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Enhancement of thermal performance of micro heat pipes using wettability gradients

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ABSTRACT

We present a methodology for enhancing thermal performance of micro heat pipes (MHPs) by creating wettability gradients on the inner surface of MHPs. We analyse the effect of wettability gradients on MHP performance using a quasi one-dimensional mathematical model that accounts for axially-varying solid–liquid contact angle. For our analysis, we consider MHPs with various wettability schemes, such as uniform, step-variation, and linear variation in the contact angle. Our model predictions show that increasing the wettability of the evaporator surface and reducing the wettability of the condenser surface of MHP can lead to an increase in the heat transfer capacity of MHP by over 35%. We demonstrate the favourable effect of wettability gradients on MHP performance for different working fluids over a wide range of operating temperature and fluid charge. We also discuss the underlying physical mechanism that leads to enhanced thermal performance of MHP with mixed wetting surfaces. We show that the optimal choice of wettability gradient in MHP is governed by the competing effects of high liquid flow resistance in the lower wetting condenser and high liquid mass in the higher wetting evaporator.

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1. Introduction

Continuous miniaturisation of electronics and increase in integration levels pose challenges in thermal management of microelectronic components [1,2]. As the failure rate of microelectronic chips increases exponentially with the operating temperature [2], cooling of chips is essential to ensure reliable operation. Micro heat pipes (MHPs) offer an efficient means of passively removing heat of order 10 W/cm^2 from microelectronic equipment using phase change phenomenon [3–5].

A typical MHP consists of a channel with sharp edges filled with a working fluid. The sharp edges of the heat pipe allow liquid flow due to capillary action, while the vapour flows through the inner core of channel. Fig. 1 shows a typical triangular cross-section MHP consisting of evaporator, adiabatic, and condenser sections. Heat input to the evaporator section vaporises the working fluid. The local increase in vapour pressure in the evaporator section drives the vapour to relatively cooler condenser section. The vapour condenses back to liquid in the condenser section and rejects the latent heat. The loss of liquid in the evaporator section results in reduced radius of curvature of the liquid meniscus. Whereas, the increase of liquid in the condenser section causes the local radius of curvature of meniscus to increase. Consequently, a pressure gradient develops in the liquid which drives the liquid from the condenser to the evaporator section, thereby completing the cycle. Although MHPs offer a reliable and passive chip cooling solution, MHP arrays in their current state can only transfer heat of order 10 W/cm^2 [6]. Therefore, any further improvement in the maximum heat transfer capacity of MHPs will help in dealing with growing challenges of thermal management of microelectronics.

The maximum heat transport capacity of an MHP depends on its geometry, working fluid, and the wettability of its inner surface. Since MHP relies on capillarity to transfer liquid from condenser to evaporator section, variation in geometry can strongly affect the performance of MHP. The capillarity of MHP can be enhanced by making the corners of MHP small and sharp. However, the reduced size of corners leads to higher hydraulic resistance to the liquid flow. Therefore, as discussed by Ma and Peterson [7], there exists an optimal geometry of MHP governed by the competing effects of capillary action and hydraulic resistance. Using an experimentally validated mathematical model, Ma and Peterson [7] showed that, for an MHP, an optimal groove size exists below which increased hydraulic resistance deteriorates its maximum heat transport capacity. Whereas, for groove size larger than the optimal size, reduced hydraulic resistance is unable to compensate

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Nomenclature

$\bar{u}$	mean velocity
$\dot{m}$	mass flow rate
A	flow area
$a/2$	groove side length
D	hydraulic diameter
fRe	Poiseuille number
h_{fg}	latent heat of vaporisation
L	length
N	number of grooves
p	pressure
Q	heat rate
R	half of the hydraulic diameter
r	radius of curvature
Re_c	radial Reynolds number in condenser section
Re_e	radial Reynolds number in evaporator section
x	distance from beginning of the evaporator section

Greek symbols

γ	half of apex angle of groove
μ	viscosity
ρ	density
σ	surface tension
θ	contact angle

Subscripts

a	adiabatic section
b	liquid block
c	condenser section
e	evaporator section
eff	effective
in	input
l	liquid
max	maximum
min	minimum
v	vapour

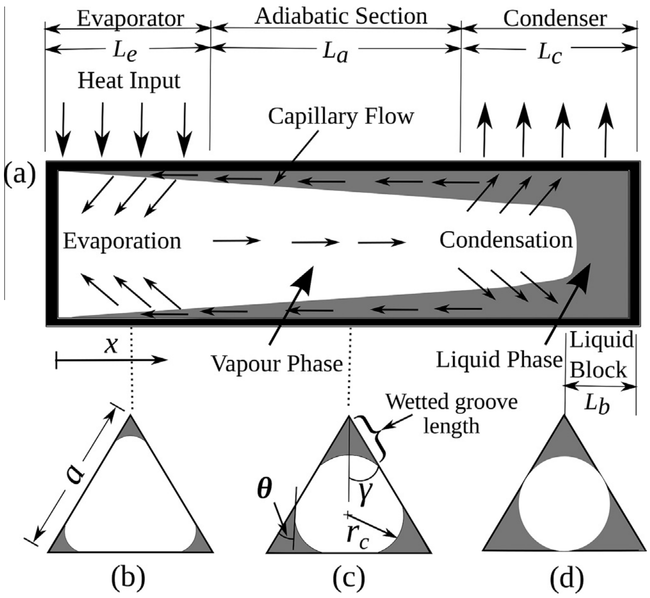

Fig. 1. Schematic illustrating operation of an MHP with triangular cross-section. (a) Heat input to the evaporator section causes the liquid in the corners of evaporator section to evaporate. The increased vapour pressure in the evaporator section drives the vapour to the condenser via the adiabatic section. The vapour condenses to liquid in the condenser section and rejects the latent heat. The increased amount of liquid in the condenser section (d) leads to larger radius of curvature of liquid meniscus compared with that in the evaporator (b) and the adiabatic sections (c). Consequently, an axial gradient in capillary pressure develops which drives the liquid back to the evaporator, thereby completing the working cycle of MHP.

for reduced capillary pumping. Here, we note that the optimal geometry of MHP is specific to the working fluid and the wettability of inner surface.

Another way of improving the heat transport capacity of an MHP is by using the right working fluid [8,9]. The operating characteristics of MHP depends on the thermo-physical properties of the working fluid, such as surface tension σ, liquid density ρ_l, latent heat of vaporisation h_{fg} and liquid viscosity μ_l. The effectiveness of the working fluid in MHP is usually characterised by a dimensional constant $(\sigma\rho_l h_{fg})/\mu_l$, termed as the Merit number [8]. The Merit number can be considered as a product of two terms, σ/μ_l and $\rho_l h_{fg}$. The first term σ/μ_l has the dimension of velocity and can be interpreted as the circulation rate of the working fluid [10]. Whereas, $\rho_l h_{fg}$ is the latent heat of evaporation per unit volume. Therefore, higher Merit number for a working fluid indicates better performance of the heat pipe. The thermo-physical properties of the working fluid and hence the Merit number are strongly dependent on the operating temperature. This affects the choice of working fluid for heat pipes operating at different working temperatures. For example, based on the Merit number, Reay and Kew [8] have shown that for operating temperatures below 323 K ammonia as a working fluid yields better performance than water. Whereas, water is preferable over ammonia as the working fluid above 323 K.

Besides the MHP geometry and working fluid, the heat transport capacity of MHP can also be increased by changing the wettability of inner surface of MHP. As shown experimentally by Wu and Peterson [11] and theoretically by Khrustalev and Faghri [12], the performance of MHP is enhanced if the working fluid wets the inner surface of MHP. This is because the capillarity increases when the liquid–vapour interface makes smaller contact angle with the solid surface. Most of the studies on the effect of wettability of surface on MHP performance have been limited to the case where the MHP surface has axially uniform wettability [9,12–15]. Recently, Hu et al. [16] experimentally demonstrated that heat pipes with axially varying wettability can yield enhanced heat transport capacity, compared with heat pipes with axially uniform wettability. Hu et al. chemically treated the inner surface of a grooved heat pipe to create a step variation of contact angle in evaporator, adiabatic, and condenser sections. Based on their experiments with water as the working fluid, Hu et al. [16] demonstrated that the heat pipe with a positive contact angle gradient from evaporator to condenser section (that is, higher wetting evaporator and lower wetting condenser), outperforms the heat pipe with uniformly higher wetting inner surface.

Using wettability gradients in MHP is particularly interesting because it can yield enhanced heat transport capacity over and above the thermal performance obtained by optimising MHP geometry and selection of appropriate working fluid. Moreover, wettability gradients can be generated on a variety of surfaces, such as using alkali surface oxidation [17] and laser etching [18] of copper, silane diffusion [19,20] on silicon wafers, and contact printing of octadecyltrichlorosilane [21] on oxidised silicon wafers.

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