

#### IV MEASUREMENTS OF MC-Si SOLAR CELLS: COMPARISON OF RESULTS FROM INSTITUTE AND INDUSTRY PARTNERS WITHIN THE EU CRYSTALCLEAR PROJECT

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**ABSTRACT:** Determination of solar cell parameters by illuminated IV measurement is a standard characterisation technique used by many partners active in photovoltaics. The aim of this work is to carry out a cross check of different measurement set-ups used by different research partners of the EU CrystalClear project using industrial-type multicrystalline Si solar cells. In a first round robin a significant spread of all cell parameters ( $V_{oc}$ ,  $j_{sc}$ , FF and efficiency) could be observed. After distribution of sister cells to selected cells calibrated at ISE CaLab, a second round robin was carried out. The spread in FF and  $j_{sc}$  could be significantly reduced. Repeatability tests showed that by using a photo diode fluctuations of light intensity can be minimised and variations in  $j_{sc}$  can be decreased down to  $0.2 \text{ mA/cm}^2$ . Remaining systematic errors are control of cell temperature, contacting geometry, and use of appropriate reference cells.

**Keywords:** Characterisation, Multicrystalline Silicon, Solar Cell Efficiency

## 1 INTRODUCTION

Measurement of illuminated IV parameters under agreed standard conditions (STC: 25°C, 1000 W/m<sup>2</sup> AM1.5G spectrum) is the most crucial characterization technique for solar cells as it delivers the conversion efficiency and therefore the value which is economically the most important one. Apart from efficiency, the measurement of current at maximum power point conditions is important for industry, too, as this value is used to sort cells into classes of similar currents to assure a good matching of the cells in the solar module. The correct and reliable measurement of the illuminated IV parameters is therefore of great interest for all players active in the photovoltaic (PV) market.

The most accurate measurements are possible at places that are certified to be independent calibration labs for solar cell measurements. These institutions are in regular contact with each other and common measurements on identical solar cells that are shipped to the various labs taking part in these so called 'round robins' ensure a good agreement of the measured parameters. Results of these common measurement rounds within the calibration labs have been published regularly [1,2]. In addition, bi-lateral proficiency tests are conducted regularly.

The measurement of a solar cell in a calibration lab is defined in IEC standards [3] and normally consists of two parts: in addition to the illuminated IV measurement under a sun simulator the determination of the spectral response is carried out to allow for spectral mismatch correction [4]. This correction is necessary as the spectrum supplied by the sun simulator is slightly different from the one that is tabulated in the standard [5]. Note that the standard was revised recently and a new "ed.2" published by the IEC. The measurements here refer to IEC 60904-3 ed.1. Traceability to international standards is in these measurements assured

via encapsulated 2x2 cm<sup>2</sup> reference cells (WPVS-design) primary calibrated at the PTB [6].

Especially for collaborations in (international) projects, comparability of IV measurements has to be ensured to allow common developments and ensure credibility. Further on, detection of systematic errors during measurement can help to improve accuracy of measurement of standard industrial-type solar cells.

In this paper eight partners of the EU integrated project CrystalClear perform a similar round robin. The aim is to use the equipment available at the project's institute and industry partners and the measurement procedures commonly used by them to check for the accuracy of the respective outcomes. Another point to address is the measurement accuracy that is reachable in a 'normal' partner's characterization environment.

## 2 EXPERIMENTAL

Four batches of mc Si solar cells each processed from around 20 neighbouring wafers have been processed using state of the art firing through SiN<sub>x</sub>:H processes. Two batches used 125x125 mm<sup>2</sup> wafers (alkaline etching and acidic texturing), the other two used 156x156 mm<sup>2</sup> wafers (alkaline etching and acidic texturing). After etching/texturing the solar cell processes continued with POCl<sub>3</sub> diffusion, PECVD (Plasma Enhanced Chemical Vapor Deposition) SiN<sub>x</sub> deposition, screen printing of front (Ag) and rear (Al) contacts, co-firing and edge isolation. 125x125 mm<sup>2</sup> cells were isolated using a wafer dicing saw, 156x156 mm<sup>2</sup> cells by laser scribing at the front. The 156x156 mm<sup>2</sup> cells had Ag/Al pads on the rear side whereas the 125x125 mm<sup>2</sup> cells had a fully covered Al rear. All cells were measured independently at the different partner's IV set-ups. After all cells had been measured, two cells from each group were sent to a

calibration lab for independent confirmation of IV data (ISE CalLab).

**Table I:** Overview of processed cells of the first experiment.

Group	Material and process	Labelling
A	125x125 mm <sup>2</sup> acidic	2-27
B	125x125 mm <sup>2</sup> alkaline	29-50
C	156x156 mm <sup>2</sup> acidic	52-85
D	156x156 mm <sup>2</sup> alkaline	101-130
E	156x156 mm <sup>2</sup> alkaline	201-225

### 3 RESULTS

#### 3.1 125x125 mm<sup>2</sup> cells

IV results of 125x125 mm<sup>2</sup> cells (group A and B) are given in the overview of figure 1. These results point out that there is a significant spread between the different partners in  $V_{oc}$ ,  $j_{sc}$ , and FF.

The observed maximum spread in the absolute values between the different partners for measurements of the same cells is approximately

- $V_{oc}$ : 6 mV
- $j_{sc}$ : 1.0-1.3 mA/cm<sup>2</sup>
- FF: 3%<sub>abs</sub>
- efficiency: 0.5%<sub>abs</sub>

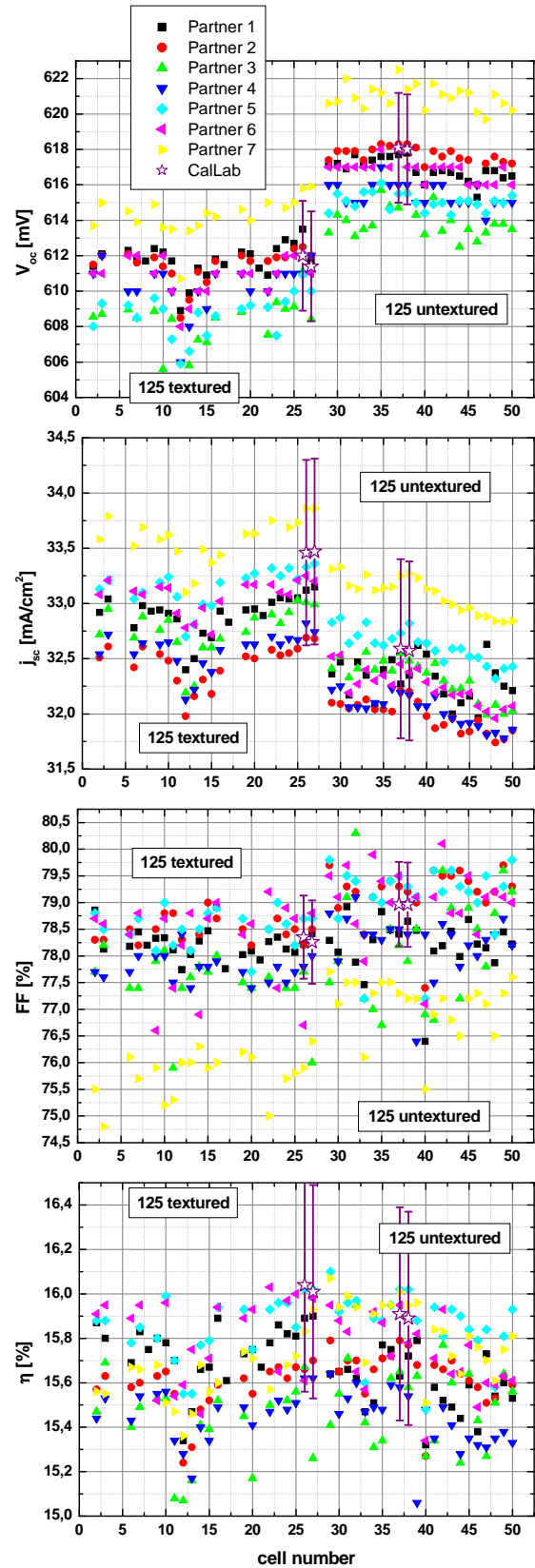
Surprisingly, the spread in efficiency is less pronounced. This might be explained by the fact that most partners use calibrated reference cells and due to the specific measurement set-ups a systematic error is tolerated (e.g. leading to lower  $V_{oc}$  values due to higher measurement temperature), whereas the efficiency value is quite reliable. Nevertheless, a spread in efficiency of up to 0.5%<sub>abs</sub> for 125x125 mm<sup>2</sup> cells could be observed (corresponding to 3%<sub>rel</sub>).

One partner (partner 7) measures significantly higher  $j_{sc}$  and  $V_{oc}$  values but lower FF values than the other partners. Some cells measured at partner 3 show unusually low FF or  $V_{oc}$ . This seems to be related to contacting problems and these cells are not included in the spread mentioned above.

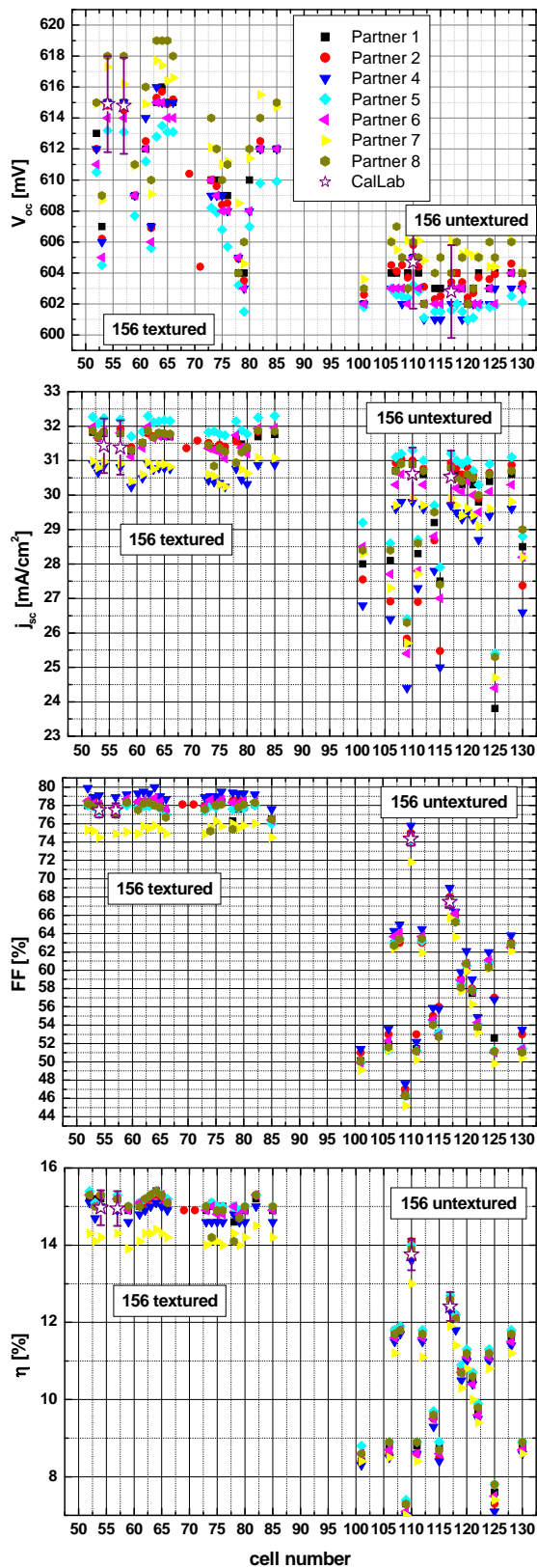
Efficiency values determined at ISE CalLab are on the higher end of the scale (uncertainties of the calibrated measurements indicated by the error bars in figure 1), proving that all partners measure either values very close to ISE CalLab or lower ones. This seems to add credibility to efficiency values published by the partners without independent confirmation, under the assumption that the same measurement set-ups and the same accuracy have been used. Apart from  $V_{oc}$  measurement of partner 7, the results lie within the uncertainties given by ISE CalLab (0.5%  $V_{oc}$ , 2.5%  $j_{sc}$ , 1.0%<sub>rel</sub> FF, 3.0%<sub>rel</sub>  $\eta$ ), included in figure 1.

#### 3.2 156x156 mm<sup>2</sup> cells

IV results of the 156x156 mm<sup>2</sup> cells (group C and D) are shown in figure 2.



**Figure 1:** IV results of the 125x125 mm<sup>2</sup> solar cells (group A and B) measured at all partners.



**Figure 2:** IV results of the 156x156 mm<sup>2</sup> solar cells (group C and D) measured at all partners.

The observed maximum spread in the absolute values between the different partners for measurements of the same cells is approximately

- $V_{oc}$ : 5 mV
- $j_{sc}$ : 1.2-1.5 mA/cm<sup>2</sup>
- FF: 4-5%<sub>abs</sub>
- efficiency: 1.1%<sub>abs</sub>

One partner (partner 7) measures again significantly lower FF values than the other partners. Efficiency values determined at ISE CalLab are again on the higher end of the scale, but not as pronounced as for the 125x125 mm<sup>2</sup> cells. The alkaline etched group of cells (marked as untextured) is affected by severe fill factor problems, most probably due to series resistance problems caused by not optimised firing conditions. Nevertheless, also for these cells extremely varying in cell parameters, the same tendencies as for the cells without processing induced problems can be seen. This is a further proof that the observed variations between the set-ups at different partners are caused by systematic errors. The uncertainties of the ISE CalLab measurements are again indicated in figure 2.

### 3.3 156x156 mm<sup>2</sup> cells – second try

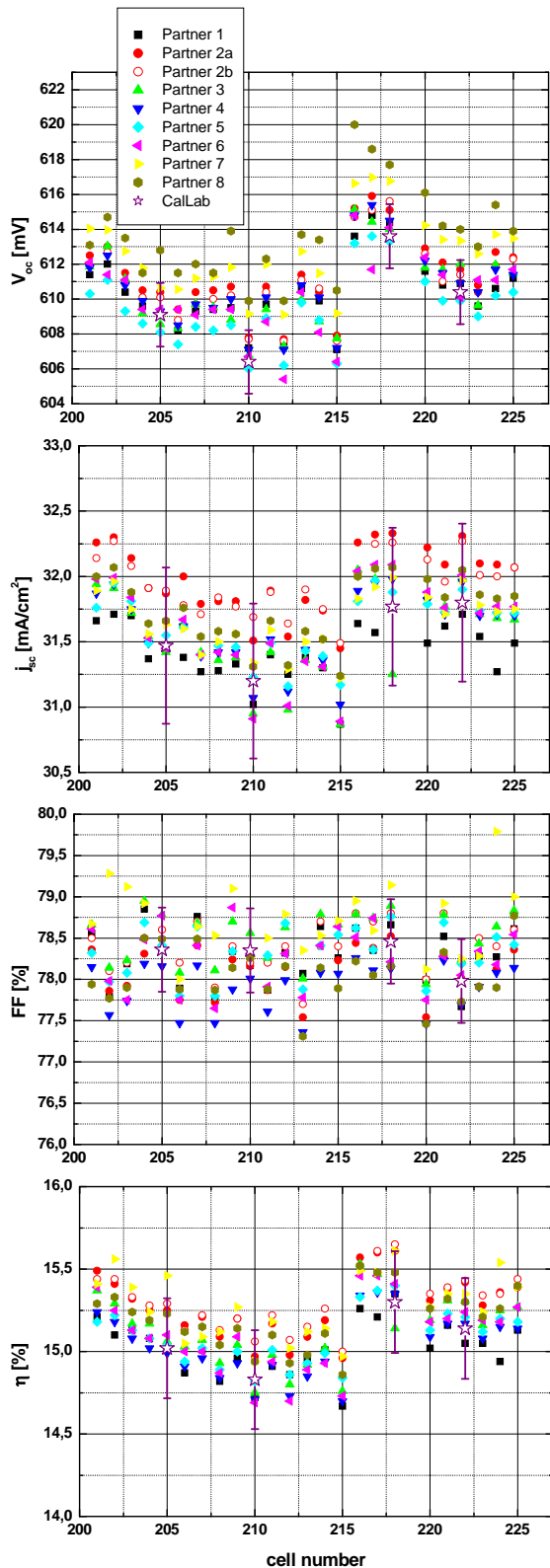
As group D from table I suffered from severe FF problems, in a second experiment an additional group of 156x156 mm<sup>2</sup> cells with alkaline etching was prepared (group E in table I). This time firing conditions have been optimised and IV results can be seen in figure 3.

For the evaluation of group E the results of the first experiment have already been distributed to the partners. Therefore the partners could make use of the outcome of the first experiment. In particular, each partner received two cells from each group A-D including their IV data and could use these cells as references for calibration of the IV set-up. In addition, the data of the cells measured at ISE CalLab have been distributed to the partners.

The observed maximum spread in the absolute values between the different partners for measurements of the same cells is approximately

- $V_{oc}$ : 5 mV
- $j_{sc}$ : 0.7-0.8 mA/cm<sup>2</sup>
- FF: ~1%<sub>abs</sub>
- efficiency: 0.5%<sub>abs</sub>

Especially in  $j_{sc}$  and FF the spread could be drastically reduced compared to the first experiment, leading to a much more narrow distribution of efficiency values (for the spread in FF some outliers measured at partner 7 have been disregarded). The  $V_{oc}$  spread remained nearly constant. Also in this second round representative cells were measured after the round robin at ISE CalLab. The values are given together with the uncertainty ranges in figure 3. Note, that between round 1 and round 2 the uncertainty calculations at ISE CalLab have been completely updated, the bars in figure 3 represent the new, reduced margins (0.29%  $V_{oc}$ , 1.9%  $j_{sc}$ , 0.65%<sub>rel</sub> FF, 2.02%<sub>rel</sub>  $\eta$ ).



**Figure 3:** IV results of the 156x156 mm<sup>2</sup> solar cells from the second experiment (alkaline etched) measured at all partners (group E).

## 4 DISCUSSION

### 4.1 Round robin IV measurements

The variations of the measurements to some degree are caused by the different set-ups used. E.g. temperature control has a direct influence on  $V_{oc}$ . Some set-ups use a temperature sensor touching the solar cell from the back to determine cell temperature during measurement whereas others measure the temperature of the metal chuck. The difference between temperatures of the chuck and the cell might be responsible for the observed spread of around 5 mV (corresponds to around 3 K difference in temperature). At ISE CalLab the temperature of the junction is probed with a calibrated sensor directly at the cell's front surface and adjusted under irradiation with a temperature controlled chuck precisely to the standard 25°C.

Electrical probing between different set-ups is different, too: while the rear side seems to be contacted similar for all set-ups, the front contact can be probed by multiprobes, differing in numbers and geometry. The impact and optimization of the contact geometry in IV-testers is addressed in [7,8]. The quite large spread in FF seems to be related to the different contacting geometries, although the picture is not clear yet.

$j_{sc}$  values are not differing due to varying cell sizes, as for all results shown in figure 1-3 the same cell size was assumed, respectively. Reason for the observed spread therefore seems to be related to illumination intensity and spectral mismatch. As calibrated reference cells have been used at the partners, a possible explanation of the differing  $j_{sc}$  values and less spread in efficiency values might be that for calibration sometimes the efficiency and not the  $j_{sc}$  value was used. This would explain a larger spread in  $j_{sc}$  but similar efficiency values. Another reason might be the use of a reference cell having a different surface texture and therefore changing the illumination intensity due to a different reflection back into the sun simulator. In addition, a various amount of shading might be introduced by the contact probe fixture. It is worth noting, that especially in the improved round 2 the spread of results is at about 2%, i.e. to be interpreted as common uncertainty.

As a last point, at least one partner (partner 8) used a flash tester, whereas most partners used a continuous light source.

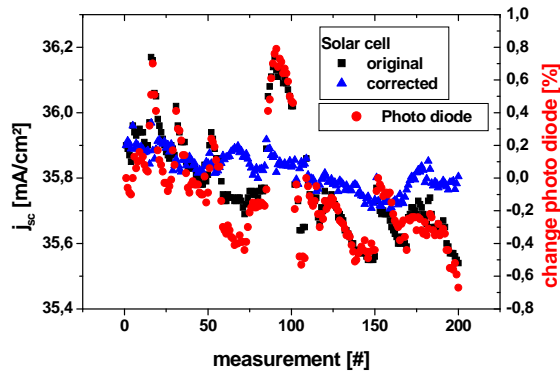
The fact that the spread in FF and  $j_{sc}$  could be reduced for the second experiment shows that some of the error sources could be identified. Especially the large discrepancy in FF at partner 7 could be reduced. The better matching of the  $j_{sc}$  values can be attributed to the fact that cells from the first experiment (so called 'sister cells' to the ones calibrated at ISE CalLab) were available for the IV measurement of the second experiment.

### 4.2 Repeatability accuracy

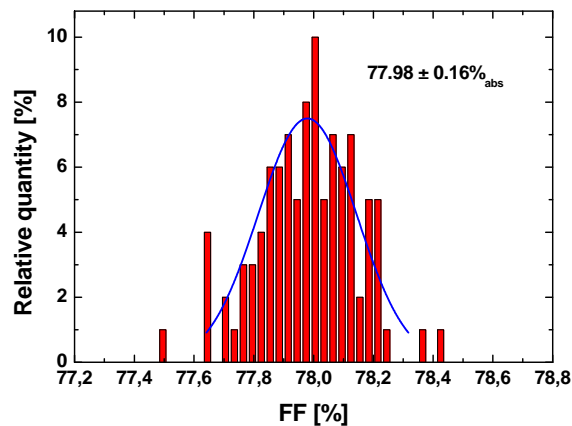
Apart from systematic errors of the specific IV measurement set-up (like temperature, contacting geometry, spectral mismatch) also the question of repeatability of the measurement arises. E.g. the change of intensity of the lamp inside the sun simulator used can cause a drift in  $j_{sc}$ . To evaluate the error involved with this light intensity variation, a series of measurements of the same cell was carried out using the set-up at University of Konstanz. The cell was contacted once and

200 illuminated IV measurements have been carried out using the same contacting. The whole measurement procedure lasted around 90 min. During the experiment the light intensity was monitored using a photo diode. Using the signal of this photo diode, the  $j_{sc}$  values measured with the cell under investigation can be corrected. Figure 4 shows the results of the experiment.

Using the intensity correction of the photo diode, the accuracy can be improved from a variation in  $j_{sc}$  of around 0.7 down to 0.2 mA/cm<sup>2</sup>. Such a monitor diode approach is also used at calibration labs.



**Figure 4:** Repeatability of IV measurements using the same contacting of one solar cell.



**Figure 5:** FF distribution of 100 measurements of the same solar cell. Contacting was renewed after each measurement.

Another question to be addressed is the spread introduced by the individual contacting of the cell. Therefore we contacted one specific cell 100 times and measured the illuminated IV curve at the sun simulator at University of Konstanz. The FF distribution is shown in figure 5. The measured standard deviation is below 0.2% absolute. We can therefore conclude that the observed spread in FF between the partners visible in figures 1-3 results indeed from the different specific contacting geometries.

## 5 SUMMARY AND OUTLOOK

A round robin of IV measurements at different institute and industry partners within the EU CrystalClear

project using 125x125 mm<sup>2</sup> and 156x156 mm<sup>2</sup> mc-Si solar cells with different surface textures was presented. In a first measurement round all partners measured the cells using the best method available at their respective set-ups. A significant spread in all cell parameters could be observed, mainly caused by different measurement conditions (cell temperature, contacting, available reference cells). Significant variations in FF of up to 5%<sub>abs</sub> and  $j_{sc}$  of up to 1.5 mA/cm<sup>2</sup> could be observed.

In a second run the spread in FF and  $j_{sc}$  could be reduced to 1%<sub>abs</sub> and 0.8 mA/cm<sup>2</sup> respectively. This could be achieved because all partners received reference cells from the first run. These reference cells were sister cells from cells calibrated at ISE CalLab which could be used for the second run. The observed spread in efficiency of 0.5%<sub>abs</sub> (or 3%<sub>rel</sub>) is well below the absolute uncertainty of cell parameters guaranteed by a calibrated measurement at ISE CalLab. This illustrates nicely the fact that the highest uncertainty is always introduced into a calibration chain, where the transfer between different sensor types has to be done (in the case of ISE CalLab from the 4 cm<sup>2</sup> encapsulated WPVS-type reference cells primary calibrated at the PTB to the large area industrial cells with bare contacts).

The repeatability of the  $j_{sc}$  measurement was tested at the IV set-up of University of Konstanz and could be improved using a photo diode for monitoring the light intensity. The variation in  $j_{sc}$  could be reduced from 0.7 to 0.2 mA/cm<sup>2</sup>.

The variation from cell to cell measured at one partner's set-up is much smaller than the variation between the partner's set-ups. Therefore relative measurements are possible with a much higher precision. Nevertheless, for absolute measurements the use of suited reference cells (same size, surface texture, reflectivity, thickness, material quality, quantum efficiency) is necessary to reach a good accuracy.

Up to now only standard type solar cells have been investigated. In the future we like to go one step further and include rear contacted solar cells in the round robin. As these cells are much more difficult to measure due to the complete contacting at the rear, adapted measurement chucks have to be developed and used. We therefore expect an even wider spread of cell parameters for the first experiments. But work in this direction is needed as more and more rear contact solar cell concepts are entering the PV market.

## 6 ACKNOWLEDGEMENTS

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## 7 REFERENCES

- [1] C.R. Osterwald et al., Results of the PEP'93 Intercomparison of Reference Cell Calibrations and newer Technology Performance Measurements, Proc. 23<sup>rd</sup> IEEE PVSC, Las Vegas 1993, 1263

- [2] S. Winter et al., The Results of the second World Photovoltaic Scale Recalibration, Proc. 31<sup>st</sup> IEEE PVSC, Lake Buena Vista 2005, 1011
- [3] IEC 60904-1: 1993, Photovoltaic devices – Part 1: Measurement of photovoltaic current voltage characteristics
- [4] IEC 60904-7, Ed.2: 1998, Photovoltaic devices – Part 7, Computation of spectral mismatch error introduced in the testing of a photovoltaic device
- [5] IEC 60904-3, Ed.1: 1989, Photovoltaic devices – Part 3, Measurement principles for terrestrial (PV) solar devices with reference spectral irradiance data
- [6] S. Winter et al., Primary Reference Cell Calibration at the PTB Based on an Improved DSR Facility; Proc. 16<sup>th</sup> EUPVSE, Glasgow 2000, 2198
- [7] J. Hohl-Ebinger et al., Contacting bare solar cells for STC measurements, this conference
- [8] B. Hund et al., Possible Impact of Systematic Errors in IV-Measurement, this conference