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THERMAL METAMATERIALS FOR ELECTRONIC THERMAL MANAGEMENT

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ABSTRACT

With advances in heterogeneous and advanced packaging strategies, differing temperature limits for safe operation have become a bottleneck for increasing computational power and performance. Thus, there is a need for effective thermal isolation between adjacent components, while maintaining effective thermal transport to the heat dissipating components. For 2.5D packages, this motivates the development of metamaterials with large thermal conductivity anisotropies such that in-plane thermal crosstalk between components can be suppressed, while cross-plane heat transfer is unimpeded. Here, we design a bi-layer structure consisting of graphite for thermal transport and aerogel for in-plane isolation to improve the thermal management of adjacent components in such packaging. Varying the percentage graphite in the system leads to a range of compositions where the thermal limits are met for both the memory and the CPU. This guides the design of a bi-layer or metamaterial structures for controlling and guiding heat within advanced packages.

KEYWORDS: Thermal Isolation, Metamaterials, Heterogeneous Packaging, Aerogels

1. INTRODUCTION

Within heterogeneous packages, components with different power dissipation levels and thermal limits are closely integrated. Thermal crosstalk between these components can limit the operation of adjacent components. There is a need to develop strategies to effectively isolate neighboring components without negatively impacting heat dissipation to the cooling solution. Metamaterials open the possibilities of unique combinations of properties that could improve heat flow control in advanced packages enabling isolation of temperature-sensitive components with efficient heat dissipation. In this work, we computationally analyze bi-layer metamaterial structures consisting of aerogels for thermal isolation between components and graphite-based materials for thermal transport. This combination yields highly anisotropic composites that can guide the heat within advanced packaging.

2. APPROACH

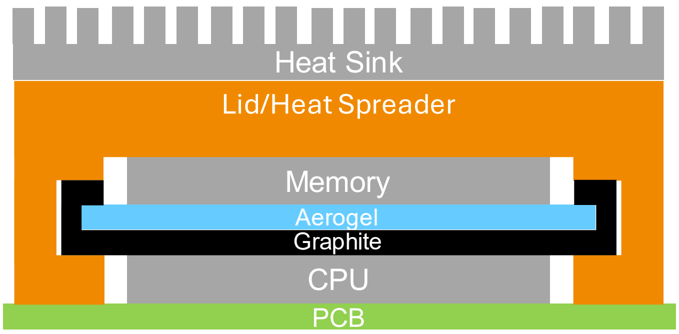

Fig. 1: Schematic of a potential integration strategy for the bi-layer structure in a 3D chip stack.

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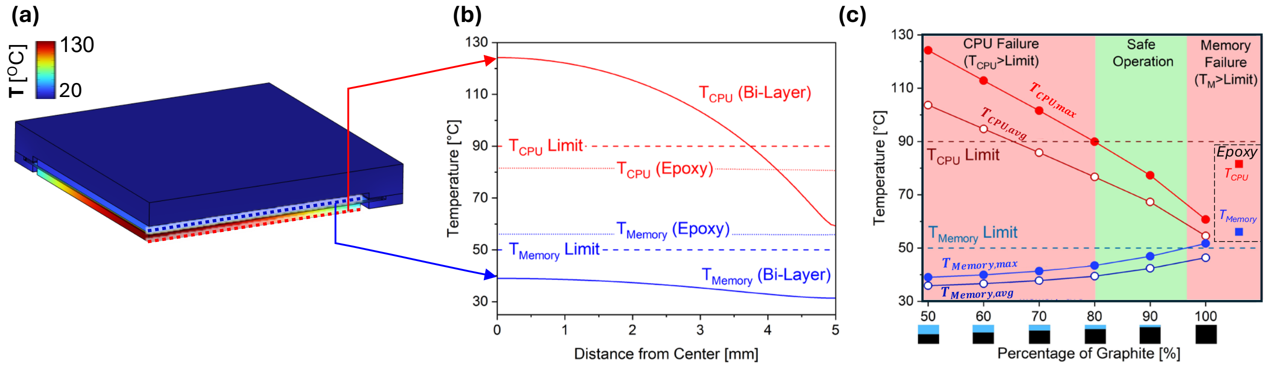

Fig. 2: (a) Temperature predictions from a COMSOL Multiphysics® model of one quarter of the system geometry. **(b)** Temperatures along cut-lines through the CPU (red) and memory (blue) for a 50/50 division of aerogel and graphite in the bi-layer compared to the maximum temperatures in each with an epoxy underfill instead of the bi-layer structure. **(c)** Maximum and average temperatures within the CPU and the memory as a function of the percentage of graphite within the bi-layer structure. For comparison, the maximum temperatures for an epoxy underfill material are shown to the right. For 80 to ~95% graphite, both components remain within the respective thermal limits.

One potential integration strategy for the bi-layer material is schematically shown in **Error! Reference source not found.**. Here the graphite is in contact with the CPU enabling effective heat spreading, and the aerogel adds thermal resistance directing the heat to flow laterally through the graphite, rather than through the memory die. The bi-layer metamaterial is designed to replace the underfill between dies. Therefore, beside functions like heat spreading and blocking, it also needs to satisfy design requirements of the underfill, including electrical insulation, mechanical support to the microbumps, and compatible thermal expansion coefficient to dies and the microbumps. Since large contrast in thermal conductivity of selected material is the key in the bi-layer metamaterial design, the thermal property is the priority in the design. Thus, we choose graphite as the highly conductive material despite its electrical disadvantage. To avoid short circuit, insulation can be built around the μ-bumps. Potential methods include spray and deposition of electrically insulating materials.

3. RESULTS

We analyze the performance of the bi-layer structure using a COMSOL Multiphysics® model of one quarter of the system geometry (see Fig. 2(a)). Key metrics include the maximum and average temperature within the memory and the CPU compared to the thermal limits (here, ~90ºC for the CPU and ~50ºC for the memory). The goal of the metamaterial is to ensure that the temperatures are below the thermal limits (dashed lines) for both the memory and the CPU. However, for a 50/50 division of graphite and aerogel in Fig. 2(b), the memory is well isolated from the CPU, but the CPU temperature exceeds the proposed thermal limit. In contrast, the epoxy-underfill leads to the memory exceeding the limit, but a lower CPU temperature.

Based on the initial results with the 50/50 division of graphite and aerogel, the percentage of graphite must be increased to reduce the CPU temperatures. Sweeping through a range of bi-layer structures (see Fig. 2(c)), we find that in the window of 80 to ~95% graphite, both components remain within the respective thermal limits. Below 80%, the CPU temperature exceeds the thermal limit due to the reduced heat transfer pathway to the heat sink. Above ~95% graphite, the thermal cross-talk between the two components increases the temperature of the memory above its thermal limit. This illustrates the delicate balance when optimizing designs of advanced packages.

4. CONCLUSIONS

This preliminary evaluation of bi-layer structures consisting of thermally insulating aerogels and thermally conductive graphite-based materials demonstrates the potential of the bi-layers or metamaterials to yield exceptionally high anisotropy in the thermal conductivity. The highly anisotropic thermal conductivity of the materials enables routing of the heat towards the cooling solution while isolating other components in the system from the high-powered and high-temperature logic die. Further engineering of the metamaterial structure could yield further improvements in performance and more detailed simulations are required to optimize the integration strategy.

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