Project full title: "Nanowire based Tandem Solar Cells"

Project acronym: Nano-Tandem **Grant agreement no: 641023**

Deliverable D6.1:

Report on adaption of EQE and IV measurement equipment for nanowire solar cells

Executive Summary

In this deliverable the work related to the preparation of the set-ups intended for the measurements of the EQE and the light IV curves of the nanowire-Silicon tandem cells to be developed within the project is described. In the case of the EQE measurements this has been mainly related to an adaption of the used bias light illumination via identification and purchase of suitable optical filters. For the light IV measurement work concentrated on the spectrum of the multi-source sun simulator. It turned out that for some potential nanowire-Silicon tandem cells particular blue rich spectra are required. This however could successfully be realized with the simulator at Fraunhofer ISE. In summary it can be stated that the set-ups are now well prepared for the measurement of more or less any potential nanowire-Silicon tandem cell.

Introduction and Motivation

Besides the opto-electrical modeling of the nanowire-Silicon tandem cells the major focus of work package 6 is the electrical characterization of the solar cells. On the one hand this will allow giving validated and certified numbers for the conversion efficiency of the cells developed within the project. However even more important throughout the development process of the cells the electrical characterization will give direct feedback on the performance and allow for identifying potential points for improvement of the cells. A major part of the electrical characterization of the cells developed within the project will be done at Fraunhofer ISE within the calibration laboratory ISE CalLab PV cells, which is one of the internationally recognized laboratories for verification of solar cell efficiencies. There is a lot of experience on characterization of single- and (III-V material based) multi-junction cells as well as on the characterization of single-junction nanowire solar cells. However up to date no nanowire-Silicon tandem cell has been characterized at Fraunhofer ISE. Consequently the first step regarding electrical characterization within the project is to prepare the equipment to be used for the specific requirements of the cells that will be developed within the project.

The electrical characterization of solar cells mainly consists of two steps – external quantum efficiency (EQE) and current to voltage curve measurement under illumination (light IV measurement) equivalent to the required standard testing conditions (STC). The EQE of a solar cell is a measure for how efficient parts of the solar spectrum are contributing to the current of the solar cell. It is thus a useful measure for identifying the origin of losses in the current of the solar cell. Additionally the EQE of the cell is used for the spectral correction procedure that is required for the light IV measurement. Spectral corrections are necessary due to the fact that on the one hand the spectral sensitivities of device under test and reference detector used for determination of absolute quantity of irradiance differ, and on the other hand sun simulators used for light IV measurements cannot reproduce the shape of the reference spectrum perfectly.

External Quantum Efficiency

The measurement of the EQE of a solar cell typically is done applying the differential spectral responsivity method [1] where monochromatic test light which is modulated in intensity with a certain frequency is used as test light. Additional continuous (DC) bias light is used for putting the cell under test into the desired working conditions, as the intensity of the monochromatic test light is comparatively low. The adaption of this measurement principle for multi-junction cells mainly relates to the selection of the spectral distribution of the DC bias light [2, 3]. For a multi-junction cell an individual measurement of each subcell that forms the tandem has to be performed. In particular for the measurement of the EQE of a certain subcell the bias light has to be chosen in a way that this subcell of interest will limit the overall current of the tandem. Only in this way the signal originating from the monochromatic test light can be detected and the EQE of the subcell of interest consequently be measured.

As mentioned above there is long term experience at Fraunhofer ISE on the measurement of non-nanowire based multi-junction cells. Typically these are triple junction solar cells based on $Ga_{(1-x)}In_xP/Ga_{(1-y)}In_yAs/Ge$ with different compositions and thus bandgap energies of the used GaInP and GaInAs. Top cell bandgaps typically are in the range between 1.9 and 1.7 eV, middle cell bandgaps between 1.4 and 1.2 eV combined with a Germanium bottom subcell (0.67 eV). Figure 1 shows the spectrum of the unfiltered bias lamp (left) as well as the normalized transmission of the filter combinations (right) that are typically used for the EQE measurement of a metamorphic $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ triple junction cell (1.7, 1.2, 0.67 eV).

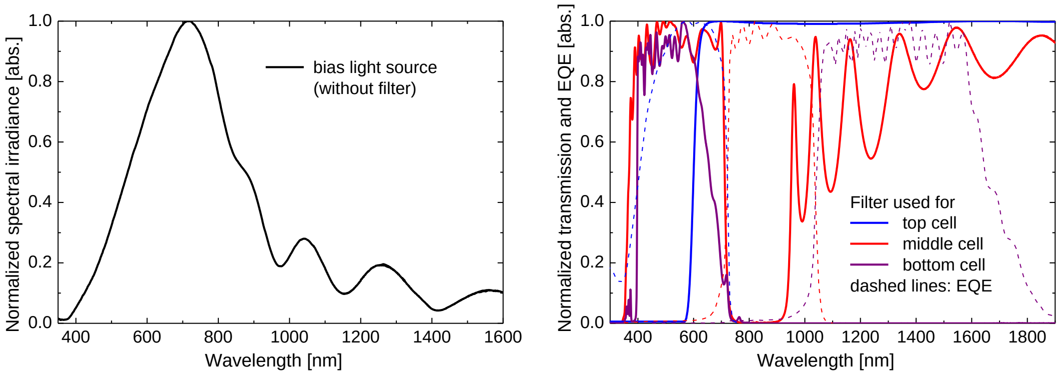

Figure 1: Left: Spectrum of an unfiltered tungsten lamp used for bias illumination for EQE measurements of multi-junction cells. Right: Normalized transmission (solid lines) of typical filter combinations used for the measurement of the EQE (dashed lines) of a metamorphic $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ triple junction cell.

As can be seen from the filter transmission curves in Figure 1 (right), for the measurement of a certain subcell light in the response region of this specific subcell is cut off with the used filters.

Initial opto-electrical modeling indicates that the bandgap of the top nanowire solar cell will be somewhere in the range between 1.4 and 1.7 eV, however not yet fixed to a specific value. Consequently the work at Fraunhofer ISE concentrated on preparing the measurement set-ups in a flexible way for any potential bandgap combination. Figure 2 shows the transmission curves of possible filter combinations for the EQE measurement of a nanowire-Silicon tandem cell with different top cell bandgap energy. Potential filter combinations were identified and missing optical filters were purchased.

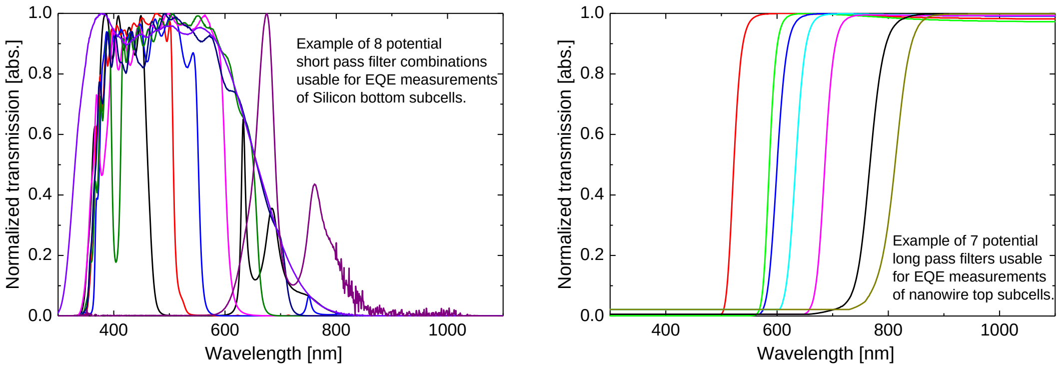

Figure 2: Transmission curves of possible filter combinations for the EQE measurement of nanowire-Silicon tandem cells with different top cell bandgap energies. Left: Short pass filter combinations for the EQE measurement of the Silicon bottom subcell. Right: Long pass filters for the EQE measurement of nanowire top subcells.

Figure 2 illustrates that a high flexibility in potential filter transmission curves could be realized. **The EQE measurement set-up consequently is well prepared for the EQE measurement of nanowire-Silicon tandem cells with more or less arbitrary top subcell bandgap energy.**

Light IV Characteristics at STC

For single-junction solar cells the spectral correction procedure – namely the mismatch correction [4, 5] - corresponds to a pure adjustment in intensity of the used sun simulator. However in the case of a multi-junction cell the intensity of the simulator consequently needs to be adjusted independently in different wavelength bands that correspond to the sensitivity regions of the involved subcells [6]. This is why preferably multi-source sun simulators are used. At Fraunhofer ISE a multi-source simulator (MuSim) with three independent light sources (one xenon lamp and two spectrally different tungsten lamp fields) is used. As in the case of the EQE measurements the spectra of the light sources were optimized for the measurement of $Ga_{(1-x)}In_xP/Ga_{(1-y)}In_yAs/Ge$ triple junction solar cells. In order to test whether the sun simulator MuSim will also be usable for nanowire-Silicon tandem solar cells, different theoretical subcell EQE pairs were used. Again the top subcell bandgap has been varied between 1.4 and 1.7 eV. In this context it is important to mention that as input for the spectral correction procedures only relative EQE data is needed. Consequently the EQE data shown in the following Figure 3 (left) has been normalized, despite the fact that the original idea in the simulations was to vary the absolute height of the nanowire subcell EQE in relation to the Silicon bottom subcell.

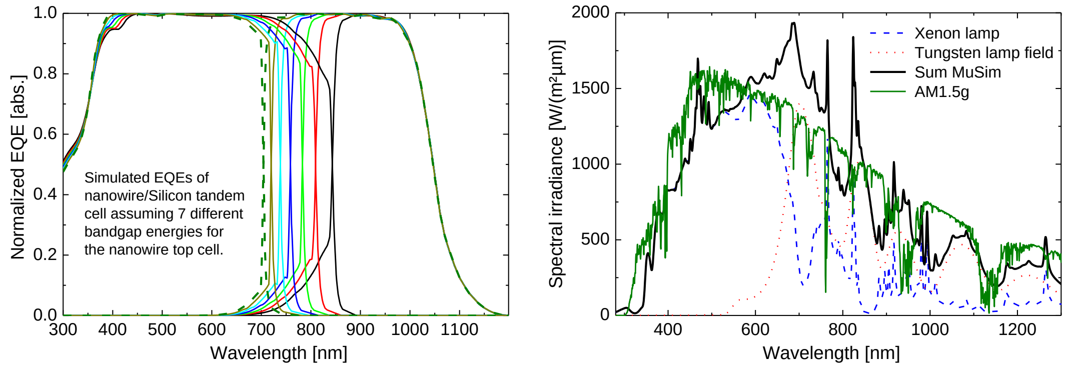

Figure 3: Left: EQE pairs from simulations with different top subcell bandgaps between 1.4 and 1.7 eV. The EQE data has been normalized, as for the input for the spectral correction procedures only relative EQE data is required. Right: Outcome of the spectral correction procedure for the most exotic bandgap combination from the graph on the left (highest top subcell bandgap, dashed lines).

It turned out that for the spectral correction of the nanowire-Silicon tandem cells the bandgap combination with highest top cell bandgap energy is the most challenging one. Here a rather blue rich xenon spectrum with high intensity below 700 nm had to be realized in order to achieve the correct current balance between the subcells. However as shown in Figure 3 (right) even for this exotic bandgap pair a combination of xenon and tungsten lamp spectra could be retrieved that will allow for spectrally adjusted measurements under spectral conditions equivalent to the standard spectrum AM1.5g [7]. The simulator spectrum shown there generates the same currents in the two subcells (see dashed lines in Figure **3**, left for EQE) as generated by the reference spectrum. **This demonstrates that the equipment for the light IV measurements is well prepared for the measurement of more or less any potential nanowire-Silicon tandem cell.**

References

1. Metzdorf, J., *Calibration of solar cells. 1: The differential spectral responsivity method.* Applied Optics, 1987. **26**(9): p. 1701-8.

2. Burdick, J. and T. Glatfelter, *Spectral response and I-V measurements of tandem amorphous-silicon alloy solar cells.* Solar Cells, 1986. **18**(3-4): p. 301-14.

3. Meusel, M., et al., *Spectral response measurements of monolithic GaInP/Ga(In)As/Ge triple-junction solar cells: Measurement artifacts and their explanation.* Progress in Photovoltaics: Research and Applications, 2003. **11**(8): p. 499-514.

4. Seaman, C.H., *Calibration of Solar Cells by the Reference Cell Method - The Spectral Mismatch Problem.* Solar Energy, 1982. **29**(4): p. 291-98.

5. IEC 60904-7, *Photovoltaic devices - Part 7: Computation of spectral mismatch error introduced in the testing of a photovoltaic device*, 2008, International Electrotechnical Commission: Geneva, Switzerland.

6. Meusel, M., et al., *Spectral Mismatch Correction and Spectrometric Characterization of Monolithic III-V Multi-junction Solar Cells.* Progress in Photovoltaics: Research and Applications, 2002. **10**(4): p. 243-55.

7. IEC 60904-3, *Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*, 2008, International Electrotechnical Commission: Geneva, Switzerland.