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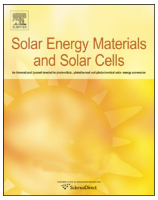

# Influence of temperature and irradiance on triple-junction solar subcells

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## ABSTRACT

Lattice matched triple-junction solar cells based on the materials $Ga_{0.50}In_{0.50}P$, $Ga_{0.99}In_{0.01}As$, and Ge are widely used in space and concentrator applications. In this study, the three subcells of this structure are investigated individually using component solar cells. The investigation covers a broad range of operating conditions, namely temperatures $T$ from 5 to 170 °C and concentration ratios $C$ from 1 to 3000. The temperature dependence of the external quantum efficiencies is analyzed. Further, the I–V-characteristics are analyzed in light of varying temperature and irradiance. The influence of temperature on current-matching is discussed. Special emphasis is given to the Ge bottom cell I–V-curve which collapses at high temperatures. Increasing irradiance counteracts this effect, however series resistance becomes influential. It is shown that at high temperatures the Ge cell can contribute negatively to the power output of the triple-junction device. The limit temperature, defined as the temperature where the open circuit voltage $V_{OC}$ of a cell vanishes, is determined from extrapolation of the measurements using an analytical model of $V_{OC}(T, C)$ and the influence of irradiance is discussed. It is shown, that for the Ge bottom cell the limit temperature lies in the range of operating conditions for space missions close to the sun and approaches operating conditions in CPVT applications.

## 1. Introduction

In concentrating photovoltaics (CPV) as well as in space applications, multi-junction solar cells made from III–V compound semiconductors are widely applied as photovoltaic converters. Compared to solar cells made from silicon, multi-junction solar cells offer higher efficiencies as well as lower temperature sensitivity. The state-of-the-art product on the market is the lattice-matched triple-junction solar cell that consists of three serially interconnected subcells made of $Ga_{0.50}In_{0.50}P$ (top cell), $Ga_{0.99}In_{0.01}As$ (middle cell), and Ge (bottom cell) [1,2]. The band gaps of the subcells decrease from top to bottom which enables an efficient utilization of the solar spectrum.

The characterization of solar cells is usually performed at a temperature of 25 °C or 28 °C and an irradiation of 1000 $W/m^2$ or 1367 $W/m^2$, depending on terrestrial or space application. However, in many applications, the actual operating conditions differ strongly from these laboratory conditions. In passively cooled CPV systems, typical concentration ratios are in the range of 300–1000 and operating temperatures can reach 70 °C [3,4]. Moreover, in concentrating photovoltaic and thermal (CPVT) systems [5,6], the generated heat is actively extracted from a dense array receiver for utilization as e.g. industrial process heat, solar thermal water desalination, or solar cooling and air-conditioning. Here, even higher operating temperatures above 100 °C are desirable so that the exergy content of the heat is increased. Then higher coefficients of performance for the heat utilization can be achieved leading to a higher value of the heat. Further on, also in space applications close to the sun, high temperature and high irradiance must be considered. As an example, in the “Bepi Colombo” mission to Mercury [7,8], the operating temperature is in the range 200–230 °C, while the irradiance reaches up to 11 solar constants. In the “Solar Probe Plus” mission [9,10], solar cells operate close to the sun at 0.044 AU at high temperatures under a maximum irradiance of up to 510 solar constants.

Thus, the knowledge of the temperature behavior of multi-junction solar cells for different irradiances is important for both terrestrial concentrator as well as space applications.

Substantial literature on the influence of temperature on solar cell operation has been published. The influence of temperature on solar cell device parameters has been treated analytically in detail in Refs. [11–15]. Experimental work on the temperature dependence of the external quantum efficiency (*EQE*) of III–V based multi-junction solar cells has been reported in Refs. [16–21]. Furthermore, existing literature covers several experimental studies on the temperature dependence of multi-junction solar cell parameters by means of temperature coefficients (determined from the slope of a linear fit), partly also with respect to the influence of increasing irradiance [15–29].

However, these experimental studies mainly focused on the influences of temperature and irradiance on the performance of multi-junction solar cells directly which imply that behavior of the

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respective subcells remained concealed. Opposed to that, investigation of component cells, i.e. cells that are optically equivalent to the triple-junction cell but feature only one electrically active pn-junction, reveals direct insight into the subcell behavior. Moreover, due to the series interconnection, knowledge of the subcell characteristics enables assertions about the related multi-junction solar cell.

To some extent existing literature covers analyses of individual subcells by using single-junction or component cells of multi-junction devices. Feteha et al. investigated single-junction solar cells made of $Ga_{0.49}In_{0.51}P$ and GaAs for temperatures from 25 to 75 °C and solar intensities from 1 to 40 [30]. Nishioka et al. presented an experimental study covering measurements of single-junction solar cells made of GaInP, GaAs, and Ge in the temperature range 30 to 240 °C at low concentration ratios of 1, 7 and 14 suns (1 sun = 1000 W/m²) [22]. Landis et al. reported on temperature dependent measurements of triple-junction subcells made of GaInP, GaInAs, and Ge, yet under low irradiance and low temperature conditions in the temperature range −160 to 20 °C and varying irradiance below 1 solar constant [27]. Bagienski et al. investigated two different sets of top and middle component solar cells for temperatures from 20 to 60 °C and concentration ratios from 1 to 900 (1 sun = 900 W/m²), and presented corresponding temperature coefficients of the open circuit voltage [28].

As to contribute to the relevant literature, in this study, temperature dependent measurements under various irradiances were performed on top ($Ga_{0.50}In_{0.50}P$), middle ($Ga_{0.99}In_{0.01}As$), and bottom (Ge) component cells of a lattice-matched triple-junction solar cell. A complete data set of *EQE*, dark and light I–V-curves, the latter under various irradiances, has been analyzed. The covered temperatures and irradiances range from 5 to 170 °C and up to a concentration ratio of 3000.

In the first section of this paper, an introduction to material structure of the investigated test samples and measurement setup is given. Thereafter, the experimental results are presented. First, temperature dependent *EQE* measurement are shown. Afterwards, the I-V-characteristics are discussed in detail. The irradiance dependence of the relative temperature coefficient of open circuit voltage $V_{OC}$ of the subcells is discussed in comparison with literature values. Further, the measured $V_{OC}$ data are fitted to an analytical model $V_{OC}(T, C)$ as a function of temperature and concentration ratio. By extrapolation of the fits the limit temperatures, at which $V_{OC}$ of the respective subcells vanishes, are determined as functions of irradiance. Consequently, the implication of vanishing $V_{OC}$ of a subcell on the contribution to the multi-junction solar cell power output is discussed. This is of special importance for the Ge bottom cell because of its low $V_{OC}$ already at 25 °C.

## 2. Materials and experiment

### 2.1. Test samples

Fig. 1 shows the layer structures of the investigated component cells in comparison with the corresponding lattice-matched triple-junction structure (tripLM). The three component cells feature only one electrically active pn-junction (patterned), whereas the other layers (gray) solely vertically conduct the current to the terminals. This feature enables the electrical characterization of a single subcell inside a structure that is optically equivalent to the triple-junction solar cell. The respective type of doping is denoted on the left of each layer. The top, middle and bottom subcells are made of $Ga_{0.50}In_{0.50}P$ (topLM), $Ga_{0.99}In_{0.01}As$ (midLM) and Ge (botLM), respectively. The bottom cell is based on p-type substrate to create a diffusive n-type emitter and, thus, the Ge pn-junction. Here, no tunnel diodes are required. Opposed to that, the top and middle cells are grown on n-type Ge to prevent the creation of a diffusive emitter into the substrate. A tunnel diode below the active subcell is used for interconnection to the substrate. In the top component cell, the $Ga_{0.99}In_{0.01}As$ layers are omitted, since they are not required for optical equivalence with the triple-junction cell.

All investigated cells have a concentrator front grid metallization, yet the top cell features a different cell design than middle and bottom cells. The designated areas are $A_d = 0.0547\ \mathrm{cm}^2$ for middle and bottom cells and $A_d = 0.0423\ \mathrm{cm}^2$ for the top cell. Each cell is soldered to a copper plate, which is mounted onto a Peltier element using thermally conductive oil as interface. A temperature sensor Pt100 RTD mounted on the copper plate beside the solar cell is used to measure the temperature which has been proven to be close to the cell temperature. The Peltier element below the copper plate is used for cooling and heating to regulate the temperature accurately over a broad range from 5 to 170 °C.

### 2.2. Measurement setup

The external quantum efficiency (*EQE*), the dark I–V-curve, one-sun light I–V-curve, and light I–V-curves under various concentration ratios up to 3000 have been measured. The *EQE* was measured in 10 nm steps using a grating monochromator. The measurements of the one-sun I–V-curves were performed with a multi-source sun simulator (AM1.5d [31], 1000 W/m²). The measurements under concentration were performed with a flash sun simulator. The irradiance is varied by changing the distance between flash lamp and cell. The concentration ratio $C$ is determined under the assumption of linear proportionality between photo current density $J_{ph}$ and irradiance from the following equation [32]:

$$C = \frac{J_{ph}^{meas}(T)}{J_{ph}^{1x}(T)} \cong \frac{J_{SC}^{meas}(T)}{J_{SC}^{1x}(T)} \tag{2.1}$$

where $J_{SC}^{meas}$ is the measured short circuit current density under concentration and $J_{SC}^{1x}$ is the calibrated one-sun short circuit current density, both being a function of temperature $T$. Note that Eq. (2.1) becomes invalid in cases where the assumed proportionality is not satisfied [33] or the short circuit current density deviates significantly from the photo current density (compare Section 3.2).

All measurements were performed using measurement equipment of Fraunhofer ISE CalLab PV Cells. For the measurement at 5 °C, a nitrogen gas shower was applied to the cell to prevent water condensation from the laboratory atmosphere.

## 3. Results and discussion

### 3.1. EQE measurements of subcells

The temperature dependent external quantum efficiencies *EQE* of the three component cells are shown in Fig. 2. Because the I–V-curve of the Ge cell collapses at temperatures above 100 °C (compare Fig. 3c in the next section), its spectral response could only be measured until this temperature.

As the temperature increases, for all component cells the drop of the *EQE* at high wavelengths shifts toward longer wavelengths. This shift is directly related to the shift of the absorption edge because of the temperature dependence of the band gap [34]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{3.1}$$

where $E_g(0)$, $\alpha$, and $\beta$ are material constants.