APPLICATION OF GRAPHITE IN THERMAL MANAGEMENT OF MICROELECTRONICS

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Abstract: This paper is shortly describing the possibility to improve the thermal management of microelectronics by implementing carbon-based materials, more exactly graphite foils. It explains current thermal challenges in the field of microelectronics and moves to commonly used materials, where it adds carbon allotropes into the scope, with a special focus on graphite foils. In the last part, this paper contains a use case of the pyrolytic graphite sheet in thermal management.

Keywords: thermal management, thermal architecture, carbon, graphite, PGS, heat

1 INTRODUCTION

We live in times where our pocket computers are way more powerful than our desktop computers were a decade ago, and the techniques that were once a standard cannot achieve the required cooling. Despite all of the development in the field of thermal management, there are still cases where devices have poor architecture and their chips have to be throttled down not to overheat. But still, two main materials being used in this field - aluminum and copper. In this paper, the option of using pyrolytic graphite foil is introduced, followed by an example of the use, demonstrated using finite volume method simulation in SolidWorks Flow Simulation.

2 THERMAL MANAGEMENT IN MICROELECTRONICS

Thermal management in microelectronics can be divided into parts, as the heat travels. In the cooling applications, heat from the heat source must at first travel by thermal conduction of some kind to a surface exposed to the cooling fluid. The system as a whole can be improved simply by reducing the amount of heat produced by the heat source. The second way is by improving the thermal conduction, the path through the heat travels to the surface area. The next option is making the contact area where heat can be exchanged between parts and systems the largest possible. Adjusting the cooling fluid itself - its composition, density and heat transfer properties can also help.

2.1 CHALLENGES

The architecture of the electronics is creating non-uniform heat dissipation across the die surface, with localized functional areas - so-called power-dense regions, where the density of power can be five to ten times higher than the average of the die. Also, the number of metal layers interconnecting the microprocessors technology had increased from seven in 2001 to thirteen in 2014. [1] At the same time, these “System on a Chip” (SoC) are changing its structure from the 2D planar chip into a 3D structure with nanowires connecting different levels of the system creating a thermal architecture maze with more attention needed. The packaging itself is also becoming more of a thermal challenge, as the single flip-chip can be cooled down by classic techniques, but as the architecture is getting more and more complicated, the layers are stacked one on top of another. And as the field of flexible electronics is becoming stronger and grows it brings questions about its thermal management and cooling.

2.2 Materials used for thermal management

Materials that are used have a high range of thermal conductivity, starting at 0.2 $Wm^{-1}K^{-1}$ for polymers and going all the way up to 3450 $Wm^{-1}K^{-1}$ for diamond. [1] Aluminium is commonly used for heat sinks in thermal management of microelectronics, because of the thermal conductivity of 220 $Wm^{-1}K^{-1}$ and low cost. [2] Copper has desirable properties for the use in thermal management, starting with high thermal conductivity - around 400 $Wm^{-1}K^{-1}$, corrosion resistance, high allowable stress, and internal pressure. Pure copper slug is the most common copper heat sink material and it is also often used as heat spreader on the chips, as a cold plate for liquid cooling or heat pipe material. [2]

Allotropes of carbon, Highly Oriented Pyrolytic Graphite - HOPG

Carbon occurs in two natural allotropes, diamond, and graphite. Both forms have different, but unique physical properties like hardness, thermal and electric conductivity and lubrication behavior. For a long time, these were the only two allotropes known, but that changed in 1985, with the discovery of fullerenes, followed by carbon nanotubes in 1991 and then graphene in 2004. The youngest from the carbon allotropes family is two-dimensional graphene, basically a single graphite sheet. Graphite can be found and make into various forms, like crystalline - which are small flakes of graphite, amorphous graphite, lump graphite, graphite fiber and highly oriented pyrolytic graphite (HOPG), which is highly pure synthetic graphite.[3]

HOPG is based on pyrolytic carbon, which is produced by heating hydrocarbon to a temperature near its decomposition, thus allowing the graphite to crystallize - pyrolysis. [4] HOPG has exceptionally high thermal conductivity along the layer plane - as much as 1600 $Wm^{-1}K^{-1}$, and very small conductivity at the plane perpendicular to the layer, where it can go as low as 7 $Wm^{-1}K^{-1}$. So it can conduct heat one way but insulate the other. This anisotropy is caused by the structure, where layers do have strong σ bonds, but parallel stacking of these layers are bonded by the van der Waals forces caused by the interactions between π-electron clouds on the neighboring layers. [5] There are several graphite products - foils and membranes - for the use in the field of microelectronics, with very high heat conductivity. Based on pyrolytic carbon there is Pyroid-HT from MINTEQ, based on graphite and Kapton it is PGS line from Panasonic. Based on natural graphite it is Grafoil from Graf Tech.[5] Heat conductivity of these foils vary, depending both on thickness and manufacturer, but they do provide highly different heat conductivity in the layer plane and the plane perpendicular to the layer, with differences as big as 1800 $Wm^{-1}K^{-1}$. [6]

3 USE CASES OF PYROLYTIC GRAPHITE SHEET

This simulation was made with a commercially available product - Pyrolytic Graphite Sheet (PGS) from Panasonic. They have both catalog [7] and datasheet [8] available online, so the product information from these sources was be used for the simulation, computed in SolidWorks Flow Simulation. In this example, the use of PGS for transferring the temperature across the material with a bad heat conductivity - poly-carbonate - will be demonstrated. This material was chosen as it is commonly used for making various cases and boxes for electronics, so the example will simulate a possible use case.

The design is simple: PCB board with IC chip with 0,5 W volume heat source on in, covered by silicon and by 0,3 μm of material - poly-carbonate, aluminum, copper, or PGS - and covered by a poly-carbonate desk. The dimensions can be seen in Table 1, and the cut through the model itself can

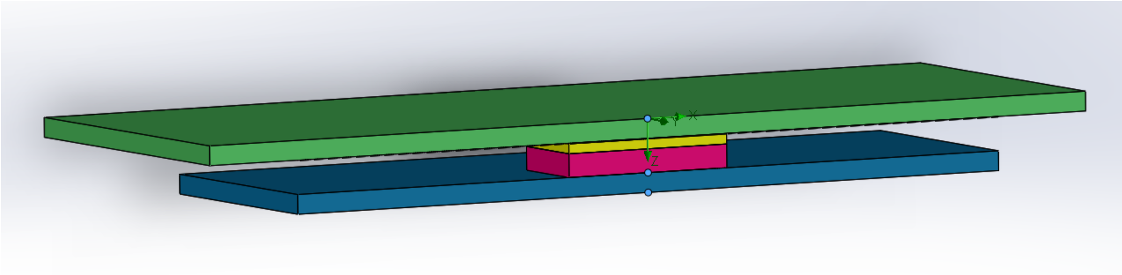

Figure 1: Cut through the design with layers described bottom up - blue is PCB, pink is the IC, yellow silicon, barely visible black layer is the thin added material, that is variable for each iteration and the top green layer is the poly-carbonate.

be seen at Figure 1. On the same figure, you can see three control points, where the temperature is measured. On the top and the sides of the poly-carbonate desk on the top of the design, there is a heat transfer coefficient $\alpha = 10\,Wm^{-2}K^{-1}$, simulating air running over the plate.

Table 1: Dimensions of the design.

material	dimensions [mm]
PCB	25 x 40 x 1
IC	9 x 9 x 1,2
Silicon	9 x 9 x 0,5
“material”	25 x 40 x 0,03
Poly-carbonate	35 x 50 x 1

Points are distributed subsequently: First one is at the bottom of the PCB, the second one is between the PCB and the IC, and the third is on the poly-carbonate. All of these three points are aligned along the z-axis.

In the Table 2, there are temperatures for the point mentioned above, for different materials, showing that PGS can distribute the heat equally to the poly-carbonate plate, preceding the IC to overheat. (The fourth material here - poly-carbonate - is in the simulation to show how would the temperature spreading look like without anything added - but to show that the better heat spreading is not provided only by extra volume, there is the 0,03 μm layer added.)

Table 2: Converged temperatures in three different points for four types of material.

material	PCB [°C]	IC [°C]	poly-carbonate [°C]
poly-carbonate	193,98	194,18	184,99
aluminium	58,18	58,38	56,12
copper	54,96	55,15	53,06
PGS	51,05	51,18	49,32

To even more understand the heat spreading, it can be demonstrated using maximal and minimal temperatures on the top plate. In all four cases, the maximal and minimal temperatures are located at the same spots - maximum in the middle of the plate, where the center of the IC lays underneath. The minimum is then located in the corners. As can be seen in the Table 3, the PGS actually have the lowest maximal temperature, but the highest minimal. That is a clear example of its heat conductivity, as it leads the heat beneath the material to the most distant corner more effectively than any other material used in this simulation.

Table 3: Minimal and maximal temperatures of the top plate for different underlaid materials.

material	minimum [°C]	maximum [°C]
poly-carbonate	21,47	184,99
aluminium	25,70	56,12
copper	26,02	53,06
PGS	26,42	49,32

4 CONCLUSION

Thermal management of microelectronics has problems, such as the creation of hot spots, complicated designs with 3D stacking of individual chips and flexible electronics and touchscreen devices. These three challenges can be solved by using not only aluminum and copper but also a Pyrolytic Graphite Sheet (PGS), which has great heat conductivity and it can be very thin and flexible. In the paper, there was a demonstration comparing the PGS with traditional aluminum and copper, revealing that PGS had 7% lower temperature than copper and 12% lower temperature than aluminum. This is showing the possibility of use of PGS, especially considering its flexibility, ability to be layered with PET (thus behaving as electric isolation) and because of the thickness of only 30 μm it can be used both between components and inside of packages.

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