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Enhanced heat transfer using metal foam liquid supply layers for micro heat spreaders

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ABSTRACT

We propose a nanostructured metal foam liquid supply layer that can efficiently provide operating fluid to evaporator hot spots and can be easily integrated within micro heat spreaders. The liquid supply layer is incorporated onto the micropost evaporator wicks to enhance the capillary performance by combining the high permeability of liquid supply layers and the high capillary pressure of micropost wicks. The coverage ratio (*CR*) between the liquid supply layer and the evaporator wicks was varied from 15% to 100% to find the proper *CR* for efficiently increasing the liquid supply performance with minimizing the parasitic thermal resistance. By incorporating the liquid supply layer of *CR* 33% onto the Cu micropost wicks of $\sim$0.4 solid fraction, the results show that a high ($>6\ \mathrm{W/cm^2\ K}$) and stable heat transfer coefficient can be achieve at a high heat flux range ($>400\ \mathrm{W/cm^2}$), which outweighs the performance of previously-reported evaporator wicks. The achieved maximum heat flux was over 150% higher than the same wicks without the liquid supply layer. Our work shows the importance of the efficient liquid supply to hot spots and provides the strategy to increase the heat transfer performance at high heat flux region. The suggested liquid supply layer will help develop micro heat spreaders for the thermal management of high power density microprocessors, IGBTs and thermophotovoltaic cells.

1. Introduction

Thermal management of high-power-density semiconductors microprocessors, power amplifiers, lasers and IGBTs has been a subject of intense research over the past decades. Micro heat spreaders offer a promising solution as they have the potential to provide high effective thermal conductivities under high heat fluxes. They also can be easily integrated into compact electronic systems due to its flat and thin form factors [1–4].

The performance of heat spreaders can be evaluated by the maximum heat flux and the heat transfer coefficient. The maximum heat flux capability of micro heat pipes is most often determined by the capillary limit of evaporator wicks determined by the permeability (K) and the effective radius (R_{eff}) of the wicks [2,5]. The heat transfer coefficient is mainly determined by the area of thin ($<2\ \mu\mathrm{m}$) evaporative film where over 60% of heat transfer occurs due to low thermal conduction resistance [6].

A number of previous studies have reported various evaporator wicks in order to achieve high maximum heat flux and/or high heat transfer coefficient. Evaporator wicks including grooves [1,7], micropost arrays [8], meshes [9,10], and hybrid types [9,10] have been suggested and their fabrication processes and heat transfer performances were experimentally discussed. More complex shapes including sphere, rib, cone, and pyramids arrays [11–13] were also numerically investigated and their thin evaporative film area and the capillary performance were investigated [11]. Recently dual-height micropost array was introduced to vertically stretch the thin evaporative film and increase the heat transfer coefficient without sacrificing the capillary performance and resulting maximum heat flux [14].

The wettability of the wick structures also has a significant effect on the heat transfer performance. Our previous studies reported that CuO nanostructured superhydrophilic Cu micropost array has over 70% enhanced maximum heat flux as well as heat transfer coefficient compared with bare Cu microposts [15] due to the increase in the wettability and resulting thin film area and capillary performance. Nanostructured titanium and silicon micropost wicks were also investigated to increase the heat transfer performance by enhancing the wettability of wick surface [16–18].

However, it is still challenging to achieve high maximum heat flux with micro heat spreaders due to the high liquid-phase pressure drop within the thin evaporator wicks. In order to overcome

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the limitation, previous studies have incorporated vertical multi-artery [19] or lateral converging multi-artery [20] structures on top of the thin (~100 μm) Cu sintered evaporator wicks. Such structures provide the condensed liquid to the evaporator hot spot directly, which can reduce the liquid-phase pressure drop between the condenser and evaporator. By incorporating such structures, the reported evaporator wicks could dissipate ~380 W/cm^2 and ~580 W/cm^2 heat flux on 1 cm^2 heat source with the vertical and lateral artery structures, respectively. The heat transfer coefficient was measured to be approximately ~4 W/cm^2 K.

Despite these improvements, it is still challenging to incorporate the patterned porous structures on top of the evaporator wicks. The previous multi-artery structures were fabricated by Cu powder sintering process that requires high and tightly controlled process temperatures and ambient conditions, which limits the available substrate materials and the degree of precision of the created structures.

In the present work, we suggest a metal-foam based liquid supply layer that can efficiently provide operating fluid to the evaporator hot spot. The liquid supply layer was fabricated by nanostructuring Cu metal foams and can be easily incorporated to heat spreaders by being squeezed between the evaporator and condenser. We investigate the effects of the suggested liquid supply layer on the maximum heat flux and heat transfer coefficient by varying the coverage ratio between the evaporator surface and the liquid supply layer from 15% to 100%. Previously reported nanostructured Cu micropost arrays with solid fraction 0.227–0.463 were applied as the evaporator wick. With the liquid supply structure, the evaporator could dissipate over 400 W/cm^2 heat flux with maintaining a high heat transfer coefficient (>6 × 10^4 W/cm^2 K which shows the benefit of the suggested liquid supply structures.

2. Proposed concept

Fig. 1(a) shows the schematic of conventional micro heat spreader including evaporator and condenser, where the condensed fluid is provided to the evaporator wick along the side wall of the envelop by the capillary pressure generated by the evaporator wick. As the heat flux increases, the required mass flux within the evaporator wick increases, and the dry out occurs when the liquid-phase pressure drop becomes larger than the capillary pressure generated by evaporator wick. Fig. 2(b) shows the concept of the suggested liquid supply layer placed between the condenser and evaporator. We suggest a metal-foam based porous liquid supply layer that can minimize the liquid-phase pressure drop between the condenser and hot spot, and delay the dry out event. The porous liquid supply layer can be patterned to cover only certain fraction of the evaporator surface to minimize the increase in the parasitic thermal resistance associated the layer itself (Fig. 1b). The coverage ratio is defined as the area ratio between the liquid supply layer and evaporator wick and symbolized as *CR* in the following discussion. The proposed metal-foam liquid supply layer can be easily patterned and integrated into the micro heat spreader by being squeezed between the evaporator and condenser.

3. Sample preparation

We fabricate Cu micropost hexagonal arrays that include microposts of diameter (D_p) ~ 50 μm, height (H) ~ 100 μm, and pitches (P) ranging from 70 to 100 μm for the evaporator wicks. The solid fraction (f_s) of microposts can be calculated as $f_s = \frac{\pi}{2\sqrt{3}}\left(\frac{D_p}{P}\right)^2$. Table 1 summarizes the design parameters of the investigated micropost arrays. Fig. 2 shows the process flow for fabricating the Cu micropost arrays. The seed layer (Ti/Cu/Ti) on silicon substrate is deposited using the E-beam evaporator. The top Ti layer (50 nm) prevents oxidation of the Cu layer (2 μm) and the bottom Ti layer (50 nm) improves adhesion between the Cu layer and silicon substrate. The photoresist (PR) layer is formed by the hot-roll lamination method using by 150 μm thick negative-tone dry film resist (DFR, DJ DEVCORP.) [21] that can provide higher uniformity compared with spin-coated thick PRs such as SU8 and KMPR.

We lithographically pattern the PR layer and grow the Cu micropost arrays using the electrochemical deposition. After removing the PR mold, the Cu micropost arrays are immersed into the hot alkaline solution composed of NaClO$_2$, NaOH, Na$_3$PO$_4$·12H$_2$O for 5 min to integrate CuO nanostructures on the entire evaporator surface. The details on the Cu electrochemical deposition and CuO nanostructure integration are summarized in our previous publications [22,23]. Table 1 summarizes the design parameters, surface wettability and solid fractions of the investigated superhydrophilic micropost arrays. Fig. 3a and b shows the SEM images of fabricated Cu micropost array.

For the liquid supply layers, we used commercially available Cu foam (PPI 100, American elements). Each Cu foam was rinsed with acetone, ethanol, iso-propanol and deionized water. Then the foams were dipped into a 2.0 M hydrochloric acid solution for ~30 s to remove native oxides on the surface and then triple rinsed with DI water. In order to increase the wettability and the capillary

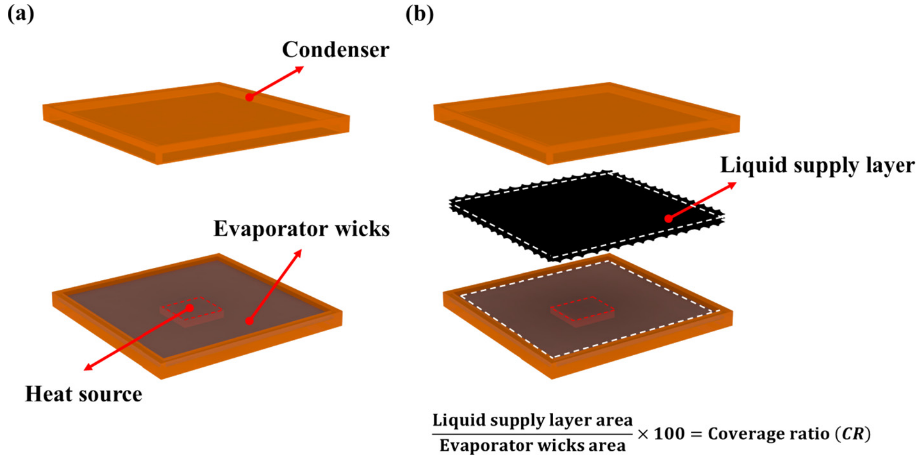

Fig. 1. The schematics of conventional micro heat spreaders (a) and the suggested micro heat spreader incorporating porous liquid supply layer squeezed between condenser and evaporator (b). We define the coverage ratio (*CR*) as the area ratio between the liquid supply layer and evaporator wick.