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Innovative experimental setup for thermal and electrical characterization of silicon solar cells under controlled environmental conditions

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ABSTRACT

The optimization of solar cells properties with thermal criteria gives the possibility to achieve higher conversion efficiency in outdoor conditions. An innovative setup that allows the control of the surroundings of a solar cell is described. Under such specific conditions, the cell temperature can be stabilized and measured. The variation of the cell temperature with the applied bias is experimentally observed and quantified. Between short circuit current density (J_{sc}) and open circuit voltage (V_{oc}), a slight difference of temperature is observed, revealing a variation of the thermal equilibrium between these two points. The resistivity of the absorber and the input power density are found to influence this temperature shift. From the experimental results, it appears that the emissivity of the solar cell increases with the applied voltage due to an increase in the excess carrier concentration. Consequently, the operating temperature at open-circuit is lower than at short-circuit.

1. Introduction

One of the biggest challenges for solar cells is to increase their electrical performance. For silicon solar cells, 26.7% conversion efficiency [1] has been recently achieved. This record was obtained under standard test conditions (STC), meaning that the cell temperature was fixed to 25 °C under a specific irradiance of 1000 W m^{-2} (1 sun) with AM1.5G spectrum. However, these conditions do not reflect the real functioning conditions. The cell is, in fact, exposed to much higher temperature, which degrades its conversion efficiency. In 1981, D.L Evans observed that the solar cell efficiency at a temperature T can be linked to its efficiency at a reference temperature T_{ref}, by defining the temperature degradation coefficient β (in °C^{-1}) [2]:

$$\eta(T) = \eta(T_{ref})\cdot(1 - \beta\cdot(T - T_{ref})) \tag{1}$$

The β coefficient depends on the device characteristics, the architecture but also the environmental conditions [3–5]. As a result, a way to improve the global solar cell conversion efficiency in outdoor conditions could be to optimize, with thermal criteria, their electrical properties and fabrication process. A better understanding of the electrical and thermal behavior (ETB) of solar cells is therefore crucial, as it has been recently shown by Weiss et al. [6]. Despite its significance, the effect of temperature on solar cell conversion efficiency is sparsely studied in the literature. There are few studies which are analyzing the behavior of solar modules in outdoor conditions. For example, Almonacid et al. [7] are relating the cell temperature variations with meteorological parameters, while Kamkird et al. [8] and Vogt et al. [9] are comparing the thermal behavior of different solar cell modules in outdoor conditions. However, none of these experimental studies allow the separation of each environmental effect on the ETB of solar cells. In this work, we present an innovative experimental setup giving the possibility to measure the cell temperature under controlled environmental conditions. Unlike the existing characterization setups usually presented in the literature, the cell temperature is not imposed by conduction at the bottom of the cell [10] but by radiative exchanges, offering more possibilities for the study of the ETB of solar cells.

This paper starts with the description of the physical phenomenon involved in the thermal equilibrium between a solar cell and its environment. Then, the innovative experimental setup developed in-house is presented. Afterwards, the evolution of the cell temperature with the applied bias is studied, and compared to numerical simulations. Finally, the influence of the base resistivity of the absorber and the light intensity on the solar cell ETB is investigated.

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2. Preliminary study: modelling of solar cells ETB

2.1. General approach: influence of the temperature on IV characteristic

The influence of the temperature on solar cell electrical characteristics has already been explored in literature: the increase of the cell temperature leads to a deterioration of its electrical efficiency. When increasing the cell temperature, on the I-V curve the consequences are the following:

- A slight increase of the short-circuit current density (J_{sc}),
- A drop of the open-circuit voltage (V_{oc}).

These variations are related to different properties of the solar cell. For most semiconductors, including silicon, higher temperatures tend to reduce the band gap of the materials [11]. More photons will have enough energy to be absorbed [12], resulting in higher short circuit current density. However, the amplification of the diode current, caused by the increase of intrinsic carrier concentration, tends to dramatically decrease the open circuit voltage [13,14]. This drop of V_{oc}, when increasing the temperature, is mainly responsible for the loss of conversion efficiency of the solar cell under operating conditions [15].

The aim of this article is to analyze the different mechanisms involved in the thermal equilibrium between a solar cell and its environment under operating conditions. This study will be used to estimate the operating temperature of the solar cell for specific environmental conditions.

2.2. Modelling the ETB of silicon solar cells: effect of the applied bias

Under illumination, a solar cell will reach an operating temperature, which not only depends on the environmental conditions but also on its properties such as the base doping or the considered architecture. The Nominal Operating Cell Temperature (NOCT) is measured under specific conditions: an input power density of 800 W/m^{-2}, an ambient temperature of 25 °C and a given wind speed of 1 $m{\cdot}s^{-1}$. This temperature is measured at V_{oc} and is supposed to stay constant whatever the applied bias. A simple power exchange analysis can be performed to invalidate this assumption. As the electrical power which can be extracted from the cell culminates at maximum power point M_{pp}, the contribution of the incident solar power to the thermal heating of the cell decreases when approaching M_{pp}. Consequently, the cell temperature at M_{pp} is lower than the ones at V_{oc} and J_{sc}. A complete study of the different heating and cooling mechanisms involved in the thermal equilibrium between a solar cell and its environment is necessary to quantify this variation of temperature with the applied bias.

This study was performed in a previous paper [16], in which the ETB of a solar cell under specific environmental conditions was simulated by coupling radiative transfer, heat transfer and transport equations. For a given applied bias and boundary conditions, the electrical output power and the cell temperature are calculated for a solar cell with the parameters defined in Table 1. The heat transfer convective coefficient between the cell and the surrounding was set to 1 $W{\cdot}m^{-2}{\cdot}K^{-1}$ (this coefficient cannot be null because of convergence issues). The numerical model does not include surface texturation, shunt resistance is supposed infinite and series resistance null. The recombination at the interface between the semiconductor and the metal are also neglected. Besides, low injection is assumed for the transport equations calculation.

Table 1
Parameters of the simulated solar cell.

Parameter	Value
Wafer thickness	275 µm
Base Doping (p-type, uniform)	1×10^{16} cm^{-3}
Emitter Doping (n-type, uniform)	5×10^{19} cm^{-3}
Junction Depth	300 nm
Front surface recombination velocity	1000 $cm{\cdot}s^{-1}$
Rear surface recombination velocity	10000 $cm{\cdot}s^{-1}$
SRH Lifetime	1 ms

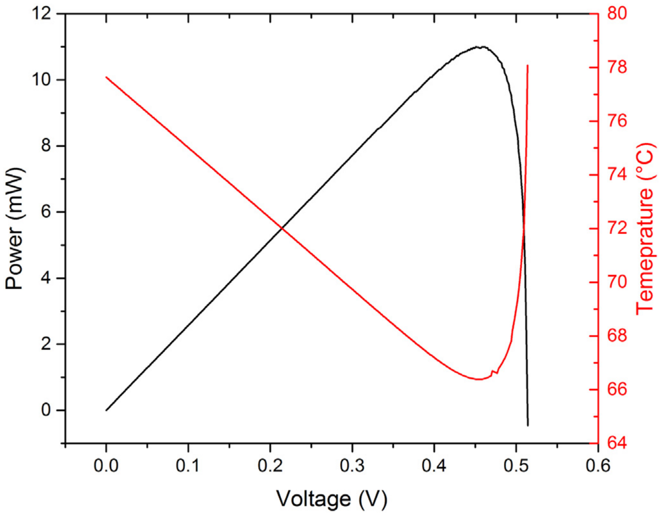

Fig. 1. Power and temperature-voltage characteristics of the simulated solar cell.

The results presented on Fig. 1 confirm the simple analysis presented in the previous study. For the given solar cell parameter, we observe the following points: the cell reaches a maximum temperature value at J_{sc} and V_{oc} (78 °C), and a minimum value at M_{pp} (66.5 °C). The numerical model gives the possibility to quantify the cell temperature variation between J_{sc}, V_{oc} and M_{pp}. Moreover, we will see in the section “Results and Discussion” that the temperature at V_{oc} may differ from the one at J_{sc}.

For three specific points (J_{sc}, M_{pp} and V_{oc}), the different heating and cooling mechanisms involved in the thermal equilibrium between the cell and its environment were fully explored in a previous investigation [16]. These mechanisms are either responsible for the heating of the cell (Joule effect, Peltier effect, recombination process or thermalization) or for its cooling (Thermal radiation, convective exchange or Thomson effect).

Due to the thermal equilibrium between heating and cooling mechanisms, the temperature of the cell can be stabilized for each applied bias. The variation of heat sources and sinks explains the cell temperature variation presented in Fig. 1 [16].

With the use of the numerical model, we have highlighted the influence of the applied bias on the ETB of unencapsulated silicon solar cells.

By limiting the different heat and sink sources, such variation of the cell temperature with the applied bias could be measured and quantified. For these reasons, an innovative experimental setup allowing the electro-thermal characterizations of silicon solar cells under controlled environmental conditions is introduced.

3. Development of an innovative experimental setup

3.1. Presentation of the experimental setup

In this paragraph, we present a setup which allows a control of the surroundings of a solar cell. At the same time, the electrical performances of the solar cell are measured. To ensure such measurement, the setup must have the following features:

- Control of the different thermal exchanges between the cell and the surroundings (including radiation, convection and conduction),