Thermal Characterization for a Modular 3-D Multichip Module

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Abstract

NASA Goddard Space Flight Center has designed a high-density modular 3-D multichip module (MCM) for future spaceflight use. This MCM features a complete modular structure, i.e., each stack can be removed from the package without damaging the structure. The interconnection to the PCB is through the Column Grid Array (CGA) technology. Because of its high-density nature, large power dissipation from multiple layers of circuitry is anticipated and CVD diamond films are used in the assembly for heat conduction enhancement. Since each stacked layer dissipates certain amount of heat, designing effective heat conduction paths through each stack and balancing the heat dissipation within each stack for optimal thermal performance become a challenging task. To effectively remove the dissipated heat from the package, extensive thermal analysis has been performed with finite element methods. Through these analyses, we are able to improve the thermal design and increase the total wattage of the package for maximum electrical performance.

This paper provides details on the design-oriented thermal analysis and performance enhancement. It also addresses issues relating to contact thermal resistance between the diamond film and the metallic heat conduction paths.

1. Introduction

A modular high-density 3-D stacked MCM was designed to accommodate large data handling needs for the future spaceflight applications. Since ASICs (application specific integrated circuits) are frequently used in these applications, the MCM was designed in a modular fashion so that each of the 3-D stacks can be manually removed from the MCM without causing damages. Thus adding or removing ASICs has become a relatively easy procedure. Fig. 1 shows the overall structure of this modular MCM. The MCM has an overall dimension of 2.6×2.6×0.8 in^3 (excluding the CGA interconnects).

Typical ASICs to be mounted onto the MCM dissipate large amount of heat. To effectively remove the dissipated heat, the MCM uses CVD thin-film diamond in three stacked layers where active power dissipating elements are mounted. A heat conduction path was also designed using copper to provide effective heat removal directly from the CVD diamond layers to the PWB heat sink. Careful consideration was given to the contact thermal resistance issue between the copper conduction path and the stacked layers.

A target total wattage of this MCM, based on the power dissipation estimates of particular chips to be mounted, is 20 W. This total power needs to be distributed onto three chip-mounting layers with the CVD diamond films so that the maximum chip temperature will be minimized. This was achieved based on the results of a series of finite element analysis (FEA) simulating heat conduction process inside the MCM.

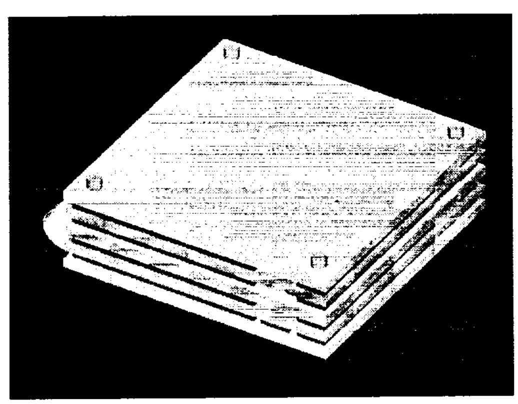

Fig. 1 Overall Structure of the Modular MCM

2. Description of the 3-D Stacked MCM

Fig. 2 shows an exploded view of the MCM. The first stacked layer (lid) is an alumina substrate with a 90 mil thickness. The backside of this substrate is deposited with a 350 μm thick metallized CVD diamond film for chip attachment. The third stacked layer (slice) is an identical substrate except both sides are deposited with the same metallized CVD diamond. The diamond hosts the metallization pattern on its surface. There are 400 bond pads on the backside of the lid, 100 to each edge. Two hundred of these are routed to the connector lands and the remaining are left available for probe testing purposes. The slice has the same metallization pattern on both sides while the lid has the metallization only on one side. There is no electrical connection through the slice, only across the surfaces. This allows the MCM layers to act as boards in a backplane. In this MCM, the connector assembly (layers 2 and 4) provides that backplane.

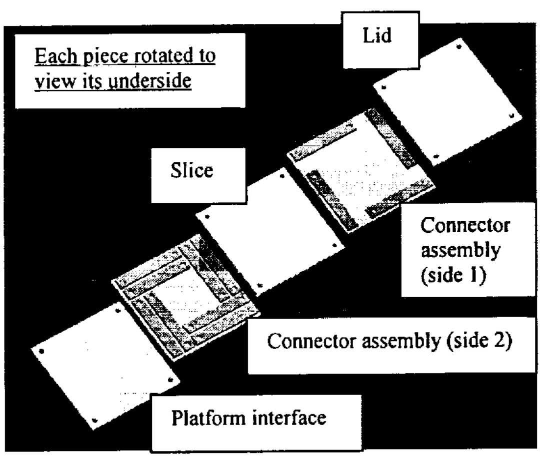

Fig. 2 Exploded View of the MCM

The backside of the lid and the both sides of the slice communicate to the rest of the MCM through the connector assembly (Fig. 3). This assembly consists of two double sided rigid PWBs connected to each other with flexible circuitry, each populated with compliant connectors. The compliant connector pins (springs) align with the lands on the metallization layers and each connector has 50 pins. When the connectors are pressed against the metallization, the connection with the backplane, or rigid-flex connector assembly, is completed. Circuit paths go across through the rigid PWBs and flexible circuitry. The flexible circuit extends from the middle of the double-sided rigid board out one side and then ends, embedded, the side of the other rigid board. The connector assembly provides for four internal surfaces in the MCM. Three of these surfaces contain electrical elements (dice) and one provides an interface path for the circuit card or platform onto which the stacks are mounted. Three of the rigid members contain four connectors each. The fourth one contains eight connectors which corresponds to the unique configuration of the platform interface that does not contain electronic dice. The connector assembly reflects the unique, application specific attributes of the electrical system design.

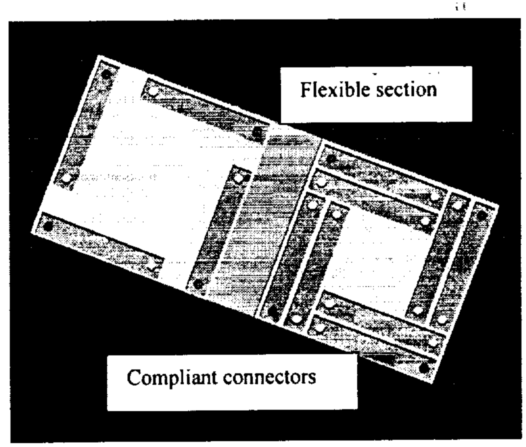

Fig. 3 Rigid-Flex Connector Assembly

The platform interface has the same geometry and material as the lid. The underside of the platform interface contains a PWB interface feature which can be selected based on cost or manufacturing constraints. The number of total electrical interconnections at this interface is 400. The interface feature can accommodate several interconnect options such as CGA, BGA or PGA. The top side of the platform interface contains pads for eight compliant connectors. Metal vias connect the traces extending from the connector pads on the top to traces leading to either pins or balls on the bottom.

To enhance the heat transfer from the stacks, a copper thermal conduction enhancer is used. Its four prongs (133 mil diameter thermal bus) extend from the top of the lid down through all the layers of the MCM and end in contact with the PWB on which the MCM is mounted. The base of the enhancer is a flat copper piece mounted on the bottom side of the platform interface. Additional non-functional trace lines are routed into the reserved plated through holes that are in contact with the enhancer base for heat conduction purposes. Thus dissipated heat is conducted from the stacked sources to the heat sink though the enhancer's four prongs as well as added traces and plated holes. This thermal enhancer effectively avoided the "bottle neck" problem of heat fluxes in systems where high conductivity diamond is utilized. In addition to thermal enhancement, the enhancer also provides key structural support of the whole MCM.

3. Finite Element Model and Analysis

Figs. 4a and 4b illustrate the FEA model of the MCM. A total of 89289 solid elements are used to construct this model. In performing the heat conduction analysis, the main interest is to control the maximum temperature rise from the heat sink. Unlike any "single stack" device where power dissipation is treated in heat transfer analysis as a single parameter, this MCM has three chip-mounting layers that dissipate a substantial amount of heat. Because the thermal resistance from each chip-mounting layer to the ultimate heat sink is different, it is critical to manipulate the chip placement depending on each chip's power rating so that the maximum temperature rise from the heat sink is minimized. Based on a total power dissipation of 20 W, a series of FEA was performed to simulate different chip placement scenarios. It must be remarked that, although there exists a theoretical "optimized placement" to achieve true minimization of maximum temperature rise, the real-life situation would prevent us from obtaining such an ideal placement due to fixed power rating of each chip. Thus the results of temperature minimization in this MCM configuration are based upon the actual power rating scenario. Table 1 lists this final power-placement.

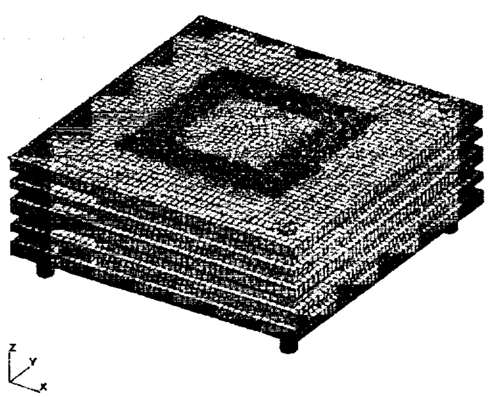

Fig. 4a FEA Model (iso-view from top)

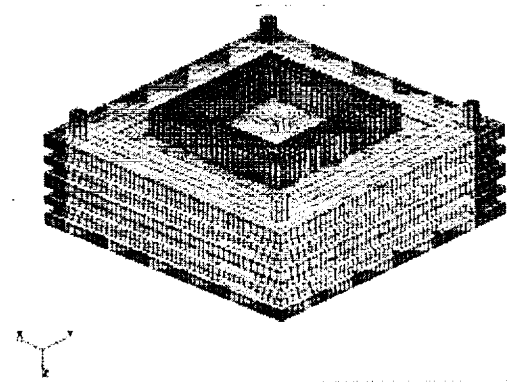

Fig. 4b FEA Model (iso-view from bottom)

Table 1

Layers of the MCM	Power Placement
Underside of the Lid	3.5 W
Topside of the Slice	7.0 W
Underside of the Slice	9.5 W

Using the power placement scheme above, more heat conduction analyses were performed to determine the overall thermal performance of this MCM. The thermal conductivity data are shown in Table 2.

Table 2

Material	Thermal Conductivity (W/m K)
Alumina	22.2
CVD Diamond	1490
Copper	375
Kovar	16.1
Silicon	146.8
Polymer*	1.2
Aluminum Oxide-Filled Silicone	0.9
Polyimide	0.3

* Polymer data shown is the effective volumetric-averaged conductivity.

3.1 Ideal Case

This is the case where the thermal contact resistances between the thermal enhancer and all the layers of the MCM are ignored. The temperature results are obtained based on the assumption that all the material interfacial contacts are "seamless". This case represents an ideal scenario and results presented are for comparison only.

3.2 Ideal Case without the Thermal Enhancer

This is the case analyzed for showing the need of the thermal conduction enhancer in this type of high power MCM module. As has been mentioned above, high power rated devices with diamond heat spreader substrate typically have "bottle neck" phenomenon in the heat flux path unless a well designed heat removal mechanism is in place. In this MCM, the copper thermal enhancer is used to avoid such a "bottle neck". The results have demonstrated the important function of this enhancer.

3.3 50% Contact Case

In this case, we assume the total contact area between the enhancer and each layer is 50%, the rest 50% being a fine air gap (see Fig. 5). Again, this is a pure assumption for producing comparative results only. Although there are few mathematical models existing for this type of contact resistance problem, each model has its own restrictions and has high dependency on the geometry. The use of these contact models may not deliver any better results for this particular MCM configuration.

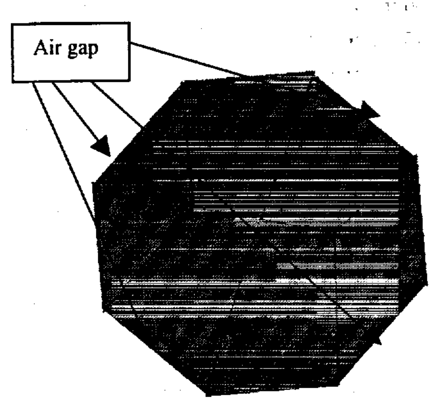

Fig. 5 50% Air Gap in the Contact Interface between the Thermal Enhancer and the Layers

3.4 "Fill the Gap" Case

This is the actual case in our application where the commercially available aluminum oxide-filled silicone pads are used to completely fill any possible contact gaps (see Fig. 6). Using this type of gap filler, the normal contact gap resistance is virtually eliminated. However, there is a trade-off using this product as the thermal conductivity of the silicone pad is quite low. Using it only in a well designed heat conduction path can the scheme of gap filling deliver good results.

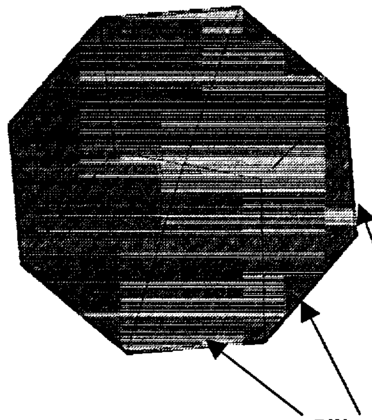

Fig. 6 Contact Air Gaps Filled with Silicone Pads

3.5 Results

Based upon a 20 W total power dissipation and a power placement outlined in Table 1, the results of temperature rise for the above four cases are summarized in Table 3.

Table 3

Max Temperature Rise From the Heat Sink	The Chip on the Lid Underside	The Chip on the Slice Topside	The Chip on the Slice Underside
Ideal Case (°C)	38.9	40.7	41.3
Ideal Case without the Enhancer (°C)	105.2	107.9	109.0
50% Contact Case (°C)	95.2	97.8	98.7
Fill-the-Gap Case (°C)	50.3	52.5	53.4

Several observations can be discussed from the data in Table 3. Firstly, the copper conduction enhancer is indeed a critical part in this assembly for effective removal of the dissipated heat out of the module. Without it, this MCM simply cannot accommodate a total power dissipation of 20 W. Secondly, when the conduction path before the contact resistance is of the high conductivity type (namely, heat fluxes spread on diamond films and then converge to the enhancer prongs across the contact gaps), the "bottle neck" phenomenon is harmful to the semiconductor chips. Measures must be taken to avoid such heat flow narrows. Thirdly, utilizing the aluminum oxide-filled silicone pads does provide a viable way to eliminate the "bottle neck" and to lower the maximum chip temperature to a manageable level. In the actual service environment, the heat sink temperature is designed to operate at no more than 60 °C, thus the maximum chip temperature should be well under 125 °C design limit.

4. Conclusions

To meet the needs of high power dissipation, several heat transfer enhancement features have been designed into this modular MCM for maximum functionality. The added features include a four-prong copper enhancer that can effectively remove the heat from the diamond films to the heat sink. The analysis has clearly demonstrated the effectiveness of using the enhancer in this MCM configuration. Also, the aluminum oxide-filled silicone pads are used to completely fill the contact gaps between the heat spreaders and the enhancer prongs so that the heat fluxes have no discontinuity in their flow paths. The criticality and effectiveness of these features have been confirmed by the analyses.

Another key measure taken in the design process is to optimize the power placement. Due to multiple layers of power dissipation, an optimized power distribution becomes critical to increase the functionality and save costs. A randomly or "conveniently" distributed power may seriously compromise the electrical performance of the module, and may require unnecessary overdesign of the heat conduction paths at an added cost. This feature shall be implemented in any electronic device design when multiple-layer power dissipation is anticipated.