International Journal of Heat and Mass Transfer 73 (2014) 438–444

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer and capillary performance of dual-height superhydrophilic micropost wicks

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ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 8 January 2014
Accepted 10 February 2014
Available online 14 March 2014

Keywords:
Micropost
Evaporator
Wick
Superhydrophilic
Thin flim
Micro heat pipes

ABSTRACT

We propose dual-height superhydrophilic (DHS) micropost evaporator wicks with improved heat transfer performance for thermal management applications such as micro heat pipes. The heat transfer coefficient and capillary performance are characterized with a numerical model that accounts for the finite curvatures of liquid menisci by varying solid fraction of micropost arrays from 0.18 to 0.54. The DHS wicks vertically stretch a thin (<2 μm) evaporative film region with low thermal resistance, which enhances the heat transfer coefficient up to ~300% compared with the previously reported single-height superhydrophilic (SHS) micropost wicks with the same solid fraction. The stretch of thin film region does not significantly affect the capillary pressure and permeability determined from microscopic menisci. The optimum solid fraction maximizing the heat transfer coefficient occurs since the maximum height ratio between tall and short posts satisfying the pinning criteria decreases with increasing solid fraction, while the total perimeter of microposts increases. The vertical stretch of thin film also lowers the sensitivity of performance to liquid fill charge over 60%. This work suggests that DHS micropost wicks can provide significantly higher heat transfer coefficient in more robust way compared with previous SHS wicks without scarifying the maximum heat transfer performance.

1. Introduction

The thermal management of high-power-density semiconductor devices has been a subject of intense research over the past decades. Micro heat pipes offer a very 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 form factor [1–6].

Evaporator wicks are core elements that determine the heat transfer performance of micro heat pipes. Ideal evaporator wicks should provide high capillary performance and large thin-evaporative film area to achieve high maximum heat flux as well as high heat transfer coefficient [7]. Previous micro heat pipes incorporated simple grooves and meshes reported low maximum heat flux capability due to the limited capillary performance of the wicks [1,4]. Some heat pipes used sintered metal powders to achieve higher maximum heat fluxes [3,5,8]. However, sintering of metal powders requires tightly controlled process temperature and ambient conditions. Recently, micropost wicks that are comparable with low temperature microfabrication processes have been suggested as alternative wicks [1,7,9,10].

A number of previous studies have investigated the performance of various micropost evaporator wicks. Our recent studies theoretically and experimentally characterized the capillary and thermal performance of uniform arrays of nanostructured superhydrophilic Cu micropost wicks [7,9]. The performances of nanostructured titanium [10] and silicon micropost wicks [11,12] were also reported by others. Carbon nanotubes were also investigated as potential evaporator wick structures [13]. Comparative studies of different geometries including uniform arrays of sphere, posts, ribs, cones, and pyramids were also conducted with numerical approaches [14–16].

These studies have shown that the topology and wettability of the wicks play a significant role in determining the wick performance. Nanostructured superhydrophilic Cu micropost wicks provided higher heat transfer coefficient and maximum heat flux compared with bare Cu micropost wicks due to enhanced thin film region and capillary pressure [7]. Nanostructuring was also suggested for other materials such as titanium and silicon to enhance wettability and resulting heat transfer performance [10,12]. Previous comparative study reported that pyramidal micropillars can provide higher thin film regions but the comparison was performed

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.02.020
0017-9310/

with fixing solid fraction and liquid volume. Microposts with pie geometries were also suggested to enhance the heat transfer coefficient, but reported improvement was not significant (<20%) [17].

Despite these previous studies, the conflict between the heat transfer coefficient and maximum heat flux is still a major challenge in determining wick geometry for previous single-height micropost wicks. The increase in the solid fraction of micropost arrays (with fixing a post diameter) enhances the heat transfer coefficient by increasing the thin-film regions but decreases the maximum heat flux by reducing the capillary performance [7,9].

In this work, we propose dual-height superhydrophilic (DHS) micropost wicks that can significantly increase the thin-film regions without reducing the capillary performance to deliver the high heat transfer coefficient without sacrificing the maximum heat flux. The capillary and thermal performance of DHS wicks are investigated with the energy minimization algorithm [18] and finite element methods reported in our previous studies [7,9]. Compared with the previous single-height superhydrophilic (SHS) micropost wicks [7,9], suggested DHS wicks can significantly enhance the heat transfer coefficient without scarifying the maximum heat flux by vertically stretching the evaporative thin film region. The sensitivity of heat transfer and capillary performance to liquid fill charge also decreases over 60% for DHS wicks compared with SHS wicks.

2. Concept of dual-height superhydrophilic (DHS) micropost wicks

Fig. 1 shows the concept of DHS micropost wicks suggested in this study. The cylindrical posts are assumed to be hexagonally-packed (Fig. 1(a)). Unlike the previous SHS wicks (Fig. 1(b)), the DHS micropost wicks consist of microposts with two different heights within a single unit cell (Fig. 1(c)). As in Fig. 1(c), the middle post in the unit cell is extended upward while other two posts are remained at the same level.

The proposed DHS micropost wicks can be manufactured using two-step electrochemical deposition processes combined with chemical oxidation. Even though this work only focuses on modeling approaches, we summarize the suggested fabrication process flow in Fig. 2 to clarify the potential of the new wicks for practical applications. First, we grow uniform Cu micropost arrays though the lithographically patterned mold layer using the electrochemical deposition. Then we pattern another mold layer and repeat the electrochemical deposition to form taller microposts. After removing the mold, the dual-height Cu microposts are immersed into a hot alkaline solution to incorporate thin CuO layers on the entire wick surfaces. The details on the Cu electrochemical deposition and CuO integration are well summarized in our previous publications [7,9,19].

The performance of DHS micropost wicks is compared with that of SHS micropost wicks by varying the design parameters. The ranges of the design parameters are determined from our previous studies on SHS micropost wicks [7,9] and listed in Table 1. Dense hexagonal arrays of cylindrical microposts of solid fraction ranging from 0.18 to 0.54 are investigated with fixing the post diameter at 50 μm or 70 μm. The contact angle of the post walls is set to be 10° based on the experimental characterizations of previously demonstrated superhydrophilic microposts with CuO nanostructures [9,19]. The reference height of microposts is determined to be 100 μm since the permeability decreases rapidly below ~100 μm with current solid fraction and post diameter ranges [9].

For DHS microposts, the maximum height ratio (HR_{max}) between the short and tall posts (h_t/h_s) is determined considering a pinning condition of liquid meniscus. Fig. 3(a) and (b) show the schematic of DHS micropost wick and cross-sectional views of DHS microposts with liquid meniscus, respectively. The angles between the meniscus and the side walls of short and tall microposts are defined as ϕ_s and ϕ_t, respectively. In near equilibrium state (Fig. 3(c)), ϕ_s and ϕ_t are less than 90° for superhydrophilic microposts. Then the meniscus is assumed to be pinned at the tip of the microposts when ϕ_s and ϕ_t are larger than the receding contact angle of the post sidewall $\theta_{r,s}$. Since ϕ_s is larger than ϕ_t, the pinning condition can be simplified as $\phi_t > \theta_{r,s}$. When the operating fluid is oversupplied, ϕ_s can be larger than 90° (Fig. 3(d)). In this case, ($\phi_s - 90$) should be smaller than the advancing contact angle of the post top wall $\theta_{a,t}$ ($\phi_s - 90 < \theta_{a,t}$) to maintain the pinning status.

To set up a conservative criterion, the cross-sectional profile of the meniscus is assumed to be circular. We note that the actual cross-sectional radius of curvature of the equilibrium meniscus is smaller than that of circular one (see Fig. 6(a) and (b)). Then, the maximum height difference (Δh_{max}) between the tall and short posts approximately equals to the wall-to-wall distance l ($\Delta h_{max} \approx l$) for superhydrophilic microposts as in Fig. 3(d). The extracted HR_{max} values for each solid fraction are listed in Table 1 with other design parameters. The HR_{max} decreases as the solid fraction increases (with a fixed diameter) due to the decrease in the wall-to-wall distance (l).

3. Model development

3.1. Capillary model

The maximum heat flux capability of micro heat pipes is primarily determined by the capillary performance of evaporator

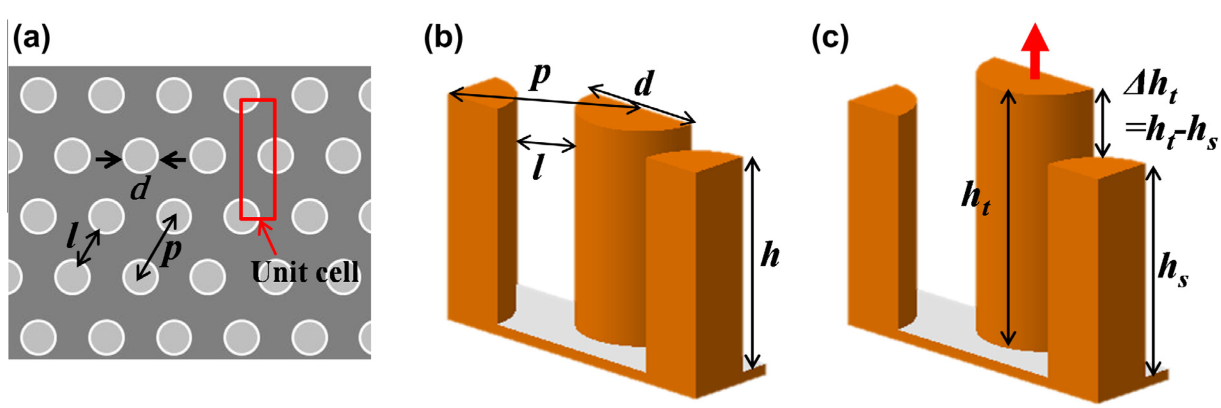

Fig. 1. (a) Top view of a hexagonal array of circular microposts, the rectangle shows the definition of the unit cell, (b) Schematic of the unit cell of SHS micropost wick and (c) Schematic of the unit cell of DHS micropost wick. d, p and l represent the diameter, pitch and wall-to-wall distance of micropost wicks, respectively. For DHS micropost wicks, the middle post is extended upward (see red arrow). h_t and h_s represent the height of tall and short microposts, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)