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Thermally anisotropic composite heat spreaders for enhanced thermal management of high-performance microprocessors

Arthur Suszko [a,c], Mohamed S. El-Genk [a,b,c,d,*]

[a] Institute for Space and Nuclear Power Studies, University of New Mexico, Albuquerque, NM, USA
[b] Nuclear Engineering Department, University of New Mexico, Albuquerque, NM, USA
[c] Mechanical Engineering Department, University of New Mexico, Albuquerque, NM, USA
[d] Chemical and Biological Engineering Department, University of New Mexico, Albuquerque, NM, USA

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ABSTRACT

Numerically investigated is the performance of thermally anisotropic composite spreaders for enhanced thermal management of high performance microprocessors. The spreaders are comprised of two 0.5 mm-thick Copper (Cu) laments separated by a thin ($\delta = 0.25$–1.0 mm) layer of thermally anisotropic material, such as graphite or highly oriented pyrolytic graphite (HOPG). The exposed rough surface ($Ra = 1.79$ μm) of the top Cu lament is cooled by saturation nucleate boiling of PF-5060 dielectric liquid. The performed 3-D numerical analyses quantify the effect of the Figure-of-Merit (*FOM*) of the thermally anisotropic layer, on the total thermal power removed, the spreader's total thermal resistance, and the maximum temperature of the underlying 20 × 20 mm chip. The spreaders suppress the propagation of the chip hot spots, and increase the total power removed. They remove 160–317 W of the thermal power dissipated by the underlying chip, at a chip maximum surface temperature of 80–120 °C. Developed empirical correlations estimate the total thermal power removed and the surface area of the composite spreaders. Increasing the *FOM* from 0 (all Cu spreader) to 400 (highly anisotropic spreader) increases the total thermal power removed from ~88 to ~450 W and the spreader dimensions from ~25 × 25 to ~69 × 69 mm. The total thermal resistance of the spreaders ranges from 0.16 to 0.4 °C/W.

1. Introduction

Over the past two decades, microprocessors experienced substantial and continued increases in the transistors density and the total power dissipation, owing to their growth in complexity, performance, and parallelization. Thermal design power (TDP) requirements for the central processing units (CPUs) are upwards of 150 W [1,2], and as high as 250 W for graphics processing units (GPUs) [2,3]. These power dissipation levels, representing two orders of magnitude increase for CPUs over the past two decades, and 500% increase for GPUs over the past decade, are expected to continue rising. Additionally, high power chips typically have hot spots with local dissipation heat fluxes that could reach 3–8 times that of the chip average [4]. The high local temperatures at the hot spots and the induced temperature differentials cause thermal stresses that could reduce the serviceable life of the chip [5,6].

The current and future power dissipations by the microprocessors require advanced methods of cooling [7–22] to remove large amounts of power, while keeping the maximum junction temperature $T_{j,max}$, of the chip at or below 85–115 °C, depending on the application [23]. Among these methods [7–22], immersion nucleate boiling of dielectric liquids offers many advantages. These include a relatively uniform surface temperature, a high heat removal rate, potential mitigation of the effect of the chip hot spots [24] and low thermal resistance [24,25]. In addition, the low saturation temperatures of dielectric liquids at atmospheric pressure (~56 °C for the Fluorinert FC-72, ~56 °C for the Performance Fluid PF-5060 and ~34 °C for the Novec HFE-7000) [26] help keep $T_{j,max}$ at or below the recommend values by the manufacturers [23–25]. For large datacenters, using immersion nucleate boiling cooling could potentially reduce energy consumption by as much as ~50%, and save floor space, compared to refrigerated air [27–31].

In immersion nucleate boiling cooling, the processor package that includes a heat spreader and the underlying chip, is submerged in a pool of dielectric liquid. The dissipated heat by the underlying chip is removed from the exposed surfaces of a spreader by

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[*] Corresponding author. Institute for Space and Nuclear Power Studies and Nuclear Engineering Department, University of New Mexico, Albuquerque, NM, USA.
E-mail address: mgenk@unm.edu (M.S. El-Genk).

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nucleate boiling. However, the maximum heat flux at the exposed surface needs to be kept sufficiently below the critical heat flux (CHF). CHF depends on the thermophysical properties of the dielectric liquid, and the material properties and surface characteristics of the heat spreader. The CHF, indicative of the departure from nucleate boiling, is associated with a large surge in temperature that could damage or melt the surface of the spreader.

Increasing the amount of heat removed by nucleate boiling requires enhancing the heat transfer coefficient and CHF, and/or increasing the wetted surface area. Experimental results for pool boiling of dielectric liquids have shown that microstructured, micro- and macro-finned, rough, and microporous surfaces and surfaces with microporous coatings [9,10,16–22] enhance both nucleate boiling and CHF. Despite the increases in the nucleate boiling heat transfer coefficients on these surfaces, in immersion nucleate boiling cooling of high power microprocessors, the total power dissipated by the underlying chip and removed from the exposed surfaces of the spreader depends on its conductance for lateral heat spreading.

El-Genk and Saber [9] investigated the cooling performance of heat spreaders for underlying 10 × 10 mm computer chips with uniform and non-uniform power dissipation. The spreaders were comprised of a Cu substrate of different thicknesses and a thin surface layer of porous graphite, cooled by saturation or subcooled nucleate boiling of FC-72 dielectric liquid. The results showed that, even though porous graphite enhances nucleate boiling and CHF [16], the isotropic thermal conductivity of the Cu substrate limited lateral heat spreading, and hence the total thermal power removed. The spreader with a surface area of 4.9 cm^2 removed 72 W for the underlying chip.

The performance results of Cu spreaders, 1.6–3.2 mm thick, with an 80 μm thick surface layer of microporous Cu (MPC), cooled by saturation nucleate boiling of PF-5060 dielectric liquid, have recently been reported by El-Genk and Ali [24]. The MPC surface layer, deposited using conventional electrochemical processes at room temperature, enhances both nucleate boiling and CHF [18,22]. The Cu/MPC spreader with ~25 cm^2 surface area removed up to 90 W of thermal power for an underlying 10 × 10 mm chip, while keeping the chip maximum temperature at ~73 °C.

The analyses in Refs. [24,25] took advantage of the enhanced nucleate boiling heat transfer coefficients on the exposed porous graphite and micro-porous Cu surfaces of the heat spreaders to increase the total power removed, and decrease the maximum chip temperature. However, the total thermal powers removed [24,25] were limited by the lateral heat spreading of the Cu substrate. Lateral spreading of the heat dissipated by the underlying high power chips is important, because the dissipation heat flux (~50 W/cm^2) [1–4], is much higher than that for nucleate boiling of dielectric liquid on the exposed surfaces of the spreaders (15–30 W/cm^2) [9,10,16–23,32]. Thus, in immersion nucleate boiling cooling of microprocessors, with power dissipations that may reach or exceed 150 W [1–3], enhancing lateral spreading of the dissipated thermal power is necessary. Hence, in order to meet the ever increasing power dissipations by microprocessors, there is a need to investigate heat spreaders with not only exposed surfaces for enhancing nucleate boiling, but also materials for enhancing lateral heat spreading.

The objective of this work is to numerically investigate the performance of thermally anisotropic composite spreaders, with an exposed rough Cu surface (Ra = 1.79 μm) cooled by saturation nucleate boiling of PF-5060 dielectric liquid, for enhanced thermal management of an underlying 20 × 20 mm microprocessor chip, with and without hot spots. The composite spreaders investigated are comprised of two 0.5 mm-thick Cu laments separated by a thin layer (0.25–1.0 mm thick) of thermally anisotropic material, such as graphite or highly ordered pyrolytic graphite (HOPG). The performed 3-D numerical analyses limit the maximum surface heat flux and the lowest temperature on the exposed surface of the spreaders, to 90% of CHF and 1 °C higher than that at boiling incipience of PF-5060 dielectric liquid, respectively [20,21,32]. The analyses quantify the effect of the spreader Figure-of-Merit (*FOM*) or the thickness and thermal conductivities (k_x = 325–2000 W/m K, and k_z = 5–20 W/m K) of the thermally anisotropic layer on the total thermal power removed, the spreader total thermal resistance, and the maximum temperature of the underlying chip. The chip either dissipates heat uniformly, or has 0.5 × 0.5 mm and 1.0 × 1.0 mm central hot spots, or multiple hot spots. The local heat flux at the hot spots varied from 5.0 to 10 times that of the chip average (HFR = 5, 10, respectively).

2. Problem statement

Fig. 1 is a schematic of a thermally anisotropic composite heat spreader that consists of a thin graphite or HOPG thin layer between two 0.5 mm thick Cu laments. Zweben [33,34] and Coppola et al. [35] list HOPG as an upcoming microprocessor heat sink material. It is being used in ground-based radars and aerospace printed circuit board heat sinks [35]. The high lateral in-plane (k_x) thermal conductivity and low axial, through-plane thermal conductivity (k_z), along with commercial availability, makes HOPG a good candidate for enhancing heat spreading. However, since HOPG is expensive [36], a cheaper alternative, such as graphite is considered in cooling applications of electronic devices. These range from microprocessors, to small hand held devices, hard drives, and even large devices such as plasma screen televisions [37–40].

The Cu laments protect the graphite or HOPG layer during handling, packaging, and use. The exposed rough (Ra = 1.79 μm) surface of the top Cu lament is cooled by saturation nucleate boiling of PF-5060 dielectric liquid. Rough Cu surfaces have recently been shown to enhance nucleate boiling of PF-5060 dielectric liquid [20,21,32], and are easily scalable and inexpensive to fabricate with consistent characteristics. The lateral thermal conductivity of the anisotropic layer, k_x, is varied from 325 to 2000 W/m K, while that in the axial direction, k_z, is varied from 5 to 20 W/m K. These are among a wide range of reported values for different grades of graphite, pyrolytic graphite, and highly oriented pyrolytic graphite [33,35,36,41–46]. The anisotropic layer thickness, δ, of the composite spreaders varied from 0.25 to 1.0 mm.

A Figure-of-Merit (*FOM*) for the composite spreader is defined as:

$$FOM = \frac{k_x}{k_z}\delta^2, \tag{1}$$

is proportional to the square of the thickness of the thermal anisotropic layer and has units of area. It is the ratio of the axial through-plane thermal resistance, R_z, to the lateral in-plane thermal resistance, R_x, of the thermally anisotropic layer (Fig. 1), multiplied by the exposed surface area cooled by nucleate boiling, w^2, as:

$$FOM = \left(\frac{R_z}{R_x}\right)w^2, \tag{2}$$

$$\text{where} \quad R_x = \frac{w}{k_x w \delta} \quad \text{and} \quad R_z = \frac{\delta}{k_z w^2}. \tag{3}$$

Thus, the *FOM* increases as the thermal conductivity ratio (k_x/k_z) and/or the thickness of the thermal anisotropic layer, δ, increases.