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Ultra-high heat flux dissipation with Piranha Pin Fins

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ABSTRACT

The *Microfluidic, Extreme heat flux, CMOS compatible, Heat-eXchanger* (MECH-X) is an embeddable silicon-based reactor-style heat sink which has been experimentally studied by the authors. The 800 μm thick MEMS heat sink discretizes the working fluid into stacked primary and secondary chambers to enhance phase change heat transfer. *Piranha Pin-Fin* (PPF) microstructures—reported previously by the authors—have been employed in the primary reaction chamber. The PPF structures vent higher-enthalpy fluid into a secondary, or booster, chamber for additional heat transfer. The MECH-X system has been shown to dissipate heat loads exceeding 10,000,000 W/m^2 with dielectric fluid HFE7000 while maintaining surface temperatures below 95 °C.

The present work reports on flow boiling experiments performed to characterize system-level performance of the MECH-X heat sink at mass fluxes of 680, 1440, and 3350 kg/s/m^2. HFE7000 was used as a coolant at ambient lab temperature (~23 °C) and a system pressure of 377 kPa. A 3.95 mm^2 heating element, which simulated a heat generating component, was maintained below 95 °C with heats loads exceeding 1 kW/cm^2. Experiments were terminated at this heat flux due to saturating a 50 V_{DC} laboratory power supply. Results are also presented at a system pressure of 239 kPa, and results are compared to first generation PPF heat sinks.

1. Introduction

Recent high-end electronics, such as those found in advanced military and avionics equipment, require dissipation of ultra-high heat fluxes exceeding 1 kW/cm^2 [1]. Flow boiling heat transfer in micro domains is a key enabling cooling technology because it leverages latent heat of evaporation, high heat transfer coefficients (HTCs), and large surface area-to-volume ratios. Researchers are now exploring new approaches to further improve the performance of liquid-to-vapor microchannel cooling systems [2–34]. As part of this effort, Woodcock et al. [4,8] and Yu et al. [15,16,18,29] developed a micro cooling architecture termed the *Piranha Pin-Fin* (PPF). The PPF microstructure resembles a streamlined cylinder which is hollowed to allow venting of heated fluids through the fin's central core.

Woodcock et al. [4,8] conducted both single and flow boiling studies for the first generation PPF heat sink. Heat fluxes up to 700 W/cm^2 were dissipated with a pressure drop below 120 kPa at a mass flux of 3300 kg/s/m^2. Leveraging what had been learned from the principal PPF devices, Yu et al. [15,16,18,29] fabricated a second generation of PPF devices and conducted a comparative study of pin-fin configurations to the effect of heat transfer performance. An improved CHF of 735 W/cm^2 and a heat transfer coefficient of 180 kW/m^2/°C were achieved at an inlet mass flux of 2569 kg/s/m^2. Correlations for two-phase heat transfer coefficient and pressure drop in the nucleate flow boiling regime were developed [29].

Knowledge gained from research into the PPF microstructure enabled the development of a bi-layer PPF system. The addition of a secondary silicon substrate (termed the booster substrate)

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Nomenclature

A_{ch}	channel cross-sectional area, [m^2]
c_p	liquid specific heat [J/kg]
G	mass flux [kg/s/m^2]
h	heat transfer coefficient [kW/m^2/°C]
h_{fg}	enthalpy of vaporization [J/kg]
I_{shunt}	shunt current [A]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [kPa]
q''	heat flux [W/cm^2]
Q	heat removed by heat exchanger [W]
Q_{loss}	estimated heat loss [W]
Q_{tot}	total heat load [W]
R	resistance [Ω]
T	temperature [°C]
T_{bulk}	bulk mean temperature [°C]
V	voltage [V]
x_e	equilibrium quality [–]

Subscripts

bulk	related to the bulk fluid
h	related to heater
i	related to the inlet
o	related to the outlet
RTD	related to the RTD

Acronyms

CHF	critical heat flux
CMOS	complimentary metal-oxide-semiconductor
DNB	departure from nucleate boiling
HTC	heat transfer coefficient
MECHX	microfluidic, extreme heat flux, CMOS compatible, heat exchanger
MEMS	micro-electro-mechanical system
ONB	onset of nucleate boiling
PPF	piranha pin-fin

was predicted to produce a heat sink with superior thermal and hydraulic performance. This advanced heat sink is termed the *Microfluidic, Extreme heat flux, CMOS compatible, Heat-eXchanger* (MECH-X) and contains the third generation PPF microstructure (Gen III PPF). Fluid vented from the Gen III PPF is captured in the booster substrate chamber to supplement the heat transfer achieved in single-layer PPF systems. The heat sink design, fabrication, and system-level performance are discussed in this paper.

2. The MECH-X microdevice

The MECH-X microdevice is a complementary metal-oxidesemiconductor (CMOS) processed heat sink, engineered and optimized to dissipate extreme thermal loads with multi-phase cooling. Micro-electro-mechanical system (MEMS) technology coupled with direct fusion silicon bonding allowed the creation of full 3D micro-architectures with bulk silicon properties [35–37]. A schematic of a 3D "unit cell" found within a PPF array is shown in Fig. 1. As shown in the figure, the primary substrate—closest to the heated surface—delivers subcooled liquid into a high heat flux chamber populated with Gen III PPFs. The fluid gains enthalpy and mass quality as it is vented through the PPF

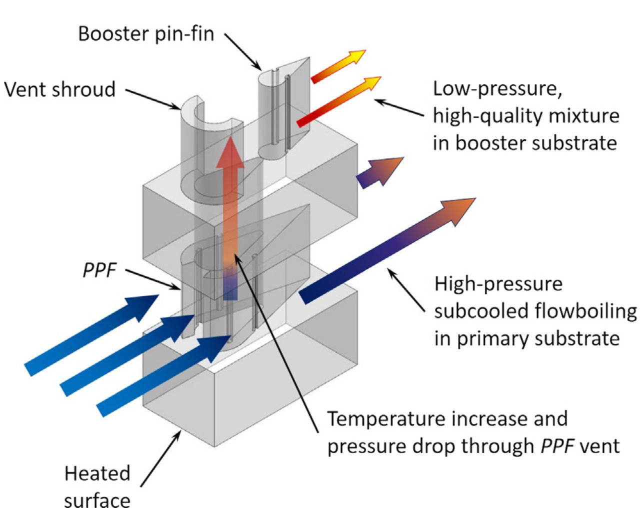

Fig. 1. *MECH-X* heat sink unit cell concept.

microstructure into the booster substrate; a low heat flux, low pressure chamber populated with solid micro pin-fins and vent shrouds (see Fig. 1).

The booster pin-fins are aligned vertically with the Gen III PPFs to provide a direct conduction pathway from the heat source to the booster chamber. The subcooled flow through the primary chamber substantially mitigates the heat flux, creating a high heat flux primary chamber and a low heat flux booster chamber. A significant pressure drop between the primary and booster substrates lowers the saturation temperature of the fluid, promoting fluid expansion as the two-phase mixture exits the PPF array. By discretizing the fluid into separate chambers where subcooled fluid is subjected to extreme heat loads and saturated fluid is exposed to residual heat loads, stable high-quality flows are achievable, which provide superior cooling well into the 1 kW/cm^2 range.

Studies into single-substrate PPF heat sinks provided a proof of concept of the PPF microarchitecture by allowing visualization of the flow boiling occurring in the primary substrate [4,8,15,16,18,29]. The MECH-X heat sink builds on the original construct and demonstrates the feasibility of a multi-level, reactor-style heat sink. The MECH-X allows visualization of the flow ejected from the PPFs as it flows through the booster substrate and exits the heat sink, which has not been studied previously. A 3D computer aided design (CAD) model of the MECH-X heat sink is presented in Fig. 2. The present design includes a heater, a resistive temperature detector (RTD), dual silicon substrates, and a borofloat glass cap to hermetically seal the channel from the top of the booster substrate. The die size is approximately 12 mm × 30 mm with a channel width of 1.8 mm, which has been selected based on the number of rows of fins to be entrenched in the channel. The microgap depth is 200 μm. The die size was selected to cool a 4 mm^2 component to satisfy DARPA ICECool Fundamentals metrics. The PPF architecture may be extended in 2 dimensions to cool larger or smaller areas. Details of the pin-fin area are shown in Fig. 3 and a completed MECH-X die, ready for bench testing is shown in Fig. 4.

The MECH-X microdevice includes Gen III PPFs of the same scale as the first-generation heat sinks (∅150 μm × 300 μm long × 200 μm tall). The vent mouth of the PPF (Fig. 5) measures 65 μm at the leading edge of the fin and tapers slightly down to 50 μm. The array used in the MECH-X system (Fig. 6) has both a longitudinal and transverse spacing of 225 μm. Aligned to the PPF array is a booster substrate with vents fabricated in the floor