Improved Grating Monochromator Set-Up for EQE Measurements of Multi-Junction Solar Cells

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***Abstract* — Grating monochromator set-ups are widely in use for the measurement of the external quantum efficiency (EQE) of solar cells. This paper describes the grating monochromator set-up for EQE measurements of multi-junction and concentrator cells at the calibration laboratory (ISE CalLab) at Fraunhofer ISE. The set-up has been updated with innovative features. This includes an optional LED based bias illumination system which is of particular interest for the measurement of multi-junction cells whose subcells show narrow or overlapping absorption bands. Additionally the set-up has been improved in order to allow for the reliable EQE measurement of concentrator cells with areas below 1 mm². Moreover, the set-up has been modified to measure the I-V-curve of the solar cell under bias light condition. In the case of multi-junction cells this allows to retrieve information about the shape of the I-V-curves of the individual subcells. Low temperature EQE measurements can be performed by replacing the measurement chuck through a cryostat.**

***Index Terms* — multi-junction cells, concentrator cells, external quantum efficiency, characterization.**

I. Introduction

The spectral response (SR) or external quantum efficiency (EQE) is an important measure for the quality of solar cells. Moreover, the EQE is required to adjust the solar simulator spectrally in order to measure the I-V-characteristic under certain standard testing conditions. In case of single-junction solar cells this procedure is known as spectral mismatch correction [1;2]. Based on that spectral mismatch correction, a more generalized procedure has been suggested for multi-junction devices [3;4].

The EQE of the device under test (DUT) is typically determined with the differential spectral responsivity method (DSR) [5]. The principle idea of the DSR method is to combine modulated (AC) quasi-monochromatic test light with continuous (DC) illumination referred to as bias light. The monochromatic light is used for determination of the EQE whereas the bias light puts the DUT to certain desired operation conditions typically categorized by the generated bias current. For multi-junction cells the spectra and intensity of the bias light is also adapted for achieving current limitation by the subcell to be measured [6]. The intensity of the bias light typically is orders of magnitude higher compared to the intensity of the monochromatic light.

During measurement of the EQE the DUT is kept at short circuit conditions with e.g. a current-to-voltage converter, whose output is a voltage signal proportional to the current of the DUT. In case of multi-junction solar cells the short circuit current condition for the current limiting subcell under test does not correspond to the short circuit of the whole device (i.e. external voltage equals zero). Thus, the DUT is operated at a certain positive bias voltage in order to compensate for this effect [7].

The AC component of the voltage corresponding to the monochromatic test light is separated from the DC component originating from the bias light by a lock-in amplifier. The correlation between magnitude of AC voltage signal and quantity of EQE at a certain wavelength is realized by comparing the signal of the DUT with the signal of a detector of known response.

Set-ups for the measurement of the EQE of solar cells are typically categorized by the way of generation of the monochromatic light. The two most important techniques for the provision of monochromatic light are: i) using narrow band-pass filters or ii) a grating monochromator.

In this paper we describe the grating monochromator set-up at the calibration laboratory at Fraunhofer ISE (ISE CalLab) and in particular we present recently introduced features that are of interest to the PV community:

- An LED based bias illumination unit has been added for the measurement of multi-junction cells whose subcells show narrow and/or overlapping response regions.
- For the EQE measurement of solar cells with areas < 1 mm² the monochromatic light is coupled into an optical fiber that is used for guiding the test light onto the DUT.
- An I-V measurement circuit has been added for the recording of the I-V-curve of the DUT under the applied bias light conditions. This is of particular interest when measuring multi-junction cells, as it allows for an easier assessment of the bias voltage to be applied and gives information about the shape of the I-V-curve of the current limiting subcell (e.g. identification of a low shunt resistance of one of the subcells).
- Replacing the measurement chuck by a cryostat allows for measurements at low temperatures.

II. Description of the Set-Up

A schematic of the grating monochromator set-up at ISE CalLab is shown in Figure 1.

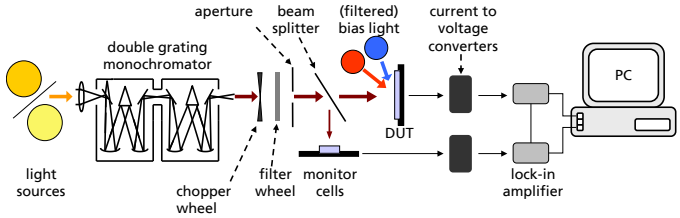

Figure 1: Schematic of the grating monochromator set-up for EQE measurements of solar cells at Fraunhofer ISE.

The monochromatic light is generated by a double grating monochromator equipped with three reflection gratings having different line densities. Two light sources are focused onto the entrance slits of the monochromator – a xenon and a tungsten halogen lamp. The xenon lamp covers the visible part of the spectrum whereas for wavelengths above 750 nm the tungsten lamp is used in order to avoid a potential influence by the discharge spikes in the xenon spectrum. The width of the entrance and exit slits of the monochromators can be adjusted. In the standard configuration the resulting bandwidth of the monochromatic light is below 10 nm for wavelengths up to 1200 nm and increases to 20 nm at 2000 nm. However, the bandwidth can be further reduced if necessary. For example, this is of interest when measuring quantum-well solar cells. The modulation of the monochromatic light is realized with a chopper wheel that is either placed in front of the entrance slits or behind the exit slit of the grating monochromator. Typical chopper frequencies in use are 130 or 180 Hz. The filter wheel carries different long pass filters in order to suppress higher refraction orders of the grating. A beam splitter is introduced in the optical path. It couples a small fraction of the monochromatic light onto one of the monitor cells. The monitor cells are either a silicon or a germanium photo diode which are applied according to the desired wavelength range. The light is guided onto the temperature controlled measurement chuck with metal coated mirrors in order to avoid chromatic aberration. Monitor cell and DUT are connected with current-to-voltage converters whose signals are analyzed by lock-in amplifiers. The set-up is calibrated with an appropriate reference detector prior to the actual measurement. The size of the monochromatic beam in the measurement plane is adjusted in a way that the monochromatic light spot is smaller than the DUT or the reference detector, depending on which of the two has the smaller area. This is realized by either changing the position of focusing mirrors or changing the opening of an aperture. The used primary calibrated reference detectors traceable to SI units are either solar cells calibrated by the PTB [5] (the highest authority for metrology in Germany) or a pyroelectric radiometer[1] traceable to NIST. Additionally GaSb or Ge cells are in use that had been calibrated in-house using the pyroelectric radiometer.

A. Realization of the bias light

The configuration of the bias light plays a key role for the measurement of the EQE of multi-junction cells. The bias light has to be adjusted in a way that the subcell to be measured is limiting the current of the DUT. This is typically done by the use of tungsten lamps in combination with different types of optical filters. In the present set-up at Fraunhofer ISE three self-focused tungsten lamps are used. The light is focused on glass fibers which guide the light on the DUT. In between lamp and fiber several optical filters can be placed – see Figure 2.

Figure 2: Standard bias light configuration – self-focused tungsten lamps in combination with optical filters. The bias light is guided on the DUT via glass fibers.

The combination of several interference, band pass, short- and long pass filters allows for a flexible adjustment of the bias light spectrum. However, in the case of multi-junction cells with more than four subcells the absorption bands of the subcells are comparatively narrow and often overlap. A LED bias illumination unit consisting of five different types of LEDs has been assembled to accommodate such cases. From each type of LED four pieces were fixed in a specially designed holder - see Figure 3.

Figure 3: LED based bias light illumination unit. Four pieces each of five different types of LEDs are used.

1 In case of using the pyroelectric radiometer the chopper frequency has to be reduced to 15 Hz due to the comparatively slow response of the detector.

The spectral distributions of the LEDs for bias illumination are shown in Figure 4 together with the EQE of the upper five subcells of a Fraunhofer ISE six-junction cell [8].

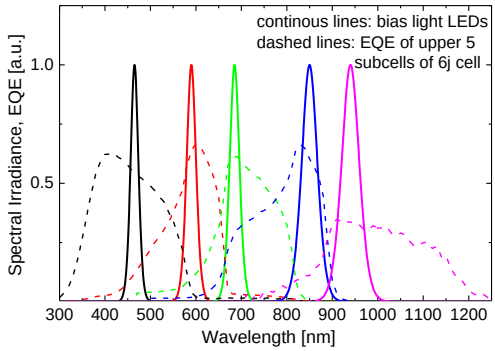

Figure 4: Spectral distribution of the LEDs used for bias illumination (continuous lines). In addition, the dashed lines show the EQE of a six-junction cell (without Germanium bottom subcell).

B. Guiding the monochromatic light on small area cells

As mentioned above, the monochromatic light spot's size is adjusted to be smaller than the DUT (or the reference detector in case the DUT has an area larger than the reference detector). For concentrator cells with areas of 1 mm² and below the adjustment of the test light's spot size is challenging and often results in erroneous measurements. In particular kinks are frequently observed in EQE measurements, mainly at wavelengths corresponding to changes of the diffraction gratings. In order to overcome this problem, a fiber based solution has been realized. This solution was motivated within the AMONRA EC funded project where nanowire solar cells were developed [7]. The area of most samples realized within the project was below 1 mm². In order to measure the EQE of such small cells a convex lens was placed in the optical path of the monochromatic light. The position of the lens was optimized to couple as much as possible of the monochromatic light into a fiber. The fiber used here has a diameter of 600 µm, see Figure 5. Alternative fibers with differing diameters can be used.

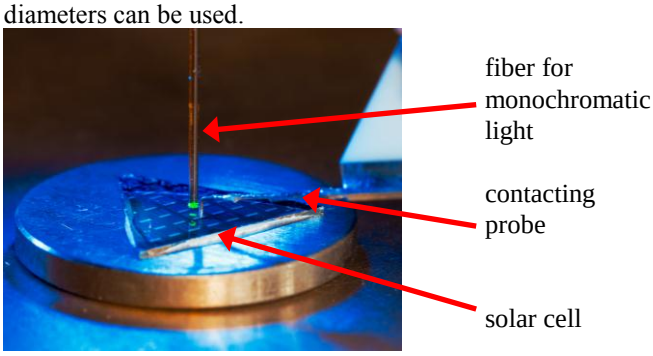

Figure 5: Exit of the fiber and monochromatic light guided on the solar cell. The fiber has a diameter of 600 µm.

The lens/fiber configuration allows for the reliable EQE measurement of solar cells with areas below 1 mm². An example of the improvement of the EQE measurement is shown in Figure 6. Using the standard procedure for EQE measurements a kink in the EQE between 530 and 540 nm is observed – this corresponds to the change of diffraction grating. With the fiber guiding the test light onto the DUT the quality of the EQE measurement is improved significantly.

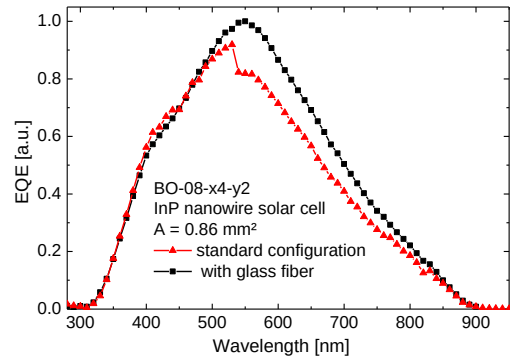

Figure 6: EQE measurement of an InP nanowire solar cell in standard configuration (triangles) and using an optical fiber for guiding the monochromatic light onto the DUT (squares).

C. I-V-curve measurements under bias light conditions

When measuring the EQE of a multi-junction cell the bias spectrum has to be adjusted in a way that one subcell after the other will limit the current of the multi-junction cell. Measuring the I-V-curve under such conditions immediately allows identifying differences in the shunt resistance or reverse breakdown behavior of the subcells. Figure 7 shows three I-V-curves of a lattice-matched triple-junction cell. Here the bias light was adjusted correspondingly so that the EQE of the three subcells can be measured. The GaInAs middle subcell shows a comparatively quick reverse breakdown (dashed line).

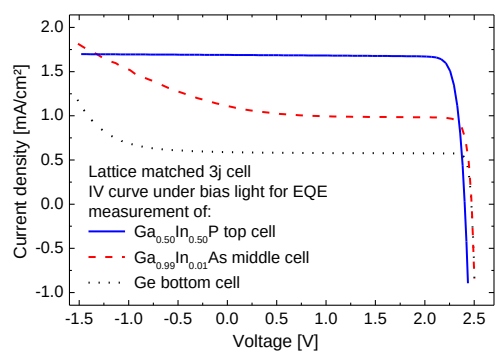

Figure 7: I-V-curves taken from a triple-junction cell while different bias light conditions were chosen, which are used to measure the EQE of each subcell.

D. EQE measurements at low temperatures

The typical temperature range that can be covered with the set-up in standard configuration is 0 °C to 90 °C depending on the quality of the thermal contact of the DUT to the measurement chuck. For temperatures below 0 °C a cryostat

can be introduced for varying the temperature of the DUT, see Figure 8. The cryostat can carry up to four samples of 2 cm x 2 cm.

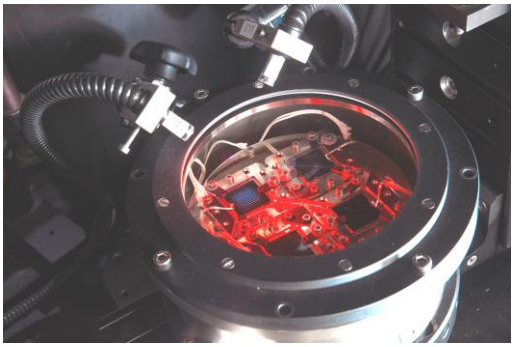

Figure 8: Four 2 cm x 2 °cm triple-junction solar cells mounted in the cryostat for EQE measurements.

The cooling of the cryostat is realized with liquid nitrogen. Temperatures as low as 100 K have been achieved allowing for the assessment of low temperature EQEs. Figure 9 exemplarily shows the EQE of a lattice matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell at room temperature and at 123 K.

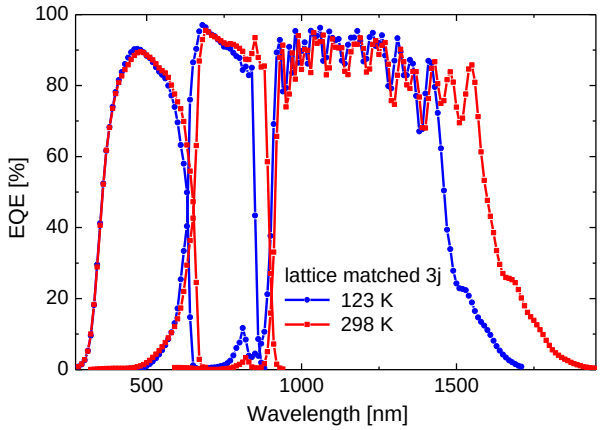

Figure 9: EQE measurement of a lattice-matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell.

The EQEs in Figure 9 show the typical shift in absorption bands due to the temperature dependence of the bandgaps of the solar cell materials.

III. Conclusions

New features have been implemented at the grating monochromator set-up for EQE measurements at Fraunhofer ISE. Flexible bias light illumination for the measurement of the EQE of almost any type of multi-junction device is available either via filtered tungsten lamps or by LEDs. Introducing glass fibers for guiding the monochromatic light onto the device under test allows for the reliable measurement of solar cells with areas below 1 mm. For multi-junction cells the recording of the I-V-curve of the solar cell under actual bias illumination permits the assessment of the behavior of the individual subcells. In that way low shunt resistances and reverse breakdown voltages of the junctions can be identified. Low temperature measurements are realized with a cryostat – temperatures down to 100 K can be achieved with a nitrogen based device.

IV. Acknowledgements

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