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Thermophotovoltaic Array Optimization

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A systematic approach to thermophotovoltaic (TPV) array design and fabrication was used to optimize the performance of a 192-cell TPV array. The systematic approach began with cell selection criteria that ranked cells and then matched cell characteristics to maximize power output. Following cell selection, optimization continued with an array packaging design and fabrication techniques that introduced negligible electrical interconnect resistance and minimal parasitic losses while maintaining original cell electrical performance. This paper describes the cell selection and packaging aspects of array optimization as applied to fabrication of a 192-cell array.

I. Introduction

The process of physically combining thermophotovoltaic (TPV) cells to create a power producing array can significantly degrade individual cell and, therefore, array performance. At best, array optimization will result in an array whose output power is close to that of the sum of the power of the individual cells.

Thermophotovoltaic array performance, for a given inventory of cells, can vary significantly based on the cells chosen, their location in the array, the array packaging design, and the fabrication techniques. In order to achieve optimal performance, a comprehensive approach to array design must include criteria for selecting and matching cells and a packaging design that introduces negligible electrical interconnect resistance and minimal parasitic radiant losses while maintaining cell electrical performance.

This paper presents the elements of TPV array optimization as applied to fabrication of a 192-cell array. This Small Array Test (SAT) was targeted to produce in the range of 25 - 50W using GaInAsSb quaternary cells. Although array optimization has been successfully applied to fabrication of eight-cell arrays, the SAT 192-cell array represents the largest application of this approach to date. SAT performance is compared to an eight-cell array to evaluate scale-up.

The first of two 192-cell arrays, SAT-1, was fabricated and produced 34 Watts at 11.4 V with a TPV conversion efficiency of 12.4% for a radiator temperature (T_{Rad}) of 950°C and cell temperature of 25°C. The array also produced 48 Watts for $T_{\text{Rad}} = 1000^\circ\text{C}$. A second 192-cell array, SAT-2, will be fabricated taking into account lessons learned from the SAT-1 array.

II. Cell Selection

The three parameters used to select cells for the 192-cell SAT-1 array were 1) cell performance, 2) cell electrical matching and 3) cell dimensional matching. A Figure-of-Merit was established as the criterion to rate cells and rank their performance. Electrical matching was based on a criterion developed from simulation studies coupled with

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results from previous small scale (i.e., eight-cell) test arrays. The dimensional matching criterion was based on maximizing array active area by minimizing gaps between cells.

Data used for cell selection were obtained by individually testing cells using a robotic cell characterization system (Danielson et al, 1998¹) that measures cell current-voltage (I-V) characteristics under dark, blackbody (1100°C), and high intensity flash illuminated conditions. The system also measures cell length and width, extracts ideal diode parameters, and measures open circuit voltage, short circuit current, fill factor and maximum power. The average cell in the SAT-1 array has an open circuit voltage of 0.277 V, a short circuit current of 1 A, and produces $\sim 1/4$ W (under prototypic illumination).

A. Cell Performance

Cells were ranked by performance using a Figure-of-Merit (FOM) calculated from measured cell characteristics. The FOM for a cell is defined as

$$FOM = V_{OC}(FF) \frac{I_{SC}}{1 - R} \quad (1)$$

Where: V_{OC} = Open circuit voltage from a flash test (prototypic current level) measured in volts,
 FF = Fill Factor from the flash test (prototypic current level),
 I_{SC} = Short circuit current for the blackbody test (prototypic spectrum) measured in amps, and
 R = average reflection of the active area.

The FOM is approximately proportional to the cell efficiency since the blackbody short circuit current divided by (1-R) is approximately proportional to the average internal quantum efficiency. The units of FOM are power (0.01 Watt). The FOM is intended to be a guideline that allows an inventory of cells to be ranked in order to choose the best available cells for an array. Figure 1 shows the distribution of FOM for the cells used to populate the SAT-1 cell array. Only cells with a FOM greater than 3.6 were used to construct the array, based on a trade-off between yield and efficiency.

Figure 1. Distribution of Figure-of-Merit for Cells in SAT-1 Array

B. Cell Electrical Matching

A simulation study was conducted using the TPV Simulation System (Oppenlander et al, 2004²) to quantify the effect of cell mismatch on network efficiency and to develop cell electrical matching guidelines for array assembly. As part of this study, cell selection and placement was used in the construction of several small-scale TPV arrays. Based on these studies, current matching between series connected cells was identified as a primary factor for optimal network efficiency. These results suggest a short circuit current mismatch criterion of 0.05 A or less for all cells connected in series. This criterion provided a reasonable trade-off between cell variability and network losses. Therefore, a maximum I_{SC} difference of 0.05 A between series connected cells was applied as the primary cell matching criterion. "Bins" of cells with similar currents (i.e., I_{SC} , within 0.05 A) were created. A minimum of 48

cells were required for each bin since the array design calls for two strings of 24 cells to be series connected to produce ~ 12 V.

C. Cell Dimensional Matching

Early in the course of the array design it became clear that cell dimensional variations would result in significant gaps between cells if they were chosen without regard to this characteristic. In particular, the lengthwise dimension is critical because variations will result in gaps along the length of the strings. Therefore, an additional constraint was added to the cell selection process that required cells also be within a specified lengthwise tolerance (± 0.05 mm). The TPV Simulation System and cell selection process were sufficiently flexible to accommodate this additional fabrication constraint.

III. Array Packaging

Proper cell selection must be combined with a good packaging design to retain the performance of individual cells in an array and, therefore, the array itself. This section discusses the impact of cell packaging on overall array conversion efficiency.

A. Effect of Cell Packaging Design on Array Efficiency

TPV array packaging design affects several terms in the expression for array efficiency. TPV array conversion efficiency can be approximated as the product of component performance factors (Brown et al, 2003³, Depoy et al 2004⁴):

$$\eta_{TPV} = (P_{out}/q_{total}) = \eta_{cell} * \eta_{spectral} * \eta_{mod} \quad \text{Eqn. 2}$$

where: η_{TPV} = conversion efficiency of the TPV array (P_{out}/q_{total})

P_{out} = electric power output of the TPV array

q_{total} = total heat absorbed by the array

$\eta_{spectral}$ = efficiency of front surface spectral control filters

η_{mod} = efficiency term to account for inactive array areas (e.g., grids, busbars, gaps between cells and filters, and interconnects) that represent parasitic photon absorption sites.

η_{cell} = efficiency of the TPV cell can be approximated as follows:

$$\eta_{cell} = F_o * QE_{int} * q_o(V_{oc}/E_g) * FF \quad \text{Eqn. 3}$$

F_o = penalty term to account for photons with energy in excess of the TPV cell bandgap since energy will be lost as heat.

QE_{int} = average internal quantum efficiency, i.e., the probability that an absorbed photon will result in a charge carrier that is collected at the cell junction.

$q_o(V_{oc}/E_g)$ = voltage factor which is the product of the elementary electronic charge times the fraction of the bandgap achieved by the open circuit voltage generated by the cell.

FF = fill factor, i.e., the penalty paid because no cell can at the same time produce the open circuit voltage and the short circuit current. FF is heavily dependent on the series and shunt resistances in the diode and connecting structures.

This approximation of TPV efficiency is applicable to very small-scale arrays (e.g., eight cells). Extrapolating to larger systems would require additional factors to accurately model overall conversion efficiency (Brown et al, 2003³, Baldasaro et al, 2004⁵). While this formulation is a convenient method to conceptualize TPV array behavior, it can be misleading because it appears that the separate factors are independent. In fact, this is often not the case.

Efforts to increase η_{module} by reducing the size of the electrical interconnects, for example, can increase the series resistance which would decrease the cell efficiency by reducing the fill factor.

Three terms in Eqns. 2 and 3 (i.e., V_{oc} , FF, and η_{module}) are affected by array packaging. These items are tabulated in Table I together with the array parameter and physical mechanism. V_{oc} is affected by array thermal conductivity. Poor thermal conductivity of the array will reduce the conduction of heat from the cells to the cooling water which will cause the cells to operate at a higher temperature which will decrease V_{oc} and therefore efficiency. FF is affected by electrical networking. High interconnect series resistance (R_s), low cell shunt resistance (R_{sh}), or poor cell electrical matching will reduce FF and, therefore, efficiency. Non-uniform illumination, which is primarily a function of the radiator, will also reduce FF. η_{module} is affected by array inactive area and inactive area reflectivity. η_{module} can be increased by 1) reducing interconnect area, 2) dimensionally matching cells, and 3) increasing the reflectivity of interconnects.

Table I - Effect of TPV Array Packaging on Terms in TPV Efficiency Equation

TPV EFFICIENCY EQUATION TERM	PHYSICAL MECHANISM	ARRAY PERFORMANCE PARAMETER
V_{OC}	Cell Temperature	Thermal Conductivity
FF	R_s , R_{sh} , Cell Mismatch	Electrical Networking
H_{MODULE}	Active Area, Crack Area, Reflectivity	Parasitic Photon Absorption

B. Packaging Design

1. Cell Physical Design

The cells used for the SAT-1 array are approximately 0.5 cm wide and 1 cm long. Cell gridlines are 10 μm wide and 100 μm apart and are connected to a busbar on each cell. The cell width is sized to minimize I^2R losses in the grid lines. Longer gridlines increase I^2R losses for a given gridline cross-sectional area. The 1 cm length chosen provides a convenient cell size for electrical characterization testing while also maximizing cell yield from the 2 inch diameter cell wafer.

2. Improved Array Design

The η_{module} term of Eqn. 2 is a strong function of active area fraction and the reflectivity of inactive area. A new thermophotovoltaic packaging design was used to fabricate the SAT-1 array. This new design increased array active area from $\sim 75\%$ to $\sim 85\%$ while decreasing the thickness of optical epoxy required between the optical filter and the TPV cell. This design also met other performance goals including low thermal resistance and low above bandgap parasitic absorption. In addition, the design is manufacturable and scalable.

The old packaging design used a TPV cell with a large busbar (1 mm wide or $\sim 10\%$ of the cell area) down the center of the cell to collect electric current from the gridlines (Figure 2a). The new packaging design uses an edge busbar (Figure 2b) that 1) significantly increases active area by reducing the width of the busbar on a 0.5 cm x 1 cm cell from 0.5 mm to 0.15 mm and 2) allows the cells to be interconnected using a low profile (i.e., 12.5 μm thick) interconnect ribbon, thereby reducing the thickness of optical epoxy between the cell and filter.

The new packaging design uses the cell gridlines rather than a separate busbar to carry electric current to the edge of the cell. This is accomplished by splitting the cell down the length of the busbar and having the current pass through the width rather than the length of the busbar (Figure 2b). This increased the effective cross sectional area of the cell busbar by a factor of 10 as shown in Figure 3. The interconnect was changed from essentially a point connection to a line connection. The edge busbar can be as narrow as is physically practical without affecting performance. The edge busbar was chosen to be 0.15 mm wide because making it much narrower would seriously increase the difficulty of interconnecting cells (Figure 4).

Cells are series connected using a gold ribbon connecting the top busbar of one cell to the back of the adjacent cell (Figure 4). The ribbon is sized to carry electric current without introducing significant series resistance. Because the new design interconnects cells along their length, the thickness of this interconnect ribbon can be as small as practical (i.e., 12.5 μm) yet still provide more cross sectional area than the much thicker interconnect used with the centerline busbar design (i.e., 62.5 μm). The low profile interconnect ribbon provides the benefit of reducing the thickness of optical epoxy required to bond the optical filter to the TPV cell. Thick optical epoxy is undesirable since it is a poor thermal conductor and is also a parasitic photon absorber.

Figure 4 depicts the packaging fabrication sequence used for the 192-cell array. Interconnects are attached to the cell using either microwelding or thermasonic bonding techniques (Step 1). The cells are then soldered to a Cu/AlN/Cu substrate (Step 2). The substrates are then attached to a cooling plate (Step 3, not shown), and optical filters attached to the front of the cells using optical adhesive (Step 4, not shown).

Figure 2. Electric Flowpath in TPV Cell for (a) Center Busbar Design, (b) Edge Busbar Design

Figure 3. Cell Busbar Cross-Sectional (a) Center Busbar Design, (b) Edge Busbar Design

Step 1. Attach Gold Ribbon Interconnect to Cell

- Direct Bond
 - Microweld, or
 - Thermasonic

Step 2. Attach Cell to Substrate

- Solder

Step 3. Attach Substrate to Cooling Plate

Step 4. Attach Front Surface Filters

Figure 4. Typical Fabrication Sequence for the 192-cell SAT-1 Array

C. 192-cell SAT-1 Array Fabrication

The 192-cell array consists of eight strings, each with 24 series connected cells. However, two strings are connected in series as shown in Figure 5 in order to produce ~ 12 Volts. The SAT-1 was intended to provide a way to evaluate array optimization for a 192-cell array. Previous optimizations were conducted for eight-cell arrays. One of those arrays is referred to as Module No. 47 and will serve as a basis of comparison for larger array fabrication. Figure 5 shows the electrical configuration, including interconnection resistances (R_i) for the 192-cell array.

Figure 5 - Electrical Network for the SAT-1 192-Cell Array

The building block for the SAT array is an eight cell substring as shown in Figure 6. Three substrings were joined to form a 24-cell string. The cooling plate was populated with eight of these 24-cell strings as shown in Figure 7. Pairs of 24-cell strings were then joined in series to produce the required voltage. The location of the two 24-cell strings were chosen in such a way as to minimize the impact of the expected radiator non-uniform illumination. Figure 8 is a picture of the SAT-1 array with spectral filters (Depoy et al, 2004⁴) applied to the front surface of the cells.

Figure 6. Typical Eight Cell Substring of the SAT-1 Cell Array

Figure 7. SAT-1 TPV Array Showing 192 cells, 1 cm x 0.5 cm each

Figure 8. SAT-1 Array with Front Surface Filters

D. Array Testing

Two types of tests were performed on the SAT-1 array during fabrication. The first type, flash lamp I-V, is performed by illuminating the array with a high intensity light and recording array I-V data. This testing is done in atmosphere with the cells near room temperature. Since there is no active cooling of the cells for this test, cells do

heat up which will add measurement uncertainty to test results. In addition, the flash lamp illumination area is approximately equal to the array area which is expected to result in non-uniform illumination of the array (i.e., the perimeter cells will be at a lower illumination than center cells). The second test is a very controlled, accurate test called an in-cavity test and is conducted under prototypical TPV system conditions. In-cavity testing is accomplished with the array under vacuum and actively cooled to maintain cell temperature at $\sim 25^{\circ}\text{C}$. A SiC radiator is heated to $\sim 950^{\circ}\text{C}$ to illuminate the array. I-V data and efficiency data are obtained during in-cavity testing.

Flash lamp I-V data is obtained several times during array fabrication (Table II). It is obtained with the bare cells in the array, after the array is anti-reflection (AR) coated, and again after the filters are attached to the array. In-cavity testing is limited to the final array configuration (i.e., cells with AR coating and filters installed).

Table II - Array Testing Summary

Test Type	Array Condition		
	Bare Cells	Cells with AR Coating	Cells with AR Coating and Filters
Flash Lamp I-V	X	X	X
In-Cavity I-V and Efficiency			X

IV. Test Results

Table III provides V_{oc} , I_{sc} , FF and P_{Max} for the SAT-1 array measured with a flash lamp at each step of the fabrication process as well as the values predicted by the TPV Simulator. The table illustrates excellent agreement between the simulated and measured results for the array V_{oc} and P_{Max} with bare cells. Measured I_{sc} and FF are close but $\sim 3\%$ lower than predicted. This discrepancy is close to the repeatability error of the test and is likely due, at least partially, to non-uniform illumination of the SAT-1 array during the flash lamp test. While the simulation is based on individual cell data for cells that are uniformly illuminated, the measured values are from a flash lamp test of the entire array with the limitations discussed above. With a previously fabricated smaller eight cell test array, Module No. 47, FF was unchanged between predicted and measured with filters (Oppenlander et al, 2004⁴). The discrepancy in I_{sc} and FF could also be due to an increase in series resistance (R_s) from poor interconnects, reduced shunt resistance (R_{sh}) due to cell damage during array fabrication, or cell mismatch. Further review of the data is expected to identify whether R_s or R_{sh} changed.

Following AR coating, the array FF remained essentially unchanged, while I_{sc} increased by $\sim 20\%$, V_{oc} by $\sim 2\%$, and P_{Max} by $\sim 24\%$. The direction of these changes was expected; however, the magnitude of the change in I_{sc} and P_{Max} was expected to be greater (i.e., 35 – 40%). Single cells that were AR coated at the same time as the SAT-1 array showed the expected 35 – 40% increase, therefore, the smaller increase in the array values may be due to non-uniform illumination from the light source during post AR testing or possibly non-uniform AR coating of the array, or it may be due to electrical networking affects. However, the discrepancy may also be due to variation in flash lamp intensity. The pre and post AR coating flash intensities were at different levels and, therefore, would produce different spectrums which could affect I_{sc} . Additional testing is being conducted to assess the uniformity of the AR coating process on an array sized object and the affect of different flash intensities.

Based on previous experience, following filter installation, all values (i.e., V_{oc} , I_{sc} , FF and P_{Max}) are expected to return close to their bare cell values due to partial reflectivity of the filter in the above-bandgap range. However, only V_{oc} returned to the bare cell value, while I_{sc} decreased by $\sim 5\%$, FF decreased $\sim 8\%$ and P_{Max} decreased $\sim 13\%$. This decrease was not seen with the eight cell test array and was not expected. The decrease may be due to different filter transmission from the individual filters, to air bubbles/gaps between the filter and cells, or to non-uniform light source. Additionally, the change may be due to an increase in R_s from interconnects that were pulled loose by optical epoxy contraction during curing. Further review of the data will be conducted and is expected to identify whether R_s changed. In addition, ultrasonic testing will be conducted to assess the existence of air bubbles/gaps between the filter and cells.

Table III - Simulated and Measured Flash I-V Results for the SAT-1 192-Cell Array

Condition	Open Circuit Voltage (Volts)	Short Circuit Current (Amps)	Fill Factor (%)	Maximum Power (Watts)
Simulation	13.24	3.96	68.4	35.83
Measured (Bare Cells)	13.21	4.04	66.3	35.19
Measured (AR Coated Cells)	13.46	4.84	66.8	43.47
Measured (Filtered Cells)	13.25	3.73	63.0	31.16

Table IV provides measured in-cavity test results for the 192-cell SAT-1 array as compared to the eight-cell Module No. 47 array and a computer model of the SAT-1 array. The computer model uses the ideal diode equation with average cell electrical characteristics (R_s , R_{sh} and ideality). The measured performance of SAT-1 was less than that predicted by modeling. This can be attributed to modeling assumptions and simplifications. The model excludes networking issues including current mismatching from non-uniform illumination, variations in anti-reflection coatings, and temperature variation across the cold plate and radiator. The model does not account for cavity photonics and neglects the effects of heat absorption in the frame and support structures.

Efficiency, power density, and FF for SAT-1 are all less than they would be for a linear scale-up of the Module No. 47 eight cell array. This can be caused by factors mentioned above. Additionally, non-uniform illumination due to geometric effects and radiator temperature gradients will reduce FF and, therefore, efficiency. Additional testing is planned to assess the uniformity of the in-cavity radiator. The lower power density and FF for the SAT-1 array is also believed to be due to a larger than prototypical gap between the radiator and the cells. Redesigned hardware is being fabricated that will produce a prototypical gap for future testing.

Table IV – Comparison of In-Cavity Test⁽¹⁾ Results for SAT-1 and Module No. 47 to SAT-1 Model

	Module No. 47 ⁽²⁾	SAT-1 Array ⁽³⁾ (modeled)	SAT-1 Array (measured)
Efficiency	19.5%	14.3%	12.4%
Power Density	0.551 W/cm ²	0.473 W/cm ²	0.331 W/cm ²
Heat Absorbed	2.83 W/cm ²	3.30 W/cm ²	2.66 W/cm ²
FF	69.3%	67.5%	60.8%
I_{sc}/area	2.54 A/cm ²	2.25 A/cm ²	1.87 A/cm ²
V_{OC}/diode	0.313 V	0.268 V	0.292V
Total Power	2.3 W	47 W	34.3 W

Notes: 1) Under Vacuum, Radiator Temp =950°C, Cell Temperature = 25°C.

2) 8 cell array, 4.1 cm² diode area (Each cell ~ 0.5 cm²)

3) 192-cell array, 103.75 cm² cell area

V. Conclusions

A systematic approach to TPV array design and fabrication was used to construct a 192-cell array. The first of two 192-cell arrays, SAT-1, was built and produced 34 Watts at 11.4 Volts with a TPV conversion efficiency of 12.4% for a radiator temperature (T_{Rad}) of 950°C and cell temperature of 25°C. The array also produced 48 Watts for $T_{\text{Rad}} = 1000^\circ\text{C}$.

Based on review of initial testing, this scale-up from eight to 192-cells was a success. Cell selection and matching produced an array that had performance nearly comparable to that of the sum of the cells in the array. Array design and fabrication successfully scaled from an eight cell array to a 192-cell array. The array design and fabrication maintained the performance of the cells through most of the array fabrication. However, a decrease in array performance was noted following attachment of front surface optical filters. The cause of this decrease is still being evaluated. Results of this evaluation will be used to guide any necessary changes in fabrication of the second 192-cell array.

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