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Experimental investigation of a novel asymmetric heat spreader with nanostructure surfaces

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ABSTRACT

A novel asymmetric vapor chamber is developed in this study. In this vapor chamber, nanostructure is patterned on the inner top surface of condensing wall and this condensing wall is made to be superhydrophobic to replace the conventional porous wick. This improvement not only results in drop-wise condensation which has a much higher heat transfer coefficient compared with film condensation, but also provides a shortcut for the condensed water to drop back directly to the center wick. Thus, a smaller liquid flow resistance and higher anti-dryout capability are achieved. The evaporator wick is made of sintered multi-layer copper powder. The dimensions of the vapor chamber are 70 × 70 × 3 mm^3. The test module includes an aluminum block with recirculated cooling water going through it and a heater with an area of 1.5 × 1.5 cm^2. The optimum working pressure is determined by testing the performance of the vapor chamber under different initial pressures. Heater temperature, horizontal resistance and vertical resistance are identified as key parameters to evaluate the performance of heat spreader. It is found that heater temperature increases with increasing heat flux. However, the vertical resistance shows the opposite tendency with increasing heat flux. The performance of the novel vapor chamber is compared with that of a conventional vapor chamber and copper plate. The newly developed vapor chamber can greatly reduce the heater temperature. Furthermore, better temperature uniformity and a lower vertical resistance can be achieved for the newly developed vapor chamber which is promising for the thermal management of high power electronic devices.

1. Introduction

With the increase of both heat dissipation and heat flux concentration of electronic devices, the cooling problem becomes more and more challenging, especially for high power electronic devices, such as the CPU, GPU and high intensity light-emitting diode (LED), a promising new generation of lighting source. However, a more critical thermal problem is that for ultra-high power μ-LEDs the heat flux in the die may reach a few hundred Watts per square centimeter. This high thermal concentration results in the hot-spot phenomenon. In addition, the high spreading resistance is caused by the heat sink, which has a larger area than the chip. The hot-spot effect and high spreading resistance result in a higher junction temperature, which not only lowers its efficiency, but also reduces the life cycle and reliability of high power devices.

Phase change liquid cooling is accepted as an attractive cooling method for an increasing number of applications. Phase change cooling devices, such as spray cooling, can be used to remove a large amount of heat from electronic devices [1]. The vapor chamber is widely used in high-flux cooling applications for its low thermal resistance and temperature uniformity over a solid conduction heat spreader. Various wick structures have been studied and reported in the literatures, both in terms of detailed experimental investigations and analytical modeling efforts [2–17]. However, the design of wicks inside a vapor chamber is not cost effective. The wick structure in the evaporator region of a heat pipe determines its thermal performance and maximum heat transport capability. Optimizing the design of the structure is crucial to its operation at high heat fluxes. Ram et al. [18] used three different micro-pillared geometries (cylindrical, conical and pyramidal) to make the capillary evaporator wick in vapor chambers. The performances of wick with these three micro-pillar geometries are compared with that of conventional sintered particle wick by a numerical method. Surfaces with pyramidal micro-pillars are found to perform the best, generating the highest capillary pressure and having the highest evaporation rate among all the microstructures.

Carbon nanotube (CNT) clusters have a high thermal conductivity, nano-pore size, and large porosity and can be used as the wick structure in a heat pipe heat spreader to provide a high capillary force for high-heat-flux thermal management. Zhou et al. [19] and Cai et al. [20] proposed the usage of CNT arrays as the wicking structure for high flux cooling applications. Justin et al. [21] de-

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Nomenclature

Letters

R	thermal resistance (°C/W)
T	temperature (°C)
q	heat flux (W/cm^2)
l	distance between thermocouples (mm)
A	area (m^2)
Q	heat load (W)
k	thermal conductivity (W m^{-1} K^{-1})

Abbreviations

hr	horizontal resistance
vr	vertical resistance
h	heater
b	bottom
avg	average
eff	effective thermal conductivity
VC	vapor chamber
CHT	critical heat flux
HTC	heat transfer coefficient
CNT	carbon nanotube

Greek symbols

α	aspect ratio
ΔT	temperature difference

signed a vapor chamber with an integrated CNT nanostructure and sintered powders in the evaporator section. The nanostructures feature very small pore sizes that support high capillary pressures, and the microstructures provide the required permeability for liquid flow. It is found that thermal resistance is reduced by a factor of thirteen through the use of the integrated nanostructured wick compared with the resistance of a homogeneous sintered powder wick. Mitsuo et al. [22] developed a nanostructured two-phase heat spreader for cooling ultra-high heat flux sources. The wicking structure in the evaporator is fabricated by coating multi-walled CNTs on the top surface of sintered copper powder. Reductions in thermal resistance are up to 20–37% with CNT nanostructure compared to a bare sintered surface.

Most of the previous works are focused on the improvement in the wick structure in the evaporator section of the phase change heat spreader. Few scholars try to change the wick structure in the condenser section. Shwin-Chung Wang et al. [23] proposed a novel vapor chamber with the conventional wicked top condenser wall replaced by a top plate with fine parallel grooves. The peaks of the grooves are in direct contact with the bottom wick, the corrugated groove walls provide not only an enlarged condensation area, but also a shortcut for the condensed water to directly flow back to the wick. Amy et al. [24] manufactured surfaces combining hydrophobic and hydrophilic zones for pool boiling experiments. As a result, the patterning of mixed hydrophilic and hydrophobic areas can improve the critical heat flux (CHF) and the heat transfer coefficient (HTC) of a plain hydrophilic surface by 65% and 100%, respectively. This improved boiling heat transfer method with a nanostructure patterned surfaces has the potential to improve the performance of vapor chamber.

In this paper, based on our previous research [25], a nanostructure patterned surface which shows a super hydrophobic feature is proposed as the condenser wall in a novel vapor chamber. The performance of the novel vapor chamber is investigated in details. The wick structure in the evaporator section is made of sintered copper powder of varying sizes. This combination of hydrophobic and hydrophilic surfaces shows further enhancement of vapor chamber performance. Besides, the optimum working pressure in the vapor chamber after feeding water is determined.

2. Experimental study

A novel design for the vapor chamber is investigated. In comparison with a conventional one, the major difference is the replacement of the conventional wick-laid upper wall with a super-hydrophobic condensing wall. Fig. 1 illustrates the working principle of our novel vapor chamber. Heat is inputted through the wall and wick structure from the center bottom, the working fluid (degassed deionized water) absorbs heat and is vaporized. When reaching the cold upper wall, the vapor condenses quickly forming a droplet and dropping down directly from the super-hydrophobic wall. This super-hydrophobic surface has several advantages: (1) It can effectively prevent the generation of a liquid film, which may significantly degrade the condensation efficiency; (2) the vapor can easily condense to a droplet on this surface, which then drops down directly into the wick. This can shorten the water feeding route and prevent dry-out in the center wick.

2.1. Design of evaporator

The base of the evaporator is made of oxygen free red copper plate and the area is 70 × 70 mm^2. Support studs are needed to prevent distortion by inward compression as shown in Fig. 2. The wick structure in the evaporator is formed by sintering a layer of copper powder. First powder of size 57 μm is selected to fill the center rectangular slot. Then powder of size of 100 μm is chosen to cover the overall plate. The thickness of this copper powder layer is 0.5 mm. Sintering is performed in a 975 °C hydrogen/nitrogen atmosphere for 2.5 h. This kind of multiple layer wick structure has an excellent anti-dryout feature which allows water to be more easily dragged into the center wick. This is because the pores in the central wick are smaller than those in the marginal wick, and smaller pores will provide a higher capillary pressure to drive the liquid flow. A copper tube is used to feed water and evacuate air.

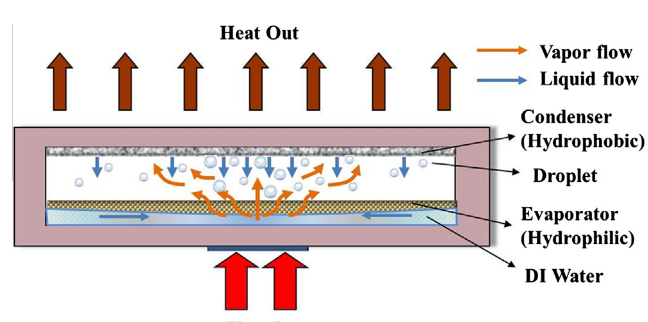

Fig. 1. Schematic of the asymmetric vapor chamber with a super hydrophobic condensing wall.