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Measurement and simulation of hot spots in solar cells

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Abstract

Solar cells can have various shunts with various origins and current-temperature characteristics. A solar cell with a local ohmic shunt can heat up during partial shadow conditions due to reverse current through the shunt. Depending on the resulting hot spot size and reverse current, the local temperature can be so high that it can damage the solar module. Especially under field conditions, if hot spots are detected, it would be worthwhile to decide on a threshold temperature for which a solar module should be de-commissioned.
This work describes experiments where four single cell modules were made with thermocouples embedded close to hot spots. The temperature development in such modules has been measured by an IR camera and simulated by a 3D finite element model. The temperature development of a hot spot was computed as a function of hot spot reverse current, reverse voltage, time, hot spot size, hot spot location and ambient temperature. The temperature development in the module is well described by the model. Temperature trends were shown to be a function of shunt size as well as location relative to the edge of the cell.

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Keywords: T Hot spot; shunt; solar cell reliability

1. Introduction

Solar cells can have various shunts with various origins and current-temperature characteristics [1]. A solar cell with a local ohmic shunt can heat up during partial shadow conditions due to reverse current through the shunt, resulting in a so-called hot spot. Depending on the hot spot size and reverse current, the local temperature can be so high that it can damage the solar module [2]. On the other hand, a solar cell can contain local heating points, which do not pose a risk to the entire module. Especially under field conditions, if hot spots are detected, it would be worthwhile to decide on a threshold temperature for which a solar module should be de-commissioned. On a finished module, only the surface temperature

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can be measured by IR camera [3]. The actual temperature inside the module will be different. This work describes experiments where four single cell modules were made with thermocouples embedded close to hot spots. In addition, the temperature was measured at the surface by an IR camera. The temperature development in such modules has also been simulated by a 3D finite element model (FEM). The model has been used to investigate how the surface and hot spot temperature depends on the hot spot reverse current, reverse voltage, time, hot spot size, hot spot location and ambient temperature.

2. Measurement setup

Four single cell modules were made with thermocouples embedded in the module as close as possible to hot spots detected by IR camera. The module layers from bottom to top are: Tedlar back sheet, EVA (ethylene-vinyl acetate), solar cell, thermocouple, 2×EVA sheets, and front glass. Two sheets of EVA were found necessary to avoid that the solar cell cracked during lamination. The temperature of the hot spot was logged automatically by IR camera every 150 ms. Thermocouple temperatures were logged manually every 2-10 s. See measurement setup in Fig. 1. The single cell modules were placed on bricks of expanded polyester with the aim of minimizing heat transport from the module to the support.

3. Model description and simulations

The thermal modeling was carried out by using an in-house FEM program [4] originally developed for simulating casting and welding processes. This program lets the user assign different thermo-physical properties to different layers of the module, and it offers a convenient way of defining heat sources on the surface of the silicon layer inside the module. The thermo-physical properties used in the simulation are listed in Table 1. The effect of a double layer of EVA between the cell and glass was taken into account by using scaled and anisotropic properties in the FEM-model, while still having the dimensions of a normal single layer module. Some uncertainty is associated with the properties of the Tedlar back sheet and EVA material, as the properties will depend on the lamination process. The heat transfer from glass and back sheet was modeled as a combination of radiation, with an emissivity of 0.9 as reported in the literature for the encapsulating materials, and thermal convection. The contribution to the heat transfer coefficient from convection was assumed to be temperature dependent with values of 6.0 $Wm^{-1}K^{-1}$ and 10 $Wm^{-1}K^{-1}$ at 20 °C and 123 °C respectively. These values may represent an overestimation of the heat transfer, but such high values were required in order to obtain a good agreement with the measurements.

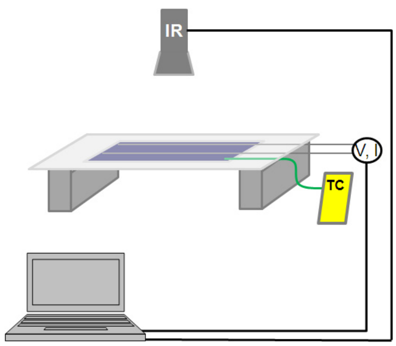


Fig. 1. Single cell module with embedded thermocouple (TC). Applied current and voltage. IR camera. Automated logging of voltage (V), reverse current (I_{rev}), temperature IR (T_{IR}), time (t). Manual logging of thermocouple temperature (T_{TC}).

In order to handle the large range of length scales and varying thermal gradient with acceptable accuracy, a FEM mesh with close to 800 000 nodes was used. Nodes are more densely packed near the hot spot for higher accuracy. Fig. 2 illustrates the effect on the temperature field around a hot spot from the varying thermal properties in the different materials. The cell had a dimension of 150 mm × 150 mm, and the thickness of the back sheet, EVA, cell and glass layer were 0.295 mm, 0.5 mm, 0.2 mm and 3.2 mm respectively.

4. Results

4.1. Correlation between simulation and measurements

The qualitative temperature development over time correlated very well with the measured temperature. Two assumptions had to be made, however, for the results to match quantitative results.

- The thermocouple was placed 2 mm away from the hot spot
- 78% of the reverse power is turned into heat at the hot spot with dimension 2.5 mm × 3.7 mm. The remaining fraction of the power was evenly distributed over the cell, accounting for the normal reverse current, possible contact resistance and additional small shunts.

Table 1. Thermo-physical properties used in the simulations

Material	Temperature (°C)	Density (kg/m^3)	Thermal conductivity (Wm^{-1}K^{-1})	Specific heat capacity (Jkg^{-1}K^{-1})
Silicon	27	2330	148	705
	77	2330	119	758
	127	2330	98.9	788
	227	2330	61.9	831
Silver	-	10490	107	235
Aluminium	20	2700	225	902
	300	2700	199	1028
EVA	-	950	0.21	1370
Tedlar	-	1220	0.165	1000

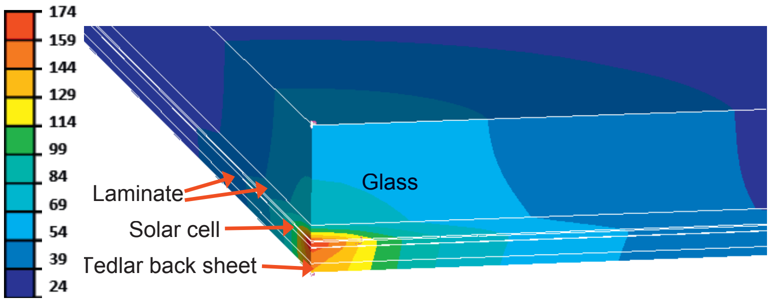


Fig. 2. Peak temperatures (in °C) on glass top surface and in cutting planes intersecting a hot spot

With these assumptions a fairly good agreement was obtained between simulated and measured temperatures as shown in Fig. 3, where the measured surface temperatures where taken as the highest temperature detected by the IR camera. However, if a comparison is made between the computed and measured surface temperatures along lines across and close to the hot spot, the agreement is better, as shown in Fig. 4. This indicates that the discrepancy for the maximum temperature may be caused by a limitation of the IR camera to resolve temperature differences within the size of a pixel (0.75 mm × 0.75 mm). Other modules were also measured and simulated, with similarly good agreement.

4.2. Relationship between hot spot size and temperature

It was found, as expected, that small hot spots develop higher temperatures than large hot spots assuming that reverse current is the same. This is due to the higher current density.

4.3. Off-set between cell temperature and module surface temperature

It is obvious that the center of the hot spot has a higher temperature than the surroundings. This means that when you observe the temperature on the front or back surface of a solar module, e.g. by IR camera, the temperature in the hot spot inside the module is higher than the measured temperature.

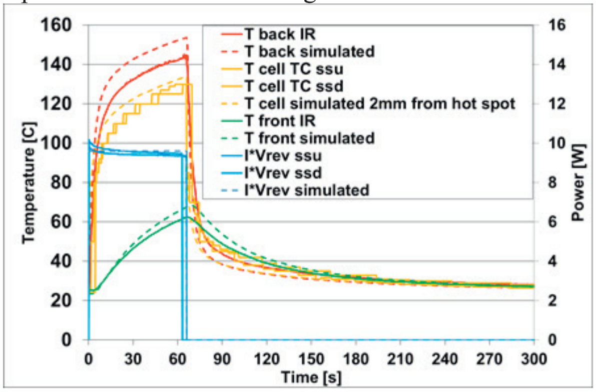


Fig. 3. Temperature development of a hot spot on a solar cell with time during and after applied reverse bias (solid lines). Simulation of a 2x2 mm hot spot placed 2 mm away from the measurement point (stapled lines). I^*V_{rev} is higher than Resistive heating power because the former includes all revers currents, while the latter only includes I_{rev} through hot spot. IR temperature was measured two times, one sunny side up (ssu) and one sunny side down (ssd).

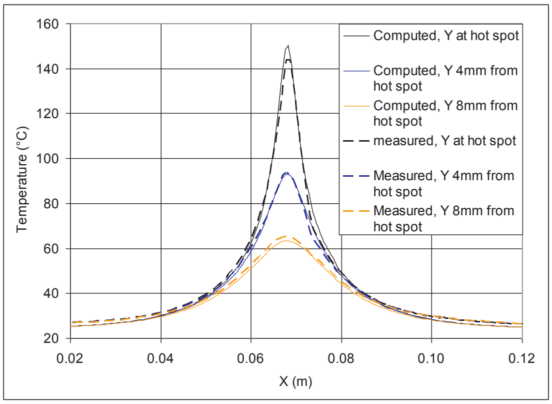


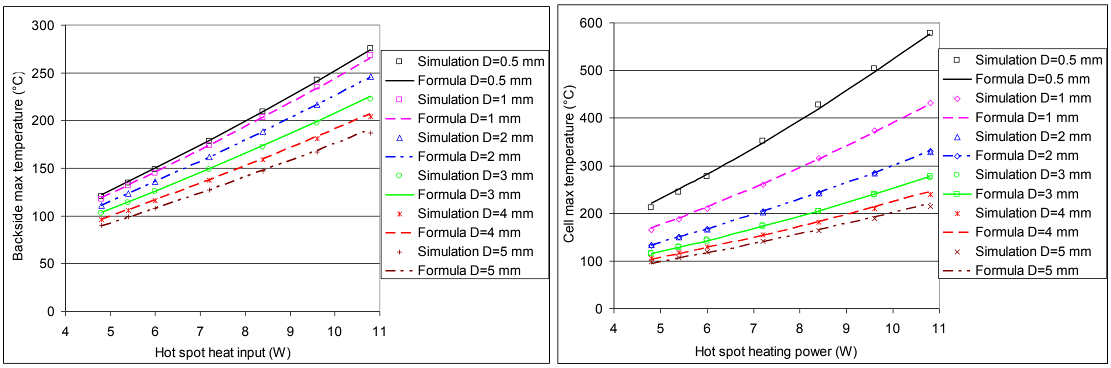
Fig. 4. Comparison of measured and computed temperature along lines across and close to hot spot at the back surface

Modeling results show that the off-set between hot spot temperature and module surface temperature depends on the size of the hot spot. I.e. if the hot spot is localized in a mm sized defect, the off-set is large. If the hot spot extends over several cm, then the surface temperature is almost the same as the hot spot temperature inside the module.

A series of simulations were run with heating power of 4.8-10.8 W (corresponds to I_{rev} 0.4 – 0.9 A) and hot spot size 0.5-5 mm. An additional heat source with 2.4 W (I_{rev} 0.2 A) was distributed over the whole cell surface. The maximum temperature after 60 s at the back side and at the hot spot inside the module is shown in Fig. 5 (a) and (b) respectively. By using regression fit on the simulation results, the back side and cell maximum temperatures (after 60 s) as function of heating power and hot spot size, were found to be well approximated by the formulas given in Eq. (1) and (2). T_C is the cell (maximum) temperature and T_B is the back side (maximum) temperature. The dimension D is the side length, in mm, of a quadratic surface hot spot with a homogeneous heat distribution. *P* is the heating power, in W, of the hot spot.

$$T_B = 24.3 + \left(\frac{310.056}{16.591 + D^{1.36}} \right) \cdot \left(P + 0.02456 \cdot P^2 \right) \tag{1}$$

$$T_C = 26 + \frac{23.544}{D^{0.455}} \left(P + 0.055 \cdot P^2 \right) \tag{2}$$



(a) (b)

Fig. 5. Simulated maximum temperature (markers) and regression fit (solid lines) for various heat inputs (corresponding to reverse currents) and hot spot size (D), (a) on back side of solar solar module directly under a hot spot, (b) at hot spot inside PV module

According to the simulation, the cell temperature is significantly higher than the hot spot temperature. By combining Eq. (1) and (2) and eliminating D, one can express the cell temperature as a function of the reverse current heating power and the back side temperature. It should therefore be possible to estimate the cell temperature from IR measurements together with measurements of voltage drop and current (for a hot spot far from the edge of the cell).

4.4. Location of hot spot

The location of the hot spot will affect the hot spot temperature. Hot spots with the same local current and same size in different locations were modeled. Fig. 6 illustrates that a hot spot near an edge reaches much higher temperatures than a hot spot in the middle. This is because the heat conductivity in the silicon solar cell is higher than in the laminate. Therefore the heat is distributed over a larger area if the hot spot is in the centre.

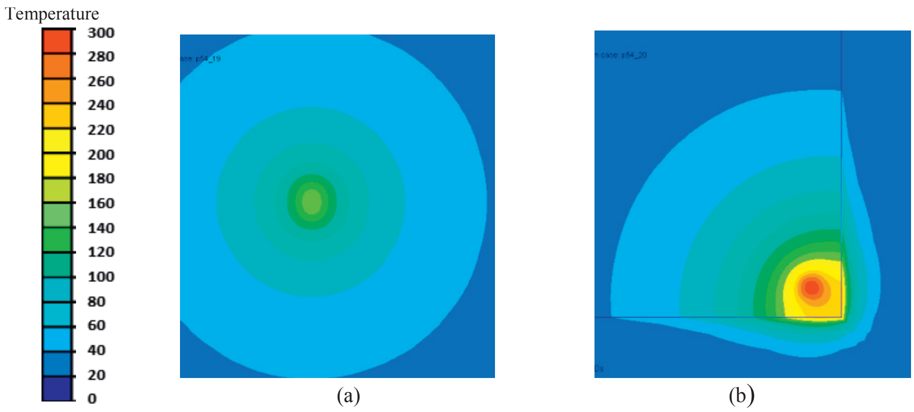


Fig. 6. Encapsulated cell temperatures after 56 s heating in (a) a hot spot near the centre of the cell, and (b) a hot spot positioned 4 mm from the edges in a corner of the cell. The plots show temperatures in squares of approximately 35 mm x 40 mm

5. Summary

Four single cell solar modules with hot spot cells were made with thermocouples embedded in order to measure hot spot temperature inside the module during reverse bias. A 3D FEM model was constructed to simulate the resulting temperatures. A good correlation between measured and simulated temperatures was achieved. The model shows how hot spot temperature (inside module) can be correlated to measured back side IR temperature using a mathematical relationship. The off-set between model and measurement depends on hot spot size and heating power. The model also shows that hot spots near the edge of a solar cell will result in higher temperature than the same hot spot in the center of the cell due to the insulating properties of the laminate.

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