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ScienceDirect
Solar Energy 103 (2014) 1–11
SOLAR ENERGY
www.elsevier.com/locate/solener

Numerical simulation of the temperature distortions in InGaP/GaAs/Ge solar cells working under high concentrating conditions due to voids presence in the solder joint

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Received 6 September 2013; received in revised form 2 January 2014; accepted 3 February 2014

Communicated by: Associate Editor Igor Tyukhov

Abstract

The presence of voids in solar cell solder joints causes a modification of the heat fluxes inside the device during its operation, which in turn leads to local increases in cell temperature and thermal resistance. These temperature increases at device surface lead to a modification of the photovoltaic cell voltage map which translates in a drop in cell output power. Moreover, for pv cells working under high concentration conditions such as III–V multi-junction solar cells for terrestrial application, very high temperature increases can arise as a consequence of void presence, both above the void volume and around it, leading in extreme cases to irreversible damages of the device. In this paper a matlab script is implemented to assess the temperature increase at the top surface of a InGaP/GaAs/Ge solar cell, in the device regions lying outside the void coverage area, for different void sizes found in concentrator solar cells. The obtained results are compared to those of finite element method (FEM) simulations, which are based on an equivalent 2.5 D thermal representation of the cell. A good agreement between FEM simulations and the developed thermal model is observed for small and medium size voids, while for larger voids the error between FEM simulations and the developed model becomes not-negligible. An analytical expression is obtained to assess the device thermal resistance in presence of a random distribution on not-interacting voids. The developed model can be used as starting point to assess the influence of void presence on the power performances of InGaP/GaAs/Ge multi-junction solar cells working under high concentrating conditions.

Keywords: Thermal simulations; FEM; Voids; Concentrating solar cells; CPV; Thermal resistance

1. Introduction

Semiconductor devices such as solar cells are commonly affected by the formation of voids in the solder joint region. Typically, the formation of voids arises from non-optimized soldering processes and from thermo-mechanical stresses of the device, which are typically introduced during its operation (Chen et al., 2008; Fleischer et al., 2006; Strifas and Christou, 1995; Xia et al., 2005). The presence of voids causes local increases in device working temperature and thermal resistance, degrading its heat

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http://dx.doi.org/10.1016/j.solener.2014.02.007
0038-092X/

dissipation performance (Timpe and Cloud, 2006; Zhang et al., 2006). In silicon solar cells voids are found to cause only negligible variations of cell performances during normal working conditions (Baricordi et al., 2013), but their presence can degrade the thermal cycling durability of the device (Cuddalorepana et al., 2010). In concentrator solar cells working under high concentration conditions, which periodically undergo large thermal flow variations, void presence can give rise to very high temperature spikes which can promote the formation of further voids, compromising the reliability of the whole device.

Only few data are available on the effect of voids in high concentration III–V multi-junction solar cells, these data indicating that voids located at the corners of the cell can lead to infant mortality failures of the device (Bosco et al., 2011). For voids close to the device corners the heat flux spreading in the device plane outside the void coverage area results partially hindered, leading to higher temperature spikes at void center (Ciampolini et al., 1999). Since these voids are considered responsible for device failures, this suggests that the spreading of the heat flux outside the void area could be non-negligible for solar cells working under high concentrating conditions, and hence an assessment of the temperature increase in III–V multi-junction solar cells outside the void area could be of some interest.

In this work an analytical thermal model is developed to assess the void induced temperature increase at the top surface of a InGaP/GaAs/Ge multijunction solar cell working at the geometrical concentration ratio of 650 suns (650×), in the device regions outside the void coverage area. The results of the analytical model will be compared to those of FEM simulations, carried out by means of ADINA 8.7 (Automatic Dynamic Incremental Nonlinear Analysis) software. The minimum distance between two identical voids for which the temperature increase is negligible is assessed starting from the results of FEM simulations. Moreover, edge effects are evaluated for different void sizes and different distances from device edge.

Typical void dimensions are retrieved from Fig. 1 which shows an X-ray image of a bad soldered (on the left) and quite good soldered (on the right) small area concentrator solar cells. The void surface is fitted with an equivalent ellipse-like area distribution and the radius of a circle with the same area is obtained, as explained in (Mulchrone and Choudhury, 2004). For the bad soldered solar cell, which experiences larger voids, most voids have a radius ranging from 0.5 to 1.5 mm, with larger voids approaching 1.7 mm of radius. As a consequence, the interval 0.5–1.7 mm is considered for the following analysis, to investigate the worst case scenario.

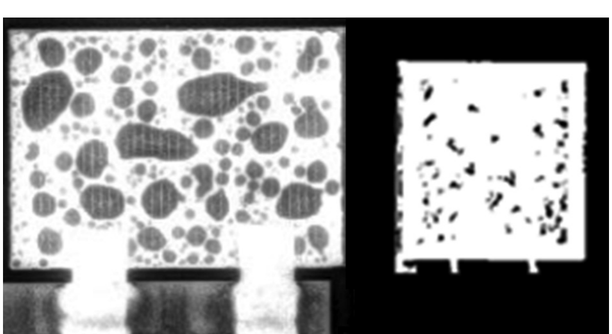

Fig. 1. X-ray image of two small area concentrator solar cells. The image on the left shows a bad soldered solar cell, while that on the right shows a quite good soldered solar cell. Voids in the solder joint are visible in both solar cells.

Typical dimensions for III–V multi-junction solar cells range from 5×5 to $10 \times 10\ \mathrm{mm}^2$ surface area. In the following analysis a $10 \times 10\ \mathrm{mm}^2$ solar cell will be considered.

2. The thermal model

2.1. Analytical approach

A 2.5 D thermal model of a InGaP/GaAs/Ge triple junction solar cell is developed in order to assess the local temperature increase at top device surface, in the regions surrounding a void.

For an easier geometrical treatment we model the solar cell stack as a 143.2-μm-thick germanium slab placed on insulated metal substrate (IMS) heat sink. The germanium slab models the thermal behavior of both the germanium substrate and bottom cell (the sum of their thicknesses being 140 μm in the model) and the GaAs middle cell (which thickness is 3.2 μm in the model), since the thermal conductivity of $Ga_{0.5}As_{0.5}$ ($k_{GaAs} = 55\ \mathrm{W\ m^{-1}\ K^{-1}}$ at room temperature) is very close to the germanium thermal conductivity ($k_{Ge} = 58\ \mathrm{W\ m^{-1}\ K^{-1}}$ at room temperature). On the other hand the InGaP top cell is not considered in the thermal model since FEM simulations (not shown here) indicates that its contribution to device temperature profile is negligible, as a consequence of its very small thickness (0.65 μm, typically). In addition, also the gold back contact of the cell has been neglected in the simulations, due to its very small thickness (few hundreds of nm) and to the very high gold thermal conductivity ($k_{Au} = 317\ \mathrm{W\ m^{-1}\ K^{-1}}$ at room temperature).

The IMS is modeled as a 70-μm-thick copper layer, which is in direct contact with the germanium slab, bounded to a 35-μm-thick insulating layer and an aluminum slab considered isothermal (at a temperature of 338 K). Even though this does not represent a realistic case, it represents a good first approximation for thick aluminum slabs, having high lateral heat spreading efficiency.

In absence of voids, and for a realistic heat sink temperature of 338 K, the equilibrium temperature at device surface is 345.5 K, as assessed by FEM simulation of the cell stack.

The presence of a single void in the solder region has been taken into account introducing a cylindrical region full of air in the solder layer, beneath the germanium slab. For a simpler treatment we consider the void as an infinite thermal resistance volume, since the air thermal conductiv-