TRANSIENT I-V MEASUREMENT SET-UP FOR PHOTOVOLTAIC LASER POWER CONVERTERS UNDER MONOCHROMATIC IRRADIANCE

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ABSTRACT: A new I-V measurement set-up called LaserSim has been developed for photovoltaic laser power converters – photovoltaic cells optimized for monochromatic artificial light - providing irradiances of up to 89 W/cm². The evaluation of the set-up and first I-V curve and efficiency measurements are presented. Similar to flash simulators used for I-V characterization of solar cells, the LaserSim is using transient measurement routines to avoid an influence of heating of the samples during measurement. An excellent light uniformity in the designated test area was realized. A beam sampler allows for in-situ irradiance determination while recording I-V data. This is mandatory for characterization of devices showing a non-linear behavior of short circuit current with irradiance. Efficiency values under monochromatic light at 809 nm have been measured for a single junction GaAs cell (55.6 %) and a dual-junction GaAs device (53.5 %).

Keywords: photovoltaics, III-V semiconductors, laser power converter, power-by-light, characterization.

1 INTRODUCTION

Laser power converters are photovoltaic (PV) cells optimized for monochromatic artificial light sources. Laser or LED light sources are typically used for “Power-by-Light” applications. These are optical power transmission systems, where instead of using copper cabling, power and data signals are guided through optical fibers, free space laser transmission is also possible. This technology inherently allows for galvanic isolation, electromagnetic compatibility, wireless solutions and other [1]. Application examples for this technology can be found in various domains and are as diverse as structural health monitoring in wind turbines [2, 3], cortical neural sensing in brain implants [4], wireless powering for implantable sensing platforms [5], monitoring of high voltage power lines [6], optically powered video surveillance [7], submarine hydrophone and seismometer networks [8], passive optical networks [9].

Photovoltaic laser power converters reach very high opto-electrical conversion efficiencies, as the semiconductor bandgap of the absorber material can be designed to match the laser wavelength of the system [10-12] and thermalization losses occurring in solar applications can thereby be minimized. A typical semiconductor compound chosen for “power-by-light” systems is GaAs with a bandgap of 1.42 eV, which is well suited for laser wavelengths in the range 800 to 850 nm [13]. Laser power converters are intended to supply electric energy to sensors and actuators, with a power consumption ranging from the milliwatt to the watt level which can well be realized with single cell devices. However, the voltage required in standard electronic applications is often higher than what is supplied by a single PV cell with one pn-junction. A single-junction GaAs cell provides ~1 V depending on irradiance and temperature, while electronic circuitry often requires voltages between 2 and 13 V. The usage of DC-to-DC converters is possible, as well as the solution of connecting several PV cells in series using several separate optical links. A more elegant solution is the monolithic series connection of cells on chip level. Both, lateral and vertical series connection schemes exist and have been realized for PV laser power converters. In the lateral realization multi-segment cells, also known as monolithic interconnected modules or MIM are realized [14-16]. There a single-junction cell is separated into several individual segments of same size by post growth technological processing. The individual segments are then connected in series by galvanic metallization [17]. Consequently, processing becomes more complex and time consuming as the number of technological steps is increased. When integrating such multi-segment devices into power-by-light systems, fiber optical coupling to the cell is less tolerant against misalignment than in the case of a single segment device [16]. This is due to the fact that for maximum current generation, uniform illumination of the segments of the series connection is required.

The approach to realize the vertical series connection is done by epitaxial growth, as in multi-junction devices for space or concentrating photovoltaic applications. In contrast to multi-junction devices designed for the solar spectrum, a laser power converter designed to absorb monochromatic light is realized with several subcells of the same absorber material [10, 11, 15, 18]. Maximum current is reached, when all subcells generate the same current. Consequently, for the design of such series connected multi-junction cells, the thickness of the subcells has to increase from top to bottom and is calculated following the Beer-Lambert law of exponential absorption [15, 16]. The temperature dependence of the bandgap energy of the used semiconductor material introduces a current mismatch as layer thicknesses can only be adapted for one temperature [19]. However, in contrast to the MIM concept, these devices are as tolerant in respect to alignment as a standard single-segment cell. Additionally, post growth technological processing is similar as for a single-junction cell, and therefore less complicated compared to the case of the MIM concept.

However, in the emerging field of photovoltaic laser power converters, the measurement of these new devices poses a challenge. Therefore, the development of adapted and new characterization tools is required. Recent publications of 5-junction GaAs devices [18] proof the relevance of developing a standard approach for comparability of characterization and discuss repeatability and measurement accuracy [20]. PV cells are usually characterized using sun simulators with a broadband spectrum tailored to be close to the solar spectrum, where the simulator spectrum will generate the same current as under the reference spectrum. In the case of multi-junction devices made of one absorber material (i.e. only one bandgap), measurement of laser power converters under such spectrally distributed light will, however, result in significantly different performance than under monochromatic illumination. The Xenon spectrum of a typical flash simulator leads to a significant current mismatch of the respective subcells connected in series, and is therefore inadequate as it will strongly influence the I-V parameters [21]. In addition, it has been demonstrated that the behavior of these multi-junction laser power converters shows a significant influence of luminescence coupling [18, 19, 22, 23], resulting in a non-linear behavior of short circuit current with irradiance. This means that for such devices it will not be possible to determine the irradiance level from the short circuit current of the measured cell itself as it is commonly done for single-junction laser power converters (and concentrator solar cells). Therefore, an alternative way for the determination of the irradiance level in the test plane during measurement is a requirement for such a set-up for the characterization of laser power converters.

2 DESCRIPTION AND EVALUATION OF LASERSIM MEASUREMENT SET-UP

2.1 Description

The laser beam profile across the PV receiver in power-by-light applications varies with the specific system specifications (light source, fiber type and length, optical elements, fiber coupling). In order to enable general comparisons of different cells, cell concepts and cell architectures (varying in size and geometry, as well as multi-junction or multi-segment cells) [15], similar design goals as applied for solar simulators have been chosen for the new measurement set-up. As illumination cannot be reproduced for all different forms of power-by-light systems, a uniform so-called flat-top laser profile (i.e. homogenous light intensity) in the test plane for typical cell sizes from 1 to 3 mm edge length was set as design criterion.

The new I-V measurement set-up is designed to enable measurements at variable irradiances. Opposed to solar simulators a **monochromatic** light source provides illumination in the test plane: For high irradiances in the 4 mm x 4 mm test plane a 50 W laser diode system emitting light at 809 nm (FWHM: 3nm), which leads to an intensity of 89 W/cm² in the measurement plane. The laser can be current modulated to emit single pulses of e.g. 4 ms duration.

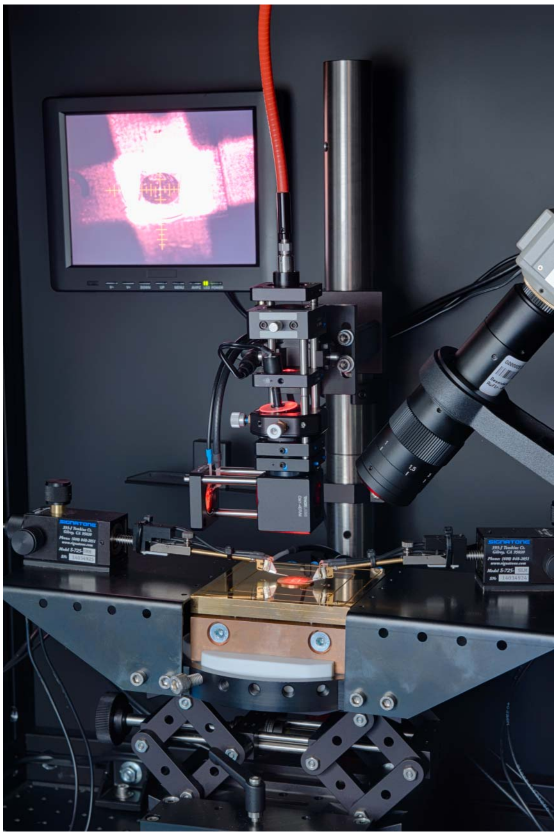

Figure 1: Photo of the LaserSim measurement set-up. The PV-sample is fixed on a temperature-controlled chuck that can be positioned by a x-y-z-stage. The sample is contacted by Kelvin probes. Above the cell the homogenizing optics are held in a cage system (see schematic in Figure 2). A digital microscope allows for accurate positioning of the cell in the light spot. A visible pilot laser (650 nm) coupled into the same fiber as the infrared main laser, is used for positioning the sample into the beam.

The homogenizing optic creating the flat-top profile is shown schematically in Figure 2. The laser beam is guided through a multi-mode fiber with 400 µm core diameter. The radiation emitted from the fiber end facet is collimated by a lens and is oriented onto a diffusor disc for initial homogenization. The main homogenization is realized in form of an “imaging multi-aperture beam integrator” as described by Dickey [24]. The specific design was realized by “Bayerisches Laserzentrum” and uses two micro-lens-arrays (MLA) from “SUSS MicroOptics”. In principle, the individual lens apertures of the first MLA, that are illuminated by the collimated laser beam, are imaged onto the measurement plane by the second MLA and the Fourier lens. Overlapping these multiple images onto the measurement plane significantly reduces inherent non-uniformities present in the collimated laser beam.

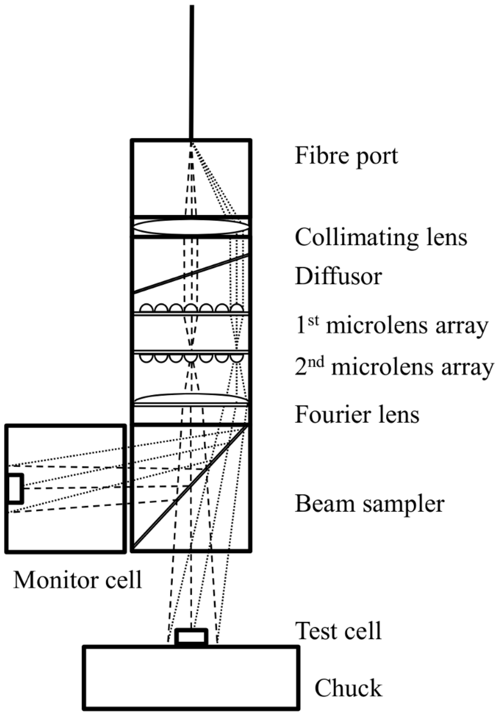

Figure 2: Schematic of homogenizing optics mounted in a cage system. Radiation emitted from the fiber is imaged multiple times onto the measurement plane by microlens arrays and a Fourier lens, thereby enabling homogeneous illumination of the PV sample. As an example single light beams are sketched into the drawing.

A beam sampler directs a small fraction of the incident radiation onto a monitor cell. The purpose of the monitor cell is twofold: On the one hand it is used for a relative correction of short term variations in intensity during the I-V measurement. On the other hand, as the beam splitting ratio or more precisely the ratio between the light intensities in test and monitor cell plane is independent of the absolute intensity, the monitor cell signal can also be calibrated for in-situ determination of the absolute intensity level in the test plane.

Similar to the flash simulator described by Siefer [25], I-V measurement data is logged using a transient recorder. After manually starting the laser pulse of 4 ms duration, the measurement is triggered after a delay of ~1.9 ms which assures stabilization of the laser. Next, the I-V measurement is performed during the following millisecond. The comparatively short illumination and measurement time is used to avoid heating of the test sample during measurement also at high laser intensities. A bipolar power supply is used as variable load in order to vary the voltage at the test sample and consequently switching the I-V curve. In order to detect capacitive or temperature effects the voltage ramp of the load is switched from I_{sc} to V_{oc} during a first measurement, followed by a second reverse measurement from V_{oc} to I_{sc} at same laser intensity settings. The two resulting I-V curves are then compared and examined for possible differences. A difference in fill factor of above 1.5 % is used as indicator for capacitive effects. In that case the measurement can be repeated with increased measurement time. However, this effect is rarely found for III-V based solar cells, but is known for Silicon based solar cells [26, 27]. Differences between V_{oc} determined from the two I-V curves – in particular a higher V_{oc} found for the I-V curve switched from V_{oc} to I_{sc} – indicate an influence from heating of the sample during measurement. This is due to the fact that for the reverse I-V curve switched from V_{oc} to I_{sc}, the V_{oc} is measured at the beginning of the measurement window (i.e. after 1.9 ms laser illumination), whereas for the forward curve (I_{sc} to V_{oc}) V_{oc} is determined at the end of the measurement window (after 2.9 ms of laser illumination). Samples are fixed with vacuum on a temperature controlled chuck, and Kelvin probes and the gold plated chuck itself are used to contact the cells electrically.

2.2 Evaluation

For the initial evaluation of the set-up, the respective standard IEC 60904-9 applicable for sun simulators was chosen as a reference [28]. The standard defines minimum requirements for equipment and allows for a solar simulator classification. Except for the monochromatic light source and thus the simulator spectrum, the set-up is based on a very similar design approach as flash based simulators in use for the characterization of photovoltaic cells or modules. In the following the results regarding temporal stability, including suitability of the intensity correction using the monitor cell signal as well as in respect to spatial uniformity are shown.

Temporal instability of irradiance in the test plane during the recording of the complete I-V curve (long term) as well as instability during the recording of one data sample of current, voltage and monitor signal (short term) show a constant behavior.

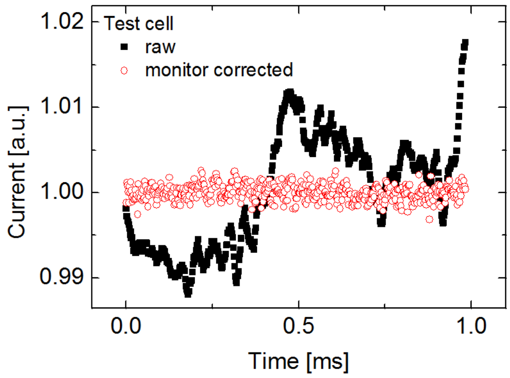

Figure 3: Temporal instability of the laser set-up, determined through the measurement of the short circuit current of a single-junction GaAs test cell (solid squares) Applying a monitor cell intensity correction the fluctuations of the raw signal are canceled out and variations are reduced to ±0.16 % (open circles).

Figure 3 shows the relative course of the short circuit current of a GaAs cell measured in the test plane without monitor cell correction (filled squares). A variation in signal and thus laser intensity for the whole measurement window well below ±2 % is found which would correspond to the requirement for a class A simulator in IEC 60904-9 in respect to long term instability. As described above the long term variations in intensity can be corrected for with the monitor cell's signal. By applying this procedure these variations almost completely vanish and reduce to ±0.16 % (open circles in Figure 3), which is even below the required 0.5 % for class A in short term instability.

Using a cell with known (calibrated) behavior of short circuit current with irradiance which is placed in the test plane, the signal of the monitor cell was calibrated. In this way the current signal measured on the monitor cell can be used for the determination of the irradiance level in the test plane. This is of special interest in the case of the measurement of non-linearly behaving cells. In particular this can be expected for multi-junction devices with strong luminescence coupling between the subcells [18, 19].

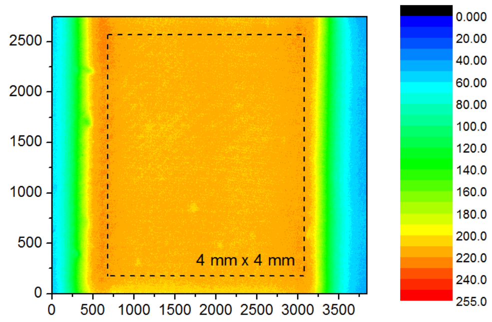

Figure 4: Contour plot of uniformity of the flat-top homogenized laser beam profile in the test plane. A 4 mm × 4 mm designated test area is indicated with dashed lines. Axis show pixel coordinates for the contour plot, whereas a color coding is used to show pixel intensity values.

The **spatial light intensity uniformity** in the test plane has a direct influence on the accuracy of irradiance determination using the monitor cell signal. When using the monitor cell for determining the intensity in the test plane, high uniformity is required for tolerant positioning of the test cell in x-y- direction. In addition, different sized test samples would need different ratios of transmission to reflection (T/R) in the beam sampler as the monitor cell is of fixed size at a fixed position.

The uniformity of the flat-top beam profile in the test plane has been assessed with a beam profiling camera sensor with a resolution of 3840 × 2748 pixels – see Figure 4. IEC 60904-9 requires dividing the test plane into at least 64 equally sized areas for determination of non-uniformity. When binning the pixels of the camera to the required minimum of 64 sub areas, a non-uniformity of 1.6 % is found for the 4 mm × 4 mm sized test plane (dashed square in Figure 4). Reducing the test plane area to 3.5 mm × 3.5 mm the non-uniformity improves to 1.2 %. Both values of uniformity fulfill the 2 % requirement for a class A simulator.

3 I-V MEASUREMENTS

For initial evaluation of the I-V measurements using the LaserSim set-up, two GaAs devices of similar size and front side grid design were measured both with a flash simulator and the new LaserSim at different intensity levels. One of the samples used is a common single-junction GaAs cell whereas the other sample is a monolithic dual-junction GaAs/GaAs device with a tunnel diode for series connection, similar to the ones presented by Schubert [15]. Both samples were chip mounted on a copper heat sink. Designated cell areas are 0.84 mm² for the single-junction and 0.87 mm² in case of the dual-junction device.

Figure 5 shows the open circuit voltage as a function of short circuit current density for the single-junction test cell. A good agreement between both set-ups is found for low current densities. However, for higher current densities >10 A/cm² (i.e. high irradiances) the open circuit voltage reveals differences between both set-ups. In particular, a lower voltage is measured with the flash simulator. This difference could be attributed to temperature effects at the flash set-up by comparing the V_{oc} values of the I-V curves switched from I_{sc} to V_{oc} and vice versa. For the flash set-up significant differences of up to 0.4 % were found at high intensities whereas for the LaserSim this difference was below 0.1 % even at highest intensity.

An explanation for the lower V_{oc} visible for the measurement performed with the flash set-up is an increased heating in the sample during the measurement. The increased heating is a result of the differences in the used irradiance sources. Obviously, the generated current in the test sample has to be the same in both set-ups. However, the irradiance of the flash simulator that is necessary to generate the same current as in the LaserSim is a factor 2.8 higher. This is due to the fact that the flash-simulator uses a Xenon flash bulb and thus a broad-band spectrum impinges on the cell. A high portion of that additional incident irradiance generates thermal energy. As an example, the high energy photons available in the broad spectrum reveal thermalization losses thus cause heating of the solar cell. The heating leads to a lower V_{oc} of the sample.

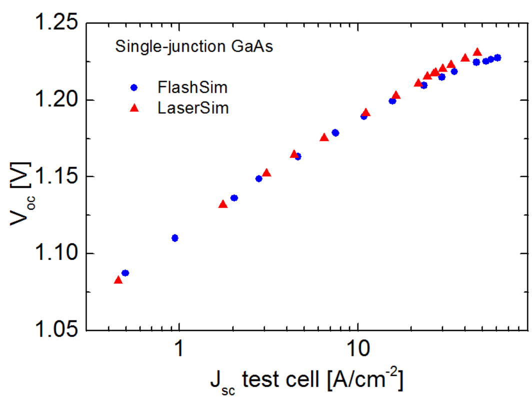

Figure 5: V_{oc} as function of J_{sc} of a single-junction GaAs cell. Measurements at the flash simulator show a decrease in values at high irradiances in comparison to measurements at the LaserSim.

Figure 6 shows the fill-factor as function of short circuit current density for both test cells measured at both set-ups. As expected for the single-junction device only small deviations below 0.5 % in fill factor between the two set-ups are found which is in the range of the measurement uncertainty and repeatability. However, for the dual-junction device higher deviations up to 1.5 % are detected for low current densities. These differences cannot be explained by measurement uncertainty or repeatability. For the 809 nm monochromatic light, the GaAs/GaAs dual-junction cell sample would be current matched at 246 K. Present measurements however were performed at room temperature (298 K). Due to the change in absorption coefficient with temperature this leads to an excess current of 17 % in the top cell. For the spectrum of the flash bulb used at the flash set-up this excess current is as high as 140 %. The significantly higher current mismatch between the two subcells leads to a shifting in operating voltage of the top cell and consequently an increase in fill factor [21]. Due to the heating of the cells at the flash set-up at high intensities and the differences found in fill factor for the GaAs/GaAs dual-junction cell, only the LaserSim measurements will be further discussed in respect to cell efficiency.

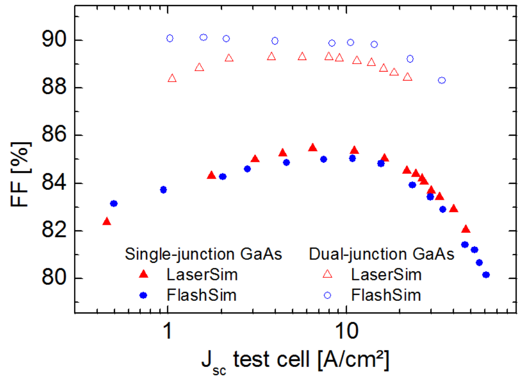

Figure 6: Fill factor as function of the short circuit current density (J_{sc}) for both test cells. Both test cells are measured at the LaserSim and the flash simulator.

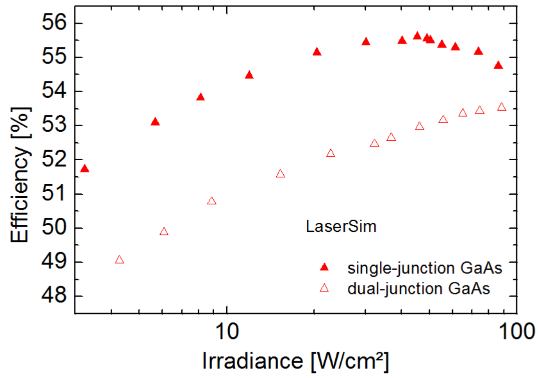

Figure 7: Efficiency as function of irradiance measured with the LaserSim set-up (809 nm). The single-junction test cell is plotted as filled symbols, whereas the dual-junction device data corresponds to the open symbols.

Figure **7** shows the efficiency as a function of irradiance for the two devices measured at the LaserSim. The relation between irradiance in the test plane and the monitor cell signal has been calibrated using the measurement of the single-junction cell. In particular, the intensity has been determined from the spectral response of the single-junction cell at 809 nm and its measured short circuit current density. This means that in the case of the single-junction cell the cell itself was used as reference for intensity determination. The linearity of the short circuit current of the cell with intensity has been verified on a similar cell structure. For the dual-junction device the irradiance in the test plane was determined using the monitor cell reading. The efficiency for the single-junction cell shows a maximum of 55.6 % at 45.3 W/cm². For the dual-junction device the course of efficiency indicates that the maximum efficiency is found for intensities above the ones that were investigated with the LaserSim set-up. The maximum found at highest intensity of 88.6 W/cm² is 53.5 %. Note that due to the splitting of current onto two subcells in case of the dual-junction cell, the current at same intensity will roughly be half the value of the single-junction device. Consequently, for the same grid design the maximum in efficiency for the dual-junction cell is expected to be found at roughly twice the intensity compared to the single-junction cell.

4 SUMMARY AND CONCLUSIONS

A new set-up for measuring PV laser power converters under laser illumination at 809 nm at varying irradiances up to 89 W/cm² has been presented. Similar to flash simulators the sample is only illuminated for a short period of time in order to avoid heating of the cell during measurement. The cell is illuminated for 4 ms in total and the I-V curve is measured in a measurement window of 1 ms. The evaluation of the set-up followed (where applicable) the procedures described in the corresponding standard for solar simulators used in photovoltaics (IEC 60904-9). Temporal stability as well as uniformity meet the requirements of a class A simulator.

The laser intensity in the test plane is calibrated using a cell with known linear behavior of short circuit current with intensity. In particular, the reading of a monitor cell, on which part of the laser beam is orientated with a beam sampler, is calibrated to enable in-situ determination of the irradiance in the test cell plane. In this way also non-linearly behaving cells can be tested. This is of special interest for cells where an influence of strong luminescence coupling is expected. Also it enables efficiency determination without the need to determine the spectral response of each test cell.

I-V curve data taken on a single-junction and a dual-junction cell, using the new LaserSim set-up and a flash set-up, have been compared. Interestingly the open circuit voltage measured using the flash simulator indicated an influence of heating at high intensities despite the short time of illumination. Such effects were not found for the LaserSim set-up. A comparison of fill factor values between the two set-ups revealed a good agreement for the single-junction cell, whereas deviations up to 1.5 % were found for the dual-junction cell. These differences could be explained by the significantly higher current mismatch between the two subcells present at the broad band flash illumination. This clearly demonstrates that such multi-junction devices require testing under appropriate laser illumination.

Finally, first efficiency measurements of two above mentioned cells were shown. For the GaAs single-junction cell a maximum efficiency under 809 nm monochromatic light of 55.6 % at 45.3 W/cm² has been determined. For the dual-junction cell a maximum efficiency of 53.5 % has been found at the highest intensity of 88.6 W/m².

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