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Optimization and thermal characterization of uniform silicon micropillar based evaporators

Mengyao Wei [a,b], Bin He [a], Qian Liang [a], Sivanand Somasundaram [a], Chuan Seng Tan [a,b,1], Evelyn N. Wang [a,c,*]

[a] *Low Energy Electronic Systems (LEES) IRG, Singapore-MIT Alliance for Research and Technology (SMART) Centre, 1 CREATE Way, Singapore 138602, Singapore*
[b] *School of Electrical and Electronics Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore*
[c] *Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States*

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ABSTRACT

The development of high power density and compact electronic devices result in the generation of large and concentrated heat loads, which need to be dissipated effectively to avoid electronics failure. Vapor chambers are promising candidates to overcome the thermal management challenges, owing to its passive working mechanism and excellent heat removal capability. Micropillar-based evaporators for these vapor chambers allow for high capillary pressure, large permeability and extended evaporation areas, which enhances the critical dryout heat flux of the vapor chamber. However, predictive models that evaluate the performance of micropillar evaporators are limited, where the selection of micropillar geometries is typically based on empirical data and the evaporator temperature rise has not been considered. In this paper, we report a comprehensive and systematic study of cylindrical silicon micropillar-based uniform evaporators. First, we constructed a semi-analytical model to predict the capillary-limited dryout heat flux. We performed an optimization to select the micropillar geometries by considering the evaporator temperature rise. Subsequently, we microfabricated uniform evaporators with various geometries and thermally characterized the evaporators in a controlled vacuum environmental chamber. Then, we validated the model with the experimental results and showed that the model and experiments have reasonable agreement within 20%. The heat transfer coefficients decreased with smaller micropillar diameter/pitch ratios and taller micropillar heights. This work provides comprehensive insights into the design of uniform micropillar-based evaporators and can serve as useful guidelines for advanced vapor chambers and other phase-change devices.

1. Introduction

The miniaturization and increasing power density of electronic devices lead to large heat fluxes and severe temperature rises. Since the lifetime of the electronic device decreases exponentially with temperature [1], thermal management is essential in maintaining device reliability. However, it is challenging to dissipate the large and concentrated heat flux with traditional thermal management techniques, such as air cooling and liquid cooling [1]. Therefore, the utilization of phase-change spreaders has drawn much attention, which takes advantage of the high latent heat associated with liquid-to-vapor phase change and its passive working mechanism [2]. A vapor chamber, which is a 2D planar heat spreader, promises large heat dissipation capability, high temperature uniformity and a thin form factor, and therefore has been of particular interest to address the large heat generation encountered by high performance electronic devices [3]. A vapor chamber is composed of evaporator, condenser and adiabatic sections with a working fluid enclosed inside. A key element for the vapor chamber is the evaporator, which absorbs the heat and circulates the working fluid to achieve continuous operation. Therefore, significant efforts have been directed toward the design of the evaporator. In particular, micropillar evaporators promise high capillary performance, high permeability, large thin film evaporation areas, and are easy to fabricate [4] as compared with conventional sintered powder, wire meshes and microgroove evaporator structures [5].

Micropillar evaporator structures are composed of periodically or randomly packed micro size posts with various shapes, i.e. cylindrical, rectangular, pyramidal or conical shapes. Past work on

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* Corresponding author at: Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, United States.

E-mail addresses: TanCS@ntu.edu.sg (C.S. Tan), enwang@mit.edu (E.N. Wang).

[1] Co-corresponding author.

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Nomenclature

A	area
I	current
K	permeability
L	wicking length
P	pressure
R	resistance
T	temperature
U	voltage
V	volume
a	slope of resistance-temperature relationship
b	intercept of resistance-temperature relationship
c	solid fraction
d	micropillar diameter
d	derivative
h	micropillar height
k	thermal conductivity
l	micropillar pitch (center-to-center distance)
q	heat flux
u	flow velocity
x, y, z	x, y, z directions
h_c	heat transfer coefficient
rf	roughness factor

Subscripts

app	applied
c	coefficient
cap	capillary
eff	effective
fg	latent heat
l	liquid
$loss$	heat loss
m	actual meniscus
p	projected meniscus
$pillar$	silicon micropillar
sat	saturation
$sensor$	RTD sensors
Si	silicon
SiO_2	silicon dioxide
$wafer$	silicon wafer
$2D$	planar

Greek symbols

Δ	difference
ε	porosity
θ	contact angle
ν	evaporation rate
μ	viscosity
π	pi constant
ρ	density
σ	surface tension

micropillar evaporators has focused on various aspects of modeling, fabrication and experimental characterization [6–22]. As the performance of the micropillar evaporator is determined by the balance of permeability and capillary pressure, accurate predictions of these parameters are essential in designing micropillar evaporators. Permeability models have been developed based on a unit cell approach and the lubrication approximation for squarely, hexagonally and randomly packed cylindrical micropillar arrays with various porosities [6–10] in the past. More accurate permeability predictions were demonstrated by the semi-analytical Brinkman model which balances viscous resistance with capillary pressure. The model estimations from Xiao et al. [11] showed good agreement with simulations, with deviations <5%. More recently, an analytical solution proposed by Hale et al. [12] considered the 2D velocity profile of liquid flow and provided accurate permeability predictions for micropillars with aspect ratios less than 5. However, the liquid meniscus was assumed to be flat in most of the previous permeability models [6–12]. Thus, Byon et al. [13] investigated pillar array permeability based on Brinkman's equation by considering the effect of meniscus shape. They concluded that the flat meniscus assumption overestimated the permeability, especially for low pillar heights and contact angles. For a micropillar surface with contact angle = 0°, $d/l = 0.5$ and $h/l = 1$, the overprediction was calculated to be 26%. Meanwhile, the capillary pressure of micropillar arrays has been modeled by Srivastava et al. [14] and Xiao et al. [11,15]. Srivastava et al. [14] calculated capillary pressure by modeling the surface energy change due to liquid front propagation only. The liquid meniscus shape was also simulated based on energy minimization approach, and capillary pressure was defined as surface energy change in filling each unit volume by Xiao et al. [11,15]. Later, Ravi et al. [16,17] fabricated silicon (Si) micropillar based evaporators and compared the accuracies of these models [6–15] based on experiments. According to this study, the capillary pressure model of Srivastava et al. [14] had an average error of around 42% compared to experimental results. Therefore, the capillary pressure model developed by Xiao et al. [11,15] and permeability model proposed by Byon et al. [13] were proven to provide more accurate estimations of the liquid transportation capabilities for micropillar arrays.

In addition to these isothermal liquid propagation models, heat transfer characterization of micropillar evaporator focusing on its maximum heat dissipation capabilities have been investigated. The liquid propagation rate and maximum heat dissipation capability with micropillar arrays were found to strongly depend on micropillar geometric factors, such as porosity and micropillar array thickness [18–20]. Adera et al. [1] modeled the capillary pressure, permeability, thermal resistance and capillary-limited maximum flux of micropillar evaporators with ±20% deviation based on accurately controlled experiments. The dryout heat flux was found to increase with micropillar wick height and identified that an optimal pillar spacing and diameter existed. A numerical model that simulated the 3D meniscus shape variation along the wicking direction was investigated by Zhu et al. [21]. They predicted the maximum heat flux and suggested a d/h range of 0.4 to 0.6 and $l/d \sim 3$ for wick structure design. The strong dependence of liquid transport and heat dissipation capability on the micropillar geometries indicated the importance of micropillar geometry optimization.

However, micropillar geometries in the past literature has been primarily selected based on experiments. The effect of micropillar geometries (diameter d, pitch l and height h) on both dryout heat flux and heat transfer coefficient have not been systematically studied. Horner et al. [22] optimized the micropillar geometries with a limited parametric sweep based on the model developed by Ravi et al. [16,17]. But, the optimization was conducted for the dryout heat flux of micropillar evaporators without considering the evaporator temperature rise in their work. The temperature rise of the evaporator is an important factor, since an evaporator that can dissipate a large amount of heat but with a high temperature rise lacks practical use and leads to device burn-out. There-