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Wicking and thermal characteristics of micropillared structures for use in passive heat spreaders

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ABSTRACT

The thermal and hydrodynamic performance of passive two-phase cooling devices such as heat pipes and vapor chambers is limited by the capabilities of the capillary wick structures employed. The desired characteristics of wick microstructures are high permeability, high wicking capability and large extended meniscus area that sustains thin-film evaporation. Choices of scale and porosity of wick structures lead to trade-offs between the desired characteristics. In the present work, models are developed to predict the capillary pressure, permeability and thin-film evaporation rates of various micropillared geometries. Novel wicking geometries such as conical and pyramidal pillars on a surface are proposed which provide high permeability, good thermal contact with the substrate and large thin-film evaporation rates. A comparison between three different micropillared geometries – cylindrical, conical and pyramidal – is presented and compared to the performance of conventional sintered particle wicks. The employment of micropillared wick structure leads to a 10-fold enhancement in the maximum heat transport capability of the device. The present work also demonstrates a basis for reverse-engineering wick microstructures that can provide superior performance in phase-change cooling devices.

1. Introduction

Heat spreading and dissipation from microelectronics packages are posing an increasing challenge due to the large heat fluxes encountered. Phase change cooling devices, such as heat pipes and vapor chambers (Fig. 1), can dissipate heat from a small high-flux heat source to a low-flux diffuse area with very low temperature drops [1,2]. These devices contain discrete evaporator and condenser regions for heat input and rejection, respectively, while utilizing a capillary porous medium, also known as the wick structure, to transport the working fluid from the condenser to the evaporator regions by capillary action. The device utilizes the latent heat of the working fluid for achieving high heat transport capability. A major bottleneck in enhancing the thermal performance of the heat pipe is the thermal resistance of the wick [3,4]. At heat fluxes below approximately 100 W/cm^2 and for thickness-constrained packaging applications, the evaporator resistance has been shown to be the most critical component in reducing the thermal resistance of the device [5,6]. The evaporator resistance is comprised of the bulk resistance of the wick material as determined by its thermal conductivity, and the resistance offered by the evaporating liquid meniscus as determined by the thickness of the liquid film near the solid–liquid contact line [7]. The temperature drop across the evaporator, ($T_e - T_v$), as depicted in Fig. 1 is typically the largest temperature drop in the heat pipe. While the resistance offered by the bulk wick structure in the evaporator section is the limiting resistance in many conventional applications, the meniscus resistance has been shown to be important for very thin (<200 μm) [5] high thermal conductivity wick structures (k > 100 W/mK) [8,9]. Furthermore, the maximum transport capability of a heat pipe (its capillary limit) is determined by the liquid transport in the wick structure. Hence, the device performance may best be improved by optimizing the wick structure. Moreover, the introduction of novel wicking structures with improved liquid transport and thermal performance characteristics is essential for the design of next-generation thermal spreaders.

In recent work, the authors [3,7] studied the wicking and evaporation characteristics of various wick microstructures, *viz.*, sintered particles, screen meshes, rectangular grooves and cylindrical micropillars, and concluded that sintered particle wicks have the best performance characteristics among those considered. They also showed that intense evaporation occurs from a very thin liquid film region (film thickness <10 μm) formed near the solid–liquid contact line in the pore of the wick structure, also known as the thin-film region [10,11]. Wick structures which sustain a larger thin-film area on the liquid meniscus lead to higher rates of evaporation heat transfer [3,7]. While sintered particle wick

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Nomenclature

A	area
C_P	specific heat
D	diameter of sphere/pillar, base side length of pyramidal pillars
h	height of liquid free surface from bottom surface in the initial configuration
h_b	base heat transfer coefficient
h_{evap}	convection heat transfer coefficient for evaporation
h_{fg}	latent heat of evaporation
h_{nat}	heat transfer coefficient for natural convection
h_l	liquid enthalpy
H	dimensionless height of liquid free surface ($=h/L$)
k	thermal conductivity
K	permeability
l	height of the pillars
L	characteristic length ($=r=d/2$)
$\dot{m}''$	evaporative mass flux
$\overline{M}$	molecular weight
Nu	Nusselt number ($h_{nat}L/k$)
p'	pitch
P'	non-dimensional pitch (p'/L)
p, P	hydrodynamic pressure
ΔP_c	capillary pressure
Pr	Prandtl number
$\dot{q}$	heat transfer rate
r	radius of pillars/spheres
r_p	pore radius
$\overline{R}$	universal gas constant
Ra	Rayleigh number ($=(g\beta|T_{wall}-T_v|d^3Pr)/\nu^2$)
Re	Reynolds number ($=\rho dV/\mu$)
S_M	mass source term
T	temperature
V	velocity/volume

Greek Symbols

α	thermal diffusivity
β	thermal expansion coefficient
δ_0	non-evaporating thin-film thickness
δ	thin-film thickness
ε	wick porosity
σ	surface tension between liquid and vapor phases
ρ	density of liquid
θ	contact angle between liquid and solid surface
ν	kinematic viscosity
μ	dynamic viscosity
$\hat{\sigma}$	accommodation coefficient

Subscripts

b	base substrate area in evaporation model
bot	bottom solid wall
cell	cell element
e	evaporator
equ	equilibrium
f	face of cell element
l	liquid
lv	liquid–vapor interface
max	maximum
mic	micro-region of the meniscus
sat	saturation
ref	reference
v	vapor
wall	non-wet portion of the solid wall

structures have been shown to have good wicking and thin-film evaporation characteristics, their bulk thermal conductivity (~40 W/mK [12]) is lower than that of recently explored micropillared geometries [13–15] for heat pipes.

Micropillared wicks have been investigated for lab-on-a-chip [16], biomedical [17] and thermal management [14] applications. Pillar structures may be used in microchannels to increase the surface/volume ratio and to increase capillary flow [18]. Xiao et al. [15] presented an experimentally-validated semi-analytical model for predicting the rate of propagation of a liquid through micropillar arrays. They used the software SURFACE EVOLVER [19] to compute the shape of the liquid meniscus in a unit cell of the micropillar array. The meniscus shape was utilized to obtain correlations for the liquid volume filling the microstructure as well as the meniscus area for a given pillar diameter and pitch. Ding et al. [13] fabricated titanium micropillars and studied the wetting behavior of the pillars using numerical and experimental techniques. Advanced photolithography techniques have enabled the fabrication of novel micropillared structures which can decrease the evaporator resistance and improve heat pipe performance. In

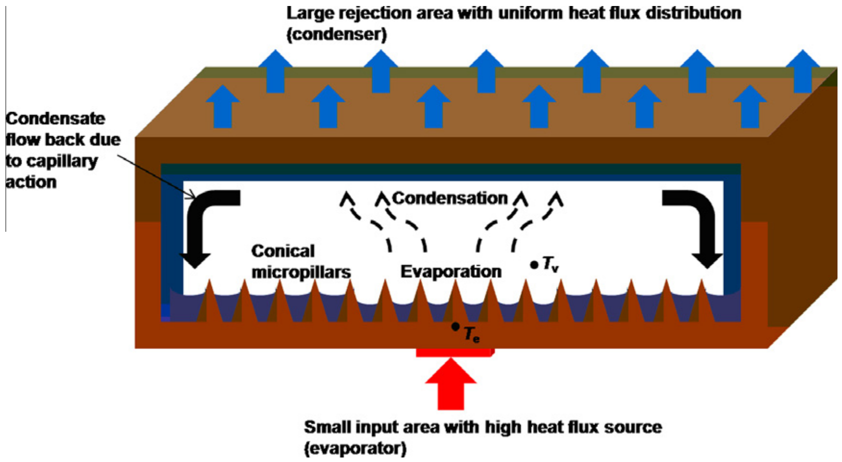

Fig. 1. Schematic of a flat heat pipe (vapor chamber).