

Temperature of Solder Contact in Back-Contact Si Solar Cells and Its Effect on Reliability of Modules under Localized Shading Environments

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ABSTRACT

Reliability of Si solar modules during thermal cycling and shading conditions strongly depends on the maximum temperature of the solder contact between the solar cells and the cell to cell interconnects [1]. While the maximum temperature of the solder contact is known to be critical for the lifetime of a solder joint, typical reliability tests and simulations are conducted under the assumption that the solder contact is the same temperature as the cells. This test condition and assumption is true for typical front-contact Si cells. However, the actual temperature of solder contacts is cooler for back contact Si cells. The present study investigated the temperature of solder contacts in the SunPower cell with a high resolution IR camera and found a substantially lower temperature for the solder contacts of a hot cell neighboring a normal temperature cell. The pads on the hot cell are 0.34 degrees C cooler for each additional watt dissipated by the hot cell over its neighbor. A finite element analysis was conducted to validate the experimental results and to simulate the temperature of the solder contacts in real-world conditions. The simulation provides important insight on the temperature of the solder contacts under various mismatch conditions induced by localized shading. The good agreement between the simulation and IR experiments indicates that the interconnect design in SunPower's back-contact cells reduces the temperature of the solder contacts under partial/full shading, providing an additional safety margin to the module reliability.

INTRODUCTION

Solar modules experience at least several tens of thousands of thermal cycles during their >25 years of expected lifetime in the field. Fatigue stress on solder joints is one of the failure modes caused by thermal cycles. Substantial research has been conducted to understand the failure mechanism in micro scale and kinetic behavior of the solder joint failure [2]. For instance, a modified Coffin–Manson equation has been developed and used to evaluate the thermal fatigue life of solder joints. The thermal fatigue life (i.e. number of cycles before failure) is proportional to

$$T_{MAX} - T_{MIN} - n \cdot \exp\left(\frac{1}{T_{MAX}}\right)$$

where n is ~1.8 from experiments [3]. Among the many variables, maximum temperature plays critical role in

determining the degree of thermal stress and failure mechanism.

In addition, at high temperature the joint will undergo further solid state reaction with the substrate and there will be intermetallic growth at the interface between the solder and the copper substrate [4]. The intermetallic-copper interface and the intermetallic-solder interface are more brittle than the copper-solder interface, and so the intermetallic interfaces are in danger of brittle failure if the stress is higher than the ultimate tensile strength.

As a part of reliability test, thermal cycle test per IEC61115 standard protocol is conducted on SunPower modules up to ~10,000 cycles without failure [5]. It demonstrates the robustness of the unique interconnect design. However, modules in the field could face even more aggressive thermal cycles, or temperatures over time to time. One of the concerns is shading's effect on solder joints. A shaded cell could become hotter than normal cells which may shorten the lifetime of the solder joint.

This paper reports that the temperature of solder joints in hot, reverse biased, SunPower cells are lower than the temperature of the hot cell itself, due to the high thermal conductivity of metal cell to cell interconnects and metal solder pads. This results in a joint that is robust even under shading conditions.

THEORY

The temperature of a solder joint is mainly determined by the temperature of the two neighboring cells attached to it and air convection and conduction of the cells and module materials. The situation can be simplified and pictured as shown in Figure 1, where cells made of silicon are connected by a metal interconnect and we want to estimate the temperature of the interconnect between a hot cell and a cell in normal operation. This situation can be modeled using a heat equation as

$$0 = k\nabla T - P_{gen}$$

where k is thermal conductivity of materials and P_{gen} is heat generated in the cells. We assume a hot cell is shaded so that power comes from neighboring cells and is equivalent to the string current multiplied by the corresponding voltage in reverse, that is $I_{str} \cdot V_{rev}$. A normally operating cell is heated up by the remaining solar incidence power not converted to electrical energy, that is $(1-\eta)P_{in}$, where η is power conversion efficiency and P_{in} is solar irradiance. Cooling by air convection can be expressed as

$$0 = hA\Delta T - P_{gen}$$

where h is heat transfer coefficient and A is surface area. Shortly, temperature reaches equilibrium by vertical air convection and lateral heat conduction through silicon and the metal interconnect. In result, metal interconnection will be cooler than the hot cell temperature due to thermal conduction and air convection.

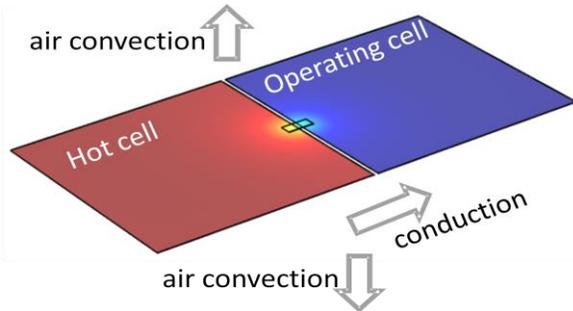


Figure 1 Model configuration of solder joint

EXPERIMENT

SunPower's all back contact cells are coated in copper on the backside, and strung together using coated copper interconnects. This excellent thermal contact between cells conducts heat away from hot cells to cooler neighboring cells. The result is lower solder joint temperatures on the hot cells. Tests in the lab with no wind and the encapsulated cells oriented vertically confirm. In Figure 2a, the cell on left has been reverse biased by running a current from the positive side through the cell via two leads attached to each side. The cell on the right is dissipating the amount of power typical to normal operation. The opposite flow of current through the cell on the left causes reverse bias breakdown, thus the cell heats up when these currents are sufficiently high. Using a Fluke Ti55FT IR camera we can measure the temperature of both cells as well as the temperature of each of the central solder joints. The camera's 20mm lens is 320x240 pixels large, which allows us to see the cell to cell interconnect when viewed through the backsheet.

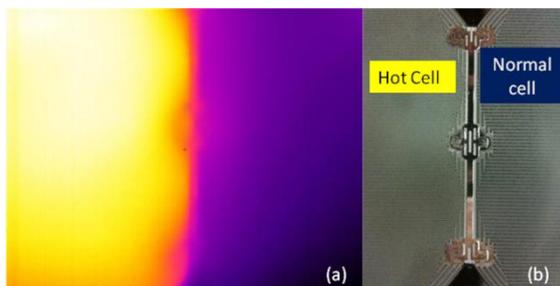


Figure 2 (a) Thermal image of a hot and a normal cell connected with metal interconnection. (b) CCD image.

Finite element method (FEM) is used to calculate temperature because heat transfer occurs in 3D [7]. The temperature profile and temperature gradient around the

metal interconnect is shown as inset in Figure 3. The temperature of the solder joint is lower than that of the hot cell because of the thermal conduction through the metal interconnects and between the surface of the metal interconnect and the air.

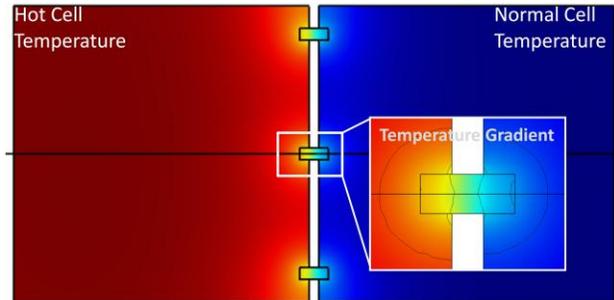


Figure 3 Simulated temperature profile of solder joint using FEM. Inset: Temperature around metal interconnect and temperature gradient shown as contour lines.

It is observed that the temperature is reduced around the solder joint to meet continuity of temperature and the metal interconnect spreads heat efficiently as shown in Figure 2a and Figure 3.

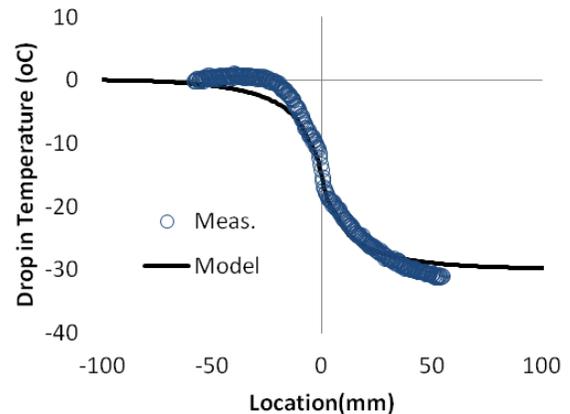


Figure 4 Temperature profile along middle of Figure 2 and Figure 3. Circles show experimental measurements and solid curve represents simulation result. Hot cell is located at $<-6\text{mm}$, interconnection at -6mm to 6mm and a normal cell is at $>6\text{mm}$.

Figure 4 shows the profile of relative change in temperature from hot cell, to interconnect and to the normal cell along a middle line in Figure 2a and Figure 3. Measurement shows good agreement with simulation results. There are discontinuities at boundaries of the interconnection (at $\pm 6\text{mm}$) observed due to changes in conductivity between silicon and metal. Also, the drop in temperature is steep along the interconnect because the heat transfer is efficient within the metal interconnect. Thus, the maximum temperature of the solder joint is

lower than that of the hot cell and the thermal fatigue life is longer than one calculated using the hot cell temperature.

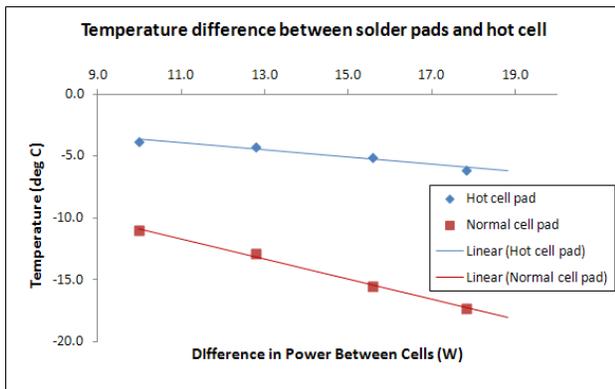


Figure 5 Temperature difference between pads and hot cell

Figure 5 shows the temperature difference between both the normal and the hot cell's central solder pad and the average temperature of the hot cell. The normal cell is dissipating the same amount of power at each data point, thus the more power put through the hot cell the larger the temperature delta between it and the solder pads. The pads on the hot cell are 0.34 degrees C cooler for each additional watt dissipated by the hot cell over its neighbor. For instance if the hot cell is dissipating 10 more watts than its neighbor its solder pad will be 3.4C cooler than the hot cell itself.

CONCLUSIONS

The reliability of solder joints depends critically on the maximum temperature reached by the joints. Standard chamber tests and reliability calculations for solar cell solder joints assume a maximum temperature for the joints based on the maximum temperature of the cell. However, we have observed that SunPower's back contact Si solar cell's solder joints are cooler than that of a hot cell when the neighboring cell is operating normally. Both experiment and FEM simulation confirm that this is due to the high thermal conductivity of the metal cell to cell interconnects and solder pads. The reduced temperature shown for solder joints results in less stress, a longer thermal fatigue life, and less growth of brittle intermetallic interface layers than if the solder joints were at the same temperature as the hot cell. Therefore, back contact Si solar cell solder joints have an additional safety margin, and are therefore more reliable when compared to front contact cells in the case of mismatched or hot cells.

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