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# Analysis of Thermally Stressed GaAs Solar Cells for Operation in Terrestrial Hybrid Systems

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**Abstract.** The exploitation of hybrid PV-thermal and PV-thermoelectric converters in the temperature range of 150 to 200 °C is currently an emerging field of research. In this context, solar cells have to be designed for operating optimally in this temperature range. Shockley-Queisser (SQ) calculations show that gallium arsenide (GaAs) is one of the optimal choices. Thus, the present work reports on the design, fabrication, and characterization of a standard GaAs solar cell, designed in the Standard Test Conditions (25 °C) but tested under thermal stress in order to analyze the physics that governs conversion performance at higher temperatures. EQE and I-V curve measurements are used to observe the decline of the cell performances at high temperature. By relating the figures of merit to the SQ limit values, it is possible to make meaningful analyses of performance at different temperatures and to compare our results with previous data sets. A key lesson is that a given cell architecture can perform better than another at room temperature but not necessarily at high temperature, thus advocating for a design of the cell in the targeted high temperature conditions. To do so, key optical and electrical properties must be investigated in the temperature range of interest. As an example, we present CTLM measurements processed with a novel parameter extraction method that includes measurement uncertainty propagation, and show that they give indications about the stack of layers to be used for the top contact grid.

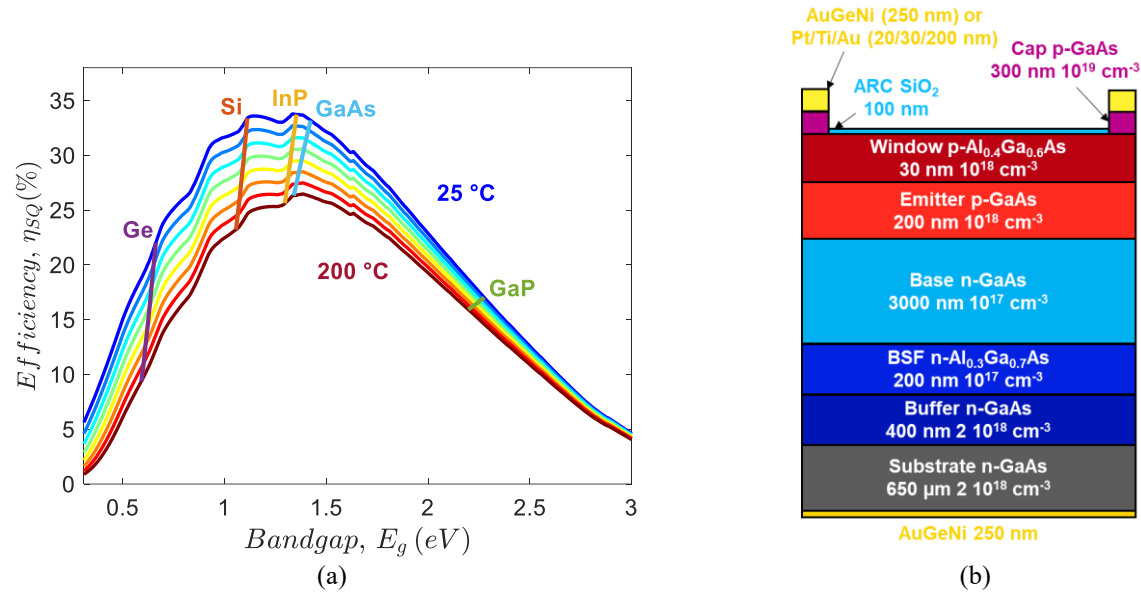
## INTRODUCTION

Even though solar cells are designed for operating under the so-called standard test conditions (STC; i.e., under the AM1.5 spectrum illumination and with the cell operating at 25 °C), it is known that in the field these conditions are barely taking place [1]. Certain applications push solar cells far from the STC [2] despite it is well known that photovoltaic conversion efficiency decreases with temperature [1]. For example, solar cells in standard concentrator photovoltaic (CPV) systems are heated and can reach temperatures above 80 °C. In this case, heat generation should be minimized as much as possible because it leads to a loss of conversion efficiency due to the temperature increase. Alternatively, hybrid systems capable of harnessing solar energy in the form of heat allow the rise in temperature of the cell to be exploited to improve global efficiency [3]. Hence, the design of PV-thermal [4] and PV-thermoelectric [5] converters in the temperature range of 150 to 200 °C to improve their performances is currently under investigation.

In this context, the selection of the semi-conductor materials and the structure of the solar cells used in these hybrid systems have to be rethought. Calculations of the Shockley-Queisser (SQ) efficiency with respect to bandgap for various temperatures (Fig. 1 (a)) show that gallium arsenide (GaAs) is one of the optimal choices in the temperature

range of 150–200 °C. Moreover, standard GaAs solar cells have been extensively studied and used in the space industry for their stability under harsh temperature and illumination conditions [6]. They have also recently demonstrated the highest efficiency for a single junction cell under concentration [7], and there is prior work testing their performance at high temperature [8, 9].

Our research work consists in studying the performances of a conventional GaAs solar cell – optimized in the STC – but operating under thermal stress (at up to 200 °C), in order to analyze the physics that governs photovoltaic conversion at temperatures much higher than that of the STC. The results of this analysis are intended to be used – in a future work - as a guide to propose solar cell materials and structures that are better suited to the operation of PV-T and PV-TE hybrid systems in the temperature range of 150–200 °C. In the next section, methods used for designing, fabricating and characterizing the cell are shortly described. The subsequent section is devoted to providing and analyzing sample results. In the analysis, variations of the usual figures of merit (efficiency, short-circuit current, open-circuit voltage, fill factor) are rated with respect to their values in the Shockley-Queisser (SQ) limit [2]. This rating allows extracting specific information and making comparisons with prior data on GaAs solar cells tested at high temperature. A focus is made on the specific contact resistivity to find an appropriate stack of materials for the top contacts.



**FIGURE 1.** (a) Shockley-Queisser efficiency from 25 °C (blue curve) to 200 °C (brown curve) with a 25 °C step (colored curves) for the AM1.5G illumination spectrum. The lines represent the variations of bandgap with temperature for a selection of semiconductor materials, calculated using Varshni’s relation [10] with Vurgaftman et al.’s parameters [11] for GaAs. (b) Structure of the standard GaAs solar cell optimized in the STC and investigated in this work.

## METHODS

In-house TCAD-1D [12] and pseudo-3D simulation codes [13] were used for designing a standard GaAs solar cell operating optimally in the STC. The resulting structure (Fig. 1 (b)) involves AlGaAs for the window and Back-Surface-Field layers. This choice was constrained by the capabilities of the Molecular Beam Epitaxy instrument used for growing the layers. AuGeNi was selected for the back-contact layer. For the top contact grid, a stack of Ti/Pt/Au layers (20/30/200 nm) was tested as an alternative to AuGeNi (250 nm). The calculated optimum grid spacing and finger width are 550  $\mu$ m and 15  $\mu$ m, respectively, with two lateral busbars having a width of 300  $\mu$ m. Standard clean room processes - photolithography and wet chemical etching - were used to process cells with an area of 1 cm<sup>2</sup>.

A temperature-controlled stage from Linkam Scientific Instruments (HFS-350EV-PB4) was used to characterize the cells at up to 200 °C. Measurements were carried out without the window to avoid possible errors coming from the determination of the optical transmittance of the window. Despite the window was not used and thus the cell was therefore subject to convection, temperature remained very stable (fluctuations smaller than 0.1 °C) at each temperature considered in the present work. The stage was incorporated into our current-voltage and external quantum

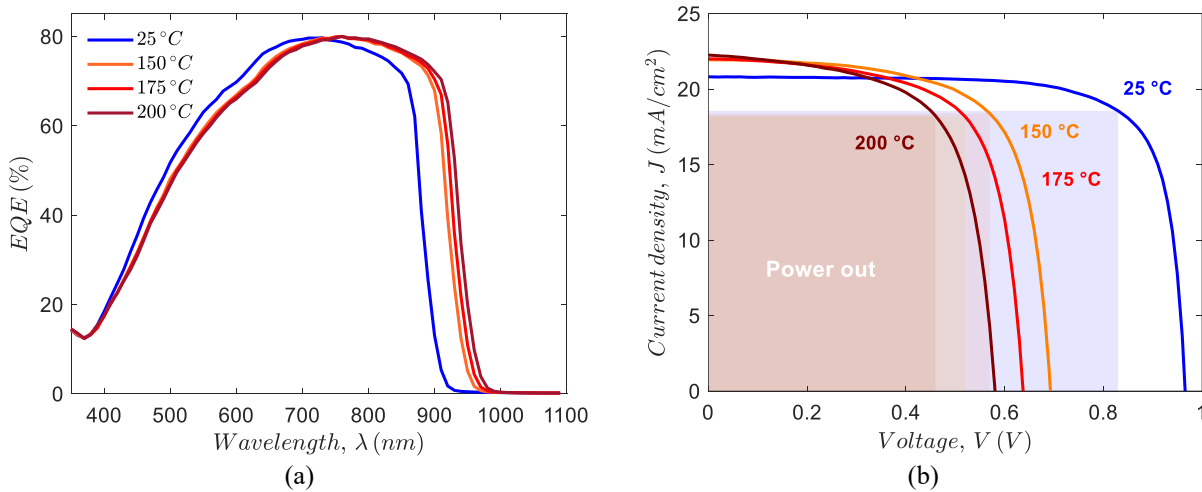
efficiency measurement setups (see e.g. [12, 13]). One sun illumination was provided by a Newport ORIEL Sol 3A solar simulator (Class AAA).

The specific contact resistivity ( $\rho_c$ ) at the interface between the p-GaAs cap layer and the metallic contact layer (AuGeNi and Ti/Pt/Au) was investigated using the Circular Transfer Length Method (CTLM) [14]. Specific samples consisting of 20 rings of the two types of layers considered for the top contacts deposited on p-GaAs substrates - having the same doping concentration as the cap layer - were fabricated. 20 rings with an outer radius ( $L$ ) of 200  $\mu\text{m}$  and a spacing ( $d$ ) ranging from 8 to 46  $\mu\text{m}$  (with a 2  $\mu\text{m}$  step) were considered. The exact nonlinear expression of the total resistance ( $R_T$ ) as a function of the outer radius, spacing, sheet resistance ( $R_{sheet}$ ) and diffusion length ( $L_T$ ) [14] was used to extract unknown parameters ( $R_{sheet}$  and  $L_T$ ) of this equation using a fitting procedure. This method was extended to include measurement uncertainty propagation by using a Monte Carlo approach [14]. Values of the known parameters ( $L$  and  $d$ ) and their corresponding uncertainty were measured by optical microscopy. Total electrical resistance ( $R_T$ ) measurements were made for each ring (each with a different spacing  $d$ ) using the four-point probe technique and an in-house heating and temperature control system. Uncertainty on temperature (from  $\pm 1.2$   $^\circ\text{C}$  at 25  $^\circ\text{C}$  to  $\pm 4.9$   $^\circ\text{C}$  at 200  $^\circ\text{C}$ ) was inferred from the calibration of the thermocouple used for temperature measurements. Uncertainty on electrical resistance measurements was found from the calibration datasheet of the sourcemeter (Keithley 2450).

## RESULTS AND ANALYSIS

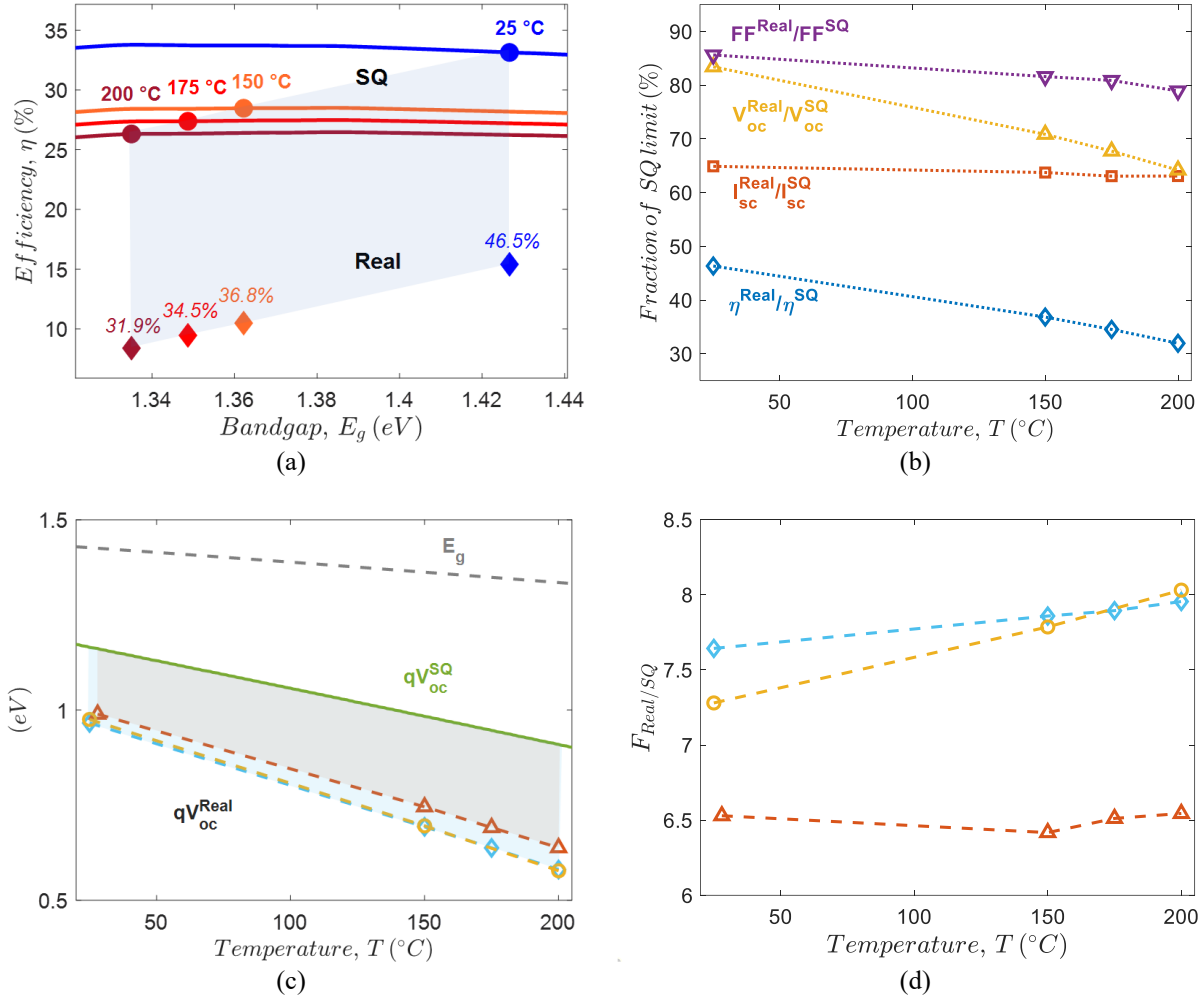
Measurements of External Quantum Efficiency (EQE), I-V curves under 1-Sun illumination of the GaAs cell, and specific contact resistivity of the samples specifically fabricated for applying the CTLM are analyzed in this section. Temperature sensitivity of figures of merit (i.e. the so-called temperature coefficients [1]) are not the focus of this work. Hence measurements were performed at 25  $^\circ\text{C}$  (STC), and then in the chosen range of interest for hybrid systems (at 150, 175 and 200  $^\circ\text{C}$ ), and the differences were examined. The figures of merit (efficiency, short-circuit current, open-circuit voltage, fill factor) are evaluated against their value in the Shockley-Queisser limit [2] to compare them at different temperatures and to evaluate our results against previous data.

At 25  $^\circ\text{C}$  the EQE is comprised between 70% and 80% in the spectral range from 600 to 860 nm (Fig. 2 (a)). The drop at short wavelengths is attributed to recombination in the AlGaAs layer caused by oxidation (TCAD-1D calculations, not shown). At higher temperatures, there is no degradation of charge generation and collection performances since shape of the EQE curve is unaffected. However, as expected, the EQE curve is shifted towards larger wavelengths, owing to the GaAs bandgap decrease with temperature. This bandgap can be determined by searching for the wavelength where the second derivative of the EQE is zero. Results indicate that the bandgap of GaAs in the fabricated cell decreases from 1.425 eV at 25  $^\circ\text{C}$  to 1.333 eV at 200  $^\circ\text{C}$ . This change is in good agreement with values calculated using Varshni's relation with Vurgaftman et al.'s parameters [10, 11].



**FIGURE 2.** (a) EQE and (b) I-V curves under 1-Sun illumination of the GaAs cell, at 25, 150, 175 and 200  $^\circ\text{C}$ .

Stability of the EQE at high temperature together with a smaller bandgap leads to a small rise in short-circuit current when temperature rises from 25 to 200 °C, as displayed by the I-V curves (Fig. 2 (b)). However, as expected, the open-circuit voltage drops from 0.97 V at 25 °C to 0.58 V at 200 °C. As a result, if conversion efficiency is 15.4% (46.5% of the SQ efficiency) at 25 °C, it falls down to 8.4% (31.9% of the SQ efficiency) at 200 °C (Fig. 3 (a)). Further analysis of the ratios of the measured figures of merit (“Real”) to the SQ values (see Fig. 3 (b)) indicates that if this ratio is stable for the short-circuit current (~65%), the causes of efficiency drop are the declines of the ratios for the open-circuit voltage and the fill factor (respectively from 82.9% to 63.8%, and from 85.6% to 78.9%, from 25 to 200 °C). Thus, it is worth analyzing further the behavior of the open-circuit voltage.

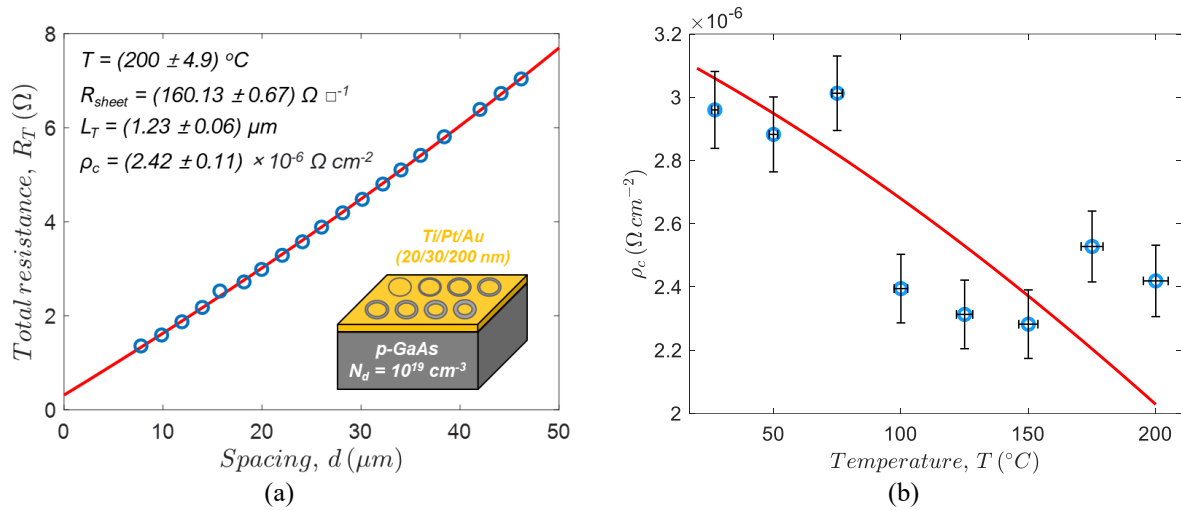


**FIGURE 3.** (a) Efficiency of the GaAs solar cell as a function of bandgap, at 25, 150, 175 and 200 °C. The lines display the SQ efficiency. The filled circles are the SQ efficiencies calculated at the bandgaps experimentally determined at each temperature. The filled diamonds are the measured efficiencies. The percentages indicate the fraction of the SQ efficiency achieved by the cell. (b) Ratio of the figures of merit to their SQ value. (c)  $E_g$ ,  $V_{oc}^{SQ}$ , and  $V_{oc}^{Real}$  as a function of temperature. (d) Variation of  $F^{Real}/SQ$  as a function of temperature. Experimental data from Maros et al. (open triangles) [8], Perl et al. (open circles) [9], and this work (open diamonds). Dotted lines connecting values at 25 and 150 °C are used as guides for the eye.

Figure 3 (c) shows how  $qV_{oc}$  (where  $q$  is the elementary charge) changes from 25 to 150-200 °C, and how our experimental results compare with previous data [8, 9]. Even though the decline in open-circuit voltage looks similar for all three GaAs cells, the representation used in Figure 3 (c) is not precise enough. The analysis proposed in Nayak et al. [16] and Guillemoles et al. [17] and applied by Vaillon et al. [2] for analyzing the behavior of solar cells operating under thermal stress, can be used to extract more information. This analysis consists in assuming that the solar spectrum is that of a blackbody at the temperature of  $T_{sun} = 5800$  K normalized to  $1000$  W/m<sup>2</sup>, and in using

Boltzmann's approximation of Planck's function, so as to express the difference  $q(V_{oc}^{SQ} - V_{oc}^{Real})$  as the product of  $kT$  ( $k$  being Boltzmann's constant) and a factor  $F_{Real/SQ}$ . This single factor tells how much the measured open-circuit voltage is far from the SQ value and allows finer comparisons between different data sets. Figure 3 (d) shows that this factor has values comprised between around 6.5 and 8 for all GaAs cells tested at high temperatures. Nevertheless, this factor is the lowest ( $\sim 6.5$ ) in the work by Maros et al. [8] and is not much different at 25 °C and in the range 150–200 °C. This factor is larger in Perl et al. [9] (7.3) and slightly more in the present work (7.6) at 25 °C, but its value increases in both cases at high temperatures ( $\sim 8$ ), while the difference between the two cells cancels out. These differences between the three cells are probably coming from differences in structures. As a matter of fact, previous works investigated p-type cells with other materials for the window and BSF layers, while in this work a n-type cell is considered. The key point of this analysis is that the performance evolution of GaAs cells from room temperature to higher temperatures can be different from one cell to another, depending on its design and fabrication.

The previous statement advocates for an optimal design of the cells in the targeted temperature range. To do so, a finer analysis of key optical and electrical properties in this temperature range is needed. Such an analysis is proposed for the specific contact resistivity ( $\rho_c$ ) at the interface between the top contact and the cap layers. In the case of AuGeNi on p-GaAs, results of the CTLM technique provide values of the order of  $10^{-4}$ – $10^{-5} \Omega \text{ cm}^2$  from the ambient up to 200 °C, which is an order of magnitude higher than typical values ( $10^{-6} \Omega \text{ cm}^2$ ) [18]. The absence of a barrier that mitigates Au migration toward the junction is thus a problem at the top contact. Nevertheless, AuGeNi can be used for the bottom contact. CTLM results show a much better behavior of the stack of Ti/Pt/Au layers on p-GaAs (Figs. 4 (a) and (b)). A slight reduction of the specific contact resistivity is observed as the temperature is increased from 25 to 200 °C. This result, consistent with a previous work [19], compares well with modeling [20] (red line in Fig. 4 (b)).



**FIGURE 4.** (a) CTLM measurement data for Ti/Pt/Au on p-GaAs: experimental total resistance (open circles) as a function of spacing; model (red line) at 200 °C. The sheet resistance ( $R_{sheet}$ ), diffusion length ( $L_T$ ) and specific contact resistance ( $\rho_c$ ) are fitted considering the propagation of measurement uncertainties using a Monte Carlo technique. (b) Specific contact resistivity for Ti/Pt/Au (20/30/200 nm) on p-GaAs ( $N_d = 10^{19} \text{ cm}^{-3}$ ) with respect to temperature: comparison of experimental data extracted from CTLM measurements (circles) against modelling (red line).

## CONCLUSION

We have designed a standard GaAs solar cell for operating optimally at ambient temperature, fabricated and characterized it at ambient temperature and in the range 150–200 °C. This range is currently of interest for designing photovoltaic-thermal hybrid systems. The observed decline of the cell performances has been scaled using the usual figures of merit and their corresponding SQ limit values. We have found that different cell architectures optimized for operation at ambient temperature lead to various behaviors at higher temperature, thus advocating for a fine analysis of key optical and electrical properties at high temperature. As an example, we have used CTLM measurements and a novel method for extracting parameters that considers the propagation of measurement uncertainties, to show that a stack of Ti/Pt/Au layers is a better choice than AuGeNi for the top contact grid.

The findings of this study illustrate the importance of optimally designing a solar cell in the targeted operating conditions, rather than designing a cell at ambient temperature. The present work has to be completed by finer analyses of the performances at high temperature. In particular, optical (complex refractive index) and electrical properties (mobility, lifetimes) have to be investigated in this range. Finally, characterization of the cell will have to be performed under concentration with factors (~30) leading to the targeted operating temperatures.

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