SPECTRAL RESPONSIVITY CALIBRATION OF GE COMPONENT SOLAR CELLS DERIVED FROM TRIPLE-JUNCTION DEVICES

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ABSTRACT: Spectral responsivity calibrations and linearity tests of the bottom Ge component cells being part of triple-junction devices are presented and discussed. The absolute spectral responsivity of such complex cells has been determined for the first time. Specific details of the PTB's Differential Spectral Responsivity (DSR) calibration facility enabling these measurements are described.

1 GE COMPONENT SOLAR CELLS

Electrical performance measurements of multi-junction solar cells (MJSC) have imposed new requirements on solar simulators and relevant testing methods.

For the accurate measurement of MJSCs for space applications, either solar simulators have to be very closely matched to the AM0 spectrum or they have to have the capability to be independently controlled with respect to the partial irradiance for each of the sensitive wavelength ranges of the different sub-cells of the MJSC stack.

For multi-zone solar simulators, it is desirable that the spectral irradiance of each sub-cell wavelength range is matched as much as possible to the corresponding AM0 spectral range.

Multi-zone solar simulators are widely used by solar cell industries and testing laboratories and they are calibrated using as a reference, solar cells with spectral responsivity ranges representative of the different sub-cells of the MJSC stack.

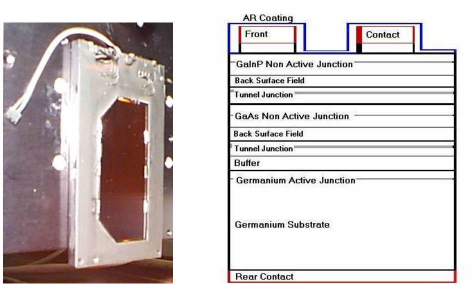

Figure 1: 4 x 8 cm² Ge component solar cell

These special solar cells are known as component cells and the process to manufacture them is basically the same of the full MJSC, but without activation of the non-desired junctions (see Fig. 1 for the example of a germanium component cell).

Component cells are primarily calibrated with respect to short-circuit current with Balloon or Global Sun Light methods. Therefore, accurate spectral responsivity measurements are needed to spectrally correct the measured values.

Spectral response measurements are performed by solar cell calibration/testing laboratories for the purpose mentioned above, using these component solar cells as a reference. Germanium sub-cells are of special importance with a high signal responsivity range between 900 nm and 1800 nm. These component cells are calibrated only by internationally recognized calibration institutions, if high-precision, primary calibration is required.

For the case of germanium component solar cells, a new calibration facility and procedures have been developed at the PTB.

2 CALIBRATION METHOD AND FACILITY

The absolute calibration of these complex cells could only be carried out at the PTB's DSR facility (Differential Spectral Responsivity, see Fig. 2) covering quasi-continuously (2 nm steps; 4 nm and 12 nm spectral bandwidth) and without any spectral gap the spectral range up to 2000 nm and spectrally resolving all the oscillations and beats due to interference effects within the thin epitaxial layers of the other sub-cells (see Fig. 4 with linear and logarithmic scale).

2.1 DSR principle

At the DSR facility, the solar cell is simultaneously illuminated in a dual beam arrangement:

Firstly, with an adjustable solar-like steady-state bias radiation (in the field of up to 36 cold light mirror lamps with dichroic reflectors between 1 W/m² and more than 2000 W/m²) for the adjustment of the operating points and

secondly, with a quasi-monochromatic, modulated irradiance for the measurement of the differential spectral responsivity. The AC photocurrent is measured with a lock-in amplifier and the DC bias signal with a standard multimeter.

2.2 Optical arrangement

The spectrometer is specially designed for optimum irradiation performance, homogeneity of the irradiation field, stability and reproducibility as well as far-reaching automation (see below). Only the essential specific features are described here (for more details and improvements concerning the continuous operation

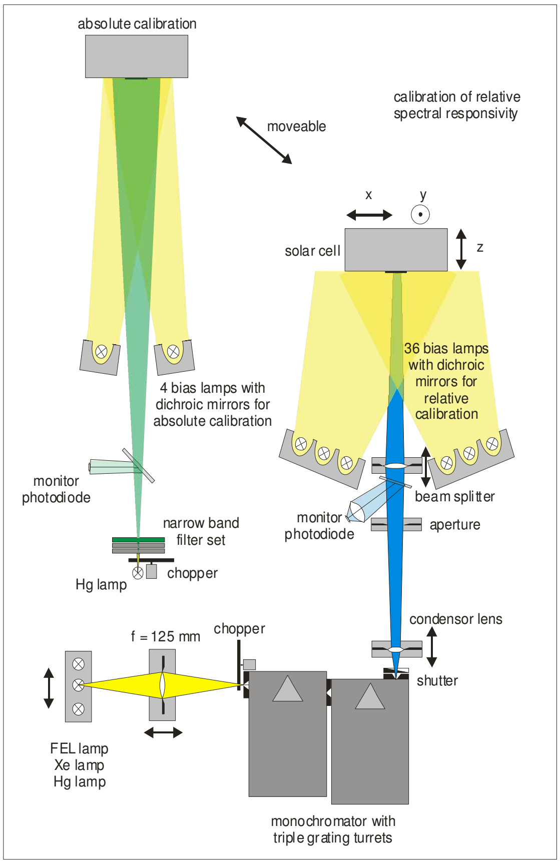

Figure 2: Dual beam optical arrangement combining AC monochromatic and DC solar-like optical radiation for the measurement of the spectral responsivity at different working points.

lasting for several days see [1, 2] and particularly [3]). In order to simultaneously minimize straylight and optimize homogeneity, a double monochromator with subtractive dispersion is used. The monochromator has triple grating turrets to cover the required spectral range (see Fig. 3). Instead of mirror optics, lens optics is used to minimize spherical aberrations while chromatic errors are compensated by an automated, wavelength-dependent movement of the lenses as well as detectors and solar cells.

2.3 Radiometric measuring principles

The following radiometric measuring principles are applied in the DSR facility:

(i) Relative and absolute measurements are carried out separately. All relative measurements at different bias irradiances (determination of spectral non-linearities for the linearity test) and/or temperatures (determination of spectral temperature coefficients) are normalized at one operating point (determined by wavelength, bias irradiance, temperature). The absolute measurement needs to be carried out only at this operating point with a monochromatic radiation field of low irradiance but excellent homogeneity.

(ii) The calibration is performed by substituting the test cell (with bias radiation) with a standard detector (without bias radiation) traceable to SI units via the cryogenic radiometer used as the most accurate primary radiometric standard.

(iii) The stability and reproducibility are improved substantially by using monitor photodiodes (behind a beam splitter) at the setups for both the absolute and the relative calibration. The signals are measured simultaneously using identical time constants.

2.4 Automatization

In order to achieve an economical measurement procedure saving also in personnel, both the control of the DSR measuring system and the data evaluation were fully automated using an integrated new data base system. The complete measuring procedures including the absolute and relative spectral responsivity measurements, the measurement of the spectral non-linearity and the spectral temperature coefficient, a position check, a simple homogeneity check and a check of the stability in the UV are carried out fully automatically for up to four solar cells. Only the careful adjustment of the solar cells on the temperature-controlled x,y,z-displacement stage must be carried out manually. One series of measurements runs, if necessary, several days without a break. In addition to the characterisation of solar cells, the characterisation of light sources (stability, homogeneity) can also be accomplished.

2.5 Extension of measurement ranges

Thus, the flexibility and performance of this calibration facility (see Fig. 2) has been utilized, including:

(i) Extension of the spectral range by using a thin film thermopile and a Ge photodiode (see also the high enough power levels in Fig. 3).

(ii) Transfer to large areas based on the mapping of the monochromatic radiation fields at all wavelength.

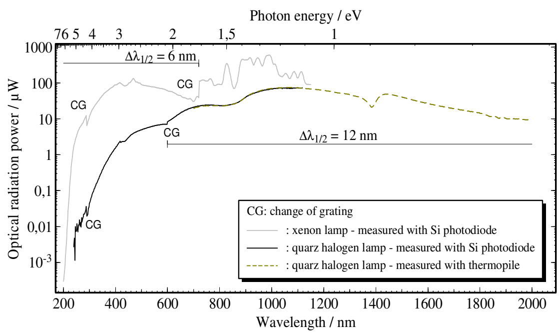

Figure 3: Optical radiation power of the monochromatic beam of the DSR facility (see Fig. 2).

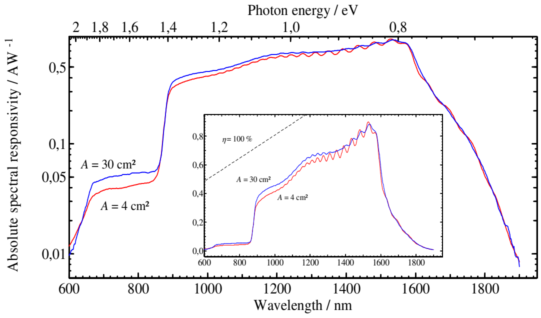

Figure 4: Spectral responsivity of two Ge component cells. The absorption of the top and the middle sub-cell (see Fig. 1) result in the absorption edges in the short wavelength region (window effect). The oscillations and the beats are due to the multiple reflections within the thin epitaxial layers of the top and the middle sub-cells. Note the logarithmic scale of the large diagram. The inset shows the same curves, but with a linear scale. The curves are plotted versus wavelength; the corresponding photon energy scale is shown in addition.

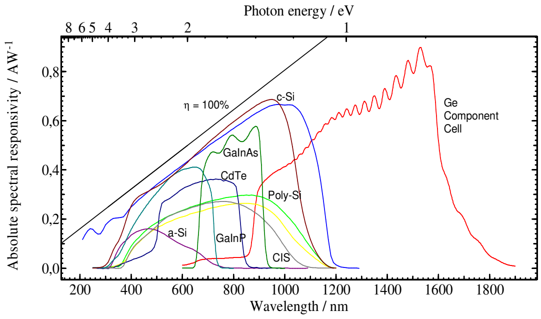

Figure 5: Different types of solar cells calibrated at the DSR facility.

3 RESULTS AND PERFORMANCE

Fig. 5 is an illustration of the variety of solar cells which can be calibrated at the DSR facility. For all types of single cells without imaging optics (i.e., no PV modules or concentrator cells), there are no principal restrictions regarding semiconductor material or spectral range. The oscillations and beats of the Ge component cells (see Fig. 4) are real and due to the multiple reflections in the two epitaxial surface layers (see Fig. 1). The non-linearities of short-current under STC of the calibrated Ge component cells are between 0.4% and 0.6%.

The complete spectral range from 210 nm to 1900 nm is completely covered with spectral bandwidths as well as signal-to-noise ratios (based on adequate power levels, see Fig. 3) sufficient to resolve all the oscillations in Fig 4. Due to the use of monitor photodiodes, the stability and reproducibility of the DSR facility between 400 nm and 1000 nm are better than $2{\cdot}10^{-4}$ over many days after performing different series of measurements.

3.1 Main uncertainty components

The uncertainty budget of the DSR measurements has thoroughly been analyzed considering all relevant uncertainty components. For high-quality reference solar cells, particularly for those with the WPVS package, the expanded uncertainty is less than 0.5 % (95 % level of confidence according to an expansion factor $k = 2$), which, in general, is small enough.

Besides the uncertainty of the standard detector used for the calibration, the following main contributions have been taken into account: the residual inhomogeneities of the monochromatic test and solar-like bias radiation fields and of the solar cells and detectors as well as inter-reflections between solar cell or detector and lens and influences of the modulation frequency.

While it is relatively straightforward to achieve an adequate homogeneity of the bias radiation field, it is particularly required to optimize homogeneity of the monochromatic radiation fields. As an example, Fig. 6 shows the deviations of the homogeneity measured directly over an area of 70 x 70 mm² (< 8 % peak-to-peak) and the smaller deviations obtained for the effective homogeneity of the mean value of the four irradiance distributions obtained after four 90° rotations of the 70 x 70 mm² cell and area, respectively (< 2 % peak-to-peak). Thus, the DSR facility is also suitable to calibrate inhomogeneous large-area photometers and colorimeters with diameters up to 60 mm needed in photometry and colorimetry.

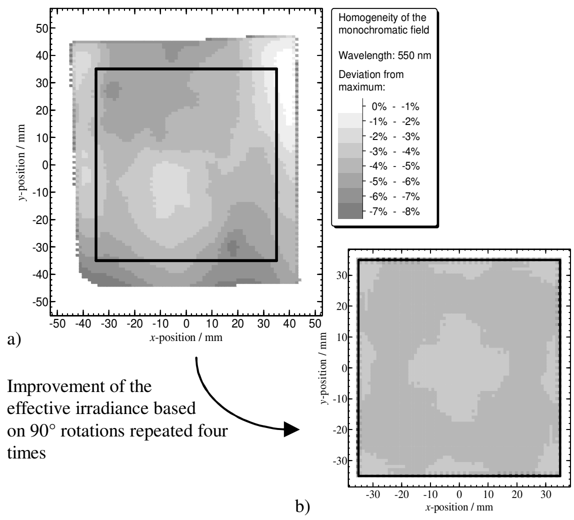

Figure 6: a) Homogeneity (between 0% and -8%) of the monochromatic radiation field (lateral distribution of the irradiance at one wavelength) determined directly; b) effective homogeneity (± 1%) of the mean value of the four irradiance distributions obtained after four 90° rotations of the 70x70 mm² cell and area, respectively, marked in Fig. 6a).

4 CONCLUSIONS

The DSR facility of the PTB has been shown to be well suited to calibrate the most important actual types of reference solar cells and even new cell technologies coming in the photovoltaic scene (see Fig. 5) up to areas of 15x15 cm² between 210 nm and 2000 nm with high spectral resolution and without any gap in the spectrum, where the calibration is traceable to the SI units and is also internationally equivalent according to the World PV Scale [5, 6]. The DSR facility enables the calibration transfer from detectors with small areas to large-area detectors and solar cells under Standard Test Conditions, which includes the transfer from low to high irradiance levels.

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