Solar Photovoltaic Cell Thermal Measurement Issues

Bernie Siegal
Thermal Engineering Associates, Inc.
2915 Copper Road, Santa Clara, CA 95054
bsiegal@thermengr.com

Abstract

The increasing importance of Solar Photovoltaic Cells in the world energy arena has created the need for thermal measurements of these devices. While no thermal measurement standard currently exists specifically for photovoltaic cells, the semiconductor junction devices are basically diodes and there are diode thermal measurement standards and approaches that can be applied to junction photovoltaic cells. This paper provides an overview how thermal measurements can be made and address related measurement issues.

Keywords

Solar Photovoltaic Cells, SPVC, Thermal Resistance,

1. Introduction

The success of the Solar Photovoltaic Cell (SPVC) as a carbon-less source of global energy is dependent on the amount of energy that it can generate, the efficiency of incident-to-output energy conversion, the capital investment required for SPVC installations, and the continuing output energy cost. All of these dependencies are based on the SPVC junction temperature. While much of this effort is being expended to address these dependencies, most of this effort is not specifically targeted to controlling the junction temperature. Thus, not much effort is being put into either the direct measurement of junction temperature or determination of the heat flow conditions from the cells to its environment.

SPVC semiconductor technology falls into three basic groups – organic, semiconductor and thin-film material – as shown below. The organic versions do not have a typical

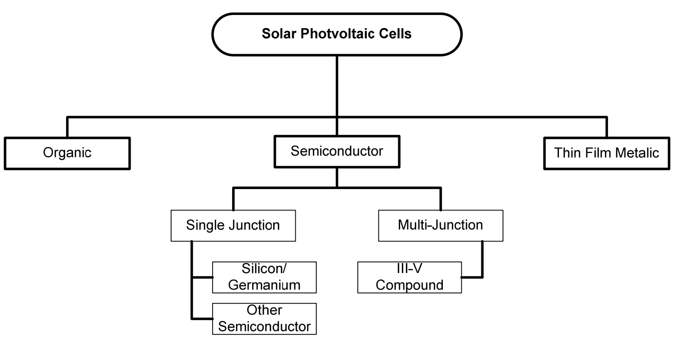

Figure 1

semiconductor junction characteristic and are supplied as a film on a substrate. The thin-film material versions usually have characteristics of a semiconductor junction, but are deposited directly onto a substrate as part of the creation of the cell. The semiconductor versions are manufactured in a manner very similar to other semiconductor devices and differ mostly based in the size of the chip. Further, these chips are then mounted using typical semiconductor packaging techniques. This paper will deal with the thermal measurement issues of the semiconductor SPVC version.

2. Junction Cells

The Single Junction SPVC devices are made from Silicon or Germanium and are usually made in the normal semiconductor manufacturing process. This results in chips – which may be as large as 200mm (8 inches) square for silicon chips and up to 100mm (4 inches) square for Germanium versions. These chips are mounted in the normal semiconductor fashion – either with eutectic, soft solder, or epoxy – to a mounting surface that acts as the "package". The equivalent circuit for a single junction SPVC is shown in Figure 2. The leakage and series resistances, junction capacitance, and ideal diode are the circuit elements usually shown for just about any diode. The conductor resistance and capacitance elements are also common to diodes in general but can usually be neglected in

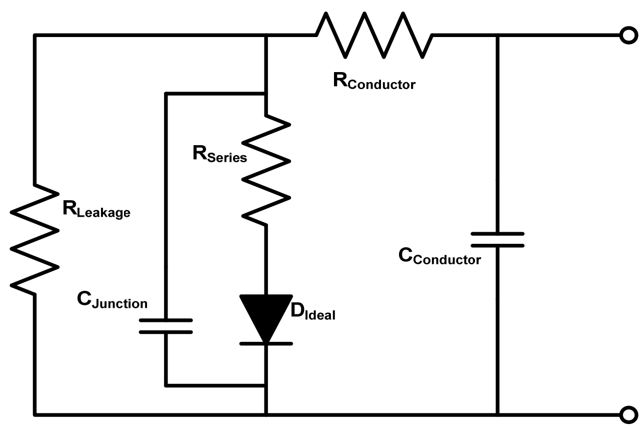

Figure 2

most cases. But these cannot be neglected in the SPVC case because the conductor is relative long, typically traveling across the whole cell, and because for the high currents involved. For reasons discussed below, both of these elements impact the measurement of SPVC thermal performance.

The Multi-Junction SPVC devices are actually three diodes in series, all implemented in one chip. The chip material is usually a III-V compound with three different sets of junction materials. Each junction is "tuned" for different solar energy wavelength range using the bandgap associated with the different material combinations. The equivalent circuit for these devices is similar to that shown in Figure 1, except that each junction has its own $R_{Leakage}$, R_{Series}, $C_{Junciton}$, and D_{Ideal}; and the three junctions are all connected in series. Because the three junctions are made form different materials, the circuit elements for each series diode will be different from the other junctions in the stack.

3. Performance Limiters

A key measure of SPVC performance is the cells ability to convert incident solar energy (i.e., light) into electrical energy. Commercially available SPVC modules currently offer conversion efficiencies in the range of 12% and 28% from single junction and multi-junction units, respectively. Some of the most important performance limiters include:

- *Semiconductor processing limitations*

The object of solar photovoltaic cells is to collect as much solar energy (i.e., light) and convert that energy into electrical energy. By definition then, SPVC are made as large as reasonably possible for both single and multi-junction cells. The large junction areas for either type make each susceptible to wafer fabrication defects. These defects may not render the cell useless but will reduce the conversion efficiency and potentially cause hot spots on the cell.

- *Conductor series resistance*

The conductor series resistance affects performance in two ways. First, a portion of the electrical energy generated by the photovoltaic diode is converted into Joule heating. This increases the junction temperature and degrades the cell output. Second, the voltage dropped across the conductor reduces the output voltage, and hence the power, available as the cell's output, thus reducing the cell conversion efficiency even further.

- *Conductor shadowing*

The natural tendency based on the conductor series resistance issues above, is to increase the size of the conductor(s) to reduce the resistance. However, any increase in the width of the conductor will cause shadowing of the cell's active area, which will in turn reduce the conversion efficiency as well. Increasing the conductor thickness does help but also introduces manufacturing issues.

- *Junction temperature*

Like all diode devices, the junction forward voltage under given current flow decreases with junction temperature. As shown in Figure 3, the SPVC has a near constant current out-

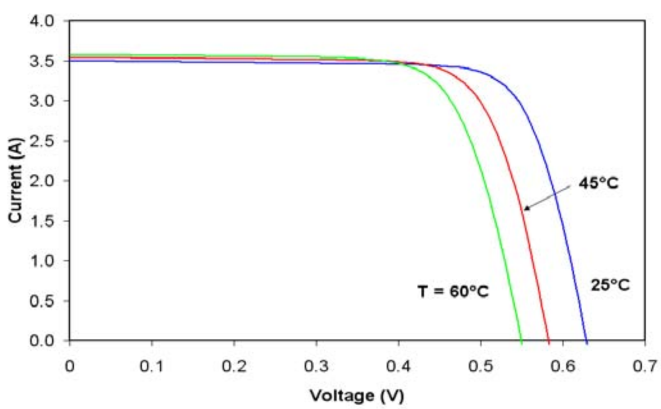

Figure 3 (from Ref. 5.)

put up to some voltage that is temperature dependent. The higher this voltage for a given current, the higher the power output of the cell. Thus, maintaining the lowest possible junction temperature maximizes the power conversion efficiency and the electrical energy output. Although this generic I-V curve is for a single- junction SPVC, the temperature dependency for a multi-junction SPVC is very similar, with the voltages about 3 times higher.

With three out of the four major performance limiters temperature limited, the importance of maintaining the lowest possible junction temperature becomes paramount.

4. Incident Power

Single Junction SPVCs typically operate in the range of 1 to 10 times the incident solar power, while multi-junction SPVC's operate with much higher concentration values – 50 to 1000 times. Thermal power is the incident power minus the electrical power conversion output. Figure 4 shows the both the incident power and the thermal power for both the single and multi-junction SPVCs operating at 12% and 28% conversion efficiencies, respectively. One sun, a term used in the

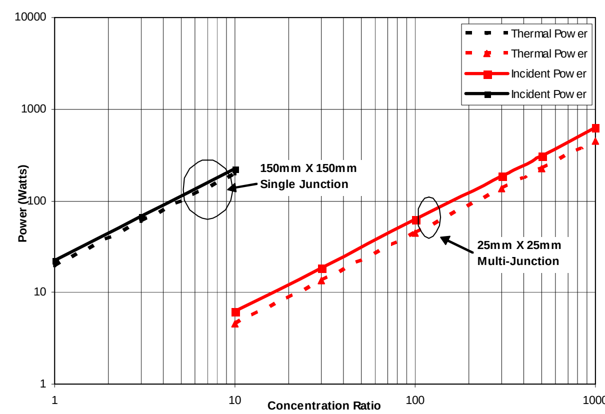

Figure 4

solar photovoltaic industry to describe the incident power, is 1,000W/m^2. A concentration ratio of 100 suns would provide a power density of 100,000W/m^2 or 10W/cm^2.

A 150mm X 150mm (6" X 6") silicon single-junction SPVC operating at one sun would have about 22.5W incident and about 19.8W in thermal power assuming 12% conversion efficiency. Similarly, a 25mm X 25mm (1' X 1") multi-junction SPVC operating at 100 suns would have about 62.5W incident and about 45W in thermal power assuming 28% conversion efficiency. The former corresponds to a thermal power density of 0.088W/cm^2 and the latter to 7.2W/cm^2. The thermal power is what the SPVC system, consisting of the cell and its mounting environment, has to properly dissipate to keep the cell junction in the desired operating range.

5. Measurement Approach

Junction solar photovoltaic cells are diodes! Thus, the same measurement method used for diodes can be applied to these devices as well, provided that the unique attributes of

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these devices are properly taken into account. The basics of diode thermal measurement are to use the diode junction for both to measure the junction temperature and to cause power dissipation in the device.

The junction temperature is measured using the well known forward voltage (V_F) – junction temperature (T_J) diode characteristic. For optimum measurement accuracy, the V_F is measured at low current values, sufficient to turn the junction on but not so high as to cause significant self-heating within the junction. These requirements usually translate into keeping the Measurement Current (I_M) to less than 1% or 2% of the current applied for heating purposes – i.e., the Heating Current (I_H). Using the electrical circuit shown in Figure 5, the I_M value is usually in the knee portion of the diode I_F-V_F curve, as shown in Figure 6. With the diode supplied with the proper I_M and subjected to an environmental temperature change, as in a temperature-controlled test chamber, the V_F will trace out a straight line characteristic as the environmental temperature changes, as shown in Figure 7.

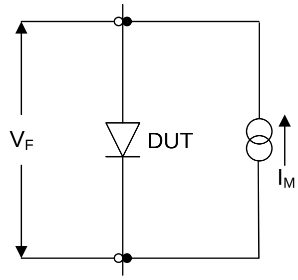

Figure 5

The reciprocal of the V_F-T_J line slope is referred to as K Factor. The K Factor (often indicated as K) is dependent on the type of semiconductor junction, the number of junctions in series, and the I_M values used in the calibration process. Typical K values for silicon single junction devices is in the 0.45ºC/mV range and for III-V compound material multi-junction devices in the range of 0.60ºC/mV. However, as shown below, the junction temperature measurement requires an accurate K value for the specific SPVC being measured at a specific value of I_M.

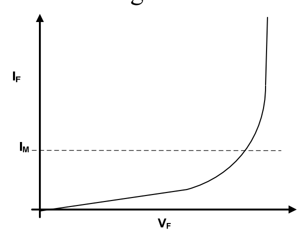

Figure 6

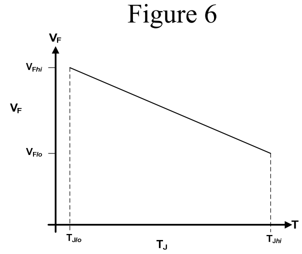

Figure 7

Once the K value is known, the basic thermal measurement circuitry (see Figure 8) and applied waveforms (see Figure 9) are used to produce the data results necessary to calculate both T_J and thermal resistance from the device junction to some reference point - Θ_{JX}. The only difference between measurements of single junction versus multi-junction SPVC is that the V_F values are typically two or three times larger for the latter as compared to the former.

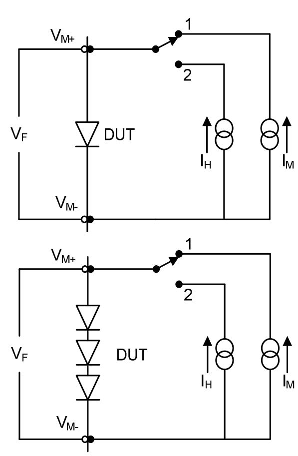

Figure 8

The circuitry and waveforms of Figures 8 and 9 below produce a value of ΔV_F – the change in V_F from the initial thermal equilibrium state (V_{Fi}) to the steady-state condition when the heat has propagated to the desired reference point (V_{Ff}). Thus,

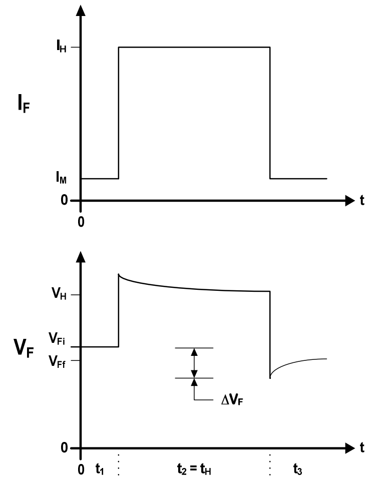

Figure 9

$$\Delta V_F = \left|V_{Fi} - V_{Ff}\right|$$

$$\Delta T_J = K\Delta V_F$$

$$T_J = T_i + \Delta T_J$$

$$\Theta_{JX} = \left[\frac{\Delta T_J}{P_H}\right] = \left[\frac{K\Delta V_F}{V_H I_H}\right]$$

T_i is the initial T_J at thermal equilibrium before the start of the measurement and the subscript X defines the reference condition in which the measurement is made.

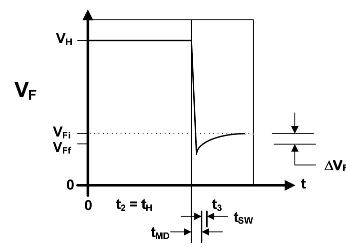

Figure 10

There are two important aspects of the measurement that must be taken into account. The first is the fact that the junction begins to cool down the instant the heating power is removed from the device. If this is not accounted for in the measurement, then resultant measurement values will not represent the peak value of T_J. Figure 10 shows in more detail the critical V_{Ff} measurement. The Measurement Delay Time (t_{MD}) must be kept as short as possible to minimize the junction cooling before the V_{Ff} measurement can be made. The Sample Window Time (t_{SW}) must also be kept as short as possible for the same reason. Further methods for obtaining the peak junction temperature are available in the literature.[3]

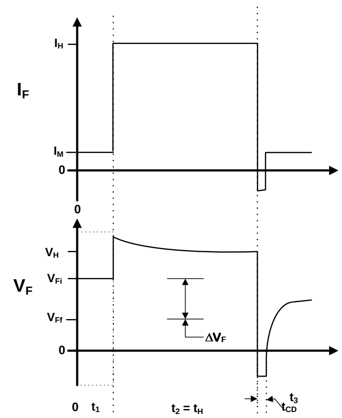

Figure 11

The second is the fact that charge stored in the SPVC junction(s) may not recombine fast enough so as to not per-

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turb the V_{Ff} measurement. The effect of the charge not recombining fast enough is that the junction appears heavily "turned-on" for some appreciable time after the heating current has been removed. This problem occurs most of the time with silicon cells but also with III-V compound cells as well. To overcome the problem, the junction must be reverse biased for a short time to draw out the excess charge and then quickly forward biased again with the measurement current to obtain the V_{FF} value. The waveforms for this measurement condition are shown in Figure 11.

6. Measurement Implementation

When making a thermal measurement, it is important to establish a reference point for the measurement. This is relatively easy to do for the multi-junction SPVC but much more difficult for the single junction SPVC. Consider the multi-junction SPVC shown in Figure 12. The devices sits on material that acts as a heat spreader and/or an interface that absorbs mechanical stresses due to mismatched coefficients of thermal expansion between the chip and the substrate. The chip through the substrate is considered a package. Junction-to-Case Thermal Resistance is then from the chip junction to the center bottom side of the substrate, and includes all the materials and interfaces within the package. A plot of the junction temperature change versus the length of time external electrical heating power is applied to the junction will produce the curve shown in Figure 13. Note that, under the proper set of circumstances, each material element in the heat flow can be identified on the curve. In this particular example, the large step between the heat spreader plateau and the substrate plateau indicates a poor attachment of the heat spreader to the substrate. The Θ_{JC} value can be calculated using the equations given above for the ΔV_F value at 4 seconds.

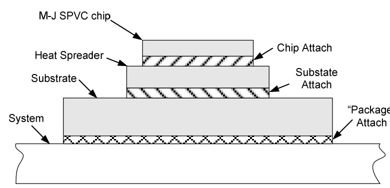

Figure 12

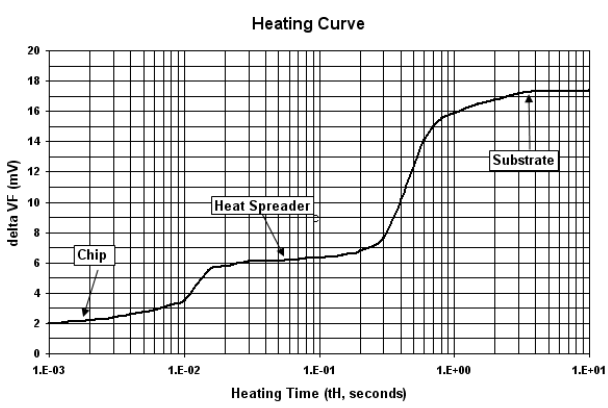

Figure 13

Setting the reference condition for Single Junction SPVC is much more difficult. Usually, the SPVC in this case is very large, 150mm by 150mm or larger, and the chip is actually a wafer. The wafer is typically the "packaged" device mounted directly on a metal plate or structure. Defining a reference point for making a Θ_{JC} becomes difficult because of the thermal mass of the plate or structure and because heat flux is traveling in multiple paths. The former makes the steady-state heating time requirements considerably longer than for the M-J SPVC case. The latter makes defining a single reference point difficult.

The Heating Power (P_H) applied to the cell during the thermal measurement must be large enough to raise the ΔV_F to a level corresponding to at least a 20ºC change at the steady- state condition.. This is necessary to insure minimal measurement noise and will improve measurement accuracy. Experimentation is usually required to find a suitable Heating Current (I_H) for a specific cell – values in the 8A to 20A are not uncommon most large high performance cells.

The ambient light surrounding the thermal measurement setup should be kept to a minimum. Otherwise, the cell becomes an electrical source energy as well as a electrical power dissipater. The incident light will have an impact both on the K Factor and on the actual power being dissipated in the cell.

7. Summary

The purpose of this paper was to provide an overview of the issues associated with the thermal performance and thermal measurement of diode-type solar photovoltaic cells. The general measurement approach follows the procedure and circuitry for standard diodes. However, the specific requirements of SPVC have been mentioned to insure better thermal measurement results.

Acknowledgments

The author wished to acknowledge Dr. Arun Raghupathy of Electronic Cooling Solutions for his assistance in the paper research and for review of the final draft. Also, acknowledgement is due to Mr. Phil Blumenfeld, EMCORE Solar Power, for his insights into conversion efficiencies of different SPVC types.

References

1. Ewa Radziemska, "Performance Analysis of a Photovoltaic-Thermal Integrated System", International Journal of Photoenergy, Volume 2009 (2009), Article ID 732093, 6 pages

2. Ricardo Borges, "Simulation of multi-junction solar cells for performance optimization", Synopsys Inc., Mountain View, CA, USA

3. Siegal, Bernie, An Introduction to Diode Thermal Measurements, Thermal Engineering Associates, Inc., Santa Clara, CA. USA

4. Military Standard 750H, Method 3101.2, Thermal Impedance (Response) Testing of Diodes, US Department of Defense

5. http://en.wikipedia.org/wiki/Solar_cell#Cell_temperature)