Microelectronics Journal 45 (2014) 1710–1715

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Characterization of solar cells by thermal transient testing

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ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form
7 June 2014
Accepted 10 June 2014
Available online 4 July 2014

Keywords:
Thermal transient testing
Solar cell
Thermal modeling

ABSTRACT

The current paper deals with the application of thermal transient testing as a characterization tool for solar modules. Based on the measurement of different samples (concentrator solar cell, single junction silicon solar cell) we prove the applicability of this measurement technique and address some specific issues of the characterization of solar cells by the thermal transient method.

From the measurement metrics such as junction-to-base plate thermal resistance and thermal capacitance(s) can be derived and can serve as a basis of a multi domain solar cell model. The used technique also enables us to verify the quality of attachment layers in a solar module allowing fair quality control and reliability analysis of these devices. Finally a method is proposed to regain the data that is covered by the initial electric transient following the power step. This initial electric transient can be high in large surface devices like solar cells, and covers valuable data describing the structure near to the p–n junction. To eliminate this, simulated transients were fitted to the part of the actual measured thermal transient where the electric transient already decayed. This way the part of the thermal transient that was covered by the electric transient can be reconstructed.

1. Introduction

Solar cells are one of the most prospering fields nowadays with yielding an average growth of over 30% per year over the last decade. Thanks to this superior growth R&D in this field has increased, and produced a wide variety of different solar cell concepts, e.g. crystalline silicon cells, amorphous silicon cells, semiconductor alloy multi-junction cells for concentrator applications, non-silicon thin film solar cells or organic solar cells. All of these cell types share a common feature, namely that they convert light into electric energy, but due to changes in the ambient conditions (such as temperature and irradiation) their behavior can be extremely varying. As an example, the power curves of crystalline silicon and organic solar cells are quite different: while the power generated by a silicon solar cell decreases with temperature [1,2], the temperature dependence of organic cells shows a positive coefficient [3].

Current standard measurements [4,5] do not incorporate the variation of temperature, although the power generated by photovoltaic devices shows a strong dependence on these parameters. Thus there is a strong need for measurement techniques that can be applied for combined electro thermal investigations. Although there are no standardized measurements for the temperature dependence of solar cells, the vast majority of solar cells are characterized for its temperature behavior. These measurements cover usually steady states, i.e. the parameters of the solar cells or modules are measured at different temperatures after reaching steady state. This kind of thermal characterization can be summarized as static electro-thermal measurement and can give valuable data (thermal dependence of electric parameters, junction to case thermal resistance) for basic electro-thermal solar cell models. However these models are only able to predict the power generation accurately, when the system and its environment are in steady state. On the other hand a variety of theoretic models incorporating the thermal dependence of the electric parameters have been presented [1,6–8], but mostly these are limited to the cell itself, and do not take the thermal behavior of the elements of the casing into account. Predictions based on these models need a feedback on the cell temperature.

As for the interlink between electric and thermal behavior of solar cells it is characteristic that the electric response to changing irradiation conditions is by orders of magnitudes faster than the thermal response. Thus for example in case of changing weather conditions models based on characteristics measured with static electro-thermal methods can result in false predictions if a feedback on the cell temperature is not available. It can be seen that prediction models based on static electro-thermal characterization need the irradiance and at least the cell temperature as input

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http://dx.doi.org/10.1016/j.mejo.2014.06.003

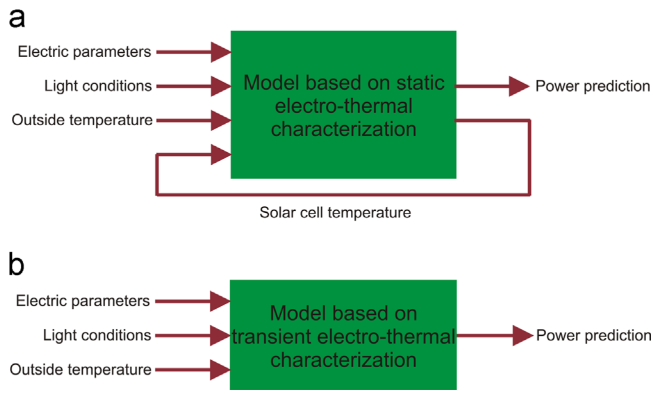

Fig. 1. Combined electro-thermal solar cell models based on (a) static electro-thermal characterization and (b) thermal transient characterization.

parameters (Fig. 1a) where the cell temperature is a feedback signal and thus does not allow explicit black box modeling. Since the cells are normally incorporated dust- and waterproof into the module, temperature sensors would have to be integrated during the fabrication process, if feedback on the cell temperature is needed. This would lead to additional costs and changes in manufacturing processes. Retrofitting of already manufactured modules with sensors for the measurement of the solar cells is also not an option.

By using the transient electro-thermal measurements and appropriate models, a more sophisticated description of solar cell behavior can be given. Using thermal-transient measurement the heatflow path between the heat generation source (the cell) and the ambient can be measured [9]. Contrary to static electro-thermal characterization methods this way not only the thermal resistance, but the heat capacitances of the solar module can be measured additionally. If together with this the heat generation in the solar cells is determined from the absorbed irradiation and the ambient temperature is known, a precise prediction can be given at every single moment of operation. With models based on thermal transient measurements no cell temperature feedback is needed, only the irradiance levels and the ambient temperature have to be introduced as input parameters to the model, thus allowing an explicit black box model of the investigated solar cell (Fig. 1b).

In addition to precise complex solar module models thermal transient testing can also provide valuable data for the thermal design and reliability testing of solar cell modules e.g. in concentrator or space applications. Another promising application possibility is the non-destructive measurement of the casing, where the quality and the degeneration of the attached layers and the elements in the heat conduction path can be characterized.

2. Experimental

For the accurate thermal modeling of an encapsulated solar module an approach similar to those used for the characterization of power electronics can be applied.

Thermal transient testing is an appropriate tool for mapping the heat conduction path between a semiconductor junction and its ambient. This technique is widely used to derive package parameters such R_{thJA} and R_{thJC} in case of power devices. In these cases the temperature sensor can be a dedicated temperature sensitive diode or a transistor.

Since a solar cell is basically a series of PN junctions with a temperature sensitive forward voltage, the thermal transient methodology is suitable for their testing in practically the same way [10].

However there are some differences which should be considered in case of the measurement of solar cells.

The packaging of solar modules is not primarily designed to enhance the cooling path from the junction, but for transmittance at the upper side and mechanical stability at the backside. For this reason the heat paths in both directions are comparable. Concentrator cells are an exception as due to the high power density of the irradiation additional measures have to be taken to increase the thermal conductivity between the cell and the ambient.

In addition the current of the solar cell varies with illumination, so it is essential to perform the temperature sensitivity calibration under dark conditions. For practical considerations we performed the measurements in a dark environment, too.

The silicon and other structural materials such as the glass and aluminum are easy to incorporate into models due to their well known material properties and geometries. The thermal resistance and capacitance of attachment materials between these layers are on the other hand difficult to calculate as their parameters are usually not well defined.

For the actual tests we used a GaAs concentrator solar cell with a $10 \times 10\ \text{mm}^2$ surface area, mounted on an aluminum based MCPCB. The structure shown in Fig. 2 below is similar to those used in case of power LEDs, therefore we may assume that the heat-conduction path is mainly one dimensional in this particular case.

The temperature sensitive parameter (TSP) value has to be calibrated in case of each device under test to measure the temperature dependence of the forward voltage of the diode. For device calibration we prefer to use a temperature controlled environment to set up different ambient temperature values. A constant sensor current is driven through the diode, while we measure the forward voltage values at each settled temperature point. With trial measurements we selected a 10 mA constant sensor current for biasing the diode, to obtain an optimal signal-to-noise ratio.

The temperature of the reference plate was controlled from 25 to 65 °C in 10 °C steps, and the forward voltages were measured. A calibration curve can be seen in Fig. 3. Based on the slope of the curve, we used a linear fit (−6.198 mV/K in Fig. 3) to convert the measured voltage data to temperature data.

Fig. 2. Cross-section of the CSC samples.

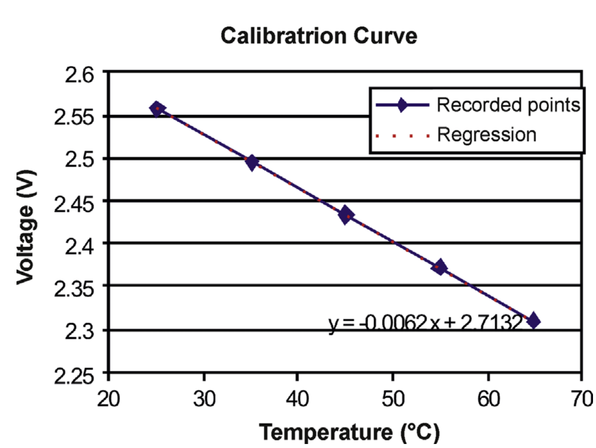

Fig. 3. Calibration curve of a triple junction cell.