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Effect of nano-structure coating on thermal performance of thermosyphon boiling in micro-channels

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ABSTRACT

A novel micro-channel thermosyphon technology for passively cooling 3D stacked chips was provided, and the thermosyphon boiling characteristics in vertical and inclined micro-channels with two open ends which simulate the specific stacked structure of actual 3D chip were experimentally carried out. In order to improve the heat transfer of micro-channel thermosyphon by surface treatment technology, four kinds of nanoparticles (CuO, Cu, Al_2O_3, SiO) were added to the base fluid to make nano-structure coatings on the heater surfaces by using a long time pool boiling treatment. Then, micro-channel thermosyphon boiling experiments were carried out with four kinds of working liquids: two kinds of pure fluids (deionized water and R113) and two kinds of moist fluids (deionized water+surfactant and R113+surfactant). The gaps and heights of micro-channels tested were in the range of 30–60 μm and 30–90 mm, respectively. Experimental results show that nano-structure coatings can significantly enhance both the maximum heat flux and heat transfer coefficient of thermosyphon boiling in micro-channels, and exist both the optimal nanoparticle kind and nanoparticle concentration in the base fluids. The experimental results provided some meaningful technology support for 3D stacked chip cooling.

1. Introduction

With the rapid development of micro electric technology, 3D stacked chips have been considered as a new chip integration technology in which that chips are no longer connected side by side, but the upper and lower parallel connection, and 3D integration technology is also considered as the preferred option to achieve miniaturization. If the heat generated by the chips cannot be dissipated in time, it will result in temperature excursion, which not only impacts the normal operation of the chips, but also reduces its longevity due to the fact that long term reliability drops by 50% for each 10° rise in junction temperature [1].

Cooling of 3D chips cannot simply apply the cooling methods of traditional 2D chips in which the cooling channels are mounted in the substrate. However, the most 3D chips cooling technologies are still the simple extension of 2D chips cooling technologies, in which micro-channels with various shapes are installed in encapsulation, and working fluid are driven by external power flows through the micro-channels to take away heat [2–7]. These cooling methods belong to active type methods and have several great drawbacks. In addition, many researchers carried out various designs, experimental and simulated studies for Three-Dimensional Integrated Circuits [8–12]. A few of researchers proposed some designs and simulations including micro flat heat pipe system and forced convective system for cooling 3-D packaged chips [13–15].

Recently, the authors provided a new passive cooling conception for 3D chips cooling and carried out an initially experimental result [19]. A vertical micro-scale thermosyphon structure was designed by utilizing 3D chips' specific micro structure to form thermosyphon boiling with the driving force composed of buoyancy and capillarity for 3D stacked chips cooling. As well known, Conventional 3D stacked chip encapsulation is placed horizontally. But if it is deliberately arranged vertically, tens of microns gaps between chips can form vertical micro-channels with two open ends. According to this geometrical characteristic, insulating liquid is filled in the lower half of the encapsulation and submerges the 3D stacked chips, and then the vertical micro-channels submerged in saturated liquid would form the evaporation section of a micro-scale thermosyphon heat pipe. The upper surface of the encapsulation can be developed as heat sink for condensation. Saturated liquid flows upward along micro-channels and absorbs heat generated in chips, then evaporates into saturated steam gradually, eventually, discharges from the upper outlet of the chips continuously by buoyancy and capillarity. This heat transfer mode

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Nomenclature

b	width of channel (m)
d	gap of channel (m)
h	heat transfer coefficient ($W/m^2 \cdot K$)
L	length of channel (m)
I	electric current (A)
P	power (W)
q	heat flux (W/m^2)
q''	critical heat flux (W/m^2)
S	surface area (m^2)
t	temperature (K)
ΔT	mean superheating (K)
U	voltage (V)

Greek letters

θ	inclined angle of channel

Subscripts

0	pure liquid
h	horizontal
v	vertical
θ	inclined angle of channels

is generally called thermosyphon boiling. A lot of research have revealed the thermosyphon boiling mode and the boiling heat transfer mechanism in micro channels [16–18]. The present concept of micro-channels thermosyphon is different from that of traditional thermosyphon. In traditional thermosyphon, the governing force is only buoyancy, but in the micro-channels thermosyphon, the governing forces are both buoyancy and capillarity. In general, capillarity will be far greater than buoyancy [19]. In other hand, the present concept of micro-channels thermosyphon is also different from that of traditional micro heat pipe, which were designed as small tubes and channels with various grooves or small triangle tubes for providing capillary force [20–24]. However, in the present study, the capillarity structure is formed by micro gaps and has not any grooves or sharp-angled corners in rectangle channel, the capillary comes from its own micro-scale.

On this basis, the authors extended the study objective from vertical micro-channels to inclined and horizontal micro-channels [25]. Experimental results show that horizontal and inclined micro-channels structure can also cause great natural convective boiling to cool 3D chips. In addition, the suitable addition of SDS into pure R113 and deionized water to form super-moist liquid will significantly improve the both critical heat flux and heat transfer coefficient in micro-channels by 70–80%.

Since the gaps of micro channels are very small in the 3D chips, so simply using of the thermosyphon boiling mode cannot meet the need of heat removal, and then various heat transfer enhancement technologies are needed. In the previous studies [19,25], super-moist fluids are applied to reduce the solid–liquid contact angle and thence enhance capillary force. In this study, another important enhanced technology for phase-change heat transfer is the surface treatment technology, which is applied to increase capillarity and activate boiling nucleate cavities on the chip surfaces. Among the all surface treatment technologies, nanoparticles deposition method by pool boiling of nanofluids on the heating surface should be the easiest and cheapest for 3D stacked chips. So far, a lot of experimental studies have been carried out for investigating both pool boiling heat transfer of nanofluids on plate surfaces [26,27], and thermal performance of conventional thermosyphon heat pipes filled up with nanofluids [28–31]. A common finding is that there exists a porous coating layer formed by nanoparticles deposited on the heating surfaces after boiling process and the coating layer enhances greatly boiling heat transfer. For the present micro-channels, it is not suitable to use directly nanofluids as the working liquid in the thermosyphon due to the fact that it may block the channels during long-term running. However, according to a lot of published research which confirmed that the nanoparticles can be attached to the heating surfaces during boiling process due to the very strong van der Waals interactions [32,33], this surface treatment method by nanofluids boiling may be used to develop a stable nano-structure coating on the chip surfaces, then, common fluids are used as the working liquids in micro thermosyphon.

In this study, spaced apart nickel heating elements which form micro-channel heat pipe structure were used to simulate 3D chips as fever ends. Both vertical and horizontal micro-channel structures were tested. Four nanoparticles (CuO, Cu, Al2O3, SiO) were added to the two base fluids (deionized water and R113) to form some especial nano-structure coating on the surfaces of chips after a long time pool boiling treatment. Then, formal experiments were carried out using four kinds of working liquids: two pure fluids (deionized water and R113) and two moist fluids (deionized water+surfactant and R113+surfactant). The gaps and heights of channels used were in the range of 30–60 μm and 30–90 mm, respectively. The research particularly focused on boiling heat transfer ability, namely the maximum heat flux, since the main obstacle to 3D chips cooling is that the intermediate chip may be overheated without adequate cooling. Experimental results show that the nano-structure coating can significantly enhance both the maximum heat flux and heat transfer coefficient of thermosyphon boiling using pure liquids as that in common pool boiling. Furthermore, it is found that there exist both the optimal nanoparticles kind and nanoparticles mass concentration to obtain the most effective coating layer. Then on this basis, different concentrations of surfactant, SDS, were dispersed to deionized water and R113 to form two super moist liquids to improve further thermosyphon boiling performance. The optimum surfactant concentrations were found out for deionized water and R113, respectively. The experimental results fulfilled the expected goals and showed potential application of horizontal micro-channel heat pipe structure for 3D stacked chip cooling.

2. Experimental apparatus, nano-structure coating making, working fluids and experimental procedure

2.1. Experimental apparatus

Fig. 1 (a) shows the diagram of basic 3D stacked chip encapsulation without any cooling methods, and Fig. 1 (b) and (c) show the schematic of micro-channels structures using present cooling method with vertical and horizontal states, respectively. Insulating working fluid is filled in the lower half of the encapsulation and submerges the 3D stacked chips. The upper surface of the encapsulation is processed as heat sink. For horizontal structure, when chips generate heat, saturated liquid flows into micro-channels from two ends of the channels along the wall driven by capillarity, absorbs heat and evaporates into saturated steam along the channels, and finally saturated steam flushes out of the channels from two ends. Strictly speaking, this heat transfer is a gas–liquid counter-flow boiling and cannot belong to thermosyphon boiling. However, since there is not strict theoretical analysis in this paper,