Thermal and Mechanical Analysis of 3D Glass Packaging for Automotive Cameras

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***Abstract* -- This paper describes advances in integrated ultra-thin wireless power module components for Internet of Things (IoT) and wireless sensor applications. A typical wireless module integrates both an inductive link for wireless power transfer, and supercapacitor as a storage element. The performance of the inductive link is enhanced with innovative high-permeability and low-loss magnetic films for improved inductive coupling between the receiver and the transmitter. Up to 4X enhancement in power transfer efficiency is demonstrated with the innovative magnetic films. Energy storage is achieved through a thinfilm micro fabricated supercapacitor layer with interdigitated graphene-based planar electrodes and solid-state electrolytes for easier integration. The component properties demonstrated through this work are projected to achieve high power levels with ultra-thin form-factors.**

Keywords: 3D glass package, thermal modeling, mechanical modeling, camera packaging

I. INTRODUCTION

Collision avoidance systems in cars are becoming more commonplace with brands such as BMW, Ford, GM, Nissan, Subaru, Tesla, and Toyota all offering collision avoidance packages. However, for a shorter reaction time, higher data rates and higher processing rates are required. Integrating image sensing and image processing components into a single 3D stacked package can lead to high data rates but integration of these components can lead to other problems with high temperatures and induced stresses.

Glass substrates can mitigate all of these problems. A 100μm thick layer of glass acting as the substrate in a 3D stacked camera system, between imaging and processing elements enables short interconnect lengths and the high resistivity of glass leads to low signal loss at high frequency. Embedded thermal vias can transport heat away from critical components to lower operating temperature and improve reliability. The glass can also be selected in order to match the coefficient of thermal expansion of camera components in order to minimize thermally induced stresses. In automotive applications the conditions are harsh, in particular the maximum and minimum ambient temperature for the system can vary from -20°C to 65°C in addition to vibration and shock due to acceleration.

The industry standard packaging technique for cameras is based on ceramic packages [2][3] in which the camera package is assembled using standard wire-bond or flip-chip technology. They provide high reliability, but at a higher cost. Competing camera packages generally have no integration between processing and sensing elements and have thermal resistance of 5 K/W [9]. In addition, ceramic packages are bulkier than this glass substrate alternative solution in which the image sensing die can be bonded directly to the glass minimizing the overall system dimensions.

This paper summarizes modeling of the thermal design and our initial studies on stress expected in such a package which uses a glass substrate for automotive cameras. Table 1 lists the objectives for this camera in terms of thermal management as well as volume minimization.

II. THERMAL MODELING

This section focusses on the thermal modeling of the glass substrate with an image processor and image sensor integrated. The lumped model in Figure 1 shows how heat is generated at the processor as well as the image sensor and then conducts to nearby surfaces and eventually is lost to the

Table 1 Table of Objectives for Thermal and Mechanical Design

Objectives	Targets	Prior Art	Challenges	Tasks
Thermal management	20°C-+65°C environment	Heatsinks, forced versus natural convection, thermal wires	1.Limited volume 2.Additional power requirements of fans 3.Low thermal conductivity of glass	Thermal modeling to determine maximum heat dissipation
Minimize camera volume	3x3x1cm^3 (mono)	Ceramic camera packages, plastic packaging	1.Maximizing surface area while maintaining structural integrity	System design: Active cooling; Passive cooling; Surface area design;

surrounding environment via convection. The increased power dissipation generating heat in a small area makes a challenge to efficiently remove the heat and limit the maximum temperature. In order to maximize data transfer rates while simultaneously minimizing noise, it is advantageous to place sensing and processing components together as close as possible. High temperatures however can cause components to malfunction or can introduce significant error. Thermal vias can be embedded in the proposed glass substrate in order to facilitate conduction away from critical components whilst directing heat to heat sinks where it can be transferred through convection to the surrounding air. Modeling was performed in COMSOL Multiphysics 5.2 with several configurations depicting either horizontal or vertical orientation to change the convection boundary conditions.

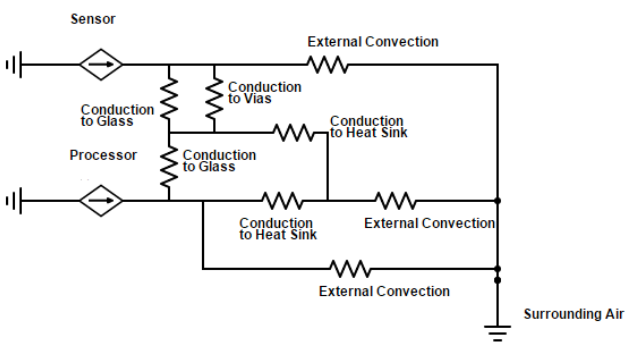

Figure 1 Thermal Circuit Model of Lumped System

A number of simplifying assumptions were taken while making the model, including steady-state conditions, constant properties, and the ambient temperature was taken to be constant at 65°C a maximum value for inside the vehicle. The model contained external convection on all external surfaces as well as conduction between all connected surfaces and heat transfer due to radiation was assumed to be negligible. Radiation heat transfer can be neglected because the heat flux due to radiation was only approximately 6% of the total heat flux. Contact resistances were estimated using "thermally resistive layers." Furthermore, solder bumps, rather than be modeled as flattened spheres or as a conical shape, were modeled as cylinders. A "finer" mesh was used composed of 365,493 elements, and properties are listed in Table 2. While the large number of thermal vias makes the model computationally difficult and time-consuming, a potential solution has been suggested by Tain et al. by replacing the glass substrate embedded with vias with a single material with an anisotropic thermal conductivity [1]. The thermal conductivity for a volume with thermal vias travelling along the z direction can be estimated with: $k_{xy} = 1.02758(k_{substrate} * \frac{P-L}{P} + \frac{k_{substrate} * k_{via} * L}{k_{metal} * (P-L) + k_{substrate} * L})$ with $L = \frac{\sqrt{\pi} * D_{via}}{2}$ and $k_z = 0.98766\left(k_{substrate}\left(1 - \frac{\pi}{4}\left(\frac{D_{via}}{P}\right)^2\right) + k_{via}\frac{\pi}{4}\left(\frac{D_{via}}{P}\right)^2\right)$ where D_{via} is the diameter of the vias and P is the distance between vias.

Table 2 Table of Materials Used in Thermal Model

Material	Heat Capacity at Constant Pressure [J/(kg*K)]	Thermal Conductivity [W/(m*K)]
SnAg3.5 Solder	220	86.6
Copper	385	400
Silicon	700	130
Glass	480	1.1

A cross section of the basic overall design is shown in Figure 2. Initial designs attached a 30mm x 30mm x 1mm copper heat sink on the bottom of the glass substrate around the processor. While this design showed promise as shown in Figure 3, the temperature exceeded 135°C as shown in figure 4. This proved the fins would be necessary for proper thermal management and thus 15 fins measuring 30mm x 0.75mm x 5mm were affixed to the bottom of the heat sink. There is no contact resistance between the fins and the heat sink. The results of this model are illustrated in Figure 5.

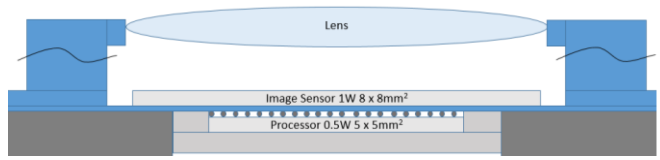

Figure 2 Cross Section of Design

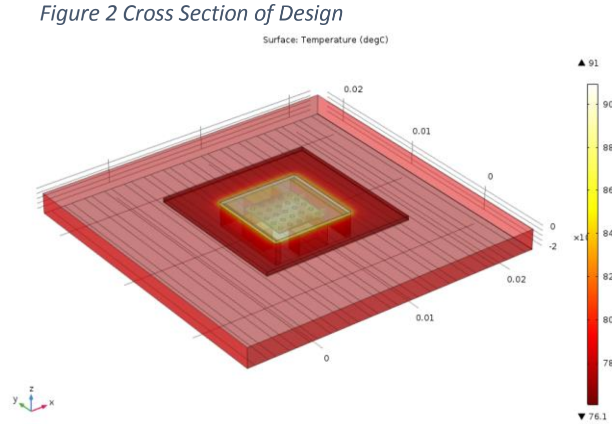

Figure 3 Results of Initial Model Tested at 20°C Ambient Temperature with Maximum Temperature of 91°C

The model was used to explore the effect of thermal contact resistance between the heat sink and the glass. Contact resistances are selected between values of $R_{th}=0.05\frac{m^2K}{W}$ and $R_{th}=0.51\frac{m^2K}{W}$ which were selected as conservative estimates in regards to thermal contact resistances between other materials. The results indicate the importance of minimizing thermal contact resistance. These results are summarized in Figure 6. This Figure shows that high contact resistances can cause maximum temperatures to vary approximately 35°C over the range of thermal contact resistances used.

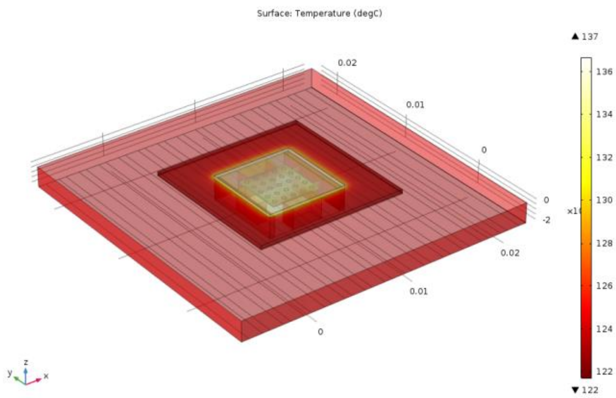

Figure 4 Results of Initial Model Tested at 65°C Ambient Temperature with Maximum Temperature of 137°C

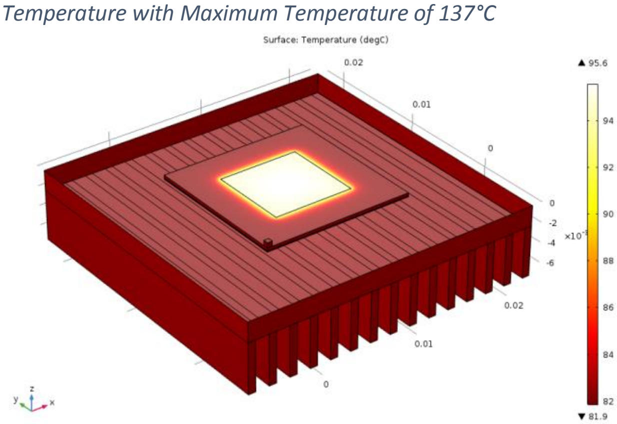

Figure 5 Result of Design with Array of Fins on Heat Sink to Facilitate Convection at 65°C Ambient Temperature with Maximum Temperature of 95.6°C

Overall, these simulations show that with the addition of a 956.25 mm3 of copper heat sink arranged into a structure with 1327.5 mm2 surface area is able to keep the glass substrate temperature below 105°C. The maximum temperature was 95.6°C and the minimum temperature was 81.9°C. The average temperature was 83.4°C.

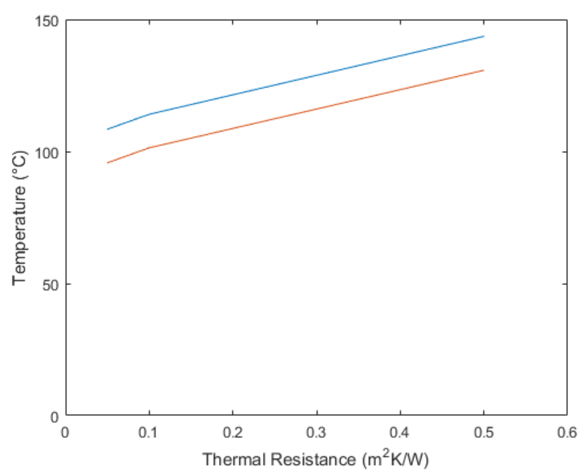

Figure 6 Compilation of Several Models Run with Varying Thermal Contact Resistance with Contact Area Between Substrate and Sensor Equal to 56mm² and Area Between Substrate and Solder Balls Connecting Processor 3.1mm²

III. Stress Modeling

This section focuses on the stress modeling of the glass substrate. When multiple materials are bonded together with varying coefficients of thermal expansion, they expand at different rates as the temperature rises or falls leading to bending depending on the stiffness of the material. Excessive stresses can lead to either mechanical failure or reduced longevity. Furthermore, if the substrate expands at different rate than the image sensor, the sensor will bend, shifting the focal point of the sensor, and impacting image quality. All of this necessitates a thorough investigation of resultant stresses and deformations.

Table 3 Table of Materials and Properties Relevant to Thermal Stress Modeling

Material	Young's Modulus [GPa]	Coefficient of Thermal Expansion [10^{-6} K^{-1}]
SnAg3.5 Solder	51	21
Silicon	170	2.6
Asahi/ Corning Glass	73	3.71
Copper	110	17

The strain from these mismatched coefficients of thermal expansion can be estimated in the 1 dimensional case by $\epsilon = \Delta T * \Delta\alpha$ where the stress can be estimated by relating it to the strain: $\sigma = \epsilon E$. The coefficient of thermal expansion of compound materials is found by taking a weighted average of the constituent materials: $\alpha = \frac{\sum L_i \alpha_i}{\sum L_i}$. This thermal expansion in each discretized length in a surface has to reconcile with inherent stiffness of the material and thermal expansions of neighboring discretized lengths. For 3 dimensional problems, the real behavior is much more complicated and involves the use of stress tensors. For continuous 3 dimensional volumes, this process of balancing thermal expansion with internal stresses is best handled by discretization within a finite element analysis program rather than attempts at an analytical solution. The COMSOL heat transfer model used in section II, was used to estimate the temperatures of the components during operation, and the stresses and deformations based upon the initial conditions of uniform room temperature distribution in the structure. The relevant material properties are shown in table 3 and were assumed to be independent of temperature. Furthermore, materials were assumed to be linearly elastic.

The coefficient of thermal expansion for glass can vary over a great range depending on the composition and type of glass with Corning glass 0080 having a coefficient of thermal expansion of $9.35 * 10^{-6} K^{-1}$ over the range of 0-300K whereas Corning glass 7913 has a coefficient of thermal expansion of $0.75 * 10^{-6} K^{-1}$ over the same temperature range. By choosing a more suitable glass and then by properly adding copper vias to raise the average coefficient of thermal expansion, the thermal stresses induced from high temperatures can be managed to extend the lifetime of the device. The results of the thermal simulation provide a temperature distribution for the solid mechanics to solve for the resulting stresses and deformations based on the assumption that the initial stresses were zero at bonding temperature. This model used the same mesh as the thermal model, except that the interface contact resistance layer was assumed to be infinitely thin, so the interfaces are joined, and has 2914741 degrees of freedom.

Figure 7 shows the resultant von Mises stress for this simulation with a maximum stress of 133 MPa. The minimum stress from this simulation was 2.57kPa. The average von Mises stress over the entire model was 2.25 MPa while averaged only over the glass substrate, the average von Mises stress was 11.37 MPa. Figure 8 shows the vertical deformation ranging up to 23.5µm.

Figure 7 von Mises Stresses from Solid Mechanics Stress Simulation for Temperature Distribution Shown in Figure 5

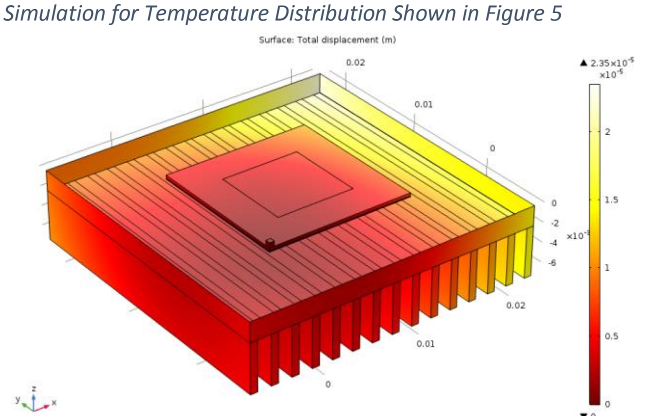

Figure 8 Deformations from Solid Mechanics Stress Simulation for 65°C Ambient Temperature

IV. Bonding Modeling

For packaging applications, it is also necessary to model this glass substrate bonded with several other materials using polymers. The three polymers tested were ABF GX92, ABF GY11, and Photo BCB. These bonding models were run under the assumption of a uniform temperature distribution both during assembly and during steady state operation with steady state operating temperature equal to 105°C. It was further assumed that the stresses within the model were zero at the time of bonding. The model consisted of three layers: a base layer, that measured 5mm by 5mm with a thickness of 300µm; a cavity layer, also measuring 5mm by 5mm with an opening of 4mm by 4mm with a thickness of 300µm; and a lid, 5mm by 5mm with a thickness of 100µm. Between each layer of glass was a 15µm layer of polymer as described in Table 4.

Figures 9 and 10 show the layout of the stresses and deformations incurred while running these simulations. Figure 9 shows the deformation measured along the diagonal along the top surface. Figure 10 shows that while there are small local minimums at the corners of the glass, the majority of the stress is carried by the polymer. Figure 11 shows the stresses as a function of height, going through the center of the bonding structure. The von Mises stresses as well as the deflections are summarized in Table 5.

Table 4 Table of Polymer Properties

Material	Young's Modulus [GPa]	Coefficient of Thermal Expansion [10^{-6} K^{-1}]	Thermal Conductivity [W/(mK)]
ABF GX92	5	39	0.15
ABF GY11	8.9	26	0.15
Photo BCB	2.9	42	0.29

Table 5 Summary of von Mises Stresses and Deformations from Polymer Bonding Simulations

Polymer	Minimum Stress [kPa]	Maximum Stress [MPa]	Average Stress [MPa]	Maximum Deflection [µm]
ABF GX92	82	39	9.6	2.45
ABF GY11	93	43	11	2.51
Photo BCB	53	25	6.4	2.32

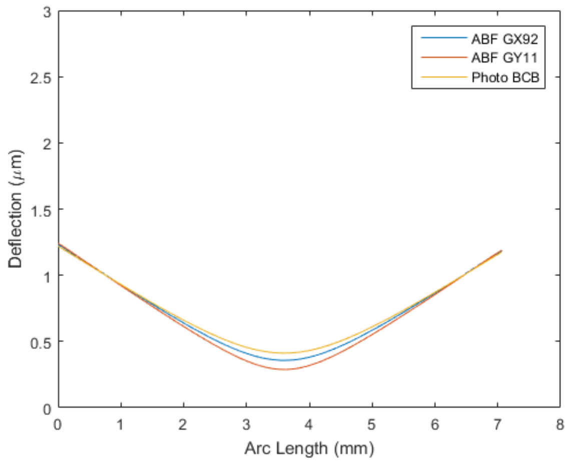

Figure 9 Solid Mechanics Deformation Simulation with 3 Layers of Glass with Middle Cavity Layer and Polymer Between Each Layer as Function of Distance along the Diagonal on the Top Surface with Bonding Temperature of 105°C

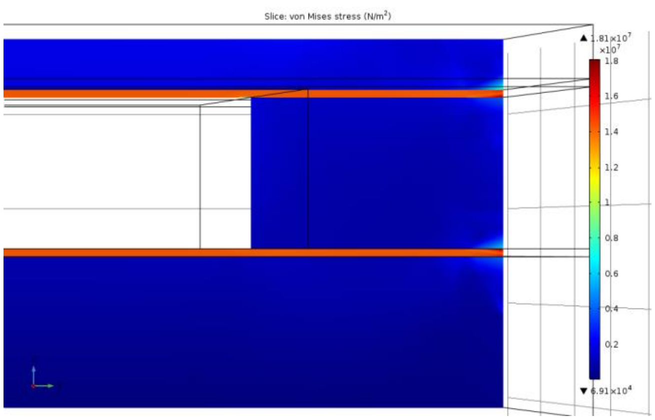

Figure 10 von Mises Stresses for a Partial Slice of Photo BCB Polymer Stress Simulation at Room Temperature After Bonding at 105°C

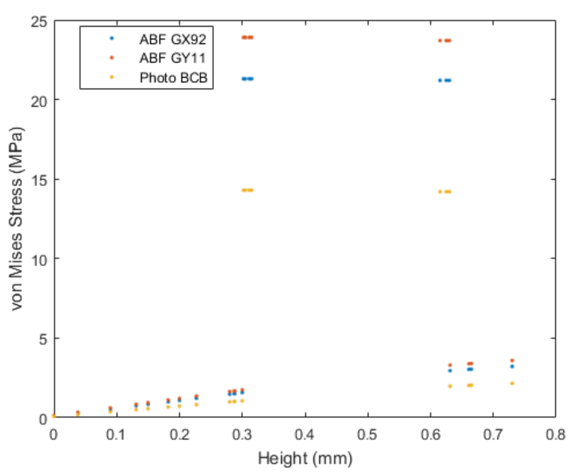

Figure 11 Stress in the Midpoint of the Bonding Structure as a function of Height at Room Temperature After Bonding at 105°C

V. Conclusions

Thermal modeling simulations showed that a glass substrate with sufficient heat sinks and with the addition of thermal vias to the substrate to facilitate conduction, in our model, a typical operating heat load of 1.5W can be transferred away from critical components and provide low enough operating temperature below 105°C. Stress modeling using this resultant temperature distribution shows a maximum stress in the model of 65.6MPa. Lastly several generic glass substrate cavity structures to examine bonding at 105°C and the resulting stresses at room temperature producing a maximum of 1.92μm deflection and 32.9MPa stress in the polymer layer.

With some simulation models having almost 3,000,000 degrees of freedom, these simulations can be very computationally intensive and certain assumptions had to be made to ensure that results could be obtained within a feasible amount of time given that all this work was done on a desktop computer as opposed to a more optimized system which could handle the higher memory uses (18GB was highest recorded memory usage, taking 1 hour, 45 minutes, and 38 seconds to compute). With more computational power, the thermally resistive layers could be replaced with actual more accurate geometry as in a realistic setting these layers would most likely be composed of some thermal paste which would allow the heat sink/ substrate interface to slip which would provide for more realistic solid mechanics results

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