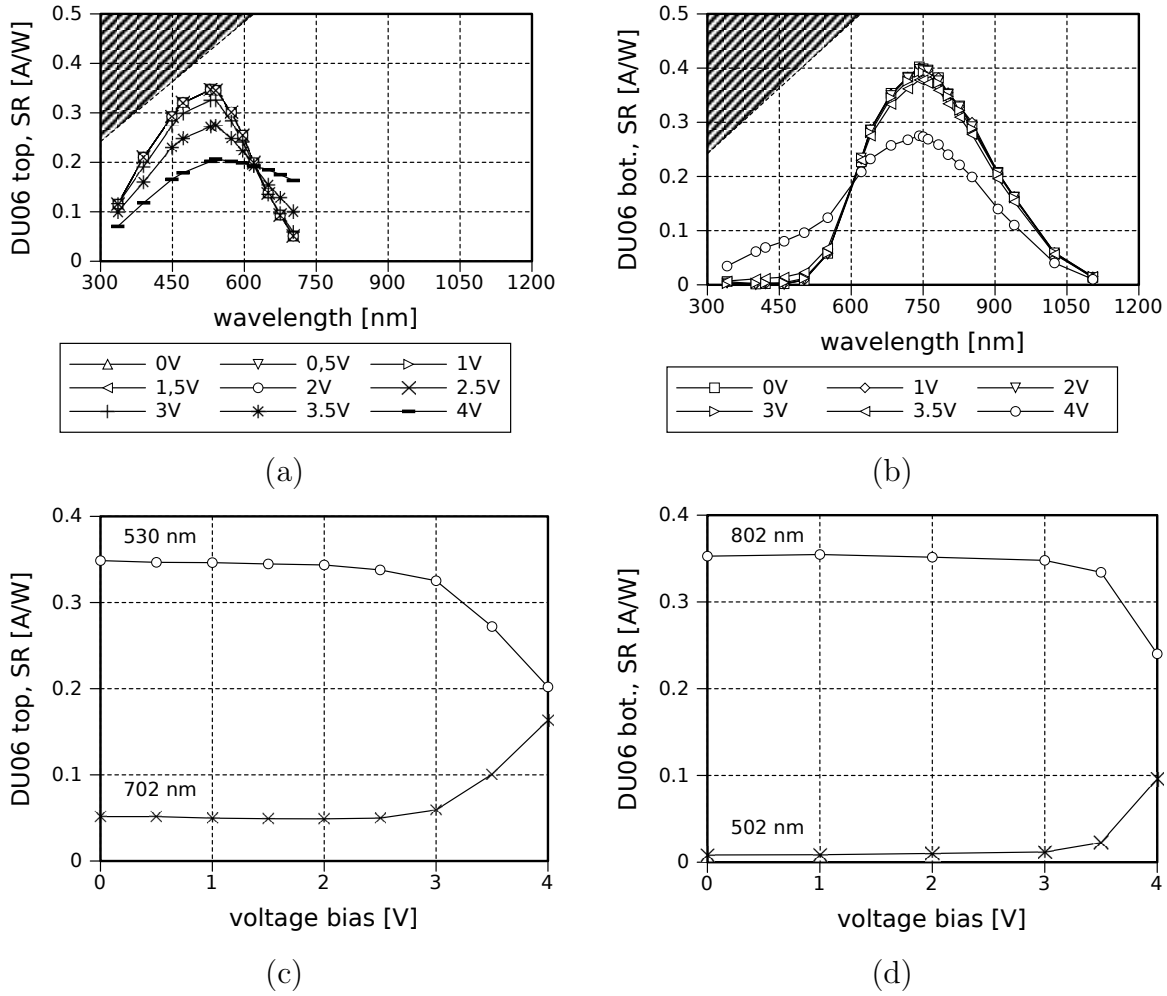


Figure 2.15: Spectral response of DU06 (a-Si/μc-Si): dependence on voltage bias. SR as a function of wavelength, at various voltage bias: (a) top and (b) bottom junction. SR as a function of voltage bias: (c) top and (d) bottom junction.

that case) delivers the equivalent of approximately 100 Wm^{-2} from 300 to 1200 nm and therefore the following values are reasonable approximations (see Table 2.3 on p. 67 for the electrical parameters of DU06 at STC): $I_{bias,bot} \approx 5 \text{ mA}$, $I \approx I_{bias,top} \approx 1 \text{ mA}$, $V_{oc,top} \approx 2 \text{ V}$. The measured AC component of current by the lock-in technique is $\delta I_{meas} \approx 10 \text{ } \mu\text{A}$ at maximum SR. Putting these values in eq. (2.14), the term within the square brackets is equal to 0.993 and thus the measurement artefact gives rise to an underestimation of the top junction SR of less than 1%, when no voltage bias is applied.

The results of bias voltage dependence shows that the best choice according to the standard is $V_{bias} \approx 2 \text{ V}$ for the top junction and $V_{bias} \approx 3 \text{ V}$ for the bottom one. These values correspond to values where the plateau of measured SRs in Fig. 2.15 ends.

However, as predicted theoretically in section 2.2.2, Figures 2.15c-d show no significant variations of top and bottom SR for bias voltage between 0 and 2.5 V. Even if a low shunt resistance in the top junction has been highlighted by the dark SR measurement, there is no evidence of SR dependence on voltage bias and no measurement artefacts were observed. This result confirms the validity of the theoretical approach presented. Though correctly stating the importance of voltage biasing, the standard procedure should therefore highlight the importance of bias light intensity to avoid SR measurement artefacts.

At time the measurements were performed on cells and small-size modules, no experimental setup was available at ESTI for SR measurement of large area multi-junction modules. In order to calculate the spectral mismatch correction of such a device, the approach taken was for the SR of a set of small samples of the same production batch of the large area module to be measured. The SR of the module was then assumed to be equal to the SR of the small samples.

DU06 is such a small sample which was measured for this purpose. Indoor characterization of the large area module has therefore been spectrally corrected and results have been compared with outdoor IV characterization at various irradiance conditions. Results of the comparison have been published by Nikolaeva-Dimitrova et al. [99, 100].

In conclusion of this first part of the chapter on SR measurements of multi-junction cells and small-size modules, Table 2.4 summarizes the comparison between the required components of a SR measurement setup for single and multi-junction PV cells respectively. A set of detailed operating instructions for SR measurements of multi-junction cells and mini-modules have been prepared by the author, taking into account the diode model described above, the results presented here and the other contributions in the literature. The procedure and the related calculation of uncertainty are in use in the ESTI laboratory and are reported in Appendix B and C.

Component	Single-J	Multi-J
Monochromatic Source	bandpass filters or monochromator	bandpass filters or monochromator
Beam chopper	YES	YES
Ref. Cell	YES	YES
Lock-in Amplifier	YES	YES
Bias light	white	coloured
Bias voltage	NO	YES

Table 2.4: SR measurement setup: comparison between the required instrument components for single and multi-junction PV device measurement.

2.3 Spectral Response Measurement of Thin-film Large-Area Modules

2.3.1 Current-limitation in multi-junction modules: the effect of non-uniform monochromatic light

It is not trivial to engineer a monochromatic beam which is uniform over a more than square metre. The easiest solution is to filter the light from a large area pulsed simulator. This is the case of the setup in use at ESTI (from now on only referred to as “PASAN” setup, from the name of the Swiss company who engineered the pulsed lamp). The monochromatic beam obtained has enough intensity that a bias light system is not necessary, lock-in technique is not required and the SR of a single junction large area module is simply obtained by the following relation

$$SR_{test}(\lambda, t) = \frac{A_{ref}}{N_{par} \cdot A_{test}} \cdot \frac{I_{sc,test}(t)}{I_{sc,ref}(t)} \cdot SR_{ref}(\lambda) \quad (2.15)$$

where N_{par} is the number of cells in parallel of the test module and A_{test} is cell area of the test module.

On the other hand, with multi-junction modules bias light is necessary to avoid current-limitation. In this case lock-in techniques could be used in principle to filter the monochro-

matic pulsed component from a DC bias signal from a coloured bias light system, but requires a high frequency chopper (order 10-100 kHz) which is mechanically prohibitive.

If a continuous monochromatic beam is used as in the previous sections and if the module is too large to allow the monochromatic beam to uniformly illuminate the entire module area, the absolute spectral response cannot be measured directly as described above.

An innovative setup is presented in section 2.3.2 that allows SR measurement of modules with a simple improvement of the previously described setup, using a non-uniform monochromatic beam on the test module. To describe the effect of non-uniformity of the monochromatic beam, consider first the equivalent circuits in the following three situations, with the diode model introduced above in section 2.2:

1. **Uniform monochromatic beam on a single cell of the module** - allowing the absolute SR measurement of a single cell (here also referred to as “Hishikawa’s method”, Ref. [92]);
2. **Uniform monochromatic beam on a set of cells in the module** - allowing the absolute SR measurement of the chosen set of cells;
3. **Non-uniform monochromatic beam on a set of cells in the module** - allowing the relative SR measurement of the module.

2.3.1.1 Spectral response measurement of a single cell in a module (“Hishikawa’s method”)

Figure 2.16 shows schematically the setup where uniform chopped monochromatic light irradiates the target cell only. The bias light on the target cell should saturate the junction not being measured. The entire module is illuminated with supplementary broad band bias light: as a result, the remaining cells do not limit the output current of the module.

This experimental setup has been described by Hishikawa et al. at AIST, Japan [92, 93] (see also Emery [102]).

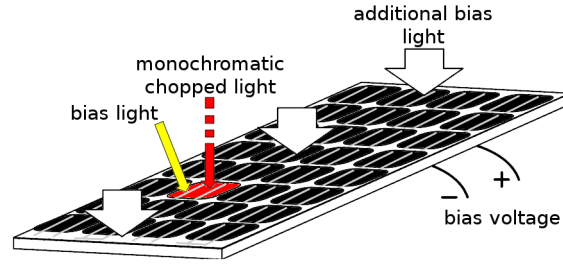


Figure 2.16: Schematic setup of the bias light setup for modules. Experimental setup in use by Hishikawa's group at AIST [92].

For simplicity but without loss of generality, consider the case where the module is made of two cells only and the top junction is under examination. Cells may be connected either in parallel or in series. Equivalent circuits are shown in Figure 2.17a-b respectively, together with I-V curve analysis. Cells are labelled with “1” and “2”: cell 1 is the target cell.

When the cells are series connected (Figure 2.19a), a long wavelength bias light saturates the bottom junction of cell 1, while cell 2 is under additional broad band bias light in order to saturate both its top and bottom junction. As a result, the top junction of cell 1 limits the total current. For intense bias light (at least, one order of magnitude more intense than the chopped monochromatic light), all junctions other than the top junction of cell 1 are in open-circuit conditions. In order to keep the top junction of cell 1 in short-circuit, a voltage bias equal to $V = 2V_{oc,top} + V_{oc,bot}$ needs to be applied.

If the cells are connected in parallel (Figure 2.19b), cell 1 and cell 2 operate at the same voltage: in order to maintain the top junction of cell 1 in short-circuit the voltage bias needs to be set at $V = +V_{oc,bot}$. The junctions in cell 2 are forward biased at some voltages below $V_{oc,bot}$ (ideally $\frac{1}{2}V_{oc,bot}$ each, if bias light equally saturates both junctions) and cell 2 gives a constant current contribution that is filtered out by the lock-in. The number of cells in parallel does not affect the voltage bias required.

In the general case where the 2-junction module is made of N cells in series and assuming each junction contributes equally to the total voltage of the module (i.e., $V_{oc,top} = V_{oc,bot}$),

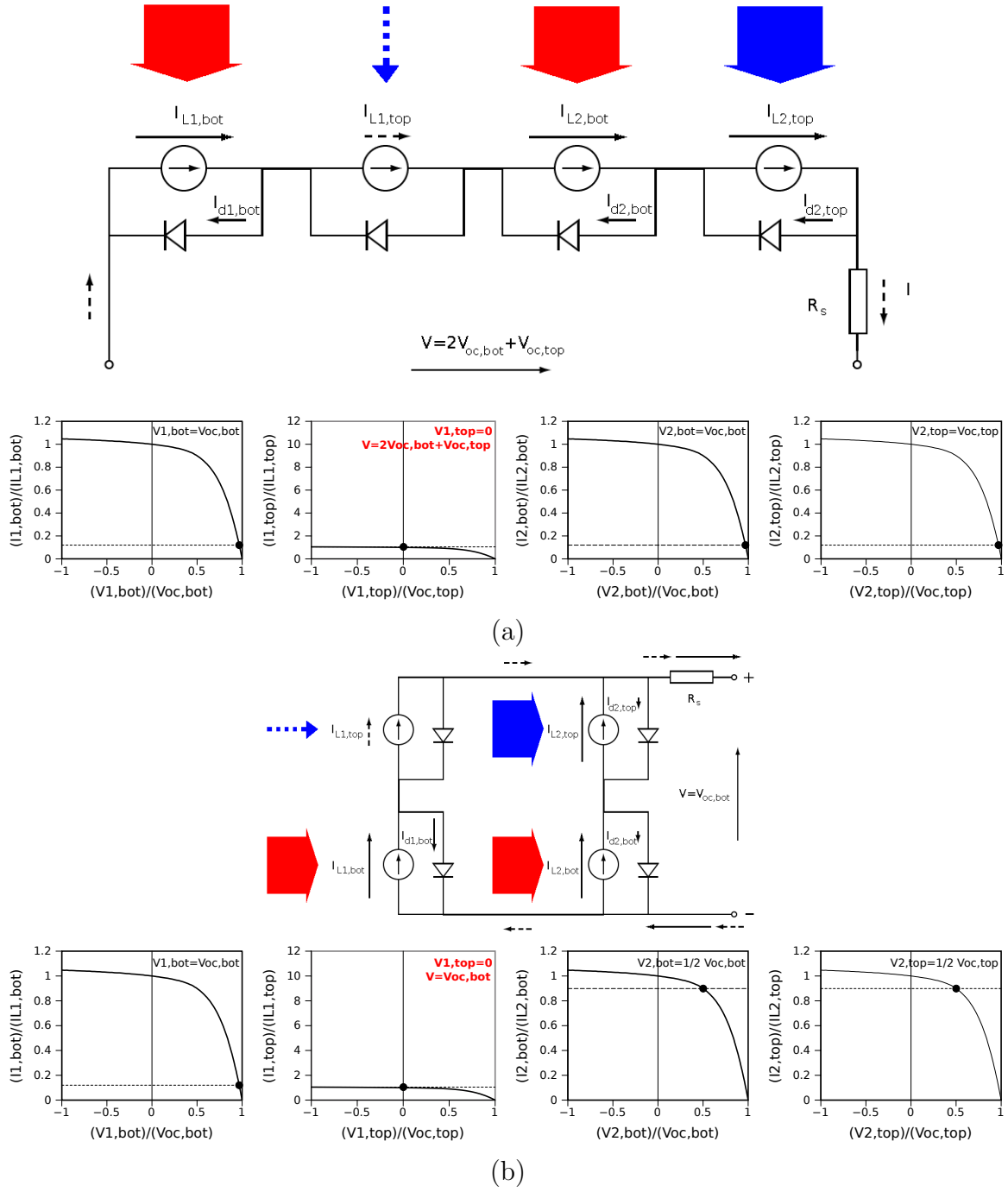


Figure 2.17: Equivalent circuit of two 2-junction cells: (a) in series; (b) in parallel. Chopped monochromatic light illuminate cell 1 only, bias light illuminates the entire module. Infinite shunt-resistance case is analysed only.

to put the target cell in short-circuit only the number of cells in series counts and the voltage bias should be tuned to

$$V = \frac{2N - 1}{2N} V_{oc}. \quad (2.16)$$

The generalization to the case of a M -junction module with N cells in series is straightforward and the voltage bias required is

$$V = \frac{MN - 1}{MN} V_{oc}. \quad (2.17)$$

2.3.1.2 Spectral response measurement of a set of cells in a module: uniform monochromatic beam

The previous case can be generalized to the case of uniform illumination of x target cells in a module (Figure 2.18a): experimental results were proposed in 2008 by the author [94] and by Hishikawa's group in the same year [93].

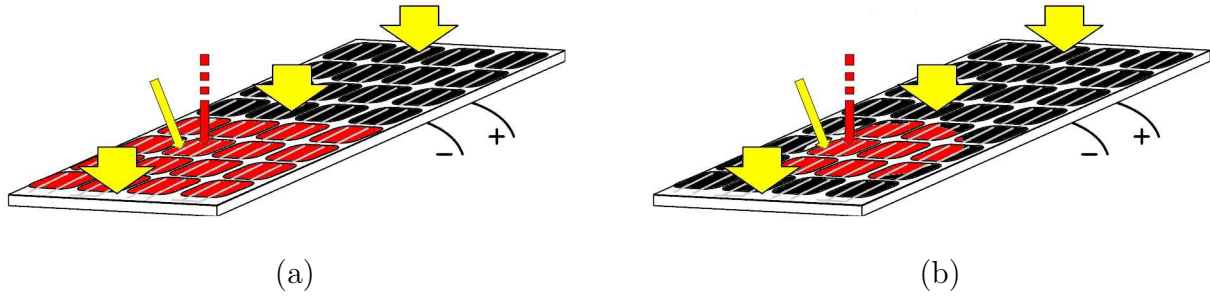


Figure 2.18: Schematic setup of the SR measurement setup for modules. (a) Partial illumination, uniform monochromatic beam (section 2.3.1.2) and (b) partial illumination, non-uniform monochromatic beam (section 2.3.1.3).

The generalization of the equivalent circuits shown above is trivial and will not be repeated here. To short-circuit all the x target cells (N of which are in series), the voltage bias required is

$$V = \frac{2N - x}{2N} V_{oc}, \quad (2.18)$$

and, in case of M -junction module,

$$V = \frac{MN - x}{MN} V_{oc}. \quad (2.19)$$

2.3.1.3 Spectral response measurement of a set of cells in a module: non-uniform monochromatic beam

As is evident from the simplified circuit diagrams of Figure 2.19, when non-uniform monochromatic beam is used it is not possible to give a general rule for the bias voltage to be applied. The correct bias voltage needs therefore to be found case-by-case by selecting a wavelength value where the junction under examination is expected to have its maximum SR and tuning the bias voltage to maximize the current output. A wavelength at which this junction is expected not to respond should then be selected, while ensuring that the SR is zero with the selected bias voltage.

The set-up and positioning of the reference cell and test module are not changed between measurements of various junctions, only different coloured bias lights are switched on and off. It is important to ensure that the monochromatic light intercepts always the same area while measuring all junctions in the same device.

This type of measurement is more straightforward than either of the previous ones, since it does not require either masking the monochromatic light or provision of a uniform monochromatic light of spot larger than the entire module to provide uniformity. On the other hand, the quality of the SR measurement strongly depends on the intrinsic uniformity of the thin-film module under examination, which depends on the thin-film deposition process. The best solution in this case is to repeat SR measurements a sufficient number of times in different target areas in order to be able to verify the uniformity of the module and if necessary to estimate the average SR of the entire module.

In section 2.3.4 the results of two different measurements on two different target areas of the same 2-junction module are presented and the additional uncertainty in the measured

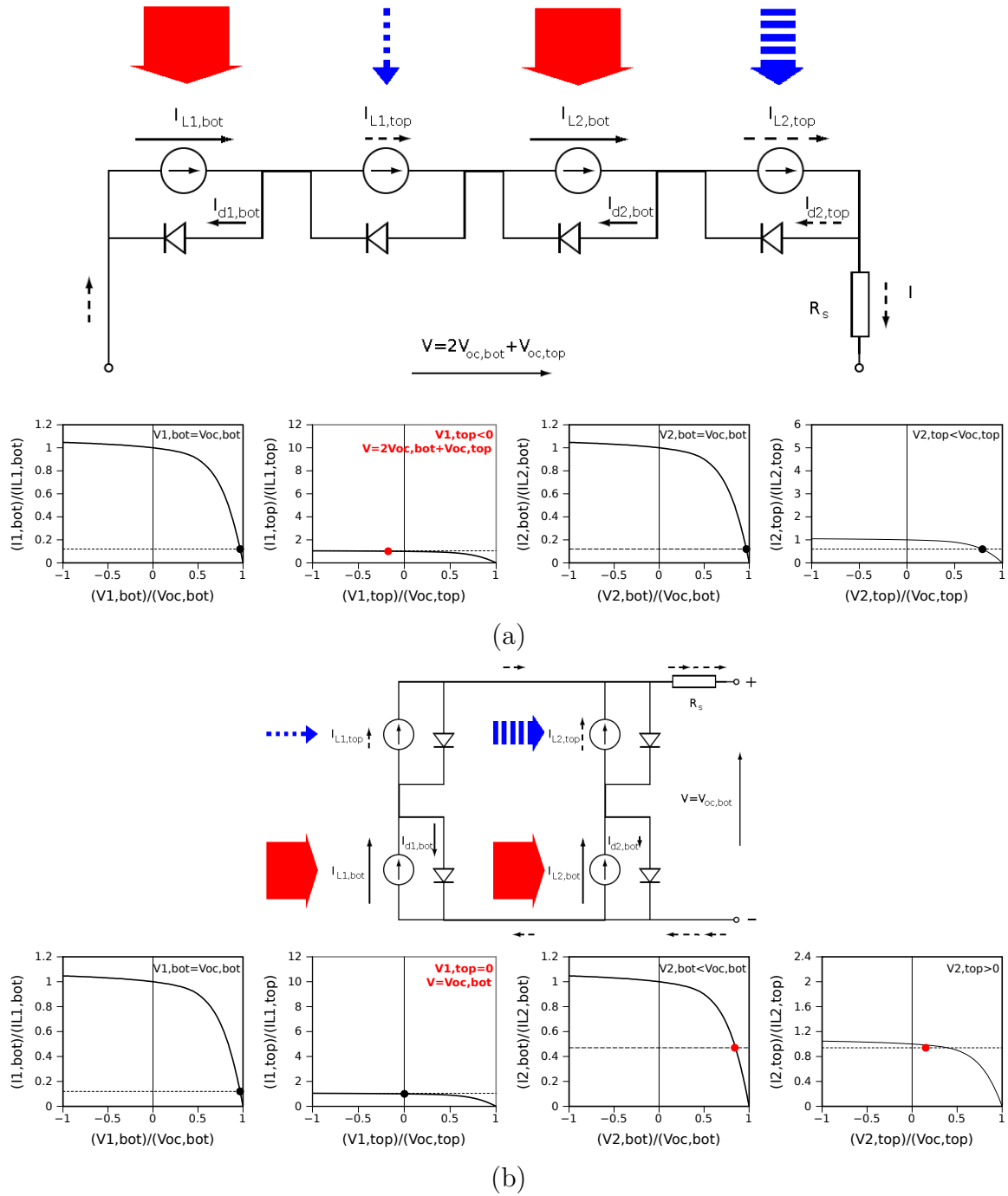


Figure 2.19: Equivalent circuit of two 2-junction cells: (a) in series; (b) in parallel. Chopped monochromatic light illuminates both cells with different intensities, bias light uniformly illuminates the entire module.

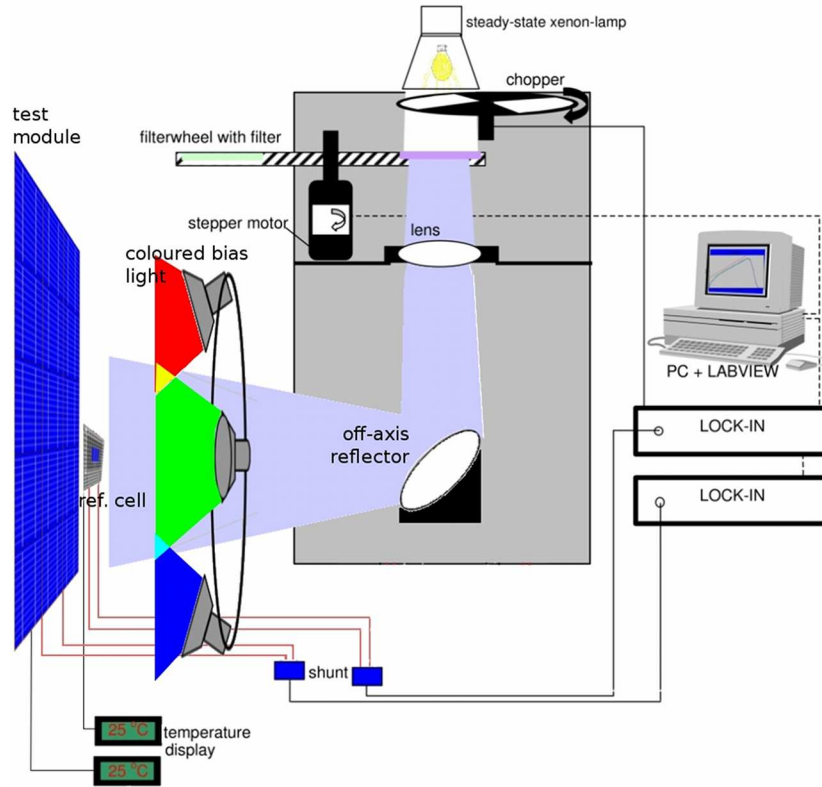


Figure 2.20: Modified Oriel experimental setup for spectral response measurement of multi-junction large area modules. The lens acts as a beam homogenizer, as in the setup for cells (see Figure 2.11); the off-axis reflector project the monochromatic beam onto the module.

SR is qualitatively investigated.

2.3.2 Experimental setup for modules

Fig. 2.20 shows a scheme of the apparatus described in the previous section, modified to allow SR measurements of large area modules, either single or multi-junction.

Two off-axis reflectors (Fig. 2.21a) project the monochromatic chopped beam out of the cabinet onto the module, which is held vertically in a rack. The module can be translated horizontally and vertically, so that the monochromatic spot can be focused on various target areas of the module, if the spot area is smaller than the module area.

Coloured bias light is also available outside the cabinet (Fig. 2.22) by means of a set of coloured LEDs (see the technical specification in Table 2.5) and a set of QTH lamps,

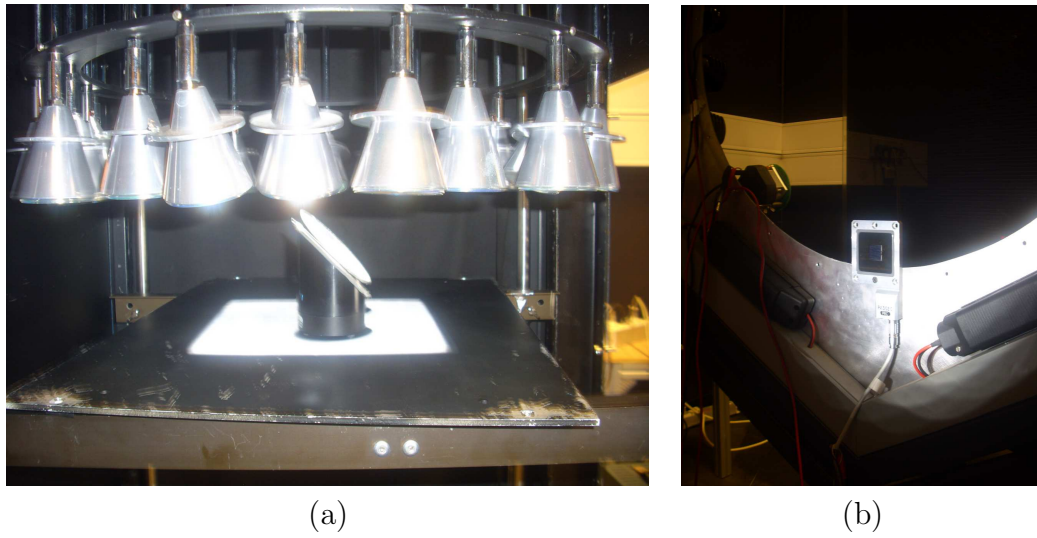


Figure 2.21: New Oriel experimental setup: (a) the off-axis reflectors and (b) the reference cell housing for relative SR measurements.

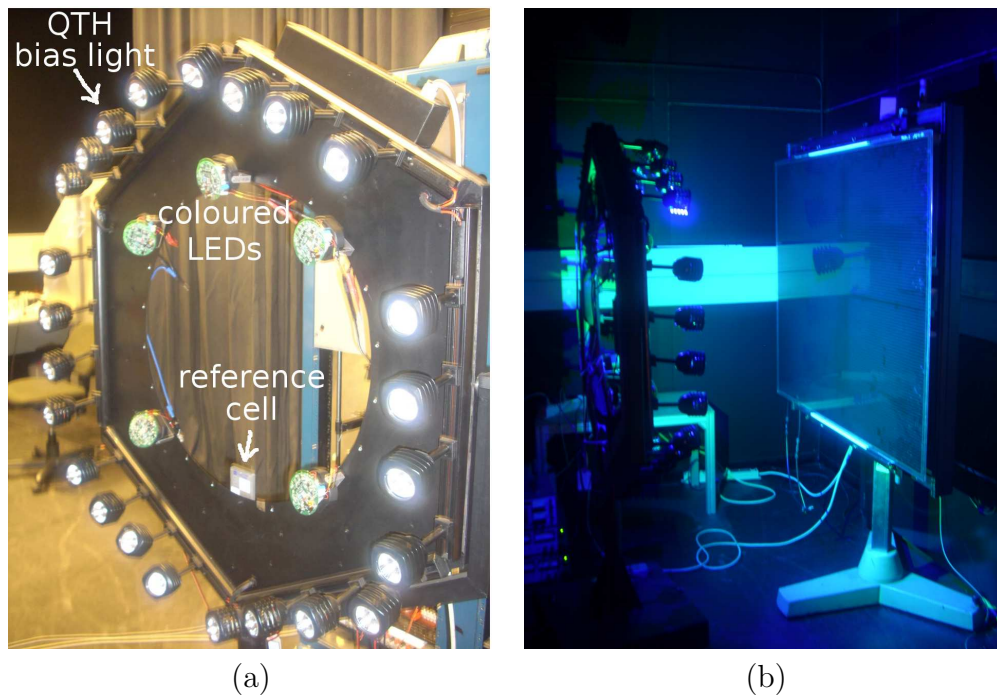


Figure 2.22: New Oriel experimental setup for large area modules: bias light system. (a) front view with QTH bias light on, (b) side view, with violet LEDs on (see Table 2.5).

Colour	Peak Wavelength [nm]	Light Output [mW]	Input Voltage [V]	Input Power [W]
Violet	405	4900	12	38
Green	520	1850	12	38
Red	630	3890	9	30
NIR	870	1750	5	16

Table 2.5: Electro-optical characteristics of the available LEDs (ENFIS UNO Air Cooled Light Engine, by ENFIS Ltd). Size: 79 mm diameter.

providing uniform illumination of the entire module and avoiding current-limitation by the cells not illuminated by the monochromatic spot.

The broad spectral reflectivity of the off-axis mirror (200 nm to 10 μm) allows it to reflect the range of monochromatic light sufficient to cover all existing modules. Since reflectance is wavelength dependent, both the reference cell and the test module need to intercept the monochromatic beam after the reflection, as shown in Fig. 2.21b-2.22a.

The setup allows only “relative” SR measurements, due to the following limitations:

- the monochromatic spot cannot intercept the entire module area, at least for many large-area modules;
- the test module and reference cell are not co-planar: as a consequence, the reference cell intercepts a higher flux than the test module.

As a consequence, eq. (2.1) needs here to be rescaled by a proper scaling factor k as described below.

2.3.3 Absolute spectral response calculation

The absolute SR of each junction is determined from the relative SR as follows:

1. The light IV curve of the module is measured on a large area solar simulator (LAPSS) of spectral irradiance $E_{LAPSS}(\lambda)$ (normalized to 1000 Wm^{-2} total irradiance), giving

the short-circuit current value $I_{sc,LAPSS}$.

2. The relative SR of each junction is measured on the experimental setup described above.
3. From the relative SR of the i -th junction, $SR_i(\lambda)$, the following “relative value” for the short-circuit current of the i -th junction can be calculated, according to eq. (2.6),

$$I_{sc,i} = nA_{test} \int SR_i(\lambda) E_{LAPSS}(\lambda) d\lambda \quad (2.20)$$

where n is the number of cells in parallel of the test module and A_{test} is the area of each cell.

4. A scaling factor k is given by the following ratio

$$k = \frac{I_{sc,LAPSS}}{\min(I_{sc,i})} \quad (2.21)$$

between the short-circuit current measured on LAPSS at step 1 and the minimum of the values calculated in step 3, corresponding to the current-limiting junction.

5. Each function $k \cdot SR_i(\lambda)$ is reported as the absolute SR of the i -th junction.

2.3.4 Validation of the large-area module SR setup

Three methods have been considered for the validation of the new experimental setup (from now on simply referred to as “ORIEL”).

The first method involves the comparison of SR measurements of single-junction thin-film modules performed on ORIEL and on the dedicated experimental setup “PASAN” at ESTI for SR measurements of single-junction modules (see section 2.3.1 above). This method validates the procedure described above for the determination of the absolute SR and gives an estimation of the additional uncertainty due to the non-uniform monochromatic illumination of ORIEL. Table 2.6 summarizes the differences between ORIEL and PASAN.

Component	ORIEL	PASAN
Monochromatic Source	steady-state + band-pass filters	pulsed (2 ms) + band-pass filters
Monochromatic Beam Size	$A_{\text{beam}} < A_{\text{mod}}$ (typically)	$A_{\text{beam}} \gg A_{\text{mod}}$
Beam chopper	YES	NO
Ref. Cell	YES	YES
Lock-in Amplifier	YES	NO
Bias light	YES	NO

Table 2.6: Comparison between ORIEL and PASAN experimental setups.

ESTI code	Num. of junctions	Cell type	Cell area [cm ²]	Module area [m ²]	Cells in series	Cells in parallel
GZ405	1	a-Si	89.68	0.295	29	1
KX711	1	CdTe	56.53	0.72	116	1
NW71	1	CIGS	46.40	0.72	67	2
NW74	1	CSG	73.08	1.38	175	1
YF810	2	a-Si/ μ c-Si	15.84	0.0660	30	1
GY405	2	a-Si/a-Si	192.0	0.315	14	1

Table 2.7: Validation of the experimental setup: test devices. Single-junction modules of various thin-film technologies have been tested for comparison with PASAN, ESTI's dedicated setup for SR measurements of single-junction large-area modules. A small-size micromorph module (ESTI code: YF810) has been tested for comparison with the measurement on the SR setup for cells (section 2.2.4).

The second method is a comparison between SR measurements on the original ORIEL setup for small-size modules with measurements on the new setup. A module that allows SR measurements to be performed with both setups has been chosen for comparison.

In the last method, a comparison between different measurements on different target areas on the same module is shown, giving confirmation of the consistency between measurements with the new ORIEL setup.

Tab. 2.7 lists the modules tested in the validation procedure presented in this section.

2.3.4.1 Large area single-junction modules

Fig. 2.23 shows the results of the comparison between SR measurements on ORIEL and on PASAN, on a selection of four single-junction thin-film large area modules based on different technologies: a-Si (GZ405), CdTe (KX711), CIGS (NW71) and c-Si on glass, or CSG (NW74).

Fig. 2.23a shows the SRs measured on GZ405 on four different target areas on ORIEL. Target areas have been selected to cover the entire module area, as the monochromatic beam size is smaller than the module area. The absolute SR of the module on ORIEL is calculated as the average of all measured SRs.

The full spectral range 300-1200 nm has been divided into several wavelength bands of 50 nm bandwidth and the percentage of SR in each band has been calculated as follows

$$\frac{\int_{\lambda_{\min}}^{\lambda_{\max}} SR(\lambda) d\lambda}{\int_{300}^{1200} SR(\lambda) d\lambda} \cdot 100\%. \quad (2.22)$$

Then the difference between the percentage of SR measured on ORIEL (four measurements) and on PASAN is plotted in Fig. 2.23b as a function of the wavelength bands.

Results of the other three modules are shown in Figure 2.23c-h, where only the average SR over several measurements on different target areas on ORIEL are considered.

2.3.4.2 Small-size multi-junction modules

In order to provide a validation for measurements of multi-junction modules, a small-size a-Si/ μ c-Si module (YF810) has been tested. The YF810 module area (660 cm²) is smaller than the total area for which the experimental setup described in section 2.2.4 provides a monochromatic beam of Class B uniformity (less than $\pm 5\%$ non-uniformity over 30×30 cm² target area, [101]). The SR of YF810 has therefore been measured on the experimental setup for cells and mini-modules and then compared with the measurement on the new experimental setup for large-area modules.

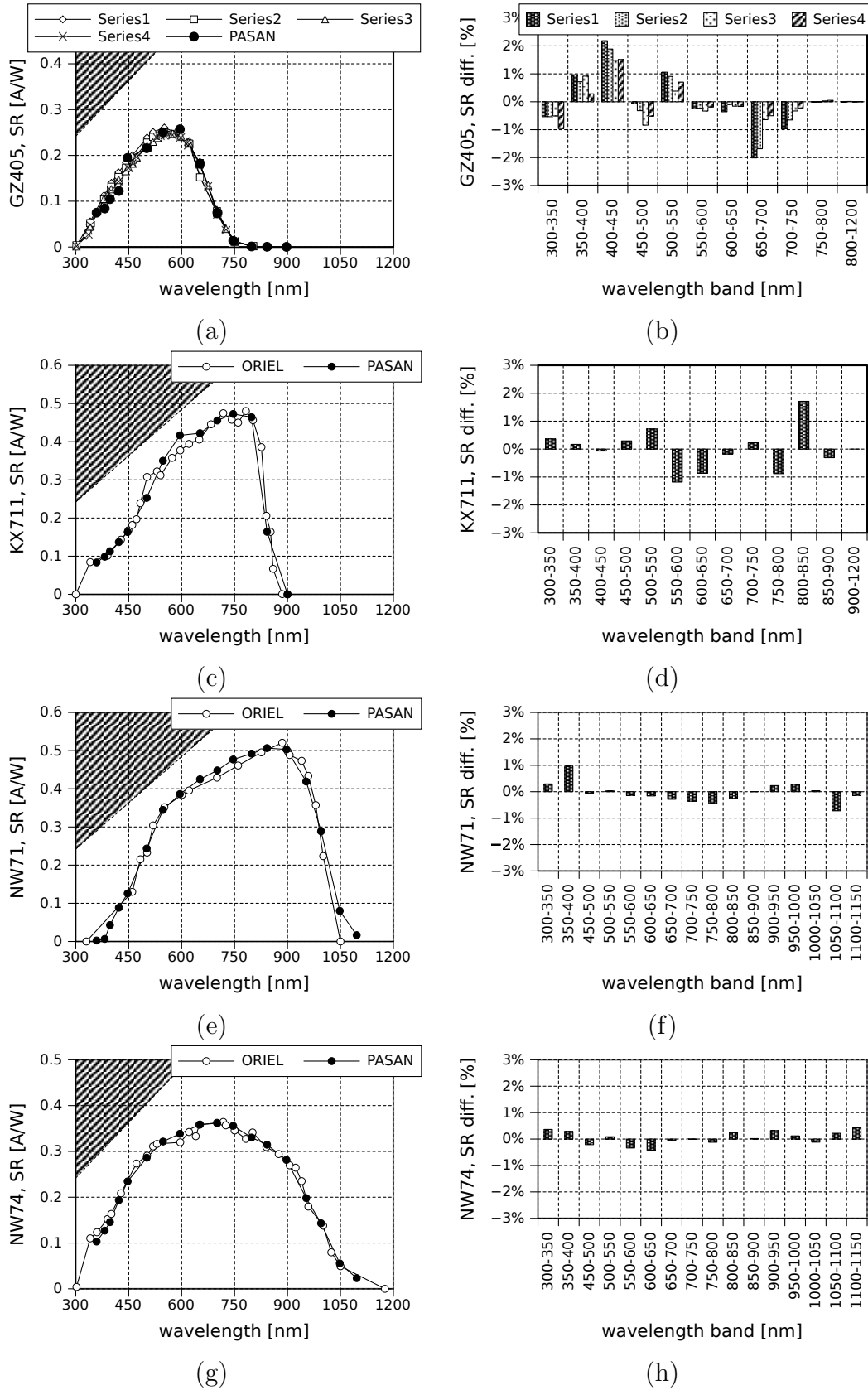


Figure 2.23: Absolute SR of large-area modules: comparison between measurements on ORIEL and on PASAN. (a) Absolute SR and (b) percentage difference of GZ405 (a-Si) according to eq. (2.22); (c) Absolute SR and (d) percentage difference of KX711 (CdTe); (e) absolute SR and (f) percentage difference of NW71 (CIGS); (g) absolute SR and (h) percentage difference of NW74 (CSG).

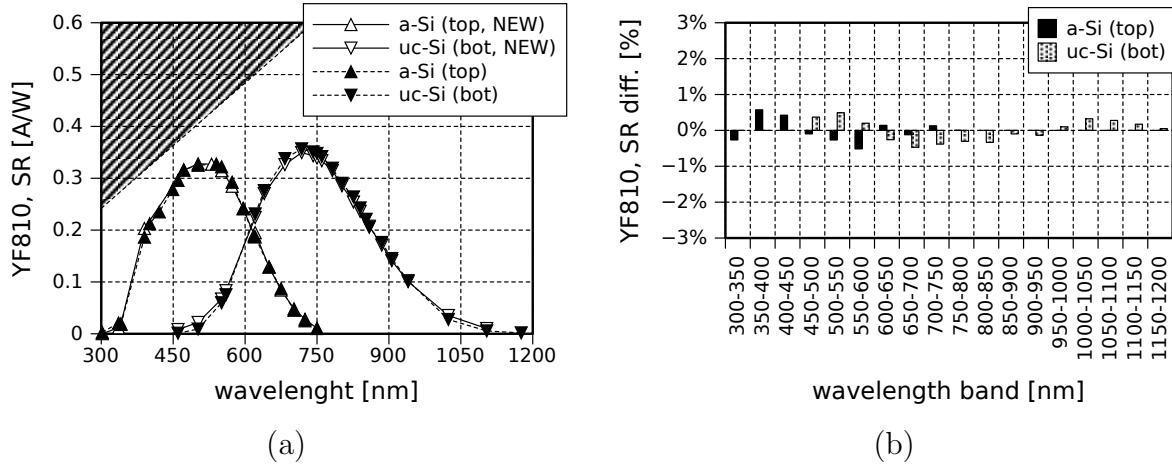


Figure 2.24: Absolute SR of large area modules: comparison between SR measurements of a small-size tandem module (YF810, a-Si/ μ c-Si), performed on the experimental setup described in sections 2.2.4 and 2.3 respectively. (a) Absolute SR; (b) percentage differences over wavelength bands of 50 nm bandwidth.

The result of the comparison is shown in Fig. 2.24 and is discussed in the dedicated section 2.3.5 below.

2.3.4.3 Large-area multi-junction modules

Results of the SR measurement of the a-Si/a-Si module GY405 are shown in Figure 2.25.

The size of the module GY405 is too large to measure its SR with the old ORIEL setup: the chart shows the comparison between two different measurements of the SR on ORIEL, where the monochromatic beam has been focused on two different target areas.

Top and bottom junction SRs have been normalized to better highlight the comparison between two measurements (figure 2.25a). As in previous sections, the percentage difference between the measurements is also shown (figure 2.25b).

2.3.5 Discussion of results

The results on large area single-junction modules show less than $\pm 2\%$ differences between the measurements with the new setup proposed and ESTI's dedicated setup for SR mea-

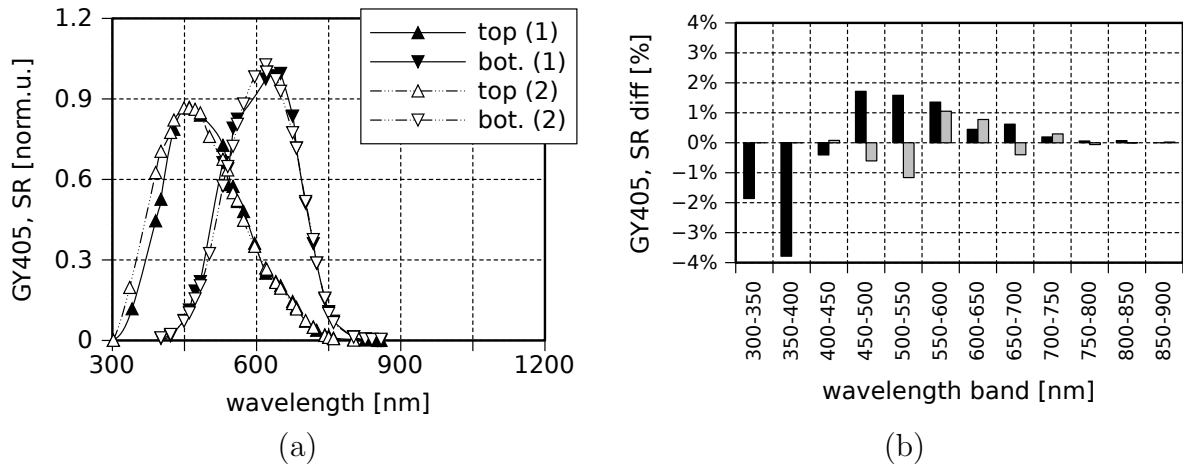


Figure 2.25: SR of large area modules: comparison between SR measurements of a large area tandem module (GY405, a-Si/a-Si), performed on the experimental setup described in section 2.3 on two different areas of the module (non-uniform monochromatic beam). (a) Normalized SR; (b) percentage differences over wavelength bands of 50 nm bandwidth.

measurements of single-junction modules. The difference is shown to be even smaller than $\pm 1\%$ when several measurements are performed on the module on different target areas and the average SR is calculated. The result shows that the uncertainty due to the non-uniformity of the monochromatic beam over the module area can be lowered by averaging over several SR measurements in different areas of the testing module.

In the case of 2-junction modules, less than 0.6% absolute percent difference in the SR distributions has been observed on the medium-size 2-junction module YF810 (a-Si/ μ c-Si).

The large area 2-junction module was measured on the new ORIEL setup but there is no means of verifying the results directly. To estimate the effects of non-uniformity of the monochromatic spot, the measurement was repeated in two different target areas. At most wavelengths, repeatability was good, but a difference in SR distributions of between $(2 - 4)\%$ was found at short wavelengths (see Figure 2.25b).

This value is higher than in the previous examples and may arise from the non-uniformity of the SR along the module area, as was also highlighted on the single-junction module GZ405 (see Figure 2.23b). This discrepancy affects the uncertainty in current balance estimation and spectral mismatch calculation, but it should be noticed that in principle

Research Centre	Target	Uniformity	Ref.
AIST, Japan	1 cell in a module	YES	[92, 93]
NREL, US	1 cell in a module	YES	[102]
Fraunhofer ISE, Germany	1 cell in a module	YES	[91]
Fraunhofer ISE, Germany	mini-module (same batch)	YES	[91]
ESTI, Italy	mini-module (same batch)	YES	[99, 100]
ESTI, Italy	module	NO	[94, 169]

Table 2.8: List of the experimental setups for SR measurement of multi-junction modules of various PV research centres for reference measurements.

the same uncertainty would also be obtained after a set of measurements of all cells with Hishikawa’s method.

If eq. (2.6) is used to estimate the short-circuit current produced by each junction at AM1.5g, 1000 Wm^{-2} , measurement 1 gives current mismatch of 10% (top junction current limiting), while measurement 2 gives current mismatch of 4% (top junction limiting). However, such a difference only slightly affects the calculation of the spectral mismatch factor that is introduced in the next section (2% difference on the top junction mismatch factor and less the 1% difference on the bottom junction).

2.3.6 Comparison between the proposed setup and the state of the art

Table 2.8 lists several experimental setups for SR measurement of multi-junction modules in use at various research centres.

The measurement procedure used both at AIST and at NREL (and similarly proposed by Hohl-Ebinger and Warta at Fraunhofer ISE, see Ref. [91]) has been described in section 2.3.1.1 as the “Hishikawa’s Method”. This is basically the generalization of the procedure for SR measurement of multi-junction cells: the monochromatic beam is shined on a single cell in the test module (with appropriate masking methods) and the bias light is set in order that the same cell is current limiting.

A different and simpler approach is to measure the SR of a cell or small size module

coming from the same batch of production the large area module. This can be easily done with a setup for cells, not requiring large area monochromatic beam and using lock-in technique. This method is also currently used at Fraunhofer ISE and at ESTI, with the setup of section 2.2.4.

The main advantage of these methods in respect to the one described in this section is that the uniformity of the monochromatic beam onto the target cell can be controlled with high precision and thus the possible uncertainties related to the non-uniformity can be neglected. On the other hand, the SR of a single cell of the testing module (or even of a cell from the same batch of production) may not be the same of the SR of the entire module. This also represents an uncertainty contribution to the SR measurement of the module: a larger monochromatic beam as in the setup described in this section may therefore be beneficial.

2.4 Spectral Mismatch Calculation and Correction to Standard Test Conditions

2.4.1 Spectral mismatch calculation

2.4.1.1 Theory and standards

According to the existing standards IEC 60904-3 [22] and ASTM E 948-05 [103], the results of electrical characterization of a non-concentrator single-junction PV device are to be related to the common reference spectral irradiance AM1.5g distribution.

The total irradiance and the module temperature can be monitored with a calibrated reference cell and a temperature probe. Outdoor characterization of PV modules could in principle be performed at spectral conditions very close to AM1.5g, but indoor measurements are affected by the spectral mismatch between the solar simulator in use and

the standard spectrum and in general by the mismatch between the SR of the test device and of the reference cell in use.

The appropriate spectral mismatch correction for single-junction PV devices is described both in the international standard IEC 60904-7 [104] and in the ASTM standard E 973–05 [105]. It involves the calculation of a *spectral mismatch factor* (MMF), which re-normalizes the photocurrent values measured by the test device and by the reference cell on the solar simulator in use to their expected values at AM1.5g. Such a re-normalization factor can be calculated from eq. (2.6), giving

$$MMF = \frac{\int SR_{test}(\lambda) E_{AM1.5g}(\lambda) d\lambda}{\int SR_{test}(\lambda) E_{ss}(\lambda) d\lambda} \cdot \frac{\int SR_{ref}(\lambda) E_{ss}(\lambda) d\lambda}{\int SR_{ref}(\lambda) E_{AM1.5g}(\lambda) d\lambda} \quad (2.23)$$

where the first term on the right is the renormalization of the photocurrent produced by the test device on the solar simulator to the expected photocurrent at STC and the second term is the analogous renormalization for the reference cell. From eq. (2.23) follows that $MMF = 1$ (no spectral mismatch correction) occurs in the following two ideal (and trivial) cases:

- **Ideal spectral irradiance:** $E_{ss}(\lambda) = E_{AM1.5g}(\lambda)$, i.e. no spectral mismatch is necessary if the spectral irradiance of the solar simulator equals the standard spectrum. This situation may occur for example in outdoor measurements under specific environmental conditions.
- **Ideal reference cell:** $SR_{ref}(\lambda) = SR_{test}(\lambda)$, i.e. no spectral mismatch is necessary if the test device has the same SR as the reference cell. In this case, since the calibration value of the reference cell has been obtained at STC, the reading of the reference cell provides both the correction to 1000 Wm^{-2} and to the standard spectral irradiance. A reference cell of the same cell type as the test device is therefore recommended for indoor electrical characterization.

2.4.1.2 Spectral mismatch calculation for multi-junction devices

In case of multi-junction PV devices, when the spectral irradiance of the solar simulator cannot be adjusted to the standard spectrum, a large difference in the solar simulator spectrum may lead to a large current-imbalance between the component junctions. For example, consider the large area pulsed solar simulators in use at ESTI (simply referred to as LAPSS, which uses a single unfiltered Xenon lamp). It is Class A in spectral match, according to the international standard IEC 60904-9 [101], but Figure 2.26 highlights the difference in spectral percentage distribution with AM1.5g and the outdoor global spectrum measured on a clear-sky day at AM1.5: spectral distributions are calculated with respect to three selected wavelength bands corresponding to the bands where the junctions of Si alloy multi-junction thin-film modules respond. Spectra have been normalized to the total irradiance between 300 and 1200 nm, the wavelength band where a c-Si reference cell responds. Xe lamp peaks between 900 and 1200 nm are not detected by a typical a-Si/a-Si double junction module, whose bottom junction SR has a cut off at 800 nm. As a result, if a c-Si reference cell is used to detect the total irradiance, the a-Si/a-Si module would show the current-imbalance highlighted (total irradiance between 600 and 800 nm 6.6% lower than at AM1.5g).

Even if a filtered reference cell is used to filter out Xe peaks, the spectral mismatch still holds. If a high-pass filter is used to block all wavelengths above 800 nm, the spectral normalization needs to be performed between 300 and 800 nm, as shown in Figure 2.27.

Spectral mismatch correction of indoor measurements of multi-junction non-concentrator PV devices is described in the ASTM standard E 2236-05 [74] and summarized in the following steps.

- **Step 1:** Select a reference cell responding in a wider wavelength band than all junctions of the multi-junction test module.
- **Step 2:** Measure the current-voltage (IV) characteristics of the test module at 1000 Wm^{-2} total irradiance detected by the reference cell.

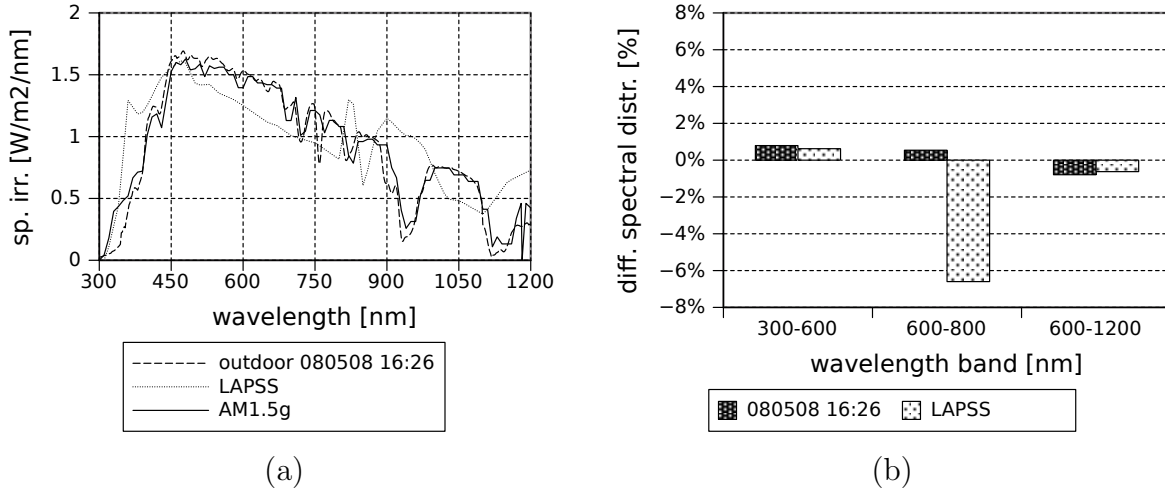


Figure 2.26: (a) LAPSS (one of ESTI's large area pulsed solar simulator) and outdoor spectral irradiance: comparison with AM1.5g (spectra are normalized over the total irradiance between 300 and 1200 nm). (b) Spectral percentage distribution: difference of percentage distribution between LAPSS/outdoor and the standard AM1.5g spectrum. Wavelength bands have been selected to fit with bandgaps of two different thin-film multi-junction Silicon alloy modules: a-Si, top junction (300-600 nm); a-Si bottom/middle junction (600-800 nm); μ c-Si bottom junction (600-1200 nm).

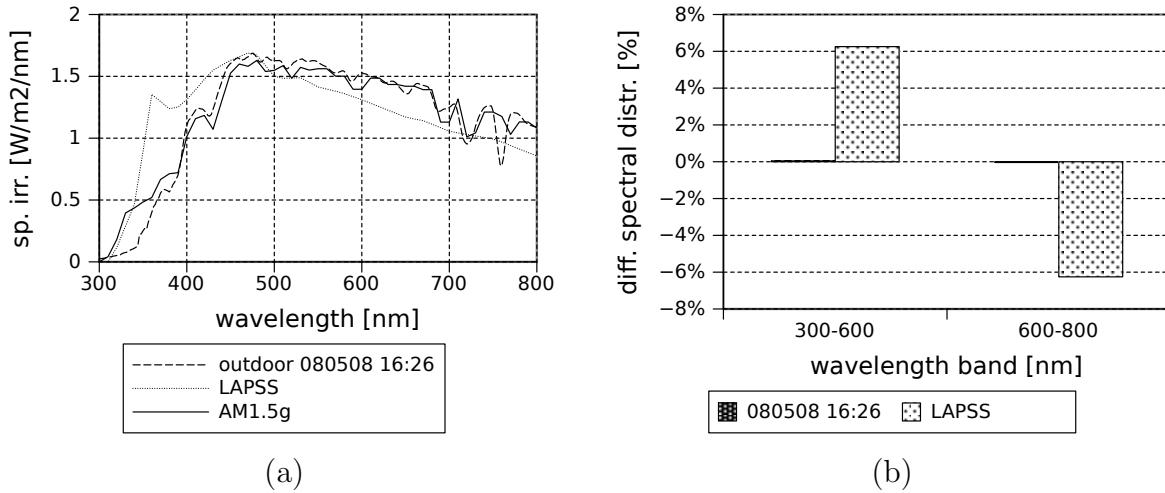


Figure 2.27: (a) LAPSS and outdoor spectral irradiance: comparison with AM1.5g (spectra are normalized over the total irradiance between 300 and 800 nm). (b) Spectral percentage distribution: difference of percentage distribution between LAPSS/outdoor and the standard AM1.5g spectrum. Wavelength bands have been selected to fit with bandgaps of an a-Si/a-Si thin-film module.

ESTI code	Num. of junctions	Cell type	Cell area [cm ²]	Module area [m ²]	Cells in series	Cells in parallel
KX711	1	CdTe	56.53	0.72	116	1
NW71	1	CIGS	46.40	0.72	67	2
KW711	2	a-Si/ μ c-Si	99.11	1.0545	47	2
GY405	2	a-Si/a-Si	192.0	0.315	14	1

Table 2.9: Test modules.

- **Step 3:** Calculate the spectral mismatch factor MMF_i from eq. (2.23) for the i -th component junction and repeat for all junctions.
- **Step 4:** Determine the current-limiting junction, i.e. the j -th component junction for which the calculated photocurrent from eq. (2.6) is minimum. Ideally, the current-limiting junction should be the same on the solar simulator in use and at STC.
- **Step 5:** Apply the mismatch factor from the j -th junction, MMF_j to the measured photo-current values point-by-point, to correct the IV curve to AM1.5g.

The current imbalance generally affects the measurement fill factor and the module efficiency at STC, as well as the calculated short-circuit current [76, 77, 106]. In the following section, results of indoor measurements on LAPSS and spectral mismatch correction of several multi-junction thin-film modules are reported. The comparison with outdoor measurements at AM1.5 and at various air masses is also discussed.

2.4.2 Results and comparison with outdoor characterization

Several thin-film modules of various technologies have been tested. Table 2.9 lists the modules presented in this section.

All devices were characterized indoor on LAPSS with a calibrated c-Si reference cell. The SR of the modules were measured on the experimental setup described in this chapter and the spectral mismatch factors calculated accordingly, to correct measured data to STC.

ESTI code	$I_{sc,LAPSS}$			MMF			I_{sc}	I_{sc}	diff. [%]
	top	mid.	bot.	top	mid.	bot.	STC	out	
KX711	1.079	-	-	1.094	-	-	1.180	1.19	0.8
NW71	2.378	-	-	0.992	-	-	2.359	2.39	1.3
KW711	2.14	-	(2.494)	1.025	-	(1.060)	2.19	2.19	< 0.5
GY405	(1.295)	-	1.123	(0.887)	-	1.067	1.198	1.206	0.7

Table 2.10: Indoor results and spectral mismatch corrections. Short-circuit current values (in amperes) are corrected to STC by applying the MMF of the current limiting junction to the short-circuit current value measured on LAPSS. Data are finally compared with short-circuit current values measured on the tracker under global normal irradiance, in clear-sky conditions, at AM1.5 and corrected to 1000 Wm^{-2} . Extrapolated current values for the saturated junctions are shown in brackets, together with their MMFs. No spectral mismatch correction has been applied to the outdoor measurements, performed at geometrical air mass AM1.5.

The final short-circuit current value at STC has then been compared with the short-circuit current measured on ESTI's outdoor solar test field. Outdoor measurements have been performed in clear-sky conditions and on a tracker, under global normal irradiance. Measurements have been performed at geometrical air mass AM1.5; the total irradiance has been detected by a calibrated c-Si reference cell and data have been corrected to 1000 Wm^{-2} [99, 107].

Table 2.10 shows the short-circuit current (I_{sc}) measured indoors on LAPSS, the spectral mismatch factor (MMF), the corrected value to STC and the short-circuit current measured outdoors.

For KX711 (CdTe) $MMF = 1.0938$, giving at STC $I_{sc} = 1.180 \text{ A}$, which is very close to the value measured outdoors (1.19 A). Slightly higher deviation (1.3%) is observed on NW71 (CIGS).

For KW711 (a-Si/ μ c-Si) and GY405 (a-Si/a-Si), the table shows in brackets the calculated photocurrent generated by the saturated junctions according to eq. (2.6). The MMF values from the SRs of the saturated junctions are also shown in brackets. I_{sc} values corrected to STC have been calculated from the MMF relative to the current-limiting junction on LAPSS. Results again show good agreement (less than 1% deviations) with outdoor measurements.

2.5 Conclusions

The procedure for the SR measurement of two-terminal monolithic multi-junction non-concentrating PV devices has been analysed. In the absence of an international standard, the ASTM standard has been applied. A set of Operating Instructions for the ESTI laboratory and uncertainty analysis for SR measurements of multi-junction devices have been prepared by the author and are reported in Appendix B and C respectively.

Quantitative analysis of current-limitation in a dual-junction device has been analysed in detail. The impact of a low shunt resistance on the SR measurement of a sub-cell has also been presented and discussed. The following three main results have been highlighted in the first part:

- the dark SR approach is able in theory to detect any low shunt resistance in a junction, which may explain the anomalous dark SR observed experimentally in a given example;
- from the same theoretical point of view, bias voltage alone (as proposed by Meusel et al. [75] and Siefer et al. [79]) is not necessarily the solution when a junction with low shunt resistance gives measurement artefacts in its SR: such artefacts may appear even when the appropriate bias voltage is applied;
- in presence of a low shunt resistance, SR measurement artefacts can be corrected even without applying a forward bias voltage, if the bias light is intense enough.

Experimental evidence supporting this theoretical description has been presented.

The SR measurement of full-size multi-junction PV modules has been modelled with further equivalent simplified circuits in three possible cases: 1) uniform monochromatic beam on a single cell in a module; 2) uniform monochromatic beam on a set of cells in a module; and 3) non-uniform monochromatic beam on a set of cell in a module. The approach 1 has been proposed among others by Hishikawa's group at AIST, Japan

[92]. Methods 2 and 3 have been investigated by the author with the experimental setup proposed, a novel modification to the experimental setup for SR measurement of multi-junction cells. Series and parallel connection of cells in a module have been analysed and the best choice for the voltage bias has been discussed case by case.

The procedure for the experimental validation of the new setup has been presented, showing positive results in the following three cases: (i) single-junction large-area modules (where SR is performed with non-uniform monochromatic beam, method 3 above); (ii) small-size multi-junction module (method 2); and (iii) multi-junction large-area modules (method 3 again).

Finally, to further confirm the SR measurement method proposed, indoor IV measurements have been spectrally corrected to AM1.5g using the measured SRs and compared with outdoor measurements at AM1.5. The procedure for spectral mismatch correction has been presented according to the available standard. Results of the comparison showed good agreement on the samples presented.

Chapter 3

Setup of a High Intensity Solar Simulator for Concentrator Photovoltaic Cells

3.1 Introduction

Within IEC TC82 (see section 1.5), Work Group 7 (WG7: “Concentrator modules”) covers the topics of CPV *“to define the requirements and test procedures for determining the module and system performance, safety and environmental reliability. Safety guidelines and requirements will also be developed to specify the electrical and mechanical construction characteristics for concentrators”* [60].

The first standard published by TC 82 on CPV is IEC 62108, published in December 2007, “Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval” [108]. The object of this test standard is to determine the electrical, mechanical, and thermal characteristics of the CPV modules and assemblies and to show, as far as possible within reasonable constraints of cost and time, that the CPV modules and assemblies are capable of withstanding prolonged exposure in climates described in

the scope.

Though methods for indoor/outdoor characterization of CPV cells and modules for space and terrestrial applications have been developed and tested over decades [109, 110, 111], the preparation of standard procedures for indoor/outdoor characterization of CPV devices is still ongoing. Even if a dedicated standard for the IV characterization is not yet available, the international standard IEC 60904-1 [112] may be applied to CPV cells, if they are irradiated using direct normal irradiance and a mismatch correction with respect to a direct normal reference spectrum is performed. Furthermore, no IEC standard for direct normal reference spectrum is given, though it is likely [65] that the direct-plus-circumsolar spectral irradiance tabulated in the American standard ASTM G-173-03 [113] will become an international standard in the near future.

Among all CPV cell types, III-V group multi-junction cells are currently the most promising solution for high efficient receivers in CPV technology [114, 49, 115], but represent a challenge in current-voltage characterization [78, 116] and correction to standard conditions (STC). The external quantum efficiency measurement may present measurement artefacts [75] and also the spectral mismatch correction needs to be performed carefully, as has been discussed in section 2.4 for multi-junction thin-film modules.

In recent years the ESTI laboratory has deepened its exploratory research in the methods for the characterization of CPV cells and modules. The activity has been strengthened by participating in the activities of TC82 WG7 and by a number of collaborations in CPV projects.

The partnership within the 5-year integrated project APOLLON [117] confirmed the importance of CPV beyond traditional ESTI activities.

3.1.1 State of the art

3.1.1.1 Solar simulators for CPV cells characterization

A high intensity simulator is required for indoor CPV cell testing. Table 3.1 lists several solar simulators available on the market for IV characterization at high intensity.

The setup of a high intensity solar simulator has been studied and developed at ESTI and is presented in this chapter. The procedure followed for fulfilling the requirements for standard classification of the simulator according to the international standard IEC 60904-9 [101] and ASTM standard¹ E 927-05 [122] is shown. A method for the calibration of c-Si reference cells duly protected with neutral density filters for irradiance measurements at high intensity is also proposed.

The characterization of a sample of CPV cells of various technologies is presented, including external quantum efficiency measurement and IV characterization of III-V group multi-junction CPV cells. Results help to explore benefits and limitations of the experimental setup developed.

3.1.1.2 Standard specifications for the classification of a high intensity solar simulator

Figure 3.1 shows the difference between the international standard AM1.5g spectrum [22] and the ASTM AM1.5d, the reference spectrum used worldwide in CPV cell testing. The total irradiance E (in Wm^{-2}) of the two standards is obtained by integration over wavelengths between 0 and 4000 nm of the spectral irradiance $E(\lambda)$ ($\text{Wm}^{-2}\text{nm}^{-1}$) and is referred in cited standards to be

$$E_{AM1.5g} = \int_0^{4000} E(\lambda) d\lambda = 1000 \text{ Wm}^{-2} \quad (3.1)$$

¹At time of writing this standard has been updated to E 927-10, presenting few differences in the definition of the classification requirements.

Name	Company	Intensity [suns]	Source	Continuous Pulsed	Rate [min ⁻¹]	Spectral Match [%]	Spatial Non-Unif. [%]	Temporal Instab. [%]	Ref.
High Flux Beam Concentrator ^a	Newport-Oriel (USA)	30-50X	Xe+lenses	continuous	-	±12%	±5% ^b	< 1%	[118]
Spectrosun X-25 Mark II	Spectrolab (USA)	(< 1)-200X	Xe+lenses +filters	continuous	-	n.a.	±3% ^c	±1%	[27]
AOPT Gen2	AlphaOmega (USA)	5-1000X	Xe	pulsed (1 ms)	120	n.a. ^d	±2.5% ^e	±5% ^f	[119]
T-HIPSS 400 series	Spectrolab (USA)	200-2000X	Xe+mirrors+ filters	pulsed (2.5 ms)	4	±14% ^g	±2% ^h	±1%	[120] [27]
AOPT Gen1	AlphaOmega (USA)	400-2400X	Xe	pulsed (1 ms)	6	n.a. ⁱ	±1.5% ^j	±5% ^k	[119]
Flash Tester	Technoexan Ltd. (RUS)	1-3000X	Xe	pulsed (1 ms)	4	±20% ^l	±3% ^m	±2%	[121]
4-lamp Flash Tester	Technoexan Ltd. (RUS)	1-3000X	Xe+filters	pulsed (1 ms)	4	±8% ⁿ	±3% ^o	±2%	[121]

Table 3.1: Solar simulators available on the market for CPV cells IV characterization.

^aMounted on an Oriel 91291 1000W Continuous Solar Simulator.^bOver 1.5 cm testing diameter.^cOver 1 cm² testing area.^dMeasured over three bands, with ±1.5% spectral match over the top and middle bands.^eOver 2.5 × 1.5 cm² testing area.^fOver 0.5 ms sweep time.^gCalculated over six distinct wavelength bands from 250 to 1800 nm.^hOver 10 × 10 cm² testing area.ⁱMeasured over three bands, with ±1.5% spectral match over the top and middle bands.^jOver 2.5 × 2.5 cm² testing area.^kOver 0.5 ms sweep time.^lFrom 350 to 950 nm: ±5%.^mOver 1 × 1 cm² testing area.ⁿMeasured over nine wavelength bands, from 300 to 1650 nm.^oOver 1 × 1 cm² testing area.

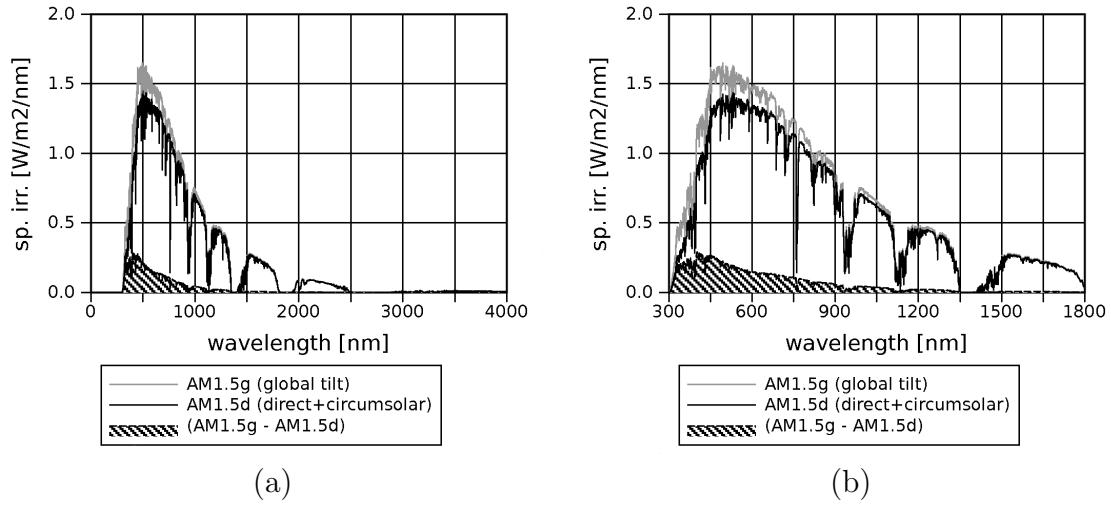


Figure 3.1: Comparison between AM1.5d and AM1.5g standard spectral irradiances: (a) 0 to 4000 nm; (b) 300 to 1800 nm. Both spectra are tabulated in ASTM standard G 173 [113]. The difference between standards is highlighted. ASTM standard spectrum AM1.5g is equivalent to the international AM1.5g spectrum [22]; no international standard is available for the direct spectral irradiance to date.

and

$$E_{AM1.5d} = \int_0^{4000} E(\lambda) d\lambda = 900 \text{ Wm}^{-2}, \quad (3.2)$$

respectively. Figure 3.1b highlights the difference between the two reference spectra in the wavelengths range from 300 to 1800 nm where CPV cells respond.

Following the interpretation widely used in the literature [19], in this chapter the total intensity is referred to in terms of “suns”, where “one sun” (1X) corresponds to 1000 Wm^{-2} of direct irradiance. The AM1.5d standard spectrum of Figure 3.1 is thus rescaled accordingly.

A solar simulator can be classified according to the requirements stated in IEC 60904-9 [101] or in the ASTM standard E-927-05 [122]. The two standards are similar, but the second one specifically refers to spectral matching to AM1.5d and will therefore be considered in this chapter.

A pulsed solar simulator is classified as Class A, B or C according to the requirements specified in Table 3.2, where:

Class	Spectral Match [a.u.]	Spatial Non-uniformity [%]	Temporal Instability [%]
A	0.75-1.25	2	2
B	0.6-1.4	5	5
C	0.4-2.0	10	10

Table 3.2: Standard requirements for the performance of a solar simulator with test area of less than 30 cm diameter, as in ASTM E927-05 [122].

- **spectral match** is the maximum percentage deviation of spectral percent distribution calculated as

$$\Delta E_i[\%] = \frac{\int_{\lambda_{i,\min}}^{\lambda_{i,\max}} E(\lambda) d\lambda}{\int_{300}^{1100} E(\lambda) d\lambda} 100\%, \quad (3.3)$$

where, $E(\lambda)$ is the spectral irradiance of the simulator and $\lambda_{i,\min}$, $\lambda_{i,\max}$ are the limits of the i -th wavelength interval band defined in the standard;

- **spatial non-uniformity** of irradiance $S_{N,E}$ is given by

$$S_{N,E}[\%] = \frac{E_{t,\max} - E_{t,\min}}{E_{t,\max} + E_{t,\min}} 100\% \quad (3.4)$$

where $E_{t,\max}$, $E_{t,\min}$ are maximum and minimum total irradiances respectively, measured with a calibrated reference cell over the test plane area;

- **temporal instability** of irradiance $T_{I,E}$ is given by

$$T_{I,E} = \frac{E_{t,\max} - E_{t,\min}}{E_{t,\max} + E_{t,\min}} 100\% \quad (3.5)$$

where $E_{t,\max}$, $E_{t,\min}$ are maximum and minimum total irradiances respectively measured with a calibrated reference cell during the plateau of irradiance of a single pulse, where data acquisition normally takes place².

The simulator is rated with three letters in the above order: a Class ABA simulator, for example, is Class A according to spectral match and temporal instability and Class B according to spatial non-uniformity. This classification scheme does not include other

²When the data acquisition system allows simultaneous measurement of irradiance, current and voltage, then Class A temporal instability requirement is reduced to $T_{I,E} \leq 5\%$.

Section	Page	Content
3.1	97	- The activity of IEC TC82 WG7 - Solar simulators (state of the art) - Standard classification of solar simulators - Structure of the chapter
3.2	104	- Setup and characterization of a high intensity solar simulator - Classification - Calibration of intensity filtered reference cells
3.4	129	- Comparison with the state of the art
3.3	124	- Preliminary results - EQE measurements - Test of linearity
3.5	132	- Conclusions
App. D	203	- Uncertainty analysis
App. E	210	- Results on III-V multi-junction CPV cells

Table 3.3: The structure of Chapter 3.

important properties such as: the test plane size; the field of view; whether steady state or pulsed source; the distance between test plane and light source; range of operating irradiances (maximum and minimum); spectral distribution data; repeatability data; map of non-uniformity over the specified test area. The focus in this chapter will be on simulators whose test plane has a diameter of less than 30 cm, also referred to as “small area” solar simulators. Other specifications will be given in the subsections below.

3.1.2 Structure of the chapter

This chapter is divided into four sections (see Table 3.3).

After this introduction, section 3.2 presents the setup and characterization of the new high intensity solar simulator developed by the author at ESTI. The classification of the simulator according to the existing standards is provided in section 3.2.4. At the end in section 3.2.5, the procedure for the calibration of a set of c-Si reference cells for the irradiance detection at high intensities is given.

Section 3.4 highlights the advantages and disadvantages of the new simulator towards the other high intensity solar simulators of Table 3.1.

In section 3.3, results of the characterization of a c-Si CPV cell are presented, including external quantum efficiency measurement and the test of linearity, as a demonstration of the applications of the simulator. For clarity, preliminary results on other cells of different technologies are presented in Appendix E.

The conclusions are in section 3.5 and the list of relevant publications by the author in the CPV field is given in Appendix A.

3.2 Setup of ESTI's High Intensity Pulsed Solar Simulator

3.2.1 Reconfiguration of GPS simulator

A large area long-pulse solar simulator by Global Photovoltaic Specialists Inc. (GPS, see Figure 3.2) especially designed and used to measure modules at 1000 Wm^{-2} has been modified to enable high intensities on the test plane. A vertical structure allows the lamp to be moved to any position starting from a maximum lamp-to-target distance of 2 m. The lamp electrical operation parameters are typically unchanged.

To estimate the intensity values that can be reached with the new setup, a simplified light source is considered so that light intensity $I(r)$ varies as r^{-2} , where r is the lamp-to-target distance (*point-like source assumption*). A point B far from the centre of the plane is considered (Figure 3.3), receiving light with lower irradiance than the point of maximum irradiance A at the centre of the plane. To ensure class A uniformity on the test plane ($\pm 2\%$), the following relation needs to be satisfied

$$\frac{E(r)}{E(r + dr)} = 1 + \left(\frac{\overline{AB}}{r} \right)^2 \leq 104\%. \quad (3.6)$$

The maximum diameter of the testing plane where the requirement is fulfilled is given

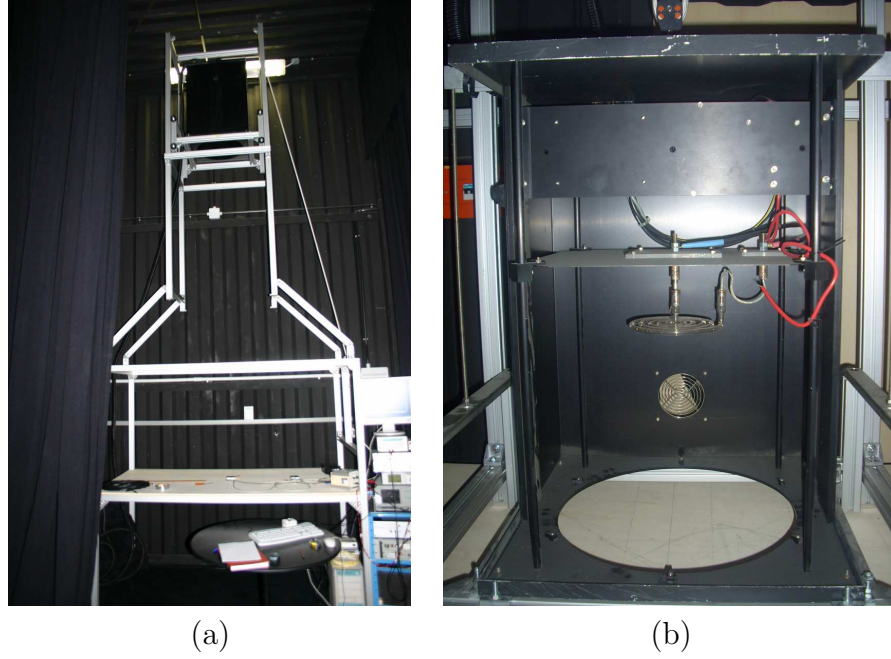


Figure 3.2: (a) The pre-existing GPS setup. (b) The lamp housing with the Xe lamp spiral bulb.

therefore by

$$2\overline{AB} \leq 0.4r. \quad (3.7)$$

Keeping GPS as a point-like source producing $E(r) = 1X$ total irradiance at a distance-to-target $r = 5$ m, then the solar simulator would theoretically produce $E(r) = 400X$ when $r = 25$ cm and up to $2500X$ when $r = 10$ cm. Table 3.4 shows theoretically calculated intensities at various distance-to-target values, together with the diameter of a testing plane where Class A uniformity is obtainable.

The test device and a reference cell are placed on the test plane, at the same distance from the centre of the optical table, within the area where a sufficiently good uniformity is provided (see section 3.2.3 below). If the size of the test device does not allow it to be placed close enough to the reference cell, two different measurements need to be performed, placing alternatively the testing device and the reference cell in the same position on the test plane and making two separate measurements. The level of irradiance is controlled in this case by a monitor cell placed as close as possible to the test plane, to correct for any difference in irradiance between the two flashes.

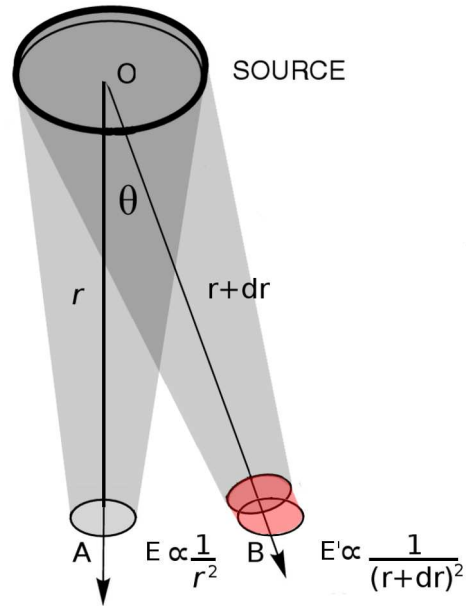


Figure 3.3: Modified GPS: dependence of light intensity with distance-to-target. Lower intensity in point B than in point A is expected due to the longer distance from the lamp (point-like source assumption).

Position	Distance-to-target, r [cm]	Irradiance, $E(r)$ [suns]	Test diameter, $2AB$ [cm]
1	500	1 ± 0.02	200
2	200	6.25 ± 0.13	80
3	100	25.0 ± 0.5	40
4	50	100 ± 2	20
5	25	400 ± 8	10
6	10	2500 ± 50	4

Table 3.4: GPS Upgrade: estimated total irradiances at various distance-to-target positions and estimated target diameter where $\pm 2\%$ uniformity (class A) is calculated (eq. (3.7)), according to a r^{-2} -law.

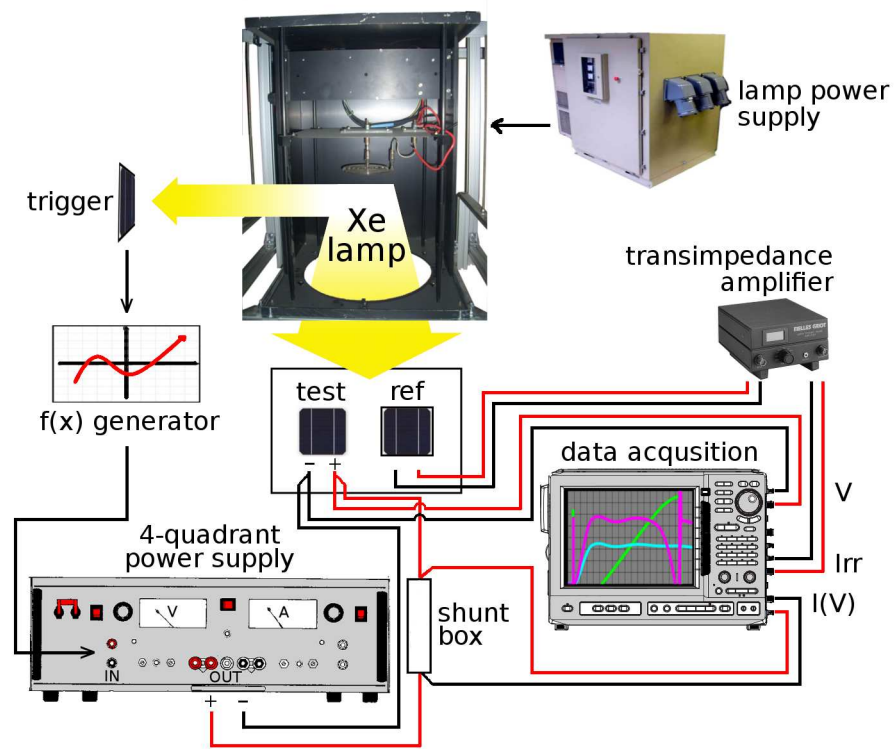


Figure 3.4: A schematic of the experimental setup of the GPS-U high-intensity solar simulator.

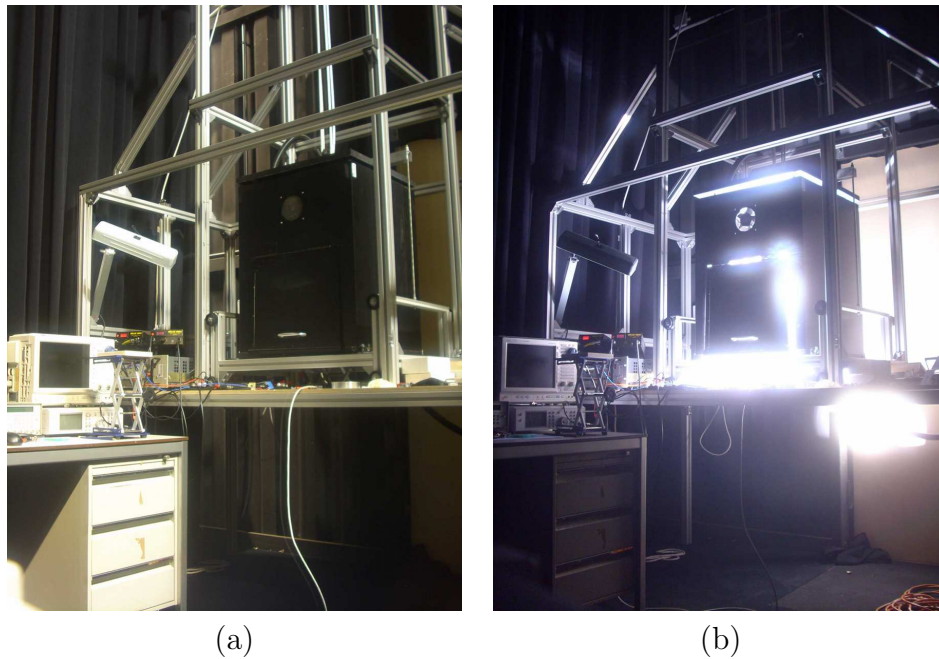


Figure 3.5: GPS-U: (a) a picture of the experimental setup and (b) during the 15 ms flash.

Figure 3.4 shows a schematic of the concentrating solar simulator (from now on simply referred to as GPS-U). A c-Si Hamamatsu photodiode covered by a neutral density filter (optical density: $OD = 3$) is attached to the side of the lamp housing, providing the trigger signal to a waveform generator. The waveform generator provides a ramp signal to the power supply that converts it into a voltage ramp between $-\epsilon$ and $V_{oc} + \epsilon$, where ϵ is the minimum voltage bias to enable zero-crossing both at short-circuit and at open-circuit conditions in the IV curve of the test device. The voltage ramp is provided by a 4-quadrant voltage-controlled bipolar operational amplifier supplied by Kepco Inc. The 4-quadrant operation is required for the dissipation of the energy produced by the test device during the measurement.

Data are recorded by a ScopeCorder DL750 oscilloscope supplied by Yokogawa, with 10 MHz maximum sample rate.

The total irradiance is measured by means of a calibrated reference cell. The reference cells are fitted with suitable neutral density filters in order to maintain them in their linear operating range. Further details on the assembly and calibration of the filtered reference cells are given in section 3.2.5.

The test plane is a copper cooling plate, furnished to pipes for the connection with a cooling/heating system which maintains the table at a desired temperature.

Figure 3.5a shows a photograph of GPS-U. Figure 3.5b shows a photograph taken during the 15 ms flash.

The uncertainty analysis for current-voltage measurements on GPS-U was performed by the author, following the indications of the standard Guide for Uncertainty Measurements (GUM, [123]) and the paper by H. Mülleijans et al. of the ESTI laboratory [124]. The detailed uncertainty calculation is reported in Appendix D.

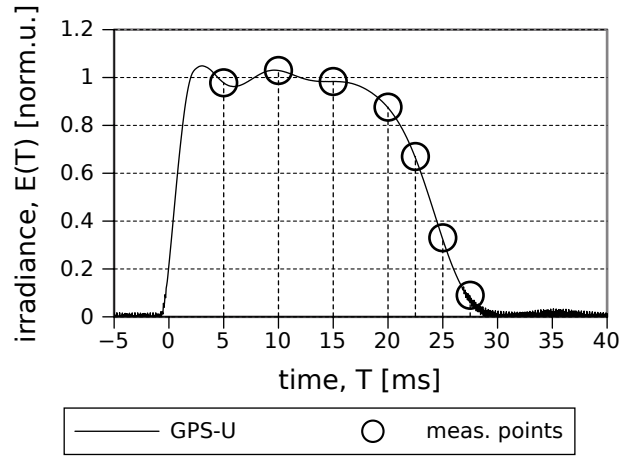


Figure 3.6: GPS-U: a typical pulse profile. Points where spectral irradiance have been measured are highlighted. The irradiance is normalized to the value at $T = 10$ ms.

3.2.2 Spectral irradiance

The spectral Irradiance of GPS-U has been measured with a fast single polychromator spectroradiometer (wavelength range: 250-1100 nm).

Figure 3.6 shows the pulse profile of GPS-U: the time scale T is referred to the photodiode trigger signal to the data acquisition system. With this time-scale, the irradiance plateau starts at $T = 2$ ms and is maintained with a systematic oscillation, up to $T = 17$ ms. A long decaying irradiance tail then follows until $T = 30$ ms.

To analyse the temporal stability of the spectral irradiance seven measurement points have been selected, both during the plateau (at $T = 5, 10, 15$ ms) and after the plateau (at $T = 20, 22.5, 25, 27.5$ ms). Spectra have been normalized to the same global irradiance and compared. Figure 3.7a shows the percentage distribution of spectral irradiance, in the bands defined in the standard [101]).

Figure 3.7b shows the difference between the percentage distributions at $T = 5, 15$ and 20 ms and the reference percentage distribution at $T = 10$ ms (in the middle of the plateau). Absolute differences in spectral distribution are less than 0.5% within the plateau region.

The GPS-U absolute spectral irradiance $E_{GPS}(\lambda)$ has been calculated in order that the

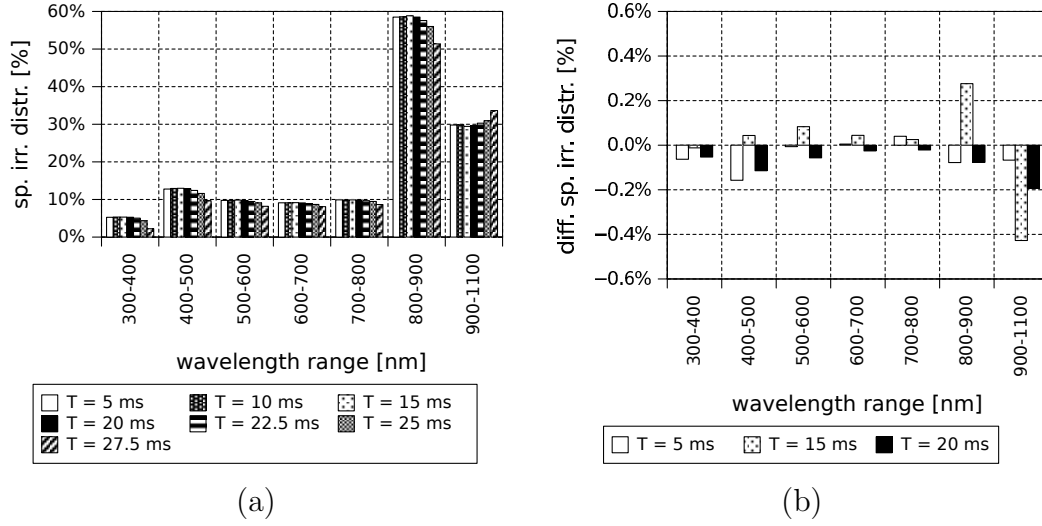


Figure 3.7: GPS-U spectral irradiances: (a) percentage distribution; (b) deviation of percentage distribution (reference spectrum: $T = 10$ ms).

short-circuit current density of a c-Si reference cell at 1000 Wm^{-2} is equal to the calculated short-circuit current density at STC, as follows

$$\int_{300}^{1200} EQE_{ref}(\lambda) E_{GPS}(\lambda, T = 10 \text{ ms}) \lambda d\lambda = \frac{1000}{900} \int_{300}^{1200} EQE_{ref}(\lambda) E_{AM1.5d}(\lambda) \lambda d\lambda, \quad (3.8)$$

where the integral has been taken within the limits of the EQE of the c-Si reference cell considered ($EQE_{ref}(\lambda)$) and the fraction $\frac{1000}{900}$ scales the total irradiance of AM1.5d spectrum to 1000 Wm^{-2} .

For the purpose of standard classification as presented in section 3.1.1, GPS-U spectral irradiance measured between 300 and 1100 nm is sufficient. Classification of GPS-U according to the standard requirements will be discussed in section 3.2.4. However the definition of wavelength bands according to the standard is certainly poor for the characterization of many III-V group multi-junction CPV cells, where typically Ge junctions respond up to 1700 nm.

The spectral irradiance from 1100 to 2000 nm could not be measured with the available fast spectroradiometer, so it has been linearly extrapolated as listed in Table 3.5, assuming a spectral percentage distribution consistent with the spectrum of a typical Xe lamp that can be found in the literature [118]. Figure 3.8 shows the percentage spectral distri-

	range [nm]	AM1.5d [%]	Xe [%]	GPS-U [%]
UVA	320-350	0.8	1.2	0.4
	350-400	2.6	3.0	3.6
VIS	400-450	5.7	4.4	5.0
	450-500	7.7	5.8	5.9
	500-550	7.8	5.4	4.1
	550-600	7.7	5.4	4.0
	600-650	7.5	5.1	3.8
	650-700	7.1	4.9	3.7
IR	700-800	12.0	8.4	8.0
	800-900	10.2	14.5	19.0
	900-1000	6.1	17.0	19.8
	1000-1100	7.1	6.1	3.8
	1100-1500	10.4	12.1	12.3*
	1500-2000	7.4	6.5	6.5*

Table 3.5: GPS-U unfiltered spectral irradiance: percentage distribution of various ranges over the entire range 320-2000 nm. The GPS-U spectrum has been rescaled in order to give the same total irradiance over the range 300-2000 nm as the standard spectrum AM1.5d. *Linear extrapolation beyond 1200 nm to give a distribution close to that of a typical Xe lamp (source: [118]). The AM1.5d spectral distribution is shown for comparison.

bution over the full wavelength range 300 – 2000 nm of the extrapolated GPS-U spectrum compared with the standard AM1.5d spectrum. The chart highlights the improvement in spectral irradiance distribution when a spectrally selective filter is used.

Table 3.6 shows the percentage spectral distribution for several wavelength bands that match the spectral response ranges of various CPV cell types. Data are plotted in the chart in Figure 3.9. The worst band is in the range 300 – 700 nm (typical top, InGaP, junction of a 3-junction CPV cell), where the percent of spectral distribution is more than 16% less in GPS-U than in the standard spectrum. Even the range 300 – 900 nm shows a high mismatch between GPS-U and AM1.5d, while the range 600 – 900 nm is better matched.

3.2.3 Spatial uniformity and temporal stability

Spatial non-uniformity of irradiance $S_{N,E}$ has been calculated according to eq. (3.4) at various level of total irradiance measured at the centre of the test plane. A c-Si photodiode

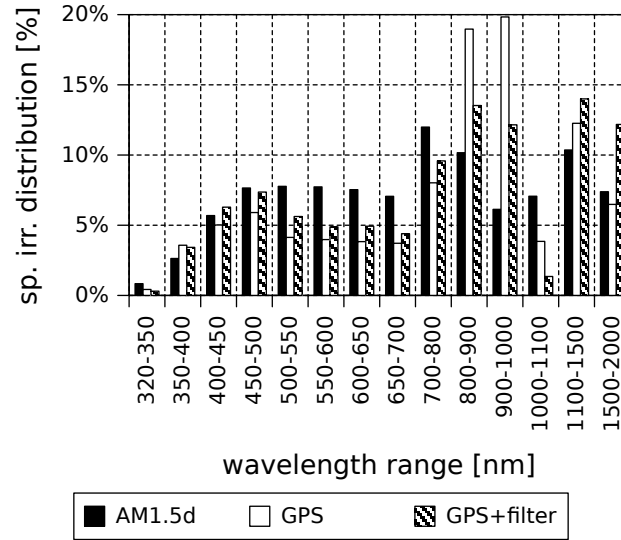


Figure 3.8: GPS-U spectral irradiance: percentage distribution.

cell type	range [nm]	AM1.5d [%]	Xe [%]	GPS-U [%]	GPS-U + filter [%]
c-Si	300-1200	82.3	81.3	81.3	73.8
GaAs	300-900	69.1	58.2	57.6	60.3
InGaP	300-700	46.9	35.2	30.6	37.2
InGaAs	600-900	36.7	32.9	34.5	32.4
Ge	900-2000	30.9	41.8	42.4	39.7

Table 3.6: GPS-U spectral irradiance: percentage distribution of spectral ranges for CPV cell types under examination over the entire range 300-2000 nm.

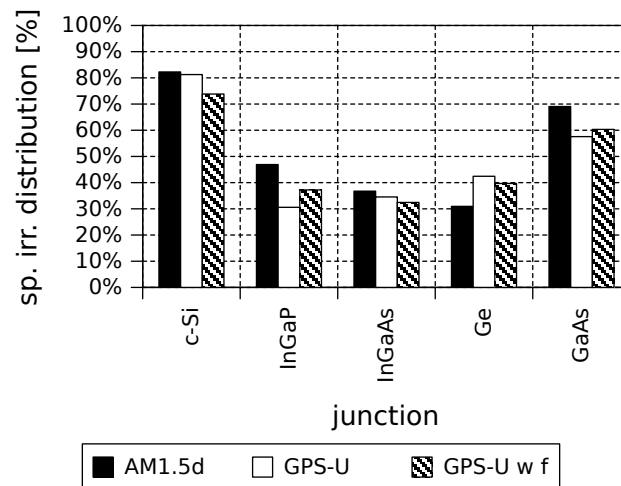


Figure 3.9: GPS-U spectral irradiance: percentage distribution of spectral ranges (per range of SR of cell type, Tab. 3.6).



Figure 3.10: Spatial uniformity. (a) c-Si photodiode used as detector (active area: 2.5 mm^2); (b) measurement setup. The detector has been covered with an $OD = 3$ neutral density filter for measurements at high intensity.

(active area: 2.5 mm^2) filtered with a neutral density filter ($OD = 3$, see Figure 3.10a) has been used as a detector.

Measurements at all points at a given concentration have been normalized to the irradiance at point $(0,0)$, the centre of the plane. Figure 3.10b shows a picture of the experimental setup with the photodiode in the middle of the measurement plane and the monitor cell on its left.

Results obtained at various concentration (30X, 120X, 240X, 470X and 880X, respectively) are shown in Figure 3.11.

Temporal instability $T_{I,E}$ has been calculated according to eq. (3.5) between maximum and minimum irradiance in four different time intervals within the 15 ms plateau of the GPS-U pulse highlighted in Figure 3.12a, giving results reported in Table 3.7. Within the uncertainty required in the standard, in all intervals $T_{I,E} \leq 5\%$ has been calculated and $T_{I,E} \leq 2\%$ in a 8 ms interval.

Repeatability of GPS-U pulse has also been tested over six different pulses shown in Figure 3.12. The percentage difference between the pulses shows repeatability to within 1%.

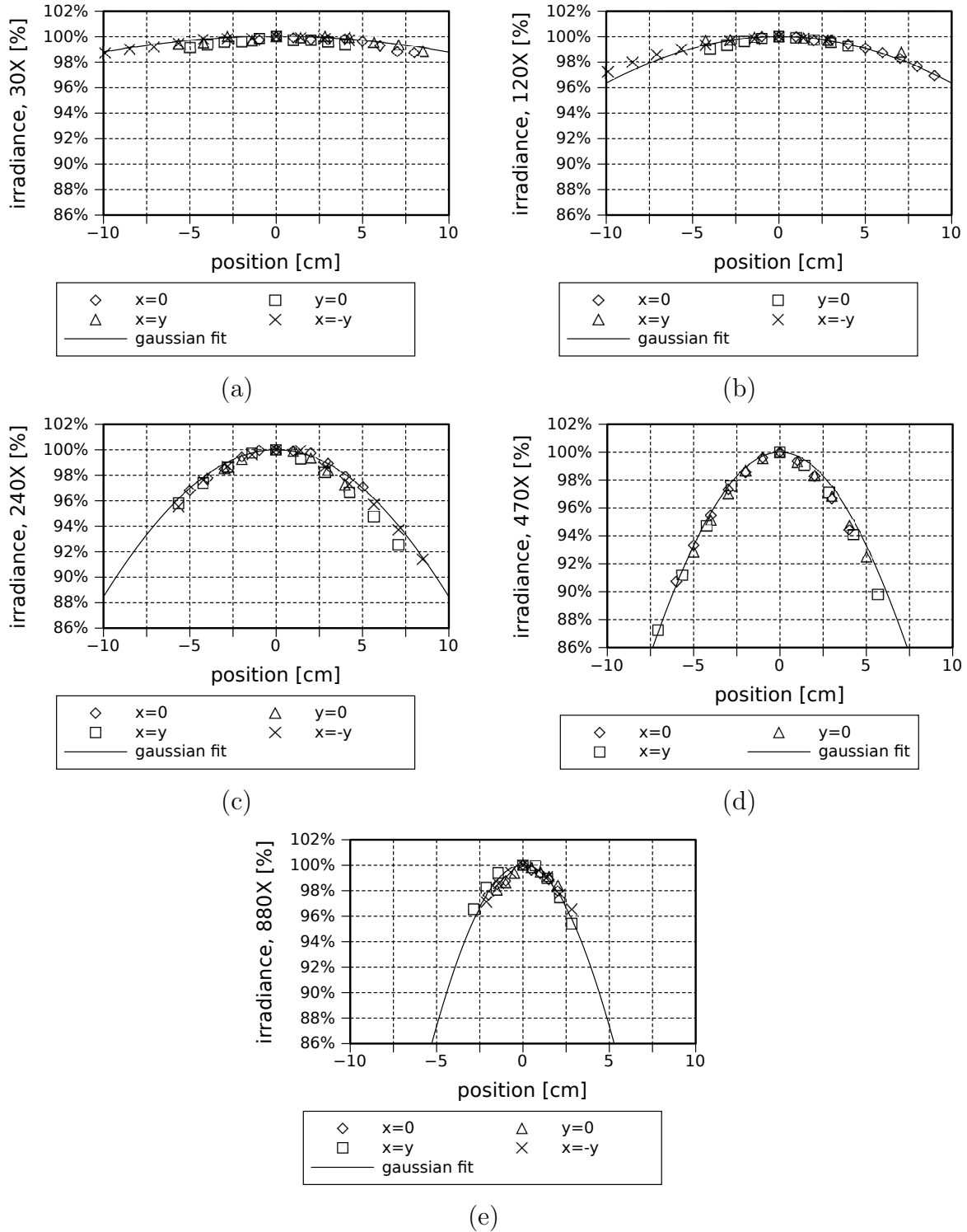


Figure 3.11: Spatial uniformity. Percentage variation over a $200 \times 200 \text{ mm}^2$ target plane at: (a) 30X, (b) 120X, (c) 240X, (d) 470X and (e) 880X.

Time interval [ms]	Pulse1	Pulse2	Pulse3	Pulse4	Pulse5	Pulse6	Average $T_{I,E}$ [%]
5-20	5.0	4.7	4.6	4.7	4.8	5.1	5
8-20	4.2	3.8	3.9	3.8	3.9	4.2	4
8-18	3.4	2.7	3.0	2.8	2.7	2.4	3
10-18	2.5	2.0	2.3	2.1	1.9	2.5	2

Table 3.7: Temporal instability of irradiance (in %) over six different pulse. Four different time intervals within the 15 ms plateau have been selected.

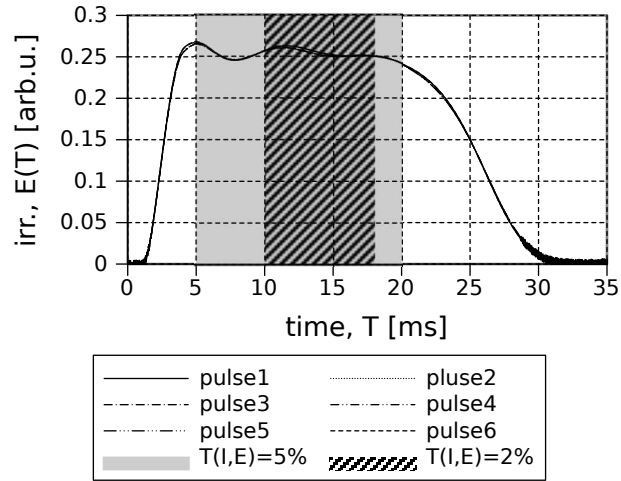


Figure 3.12: Temporal instability of irradiance: comparison between a series of six consecutive pulses (time intervals where $T_{I,E} = 2\%$ and 5% are highlighted).

Band [nm]	AM1.5d [%]	GPS [%]	Spectral match	Class	GPS + filter [%]	Spectral match	Class
300-400	not spec.	-	-	-	-	-	-
400-500	16.9	14.1	0.8	A	19.5	1.2	A
500-600	19.7	10.5	0.5	C	15.0	0.8	A
600-700	18.5	9.8	0.5	C	13.3	0.7	B
700-800	15.2	10.4	0.7	B	13.7	0.9	A
800-900	12.9	24.6	1.9	C	19.3	1.5	C
900-1100	16.8	30.7	1.8	C	19.3	1.1	A
1100-1400	not spec.	-	-	-	-	-	-

Table 3.8: Classification of distribution of spectral irradiance, with respect to the standard spectrum AM1.5d, according to the ASTM standard [122]. No specifications are currently given outside the range 400-1100 nm. GPS-U is classified as a Class C simulator, related to spectral distribution. With the spectrally selective filter, the spectral distribution improves: nevertheless, GPS-U remains a Class C simulator due to the poor performance in the wavelength interval 800-900 nm.

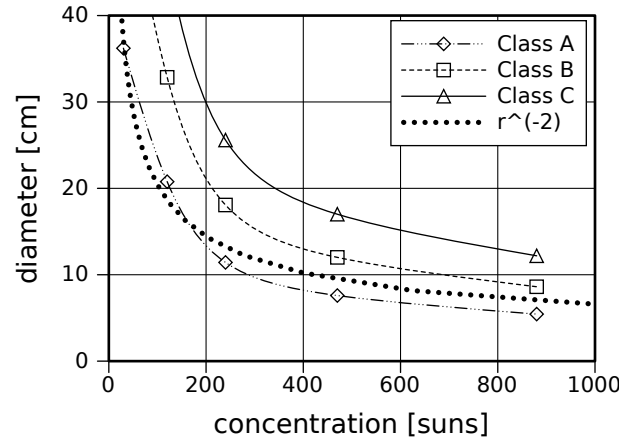


Figure 3.13: Classification of spatial uniformity performance, according to the ASTM standard [122]. Theoretical r^{-2} -estimation for class A uniformity is also shown (see Table 3.4).

3.2.4 Classification according to the ASTM Standard

In Table 3.8 comparison is made between the distribution of spectral irradiance of the standard AM1.5d spectrum with that of GPS-U. Several wavelength intervals lead to Class C spectral irradiance classification. Better spectral distribution is observed when an available spectrally selective filter is added on top of the spectroradiometer detector: nevertheless even with the filter used GPS-U remains a Class C simulator due to the poor performance in the wavelength interval 800-900 nm.

Figure 3.13 shows the calculated spatial non-uniformities $S_{N,E}$ calculated at different concentrations and on different circular test areas. The maximum diameter of the test area where GPS-U still meets the standard requirements indicated is shown. Class A spatial uniformity has been verified up to 880X.

The temporal instability $T_{I,E}$ has been calculated in the previous section, being within 5% even in the full 15 ms plateau for data acquisition. When test device and reference cell sizes allow simultaneous measurement of current, voltage and irradiance, this value is enough to classify GPS-U as a Class A simulator for temporal instability. When this is not the case, Class A requirement for temporal instability is reduced to $T_{I,E} \leq 2\%$ and therefore the maximum available sweep time for measurements needs to be reduced to

8 ms, the time interval where this condition is met.

In conclusion, at present GPS-U can be classified as a Class CAA solar simulator. A better classification may be possible in principle by means of a more appropriate spectrally selective filters to improve the spectral percent distribution according to the standard.

3.2.5 Calibration of intensity filtered c-Si reference cells for CPV cells characterization

The following measurement protocol has been developed for the calibration of a set of N reference cells for high intensity measurements up to a maximum irradiance $E_{\max}$.

Step 0: Select a set of N reference cells of known linearity. Reference cells are labelled with $j = 0, \dots, N - 1$.

The range of linearity of the short-circuit current with irradiance of each reference cell (from $E_{j,\min} = E_{0,\min}$ to $E_{j,\max} = E_{0,\max}$) determines the number of cells N required to cover the total range of irradiance for high intensity CPV cell characterization up to $E_{\max}$.

To test the linearity of short-circuit current with respect to irradiance, ASTM standard test method E 1143-05 may be used [125]: a set of n (minimum $n = 4$) equally spaced irradiance values E_i is selected; short-circuit current of the test reference cell is measured at each irradiance; the slope of the linear interpolation of n data pairs is calculated as follows

$$m = \frac{\sum_{i=0}^{n-1} E_i I_{sc,i}}{\sum_{i=0}^{n-1} E_i^2}; \quad (3.9)$$

the estimated variance of the slope is calculated as follows

$$s = \sqrt{\frac{\sum_{i=0}^{n-1} (I_{sc,i} - m E_i)^2}{n \sum_{i=0}^{n-1} E_i^2}}. \quad (3.10)$$

The chosen reference cell is linear in the selected range if $\frac{s}{m} \leq 2\%$.

The following steps describe the calibration procedure to the $N - 1$ reference cells, with

respect of the $j = 0$ reference cell. Reference cells with $j = 1, \dots, N - 1$ are used at irradiances higher than $E_{0,\max}$ where linearity is fulfilled and are therefore equipped with a neutral density filter (NDF) with an appropriate optical density OD_j . NDFs provide broadband attenuation of the irradiance, allowing the j -th reference cell to be used at a higher intensity range from $E_{j,\min}$ to $E_{j,\max}$ where it responds linearly.

Step 1: Select the maximum level of irradiance for the $j = 0$ reference cell, $E_{0,\max}$, on the high intensity solar simulator and calibrate at that level the $j = 1$ reference cell, equipped with a NDF of $OD = OD_1$. The NDF chosen needs to satisfy the following relation

$$OD_1 \leq \log_{10} \frac{E_{0,\max}}{E_{0,\min}} \quad (3.11)$$

in order the $j = 1$ reference cell to be linear from $E_{1,\min} = E_{0,\max} = E_{0,\min} \cdot 10^{OD_1}$ to $E_{1,\max} = E_{0,\max} \cdot 10^{OD_1}$.

Step 2: Select the maximum level of irradiance for $j = 1$ reference cell, $E_{1,\max}$ and calibrate at that level the $j = 2$ reference cell, equipped with a NDF with $OD_2 = 2 \cdot OD_1$. The $j = 2$ reference cell will then be linear from $E_{2,\min} = E_{1,\max} = E_{0,\min} \cdot 10^{2 \cdot OD_1}$ to $E_{2,\max} = E_{0,\max} \cdot 10^{2 \cdot OD_1}$.

Step j : Proceed as above with the j -th reference cell, setting the simulator irradiance to the maximum level for the $(j - 1)$ -th reference cell, $E_{j-1,\max}$ and calibrating the j -th reference cell which is equipped with a NDF of $OD = j \cdot OD_1$. As a result, the j -th reference cell will be linear from $E_{j,\min} = E_{j-1,\max} = E_{0,\min} \cdot 10^{j \cdot OD_1}$ to $E_{j,\max} = E_{0,\max} \cdot 10^{j \cdot OD_1}$.

Step $(N - 1)$: The procedure stops at the $(N - 1)$ -th reference cell, that is linear from $E_{N-1,\min} = E_{N-2,\max} = E_{0,\min} \cdot 10^{(N-1) \cdot OD_1}$ to $E_{N-1,\max} = E_{0,\max} \cdot 10^{(N-1) \cdot OD_1}$.

The following relation holds, giving the total number of reference cells N as a function of

$E_{0,\min}$	$E_{0,\max}$ [suns]	$E_{N-1,\max}$	OD_1 [a.u.]	N
0.75	1.1	1500	0.15	22
0.5	1.1	1500	0.3	11
0.1	1.1	1500	1	4

Table 3.9: Calibration of reference cells equipped with neutral density filters. Given reference cells linearity range ($E_{0,\min}$, $E_{0,\max}$) and maximum irradiance available $E_{N-1,\max}$, maximum optical density for the first step (OD_1) and minimum number of reference cells needed N can be calculated as shown. $OD_j = j \cdot OD_1$, for $j = 2, \dots, N - 1$.

Ref. cell	Type	Area [mm ²]	NDF	OD, nominal at 632.8 nm [a.u.]	range [suns]
PX501C	c-Si	400	-	-	0.75-1.1
ASP004	c-Si	200	-	-	0.1-1.5
ASP009	c-Si	200	one	1.5	1-50
ASP010	c-Si	200	two	1.5+1.3	50-500
ASP004	c-Si	200	one	3.0	100-1500

Table 3.10: Set of ESTI reference cells with number of neutral density filters used and nominal optical density value. The range of intensity where the linearity of the device is certified is shown. ASP004 has been used in two different configurations.

the limits of irradiance $E_{0,\min}$, $E_{0,\max}$ where the chosen reference cells respond linearly

$$N \geq 1 + \frac{\log_{10} \frac{E_{N-1,\max}}{E_{0,\min}}}{\log_{10} \frac{E_{0,\max}}{E_{0,\min}}}. \quad (3.12)$$

If reference cells have minimal linearity requirement (e.g. 0.75 to 1.1X), $N = 22$ reference cells are needed in principle, to cover the full irradiance ranges from 1X to 1500X, as shown in tab. 3.9. The number of reference cells required decreases if devices with wider linearity ranges are chosen. If reference cells with linear response between 0.1X and 1.1X are available, then four reference cells are enough to cover the full range, three of them equipped with NDFs, $OD = 1, 2$ and 3 respectively.

All ESTI c-Si reference cells are calibrated annually at 1X, AM1.5g spectral irradiance. A set of reference cells developed within the ASPIRE project have linear response between 0.1X and 1.5X. Table 3.10 lists the five c-Si reference cells used in the calibration procedure.

<i>OD</i> , nominal at 632.8 nm	<i>OD</i> , meas. at 630 nm	<i>OD</i> _{max}	<i>OD</i> _{min}	<i>OD</i> average
1.3	1.28	1.30	1.23	1.26 ± 0.02
1.5	1.44 1.6*	1.57 1.7*	1.39 1.2*	1.43 ± 0.03 $1.5 \pm 0.1^*$
1.3+1.5	2.7*	2.7*	2.2*	$2.7 \pm 0.1^*$
3.0	3.1 3.1*	3.7 3.3*	2.6 2.7*	3.1 ± 0.2 $3.0 \pm 0.1^*$

Table 3.11: OD calibration of NDFs (in dimensionless units): comparison between nominal and measured values. Results from the “EQE method” are labelled with an *.

A set of quartz metallic neutral density filters (NDFs) supplied by NewportTM has been used. Quartz neutral density filters with metallic coating provide flat and broadband attenuation between UV and NIR. The coating is deposited on one side of the 3.0 mm thick slab.

The maximum energy density to which a NDF may be subject without failures (called the *damage threshold*) is a critical issue. These NDFs have a 0.030 kWcm^{-2} continuous wave (CW) damage threshold, corresponding to a concentration of 300X. However there is no indication of the damage threshold under pulsed, non-laser irradiation: the author has postulated that the damage threshold in this case is high enough to freely allow measurements up to 500X and after measurements above 600X the spectral response of the reference cells has been remeasured, providing evidence of no permanent damage.

Reference cells PX501C and ASP004 have been used without NDFs for the calibration at 1X on ESTI’s continuous solar simulator WXS-155S-L2 supplied by WacomTM (from now on simply referred to as WACOM). It is a Class AAA steady state, multi-lamp (Xe + QTH) solar simulator, with $155 \times 155 \text{ mm}^2$ test area and $\pm 1\%$ temporal instability.

ASP009 has been equipped with a nominal $OD = 1.5$ NDF, while ASP004 with a nominal $OD = 3.0$ NDF. To be able to cover all testing range of intensities, ASP010 has been equipped with two stacked NDFs of nominal $OD = 1.5$ and $OD = 1.3$, respectively.

The transmittance and OD of the NDFs used have been calibrated in the ESTI optical calibration laboratory on a spectrophotometer UV/VIS/NIR supplied by Perkin ElmerTM,

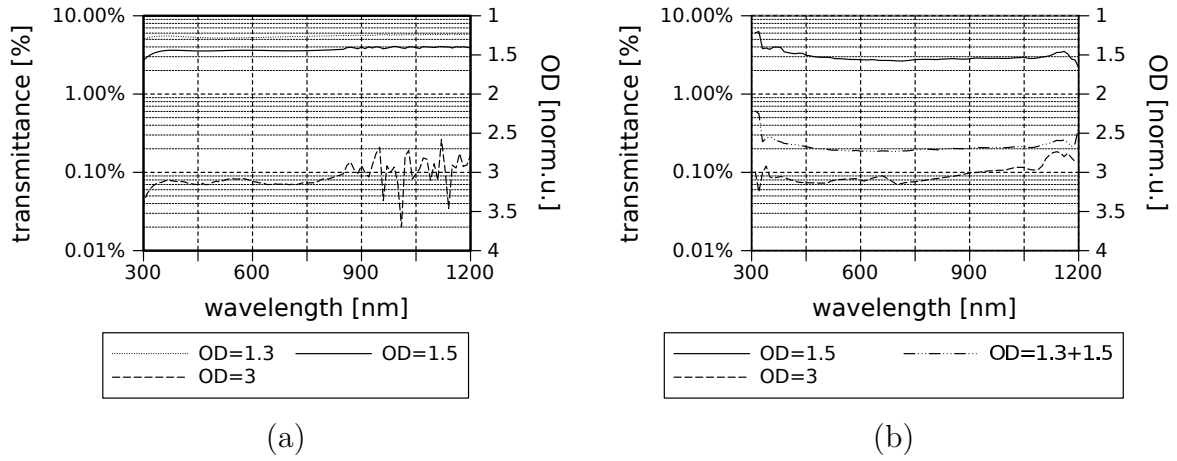


Figure 3.14: ESTI reference cells. Transmittance (in logarithmic scale) and OD (in reversed linear scale) of the NDF used: (a) calibration with the spectrophotometer and (b) from relative EQE measurements (“EQE method”).

a double beam double monochromator recording UV, visible and NIR radiation from 250 to 2500 nm. Results are shown in Figure 3.14a.

Transmittance values below 1% lead to very low signal-to-noise ratio, therefore the NDFs were further characterized, calculating the ratio between the EQEs of a reference cell with and without NDFs (here also referred to as the “EQE method”). Results of the calibration according to this second method are shown in Figure 3.14b. Table 3.11 summarizes results in each NDF configuration considered.

The EQE of all five reference cells with and without filters have been measured on ESTI’s spectral response measurement setup (ORIEL) described in section 2.2.4. Results for the ASP009, ASP010 and ASP004 reference cells are shown in Figure 3.15, where the EQE of each reference cell with and without the NDF are shown on different scales.

Table 3.12 shows results of the calibration procedure, giving calibration values at STC (in mA). The calculated MMF between the test device and the reference cell in each step is also shown. Results of the calibration have been verified during the characterization of c-Si CPV cells of known linearity. An example of the verification will be presented in section 3.3.

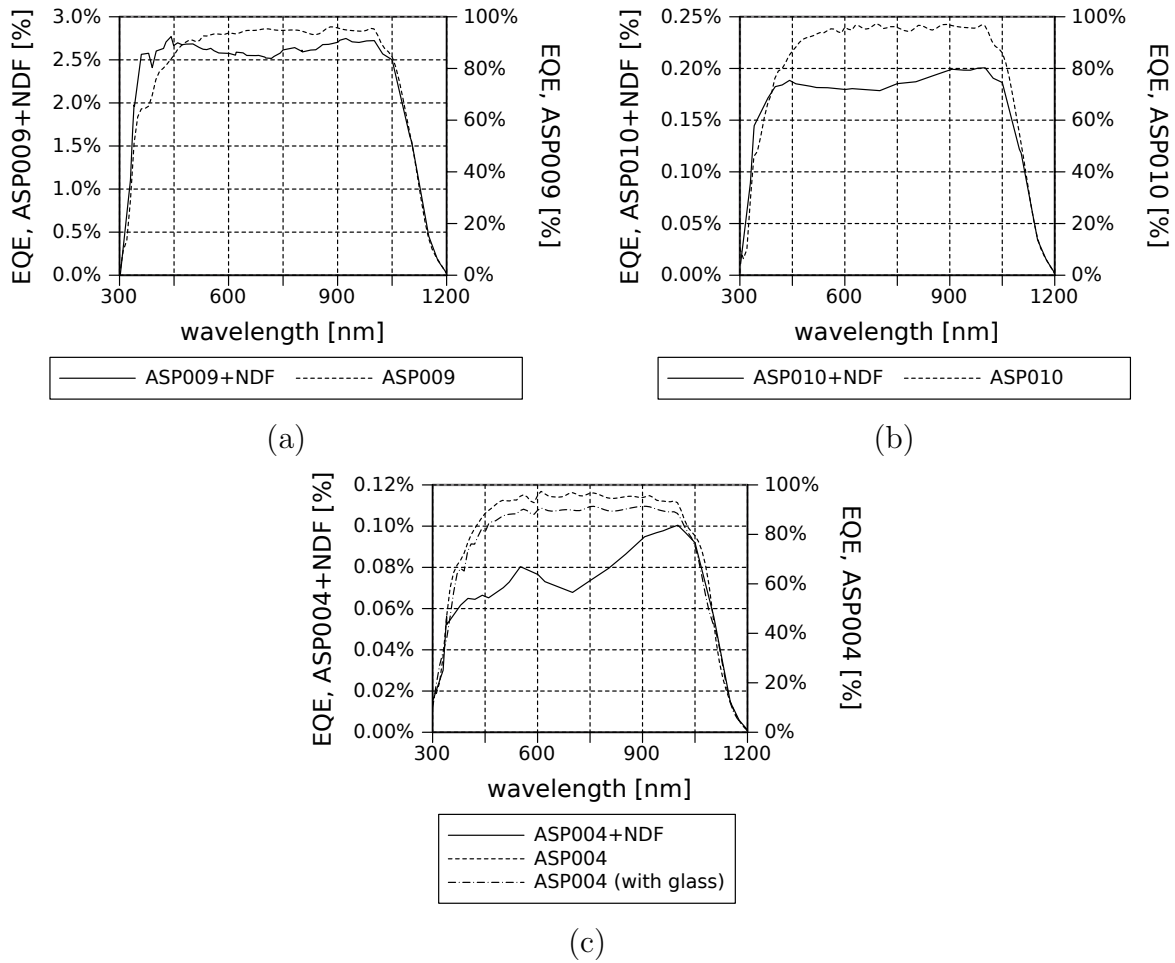


Figure 3.15: ESTI reference cells. External quantum efficiency measurements and comparison with and without NDFs: (a) ASP009 (nominal $OD = 1.5$), (b) ASP010 (nominal $OD = 1.5 + 1.3$) and (c) ASP004 (nominal $OD = 3.0$).

Step	Ref. Cell	Cal. Value [mA]	MMF [norm.u.]	Test Cell	Cal. Value [mA]
1	ASP004 (wo NDF)	80.12	0.996	ASP009	2.47
2	ASP009	2.47	0.990	ASP010	0.201
	ASP009	2.47	0.994	ASP004	0.0765
3	ASP010	0.201	1.004	ASP004	0.0767

Table 3.12: Calibration procedure of high intensity c-Si reference cells by means of NDFs. ASP004 has been used both without NDF as a reference at 1X (step 1) and with NDF ($OD = 3$) to be calibrated at higher intensities.

3.2.6 Linearity of CPV cells: the proposed self-reference method

The calculation of cell efficiency from measurements at high intensities is not trivial due to the high uncertainty that may be involved. Uncertainty in the intensity measurement may come from the following sources (see Appendix C for details): (a) spatial non-uniformity, if the test device and the reference cell are not perfectly centred within the measurement plane; (b) reference cell and test device alignment (i.e. orientation and co-planarity), especially when the geometry of the two devices is different; (c) uncertainty in reference cell calibration factor; (d) uncertainty in MMF calculation. The latter especially has been shown to be as high as 1.8 for III-V CPV multi-junction cells on GPS-U when c-Si cells are used as reference (see Appendix E).

Efficiency calculation as a function of intensity is much more straightforward if the short-circuit current of the device is a linear function of the irradiance up to the maximum intensity $E_{\max}$ required. In this case the irradiance intensity $E(X)$ (in suns) can be determined directly from the short-circuit current value measured at that irradiance $I_{sc,X}$ and from the calibrated value at 1X $I_{sc,1X}$, as follows

$$E(X) = \frac{I_{sc,X}}{I_{sc,1X}}. \quad (3.13)$$

The following protocol is therefore suggested (*self-reference method*):

1. Linearity verification of the test device (*linearity test*)

The test device and a reference cell are placed in the centre of the test plane, where Class A uniformity is fulfilled. The short-circuit current of the reference cell and of the test device are measured at various irradiances: at least four different equally-spaced irradiance values should be tested for each calibrated reference used.

Linear regression parameters m and s as defined in eqs. (3.9)-(3.10) are calculated for each of the reference cells in use. Linearity of the device can be assumed if $\frac{s}{m} \leq 2\%$ [125].

2. Characterization of the test device at 1X

The test device is calibrated at 1000 Wm^{-2} on the solar simulator with the best classification for spectral irradiance, in order to minimize the mismatch calculation and optimize current balance. The short-circuit current is then spectrally corrected to AM1.5d, applying the proper MMF.

3. Characterization of the test device at higher irradiances

IV characterization at desired values of irradiance is performed on the high-intensity solar simulator. Since linearity of the devices has been proven in point 1, there is no need to use a reference cell, but the test device itself gives the value of irradiance at each step, by means of eq. (3.13). Using no reference cell, spectral mismatch correction is also not necessary in this method at this step.

The validity of the method above is predicated on points 1 and 2. Uncertainty in the short-circuit current value measured at 1X propagates in results of measurements at higher intensities and should be minimized. Fill factor and cell efficiency may be affected by incorrect current balance on multi-junction CPV cells, due to the Class C spectral irradiance of GPS-U.

3.3 Characterization of CPV Cells: Results on c-Si

3.3.1 Current-voltage characterization

Several CPV cells (see Table 3.13) have been characterized on GPS-U, focusing on the measurement procedure, not on the particular cells. In this section results of a c-Si CPV cell (LX701) will be presented. Results of the characterization of III-V CPV cells are reported in Appendix E.

Figure 3.16 shows a typical data acquisition procedure on LX701. Current, voltage and irradiance data are acquired simultaneously by the data acquisition system, therefore the sweep time has always been chosen as the maximum available in the measurement plateau.

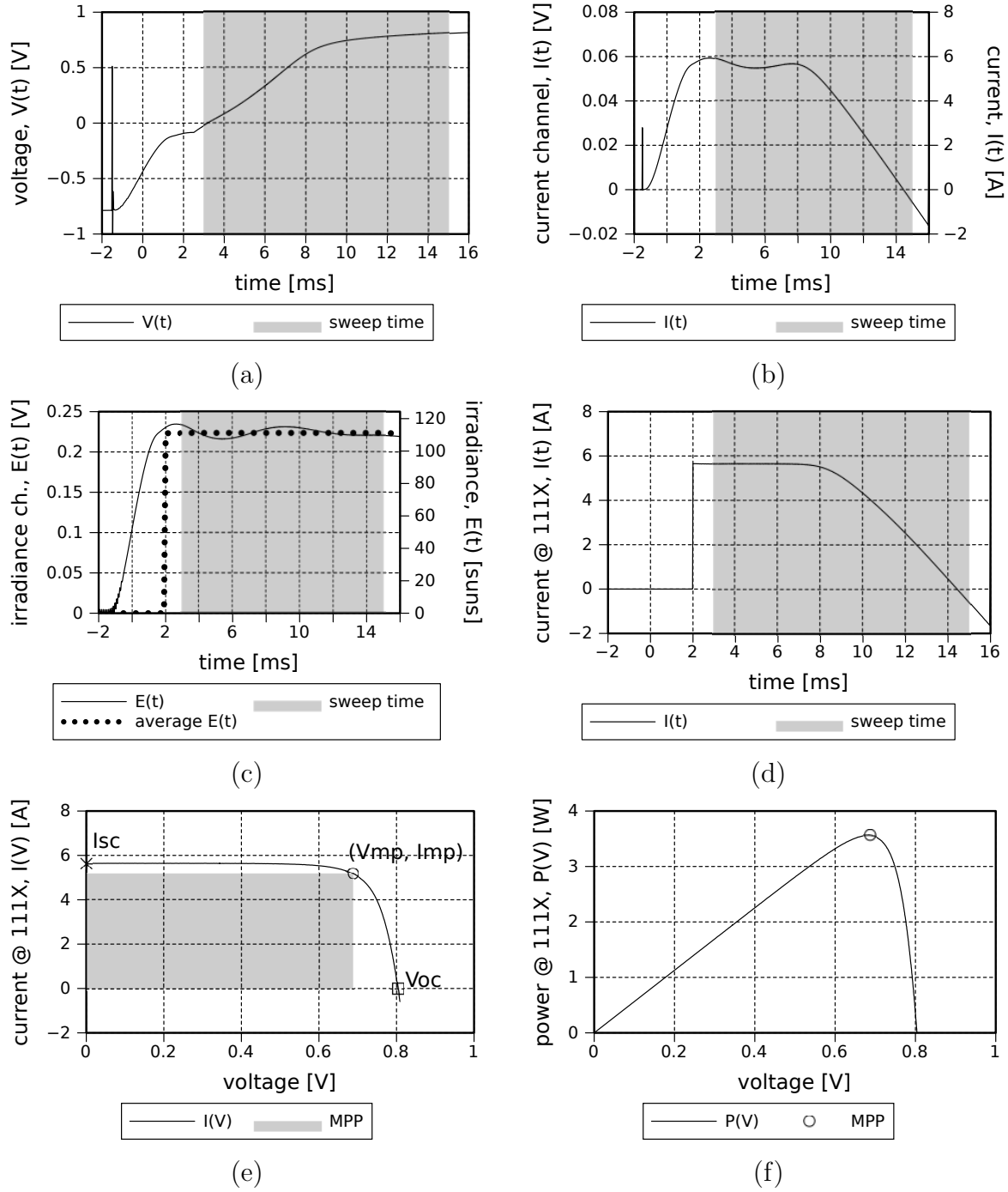
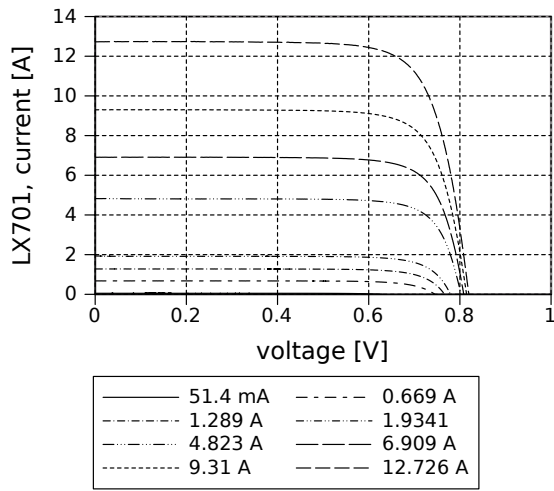


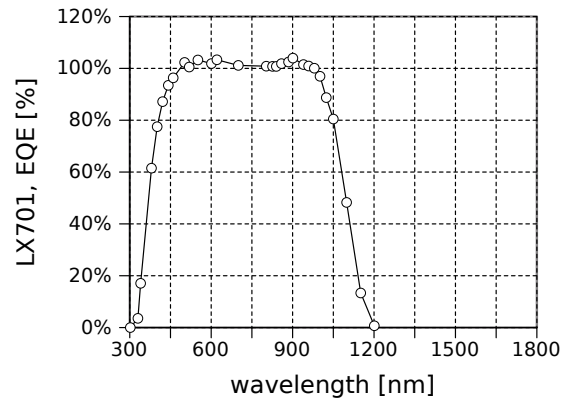
Figure 3.16: An example of data acquisition output. Test device: LX701; sweep time: 12 ms, from $t = 3$ to $t = 15$ ms; sample rate: 5 MHz (recorded), 50 kHz (displayed). (a) Voltage versus time $V(t)$ (in V), (b) current versus time $I(t)$ (channel signal in volts and data output in amperes via shunt resistor, $R = 0.01 \Omega$); (c) irradiance versus time $E(t)$ (channel signal in volts and data output in “suns” via shunt resistor, $R = 10.0051 \Omega$, ref. cell. ASP010, ref. cell cal. value $I_{sc,ref}^{STC} = 0.201$ mA); (d) current, normalized over average irradiance $E = 111X$; (e) current versus voltage $I(V)$ at 111X; (f) power versus voltage $P(V)$ at 111X.

ESTI code	cell structure	area [mm ²]	range
LX701	c-Si	121	(1-300)X
NE505	GaInP/GaInAs/Ge	30	(1-1000)X
MO703	GaInP/GaInAs/Ge (MQW)	32.9	(1-500)X
MO705	GaAs/Ge (MQW)	32.9	(1-500)X

Table 3.13: The CPV cells tested. Results on NE505, MO703 and MO705 are reported in Appendix E.



(a)



(b)

Figure 3.17: LX701: (a) IV characterization at various irradiances; (b) External quantum efficiency.

Ref. cell Simulator	ASP004 (wog) WACOM	PX501C WACOM	ASP009 GPS-U	ASP010 GPS-U	ASP004 GPS-U
LX701	0.995	-	0.999	1.010	-

Table 3.14: MMF calculation.

Figures 3.16a, b and c show the voltage ramp, the test device current and reference cell irradiance signals, respectively. The average irradiance value is calculated within the measurement plateau highlighted (from 3 to 15 ms), giving the intensity value of 111X in the example shown. The current signal of the test device $I(t)$ is then normalized to the average irradiance, giving the curve plotted in Figure 3.16d. The final IV curve is then obtained by plotting the current signal I as a function of the voltage ramp V (Figure 3.16e). Output power as a function of voltage is shown in Figure 3.16f.

IV curves measured on LX701 are shown in Figure 3.17a. Each curve has been labelled by its short-circuit current value.

3.3.2 External quantum efficiency and spectral mismatch factor calculation

The EQE of each testing device has been measured with the experimental setup described in Chapter 2. The EQE of LX701 is shown in Figure 3.17b.

Calculated MMF values with respect to c-Si reference cells and solar simulators used are listed in Table 3.14. The WACOM solar simulator has been used for cell characterization at 1X. Using a c-Si reference cell (ASP004 without NDF) in the characterization at 1X on WACOM of LX701 determines a MMF close to unity ($MMF = 0.995$), giving a small correction to the measured short-circuit current. A similar result occurs when measurement is performed on GPS-U Class C spectrum (result calculated at 1000 Wm^{-2} ; ref cell.: ASP009; $MMF = 0.999$): this result confirms that the Class C spectral irradiance of GPS-U does not affect measurements of c-Si CPV test devices.

Unlike LX701, III-V group test devices generally have significantly larger MMFs on GPS-

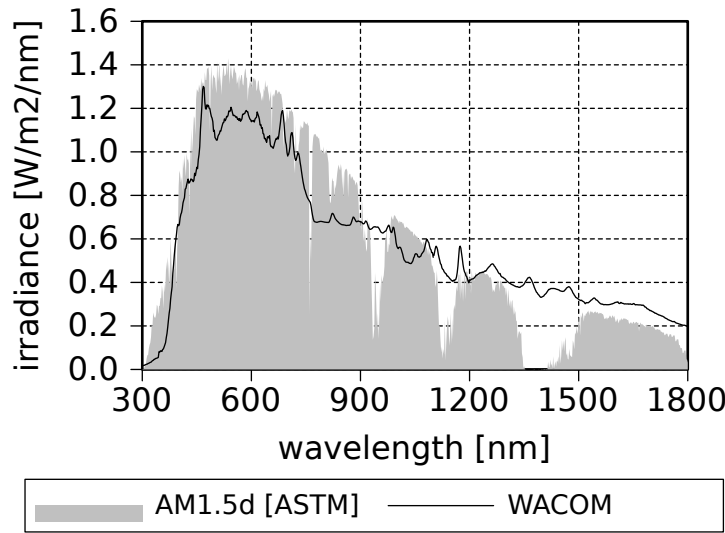


Figure 3.18: WACOM Class A spectral irradiance.

U than on WACOM (see Appendix E).

3.3.3 Linearity test and cell efficiency

Figure 3.19 shows the linear response of LX701 short-circuit current to increasing irradiance on GPS-U. Linearity is verified by comparison of the test device short-circuit current values measured on GPS-U with the known linear responses of the filtered reference cells ASP009 (between 10X and 30X) and ASP010 (between 90X and 250X). The comparison is a relative measurement and no spectral mismatch correction is needed.

According to ASTM standard test method E 1143-05 [125], the slope of the linear regression can be calculated by eq. (3.9), giving for the linearity versus ASP009 and versus ASP010, respectively: $m_{ASP009} = 0.0202 \text{ A mA}^{-1}$ and $m_{ASP010} = 0.251 \text{ A mA}^{-1}$. The estimated variances of the slope, eq. (3.10), are $s_{ASP009} = 3 \times 10^{-4} \text{ A mA}^{-1}$ and $s_{ASP010} = 0.002 \text{ A mA}^{-1}$, giving

$$\frac{s}{m}[\text{ASP009}] = 1.4\% \quad (3.14)$$

$$\frac{s}{m}[\text{ASP010}] = 0.7\%, \quad (3.15)$$

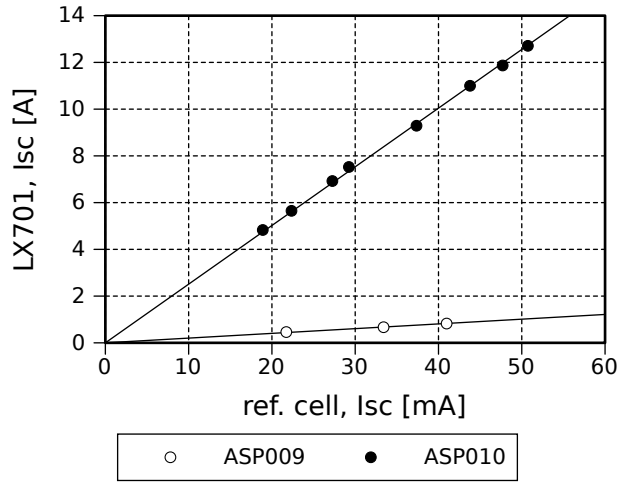


Figure 3.19: Linearity on GPS-U: LX701.

respectively, both meeting the linearity criterion $\frac{s}{m} \leq 2\%$.

Linearity of LX701 within $\pm 2\%$ all over the irradiance testing range can also be verified from results listed in tab. 3.15, where the following parameter has been calculated

$$\text{Linearity}[\%] = \frac{I_{sc}}{E \cdot I_{sc,1X}} \cdot 100\%, \quad (3.16)$$

where I_{sc} is the short-circuit current measured at irradiance E (in suns) corrected to AM1.5d and $I_{sc,1X}$ is the short-circuit current value at 1000 Wm^{-2} .

Electrical parameters of LX701 are plotted versus the concentration level in Figures 3.20a-d.

The concentration level has been calculated in the following two ways. First, directly from the reference device, in line with the standard procedure for non-CPV cells IEC60904-3 [22]. Secondly, from the self-reference method described above in section 3.2.6.

3.4 Comparison of GPS-U with the State of the Art

The performance of GPS-U can be compared with the performances of the other high intensity solar simulators on the market (see Table 3.16).

Irradiance, E [suns]	V_{oc} [V]	I_{sc} [A]	FF [%]	MMF [norm.u.]	$I_{sc}^{AM1.5d}$ [A]	MPP [W]	η [%]	Linearity [%]
1	0.632	0.051	76.6	0.996	0.051	0.0248	20.5	100
9	0.727	0.460	77.0	1.001	0.461	0.258	23.7	100
13	0.745	0.669	77.2	1.001	0.669	0.385	24.5	101
16	0.752	0.82	77.4	1.001	0.83	0.481	24.8	101
25	0.766	1.29	77.9	1.001	1.29	0.771	25.5	101
95	0.803	4.8	78.7	1.012	4.9	3.1	26.7	101
111	0.804	5.6	78.6	1.012	5.7	3.6	26.7	100
136	0.809	6.9	78.1	1.012	7.0	4.4	26.8	100
187	0.815	9.3	77.4	1.012	9.4	5.9	26.3	98
219	0.817	11.0	76.8	1.012	11.1	7.0	26.3	99
238	0.817	11.8	76.2	1.012	12.0	7.5	25.9	98
254	0.819	12.7	76.1	1.012	12.9	8.0	26.1	99

Table 3.15: LX701: summary. Data are displayed to the significant digit and with 95% confidence ($k = 2$). For the uncertainty analysis see Appendix D.

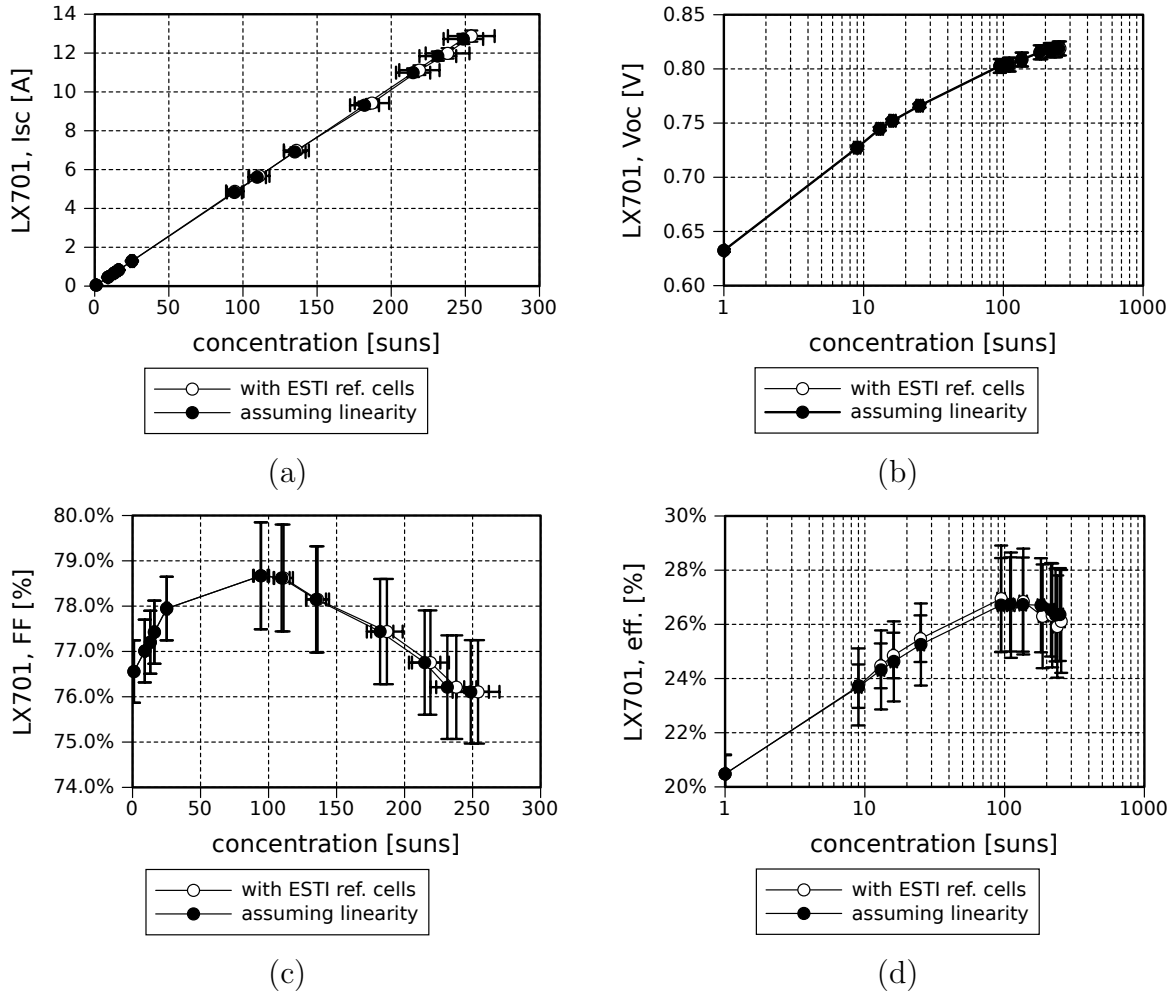


Figure 3.20: Electrical performance at various concentration: LX701. The $k = 2$ (95% confidence) uncertainty bars are plotted according to the analysis in Appendix D.

Name	Intensity [suns]	Target Size [cm]	Spatial Unif. [%]	Temporal Stab. [%]	Spectral Match [%]
Newport-Oriel	30-50X	1.5 (diam.)	$\pm 5\%$	$< 1\%$	$\pm 12\%$
Spectrosun X-25	< 1 -200X	1×1	$\pm 3\%$	$\pm 1\%$	n.a.
AOPT Gen2	5-1000X	2.5×1.5	$\pm 2.5\%$	$\pm 5\%$	n.a.
GPS-U	5-1000X	6 (diam.)	$\pm 2\%$	$\pm 2\%$	$\pm 50\%$
T-HIPSS	200-2000X	10×10	$\pm 2\%$	$\pm 1\%$	$\pm 14\%$
AOPT Gen1	400-2400X	2.5×2.5	$\pm 1.5\%$	$\pm 5\%$	n.a.
Flash Tester	1-3000X	1×1	$\pm 3\%$	$\pm 2\%$	$\pm 20\%$
4-lamp Flash Tester	1-3000X	1×1	$\pm 3\%$	$\pm 2\%$	$\pm 8\%$

Table 3.16: Comparison between GPS-U and the other simulators of Table 3.1, page 100 (further specifications on these simulators can be found there).

Intensities up to 1000X have been proven (see the results on NE505 in Appendix E): this is not a strong limitation towards the simulators showing higher intensities, since CPV cells currently produced have maximum efficiencies between 100X and 600X and little interest is shown in the literature on measurements above 1000X. From this point of view, the range of intensities of GPS-U is the best one together with AOPT Gen2, allowing in principle the characterization of all CPV cells of interest, from middle intensity (c-Si) to high intensity CPV (III-V group multi-junction cells).

The high spatial uniformity (among the highest ones: only T-HIPSS has a larger target area that satisfies the Class A requirement) allows the simultaneous measurement of the test device and of a reference cell for linearity tests, whose importance has been discussed.

While the temporal stability is not a stringent requirement, the absence of Fresnel concentrating optics in GPS-U is in principle beneficial, since these typically affect the spectrum negatively (*dichroic aberration*). Nevertheless, the strongest limitation of GPS-U is its Class C spectral match, which finally results in the need of spectrally selective filters to let it compete with the best simulators on the market to date.

3.5 Conclusions

The development of a pulsed high intensity solar simulator from an existing pulsed, single-source, 1000 Wm^{-2} solar simulator was described in detail in this chapter. In the absence of an international standard for the classification of a high intensity simulator, the new simulator was classified according to the requirements specified by the American standard ASTM E-927-05.

The spectral irradiance was carefully measured by the author at different time intervals during the 15 ms measurement plateau, showing that the spectral distribution does not vary significantly during the pulse. The spectral irradiance was then classified according to the standard requirements, resulting in a Class C solar simulator for spectral irradiance.

Since the interest in III-V CPV cells is continually growing in importance, it is important to know the spectral distribution of GPS-U above the limit of 1100 nm where the standard requirements for spectral irradiance end. In the absence of a fast spectroradiometer sensitive in this range, spectral irradiance from 1100 to 2000 nm was extrapolated to match the spectral characteristics of Xe lamps commonly used in flash simulators. The spectral distribution of GPS-U was then analysed, highlighting possible problems that may be found in the characterization of multi-junction CPV cells.

To complete the classification of GPS-U, spatial non-uniformity and temporal instability were also analysed. As a result, GPS-U is classified as a Class CAA solar simulator, with possible improvements of spectral irradiance by means of spectrally selective filters available on the market. This additional upgrade is beyond the objectives of the author's research activity.

To allow standard measurement of the irradiance at high intensity, the use of non absorptive neutral density filters with high damage threshold, to shield the reference cells from the concentrated light, was implemented. The ideal testing protocol for the calibration of a set of reference cells was proposed, each reference cell being equipped with a NDF of different optical density value, to cover the widest range of irradiance. It was shown that

four reference cells allow the range of irradiance from 1X to 1500X to be covered, if the linearity range of each non-filtered cell is between 0.1X to 1.1X, which is reasonable for high quality reference cells in use at ESTI. A set of reference cell were then calibrated to be used in the preliminary characterization of CPV cells of various technologies.

Preliminary results obtained on a set of CPV cells were finally presented and discussed in this chapter (c-Si) and in Appendix E (III-V group cells), with particular attention to the linearity test of the devices.

Spectral mismatch correction was also analysed in detail on test devices. c-Si test cells do not present particular problems in the calibration, confirming GPS-U as an optimum high intensity simulator for that technology. The current balance of multi-junction CPV cells is a critical issue and a solar simulator with a spectrum significantly different to the reference one may result in measured fill factors higher than the correct value at STC. The impact of this artefact has been analysed in the literature and may affect the FF and cell efficiency calculation.

Chapter 4

Pre-normative Characterization of Luminescent Solar Concentrators

4.1 Introduction

The collaboration between ESTI and Imperial College has been particularly fruitful within the European Integrated Project FULLSPECTRUM [126], whose overall objective was to pursue a better exploitation of the whole solar spectrum via developing high-level research in five different areas (the five “work-packages”, WP): (1) III-V multi-junction cells for CPV; (2) solar-thermal PV converters; (3) intermediate bandgap materials and PV cells; (4) molecular-based concepts; and (5) manufacturing technologies for novel concepts and pre-normative work.

Imperial College was involved in WP4 (molecular-based concepts), where research was mainly dedicated to luminescent solar concentrators (LSCs), whose principle of operation has been described in Chapter 1 (section 1.4.3). The following partners made their contribution to the activity of the work package: the Energy Research Centre of the Netherlands (ECN, work-package leader), the University of Utrecht (the Netherlands), the Swiss company Solaronix, the Dublin Institute of Technology (EIRE), the Fraunhofer Institute for Applied Polymer Research (IAP, Germany) and of course ICL and ESTI.

ESTI's role (and the author's role in ESTI and within WP4 of FULLSPECTRUM) was to study and develop suitable procedures for indoor/outdoor characterization of novel devices such as LSCs, where standards do not exist. Among other problems to be defined in the pre-normative process, the following topics are discussed in this chapter: (a) the importance of computational models to describe the dynamics of light in the LSC; (b) differences in EQE measurements with a point-like or a wide beam monochromatic source; (c) angle of incidence effects in LSCs; (d) limits of applicability of the available standards for flat-panel modules to the current-voltage characterization of LSCs; and (e) the specific problems connected with the acceptance area definition of LSCs.

4.1.1 State of the art of LSCs

When FULLSPECTRUM ended in 2008, several results had been achieved on LSCs, among which: (a) the development of new computational models describing the performance of LSCs, especially regarding the optical efficiency of the concentrator plate, where experimental characterization is not straightforward; (b) the development of new and more stable luminescent dyes and, above all, of new quantum dots (QDs), in order to meet the stability requirement of LSCs and to provide new luminescent species with emission spectra that can be modified by tuning the QD dimensions (both these limitations have contributed in the past to slow the development of such devices); (c) stability tests, showing that candidates with more than two years of stability exist for commercially exploitable LSCs, and (d) cost-optimization studies [127].

A significant result of WP4 was the demonstration of a 7.1% efficient LSC module, jointly developed by ECN and Fraunhofer IAP, representing the highest efficiency reported to date for this kind of device [128, 38]. The record device has been characterized by the author and colleagues at ESTI [30] and details of the characterization are presented in this chapter.

LSCs were first proposed in the 1970s in parallel by Weber and Lambe [56] and by Goetzberger and Greubel [57]. In 1984 Luque proposed LSCs as a “venture to meet

the low cost target in PV” [129]. In a recent paper Van Sark et al. [130] described the most recent results in LSC development and characterization.

Computational methods have been applied as an important tool for the description of light dynamics in LSCs since the 1980s [131]. There are basically two different approaches that are traditionally followed. The first one is the thermodynamic approach [132, 133, 134], based on a detailed balance principle and describing the radiative energy transfer between mesh points in the concentrator plate. Limits of efficiency for LSCs have been investigated in the past based on this approach [135].

A second approach is the “ray-tracing method”: light is described as particle-like (photons) and each particle is tracked. A ray-tracing code is usually a Monte Carlo code, where a number generator is used to place photons randomly in their configuration space. The ray-tracing approach is particularly suitable for describing absorption/re-emission events and for arbitrarily shaped LSCs [136]. It is also a very useful tool for the description of LSC edge effects [137, 138].

Apart from computational methods, LSCs provide a challenge for their optical and electrical characterization, as has been early discussed by Batchelder et al. [139, 140] and by S3ti et al. [141]. The impact of scattering layers has been recently analysed in Ref. [142], in parallel with the work by the author presented in this chapter. The outdoor performance of LSCs has also been discussed, for example in Refs. [143, 144].

The interest in LSCs has increased in the last few years, due to improved stability of luminescent dyes [145], the introduction of quantum dots and nanorods [59, 146, 147] and the overall reported increase in module efficiency [148, 149].

4.1.2 Structure of the chapter

This chapter is structured into this introduction (section 4.1) and three further sections (see Table 4.1).

Section	Page	Content
4.1	134	- IP FULLSPECTRUM - State of the art - Structure of the chapter
4.2	138	- A basic Monte Carlo ray-tracing code - Experimental apparatus for the measurement of output light distribution - Uncertainty analysis - Results and comparison - Discussion of results
4.3	152	- Indoor/outdoor characterization of LSCs - Standard and “local” EQE measurements - The impact of a diffusive rear reflector - The angle-of-incidence effects - Record efficiency LSC
4.4	169	- Conclusions

Table 4.1: The structure of Chapter 4.

In section 4.2 a basic Monte Carlo code is presented [150]. Computational results have been confirmed with a second ray-tracing code developed independently by Rahul Bose (ICL, Experimental Solid State Group, Refs. [147, 151]). Bose and the author have also jointly developed a set of experiments to compare modelling predictions with experimental results. The experimental apparatus and a selection of results are presented in sections 4.2.2-4.2.3.

Section 4.3 discusses the electrical characterization of a set of LSCs both indoors and outdoors. As briefly introduced above, no dedicated standards exist for LSC measurements and section 4.3 emphasizes the following unusual aspects that need to be considered with particular attention when characterizing LSCs: (a) the intrinsic non-uniformity of the spectral response in a LSC; (b) the impact of a diffusive rear reflector (section 4.3.1, Ref. [152]); (c) the angle-of-incidence effects (section 4.3.2, Refs. [153, 154, 155]); and (d) the critical definition of the aperture area in LSCs (section 4.3.3).

The characterization of a set of LSC modules including the 7.1% record efficiency one is also presented at the end of section 4.3.

The conclusions are in section 4.4.

4.2 A Basic Ray Tracing Method for the Optical Performance Evaluation

4.2.1 Theoretical assumptions and description of the code

A Monte Carlo ray-tracing code was developed by the author to model the classical dynamics of light re-emitted by luminescent species in an LSC and the distribution of output light at the LSC edges.

Light behaviour is modelled by means of a set of N monochromatic, unpolarized, non-interacting classical particles in a rectangular box. When reaching the matrix-to-air interface, particles undergo the laws of classical optics: particles reaching the interfaces may bounce back inside (Fresnel reflection and total internal reflection, TIR) or be refracted by Snell's law. Secondary absorption is not taken into account.

A percentage of particles can be set to diffuse randomly when reaching the matrix-to-air interface, thus accounting for non-perfectly polished surfaces or the presence of a diffusive reflector (from now on, simply referred to as a “diffuser”).

The origin of the coordinate system (see Fig. 4.1) is set in the middle of the edge under examination, where the PV cell is placed; the z -axis is along the edge main axis; the y -axis is perpendicular to the LSC receiving surface and the x -axis forms a right-handed coordinate system.

The code was first developed in 2-dimensions (2D), to simulate the output angular distribution of light in the xy plane ($z = 0, x > 0$) at a given radius r from the origin. Alternatively, the z -distribution in a plane perpendicular to the xy plane at a given angle θ with the xz plane could be modelled. The model was then extended to 3D.

A fixed number N of particles are placed on a sub-grid $S_1 \times S_2 \times S_3$ inside a rectangular box $L_1 \times L_2 \times L_3$. Since the model does not describe the absorption and emission of light, but only the dynamics of emitted photons, two possible geometries can be chosen for the

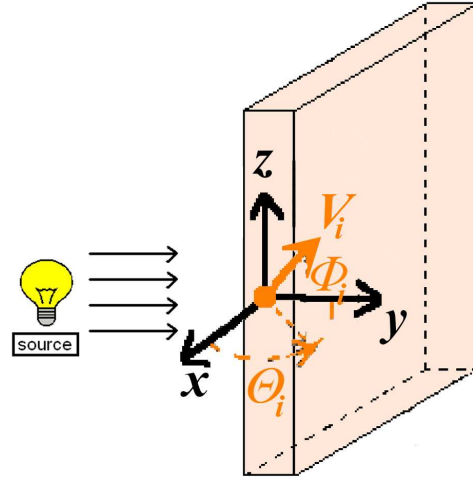


Figure 4.1: Ray-tracing model: coordinate system. The i -th particle position is in Cartesian coordinates (X_i, Y_i, Z_i) ; the i -th particle velocity is in polar coordinates (V_i, Θ_i, Φ_i) . For each particle is $V_i = V$.

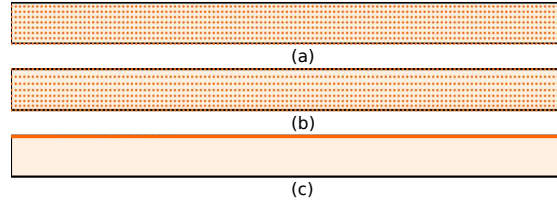


Figure 4.2: Ray-tracing model: starting particle distribution. (a) Uniform distribution ($N = 1040$); (b) Exponential distribution ($N = 1040, A = 2.5$); (c) Thin-film ($N = 1040$).

starting sub-grid:

- **Uniform distribution:** a rectangular grid of lattice constant $D = \left(\frac{S_1 S_2 S_3}{N}\right)^{\frac{1}{3}}$;
- **Exponential distribution:** the distance of neighbouring particles in y -direction grows as $\exp(Ay)$, A describing the absorbance of the matrix.

Typical values used in the simulations were: $L_1 = L_3 = S_1 = S_3 = 5$ cm, $L_2 = 0.5$ cm and $S_2 = 0.3$ cm (homogeneously doped LSC) or $S_2 = 0.01$ cm (thin-film composite LSC). Figure 4.2 shows examples of the cross section of three different starting configurations considered.

Each simulation consists of T runs (“throws”). At each throw, the i -th particle moves

with constant velocity¹ $\mathbf{V}_i$, whose magnitude is set in the input file. Here and in the following equations unit (dimensionless) time is used: therefore V has the dimension of a length and $V_i \ll \min\{L_1, L_2, L_3\}$. The dynamic of the i -th particle is described by six coordinates in its phase space $(X_i, Y_i, Z_i; V_{i,x}, V_{i,y}, V_{i,z})$, where X_i, Y_i and Z_i give the position over the axis x, y and z respectively; $V_{i,x}, V_{i,y}$ and $V_{i,z}$ are the three coordinates of the i -th particle velocity and are given by

$$\begin{aligned} V_{i,x} &= V \cos \Theta_i \cos \Phi_i \\ V_{i,y} &= V \sin \Theta_i \cos \Phi_i \\ V_{i,z} &= V \sin \Phi_i. \end{aligned} \tag{4.1}$$

Since V is constant, the i -th particle configuration is determined by the five coordinates $(X_i, Y_i, Z_i; \Theta_i, \Phi_i)$, being $\Theta_i, \Phi_i \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ (i.e., $V_{i,x} \in [0, V]$ - particles move only towards the positive- x direction -, $V_{i,y} \in [-V, V]$, $V_{i,z} \in [-V, V]$).

At the start, the code sets the N particles on the sub-grid and then moves them according to the randomly generated coordinates Θ_i and Φ_i . The new particle positions is thus given by

$$\begin{aligned} X'_i &= X_i + V \cos \Theta_i \cos \Phi_i \\ Y'_i &= Y_i + V \sin \Theta_i \cos \Phi_i \\ Z'_i &= Z_i + V \sin \Phi_i. \end{aligned} \tag{4.2}$$

For the i -th particle at new velocity $\mathbf{V}'_i$, the following cases may occur (Figure 4.3: n and n_0 are the refractive indexes of the LSC matrix and of air respectively):

- $(X'_i, Y'_i, Z'_i) \in L_1 \times L_2 \times L_3$: particle in the box (free-particle motion). Then simply

$$\begin{aligned} \Theta'_i &= \Theta_i \\ \Phi'_i &= \Phi_i. \end{aligned} \tag{4.3}$$

¹To avoid confusion, particle coordinates are in capital letters $(X_i, \dots, \Theta_i, \Phi_i, \mathbf{V}_i)$ while the coordinates in the system of reference are printed in small $(x, \dots, \theta, \phi)$. Vectors are in **bold**, scalars in *italic*.

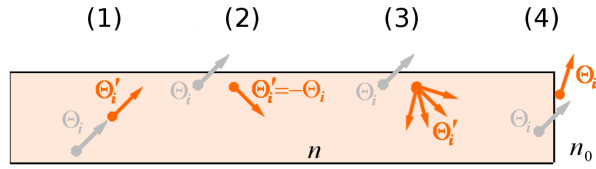


Figure 4.3: Ray-tracing model: particle dynamics after an iteration. (1) particle still in the box; (2) TIR; (3) scattering (diffusion); (4) refraction. n and n_0 are the refractive indices of the matrix and of air respectively.

- $(X'_i, Y'_i, Z'_i) \notin L_1 \times L_2 \times L_3$ and either $\frac{n}{n_0} \sin \Theta_i \notin [-1, 1]$ or $\frac{n}{n_0} \sin \Phi_i \notin [-1, 1]$: particle in the box (TIR). Then, depending on the geometry, either one of the following may occur

$$\begin{aligned}\Theta'_i &= \pm \Theta_i \\ \Phi'_i &= \pm \Phi_i\end{aligned}\tag{4.4}$$

and the new position (X'_i, Y'_i, Z'_i) is recalculated accordingly.

- $(X'_i, Y'_i, Z'_i) \notin L_1 \times L_2 \times L_3$ and both $\frac{n}{n_0} \sin \Theta_i \in [-1, 1]$ and $\frac{n}{n_0} \sin \Phi_i \in [-1, 1]$: Fresnel reflection. Then the particle is in the escape cone and may undergo either refraction or Fresnel reflection. A random number generator gives the unpolarized reflection coefficient R : if $R \leq \frac{1}{2}(R_p + R_s)$ then the particle is reflected as in eq. (4.4); otherwise it is refracted at a direction given by

$$\begin{aligned}\Theta'_i &= \arcsin\left(\frac{n}{n_0}\Theta_i\right) \\ \Phi'_i &= \arcsin\left(\frac{n}{n_0}\Phi_i\right).\end{aligned}\tag{4.5}$$

R_p and R_s are p -polarised and s -polarised reflection coefficients respectively and are given by

$$\begin{aligned}R_s &= \left(\frac{n \sin \Theta_i - n_0 \sin \Theta'_i}{n \sin \Theta_i + n_0 \sin \Theta'_i}\right)^2 \\ R_p &= \left(\frac{n \sin \Theta'_i - n_0 \sin \Theta_i}{n \sin \Theta'_i + n_0 \sin \Theta_i}\right)^2\end{aligned}\tag{4.6}$$

(similar relations hold for Φ_i and Φ'_i). The new position (X'_i, Y'_i, Z'_i) is recalculated accordingly.

Particles reflected back towards the negative x -direction are neglected. The position of

particles exiting the right hand edge at (4) in Fig. 4.3 is recorded in an output file. The simulation goes on until all particles have left the box or can be neglected.

The whole procedure is repeated a number of T runs, to improve the statistics while keeping N reasonably low and reducing the memory need. At each run the random number generator recalculates the coordinates Θ_i and Φ_i : as classical non-interacting free-particles in a box, the result of a simulation of $N = M \times T$ particles is statistically assumed to be equal to the result of a series of T throws of M particles.

Output particles can be counted at a chosen radius r as a function of θ and z or at the interface $x \approx 0$ as a function of y and z . They may also be counted at $|y| > \frac{L_2}{2}$ to calculate the spatial distribution of the particles that exit at the interface.

In addition, the elastic scattering (“diffusion”) of particles at the interfaces can be modelled, setting a certain fraction of particles at the interfaces to reflect in random directions. One or more interfaces can be selected to generate particle diffusion.

Figure 4.4a shows the $z = 0$ cross section of five steps in a single run of $N = 10^4$ homogeneously distributed particles in a $5 \times 5 \times 0.3 \text{ cm}^3$ box. Figure 4.4b shows the thin-film composite start distribution case ($S_2 = 0.1 \text{ mm}$).

Results of the simulation of output light distribution from the interface at $x = 0$ is presented in section 4.2.3. Data are compared with the experimental results observed with an original method developed at ICL and presented in the next section. In section 4.3.1, results of the modelled output particle distribution at $y = \frac{L_2}{2}$ are presented and compared with results obtained from the external quantum efficiency measurements of LSCs when a backside diffuser is added.

Table 4.2 lists a summary of the physical processes modelled by the ray-tracing code proposed.

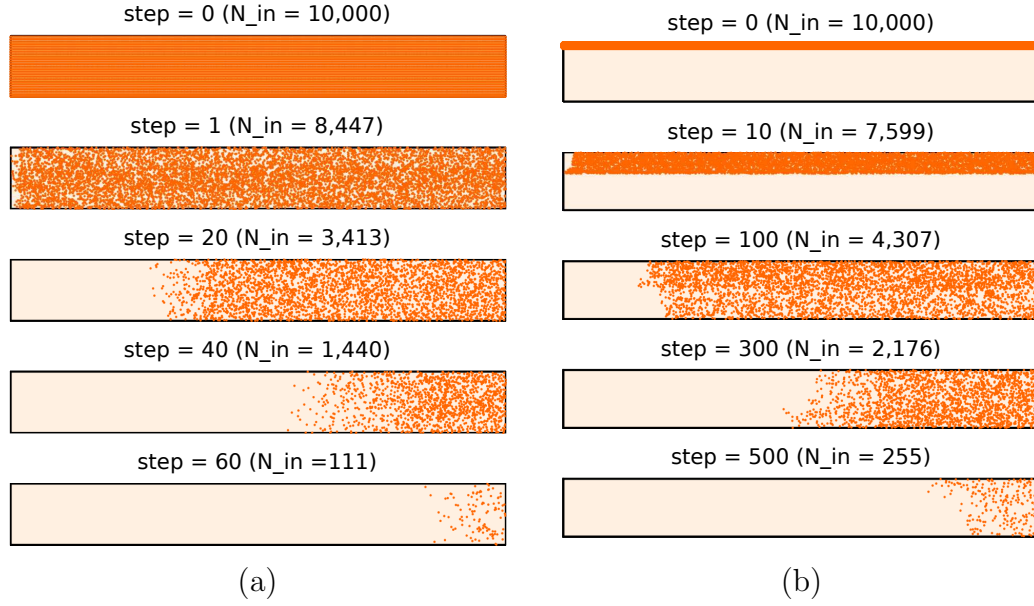


Figure 4.4: Ray-tracing model: 2D dynamics in the XY axis of $N = 10,000$ particles. Particle distribution at start and after several steps: (a) homogeneously doped and (b) thin-film composite LSC simulations ($S_3 = 0.1$ mm).

Physical Process	Classical Theory	Quantum Theory	Monte Carlo Code
Fresnel Reflection	●	●	●
Refraction	●	●	●
Polarization	●	●	○
Elastic scattering (diffusion)	●	●	●
Diffraction	●	●	○
Polychromatism	●	●	○
Dispersion	●	●	○
Inelastic scattering	○	●	○
Absorption	○	●	○
Photoluminescence	○	●	●

Table 4.2: Ray-tracing model: summary of classical and quantum physical processes taken into account in the simple model presented [156].

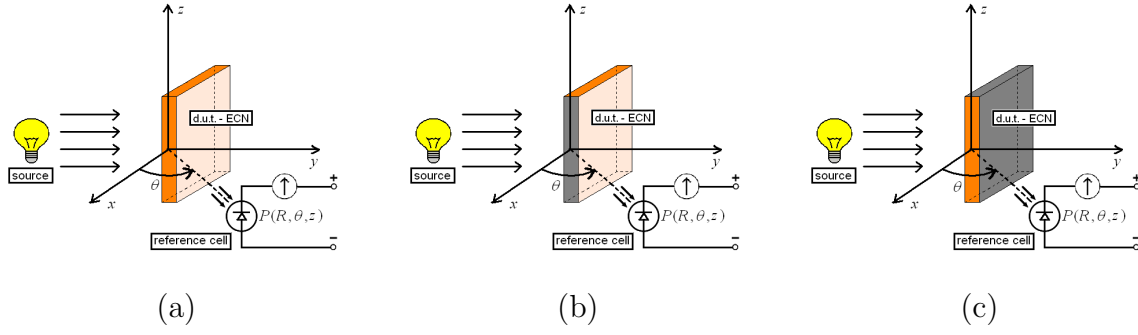


Figure 4.5: Output light spatial distribution: method of measurement. The background signal measured in (b) is subtracted by the raw signal from (a), giving the output light spatial distribution (c).

4.2.2 Experimental setup for output light distribution measurements

To measure the output light distribution from an edge of a LSC, output light coming from other faces and edges need to be blocked. Various methods have been proposed in the literature, involving the use of black shields [157] or integrating spheres [142, 158, 159, 160].

A new straightforward method has been developed by the author and Rahul Bose within the Experimental Solid State Physics group at ICL, and is described in Figure 4.5.

A square LSC is fixed in a vertical plane, facing the incoming light from the negative y -axis, with respect to the coordinate system introduced in the previous section. A reference c-Si PV cell is set to move in the half-space $x > 0$, at different (r, θ, z) positions.

Light striking the reference cell is assumed to be the sum of the output light from the edge under examination (from now on simply referred as the “output light”) plus light coming out from the other faces of the device and from the environment (from now on, simply the “background”, see Figure 4.5a). In order to separate the output light from the background, first the edge under examination is blackened, giving the background only (Figure 4.5b). Then subtracting the background from the whole signal gives the output light intensity measurement (Figure 4.5c).

Figure 4.6a shows a picture of the experimental apparatus described.

Uncertainty	Component	Type	Distr.	Comp.	k	Combined
Positioning	reference cell (R)	A	G	± 0.79	1	
	reference cell (θ)	A	G	± 1.45	1	
	coordinate system (x)	A	G	± 0.79	1	
	coordinate system (y)	A	G	± 0.79	1	
	coordinate system (z)	A	G	± 0.79	1	
Combined					1	± 2.144
Electrical	data acquisition syst.	B	R	± 0.1	$\sqrt{3}$	
Combined					1	± 0.058
Optical	test device alignment	-	-	-		
	background	-	-	-		
	source temp. stability	A	G	± 0.08	1	
Combined					1	± 0.075
Total					2	± 4.29

Table 4.3: Output light distribution measurement: uncertainty components for the measurement of irradiance in the setup shown in Figure 4.6. Data are in %. It is indicated whether the uncertainty distributions are type A or B, rectangular (R) or gaussian (G) and the coverage factor k (see Appendices C and D for definitions and further details).

4.2.3 Results and comparison

The output light distribution of several $5 \times 5 \times 0.3 \text{ cm}^3$ homogeneously doped and thin film composite LSCs were tested, to investigate how the doping differences may affect the performance of an attached PV cell.

The following sections report the results of the experimental investigation and the comparison with the predictions of the Monte Carlo ray-tracing model introduced above.

4.2.3.1 Output light distribution as a function of θ

Figure 4.7 shows the comparison between the measured angular distribution of output light from the $x = 0$ edge and results from the simulation with the ray-tracing model. Measurements were performed at $r = 5 \text{ cm}$ and over the $z = 0$ plane. Experimental results are shown in dots, while the model prediction is the continuous line.

Particles at angles between $\theta - \frac{\Delta\theta}{2}$ and $\theta + \frac{\Delta\theta}{2}$ are counted and plotted as a function of θ ($\Delta\theta$ is chosen in order that $r\Delta\theta$ matches the aperture size of the reference cell in the

experimental setup described above).

Figures 4.7a-b refer to a homogeneously doped LSC, whose measured angular distribution showed an asymmetry near $\theta = 0$. This asymmetry has been observed also by Bendig et al. in 2008 [157]: as Figure 4.7b shows it can be easily reproduced by the ray-tracing model discussed with a non-uniform distribution of starting particles, taking into account the exponential decrease of the absorbed particles within the PMMA matrix with increasing depth.

A stronger asymmetry at $\theta = 0$ is observed experimentally on the thin-film composite LSC and was also qualitatively reproduced by the ray-tracing model. However, the high peak at $\theta < 0$ in the model was not observed experimentally (Figure 4.7c).

Furthermore, a smaller but systematic difference between the model and the experiment can be observed in the distributions at wider angles. Both the latter discrepancies are discussed in a dedicated section below.

4.2.3.2 Output light distribution as a function of z

Figure 4.8 shows the distribution of output light as a function of z at fixed θ and $r = 5$ cm.

In the ray-tracing simulation, particles at height between $z - \frac{\Delta z}{2}$ and $z + \frac{\Delta z}{2}$ are counted and plotted as a function of z : as in the previous section, Δz is chosen to match the size of the reference cell in use.

No significant differences were observed between homogeneously doped and thin-film composite LSCs. The distribution shape found on LSCs with the rectangular geometry under examination was Gaussian in both cases, resulting from the uniform distribution of luminescent dyes along z direction.

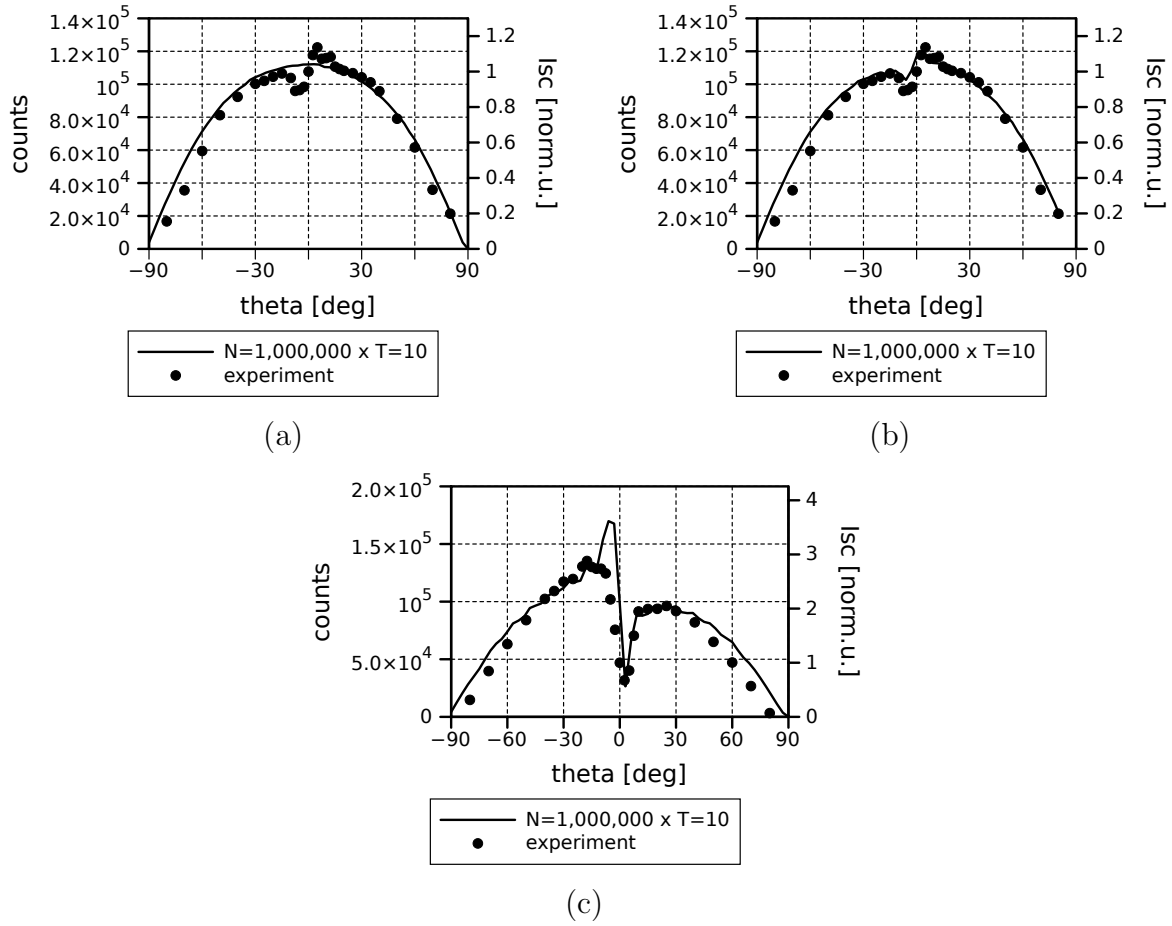


Figure 4.7: Comparison between ray-tracing and experiment. (a) Homogeneously doped LSC modelled with uniform initial distribution of particles; (b) Homogeneously doped LSC modelled with exponential initial distribution of particles ($A = 2.5$); (c) Thin-film composite LSC (thin film layer orientation: $y = +\frac{L_2}{2}$).

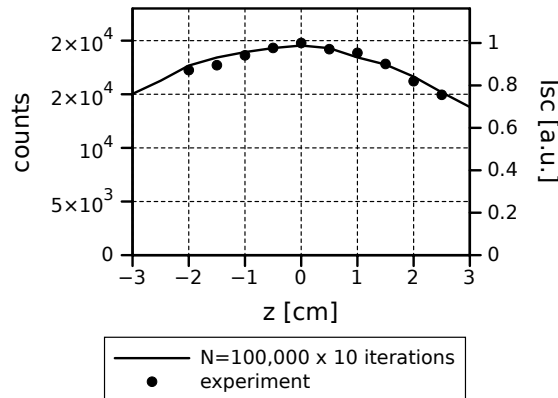


Figure 4.8: Comparison between ray-tracing and experiment: output light distribution as a function of z .

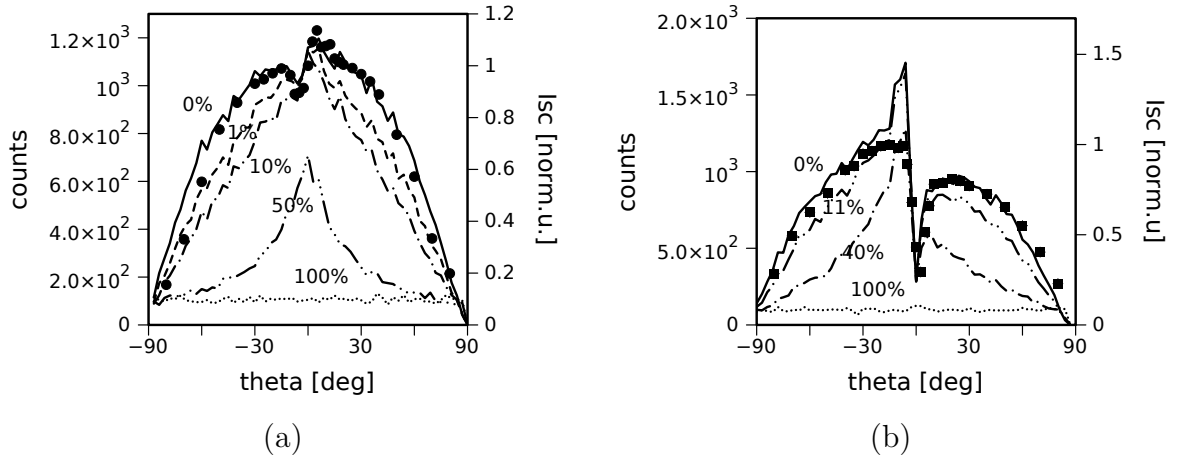


Figure 4.9: Ray-tracing model: the impact of elastic scattering of light (“diffusion”) at the interface. (a) Homogeneously doped and (b) thin-film composite LSC.

4.2.3.3 Impact of elastic scattering on light angular distribution

Elastic scattering of particles (“light diffusion”) was modelled by setting a certain percentage of particles to randomly change their velocity direction (Θ_i, Φ_i) when hitting selected matrix-to-air interfaces. Experimentally this effect could be due either to non-polished surfaces or to the presence of a diffuser glued and index-matched to the matrix.

Figure 4.9 shows the results of ray-tracing simulations on a homogeneously doped (Figure 4.9a) and on a thin-film composite LSC (Figure 4.9b), when different fraction of particles are set to diffuse at the $y = \pm \frac{L_2}{2}$ interfaces. As a result, the model predicted a general decrease in output light distribution, more rapid at wide angles than at $\theta \approx 0$, which is the most probable direction of motion of particles in the waveguide. In the extreme case of 100% diffusion at the interfaces, the output light is fully randomized and the predicted distribution is flat.

4.2.3.4 3D ray-tracing simulation

Figure 4.10a-b shows the result of 3D simulations of a homogeneously doped and a thin-film composite LSC respectively, as distribution of output light at a distance $r = 5$ cm and as a function of (θ, z) .

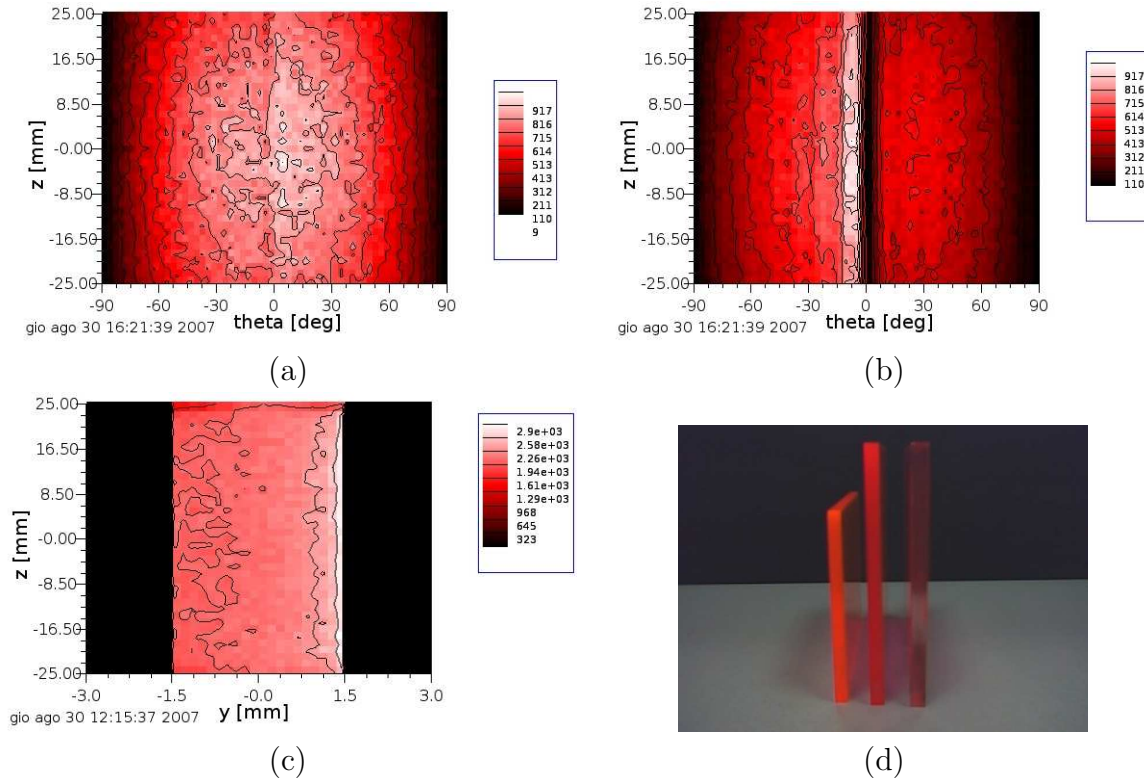


Figure 4.10: 3D ray-tracing model: output light distribution of: (a) homogeneously doped and (b) thin-film composite LSC at $R = 25$ mm, as a function of (θ, z) ; (c) thin film composite LSC at the $x = 0$ interface, as a function of (y, z) (thin-film layer orientation: $y = +\frac{L_2}{2}$); (d) the edge view of two homogeneously doped and a thin-film composite LSC.

The comparison between the two simulations and a picture of the profile of LSCs in both cases (Figure 4.10d) shows the effect of thin-film deposition of luminescent dyes as a strongly non-uniform distribution of light near $\theta = 0$ in comparison with the homogeneously doped case, which is evident also by the naked eye.

However, the ray-trace model shows a different non-uniformity of particles at the $x = 0$ interface (Figure 4.10c): in this case, particle distribution peaks at $y = +\frac{L_2}{2} = 1.5$ mm (where the thin-film layer is placed) and then decreases smoothly from $y = 1.2$ mm to $y = -1.5$ mm.

4.2.4 Discussion of results

The simple ray-tracing Monte Carlo model proposed showed its ability to reproduce the distribution of output light from a edge of a LSC, where typically the PV cell is placed. The model is based on basic assumptions from classical and quantum optics.

The non-uniform light distribution observed experimentally on a set of homogeneously doped LSCs was well reproduced by the assumption of non-uniform photoluminescent generation of particles across the matrix thickness. The exponentially decreasing distribution proposed corresponds to the exponentially decreasing absorption within the material.

The stronger non-uniformity typical of thin-film composite LSCs and easily observable by the naked eye could only be qualitatively reproduced by the model. The model predicts a more intense distribution of light at angles pointing away from the face where the thin-film layer is deposited (i.e. at $\theta < 0$ if the thin-film is deposited at $y = +\frac{L_2}{2}$ and vice versa) then observed experimentally. This result is most probably due to the approximation that no secondary absorption was taken into account in the model. Particles randomly generated by the code at an angle $\Theta_i \approx 0$ accumulate while travelling through the computational box and give rise to a large peak of distribution at $\theta \approx 0$. In reality, photons generated by photoluminescence are more likely to be secondary absorbed and re-radiated randomly (or be scattered either elastically or inelastically) during such a long optical path, thus smoothing out the output light distribution at those angles.

The addition of elastic scattering at the matrix-to-air interfaces in the ray-tracing model has shown to favour generally the output light distribution at $\theta \approx 0$, while smoothing out light distribution at wider angles. This helps to explain the small differences observed at large angles in Figure 4.7.

While the distribution of light at a distance $r \gg 0$ of a thin-film composite LSC shows a strong non-uniformity, the 3D ray-tracing model predicts a much more uniform distribution of light at the edge ($x = 0$, see Fig. 4.10c). This result is reasonable within the assumption of the model itself: the random particle dynamics leads them to exit all over

ESTI code	Dimension [cm ³]	Matrix	Fluorescent dye(s)	Cell type	Number of cells	Geom. gain, G
LM701	$5 \times 5 \times 0.5$	PMMA	Yellow CRS040 + Lumogen F Red305	GaAs	1	10
LM702	$5 \times 5 \times 0.5$	PMMA	Yellow CRS040 + Lumogen F Red305	GaAs	4	2.5
LM703	$5 \times 5 \times 0.5$	PMMA	Lumogen F Red305	c-Si	1	10
LM704	$5 \times 5 \times 0.5$	PMMA	Yellow CRS040 + Lumogen F Red305	GaAs	4	2.5

Table 4.4: Test devices [128].

the possible points in the xy plane edge, both in the homogeneously doped LSC and in the thin-film composite one (see Figure 4.4).

A uniform distribution of light all over the edge is of pivotal importance to ensure the PV cell attached performs at its best. An experimental verification of this effect is beyond the scope of this work and cannot be investigated here.

4.3 Indoor/Outdoor Characterization of High Efficiency LSC Modules

Table 4.4 lists four LSC modules that have been tested and characterized by the author at ESTI. All devices have been prepared by ECN and Fraunhofer IAP, within the activities of IP FULLSPECTRUM.

All modules were made using either one or four 5×50 mm² PV cells (GaAs on LM701, LM702 and LM704; c-Si on LM703) placed on the edges of $5 \times 5 \times 0.5$ cm³ Poly(methyl methacrylate) (PMMA) matrices. Mirror tapes by 3M (97% reflectivity) were fixed to the free edges of LM701 and LM703. Cells were connected with index matched PE 399 KrystalFlex film. Temperature control of the PV cell is possible on the backside of the copper plates that act as substrate and back contact of the PV cells.

The characteristics of the fluorescent dyes used are indicated in Tab. 4.5. Lumogen F

Fluorescent dye	Chemical	Produced by	Absorption peak [nm]	Emission peak [nm]	Ref.
Lumogen F Red305	Perylene	BASF	578	613	[161]
Yellow CRS040*	Coumarin	Radiant Color	440	506	[162]

Table 4.5: Luminescent dyes used: nominal values given in the cited references. *Later on renamed CFS002 Yellow.

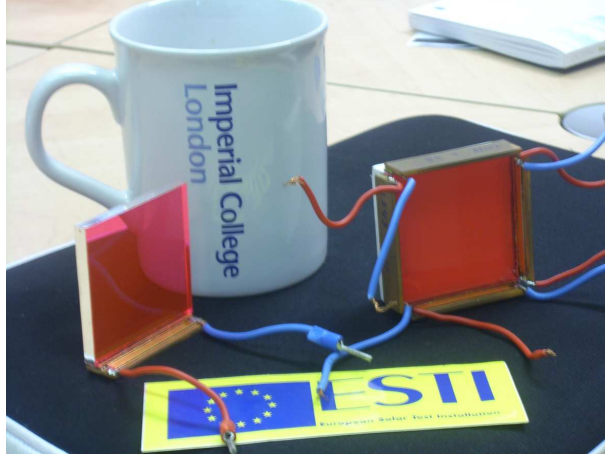


Figure 4.11: Test devices: LM701 (*left*) and LM702 with backside reflector (*right*).

Red305 is a perylene colour by BASF; yellow CRS040 is a coumarin by Radiant Color. All devices were homogeneously doped. In LM702 and LM704 PV cells were connected either in series or in parallel.

At the rear side of the collector, diffusers of different materials, size and shape were used, with air gaps between diffusers and LSCs. The impact of the presence of a backside diffuser to the EQE of the test modules is discussed in the next sections. Figure 4.11 shows two of the four test devices (with a diffuser behind LM702).

4.3.1 External quantum efficiency measurements of LSCs

External quantum efficiency (EQE) measurements of LSC modules were performed both at ESTI and at ICL. The two experimental setups differ significantly and a comparison between EQE measurements of the same device is given, thus helping to understand the

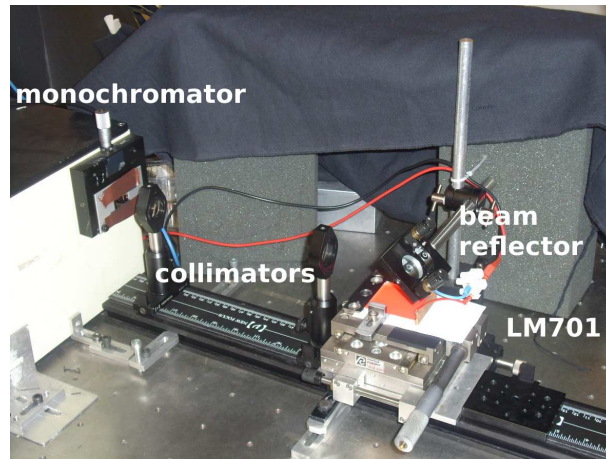


Figure 4.12: External quantum efficiency of LSC modules: the measurement apparatus at ICL. The setup has been developed in cooperation with Daniel Farrell (ICL).

problems that arise when applying standard methods of measurements to LSC modules.

The experimental setup at ESTI has already been presented in section 2.2.4. Measurements were performed at short-circuit with full bias light provided by QTH lamps.

Figure 4.12 shows the experimental setup in use at ICL as has been modified by the author and Daniel Farrell (ICL) for the characterization of LSCs. A horizontal point-like beam of chopped monochromatic light is reflected by a mirror mounted at 45 degrees mounted onto the target plate. The test device (LM701 in the picture) is placed on a XY stage. While the device is kept at short-circuit by a shunt resistor, the current produced is measured using a lock-in technique.

A c-Si reference cell of known absolute spectral response is used to measure the monochromatic light intensity as a function of wavelength. The temporal stability of the monochromatic source allows measurements from the reference cell and the test device to be made at different times. No bias light is used and no temperature control is performed.

Changing the position of the test LSC allows the measurement of “local” EQE: the comparison between measurements performed at different points may highlight the non-uniform contribution of the luminescent concentrator to the overall performance of the test device. The impact of a backside diffuser to the EQE of a LSC may also be quantified

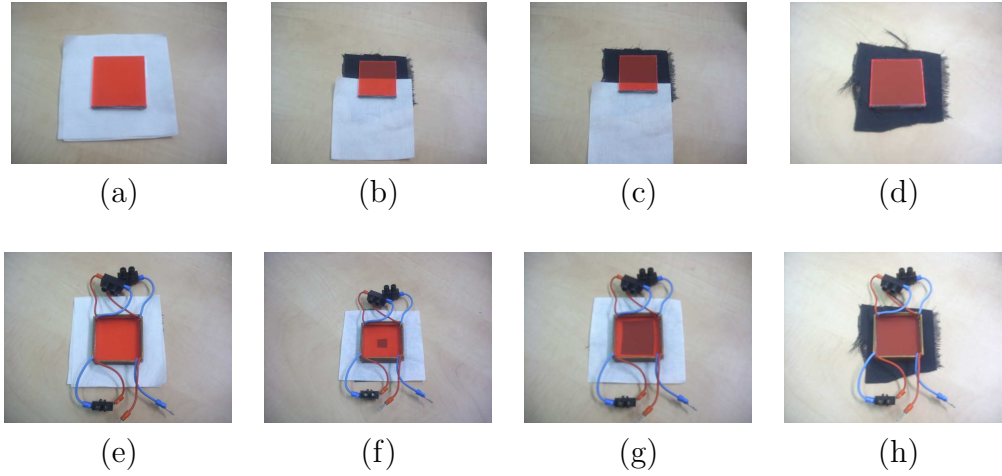


Figure 4.13: External quantum efficiency: impact of a diffuser. LM701 with: (a) full area, (b) half, (c) a quarter and (d) no reflector. LM704 with: (e) full area, (f) large, (g) thin and (h) no reflector.

locally.

In contrast, the EQE setup at ESTI is able to provide an “integral” EQE, averaging out any non-uniformity and putting the device in operating conditions.

With the aid of results from both setups, the following subsections investigate the impact of various backside diffusers to the performance of the LSCs tested.

4.3.1.1 Dependence on the backside diffuser size and shape

The EQE of LM701 and LM704 were measured at ESTI. Several measurements were performed with various backside diffuser configurations. In all measurements reported below, the backside diffuser is a sheet of white paper. Different covering areas and shapes have been used and a black cloth has been used as an absorber.

Figure 4.13a-d show the four configurations tested on LM701: the backside diffuser covers the rear side of the LSC only partially, near the edge where the GaAs cell is placed. This is shown to enhance photon recycling, by diffusing them back to the PMMA matrix or directly into the PV cell.

Results of EQE measurements on LM701 are shown in Figure 4.14a. The two peaks

highlighted correspond to wavelengths where luminescent dyes absorb and re-emit at the higher wavelengths where the PV cell responds (here simply referred to as peaks of “luminescent absorption”): high luminescence efficiency leads therefore to high EQE at 440 nm (yellow dye, see Tab. 4.5) and at 578 nm (red dye). The luminescent absorption cuts off just above 600 nm: the shoulder of non-zero EQE between 600 and 900 nm arises from light not absorbed by the dyes but diffused at the matrix-to-air interfaces, then reaching the GaAs cell, which has its bandgap cutoff at 900 nm.

The largest overall EQE was measured with the full diffuser covering the entire backside surface, while the smallest EQE resulted when no diffuser was used, as expected.

Similar results are shown in Figure 4.14b (LM704) and 4.14c (LM703, showing one luminescent peak only - LM703 is a single dye device, see Tab. 4.5 -, and a wider non-luminescent absorption due to the smaller bandgap of c-Si).

LM704 was tested with the various configurations shown in Figure 4.13e-h (cells in parallel): in this case diffusers with square apertures of different sizes have been employed.

The different response to the presence of various diffusers on LM701 and LM704 is summarized in Figure 4.15, where the normalized EQE is plotted as a function of the fraction of the diffuser area coverage, at four different wavelengths: at 450 and 550 nm (near the peaks of luminescent absorptions), at 483 nm (between the peaks) and at 850 nm (where no-luminescence occurs).

As a result, the EQE at wavelengths where luminescent absorption in the dyes occurs is shown to increase linearly with the fraction of area coverage. At 850 nm, the EQE increase is sharp and, especially in LM704, nearly constant when any diffuser is present, while it decreases significantly when no diffuser is used (65% EQE increase at 850 nm on LM704 between the “no diffuser” and the “full area diffuser” case; less than 5% increase at peak of irradiances).

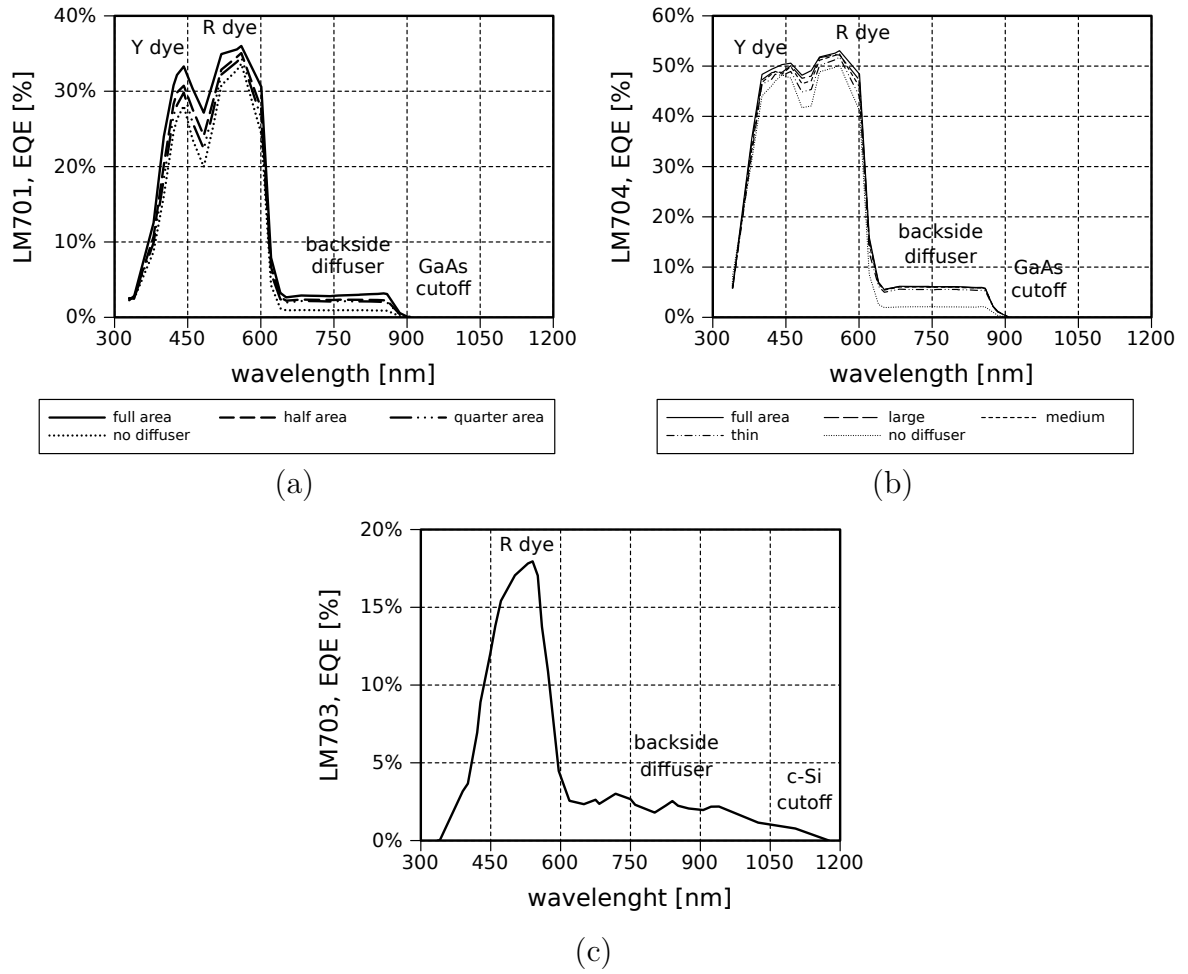


Figure 4.14: External quantum efficiency measurements: impact of a backside diffuser. (a) LM701; (b) LM704 (cells in parallel) and (c) LM703 (full area diffuser only).

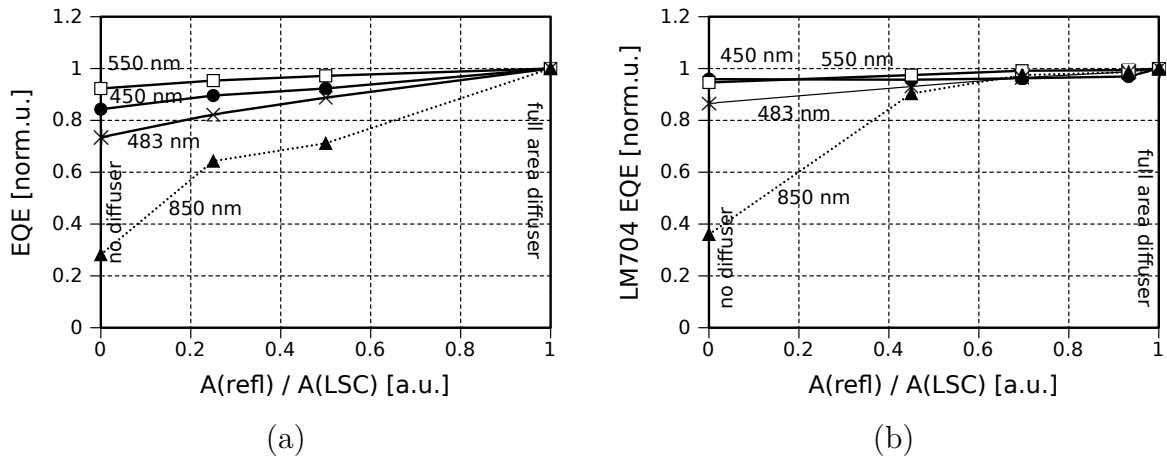


Figure 4.15: External quantum efficiency as a function of the diffuser area. (a) LM701; (b) LM704. Four relevant wavelength are shown: 450 nm (yellow dye absorption), 550 nm (red dye absorption), 483 nm (in between dye absorption peaks) and 850 nm (no dye absorption). EQE is normalized to its maximum value at maximum backside area coverage.

4.3.1.2 “Local” EQE measurements at ICL

Figure 4.16 shows results of EQE measurements of LM701 on the experimental setup at ICL described above. “Local” EQE measurements were performed at 25 points, equally distributed on a 5×5 square matrix. A white backside diffuser was placed on the rear side of the LSC.

Figure 4.16a shows the comparison between the average EQE over the five measurements of a single row at position x (mirror: $x = 0$ cm; GaAs cell: $x = 5$ cm). Figure 4.16b illustrates the EQE (from Figure a) at four selected wavelengths as in the previous section, plotted as a function of x .

Figure 4.16c shows on a grayscale colourmap, the contribution of each of the 25 test positions to the overall integrated EQE (white is where the integral of the EQE over wavelengths is maximum, black where it is minimum). All charts show that monochromatic light between $x = 1$ and $x = 2$ cm and in the middle of the LSC gives less contribution to the global EQE, while the biggest contribution is given in the LSC region closest to the PV cell.

4.3.1.3 Comparison with the ray-tracing code results

To better interpret the results of the previous sections, the impact of a backside diffuser was investigated with the Monte Carlo ray-tracing code described in section 4.2.

With respect of the system of coordinates introduced above (see Figure 4.1), the backside diffuser has been modelled by letting each particle that exits at the interface $y = +\frac{L_2}{2}$ to be randomly diffused back into the PMMA matrix, when $-\Delta x \leq x \leq 0$. The size Δx of the diffuser has been varied from L_1 to 0. Concentrator size has been set as LM701: $L_1 = L_3 = 5$ cm, $L_2 = 0.5$ cm.

Figure 4.17a shows the four possible cases each particle may undergo when striking the $y = +\frac{L_2}{2}$ interface, depending on its trajectory and the presence of the diffuser. Case

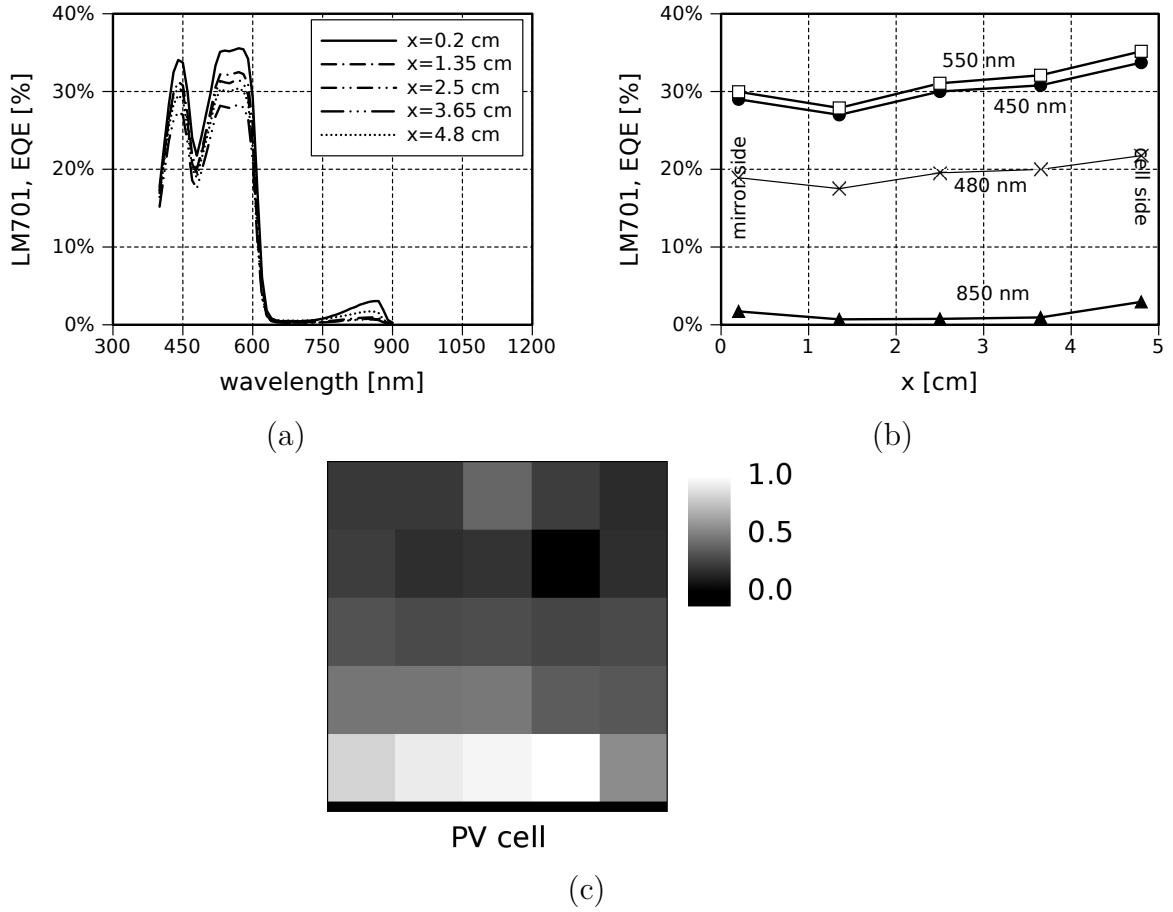


Figure 4.16: External quantum efficiency: LM701 with diffuser measured with ICL experimental setup (point-like source). (a) EQE at various distances from the cell side; (b) EQE as a function of the measurement point position (mirror: $x = 0$ cm; PV cell: $x = 5$ cm). EQE data are the average of five equally spaced measurements along the cell side length. (c) Percentage distribution of EQE over LM701 receiving area (PV cell position is indicated).

1 shows TIR, while case 2 shows a particle undergoing refraction or Fresnel reflection. When a particle is refracted at the diffuser (case 3), the code sets a new random trajectory $\Theta_i \in \left(-\frac{\pi}{2}, 0\right)$ and the particle is refracted back into the matrix. Since now the particle is inside the escape cone again, it exits the waveguide at $y = -\frac{L_2}{2}$, unless it is absorbed by a luminescent centre (which is not taken into account in the ray-tracing code presented above) or it intercepts the PV cell at the $x = 0$ interface (case 4). Here the PV cell is index matched with the PMMA matrix: in a no refraction approximation, the particle is collected for any trajectory $\Theta_i \in \left(-\frac{\pi}{2}, +\frac{\pi}{2}\right)$.

The code counts the fraction of particles collected, lost from $y = -\frac{L_2}{2}$ (“out down”) and

from $y = +\frac{L_2}{2}$ (“out up”). The result for various diffuser sizes is shown in Figure 4.17b. The graph shows that, according to this simple approach and for this LSC geometry, particles diffused at $y = +\frac{L_2}{2}$ are mainly lost at $y = -\frac{L_2}{2}$.

Figure 4.17c shows the total number of collected particles (in normalized unit) as a function of the fraction of area covered by the diffuser. According to the model, less than 3% more particles are collected by the diffuser, and this contribution is almost totally due to the presence of the diffuser close to the edge where the PV cell is placed (diffuser area within 1/10 of the $y = +\frac{L_2}{2}$ interface area). This result gives qualitative confirmation of the results observed experimentally in Figure 4.15.

Figure 4.17d shows that the positive contribution of the diffuser comes mainly from the output particles at wide negative angles (compare with case 4 in Figure 4.17a), while all the other collected particles are largely unaffected by the presence of the diffuser of any size.

4.3.1.4 Discussion of results

Both experimental and computational results presented in the previous sections demonstrate the impact of a backside diffusive reflector on the performance of a LSC of given size.

The measured EQE of LSCs with different configurations of PV cells and diffusers showed that the impact of the latter can be twofold. With regard to light at wavelengths where luminescent species absorb, a diffuser is shown to increase the absorption probability, by increasing the optical path of this fraction of light: light that has not been absorbed while passing through the LSC once, has an additional chance after elastic scattering. As a matter of fact, at those wavelengths the EQE seems to increase almost linearly with the diffuser area.

Light at wavelengths above the luminescent cut-off is also affected by the presence of a diffuser. The experimental results show also that the EQE at those wavelengths is more

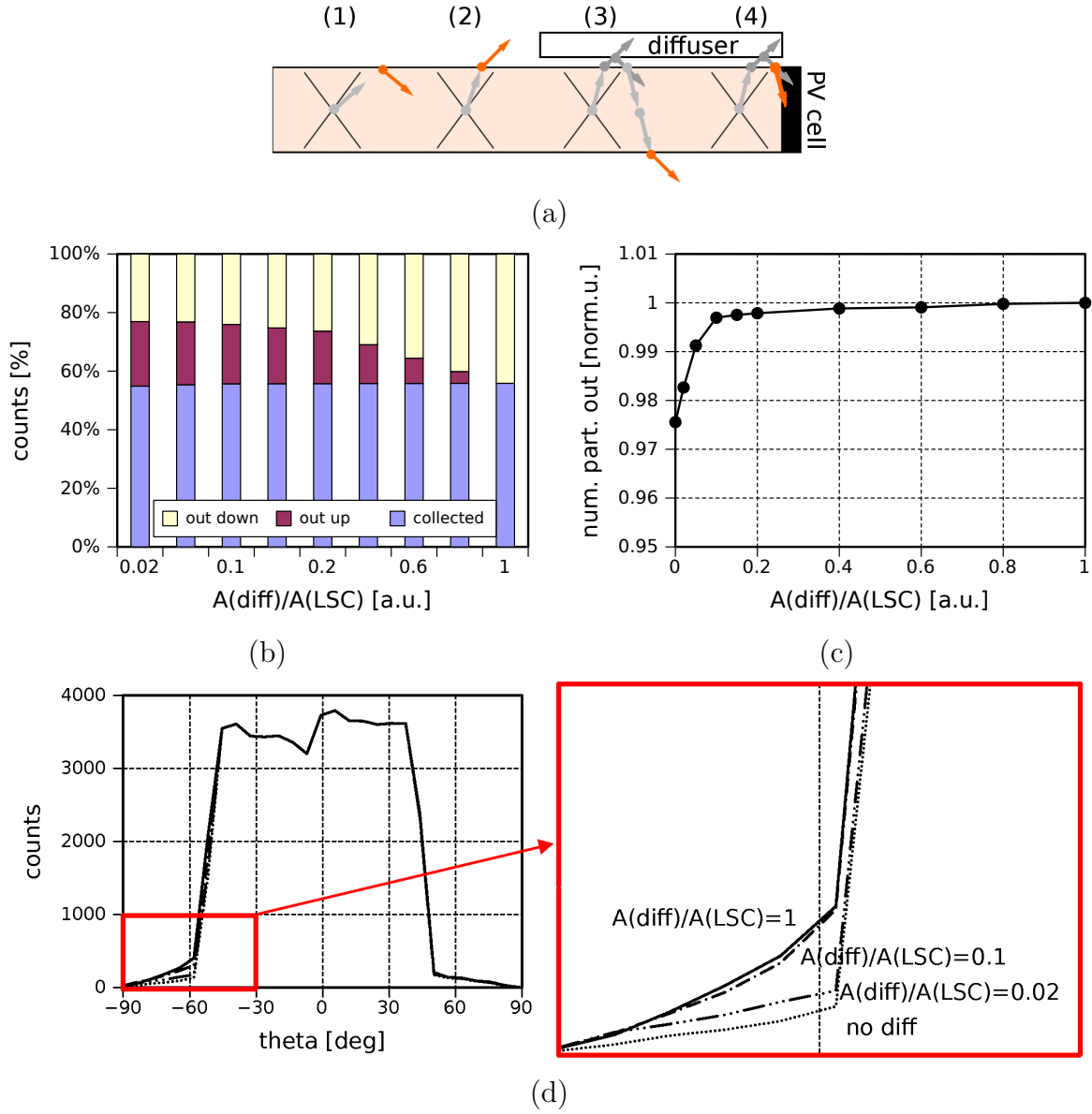


Figure 4.17: External quantum efficiency as a function of the diffuser area: Monte Carlo ray-tracing model. (a) Model, with four different cases shown (number of particles: $N = 10^4$; iterations: $T = 1$): (1) TIR, (2) lost photon (or Fresnel reflected), (3) photon diffused, then lost, (4) photon diffused, then collected. The escape cone is indicated in each case. (b) Percent distribution of photon collected, lost at $y = +\frac{L_2}{2}$ ("out up") and at $y = -\frac{L_2}{2}$ ("out down"). (c) Percentage of photons collected as a function of the diffuser area (see Figure 4.15). (d) Angular distribution: the detail shows the impact of a backside diffuser for output light at $-90^\circ < \Theta_i < -30^\circ$ (case (4) in figure (a)).

than doubled even when the diffuser is placed only close to the PV cell and not necessarily covering the entire backside.

The latter experimental result has been qualitatively confirmed by the ray-tracing code. Based on the simplest classical optics approach, the diffuser will recycle the majority of the exiting photons back to the interface: only the fraction of photons lost close to the edge where the PV cell is placed can be scattered into the cell and collected. All other recycled photons most probably are lost from the opposite side of the LSC: only particles diffused far from the PV cell edge at very wide angles may reach the cell. In reality, such particles are most probably re-absorbed and scattered again before reaching the cell.

Furthermore, while increasing the size of a LSC generally decreases the probability that photons emitted by photoluminescence at greater distance from the PV cell reach the cell, it does not affect the recycling enhancement at the edge which results from a backside diffuser. Thus, even if results shown in these sections strongly depend on the geometry of LSCs, the positive impact of a backside diffuser at the edges of the LSC is a result based on the basic optical properties discussed. What has been shown then suggests that, in view of the application of LSCs as smart windows, a full backside diffuser may be replaced by a thin diffusive frame all along the edges where PV cells are located. As a result the functionality of the window will not be affected but the LSC performance will benefit [154].

4.3.2 Angle-of-incidence effects and outdoor performance

Measurements of the dependence of a PV device on the angle-of-incidence (AOI) is a crucial tool in performance testing and energy rating. At time of writing, the only available international standard on energy rating is IEC 61853-1 (“PV module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating”, Ref. [163]), whose first edition has been published in January 2011. IEC 61853-2 (“PV module performance testing and energy rating - Part 2: Spectral Response,

Incidence Angle and Module Operating Temperature Measurement”, Ref. [164]), which describes the AOI measurement procedure, is still in a working draft stage.

Deviations from the geometrically expected cosine response (i.e., the decrease of short-circuit current due to the cosine-decreasing incident total irradiance), especially at wide angles are well known for radiometric and photometric sensors since the 1990s [165]. For conventional flat-panel PV modules these deviations are described in the literature as “AOI optical effects” [166, 167] and are mainly due to reflectance from the glass surface in front of the module. Anti-reflective coatings and textured surfaces are applied to reduce this effect, which typically decreases the PV device response at AOI greater than 50-60 degrees.

In outdoor measurements, the AOI determines the fraction of the direct and diffuse irradiance available for conversion into electricity inside the PV device. Both the external (the front surface) reflection and internal reflections are functions of the solar incidence angle and of the module design.

LSCs present additional aspects to be considered when analysing the AOI effects. The optics in a LSC is an active element of the device and increasing the AOI increases both luminescent absorption (via increasing the average light path within the PMMA matrix) and direct light scattering into the PV cell attached. In this section, results of indoor and outdoor measurements of the AOI effect are presented and analysed.

Figure 4.18 shows the results of a 1-day performance test of LM701 without backside diffuser. The device was fixed at 45° elevation on a rack.

Global normal irradiance $E(t)$ was measured every 8 minutes by means of a spectroradiometer. From eq. (2.4) and (2.6) of section 2.2.1, the short-circuit current $I_{sc,calc}(t)$ can be calculated as a function of solar time t , using the EQE measured in the previous section and the global irradiance.

Figure 4.18a shows the comparison between the measured $I_{sc,meas}(t)$ (continuous line) and

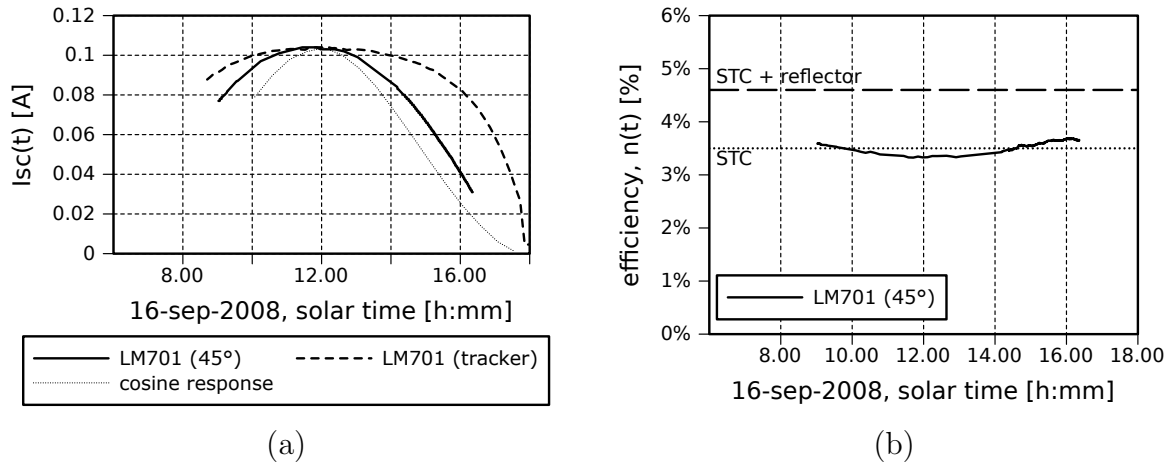


Figure 4.18: Enhanced optical efficiency with increasing AOI: (a) comparison between the short-circuit current of LM701 measured at 45° tilt (continuous line) and the expected performance on the tracker (dashed line), based on spectral irradiance (GNI) data; (b) enhanced module efficiency, as measured at 45° tilt (comparison between the STC values with and without a backside diffuser).

$I_{sc,calc}(t)$ (dashed line). The dotted line shows the cosine response given by

$$I_{sc}(t) = I_0 \cos(\theta(t) - 45^\circ) \cdot \cos(\phi(t) - 180^\circ) \quad (4.7)$$

where $I_0 = I_{sc,calc}(t = 12.00)$, $\theta(t)$ and $\phi(t)$ are the elevation and the azimuth of the sun at solar time t . The dotted line in Fig. 4.18a therefore represents the performance expected of a flat panel at 45 degrees with perfect cosine response and no AOI optical effects. It can be seen from this figure that the LSC has a better performance mainly due to the light entering the cell directly at wide angles.

The better performance of LM701 under light coming at wide angles is shown in Figure 4.18b, where the module efficiency is plotted as a function of solar time. In the chart the calculated efficiencies at STC (see next section) are also reported, with and without the backside diffuser.

Two other important aspects may contribute to improve the LSC module efficiency when light goes onto it from wide angles: the larger contribution of the diffuse component, that is efficiently absorbed by the LSC and the longer optical-path that direct rays undergo in the same conditions.

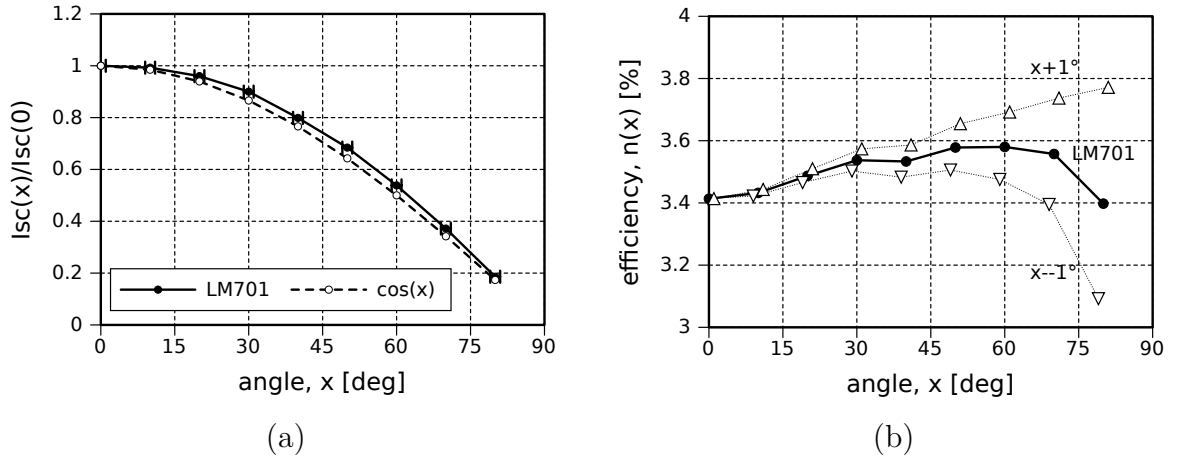


Figure 4.19: Enhanced optical efficiency at wide angles: (a) normalized short-circuit current of LM701 as a function of the AOI (comparison with the cosine response); (b) enhanced module efficiency. $\pm 1^\circ$ confidence is shown and the impact in efficiency calculation.

Longer optical-light path may indeed improve the optical efficiency of the LSC, as has been shown when analysing the impact of a diffuser on the EQE of a LSC in previous sections 4.3.1.1-4: a longer optical-path of light will improve light absorption by the luminescent dyes.

To further investigate the impact of an increase in the optical-path of light to the overall performance of the LSC, several measurements of the AOI were also performed on the solar simulator, by varying the angle of incidence of the incoming light.

IV characterization was performed on ESTI's class-A large area pulsed solar simulator (LAPSS). A c-Si calibrated reference cell recorded normal irradiance, allowing correction to the standard irradiance value of 1000 Wm^{-2} ; LM701 under examination was placed on a protractor, measuring IV curves at various AOI in the range 0° to 80° . Both devices were kept at standard temperature $(25.0 \pm 0.2)^\circ\text{C}$; no spectral mismatch correction was performed.

Figure 4.19a shows the comparison between $I_{sc,meas}(\theta)$ (the short-circuit current measured at AOI θ) and the theoretically calculated cosine-dependent value $I_{sc,theor}(\theta) = I_{sc,meas}(\theta = 0) \cos(\theta)$. A small increase of current is observed with respect of the cosine response, giving rise to up to 6% relative improvement in module efficiency (from 3.4%

to 3.6%, Figure 4.19b). A $\pm 1^\circ$ uncertainty in the measurement of θ is indicated.

Improved LSC angular response under incoming light from wide angles due to light scattering directly to the PV cell and better optical efficiency of the LSC in those conditions has also been reported in the literature, for example by Salem and coauthors in 2000 [143] and by El-Shaarawy and coauthors in 2007 [144].

4.3.3 Current-voltage characterization

Full indoor current-voltage (IV) characterization of LM701 and LM702 was performed at ESTI by the author and then compared with measurements at ECN, the Netherlands, within the cited FULLSPECTRUM project.

IV measurements at ESTI were performed at 25°C and 1000 Wm^{-2} on the Class AAA large area pulsed solar simulator (LAPSS) already introduced in section 2.4.1.2.

In the absence of dedicated standards for static concentrators and since LSCs do not require a collimated beam solar simulator (as conventional concentrators do), measurements were performed according to the standard procedure for flat panel modules described in IEC 60904-1 (Ref. [112], see also section 3.3.1 above for a schematic procedure of the data acquisition of an IV curve). SR (EQE) measurements were performed on the experimental apparatus already discussed (see sections 2.2.4 and 4.3.1).

Measurement data were then spectrally corrected to AM1.5g, also according to the standards for flat-panel PV device [104] (instead of AM1.5d, as for conventional concentrators, see section 3.3.2). No spectral mismatch correction has been performed at ECN, giving rise to the small differences observed in the comparison. Results are given in Table 4.6 and have been published in Ref. [128]. The uncertainty analysis of measurements on LAPSS at ESTI has been presented by H. Müllejans et al. in Ref. [124].

LM701 reaches an efficiency of 4.6% with the backside diffuser. When four GaAs cells are used on the same LSC geometry (LM702) the measured module efficiency ranges between

Test dev.	Test centre	Diff. refl.	I_{sc} [mA]	V_{oc} [V]	FF [%]	Mod. eff. η_{mod} [%]
LM701	ESTI	no	106	1.038	80.1	3.5
	ESTI	yes	138	1.048	79.9	4.6
	ECN	yes	134	1.025	83.6	4.6
LM702 parallel	ESTI	no	174	0.997	76.8	5.3
	ESTI	yes	220	1.008	79.5	7.1*
	ECN	yes	213	0.99	79.4	6.7
LM702 series	ESTI	no	42	3.99	78.7	5.2
	ESTI	yes	53	4.04	81.1	7.0
	ECN	yes	53	4.0	80	6.8

Table 4.6: Current-voltage characterization: comparison between measurements performed at ESTI with measurements performed at ECN [128]. No spectral mismatch correction has been applied at ECN. *7.1% has been reported by M. A. Green et al. in Ref. [38] as the highest efficiency value for a LSC module.

7.0% and 7.1% (depending on the series or parallel connection of PV cells).

Each device was also measured without the backside diffuser at ESTI and results are also shown in Table 4.6. LM701 without diffuser shows a decrease in efficiency of 32% (26% for LM702). This result highlights once more the importance of a backside diffuser to enhance the overall performance.

The 7.1% efficiency value measured at ESTI by the author represents the highest LSC efficiency reported in the literature to date. The measurement has been recognized as an independent confirmation of the world record efficiency of LSCs in Version 37 of the consolidated tables reported by M. A. Green et al., published in January 2011 [38].

Together with the impact of a backside diffuser to the SR of the device, the aperture area needs to be specified carefully, as stressed in the next subsection.

4.3.3.1 Importance of the definition of the aperture area in reported efficiency values

When reporting efficiency values it is important to define the aperture area of the PV device under examination (see Ref. [38]). This is because the module efficiency, as defined in section 1.2, is the total power produced by the test device at STC divided by the incident

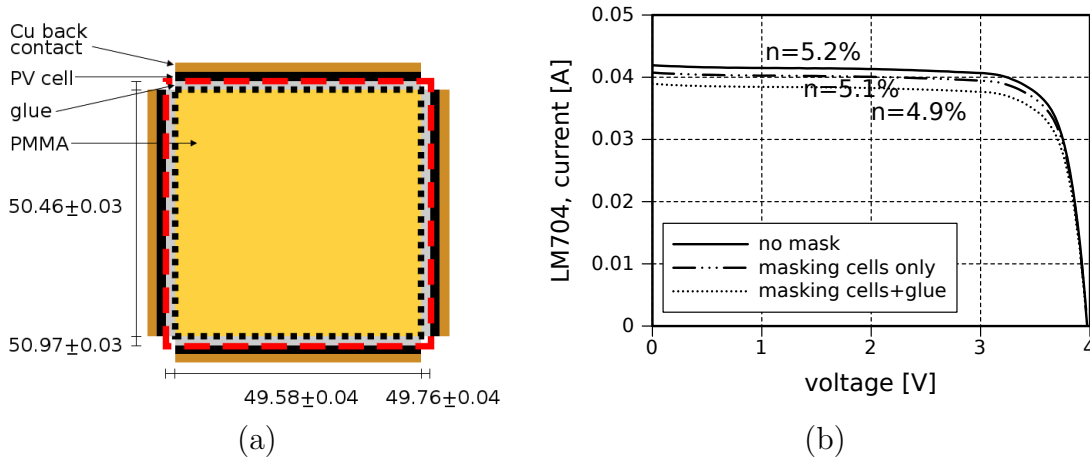


Figure 4.20: LM704 (cells in series): (a) active area measurements performed at ESTI by Roberto Galleano highlight the difference between the matrix area (2501.8 ± 0.7) mm², inside the black dotted line, and the area including the thin glue layer (2536.3 ± 0.7) mm², inside the red dashed line. (b) IV curves (and module efficiencies) in the two different masking conditions shown in figure (a) and when no mask is applied. (Data corrected to 1000 Wm^{-2} ; no spectral mismatch correction; no backside diffuser).

power (1000 Wm^{-2} times the test device's aperture area). Defining the aperture area of a novel device like an LSC introduces additional complications.

Several different areas can be defined for the LSCs tested and reported in this chapter, whether or not the thin glue layer connecting the PMMA matrix to the cells and the PV cells themselves are taken into account (see Figure 4.20a). Accurate area measurements have been performed at ESTI by Roberto Galleano: results on LM704 are reported in the caption of Figure 4.20a.

In conventional flat panel modules the area definition affects only the module efficiency calculation, since the area between cells is not active and does not contribute to the output power. This is not the case of LSCs, where the glue layer may diffuse light to the PV cell and the cell itself can intercept direct light, rather than light emitted by the luminescent species only. As a result, when IV characterization is performed it is of pivotal importance to define the aperture area, eventually through the application of a mask.

Figure 4.20b shows three different IV curves at 1000 Wm^{-2} (and the calculated efficiency values respectively), measured on LM704 with no backside diffuser in the following three

cases (no spectral mismatch correction was applied):

1. masking both the PV cells and the glue layer (dotted line, corresponding to the back-dotted area of Figure a): measured efficiency value $\eta = 4.9\%$;
2. masking the PV cells only (dash-dotted line, red-dashed area of Figure a): $\eta = 5.1\%$;
3. without any mask (continuous line): $\eta = 5.2\%$.

The increase in the active area (due to light scattering by the glue or light arriving directly into the cell) gives rise to an increase in the power produced by the module: 123.5 mW, 129.8 mW and 133.7 mW in cases 1, 2 and 3 respectively. Taking into account the different aperture areas results in the different values of efficiencies that were obtained².

4.4 Conclusions

LSCs are novel PV devices for which no existing standard procedures of electrical characterization are available. The following aspects have been analysed, among the new challenges that needed to be considered in the pre-normative characterization procedure to be followed: (a) the concentrating optics is a key active element in LSCs that may be characterized with ray-tracing methods taking into account many of the physical processes involved; (b) the EQE of LSC modules is inherently dependent on the position where the monochromatic light beam hits the matrix; (c) the EQE is highly dependent on the backside diffuser size and shape; (d) LSCs respond generally better than a cosine response to the incident light angle; (e) IV characterization requires a careful definition of the active area of the receiver.

In this chapter a Monte Carlo 3D ray-tracing code based on basic physical processes has been presented, which was able to give a satisfactory description of a number of experimental features (despite not taking into account the luminescence absorption/reemission

²The efficiencies reported in Table 4.6 were obtained with no mask and taking into account the glue layer and the PV cell thickness.

process) such as output light distribution from the edges of LSCs. The differences between homogeneously doped and thin-film composite LSCs that were highlighted on a dedicated experimental setup, were successfully reproduced by the model. A higher peak of output light distribution was predicted by the model and was discussed qualitatively as a consequence of the approximation of no secondary absorption. The impact of elastic scattering at the matrix-to-air interfaces was also analysed quantitatively with the Monte Carlo model.

The EQE of LSCs has been analysed with three different approaches: (a) with the experimental setup in use at ESTI and presented in previous chapters; (b) with the modified experimental setup of ICL, allowing EQE measurements at high-resolution (point-like EQE measurements); and (c) with the ray-tracing code above. Results highlighted the twofold impact of a backside diffuser to the performance of LSCs: it both increases the absorption probability of light at wavelengths where the luminescent species absorb and recycles light at wavelengths where the luminescent species is transparent. The latter effect was shown to be particularly important at the edges of LSCs, as it was also confirmed by the Monte Carlo ray-tracing approach.

Several LSC modules have been characterized by the author within IP FULLSPECTRUM: among them, the 7.1% world record efficiency LSC, which has recently received official recognition in the literature.

Other aspects affecting the indoor/outdoor performance of LSCs have been analysed and presented. The impact of incident light direction has been investigated both on a solar simulator and outdoors, showing a higher response than the theoretically cosine shape expected. The effect of different choices of the aperture area definition was finally discussed, showing how in LSCs this choice not only affects the module efficiency, but also the overall performance.

Finally, though the size of the LSCs tested is probably too small to be representative, the results presented in this chapter can help in the development of standards in this field of PV technology.

Chapter 5

Conclusion

5.1 Summary of Thesis Achievements

The list of thesis achievements is summarized in Table 5.1: relevant publications resulting from this work is also shown for each topic.

Within the overall binding theme of the thesis, which is the improvement in characterization and pre-normative studies on new generation PV devices, the following three main areas have been covered.

5.1.1 Multi-junction devices and multi-junction thin-film modules

Following the growing international demand for a certified characterization of multijunction thin-film modules, the author has been in charge of developing a dedicated SR measurement setup. The SR measurement procedure of such devices was analysed based on the straightforward theoretical approach of the 2-diode electrical model. The model gave important insight into the effect of finite shunt resistances of one subcell, which, according to the theory, was shown to be detectable from the SR measured with no bias light (the

motivation:	dedicated experimental setup for SR meas. of multijunction cells and modules			
section	achievement	ref.	application	future work
2.2	Effect of finite shunt resistance (theory)	[168]	Standard SR meas. method	- Generalization to $N > 2$ junctions - Effect of bias light intensity ($\gg 1X$) on CPV cells - Effect of series resistance - Statistics of historical data
2.2	Analysis of the dark SR (theory+exp.)	[168]	Detection of $R_{sh,i}$	
2.2	Critical analysis of bias voltage technique	[168]	Standard SR meas. method	
2.3	SR meas. setup for modules	[169]	Standard SR meas. method	
2.4	Indoor/outdoor comparison	[96]	Spectral mismatch	
motivation:	indoor characterization of CPV cells			
section	achievement	ref.	application	future work
3.2	Setup of a high-intensity solar simul.	[170]	Std. characteriz. CPV cells Industry of solar simulator	- Improving the spectral match - Set of neutrally filtered iso-cells - Automatic data acquisition system - SR measurements above 1200 nm - Characterization of multi-junction CPV cells
3.2.5	Calibration of ref. cells for linearity	[171]	Std. characteriz. CPV cells	
3.3	Preliminary results (c-Si) evaluation	[171]	Std. characteriz. CPV cells	
D	Uncertainty calculation	[172]	Std. characteriz. CPV cells	
E	Current imbalance in multi-junction CPV cell	[173]	Std. characteriz. CPV cells	
motivation:	LSC pre-normative characterization			
section	achievement	ref.	application	future work
4.2	Output light angular distribution	[150]	LSC geometry design	- Implementing absorption/emission events into the ray-tracing code - Modelling of LSC performance vs incident light direction - Energy rating - Test on larger size LSCs - Efficiency improvements
4.3.1	EQE of LSCs (theory + experiment)	[152]	Std. characteriz. LSCs	
4.3.2	Dependence on incident light direction	[154]	Std. characteriz. LSCs	
		[155]	Building integration	
4.3.3	Pre-normative characterization of LSCs	[153]	Std. characteriz. LSCs	
4.3.3	Record efficiency LSC module	[128]	Enhancement of PV technol.	

Table 5.1: Summary of thesis achievements, related publications of the author, applications and future work.

“dark SR”). Successful experimental support of the theoretical approach followed was given.

An innovative SR measurement method for large area modules was also proposed, involving non-uniform monochromatic light illuminating part of the module. Experimental verification confirmed the validity of the method.

Finally, results from the indoor characterization of multijunction thin-film modules were corrected for spectral mismatch using the SRs obtained by the new method. Then they were compared with outdoor measurement at AM1.5, again confirming the accuracy of the method proposed.

5.1.2 CPV cell characterization

A dedicated high intensity solar simulator was constructed based on a modified existing large area pulsed solar simulator and used for the characterization of CPV cells. The new apparatus was calibrated, characterized and classified according to the available standards that have been adapted by the author to CPV technology.

A linearity test for devices over the full range of operating intensities for CPV cells was proposed. The test involves the preparation of an appropriate number of reference cells, protected with neutral density filters to allow them to operate in their range of known linearity even at high intensities. Results were provided on c-Si reference cells, between 1X and 200X, while further preliminary results on III-V group multi-junction CPV cells are reported in Appendix E, where the current imbalance between subcells is briefly analysed.

Using reference cells to detect the total irradiance is the standard method for non-concentrator devices. In the CPV community reference cells are typically used at 1X measurements only: at higher intensities the linearity of the test device may be assumed or measured as proposed by the author. Using reference cells to detect the total irradiance at high intensities was also explored, which however does result in larger uncertainties, as was reported in Appendix D. All these achievements are expected to provide an impor-

tant input both towards the preparation of dedicated standard procedures for CPV and to the design of solar simulators.

5.1.3 Luminescent Solar Concentrators

The challenges linked to the optical and electrical characterization of the much less developed field of LSCs were also examined. The angular distribution of output light from the edge of the LSC was studied by means of a theoretical approach mainly based on classical optics. A Monte Carlo ray-tracing model was developed, being able to describe the output light distribution of both homogeneously doped and thin-film composite LSCs.

Results from the computational model gave significant explanations of the asymmetries observed experimentally and helped to compare the output light behaviour of both types of LSC samples under examination.

The ray-tracing model was also used to describe the impact of a backside diffusive reflector to the EQE of LSCs. Results from both the computational model and from the experiment highlighted the important contribution of the diffuser along the edges of the LSC. This result was also confirmed by the comparison between results from two different experimental apparatus at ESTI and at ICL.

A third aspect, the performance dependence on the angle of incidence of LSCs, was also studied. Indoor and outdoor measurements of the angular dependence were performed, showing better performance than the expected cosine law: this result was interpreted as an increase in the optical efficiency of LSCs due to the increased light path across the concentrator.

The importance of a careful definition of the aperture area was also discussed: the impact of the light scattered by the glue between the PMMA matrix and the PV cell was shown to give non negligible contribution to the overall performance and especially to the LSC efficiency.

A significant recognition of the author's research was finally the indoor characterization of the world's most efficient LSC that has been developed by partners of the European Project FULLSPECTRUM, including both Imperial College and ESTI. The result has been recognized in the literature as an official PV highlight in the 2011 list of record efficiencies.

5.2 Future Work

Table 5.1 shows also some suggestions for possible future work following the results illustrated in previous chapters.

As to the first research sector (SR measurement of multi-junction cells and modules), the basic theoretical approach of the multi-diode description can be generalized to $N > 2$ junctions. Results will help to investigate the measurement artefacts that are common in 3-junction CPV cells.

CPV cells operate at concentrations that may exceed 100X, while typically the SR on CPV cells is measured at bias light levels generally below 1X. To the author's knowledge only results of SR dependence on bias light intensities close to 1X have been investigated in the literature. The study of the effects of high intensity to the SR is important and is required to confirm the validity of the assumption of SR linearity over several order of magnitude of intensities.

Furthermore, in the theoretical model described in Chapter 2 the series resistance has been neglected: a complete approach should take into account the series resistance as well, which is particularly important in case of SR measurement with high intensity bias light.

The novel method for SR measurements of multi-junction modules introduces an additional uncertainty due to the intrinsic non-uniformity of the monochromatic beam over the testing module. A detailed uncertainty calculation could be performed with statistical

methods once a significant set of measurement data are collected (type A uncertainty).

In the second research sector (indoor characterization of CPV cell), Class C spectral irradiance of the high intensity pulsed simulator is a strong limitation to its use for III-V CPV cells. An improvement in the spectral match was shown to occur if spectrally selective filters are introduced, but this could be further improved if more appropriate filters were used. A set of filtered isotype cells may also be used to characterize such devices.

While the characterization of c-Si CPV at high intensities is already reliable, new effort is needed for III-V multijunction CPV cells. The SR of such devices could only be measured up to 1260 nm in this work, but the update of the SR measurement setup to wavelength up to 1800 nm by the addition of further bandpass filters and a broadband reference cell is ongoing.

Among possible future activities following the results in the third research sector (LSC pre-normative characterization), the implementation of absorption/emission events in the basic ray-tracing model described could help to explain the deviations observed in the experimental results from the theoretical predictions. This implementation may also help to further investigate the LSC performance as a function of the angle of incidence, which is important for energy rating purposes.

Larger size devices more representative for practical applications of LSCs shall also be studied, to ensure that their performance can scale-up from the small prototypes studied.

From a device physics point of view, the efficiency of LSCs needs to be further improved to allow them to be commercially feasible, for example as smart windows. A-Si cells, whose SR is well matched with the emission spectra of commercially available luminescent dyes, is a promising material, though its limited efficiency may limit the exploitation of such material in LSCs.

Appendix A

List of Publications

A.1 Chapter 2: Spectral Response Measurement of Multi-junction Thin Film Solar Cells and Modules

- M. Nikolaeva-Dimitrova, M. Pravettoni, R. P. Kenny, E. D. Dunlop, “Comparison of the Long Term Performance of Silicon Based Thin Film and Crystalline Modules”, *Proceedings of the Twenty-second European Photovoltaic Solar Energy Conference*, Milan (2007), 2782–2787.
- M. Pravettoni, A. Virtuani, H. Müllejans, R. P. Kenny, E. D. Dunlop and K. W. J. Barnham, “Spectral Response Measurements of Multi-junction PV Modules at the European Solar Test Installation Laboratories and Their Usage in Clear Day Outdoor Characterization”, *Proceedings of the Twenty-third European Photovoltaic Solar Energy Conference*, Valencia (2008), 2908–2912.
- A. Virtuani, M. Pravettoni and H. Müllejans, “Comparison of Indoor and Outdoor Performance Measurements on Micromorph (a-Si/ μ c-Si) Large-area Thin Film Solar Modules”, *Proceedings of the Twenty-third European Photovoltaic Solar Energy Conference*, Valencia (2008), 2378–2382.

- M. Pravettoni, A. Virtuani, H. Müllejans, R. P. Kenny, E. D. Dunlop and K. W. J. Barnham, “Spectral Response Measurements of Large Area Thin Film Multijunction Photovoltaic Modules at the European Solar Test Installation and Spectral Mismatch Calculation”, *Proceedings of the Twenty-fourth European Photovoltaic Solar Energy Conference*, Hamburg (2009), 3338–3342.
- A. Virtuani, M. Pravettoni and H. Müllejans, “Comparison of Indoor and Outdoor Performance Measurements on Amorphous Silicon and Micromorph (a-Si/ μ c-Si) Large-area Thin Film Solar Modules”, *Proceedings of the Twenty-fourth European Photovoltaic Solar Energy Conference*, Hamburg (2009), 2379–2385.
- M. Nikolaeva-Dimitrova, R. P. Kenny, E. D. Dunlop and M. Pravettoni, “Seasonal Variation on Energy Yield of a-Si, Hybrid and Crystalline Si PV Modules”, *Prog. Photovolt: Res. Appl.*, 18(5), 311–320 (2010).
- M. Pravettoni, G. Tzamalīs, K. Anika, D. Polverini and H. Müllejans, “Electrical Characterization of Multi-junction Thin-film Photovoltaic Modules: Spectral Mismatch Correction to Standard Conditions and Comparison with Outdoor Measurements”, in *Amorphous and Polycrystalline Thin-Film Silicon Science and Technology 2010*, edited by Q. Wang, B. Yan, S. Higashi, C.C. Tsai, A. Flewitt (Mater. Res. Soc. Symp. Proc. Volume 1245, Warrendale, PA, 2010), A13–06.
- M. Pravettoni, K. Anika, R. Galleano, H. Müllejans and E. D. Dunlop, “An Alternative Method for Spectral Response Measurements of Large-area Thin Film Photovoltaic Modules”, accepted for publication to *Prog. Photovolt: Res. App.*
- M. Pravettoni and A. Virtuani, “Impact of a Finite Shunt Resistance on the Dark Spectral Response of an a-Si/ μ c-Si Thin-film Multi-junction Photovoltaic Device”, to be published on the Proc. of 2011 MRS Spring Meeting, San Francisco, CA, April 2011.
- M. Pravettoni, R. Galleano, A. Virtuani, H. Müllejans and E. D. Dunlop, “Spectral Response Measurement of Double-junction Thin-film Photovoltaic Devices: the

Impact of Shunt Resistance and Bias Voltage”, *Meas. Sci. Technol.* 22, 045902 (2011).

- M. Pravettoni and H. Müllejans, “A Method for the Detection and Quantitative Estimation of Low Shunt Resistances via the Dark Spectral Response Measurement of Multi-junction PV Cells: Theory and Results”, submitted to the 37th IEEE Photovoltaic Specialist Conference, Seattle (2011).

A.2 Chapter 3: Setup of a High Intensity Solar Simulator for Concentrator Photovoltaic Cells

- M. Pravettoni, R. Galleano, T. Aitasalo, R. P. Kenny, E. D. Dunlop and K. W. J. Barnham, “From an Existing Large Area Solar Simulator to a High Intensity Pulsed Solar Simulator: Characterization, Standard Classification and First Results at ESTI”, *Proceedings of the Thirty-fifth IEEE Photovoltaic Specialists Conference*, Honolulu (2010), 2724–2728.
- M. Pravettoni, R. Galleano, R. Fucci, A. Romano, M. Pellegrino, T. Aitasalo, G. Flaminio, C. Privato, W. Zaaiman, R. P. Kenny and E. D. Dunlop, “Characterization of High Efficiency CPV Cells”, *Proceedings of the Twenty-fifth European Photovoltaic Solar Energy Conference*, Valencia (2010), 958–963.
- M. Pravettoni, R. Galleano, R. Fucci, A. Romano, M. Pellegrino, T. Aitasalo, G. Flaminio, C. Privato, W. Zaaiman, R. P. Kenny and E. D. Dunlop, “Characterization of High Efficiency CPV Cells”, *Progr. Photovolt: Res. App.* (2010), Published online in Wiley Online Library, March 2011.
- M. Pravettoni, M. Norton, T. Aitasalo, R. Galleano, G. Georghiou, R. P. Kenny, “Electrical Characterisation of Concentrating Photovoltaic Cells: a Comparison between Outdoor Testing under Direct Solar Radiation and Indoor Measurements on

a High Intensity Solar Simulator”, *Proceedings of the Thirty-fifth IEEE Photovoltaic Specialists Conference*, Honolulu (2010), 2729–2734.

- M. Pravettoni, R. Galleano, R. P. Kenny and E. D. Dunlop, “Characterization of a Pulsed Solar Simulator for Concentrator Photovoltaic Cell Calibration”, *Meas. Sci. Technol.* 21, 115901 (2010).
- M. Pravettoni, M. Cadruvi, D. Pavanello, T. Cooper and G. Friesen, “Characterization of CPV Cells on a High Intensity Solar Simulator: a Detailed Uncertainty Analysis”, submitted to the 37th IEEE Photovoltaic Specialist Conference, Seattle (2011).

A.3 Chapter 4: Pre-normative Characterization of Luminescent Solar Concentrators

- R. Bose, D. J. Farrell, A. J. Chatten, M. Pravettoni, A. Büchtemann and K. W. J. Barnham, “Novel Configurations of Luminescent Solar Concentrators”, *Proceedings of the Twenty-second European Photovoltaic Solar Energy Conference*, Milan (2007), 210–214.
- L. H. Slooff, E. E. Bende, A. R. Burgers, T. Budel, M. Pravettoni, R. P. Kenny, E. D. Dunlop and A. Büchtemann, “A Luminescent Solar Concentrator with 7.1% Power Conversion Efficiency”, *Phys. Stat. Sol. (RRL)* 2(6) (2008), 257–259.
- M. Pravettoni, R. Bose, K. W. J. Barnham, A. J. Chatten and R. P. Kenny, “Classical Behaviour of Output Light Emitted by the Edge of a Luminescent Solar Concentrator”, *Proceedings of the Thirty-third IEEE Photovoltaic Specialists Conference*, San Diego (2008), DOI: 10.1109/PVSC.2008.4922806.
- R. Bose, D. J. Farrell, A. J. Chatten, M. Pravettoni, A. Büchtemann, J. Quilitz, A. Fiore, L. Manna and K. W. J. Barnham, “Luminescent Solar Concentrators:

- Nanorods and Raytrace Modeling”, *Proceedings of the Thirty-third IEEE Photovoltaic Specialists Conference*, San Diego (2008), DOI: 10.1109/PVSC.2008.4922450.
- M. Pravettoni, A. Virtuani, W. Zaaiman, R. Galleano, R. P. Kenny, E. D. Dunlop, R. Bose and K. W. J. Barnham, “Indoor-Outdoor Characterisation of Luminescent Solar Concentrators at the European Solar Test Installation”, *Proceedings of the Twenty-third European Photovoltaic Solar Energy Conference*, Valencia (2008), 744–747.
 - R. Bose, D. J. Farrell, A. J. Chatten, M. Pravettoni, A. Büchtemann, J. Quilitz, A. Fiore, L. Manna, J. Nelson, A. P. Alvisatos and K. W. J. Barnham, “The Effect of Size and Dopant Concentration on the Performance of Nanorod Luminescent Solar Concentrators”, *Proceedings of the Twenty-third European Photovoltaic Solar Energy Conference*, Valencia (2008), 552–555.
 - M. Pravettoni, F. Pravettoni, A. Virtuani, R. P. Kenny, A. J. Chatten and K. W. J. Barnham, “Outdoor Characterization of Luminescent Solar Concentrators and Their Possible Architectural Integration on a Historically Relevant Site in Milan (Italy)”, *Proceedings of the Thirty-fourth IEEE Photovoltaic Specialists Conference*, Philadelphia (2009), 187–192.
 - M. Pravettoni, A. Virtuani, R. P. Kenny, D. J. Farrell, A. J. Chatten and K. W. J. Barnham, “Outdoor Characterisation of High Efficiency Luminescent Solar Concentrators”, *Mater. Res. Soc. Symp. Proc: Three-Dimensional Architectures for Energy Generation and Storage* (2009), 1168–P02–06.
 - M. Pravettoni, D. J. Farrell, A. J. Chatten, R. Bose, R. P. Kenny and K. W. J. Barnham, “External Quantum Efficiency Measurements of Luminescent Solar Concentrators: a Study of the Impact of Backside Reflector Size and Shape”, *Proceedings of the Twenty-fourth European Photovoltaic Solar Energy Conference*, Hamburg (2009), 332–335.
 - R. Bose, D. J. Farrell, C. Pardo-Sanchez, M. Pravettoni, M. Mazzer, A. J. Chatten

- and K. W. J. Barnham, “Luminescent Solar Concentrators: Cylindrical Design”, *Proceedings of the Twenty-fourth European Photovoltaic Solar Energy Conference*, Hamburg (2009), 359–362.
- M. Pravettoni, “A Complementary Concentrating System: the Luminescent Solar Concentrator”, *PV Technology* **3** (2009), 42–45 (in Italian).

Appendix B

Spectral Response of Multi-junction cells and Modules with ORIEL CSS (SR): ESTI Operating Instructions

1. Reference to Norms and Standards

- 1.1. Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data IEC 60904-3 (1998).
- 1.2. Computation of spectral mismatch error introduced in the testing of a photovoltaic device IEC 60904-7 (1998).
- 1.3. Measurement of spectral response of a photovoltaic (PV) device IEC 60904-8 (1998).
- 1.4. Measurement of electrical performance and spectral response of non-concentrator multi-junction photovoltaic cells and modules ASTM E 2236-05 (2005).
- 1.5. M. Meusel et al., *Spectral Mismatch Correction and Spectrometric Characterization of Monolithic III-V Multi-junction Solar Cells*, Prog. Photov. 10(4), 243-255 (2002).
- 1.6. M. Meusel et al., *Spectral Response Measurements of Monolithic GaInP/Ga(In)As/*

Ge Triple-junction Solar Cells: Measurements Artefacts and Their Explanation, Prog. Photov. 11(8), 499-514 (2003).

2. Scope

- 2.1. This measurement procedure describes the determination of the spectral response of two-terminal (*monolithic*), multi-junction PV devices, both cells and modules, and the subsequent determination of the spectral mismatch correction factor.
- 2.2. This method does not include temperature and irradiance corrections for spectral response measurements.
- 2.3. This method applies to concentrator terrestrial multi-junction PV cells as well.

3. Definitions and Principle

3.1. Physical parameters

- R = shunt resistance (in Ω)
- V_{oc} = open-circuit voltage (in Volt)
- V_b = bias voltage (in Volt)
- n = total number of junctions of the multi-junction device (a.u.)
- $E_{ss}(\lambda)$ = spectral irradiance of the solar simulator (in $\text{W m}^{-2} \text{ nm}^{-1}$)
- A = cell area (in m^2)
- T = temperature (in $^{\circ}\text{C}$)
- λ = wavelenght (in nm)

3.2. Calculated parameters

- $EQE(\lambda)$ = external quantum efficiency (%)
- $SR_i(\lambda)$ = relative spectral response of the i -th junction (in A W^{-1})
- $ASR_i(\lambda)$ = absolute spectral response of the i -th junction (in A W^{-1})
- k = scaling factor (a.u.)
- $I_{sc,i}$ = short-circuit current of the i -th junction (in Ampere)
- M_i = mismatch factor relative to the i -th junction (a.u.)

- 3.3. *Cell type* - type of material for which the cell is manufactured.
- 3.4. *Cell area* - frontal area of the test cell including the area covered by the grids and contacts.
- 3.5. *Module area* - frontal area of the test module, including the frame and area covered by grids and contacts.
- 3.6. *Multi-junction device* - a PV device (cell or module) composed of more than one PV junction stacked on top of each other and electrically connected in series.

The principle of this method is the determination of the spectral response of each junction of a multi-junction PV device using light- and voltage-biasing techniques, a chopped quasi-monochromatic light beam (obtained by band-pass filtering light from a Continuous Solar Simulator - CSS) and measuring the current density of the current-limiting junction via lock-in technique.

4. Instruments

- 4.1. *Light source* - Oriel CSS (300 W).
- 4.2. *Monochromatic band-pass filters* - eighty monochromatic interference filters (typically full width at half maximum 10 nm) placed in the beam path.
- 4.3. *Light beam chopper*.
- 4.4. *Reference cell* - one of the working standard reference cells with calibrated absolute spectral response.
- 4.5. *Suitable current to voltage converter* - shunt box ($R = 1\ \Omega$ for the reference cell; $R = 10, 20, 50, 100, 200, 500\ \text{m}\Omega, 1\ \Omega$ for the test device), transimpedance amplifiers.
- 4.6. *Dual phase digital lock-in amplifiers* - SR830 DSP.
- 4.7. *SPR Software*.
- 4.8. *QTH bulbs for additional bias light*.

- 4.9. *Two temperature control units* - for the reference cella and for the test device, respectively.
- 4.10. *Set of coloured LEDs for light-bias* - 410 nm (violet, output light: 4.68 W); 520 nm (green, 1.98 W); 630 nm (red, 1.76 W); 870 nm (NIR, 2.25 W) available, in order to saturate junctions not being measured.
- 4.11. *Voltage source for voltage-bias* - A variable DC power supply capable of providing at least voltage equal to the open-circuit voltage (V_{oc}) of the multi-junction device to be tested.
- 4.12. *Off-axis paraboloidal reflectors*.

5. Calibration Devices

This method requires:

- a reference cell as a calibrated effective irradiance detector;
- monochromatic interference filters with calibrated wavelengths reported into the software.

6. Maintenance

The maintenance of the instruments listed in point 4. can be divided into three groups:

- 6.1. *Calibration* - Central wavelength of monochromatic filters, shunts, lock-in amplifiers, absolute spectral response of the reference cells, spatial uniformity of the monochromatic beam, voltage source, temperature controllers.
- 6.2. *Maintenance* - Light bulbs, LEDs, cooler.
- 6.3. *No maintenance nor calibration* - Software programs (only update of the centre wavelength values of the used filters).

7. Measurement Procedure

- 7.1. Mounting /connection instructions:

7.1.1 Mounting the test device (module area below $0.3 \times 0.3 \text{ m}^2$)

- Place the test device in the centre of the temperature controlled plate.

Note: Check that: the device is not shaded by cables; the plate is positioned correctly on the measurement plane; the temperature controlled plane is connected to the cooler and the cooler is turned on.

7.1.2 Mounting the test device (module area above $0.3 \times 0.3 \text{ m}^2$)

- Place the test device on the rack in front of the cabinet.

Note: Check that: the device is not shaded by cables; the rack is positioned correctly in front of the cabinet.

7.1.3 Mounting the reference cell (module area below $0.3 \times 0.3 \text{ m}^2$)

- Next to the temperature controlled plane at predefined position. The position should be adjusted for height (centre of the test device).

Note: Check that: the cell is not shaded by cables; the cell is positioned correctly on the measurement plane; the cell is connected to the cooler and the cooler is turned on.

Note: If the reference cell is not provided with internal cooling system, it should be placed on the temperature cooling plate, next to the test device.

7.1.4 Mounting the reference cell (module area above $0.3 \times 0.3 \text{ m}^2$)

- In any place within the monochromatic beam spot.

Note: Check that: the cell is not shaded by cables; the cell is positioned correctly on the measurement plane. Make sure that the reference cell is fully illuminated by the monochromatic beam.

7.1.5 Connecting reference and test device

- Connect the device (reference or test device) to a suitable current-to-voltage converter.

7.1.6 Connect the current-to-voltage converters to the respective lock-in amplifiers.

7.1.7 Connect the reference frequency output from the chopper control to both lock-in amplifiers.

7.1.8 Temperature sensors

- Check that the temperature sensor is attached to the front of the temperature controlled plate or behind the module on the rack and the cable to the reference cell and both temperature readers are switched on.
- Set the coolers to 25°C (not necessary for module measurements).

7.2. Apply light bias to the junction not being measured using the bias light source.

7.2.1 Select the junction to be measured

7.2.2 Choose LEDs with emission wavelength corresponding to the spectral response of the junctions not being measured.

7.2.3 Turn on the bias light source and illuminate the entire module or, as a minimum, the region where the monochromatic beam illuminates the device.

7.3. Apply additional bias light.

7.3.1 Ideally, the illumination on the junction being measured should be at STC (1000 W m^{-2}) and the junction not being measured at higher levels.

7.3.2 Turn on the additional bias light source and illuminate, as a minimum, the region where the monochromatic beam illuminates the device.

7.4. Cabinet setup

7.4.1 For measurements of devices below $0.3 \times 0.3 \text{ m}^{-2}$ testing module area:

- Close the cabinet.

7.4.2 For measurements of devices above $0.3 \times 0.3 \text{ m}^{-2}$ testing module area:

- Keep the cabinet open and place the off-axis paraboloidal reflectors on a plane below the collimating lens system to drive the monochromatic beam onto the module

7.5. Check that temperature sensors read $25.0 \pm 0.5^\circ\text{C}$.

7.6. Test device specification.

- The specification about the test device can be found in the document (E31B7) belonging to the device, stating its characteristics: cells in parallel/series, cell area, module area, ESTI code and cell type.

7.7. Setting of the instruments.

7.7.1 Calculate the bias voltage to use during the test.

7.7.1.1 Measure the open-circuit voltage of the test device.

7.7.1.2 For devices with junctions that contribute similar voltages, calculate the bias voltage (V_b) according to the following equation

$$V_b = \frac{n-1}{n} V_{oc} \quad (\text{B.1})$$

7.7.1.3 For devices with junctions contributing substantially different voltages, calculate V_b as the sum of the expected voltages contributions from the junctions not being measured.

7.7.1.4 Set V_b on the bias voltage source.

7.7.2 Maximize the AC signal from the junction under examination using a wavelength at which it is expected to respond.

7.7.2.1 Set the monochromatic light source to a wavelength in the expected spectral response region of the junction to be measured.

7.7.2.2 Adjust the bias light and bias voltage intensities to saturate or maximize the test device signal.

7.7.3 Minimize the test device AC signal at wavelengths where the junctions not being measured are expected to respond.

7.7.3.1 Set the monochromatic light source to a wavelength in the expected spectral response region of the junction not being measured.

7.7.3.2 Adjust the bias light and bias voltage intensities to minimize or zero the test device signal.

7.7.3.3 The signal should correspond to external quantum efficiency less than 1% in wavelengths regions where the junction being measured is known to have zero response.

7.7.3.4 Repeat - for all other junctions not being measured, if any.

7.7.4 Current-to-voltage converters.

7.7.4.1 This instruments have not only to handle with the AC signal produced by the chopped monochromatic light (which is generally small), but also the DC offset generated by the additional bias light.

7.7.4.2 The shunt value should be selected so that the DC voltage drop across it is less than 5% of the V_{oc} of the test device.

7.7.4.3 Before using a transimpedance amplifier, check that the range of input current (AC+DC) is compatible with the output voltage signal from the test device or the reference cell.

7.7.5 Chopping frequency setting.

- This setting is done by the software and should be around 70 Hz.

7.7.6 Data acquisition system settings /lock-in settings.

- These settings are done automatically by the software.

7.8. Operating the software.

- The use of the software package is explained in the user manual of the program.

7.9. Measure the relative spectral response of the junction under examination.

7.10. Repeat - for each junction of the test multi-junction device.

8. Calculation and Interpretation of Results

8.1 Relative spectral response.

8.1.1 For each wavelength the current produced in each junction of the test device and the reference cell are measured and their ratio is calculated.

8.1.2 At the end of the measurement these values are converted to the ratio of current densities (using the device and reference cell areas from the loaded files) and multiplied with the absolute spectral response of the reference cell also loaded at the beginning.

8.1.3 The raw data (including errors) and the calculated relative spectral response $SR_i(\lambda)$ (including errors) of each junction of the test device can be saved to a file.

8.2 Absolute spectral response.

8.2.1 From the relative spectral response of the i -th junction calculated above, the short-circuit current of the component cell can be calculated as follows

$$I_{sc,i} = kA \int_0^{4000} SR_i(\lambda) E_{ss}(\lambda) d\lambda \quad (\text{B.2})$$

where the integral is performed in the range where $SR_i(\lambda)$ is non-zero.

8.2.2 Once the integral (B.2) has been calculated for each junction, the scaling factor k is calculated by comparison of the minimum of those integrals with the short-circuit current measured at the solar simulator as follows

$$I_{sc,meas}, \quad k = \frac{I_{sc,meas}}{\min_i (I_{sc,i})} \quad (\text{B.3})$$

8.2.3 The curve $ASR_i(\lambda) = k \cdot SR_i(\lambda)$ should be reported as the absolute spectral response of the i -th junction.

8.3 Mismatch correction.

8.3.1 Calculate M_i for the i -th junction using the absolute spectral response obtained in point 8.2 and the spectral irradiance of the solar simulator used for measuring the electrical performance and the standard AM1.5g spectral irradiance, as specified in IEC 60904-7 (terrestrial non-concentrating systems) or the standard AM1.5d (direct+circumsolar) spectral irradiance, as specified in ASTM G173-03.

8.3.2 Repeat for each junction.

8.3.3 Perform the mismatch correction as specified in ASTM E2236-05, using the mismatch factor of the component cell that limits the current through the multi-junction device under examination when illuminated by the standard spectral irradiance.

9. Estimation of Uncertainties

For detailed description of the Estimation of Uncertainties see document UC42 (Appendix C).

10. Report

In addition to the reporting requirement specified in IEC 60904-7, the following data and information should be reported:

10.1 A description of the measurement system and, for each junction, the DC bias light intensity, a description of the bias light used and the bias voltage level.

10.2 Spectral mismatch M_i of each junction.

10.3 If a non-spectrally adjustable solar simulator has been used for electrical characterization, report with junction selected for irradiance and spectral mismatch corrections.

Appendix C

Spectral Response of Multi-junction cells and Modules with ORIEL CSS (SR): ESTI Uncertainty Calculation

1. Scope

This instruction describes uncertainty calculation for the measurement of spectral response (SR) of photovoltaic (PV) multi-junction devices using the dedicated device calibration setup. It also includes the uncertainty calculation for the subsequently determined spectral mismatch correction factor (MMF) and the short-circuit current (I_{sc}) calculated for the reference spectral irradiance for air mass 1.5 global (AM1.5g) and air mass 1.5 direct+circumsolar (AM1.5d).

2. Reference to Norms, Standards and Publications

- 2.1 Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data IEC 60904-3 edition 2 (2008-04).
- 2.2 Computation of spectral mismatch error introduced in the testing of a photovoltaic device IEC 60904-7 (2008-11).
- 2.3 Measurement of spectral response of a photovoltaic device IEC 60904-8 (1998).

- 2.4 Procedure ISO-GUM “Guide to the expression of uncertainty in measurements”, 1st Edition (1995).
- 2.5 ISO/IEC Guide 999 - “VIM - International vocabulary of basic and general terms in metrology” (2007).
- 2.6 “The World Photovoltaic Scale: An International Reference Cell Calibration Program”, Prog. Photov. Res. Appl. 7, 287-297 (1999).
- 2.7 H. Field and K. Emery, “An uncertainty analysis of the spectral correction factor”, IEEE, 1180-1187 (1993).
- 2.8 I-V characteristic SpectroLab LAPSS LS-3 uncertainty calculation [UC05].
- 2.9 Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules, ASTM E2236-05 (2005).
- 2.10 M. Meusel et al., “Spectral response measurements of monolithic GaInP/Ga(In)As/Ge triple-junction solar cells: measurements artefacts and their explanation”, Prog. Photov. Res. Appl., 11(8), 499-514 (2003).
- 2.11 M. Meusel et al., “Spectral mismatch correction and spectrometric characterization of monolithic III-V multijunction solar cells”, Prog. Photov. Res. Appl., 10(4), 243-255 (2002).

3. Definitions, Instrument Characteristics and Assumptions

Light source Oriel continuous (300W) Solar Simulator.

Bandpass filters Eighty (80) monochromatic interference filters (typical full width at half maximum: 10 nm) placed in the beam path.

Photovoltaic devices ESTI reference cells with calibrated absolute spectral responsivity (see instruction manual); device under test (DUT) (module or cell).

Current to voltage Converter Isabellenhütte Dng. precision shunt, $\pm 0.1\%$; calibrated transimpedance amplifier Melles-Griot.

Data acquisition system Dual phase digital lock-in amplifier SR830 DSP.

Temperature sensors For reference cell and DUT; measurement performed at a temperature of $(25 \pm 2)^\circ\text{C}$; temperature non-uniformity in the DUT neglected; no temperature dependence for the instruments are taken into account, as these are operating in a controlled environment.

Calibration of reference cells SR of ESTI reference cells.

Calculated mismatch factor See below.

Calculated short-circuit current See below.

The reference cell and the DUT are illuminated simultaneously by chopped quasi monochromatic light obtained with bandpass filters from a continuous Xe light source (which incidentally is a solar simulator). In addition, coloured bias light is applied to saturate the junctions not being measured. During 5 sec, 320 values of the short-circuit currents of both devices are recorded.

For each wavelength the value of the ratio $R_i(\lambda)$ is calculated by

$$R_i(\lambda) = \text{Average} \left[\frac{I_{dut,i}(t)}{I_{ref}(t)} \right] \quad (\text{C.1})$$

where I is the measured current.

The spectral response of the i -th junction (the current limiting junction being measured) of the DUT is calculated as follows

$$SR_{dut,i}(\lambda) = R_i(\lambda) \frac{A_{ref}}{A_{dut}} \cdot SR_{ref} \quad (\text{C.2})$$

where A designates the area of the devices. A mismatch correction factor MMF_i is calculated for the i -th junction from

$$MMF_i = \frac{\int SR_{dut,i}(\lambda) E_{AM1.5}(\lambda) d\lambda}{\int SR_{dut,i}(\lambda) E_{ss}(\lambda) d\lambda} \frac{\int SR_{ref}(\lambda) E_{ss}(\lambda) d\lambda}{\int SR_{ref}(\lambda) E_{AM1.5}(\lambda) d\lambda} \quad (\text{C.3})$$

where $E_{AM1.5}(\lambda)$, E_{ss} are the spectral irradiances of the reference spectrum AM1.5g (or AM1.5d where is the case) and of the solar simulator.

(Normally the mismatch is defined as the inverse of eq. (C.3) and denoted by M_i . The measured I_{sc} has to be divided by M_i or multiplied by MMF_i , corresponding to the junction which is current-limiting on the solar simulator under examination).

The integrals in eq. (C.3) should be calculated over all wavelengths (from 0 to infinity). As the calibrated SR of the reference cell is either limited to the wavelength range 300 – 1200 nm (c-Si reference cell) or to the range 950 – 1750 nm (InGaAs reference cell) the integrals can be taken over one of those intervals. The short-circuit current of the DUT at standard test conditions (STC) I_{sc}^{dut} is then obtained by multiplying the measured short-circuit current I_{sc}^{meas} with MMF_i calculated for the junction that limits the current of the DUT on the simulator in examination:

$$I_{sc}^{dut} = MMF_i \cdot I_{sc}^{meas}. \quad (C.4)$$

The uncertainty of the SR will be treated in detail in the following sections. The uncertainties for the MMF and the short-circuit current will then be deducted at the end.

4. History of Changes

Edition a first issue

Edition b reduction factor from 99% confidence from 2.586 to 2.576

treatment of temperature as wavelength dependent factor

improved treatment of spectral response uncertainty

introduction of scaling factor k

Edition c (Jan 2010) renumbered par. 1 and 2; updated ref. 2.1, 2.2, 2.5

introduction of spectral response of multijunction devices

5. Identification of Contributions to Uncertainty

The following items contribute to the uncertainty in the determination of SR:

5.1 Electrical uncertainty

- Current to voltage converters: from manufacturers' data sheet and in-house verification.
- Data acquisition system: from manufacturer data sheet and in-house calibration procedure.
- Voltage bias generator: from manufacturers' data sheet and in-house verification.

5.2 Temperature uncertainty.

- Indicators: from internal calibration.
- Measurement conditions: $(25 \pm 2)^\circ\text{C}$ (according to IEC 60904-1).

5.3 Optical uncertainty.

- Spatial non-uniformity in the target plane.
- Alignment of reference cell and DUT (cosine response).
- Area of DUT and reference cell.

5.4 Reference cell uncertainty.

- From PEP'93 for PX201C.
- From calibration certificates of ESTI reference cells.
- Reference cell drift.

Furthermore, the uncertainty in the spectrum of the solar simulator contributes to the uncertainty of the MMF calculation. This is taken from [M39] and [M44].

6. Calculation Procedure

All uncertainty calculations are in % and rounded to 3 significant digits for single contributions and 2 significant digits for combined uncertainties.

6.1 Electrical uncertainty

- ### 6.1.1 Precision shunts are stated as $\pm 0.1\%$. Assuming a rectangular distribution gives $\pm 0.058\%$ ($\pm \frac{0.1\%}{\sqrt{3}}$) 1σ uncertainty value using a "B" type Standard

Uncertainty¹. This value is almost negligible so that in-house calibration is unlikely to improve it. The combined uncertainty for the current ratio is $\pm 0.058\% \cdot \sqrt{2} = \pm 0.082\%$.

Standard Uncertainty Type	Distribution	SR [%]
B	Rectangular	± 0.082

6.1.2 Lock-in amplifier

Statement of manufacturer: $\pm 1.0\%$ full scale. Assuming a 99% confidence level would give a $\pm 0.338\%$ 1σ uncertainty value, using “B” type Standard Uncertainty and a Gaussian distribution. The combined uncertainty for the current ratio is $\pm 0.549\%$. Drift of the instrument is neglected as it is operated in a controlled environment.

Standard Uncertainty Type	Distribution	SR [%]
B	Gaussian	± 0.549

6.2 Temperature uncertainty

The uncertainties of temperature due to the indicators are not correlated for the reference cell and the DUT (two separate measurements channels), whereas the influence of the ambient temperature is similar on both devices. The temperature coefficient for SR is a wavelength dependent quantity. In the wavelength interval 400 – 950 nm it is on average $0.05\%(\text{°C})^{-1}$.

6.2.1 The temperature indicators are specified (manufacturer data) with an uncertainty of $\pm 0.5\text{°C}$. The temperature indicators are verified and calibrated in-house, therefore this data point will be used in the determination of the uncertainty. The maximum deviations of all the indicators at $25 \pm 2\text{°C}$ is less than 0.3°C . Using a “B” type Standard Uncertainty and assuming a rectangular distribution, the 1σ uncertainty would be $\pm 0.17\text{°C}$. This 1σ uncertainty contributes $0.05\%(\text{°C})^{-1} \cdot 0.17\text{°C} = 0.009\%$ to the measured current of both devices. The combined uncertainty for the ratio is therefore $\pm 0.012\%$.

¹See Appendix D for definitions and details.

Standard Uncertainty Type	Distribution	SR [%]
B	Rectangular	± 0.012

6.2.2 The measurements are executed at $25 \pm 2^\circ\text{C}$. Using a “B” type Standard Uncertainty and assuming a rectangular distribution, the 1σ uncertainty contributes $0.05\%(\text{°C})^{-1} \cdot 1.15^\circ\text{C} = 0.058\%$ for each measurement (of reference cell and DUT). The maximum difference in temperature between the two devices is assumed to be $\pm 2^\circ\text{C}$, contributing 0.058% uncertainty (with the same assumptions as above).

Standard Uncertainty Type	Distribution	SR [%]
B	Rectangular	± 0.058

6.3 Optical uncertainty

6.3.1 Spatial non-uniformity

The non-uniformity averaged over the area of the DUT is $\pm 1\%$. Assuming a rectangular distribution gives $\pm 0.577\%$ ($= \frac{\pm 1.0\%}{\sqrt{3}}$) $1\text{-}\sigma$ uncertainty value. This value could potentially be reduced by explicitly using the measured values for the non-uniformity determination.

Standard Uncertainty Type	Distribution	SR [%]
B	Rectangular	± 0.577

6.3.2 Alignment of devices Assuming a maximal misalignment of 2° between the module and the reference cell, the 1σ would be 1.15° ($1.15^\circ = \frac{2^\circ}{\sqrt{3}}$). This misalignment can occur in two orthogonal directions giving a total uncertainty contribution of 0.028%.

Standard Uncertainty Type	Distribution	SR [%]
B	Gaussian	± 0.028

6.3.3 Area of devices For the reference cell this contribution is negligible. For the DUT the size can be measured to ± 1 mm, which for a $0.1 \times 0.1 \text{ m}^2$ square cell amounts to an uncertainty of $\pm 0.200\%$ (less, for bigger modules). Using a “B” type Standard Uncertainty and assuming a gaussian distribution, the 1σ uncertainty would be 0.067%.

Standard Uncertainty Type	Distribution	SR [%]
B	Gaussian	± 0.067

6.4 Reference cell uncertainty

6.4.1 Calibration of reference cell.

For PX201C (WPVS cell) the uncertainty is stated in document 1.6 with a 2σ value of 1.9% for the short-circuit current. We assume the same uncertainty for the SR of ESTI reference cells, giving a 1σ uncertainty of $\pm 0.95\%$.

Standard Uncertainty Type	Distribution	SR [%]
B	Gaussian	± 0.950

6.4.2 Reference cell drift.

The reference cell drift is assumed to have the same effect on all wavelengths for the SR. The results of the yearly verifications of the short-circuit current at 1000 Wm^{-2} is shown in the table below and will be used to assess the drift in the reference devices.

Reference Device	I_{sc} [mA] at 1000 Wm^{-2}	2000	2001	2002
		[%]		
PX201C	123.29	-0.05	0.01	-0.18

The drift between 2001 and 2002 was for PX201C -0.19% . Using a “B” type Standard Uncertainty and assuming a rectangular distribution, the 1σ uncertainty would be -0.110% . Long-term calibration data confirmed the value.

Standard Uncertainty Type	Distribution	SR [%]
B	Rectangular	± 0.110

7. Final Uncertainty Budget Calculation

7.1 Uncertainty for SR

Standard Uncertainty Component	Type [A/B]	Distribution [R/G]	SR [%]
Shunts	B	R	± 0.082
Lock-in amplifier	B	G	± 0.549
Comb. electrical uncertainty			± 0.56
Temperature indicators	B	R	± 0.012
Measurement conditions $25 \pm 2^\circ\text{C}$	B	R	± 0.058
Comb. temperature uncertainty			± 0.06
Non-uniformity of spatial irradiance	B	R	± 0.577
Alignment of DUT and reference cell	B	R	± 0.028
Area of devices	B	G	± 0.067
Comb. optical uncertainty			± 0.58
Calibration of reference cell	B	G	± 0.950
Reference cell drift	B	R	± 0.110
Comb. reference dev. uncertainty			± 0.96
Combined standard uncertainty			± 1.26
Expanded comb. uncertainty ($k = 2$)			± 2.52

The reported combined uncertainty is calculated as the square root of the sum of the squares of the individual contributions. A coverage factor with $k = 2$ gives a confidence level of 95% for a Gaussian probability distribution.

7.2 Uncertainty for MMF

Uncertainties in SR and spectral irradiance propagate into the calculation of MMF. Uncertainties which are not wavelength dependent cancel out in the MMF calculation whereas all uncertainties which vary between measurements at different wavelengths remain. However they are reduced 10 times, as stated in document 2.7. In the above table, the uncertainties of shunts, alignment of devices and area of devices are identical for each wavelength and can be neglected. (Incidentally they are so small that they almost do not make a

difference). The relevant uncertainty for the SR of the DUT is then 0.125%.

For the PX201C (WPVS cell) the 1σ uncertainty relevant for MMF calculation is $\pm 0.096\%$. The reference spectrum AM1.5g (or AM1.5d) is without uncertainty by definition but the uncertainty in the knowledge of the spectrum of the simulator (used for the measurement of the IV curve) contributes. This value depends on the actual simulator. For the SpectroLab LAPSS this calculation has already been performed in [UC04], as modules are normally measured on these two systems. Cells are normally measured on the WACOM CSS. The uncertainty of the spectral irradiance is 1.12% ($k = 1$) based on [M93] and [M44]. This contribution is also reduced by a factor 10:

SR measurement of DUT	B	G	± 0.125
SR of reference cell	B	R	± 0.096
Spectrum of the solar simulator	A	G	± 0.112
Comb. uncertainty for MMF			± 0.19
Expanded comb. uncertainty ($k = 2$)			± 0.38

Note: This uncertainty could be slightly reduced by measuring the SR of a cell on PASAN, because according to UC04 the relevant uncertainty of the SR measurement is 0.106% (rather than 0.125% here). This is neglected as cells are normally measured on ORIEL CSS.

The final SR and the I_{sc} of the DUT are obtained by multiplying with the scaling factor. Experience that uncertainty in the scaling factor is typically 2.0% for c-Si. Using a “B” type standard uncertainty and a Gaussian distribution assumint 2.0% to be the 2σ uncertainty, the combined uncertainty for the final SR is:

SR measurement	A	G	$\pm 1.26\%$
Scaling factor	B	G	$\pm 1.00\%$
Comb. uncertainty for I_{sc}			± 1.61
Expanded comb. uncertainty ($k = 2$)			± 3.22

Appendix D

GPS-U: Uncertainty Calculation

The uncertainties in the measurement of current (u_I), voltage (u_V), irradiance (u_E) and fill factor (u_{FF}) are analysed, by means of the following types of distribution [123, 174, 175]:

- **Type A:** method of evaluation of uncertainty by the statistical analysis of series of observations.
- **Type B:** method of evaluation of uncertainty by means of other than the statistical analysis of series of observations (e.g., previous measurement data; experience with, or general knowledge of, the behavior and property of relevant materials and instruments; manufacturer’s specifications; data provided in calibration and other reports; uncertainties assigned to reference data taken from handbooks).
- **Rectangular (R):** the uniform probability distribution

$$f_{X,a}(x) = \begin{cases} \frac{1}{2a}, & \text{if } |x - X| < a \\ 0, & \text{if } |x - X| > a \end{cases} \quad (\text{D.1})$$

such that each value within the given interval of width $X \pm a$ is equally probable.

In this case the standard uncertainty is $u = \frac{a}{\sqrt{3}}$ (with “coverage factor” $k = \sqrt{3}$).

- **Gaussian (G)**: the probability distribution defined by the Gaussian function

$$f_{X,a}(x) = \frac{1}{a\sqrt{2\pi}} \exp \left[-\frac{(x - X)^2}{2a^2} \right], \quad (\text{D.2})$$

where X is the mean value and a the standard uncertainty; 68% is the probability that the real value is within $X \pm a$ ($k = 1$, $u = a$); 95% is the probability that the real value is within $X \pm 2a$ ($k = 2$, $u = 2a$ also referred to as “expanded uncertainty”); 99%, within $X \pm 2.586a$.

The uncertainty calculation of each electrical parameter depends on which of the two methods of measurements introduced in Chapter 3 is used: the “reference cell method” and the “self-reference method”. Both methods are analysed in dedicated sections below.

All sources of uncertainties are grouped in four categories: (1) electrical uncertainties (data acquisition system, shunt resistance and transimpedance amplifier for the detection of current from the test device and the reference cell respectively); (2) temperature uncertainties (temperature sensor and temperature instability during the single measurement); (3) optical uncertainties (spatial non-uniformity; orientation; co-planarity and reference cell and test device alignment); and (4) reference cell uncertainties (spectral response, spectral mismatch, calibration drift and non-linear response of the neutral density filters).

The uncertainty on the FF is calculated from a brief statistical analysis of the measurements performed (type A uncertainty).

D.1 Uncertainty Calculation for Measurements with Filtered Reference Cells

Table D.1 quantifies the uncertainty contributions in current-voltage measurements on GPS-U with reference cells.

Uncertainty	Type	a	k	u_I	u_V	u_E (10X)	u_E (100X)	u_E (1000X)	u_{FF}
Electrical									
Data acquisition	B/G	± 0.25	2.59	± 0.097	± 0.097	± 0.097	± 0.097	± 0.097	
Shunt	B/R	± 0.20	$\sqrt{3}$	± 0.115					
Transimpedance Amp.	B/R	± 0.10	$\sqrt{3}$			± 0.058	± 0.058	± 0.058	
Combined			1	± 0.151	± 0.097	± 0.113	± 0.113	± 0.113	
Temperature									
Sensor	B/R	± 0.10	$\sqrt{3}$	± 0.004	± 0.019	± 0.003	± 0.003	± 0.003	
Instability (< 100X)	B/R	± 0.10	$\sqrt{3}$	± 0.004	± 0.019	± 0.003			
Instability (> 100X)	B/R	± 1.15	$\sqrt{3}$	± 0.082	± 0.381		± 0.058	± 0.058	
Combined (< 100X)			1	± 0.006	± 0.027	± 0.004			
Combined (> 100X)			1	± 0.082	± 0.381		± 0.058	± 0.058	
Optical									
Spatial uniformity (10X)	B/R	± 0.40	$\sqrt{3}$	± 0.231		± 0.231			
Spatial uniformity (100X)	B/R	± 1.00	$\sqrt{3}$	± 0.231			± 0.577		
Spatial uniformity (1000X)	B/R	± 5.00	$\sqrt{3}$	± 0.231				± 2.887	
Orientation (10X)	B/G	± 0.03	1	± 0.030		± 0.030			
Orientation (100X)	B/G	± 0.29	1	± 0.293			± 0.293		
Orientation (1000X)	B/G	± 2.44	1	± 2.438				± 2.438	
Co-planarity (10X)	B/R	± 0.19	$\sqrt{3}$	± 0.109		± 0.109			
Co-planarity (100X)	B/R	± 0.60	$\sqrt{3}$	± 0.345			± 0.345		
Co-planarity (1000X)	B/R	± 1.87	$\sqrt{3}$	± 1.080				± 1.080	
Combined (10X)			1	± 0.257		± 0.257			
Combined (100X)			1	± 0.508			± 0.577		
Combined (1000X)			1	± 2.677				± 3.930	
Reference cell									
Calibration	A/G	± 1.90	2	± 0.950	± 0.050	± 0.950	± 0.950	± 0.950	
MMF	B/G	± 0.19	1	± 0.190					
Drift	B/R	± 0.19	$\sqrt{3}$	± 0.110		± 0.110	± 0.110	± 0.110	
NDF (> 100X)	B/R	± 5.00	$\sqrt{3}$				± 2.887	± 2.887	
Combined			1	± 0.975	± 0.050	± 0.956	± 3.041	± 3.041	
Fill Factor									
FF (< 100X)	A/G	± 0.45	1						± 0.450
FF (100X)	A/G	± 0.75	1						± 0.750
FF (1000X)	A/G	± 1.00	1						± 1.000
Total expanded (10X)			2	± 2.04	± 0.22	± 1.994			± 0.90
Total expanded (100X)			2	± 2.23	± 0.79		± 6.20		± 1.50
Total expanded (1000X)			2	± 5.71	± 0.79			± 9.94	± 2.00

Table D.1: Uncertainty calculation: measurements with filtered reference cells.

The electrical and temperature components arise from manufacturer's data sheet, as reported in the cited Ref. [124]. For temperature instability above 100X a larger uncertainty is assumed.

The spatial non-uniformity contribution to the optical uncertainty depends on the intensity: referring to the data of Figures 3.11 and 3.13 and to the typical sizes of test devices and reference cells, $\pm 0.40\%$ uncertainty at 10X, $\pm 1\%$ at 100X and $\pm 5\%$ at 1000X were assumed, all with rectangular distributions. Such uncertainty affects the measurement of irradiance; the non-uniformity across the test device is constant and gives $\pm 0.40\%$ uncertainty at all intensities, due to the small size of such cells.

Test device and reference cell orientation and co-planarity were considered as other im-

portant sources of uncertainty, giving rise to possible different intensities seen by the reference cell and by the test device. The uncertainty in the orientation of the test and reference cell takes into account two possible different angles of incidence and can be as high as $\pm 2.438\%$ at 1000X, where the devices are at few centimeters distance from the lamp.

Taking into account the reference cell encapsulation, a reasonable choice for the uncertainty in co-planarity is ± 0.25 cm. Such an uncertainty poorly affects current and irradiance measurements at 10X or below, while gives a $\pm 0.345\%$ at 100X and up to $\pm 1.080\%$ at 1000X.

The uncertainty in ESTI's reference cell spectral responses is taken from the World Photovoltaic Scale (WPVS, [176, 177]) primary reference cell calibration report (type A), with an uncertainty of $\pm 1.9\%$ ($k = 2$). MMF uncertainty and reference cell drift are the same as in Ref. [124], while an additional uncertainty due to the linear response of NDF at high intensities ($> 100X$) was estimated to $\pm 5\%$ based on manufacturer's data.

The total combined uncertainties at 10X are in line with results in the cited Ref. [124], while as expected the optical uncertainties have a strong impact on the total uncertainties at 100X and at 1000X.

D.2 Uncertainty Calculation for Measurements with the “Self-reference Method”

As already stressed in Chapter 3, the assumption of linearity of the test device towards increasing irradiance allows the “self-reference method” to be used.

In this case, the uncertainty on measurement of I_{sc} at 1X propagates to all values of irradiances at higher intensities, but, as a positive result, the sources of the largest uncertainties analysed above (i.e., all the optical uncertainties referred to the reciprocal positions of

the test and reference cells) do not affect measurements. (Uncertainties on the NDF do affect the test of linearity, which is not analysed here).

Results of the uncertainty calculation for measurements with the self-reference method are analysed in Table D.2, showing an improvement in the total combined uncertainties above 100X. (Uncertainties at 1X refer to measurements on WACOM and come again from Ref. [124]).

Uncertainty	Type	a	k	u_I	u_V	u_E (1X)	u_E (> 10X)	u_{FF}
Electrical								
Data acquisition	B/G	± 0.25	2.59	± 0.097	± 0.097	± 0.097	± 1.018	
Shunt	B/R	± 0.20	$\sqrt{3}$	± 0.115				
Transimpedance Amp.	B/R	± 0.10	$\sqrt{3}$			± 0.058		
Combined			1	± 0.151	± 0.097	± 0.113	± 1.018	
Temperature								
Sensor	B/R	± 0.10	$\sqrt{3}$	± 0.004	± 0.019	± 0.003	± 1.013	
Instability (< 100X)	B/R	± 0.10	$\sqrt{3}$	± 0.004	± 0.019	± 0.003	± 1.013	
Instability (> 100X)	B/R	± 1.15	$\sqrt{3}$	± 0.082	± 0.381		± 1.017	
Combined (< 100X)			1	± 0.006	± 0.027	± 0.004	± 1.433	
Combined (> 100X)			1	± 0.082	± 0.381		± 1.435	
Optical								
Spatial uniformity	B/R	± 0.40	$\sqrt{3}$	± 0.231		± 0.231	± 0.231	
Reference cell								
Calibration	A/G	± 1.90	2	± 0.950	± 0.050	± 0.950	± 1.389	
MMF	B/G	± 0.19	1	± 0.190			± 1.031	
Drift	B/R	± 0.19	$\sqrt{3}$	± 0.110		± 0.110	± 1.019	
Combined			1	± 0.975	± 0.050	± 0.956	± 2.008	
Fill Factor								
FF (< 100X)	A/G	± 0.45	1					± 0.450
FF (100X)	A/G	± 0.75	1					± 0.750
FF (1000X)	A/G	± 1.00	1					± 1.000
Total expanded (1X)			2	± 2.03	± 0.22	± 1.98		± 0.90
Total expanded (10X)			2	± 2.03	± 0.22		± 5.36	± 0.90
Total expanded (100X)			2	± 2.03	± 0.79		± 5.36	± 1.50
Total expanded (1000X)			2	± 2.03	± 0.79		± 5.36	± 2.00

Table D.2: Uncertainty calculation: measurements with the “self-reference method”.

D.3 Uncertainty calculation for $P_{\max}$ and cell efficiency

The uncertainty for the maximum power is given by the combined uncertainty

$$u_{P_{\max}} = \sqrt{u_I^2 + u_V^2 + u_{FF}^2}. \quad (\text{D.3})$$

In the uncertainty calculation of cell efficiency, the additional uncertainty due to the test cell area measurement u_A should be considered. However, this contribution does not depend on the experimental setup under discussion and is usually smaller than $u_{P_{\max}}$ and u_E . In order to compare the relative contributions of the sources of uncertainties arising from IV measurements on GPS-U and to highlight the combined contribution of $u_{P_{\max}}$ and u_E , the uncertainty in cell area measurements will be neglected and the uncertainty for cell efficiency is thus given by

$$u_\eta = \sqrt{u_{P_{\max}}^2 + u_E^2 + u_A^2} \approx \sqrt{u_{P_{\max}}^2 + u_E^2}. \quad (\text{D.4})$$

Figure D.1 shows the comparison between the component contributions ($k = 1$) to $u_{P_{\max}}$ and u_η and the total combined uncertainties ($k = 2$) in both methods of measurements. The charts highlight the higher calculated uncertainties of measurements with filtered reference cells than with the self-reference method at high intensities.

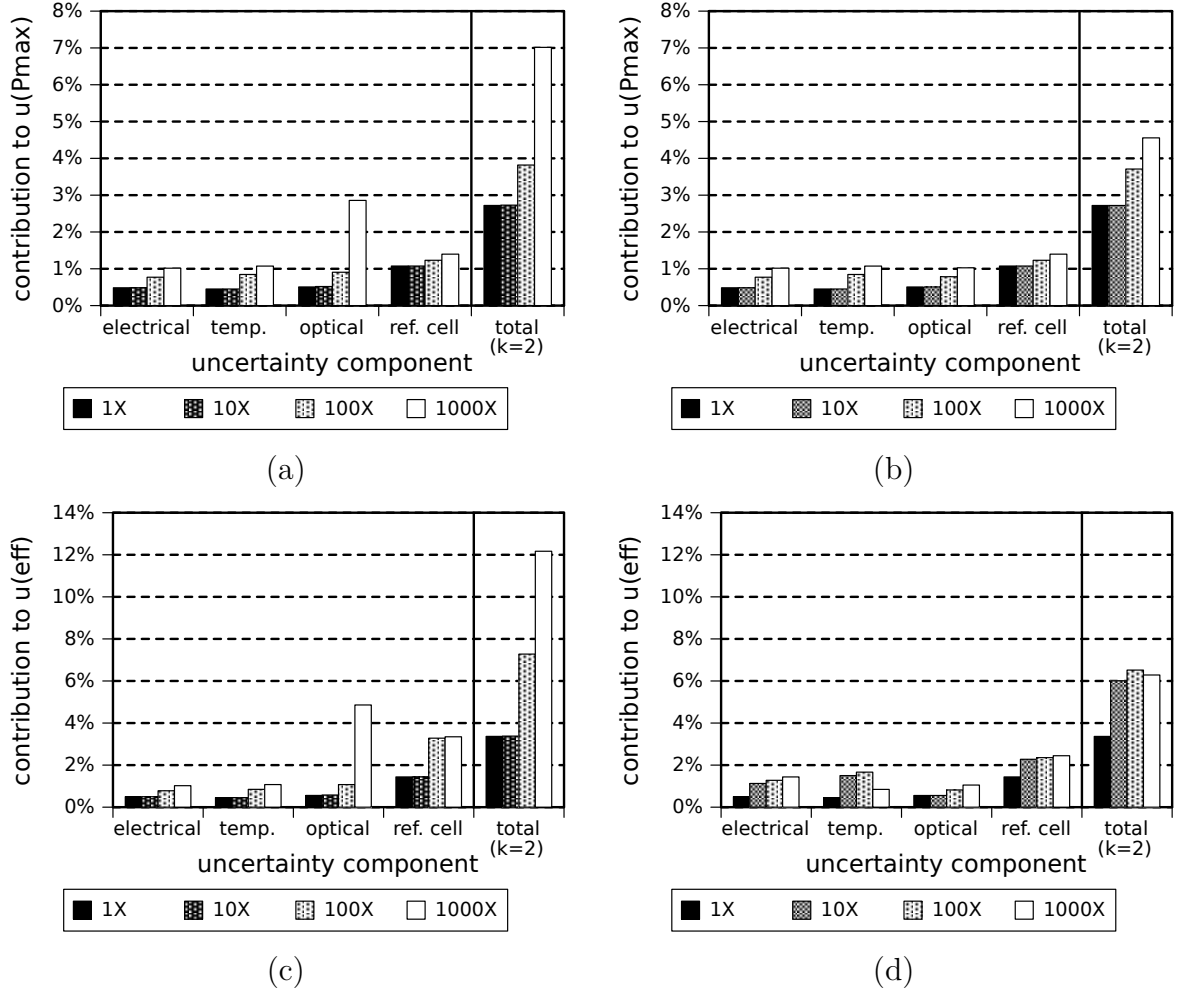


Figure D.1: Contribution to the uncertainty of $P_{\max}$ ((a) measurements with filtered reference cells; (b) “self-reference method”) and efficiency ((c) reference cells; (d) “self-reference method”). Standard component uncertainties ($k = 1$) and expanded total uncertainty ($k = 2$).

Appendix E

Preliminary Results on III-V Multi-junction CPV Cells

E.1 External Quantum Efficiency

At time measurements were performed, the spectral response (SR) experimental setup described in section 2.2.4 did not allow measurements above 1263 nm: the bottom junction SRs of¹ NE505, MO703 and MO705 were therefore extrapolated with reasonable assumptions based on the literature of constant 75% EQE up to 1700 nm cut-off, corresponding to the 0.74 eV band-gap of a Ge junction. An extrapolation may be sufficient for quantitative results, if the device under examination has a good current-balance and is not current-limited by the bottom junction, neither on GPS-U, nor at AM1.5d.

The quantum well peak at 940 nm in the middle (GaInAs) junction of MO703 was recorded. Similarly, MO705's top junction shows a cut-off at 1000 nm, above the GaAs usual cut-off at 900 nm (band-gap: 1.43 eV): the small peak between 950 and 1000 nm is probably due to the low resolution of the spectral response measurement setup in use.

WACOM has Class A spectrum, but in the present standard there is no requirement for

¹For details on the test devices see Table 3.13 in section 3.3.1.

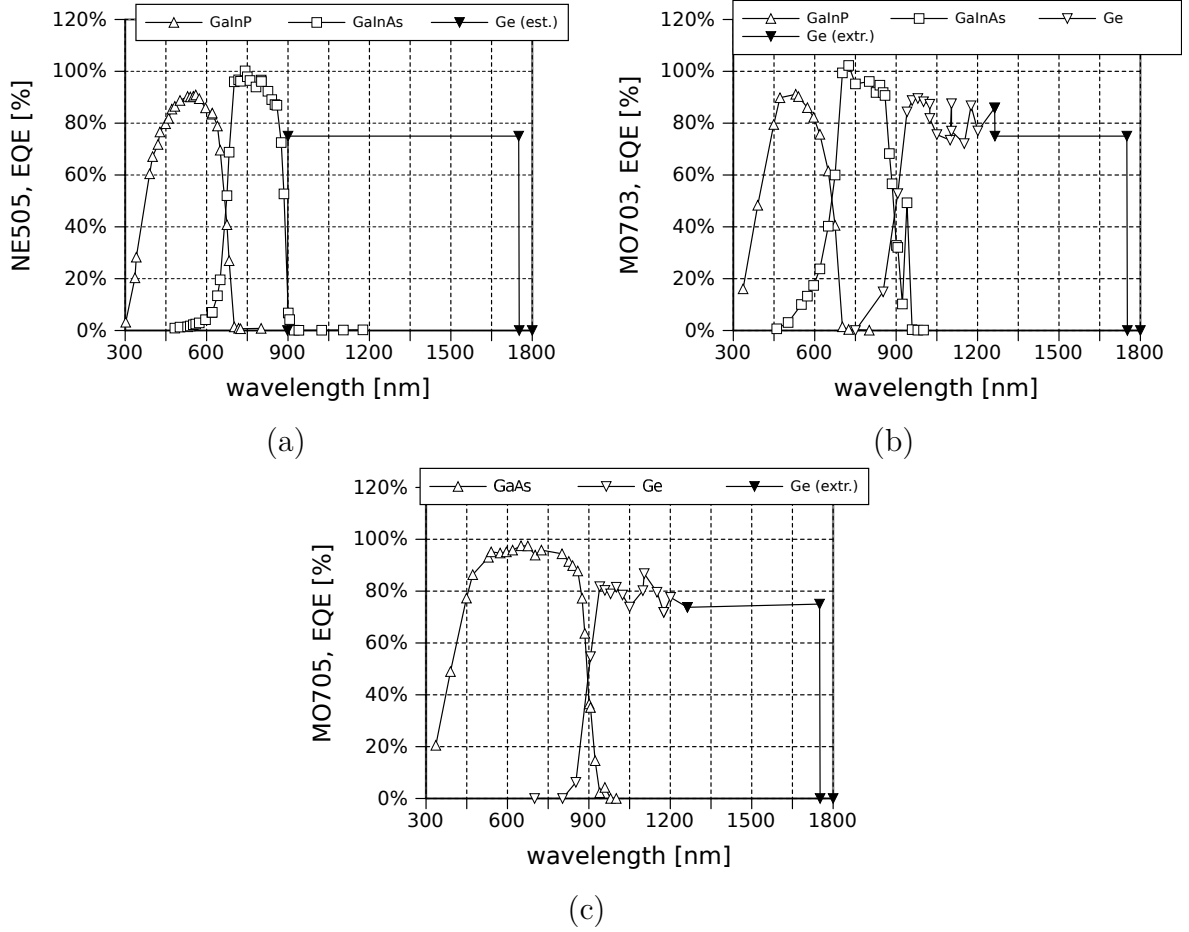


Figure E.1: External quantum efficiency: (a) NE505 (GaInP/GaInAs/Ge), (b) MO703 (GaInP/GaInAs/Ge, multi-quantum-well) and (c) MO705 (GaAs/Ge, multi-quantum-well). Ge junction EQEs have been extrapolated from measurements available, data in the literature and data given by the suppliers.

Ref. cell Simulator	ASP004 (wog) WACOM	PX501C WACOM	ASP009 GPS-U	ASP010 GPS-U	ASP004 GPS-U
NE505 (top)	-	1.029	1.787	1.806	1.863
NE505 (mid.)	-	1.89	1.067	1.078	1.112
NE505 (bot.)	-	0.611	0.882	0.892	0.920
MO703 (top)*	1.037	-	1.208	1.212	1.213
MO703 (mid.)*	1.054	-	0.880	0.882	0.884
MO703 (bot.)*	0.637	-	0.804	0.806	0.808
MO705 (top)*	1.061	-	1.056	1.058	1.060
MO705 (bot.)*	0.628	-	0.799	0.801	0.802

Table E.1: MMF calculation.

the spectral distribution of irradiance above 1100 nm, as was already discussed in section 3.1.1. WACOM is therefore not calibrated to match the standard spectrum above that limit (see fig. 3.18): as a consequence, when c-Si cells are used as a reference, MMF values for Ge junctions of III-V group test devices are significantly lower than unity. Low MMF is due to the larger content of NIR radiation in WACOM spectrum than in AM1.5d: while in the latter 30.6% percent of spectral irradiance lies in the range 900 to 1800 nm (over total integrated irradiance between 300 and 1800 nm, where III-V group CPV cells respond), in WACOM that percentage is 44%, giving rise to a $MMF = 0.06 - 0.07$ for a junction that responds in that range. Better MMF for Ge junctions can be obtained tuning WACOM spectral irradiance to better match the AM1.5d spectrum above 1100 nm.

As expected, due to Class C spectral irradiance of GPS-U, MMF values significantly different from unity are shown for the III-V group test devices.

E.2 Spectral Mismatch Correction and Discussion

Results of spectral mismatch calculation of the four testing devices considered are shown in tab. E.2. MMF values listed in tab. 3.14 have been applied, with respect of the solar simulator shown and the reference cell used for characterization at 1X (WACOM) and at higher irradiances (GPS-U). The current-limiting junction on a given solar simulator is highlighted in bold type; spectrally corrected short-circuit current values of junctions that are saturated under the simulator considered are in brackets. A spectrally selective (AM0) filter has been applied to GPS-U for MO703 and MO705 characterization.

I_{sc} measurements at 1000 Wm^{-2} on WACOM show large differences on 3-J CPV cells with respect to those on GPS-U normalized to the same irradiance.

NE505 is largely current-limited by the top (InGaP) junction on GPS-U (result calculated at 1000 Wm^{-2} ; ref cell.: ASP004; $MMF = 1.868$), while corrected values to STC show that top and middle junctions of the device are well current-matched and only slightly current-limited by the middle junction (InGaP) on AM1.5d spectral irradiance. Based

Test Cell	I_{sc}^{calc} [mA]			I_{sc}^{corr} [mA]			I_{sc}^{STC} [mA]
	top	mid.	bot.	top	mid.	bot	
WACOM							
LX701	51.4	-	-	51.2	-	-	51.2
NE505	4.23	4.00	10.0	(4.36)	4.35	(6.1)	4.35
MO703	4.41	5.6	12.2	4.58	(5.9)	(7.8)	4.58
MO705	9.2	-	11.5	9.8	-	(7.2)	N.A.
GPS-U							
LX701	51.1	-	-	51.2	-	-	51.2
NE505	2.34	3.91	6.7	4.36	(4.35)	(6.1)	N.A.
MO703*	3.79	6.7	9.6	4.58	(5.9)	(7.8)	4.58
MO705*	9.3	-	9.0	(9.8)	-	7.2	7.2

Table E.2: Short-circuit current values calculated with WACOM and GPS-U spectral irradiances at 1000 Wm^{-2} and spectral correction to AM1.5d. Current limiting junctions in multi-junction test devices are highlighted in bold types; spectral correction applied to the saturated junctions are in brackets. Spectrally selective (AM0) filter has been applied to GPS-U at MO703 and MO705 characterization (*). MO705 on WACOM and NE505 on GPS-U are current-limited by different junctions than at STC: the short-circuit current values measured on those solar simulators cannot be spectrally corrected to match AM1.5d spectrum.

only on GPS-U data, spectral mismatch correction should be applied to the top junction, which is current-limiting on that simulator, giving a corrected short-circuit current value which is larger than the current that should be produced by the middle junction at STC. The corrected value found cannot therefore be referred to as the short-circuit current of the device at STC.

On WACOM, NE505 is current-limited by the middle junction instead: it is therefore possible in this case to apply the proper MMF and correct the short-circuit current value to STC, because it was calculated from a different junction than the current-limiting one at STC.

Another switch in current-limiting behaviour of the test device occurs on MO705 on WACOM. Based on the extrapolated EQE of the test device, MO705 is current-limited by the bottom junction (Ge) at STC, while is limited by the top junction (GaAs) on WACOM. On GPS-U instead (based on the extrapolation of GPS-U spectrum above 1100 nm) MO705 is current-limited by the bottom junction: correction to STC can therefore be performed,

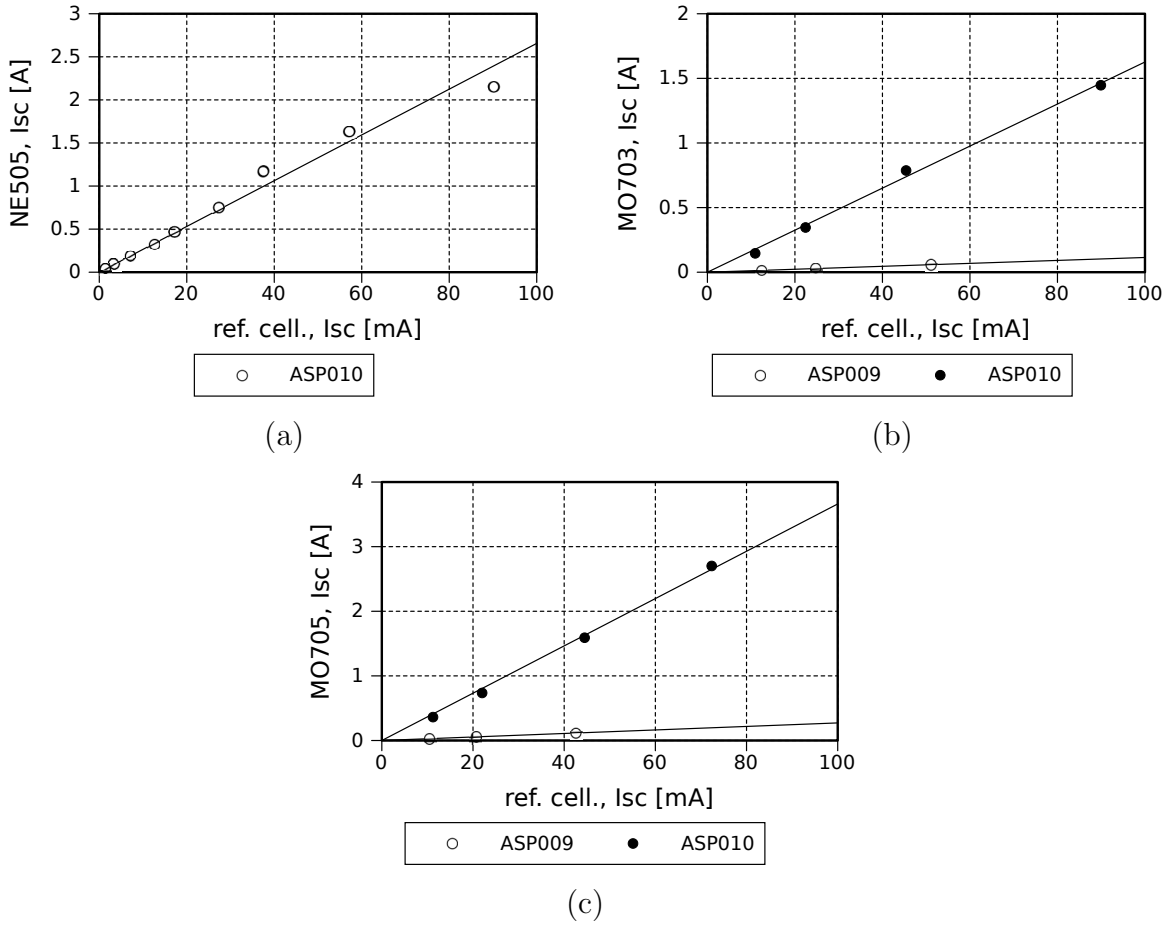


Figure E.2: Linearity on GPS-U: (a) NE505, (b) MO703 and (c) MO705. ASP009 has been used as reference cell up to 30X, ASP010 from 90X to 250X. Linearity criterion according to ASTM standard method E 1143-05 [125] is met for all test devices as follows from eqs. (3.14)-(3.15).

though complete measurements of the EQE of the bottom junction of the test device and of the spectral irradiance above 1100 nm are of pivotal importance in this case.

E.3 Linearity and Electrical Performance

Verification of the linearity of the test devices is shown in tab. E.3: all four devices tested meet the requirements of linearity versus the reference cells used over the range of irradiances considered, according to the cited ASTM standard E 1143-05 [125].

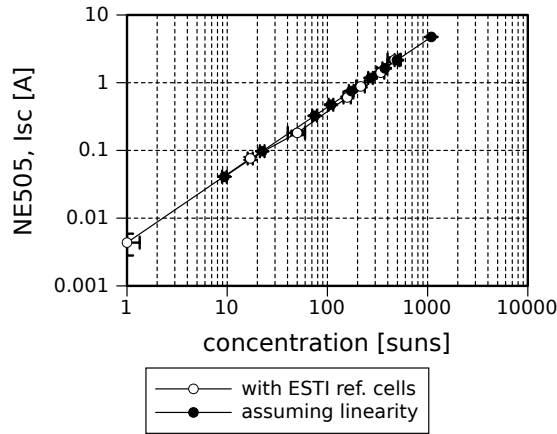
NE505 shows deviations from linearity within the optical uncertainties described in Appendix D: those deviations affect the efficiency calculation, as shown in fig. E.3. Figs.

Test cell	Ref. cell	m [A mA ⁻¹]	s [A mA ⁻¹]	$\frac{s}{m}$ [%]
NE505	ASP004	0.0266	6×10^{-4}	2.1
MO703	ASP009	0.00114	10^{-5}	0.8
	ASP010	0.0163	4×10^{-4}	2.2
MO705	ASP009	0.00272	5×10^{-5}	1.7
	ASP010	0.0366	7×10^{-4}	1.9

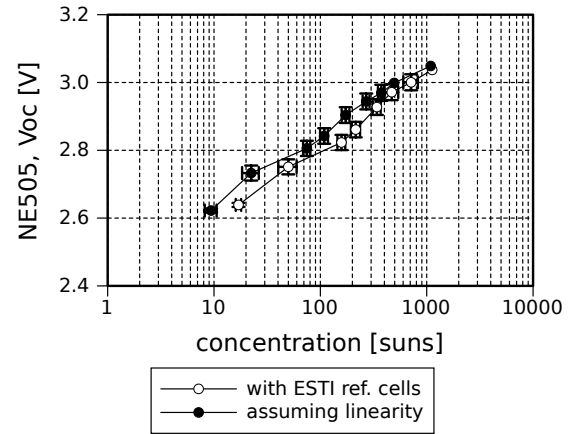
Table E.3: Linearity test, according to ASTM standard E 1143-05 [125]. $\frac{s}{m} = 2.1\%$ on NE505 is affected by the optical uncertainties at higher irradiances discussed in Appendix D.

E.4 and E.5 present results of MO703 and MO705 respectively, where linearity of the devices has been assumed.

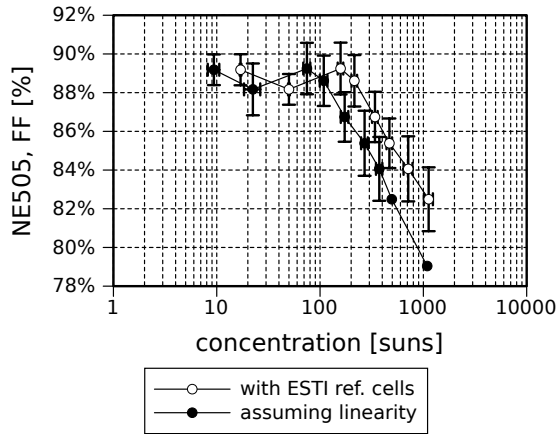
Fill factor values reported in figs. E.3, E.4 and E.5 may be affected by 1-2% difference to values measured on a simulator with better spectral match to AM1.5d. This is due to the non-optimal current-balance under GPS-U spectral irradiance. This may finally result in an additional cell efficiency additional uncertainty in the order of 1%, as reported in the literature [178, 116, 78].



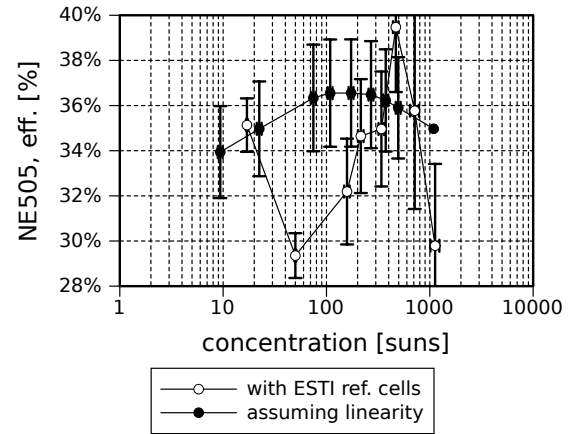
(a)



(b)

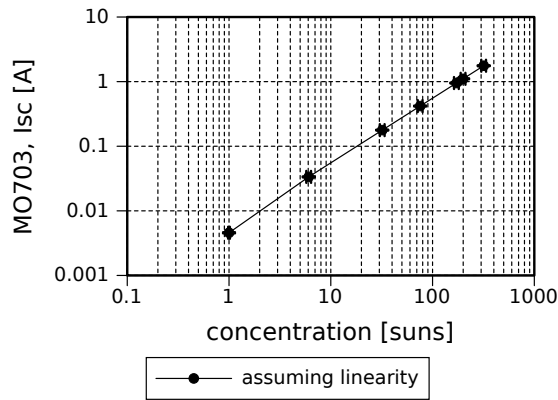


(c)

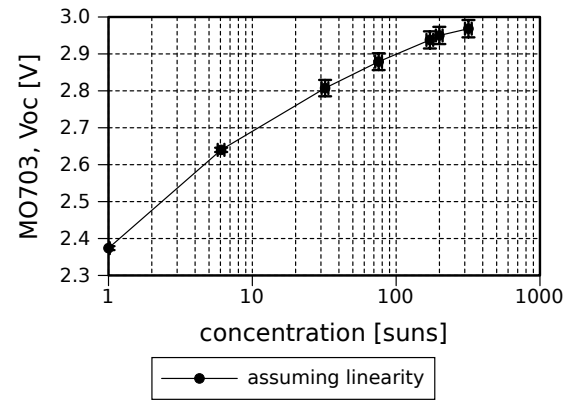


(d)

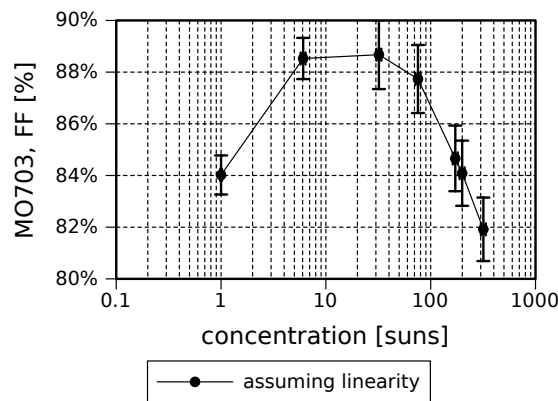
Figure E.3: Electrical performance at various concentration: NE505.



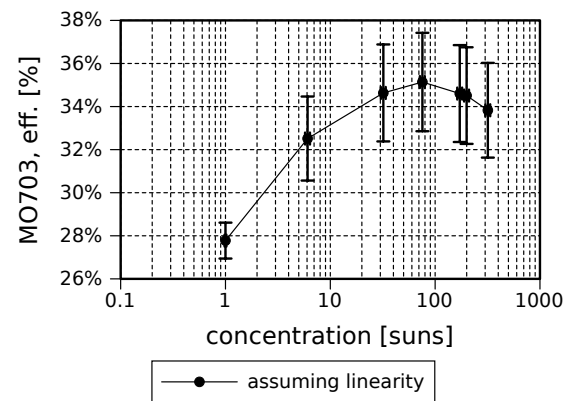
(a)



(b)



(c)



(d)

Figure E.4: Electrical performance at various concentration: MO703.

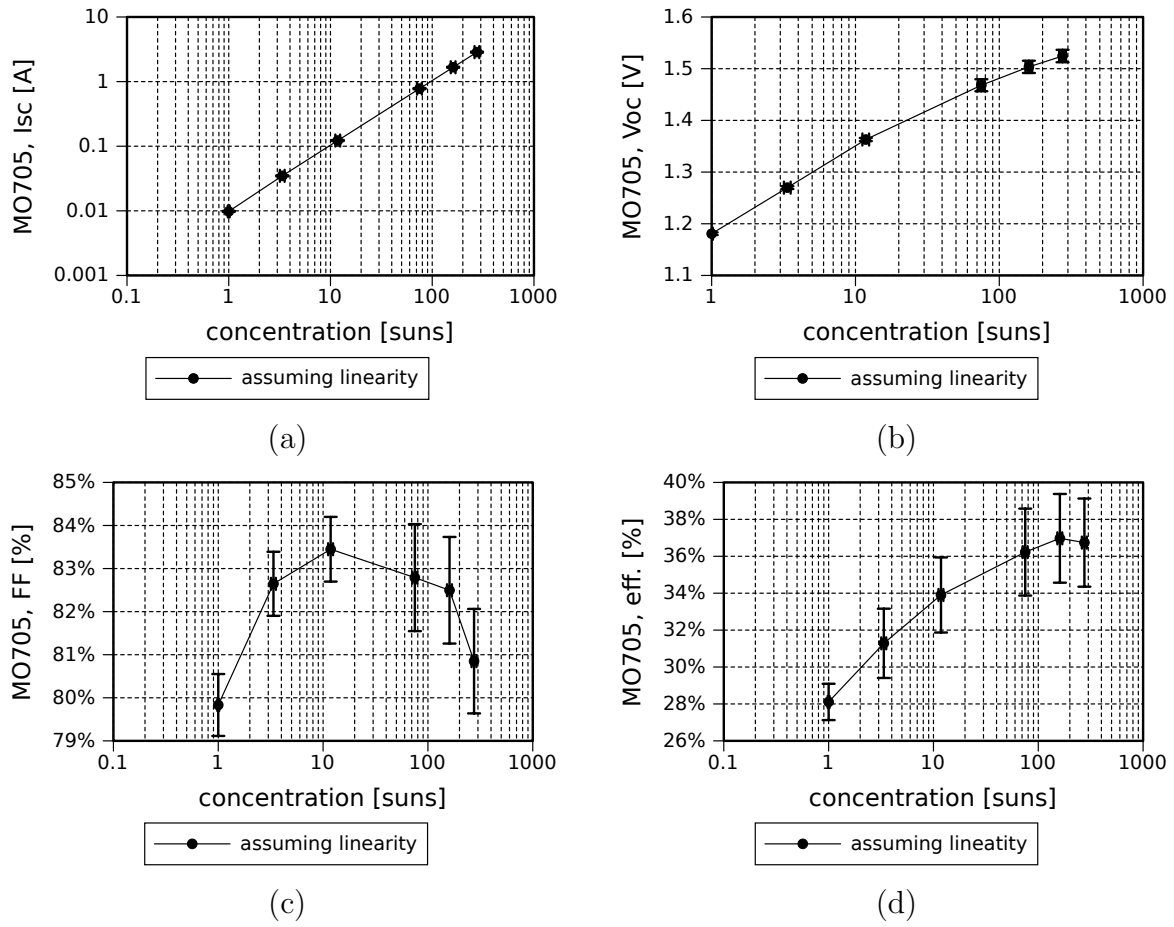


Figure E.5: Electrical performance at various concentration: MO705.

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