Development of a novel 16-cell densely packed 500x CPV assembly on insulated metal substrate

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Abstract: A novel densely packed assembly for concentrating photovoltaics (CPV) has been designed and is presented in this paper. It has been developed to fit a 125x primary and a 4x secondary reflective optics and can allocate 16 multi-junction cells. The expected power output is about 300W, with a short-circuit current of 6.6A. Based on a preliminary thermal simulation, an aluminum-based Insulated Metal Substrate has been used as baseplate: this technology is commonly exploited for Light Emitting Diodes applications, due to its optimal thermal management. The original outline of the conductive copper layer has been developed to minimize the Joule losses, by reducing the number of interconnections between the cells in series. Slightly oversized Schottky diodes have been applied for bypassing purposes and the whole design fits the IPC-2221 requirements. The assembly will be used to run experimental tests to optimize the design of a novel actively cooled 144-cell receiver for High CPV applications. The same setup will be then used to study the reliability of integrated micro/nano cooling systems developed on the back of the aluminum layer.

Keywords: CPV, assembly, IMS.

1. INTRODUCTION

A Printed Circuit Boards (PCB) is a laminated material bonded with heat cured flame retardant epoxy resin and clad on either one or both sides with copper. PCBs are widely used in electronics, because of their high flexibility and relatively low costs. Usually the laminated material is a low thermal conductive fiberglass, but it can be replaced with a metal baseplate, in which case the thermal management of the system can be enhanced and the board is referred to as an Insulated Metal Substrate (IMS). IMSs have been developed to be used in LED (Light Emitting Diodes) applications, and they show a heat transfer management similar to that needed by Concentrating Photovoltaic (CPV) technologies [1]. For this reason, CPV assembly manufacturers interest in IMS technology is increasing [1–4]. Mabille et al. [2] have demonstrated that, when exposed to accelerated aging tests, IM substrates behave similarly to the Direct Bonded Copper (DBC)substrates, the most widely used in CPV applications.

This paper presents a 16-cell assembly on an IMS board for 500x CPV applications. The novel structure of the copper layer has been designed to minimize the electrical resistivity and to make the prototype easily scalable.

2. PRELIMINARY THERMAL SIMULATION

2.1 The design

A preliminary thermal simulation has been run to demonstrate the feasibility of an IMS based high CPV receiver. A production of 20 to 25 W of waste heat was estimated for any 500x CPV cell. Many commercial companies use DBC substrates to remove the waste heat from CPV cells. A preliminary three-dimensional simulation was carried out in COMSOL Multiphysics 4.3 to predict the thermal behavior of three different backplates: a PCB, a DBC substrate and an IMS. A 20x20mm single cell assembly has been designed using the software (Figure 3 and Figure 4).
The geometry of the conductive copper layer and the position of the cell refer to the design presented in this paper. The thicknesses of the lower layers have been established on the basis of commercially available products (Table VII).

**Figure 3** Geometry of the single cell assembly developed in COMSOL (dimensions in mm)

**Figure 4** Side view of layers of the assembly

The thicknesses of the different layers in the three developed assemblies are shown in Table VII.

<table>
<thead>
<tr>
<th>Layers</th>
<th>PCB</th>
<th>DBC</th>
<th>IMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnectors</td>
<td>0.025mm silver</td>
<td>0.025mm silver</td>
<td>0.025mm silver</td>
</tr>
<tr>
<td>Cell</td>
<td>0.190mm germanium</td>
<td>0.190mm germanium</td>
<td>0.190mm germanium</td>
</tr>
<tr>
<td>Conductive layer</td>
<td>0.035mm copper</td>
<td>0.30mm copper</td>
<td>0.035mm copper</td>
</tr>
<tr>
<td>Dielectric</td>
<td>4.5um marble resin</td>
<td>0.63mm AlN</td>
<td>4.5um marble resin</td>
</tr>
<tr>
<td>Heat Sink</td>
<td>1.6mm FR-4 fiberglass</td>
<td>0.30 mm copper</td>
<td>1.6mm aluminum</td>
</tr>
</tbody>
</table>

**2.2 The materials**

The COMSOL’s “Heat transfer” module, used in this simulation, requires three properties for each material: the thermal conductivity, the density, and the heat capacity at constant pressure. Where possible, the COMSOL values have been used, such as for copper and aluminum. In other cases, the values have been set according to external references.
Table VIII Proprieties of materials (Materials marked with * are COMSOL built-in materials)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W/Km]</th>
<th>Density [kg/m$^3$]</th>
<th>Heat Capacity [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Nitride</td>
<td>285</td>
<td>3260</td>
<td>740</td>
</tr>
<tr>
<td>Aluminum*</td>
<td>160</td>
<td>2700</td>
<td>900</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>8700</td>
<td>385</td>
</tr>
<tr>
<td>FR-4</td>
<td>1.7</td>
<td>1850</td>
<td>600</td>
</tr>
<tr>
<td>Germanium*</td>
<td>60</td>
<td>5323</td>
<td>320</td>
</tr>
<tr>
<td>Silver</td>
<td>430</td>
<td>10490</td>
<td>235</td>
</tr>
</tbody>
</table>

In the PBC and IMS simulation, the dielectric was considered as a thin thermally resistive layer: for this reason, only the thickness and the heat transfer coefficient were required. According to the supplier datasheet, the marble resin has a thickness of 0.0045 mm and a thermal conductivity of 3 W/mK. The cell was modeled only with the germanium substrate. The interconnectors are supposed to be of pure silver.

2.3 The parameters
Consider the 500x concentration, a cell efficiency of 40% and an optical efficiency of 90%, an overall heat production of 22.95 W per cell was predicted. Therefore, the cell was set as heat source to model the conversion of part of the sunlight into waste heat. An active cooling design was then introduced on the back of the heat sink. A heat transfer coefficient of 10$^4$ W/m$^2$K was considered - the minimum value for a densely-packed system over 150 suns [5].

2.4 Results
The model ran in a stationary mode. As expected, the PCB based assembly is the worst performing (Figure 5). In the setup studied, it reached a maximum temperature of 146.6 C, more than 100 degrees higher than recorded for the DBC and IMS assemblies (Figure 6 and Figure 7 respectively), and 60 degrees higher than the conventional CPV operating temperature [6]. This eliminates PCB as a reliable backplate for high CPV applications, even in presence of a high performance active cooling.

The performances of the DBC and of the IMS assemblies were similar and acceptable: the temperature for both is lower than 40°C. This preliminary simulation showed that an aluminum based IMS can be used in the present 500x CPV application instead of a more expensive DBC as backplate.

![Figure 5: Temperature distribution in the PCB based assembly](image-url)
3. MATERIALS AND METHODS

A 10x10cm IMS board has been developed to allocate 16 cells and to fit the 4x secondary concentrators designed by the Indian Institute of Technology Madras (Figure 8). A set of 1cm$^2$ sized GaInP/GaAs/Ge cells with an efficiency up to 37.2% at 500x provided by Azurspace has been used in this application. The whole setup has a peak power of about 300 We, with a short-circuit current of 6.587A and an open-circuit voltage of 50.72V. The IMS has a 1.6mm thick aluminum baseplate and a 35µm-thick copper layer, bonded together with a 4.5 µm thick marble resin. The board has been developed using a chemical etching process. All the electrical components (i.e. the cells, the diodes, the interconnectors) have been soldered using a Sn96.5/Ag3.5 solder paste.
One bypass diode per cell has been applied, in order to maximize the performances of the system [7]. The Vishay V10P45S Schottky Rectifier has been used in this assembly as it appears a compromise between dimensions and performance. Schottky diodes are usually employed as bypass devices for multijunction cells: they have a lower forward voltage drop and, therefore, lower losses and lower temperature while in bypass operation than the one of the silicon diodes. The diodes have been slightly oversized to reduce the increase in reverse voltage and to reduce the risk of breakage: diodes can easily break when working closer to the maximum rating. Taking into account the cell’s short circuit current (6.587A), a 10A Schottky diode grants an acceptable safety factor of 1.52. The diodes applied in the systems are surface-mount diodes (SMD), as they are cheaper and easier to replace than discrete ones [8].

There are two main processes for producing the printed circuit boards: chemical etching or mechanical milling. Although it has a lower repeatability than mechanical milling, chemical etching grants higher precision. The etching comprises different steps. Firstly, the laminate is covered with a mask and then exposed for a few minutes under a high resolution UV lamp. Immediately after the exposure, the laminate is immersed in a developer which removes the photosensitive resin previously exposed. The board is then moved into an etching tank in which a pre-heated etchant solution removes the copper no longer protected by the resin. Finally, the laminate is re-exposed under the UV lamp and then immersed into the developer solution: the remaining resin is then removed and the circuit is complete.

4. DESIGN

The original design of the copper pattern has no intermediate interconnections between the negative pads of adjacent cells (Figure 9): one shape of copper is used for both purposes. This allows lowering the electrical resistivity of the copper and, thus, the electrical losses. The design has been drawn up accordingly to the IPC-2221 Generic Standards on Printed Board Design [9]. A copper width of at least 3.0 mm is used where a current of 6.6 A flows (a), while at least 0.7 mm where only half of the current flows (b).
With a 35µm-thick copper layer, this geometry is fine when the assembly is working at temperatures at least 40°C higher than the ambient temperature (Table IX). Considering an ambient temperature of 25°C, the system can work at 65°C or over, which is the range in which the concentrating photovoltaic cells usually operate [6]. However, with a 70µm-thick copper layer, the system is able to work at any temperature higher than 35°C. These dimensions have been calculated taking into account both adequate 10%-tolerances and the effect of the thermal expansion at the cell’s maximum operating temperature (150°C). A gap of 1 mm has been left between the negative and the positive pad of each cell and between each row: this distance is above the minimum value recommended by the standards (0.13 mm).

Table IX Minimum 35um-thick copper width [mm] required by the IPC-2221 Standards [10], for ambient temperature of 25°C.

<table>
<thead>
<tr>
<th>Copper temperature [°C]</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current [A]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>658</td>
<td>2.</td>
<td>2.</td>
<td>1.</td>
<td>1.</td>
<td>1.</td>
<td>1.</td>
<td>1.</td>
</tr>
<tr>
<td>3.29</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
<td>0.</td>
</tr>
</tbody>
</table>

The geometry has been specifically developed to fit the original 500x optics designed in IITM. This system is made of a 125x primary reflecting concentrators and of an array of 4x secondary ones. All the assembly components, such as the cell and the diodes, have been placed within a space of 4cm², to make the densely packed structure possible. A second feature of the design is the scalability: it can be converted to allocate a lower or a higher number of cells (Figure 10 and Figure 11 respectively).
The structure is characterized by high modularity. Each row consists of four series-connected cells. The copper layers at the end of each line can easily be connected to the first cell of the following line. The user can then decide to connect the rows either in series or in parallel, to enhance the voltage or the current intensity respectively.

5. THERMAL AND ELECTRICAL VALIDATION

To test the thermal reliability of the design, a full scale simulation was developed and run. The complete setup was implemented in COMSOL: 16 cells were placed on the 10x10cm aluminum substrate. Concentrator Standards Operating Conditions were considered: a direct normal irradiance of 900W/m² and an ambient temperature of 20°C. Under these conditions, a 40%-efficiency cell generates a waste heat of 24.3W. On the reverse of the IMS a 10W/m²K cooling system was introduced. The simulation demonstrated the thermal response of the assembly and the ability to manage heat removal even in a densely packed system (Figure 12 and Figure 13). The final maximum temperature was similar to that reached in a single cell simulation: 32.30°C.

Figure 12 Thermal simulation of a densely packed assembly

Figure 13 Isothermal contours in the assembly

To complete the investigation, the effect of the Joule heating was also studied. A current of 6.857A was forced through the cells and each conductive shape. This resulted in a small, negligible increase in the maximum temperature (Figure 14), proving the acceptable thermal behavior of the design and of the IMS board.
6. CONCLUSIONS

A new assembly for 500x CPV applications has been developed on an insulated metal substrate. This assembly represents a novelty for the unique low-resistance design of the conductive layers. The reliability of IMS based assembly has been demonstrated using a software simulation. The simulation shows that IMS thermal behavior is similar to the more expensive DBC in terms of heat removal. The geometry of all the components has been designed to fit the requirements of the Standards and to grant acceptable thermal management and electrical performances to the assembly. The shape of the electrically conductive layer has been designed to minimize the electrical resistances, by reducing the number of interconnections and to assure easy scalability to the structure. The use of slightly oversized Schottky diodes ensures good performances and an affordable safety factor. The electrical and thermal behaviors have been proven using a 3D multiphysics simulation: the densely packed structure can be cooled using an active cooling system, even accounting for the Joule heating.

The use of an IMS as baseplate will help in experimentally understanding the potential and the weaknesses of this kind of substrates in CPV applications. The results obtained by the experimental tests run on this board will be used to design a new actively cooled 144-cell assembly and to test the employability of aluminum micro-fin arrays as a passive cooling system for CPV.

7. ACKNOWLEDGMENTS

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8. REFERENCES