HEAT TRANSFER MODELING OF CONCENTRATOR MULTIJUNCTION SOLAR CELL ASSEMBLIES USING FINITE DIFFERENCE TECHNIQUES

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ABSTRACT

Information on the temperature of a packaged III-V multijunction solar cell mounted on a heat sink, operating under concentrated light is often not readily available. Availability of such information would facilitate the design of different receiver module configurations in a concentrating photovoltaic system (CPV). To this end, a heat transfer model is developed from finite difference techniques to predict the temperature from various parts of a concentrator cell assembly (CCA). The CCA consists of a solar cell mounted on a direct-bonded copper ceramic substrate with bypass diode. Temperatures of the solar cell with applied conformal coating are modeled as well as the temperature difference, ΔT, between the various layers within the CCA. Isotherm contour plots are generated for the cell under different conditions. It is found that the solar cell temperature in the CCA without conformal coating is 32 ^{o}C when illuminated at 50 W/cm^2 with the CCA back surface temperature at 25 ^{o}C. When the CCA is bonded to a surface with thin bondline of a silicone-based thermal adhesive of 2 W/m K under the same intensity and back surface temperature, the cell rises to 37.3 ^{o}C. Further, the effects of the thermal adhesive thickness as well as the adhesive thermal conductivity on the solar cell temperature are examined. An effective thermal resistance of the CCA is determined to help in the design of a CPV system. The results from the model are validated against conservation of energy where the heat input from solar radiation on the solar cell is equal to the heat rate by conduction minus the converted electrical power of the cell.

INTRODUCTION

Concentrating photovoltaics (CPV) built from GaAs-based and Ge semiconductors have been used in pilot power production programs for delivering centralized electrical energy, offering an alternate path to conventional power generation [1-3]. A CPV system using high efficiency multijunction cells can be an economically viable technology as long as high solar flux is produced for maximizing the power output. Point focus and dense array CPV systems typically employ concentration levels between 500 and 1000 suns. A challenge in generating power at these levels is devising ways to dissipate the heat in the cell with temperatures reaching well over 1200 ^{o}C at 500 suns [4]. The extent to which a CPV cell can operate at high efficiency is, in large part, dependent on how the solar cell is packaged prior to mounting on the receiver, and how well it is cooled.

Various substrate materials are available to package multijunction solar cells. Alumina (Al), aluminum nitride, beryllium oxide and insulated metal carriers have been used in solar cell surface mount techniques. But perhaps the most inexpensive material with adequate thermal performance is direct-bonded copper on alumina as shown in Fig. 1 for a Boeing Spectrolab state of the art GaInP/InGaAs/Ge triple junction Concentrator Cell Assembly (CCA). The copper is plated with Au/Ni to prevent corrosion and to promote a wet surface for solder. A bypass diode is mounted on the positive copper trace for cell protection in case of a reverse bias event. The CCA lends itself to a simple "plug-in-play" component for point focus systems; however, selection of a thermal adhesive to bond the CCA to a receiver is crucial to minimize the thermal resistance to heat transfer.

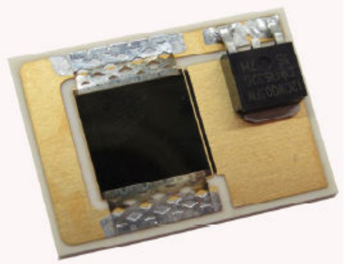

Figure 1: Example of a prototype CCA100 concentrator cell assembly using a 1x1 cm^2 cell which is available for sale at Spectrolab and designed to operate at 555 suns under the terrestrial spectrum.

Details of the thermal characteristics of each layer in the CCA under different operating conditions are currently not available. In the present study, steady-state heat transfer modeling using finite difference techniques is employed to examine the solar cell temperature under different packaging scenarios by varying the adhesive thermal conductivity and thickness. The analysis and the results are then checked against conservation of energy principles used to formulate the model.

CONCENTRATOR CELL ASSEMBLY DESIGN

Several assembly methods have been investigated at Spectrolab to build CCAs from multijunction solar cells. An assortment of substrates and die-attach bonding media such as solder, thermoset adhesives and thermal greases have been used to determine appropriate cooling solutions for the CCAs. Concentrator cell assemblies like the CCA100 consisting of a C2MJ, C3MJ or C4MJ (concentrator 2nd, 3rd or 4th generation multijunction)

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GaInP/GaInAs/Ge triple junction cell have been developed at Spectrolab. Depicted in Fig. 2 is a diagram showing some details of the cell assembly. In the past, a high optically transmissive conformal coating layer deposited on the cell surface was often requested during purchase to protect the device against moisture.

Although the coating provided protection, due to its hygroscopicity, environmental tests of continuous exposure to heat and moisture (85 °C/85%) for 2000 hours changed the coating to a yellow translucent color resulting in the absorption of incident light with an 8% decrease in the short circuit current of the solar cell. Since this film is no longer offered, its effects on the thermal properties of the CCA, however, will be briefly discussed because a non-hygroscopic protective coating is still ideal to have for the CCA operating without a secondary optical element which is attached to the cell in a CPV receiver to homogenize the incident rays.

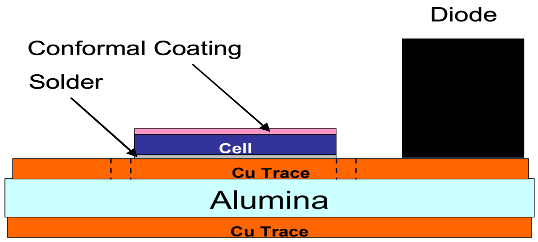

Figure 2: Side view of CCA100 showing all components and layers that make up the cell assembly with a manufacturer's silicone-based conformal coating applied to the surface of the multijunction solar cell.

High temperature Sn95Ag5 non-eutectic solder, with solidus temperature of 221 °C and liquidus temperature of 240 °C is used for die-attach. This solder complies with the RoHS international directive for banning use of hazardous substances in microelectronic and optoelectronic components [5]. Copper on both sides of the alumina strengthens the ceramic and balances the stress at the cell-solder interface during solder reflow. Attaching the CCA to a receiver module with low thermally conductive adhesives can lead to excessive heat build-up on the solar cell, decreasing its performance due to lowering of the open circuit voltage (V_{oc}). Fortunately, thermal adhesives can be screened for their effectiveness to heat transfer by modeling with finite difference techniques.

FINITE DIFFERENE TECHNIQUES

Finite difference techniques (FDT) are based on formulating a steady-state heat transfer problem using the concept of thermal resistance with a set of boundary conditions. It differs from finite element analysis (FEA) in several aspects but the main difference is that FDT is simple to implement. Greater accuracy can be obtained by decreasing the size and increasing the number of elements at the expense of longer computation time. An overview of FDT is outside the scope of this section but a brief description of the theory will be covered next. The thermal analysis of the CCA will be based on heat transfer due to conduction, convection and thermal radiation. Figure 3 illustrates 2 three-dimensional unit cells showing the thermal resistance in each direction for two nodes, with one positioned at the interface between the two unit cells and the other on the surface.

The thermal resistance due to conduction at node *m,n,l* in either the positive, *m+*, or negative, *m-*, x-direction is defined (in units of °C/W) as

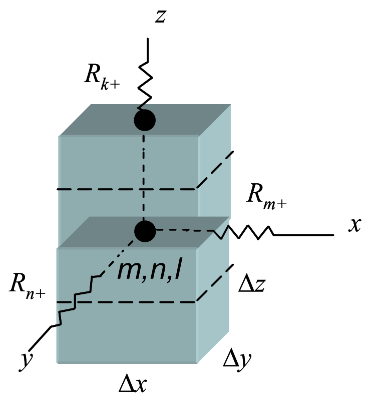

Figure 3: Volume element or unit cell illustrating thermal resistance in each direction of heat flow.

$$R_{cond\_m\pm} = \frac{\Delta x_{\pm}}{\Delta y_{\pm}(\Delta z_{\pm}/2)k} \tag{1}$$

where Δx_{m+} (Δx_{m-}) is the distance between the *m* and the *m+1 (m-1)* nodes in the positive (negative) x-direction, Δy_{n+} (Δy_{n-}) the distance between the *n* and *n+1 (n-1)* nodes in the positive (negative) y-direction, Δz_{l+} (Δz_{l-}) is the distance between the *l* and *l+1 (l-1)* nodes in the positive (negative) z-direction, and *k* is the thermal conductivity. Similarly, conduction at a node in the y- and z-directions are:

$$R_{cond\_n\pm} = \frac{\Delta y_{\pm}}{\Delta x_{\pm}(\Delta z_{\pm}/2)k}, \tag{2}$$

and

$$R_{cond\_l\pm} = \frac{\Delta z_{\pm}}{\Delta x_{\pm}\Delta y_{\pm}k}. \tag{3}$$

The thermal resistances due to convection for any surface node positioned either at the x-, y- or z plane of a volume element is:

$$R_{conv\_m\pm} = \frac{1}{\Delta y_{\pm}\Delta z_{\pm}h}, \tag{4}$$

$$R_{conv\_n\pm} = \frac{1}{\Delta x_{\pm} \Delta z_{\pm} h}, \qquad (5)$$

and

$$R_{conv\_l\pm} = \frac{1}{\Delta x_{\pm} \Delta y_{\pm} h}, \qquad (6)$$

where h is the convective coefficient.

The thermal resistance due to thermal radiation from concentrated sunlight impinging on a surface node m,n,l in the z-direction is

$$R_{therm\_l\pm} = \sigma \varepsilon A \left(T^2 + T_a^2\right)\left(T + T_a\right). \qquad (7)$$

where σ is the Stefan-Boltzmann constant, ε is emissivity of the surface, A is the area perpendicular to the emitted thermal radiation, T the temperature of the surface node and T_a is the ambient temperature. Details of the thermal resistances at corners and curved surfaces can be found elsewhere [6]. A mesh of over 400 points was constructed and the finite difference heat equations were solved simultaneously to determine the thermal characteristics of the CCA. A MathCAD program was written to model the heat transfer.

RESULTS AND DISCUSSION

CCA with and without Conformal Coating

CPV systems employ either active or passive cooling depending on their size and concentration level. Active cooling is typically applied to dense arrays consisting of a fluid flowing through a closed loop cycle at some specified, practically low temperature for concentrations higher than 50 W/cm^2 but CCAs for point focus applications may also use active cooling. In either case, using different ambient and back surface CCA temperatures in the model characteristic of various geographical locations and CPV system designs would be impractical to carry out. Instead, the isotherm contour plots shown in the following sections will be based on laboratory conditions. That is, the ambient temperature and the back copper surface of the CCA are at 25 ^{o}C. Also, the cell efficiency for all contour plots is 38%.

The cell parameters and boundary conditions defining the model are summarized in Table I. Figure 4 shows isotherm contour plots for a CCA when illuminating the cell surface with uniformly incident light and with the back copper surface of the CCA at 25 ^{o}C.

Table I: Material parameters and boundary conditions used for the results generated in Fig. 4. The concentration of incident light is 555 suns with 1 sun intensity of 901 W/m^2.

Material	Thermal Conductivity (W/m K)	Thickness (µm)
Conformal Coating	0.18	50
Solar Cell	60	200
Sn95Ag5 Solder	37.8	50
Copper	385	406 (2x 203)
Alumina (96% Al$_2$O$_3$)	25	381
Diode Package	0.1	2250
Boundary Conditions	**Value**	
Light Intensity	50 W/cm^2	
Conformal Coating Average Optical Transmittance	93%	
Convective Coefficient	10 W/m^2 K	
Ambient Temp.	25 ^{o}C	
Heat Sink Temp.	25 ^{o}C	
Cell Emissivity	0.85	

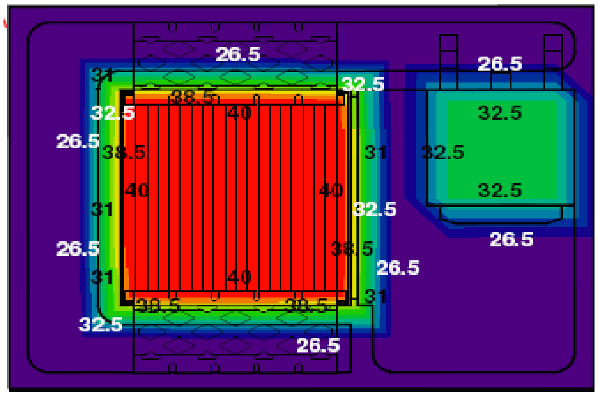

Figure 4: Isotherm contour plot of the conformal coating surface in the CCA and superimposed on a CCA drawing for a 1.11 x 1.01 cm^2 multijunction cell under uniform illumination at 555 suns (50 W/cm^2) with 1-sun intensity of 0.0901 W/cm^2. Values summarized in Table I were used to make the plot.

Several points worth mentioning can be drawn from Fig. 4. The temperature difference, ΔT_{cc}, between the surface of the conformal coating and the back copper surface of the CCA is 15 ^{o}C (40 – 25 ^{o}C) with respect to the hottest portion in the center of each plane. The thermal gradient caused by temperature differences between the center and an edge in the plane of the conformal coating is due to differences in heat dissipation from convection and conduction. Had the boundary conditions been such that the edges of the layers are adiabatic, there would be no temperature gradient in the x-y plane since there is no heat flowing beyond the edges. In this case, all heat would have been conducted perpendicular to the plane of the CCA. Spreading of heat along the front copper surface between the cell edge and diode should be present but is not obvious at this point since almost all the heat is conducted into the plane of the CCA with a miniscule amount of heat conducted laterally. Although copper on the back of the CCA is a low thermally resistive layer that provides re-enforcement against bowing during solder reflow, it helps spread heat away from the cell, specifically, when the CCA is bonded with a thermal adhesive. The surface temperature of the conformal coating is 40 ^{o}C based on the conditions in Table 1 but the temperature of solar cell (not shown in the contour plot of Fig. 4) under the coating is 31 ^{o}C. Table II illustrates the temperature difference across each layer in the CCA with and without conformal coating. The most significant ΔT is across the conformal coating and across the alumina in the CCA stack. Other ceramic substrates with higher thermal conductivity and providing lower ΔT are available but these are costly.

In Fig. 5 is the corresponding surface plot showing the magnitude of the cell temperature at different points along the normal to the surface of the CCA. The near-planarity of the top surfaces of the conformal coating and the diode indicate a uniform temperature distribution across these surfaces due to poor thermal conductivity of the two materials. Many lenses leak some light away from the cell under concentration due to chromatic aberration effects [7]. Because of this, it was assumed that the intensity of light impinging on the diode and around the solar cell is about 1 sun although it is plausible that higher intensity could be hitting the diode.

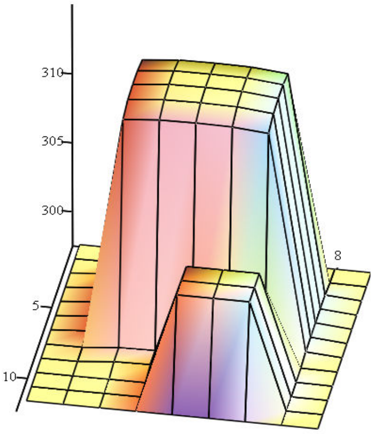

Figure 5: Surface plot of the CCA100 modeled in Fig. 4 showing the spatial differences in temperature perpendicular to the CCA surface.

Table II: Temperature difference, ΔT, across each layer in the CCA stack with and without conformal coating and uniformly illuminated with intensity of 50 W/cm^2.

Material	ΔT (^{o}C)	ΔT (^{o}C) No Conf. Coat.
Conformal Coating	8.70	
Solar Cell	1.80	2.10
Sn95Ag5 Solder	0.35	0.40
Copper	0.14	0.15
Alumina	3.90	4.20
Copper	0.14	0.15

Considering the conformal coating average optical transmittance is 93% at 50 μm thick, it should be pointed out that a noticeable ΔT exists between the conformal coating and solar cell surfaces of 8.7 ^{o}C due to the film 's low thermal conductivity. Since most silicone-based encapsulants have low thermal conductivities, it is important when applying these films to solar cells that they be both as optically transparent and as thin as possible. Otherwise a film exhibiting low light transmission can quickly degrade due to accumulated heat in the material. For example, Fig. 6 is illustrating the modeled effects of a manufacturer's silicone coating temperature on the film thickness when applied to the solar cell surface. The film temperature reaches a critical value when its thickness is approximately 238 μm (71.5% transmittance). Above this value, the film is at risk of severe degradation due to exceeding the maximum operating temperature. It is important to note that the conditions used to generate Fig. 6 are based on the values summarized in Table I. For a passively cooled CPV system, however, the receiver temperature is much higher than that assumed under laboratory conditions so the critical thickness will be lower than 238 μm.

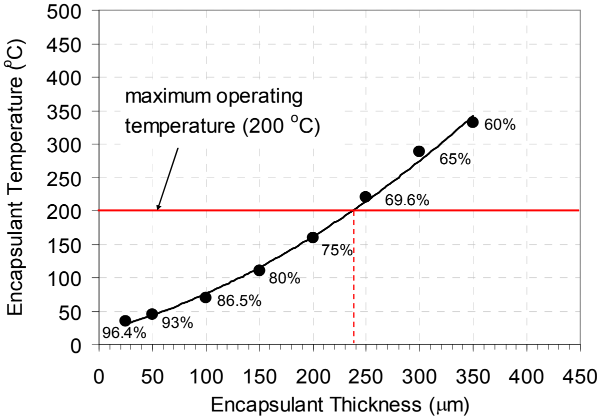

Figure 6: Dependence of the conformal coating temperature on its thickness. Its maximum operating temperature is 200 ^{o}C, and is reached at 238 μm. Each transmittance value corresponds to the thickness of the conformal coating at that point.

Effective Thermal Resistance of the CCA

It is convenient to define an effective thermal resistance of the CCA in Fig. 1 to help in the design of a CPV system. Such information would aid in establishing boundaries to common thermal management issues in CPV. An effective thermal resistance of the CCA to ambient is calculated as 0.43 ^{o}C/W for a 38% solar cell efficiency including conformal coating and using a cell area of 1.11 X 1.01 cm^2 with incident intensity of 50 W/cm^2 and $\Delta T_{cc} = 8.7$ ^{o}C.

Figure 7 shows contour plots for a cell without conformal coating illuminated at 50 W/cm^2 with temperature difference between the cell and receiver surfaces of $\Delta T_{sc} = 7$ ^{o}C, and corresponding effective thermal resistance of 0.2 ^{o}C/W for the same cell size. Spreading of heat along the front copper surface between the cell edge and diode shows that it is 2 ^{o}C cooler compared to the other cell edges.

CCA Bonded to Receiver with Thermal Adhesive

Often, finding a reliable thermal adhesive with high thermal conductivity to bond a CCA to a receiver module can be a challenge. In reality, solder with a lower melting temperature than the solder used in the die-attach of the cell is the preferred way for CCA attachment. Due to the fact that solder has a high thermal conductivity, it requires specialized handling equipment whereas silicone-based thermal adhesives are relatively simple to use but have lower thermal conductivity.

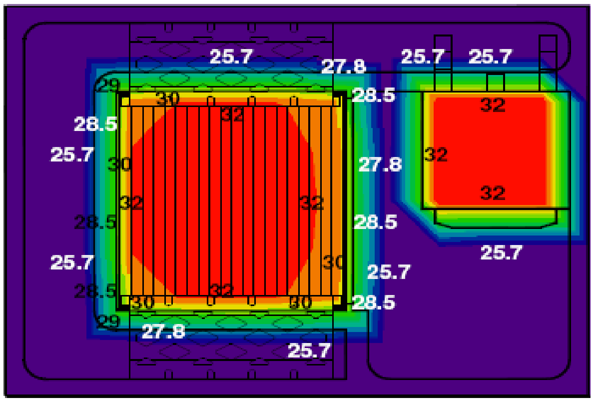

Figure 7: Isotherm contour plot for the same conditions described in the caption of Figure 4. The solar cell temperature is 32 °C.

Adding a Dow Corning (DC 1-4173) thermal adhesive layer in the model with bondline of 50 µm increases the temperature in the center of the solar cell to 37.3 °C, corresponding to a temperature difference of the adhesive, ΔT_{adh}, of 5.5 °C for a CCA without conformal coating as shown in Fig. 8. This adhesive adequately transfers heat but other bonding materials with higher thermal conductivity are necessary to increase heat dissipation. Figure 9 illustrates the solar cell temperature in the CCA without conformal coating for several thermally conductive adhesives and a solder. The conditions used to obtain the data are based on the parameters summarized in Table I for 50 and 100 µm bondlines, and Table III shows the respective ΔT's.

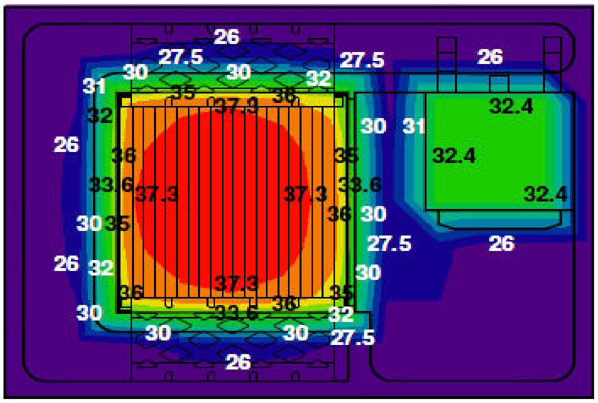

Figure 8: Isotherm contour plot of cell with no conformal coating for the same conditions described in the caption of Figure 4. The solar cell temperature is 32 °C. The adhesive bondline is 50 µm.

Greater heat removal from the CCA makes the solar cell run cooler allowing the device to operate at a higher performance level. A common misconception is using low thermally conductive adhesives with an ultra-thin bondline to minimize thermal resistance. A thin bondline can compromise the adhesion of the CCA to a receiver module since it is difficult to attain thin uniform bondlines in practice, offering no compliance to the bonded CCA, and possibly contributing to delamination.

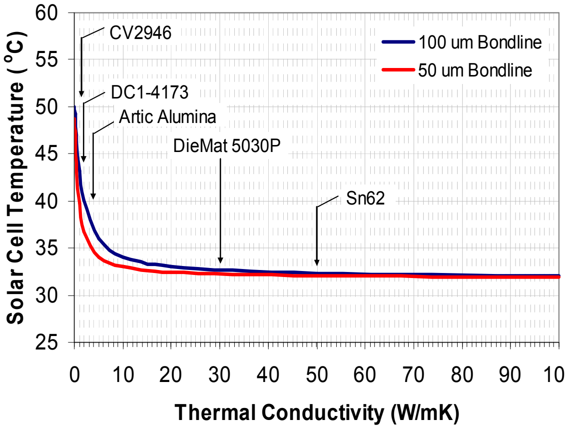

Figure 9: Modeled solar cell temperatures based on the conditions in Tables I and III for various industrial adhesives that are commercially available.

Table III: Temperature difference, ΔT, across DC1-4173 for 50 and 100 µm bondlines modeled with the conditions summarized in Table 1.

Material	ΔT (°C) @ Adhesive
50 µm DC1-4173	5.5
100 µm DC1-4173	9.6

Impact of Heat Transfer Mechanisms on the CCA and Validity of the Model

Without a thermal model, it is not intuitively clear how much heat is dissipated from conduction through the materials in the CCA stack, from static convection due to no air flow and from thermal radiation emitted from the top surface of the solar cell. Table IV illustrates the thermal mechanisms responsible for dissipation of heat and how much each one is involved in heat extraction from the solar cell. The main contribution to the removal of heat away from the solar cell modeled under laboratory conditions is approximately 99.96% due to conduction.

Table IV: Impact of CCA by heat mechanisms in percentage.

Heat Mechanism	How Much Impact
Conduction	99.96%
Convection	0.02%
Thermal Radiation	0.02%

Any time a numerical model is used to generate results, it is always a good idea to test how sound the model is. To check the validity and accuracy of the modeled temperatures, two methods are used. In the first method, the heat input to node *m,n,l* is equal to the heat output from the same node. This can be expressed as:

$$\frac{T_{m+1,n,l}}{R_{m+1,n,l}}+\frac{T_{m-1,n,l}}{R_{m-1,n,l}}+\frac{T_{m,n+1,l}}{R_{m,n+1,l}}+\frac{T_{m,n-1,l}}{R_{m,n-1,l}}+\frac{T_{m,n,l+1}}{R_{m,n,l+1}}+\frac{T_{m,n,l-1}}{R_{m,n,l-1}}=T_{m,n,l}\sum\frac{1}{R_{m\pm1,n\pm1,l\pm1}} \qquad (8)$$

Imagine each plane in the stack consisting of the conformal coating, solar cell, solder, front copper layer, ceramic substrate, back copper layer and thermal adhesive with each layer divided into an array of 25 elements, and take the center node as *m,n,l* on the solder surface. (Any node from any surface could have been chosen.) Substituting values in Eqn. (3) gives:

$$700.58\,W = 698.66\,W$$

The agreement is good.

In the second method, the heat rate, *q* (in W), flowing through each plane in the CCA is constant. The heat rate is defined from Fourier's law as:

$$q = \frac{Ak\,\Delta T}{d} = \frac{\Delta T}{R_{th}} \qquad (9)$$

where A is the area perpendicular to heat flow, *k* the thermal conductivity, *d* the thickness of a layer and ΔT is the temperature difference between the front surface and back surface of a layer. Eqn. (4) is similar to Ohm's law in that *q* is analogous to the electrical current, *I* (which is constant in a series circuit); ΔT is analogous to the voltage, *V*; and R_{th} is analogous to the electrical resistance, *R*. The sum of the heat rate through each elemental area for a given plane in the CCA gives the total heat rate for that plane. Table V shows the modeled values of *q* through each layer in the CCA stack, and the calculated values as a result of multiplying the cell area of 1.11 x 1.01 cm^2 by 50 W/cm^2 of concentrated light.

The calculated values in Table V deserve a bit more explanation. Incident light of 50 W/cm^2 on a 1.11 x 1.01 cm^2 multijunction solar cell produces 55.56 W at the conformal coating surface. From this incident power, 7% of light is blocked by the silicone encapsulant, i.e., 55.56 W x 0.07 of power is absorbed in the coating. The rest of the light (51.7 W) that exits the film is absorbed by the solar cell with 38% of it converted to electrical power. When these losses are applied to 55.56 W, 32 W of the heat rate will be transferred through each layer in the CCA underneath the solar cell. Percent difference errors between the modeled and the calculated heat rates are also shown in Table V which show good agreement, and indicates the model is sound and consistent.

Table V: Sum of the heat rates through each node for each layer in the CCA stack.

Material	Modeled q (W)	Calculated q (W)	Error (%)
Conformal Coating	3.9	3.9	0
Solar Cell	51.9	51.7	-0.4
Sn95Ag5 Solder	32.2	32.0	-0.6
Copper	32.3	32.0	-0.9
Alumina	31.9	32.0	0.3
Copper	31.9	32.0	0.3
Adhesive (50 μm thick)	32.0	32.0	0

CONCLUSIONS

Finite difference techniques were used to predict the temperature from various layers of the CCA. The temperature of the conforming coating applied to the surface of the solar cell is 40 °C while the temperature without the coating is 31 °C. As long as the coating is thin and therefore optically transparent, its surface temperature will be low enough to prevent damage by the heat from concentrated sunlight. To design a CPV system, it is helpful to know the thermal resistance of the CCA to help anticipate thermal management issues. An effective thermal resistance of the CCA with a conformal coating applied to the multijunction solar cell was calculated to be 0.43 °C/W whereas without the coating the resistance was 0.20 °C/W.

The introduction of a silicone-based thermal adhesive (DC1-4173) to mount the CCA on a receiver module and to bridge heat transfer between the back copper surface of the CCA and the surface of the receiver at 25 °C, raised the CCA cell temperature to 37.3 °C from 32 °C. Of note, the cell temperature will be higher if used in a system with passive cooling. Conservation of energy principles were used to validate the accuracy of the heat transfer rate flowing through the different layers of the CCA giving good agreement.

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