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Design, Fabrication, and Characterization of a Compact Hierarchical Manifold Microchannel Heat Sink Array for Two-Phase Cooling

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Abstract—High-heat-flux removal is critical for next-generation electronic devices to reliably operate within their temperature limits. A large portion of the thermal resistance in a traditional chip package is caused by thermal resistances at interfaces between the device, heat spreaders, and the heat sink; embedding the heat sink directly into the heat-generating device can eliminate these interface resistances and drastically reduce the overall thermal resistance. Microfluidic cooling within the embedded heat sink improves heat dissipation, with two-phase operation offering the potential for dissipation of very high heat fluxes while maintaining moderate chip temperatures. To enable multi-chip stacking and other heterogeneous packaging approaches, it is important to densely integrate all fluid flow paths into the device; volumetric heat dissipation emerges as a performance metric in this new heat sinking paradigm. In this work, a compact hierarchical manifold microchannel (MMC) design is presented that utilizes an integrated multi-level manifold distributor to feed coolant to an array of microchannel heat sinks. The flow features in the manifold layers and microchannels are fabricated in silicon wafers using deep reactive ion etching. The heat source is simulated via Joule heating using thin-film platinum heaters. On-chip spatial temperature measurements are made using four-wire resistance temperature detectors. Individual manifold layers and the microchannel-bearing wafers are diced and bonded into a sealed stack via thermocompression bonding using gold layers at the mating surfaces. Thermal and hydrodynamic testing is performed by pumping the dielectric fluid HFE-7100 through the device at a known flow rate, temperature, and pressure at different levels of chip heat input. A volumetric heat density of up to 2870 W/cm³ is dissipated at a chip temperature less than 112 °C and microchannel pressure drop less than 27 kPa. The overall pressure drop is governed by flow through the manifold, rather than the microchannels, in this compact heat sink that occupies envelope of 5 mm × 5 mm × 2.3 mm including all functional flow features.

Index Terms—microfluidics, microchannel heat sink, volumetric heat density, microheater, resistance temperature detector

I. Introduction

The continuing miniaturization of electronic devices and increasing die-level heat fluxes requires thermal management technologies that can provide the necessary cooling capacity while maintaining chip temperatures within allowable limits. High-power computing, switching, and radar electronics have reached power densities above 100 W/cm², with future systems projected to reach 1000 W/cm² [1]. Optical devices such as laser diodes and photovoltaic systems also need proper thermal management to perform at design specifications and to achieve their desired reliability [2]–[4]. Traditional heat dissipation has relied on heat spreaders; however, heat spreading is not a solution in cases where heat is generated over a large fraction of the chip surface area. Furthermore, volumetric heat density becomes a concern with increasing levels of integration, such as 3D stacking of devices in data centers [5], which requires a more compact cooling system. Integrated motor drives offer higher power density but similarly raise operating temperature concerns [6].

Microchannel heat sinks have been shown to dissipate high heat fluxes at moderate chip temperatures for electronics cooling applications. In their pioneering work, Tuckerman and Pease [7] experimentally tested a silicon microchannel heat sink. The 50 µm-wide and 302 µm-deep channels were wet-etched using potassium hydroxide (KOH) and the simulated heat load was applied to the base of the channels using thin-film tungsten silicide (WSi_2) resistors. The silicon heat sink was bonded to a glass top cover using anodic bonding. Heat fluxes up to 790 W/cm² were dissipated over a 10 mm × 10 mm area using single-phase water as the working fluid at pressure drops up to 214 kPa. Many studies have since shown that microchannel heat sinks are a viable technology for electronics cooling applications [8], [9].

The performance of microchannel heat sinks can be improved by allowing the working fluid to undergo phase change in the channels. For most fluids, the latent energy absorbed during evaporation is orders of magnitude larger than the specific heat capacity associated with moderate temperature rises. Two-phase microchannel heat sinks yield more uniform temperature along the channel length because evaporation is an isothermal process at a given pressure. Achieving complete evaporation of the coolant in heat sinks is

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unfeasible because local dryout—when vapor is in contact with the channel wall—results in extreme temperature spikes. To support extremely high heat fluxes, high fluid flow rates are required to prevent dryout but may lead to exorbitant pressure drops. One heat sink design approach to overcome this challenge is to use a manifold which delivers the flow to the channels at multiple locations along their length thereby reducing the effective flow length—this design is termed a manifold microchannel (MMC) heat sink.

Harpole and Eninger [10] developed a numerical model to solve for the temperature distribution in MMC heat sinks during single-phase operation. The model was used to optimize the geometric parameters for the dissipation of high heat fluxes over a 10 mm × 10 mm area using a water/methanol mixture as the working fluid. The design called for small-diameter, high-aspect-ratio channels fed by a manifold that distributed the flow to the channels at multiple locations along the flow length. The optimal design had channels between 7 μm and 15 μm-wide and ~167 μm-deep, and a manifold with 200 μm-wide inlets and outlets spaced by a center-to-center distance (i.e., the effective flow length) of ~333 μm. The design was demonstrated by wet-etching microchannels (9 μm-wide and 334 μm-deep) and manifold features in silicon using KOH. The manifold and microchannels were joined and sealed using diffusion bonding. Since this initial demonstration, many numerical and experimental studies have shown that MMC heat sinks are a high-performance heat sink design for single-phase operation [11]–[14]. Two-phase cooling is more efficient than single-phase cooling because it exploits the latent heat of vaporization, resulting in a higher heat dissipation per fluid mass. Although less commonly studied than single-phase approaches, two-phase cooling in MMC heat sinks has been successfully demonstrated [15].

In addition to investigating and optimizing the channel geometries, a number of studies have demonstrated the importance of manifold designs and dimensions on the overall performance of MMC heat sinks [16]–[21]. Proper manifold design is required to prevent significant flow maldistribution to the channels; this is a concern for all microchannel heat sinks but is especially important in MMC heat sinks due to the large number of parallel flow paths. Flow maldistribution can cause drastic performance differences between channels which can result in large temperature gradients across the chip surface. During two-phase operation, intrinsic flow instability mechanisms can lead to exacerbated flow maldistribution [22]–[24].

Hierarchical manifolds distribute the flow from a single inlet/outlet to the heat sink using a series of branching flow paths. This allows the manifold to be designed such that the hydraulic resistance of each flow path is similar, which results in an even flow distribution. Brunschwiler *et al.* [25] demonstrated a direct liquid-jet-impingement cold plate with a nozzle array. They designed a vertical hierarchical manifold structure to minimize the hydraulic resistance of the flow path from the top inlet to the bottom 30 μm-diameter nozzle array and achieved a pressure drop of 35 kPa from single phase operation. Calame *et al.* [26] designed horizontally hierarchical branched microchannels with different levels of hierarchies and achieved an average heat flux dissipation of 960 W/cm² using water. Dang *et al.* [27] and Schultz *et al.* [28]

designed an embedded radially expanding hierarchical microchannel heat sink for two-phase cooling of 3D stacked chips.

Advancements in microelectromechanical systems (MEMS) fabrication methods have allowed more flexibility in microchannel heat sink design. Deep reactive ion etching (DRIE) techniques have been used to fabricate high-aspect-ratio microchannels having complex channel/manifold flow profiles [29]–[31]. Hermetic sealing throughout the system has been achieved using a variety of bonding techniques including fusion [32], anodic [33], eutectic [34], and thermocompression [35]. Alternative bonding materials such as photoresist [36] and adhesive tapes [37] have also been used to achieve fluidic sealing.

Recently, we demonstrated fabrication and testing of a hierarchical manifold microchannel heat sink in two-phase operation [38]. Heat fluxes up to 1020 W/cm² were dissipated over a 5 mm × 5 mm area by flowing the dielectric working fluid HFE-7100 through a 3 × 3 array of embedded, high-aspect-ratio microchannel heat sinks. Despite this extreme level of heat flux dissipation based on the heat input footprint area, the manifold was attached to the heat sink as a separate component that increased the system size. In the current work, a manifold microchannel heat sink is developed with an embedded, compact hierarchical manifold that significantly reduces the envelope of the flow features. Fabrication of all flow features in silicon using DRIE allows a dense 9 × 9 array of embedded microchannel heat sinks to be aligned and thermocompression-bonded to the hierarchical manifold layers. Microheaters and resistance temperature detectors (RTDs) are patterned directly on the microchannel wafer; these individually addressable devices provide heating and local temperature sensing. Hydrodynamic and thermal performance of the heat sink is characterized for a range of flow rates; the efficacy of the design is evaluated based on the volumetric heat dissipation within the system envelope.

II. DEVICE FABRICATION

A. Hierarchical manifold microchannel heat sink array design

In a hierarchical manifold microchannel heat sink array, fluid is delivered to an array of microchannel heat sinks using a multi-level manifold, as shown schematically in Figure 1(a). The manifold consists of multiple layers that split the flow into gradually finer features. Maximum granularity occurs at the channel inlet/outlet plenum where flow is delivered to the individual microchannel heat sinks, each having an effective flow length that is significantly shorter than the overall length of the channel. In this work, a 9 × 9 array of microchannel heat sinks is etched into a single silicon die with a total heated area of 5 mm × 5 mm. Each of the 81 heat sinks consists of 18 high-aspect-ratio microchannels that are 19 μm-wide and 150-μm deep. The detailed dimensions of the plenum and microchannels are shown in Table 1. The base thickness is the thickness of the silicon substrate at the bottom of the microchannels.

A three-dimensional drawing of the hierarchical MMC heat sink array used in this work is shown in Figure 1(b). The manifold comprises four silicon wafers (A-D), each etched from both sides, for a total of eight feature levels (1-8), as
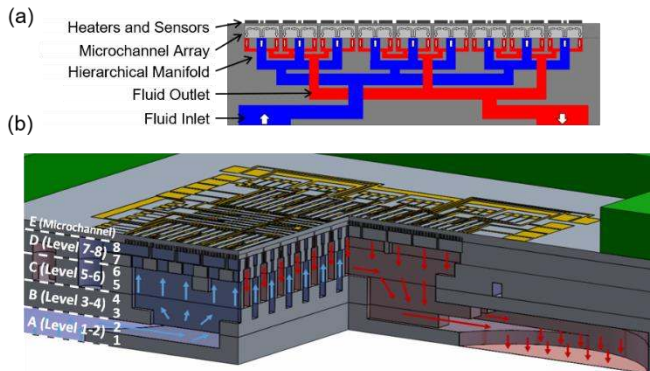
Figure 1. (a) Schematic diagram showing a hierarchical manifold microchannel heat sink array (not to scale), and (b) three-dimensional drawing of the specific design used in this work with sections removed to show the internal flow features (all features are to scale except the microchannels).

Table 1. Summary of plenum and microchannel dimensions.

Parameter	Value	Units
Channel width	19	μm
Channel height	150	μm
Aspect ratio	7.9	
Fin width	11	μm
Base thickness	50	μm
Plenum inlet length	100	μm
Plenum outlet length	50	μm
Effective flow length in channels	175	μm

labeled in the figure. Fluid enters the manifold at Level 1 (Wafer A) where there is a single inlet; as the fluid travels through Levels 2 through Level 8 (Wafers A-D), it is gradually split into finer flow paths. After reaching Level 8, where there is a distinct inlet plenum feature for each of the 81 microchannel heat sinks, the fluid enters the microchannels (Wafer E) and turns 90 degrees, i.e. flows parallel to the wafer surface. The fluid is heated by microfabricated heaters (top surface of Wafer E) as it flows through the microchannels. After traveling along the length of the channels, the fluid turns 90 degrees and exits back through the manifold where the fluid is recollected from the channel outlet plenums (Level 8) into a single fluid exit (Level 1).

B. Heater and sensor layout

The heater and RTD sensor layout are designed to provide a uniform background heat flux and local temperature measurements over the 5 mm × 5 mm die area. For ease of fabrication, the heaters and RTDs are deposited and patterned at the same time. Because all the features are constrained to the same plane, the heaters and RTDs—and their traces—cannot overlap. The heater consists of a 3 × 3 array of individually addressable heaters; All traces have the same width and are equally spaced across the entire heated area as shown in Figure 2. In addition, metal pads of low resistivity are periodically patterned on top of the heaters to achieve a more uniform heat flux by creating heating elements that are periodic in both horizontal and vertical directions. RTDs are placed between the lines of the heaters; each heater footprint area contains two RTDs for a total of 18 temperature measurements across the die surface. All RTDs are connected using the four-wire technique to eliminate the lead wire resistance from the measured resistance.
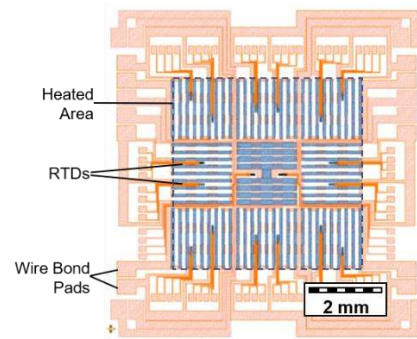

Figure 2. Heater and RTD layout. The 3×3 heater array covers a 5×5 mm^2 area (blue) and each heater is individually addressable. Each section has two four-wire RTDs for local temperature sensing.

Electromigration has been shown to create voids and hillocks on metals due to the movement of ions under bias, and is likely to happen at large current densities and high temperatures [39]. Electromigration can be avoided by increasing heater resistance, which results in lower current densities for a given power. However, higher resistance will require a higher voltage and this may cause dielectric breakdown. Therefore, the resistances of the heaters are designed based on both the electromigration limit (10^7 A/cm^2) and breakdown voltage limit of the dielectric layer (200 V for 200 nm SiO$_2$). An individual heater of 333 Ω satisfies these requirements, as both the current density and the voltage are below the limits at the heater design flux of 1 kW/cm^2. Platinum (Pt) is chosen as the heater/sensor material as it has strong resistance to oxidation and other chemical reactions. In addition, the electrical resistance of Pt is linear with respect to temperature over the expected operating range, making it a good candidate for RTDs [40]. Gold (Au) is chosen as the lead wire material to minimize heat generation in the leads and for robust connections to printed circuit board (PCB) using Au wire-bonding.

C. Microchannel plate and manifold plate fabrication

The overall fabrication processing flow is as follows: i) bottom-side etching of the microchannel plate and manifold plates, ii) top-side heater and RTD patterning on the microchannel plate and etching of the manifold plates, and iii) metallization and bonding, as shown in Figure 3. The microchannel wafer fabrication process, which is outlined in Figure 4(a), begins by etching the microchannel features into the bottom side of a 300 μm-thick, 4 inch-diameter silicon wafer. A single wafer yields 12 dies, each 20 mm × 20 mm in size. The channels occupy the center 5 mm × 5 mm footprint area of the die, with the remaining area available for top-side traces, wire-bond pads, and mounting of the wafer to a PCB. The wafer is cleaned using piranha solution and a 2 μm-thick silicon dioxide (SiO$_2$) hard mask layer is thermally grown on the wafer. Photolithography was with hexamethyldisilazane (HMDS) adhesion promoter and AZ9260 positive photoresist layer throughout, unless otherwise stated. HMDS/AZ9260 are coated using a spin coater (Specialty Coating Systems G3). The photoresist layer is exposed using a mask aligner (Karl Suss MA6) and developed in a diluted AZ400K solution (DI water:AZ400K = 3:1). The SiO$_2$ layer is removed from the
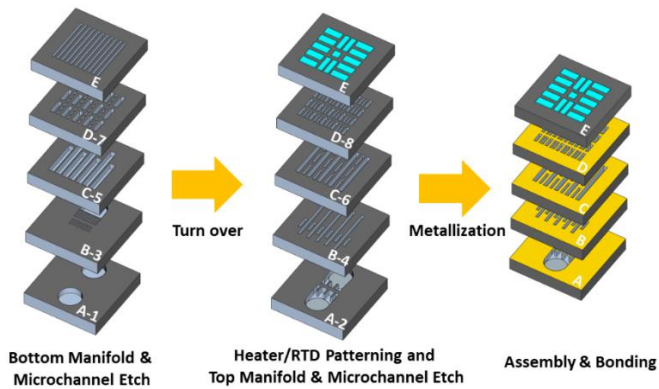
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Figure 3. Overall fabrication flow: i) bottom manifold and microchannel etch, ii) top manifold and microchannel etch and heater/RTD patterning, iii) interface metallization, assembly and bonding of all chips (not to scale, refer to Figure 1(b) for wafer labels A-E and level numbers 1-8).

open areas using a plasma dry etch (Surface Technology Systems-Advanced Oxide Etch). The microchannels are then etched to the desired depth using the Bosch process (STS-Advanced Silicon Etch). For the etching of high-aspect-ratio microchannels, the photoresist provides the soft mask after microchannel patterning while the SiO_2 provides sharper edges and more vertical sidewalls. The key DRIE parameters are listed in Table 2. Once the channels are etched, the photoresist and SiO_2 layers are removed using PRS2000 and buffered oxide etch (BOE), respectively.

Heater and RTD patterns are fabricated directly on the top side of the microchannel wafer. After the microchannel etch process, a 200 nm-thick layer of SiO_2 is thermally grown on the wafer as a dielectric barrier. The same photolithography procedures as for the microchannel patterning are employed, and backside alignment was used to align the heater and RTD patterns with respect to the microchannels. Once the patterns are defined, 5 nm of Titanium (Ti) and then 20 nm of Pt are deposited via electron beam evaporation (CHA Industries, Inc.). This was done at a pressure level of 2.0×10^{-6} torr and the deposition rate was 1.0 Å/s. A lift-off process is performed by stripping off the photoresist using PRS2000. To fabricate the heater and RTD lead wires, this lithography procedure is repeated with two differences: the trace locations are defined using a new mask and the metal depositions are 10 nm of Ti and then 400 nm of Au.

Because the hierarchical manifold requires a large number of layers for flow distribution, etching features into both sides reduces the required number of wafers and bonding interfaces, while also mitigating risk for misalignment between layers. Two Levels are fabricated in each wafer, by etching from the bottom side and then from the top side, with the patterns from the two Levels meeting at the middle of the wafer. The processing steps in manifold wafer fabrication are shown in Figure 4(b). The 500 μm-thick wafers are cleaned and oxidized with a 2 μm-thick SiO_2 layer. The fabrication procedure follows that used for the microchannel etch and the same procedure is repeated on the opposite side of the wafer. Backside lithography is used to align with the features already etched in the wafer.

Figure 5(a) shows a microscope image of the heaters and RTDs deposited on the opposite side of microchannel wafer
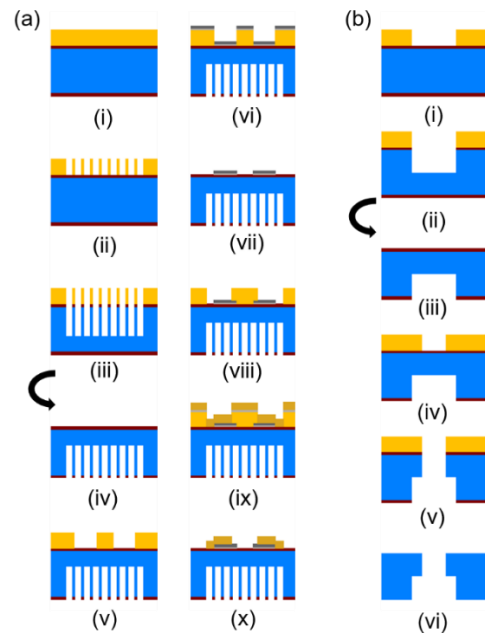

Figure 4. Cross-section of the fabrication process. a) microchannel and heater/RTD bottom side: (i) HMDS and photoresist (PR) coating; (ii) microchannel lithography; (iii) SiO_2 and Si etch; Top side: (iv) PR removal, BOE & re-oxidation; (v) heater/RTD backside lithography; (vi) Ti and Pt deposition; (vii) lift-off; (viii) lead wires lithography; (ix) Ti and Au deposition; (x) lift-off. b) manifold bottom: (i) PR coating and bottom side lithography; (ii) SiO_2 & Si etch. Top side: (iii) PR removal, BOE & re-oxidation; (iv) PR coating and top side lithography; (v) SiO_2 & Si etch; (vi) PR removal and BOE.

Table 2. Key parameters using for deep reactive ion etching (DRIE) of the high-aspect-ratio microchannels.

Parameter	Value	Units
Etch rate (approx.)	3	μm/min
Etch step time	10	s
Passivation step time	10	s
RF power	1000	W
Platen power	10	W
C_4F_8 flow rate	100	SCCM
SF_6 flow rate	250	SCCM
O_2 flow rate	30	SCCM

(Level E). Heating elements are clearly patterned in the 5×5 mm^2 area, and RTDs are located in between the heaters. Each heater is connected to Au traces for wirebonding. Figure 5(b) shows a scanning electron microscope (SEM) image of the cross section of the etched microchannels. Straight walls are achieved and all channels have consistent width; the side walls and bottom surfaces are smoothly finished.

D. Assembly and Integration

All layers of the manifold and microchannels are joined to seal surfaces between the fluid routing features and prevent fluid from bypassing the microchannels. An evaluation of thermocompression bonding was performed using two dummy silicon wafers, one containing through plenum features and another with etched microchannels (nominally 15 μm × 150 μm). The samples were thermocompression bonded, diced, and the open plenum features sealed to evaluate the leakage rate of helium. The leakage rate was measured to be $<1.3 \times 10^{-7}$ atm-cc/sec across 4 samples. The bonds were also subjected to 500 temperature cycles (MIL-STD-883, Condition B, -55 to +125°C) without failure. Based on these hermiticity results and
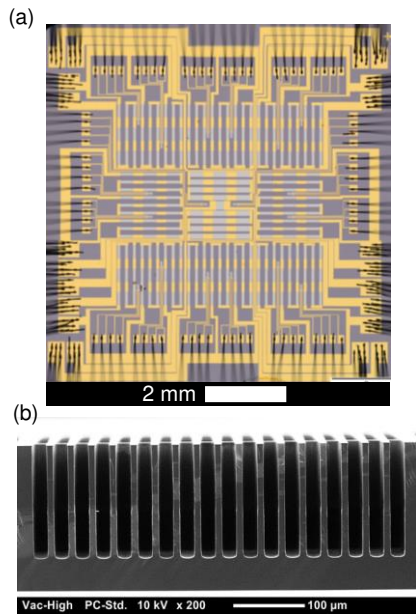
Figure 5. (a) Microscope image of fabricated heater/RTD layer. Heating elements (Pt) are located in a 5×5 mm^2 area and 18 RTDs are placed in between the heaters. (b) SEM image of the microchannel cross-section. The width and depth of each channel is 19 μm and 150 μm, respectively.
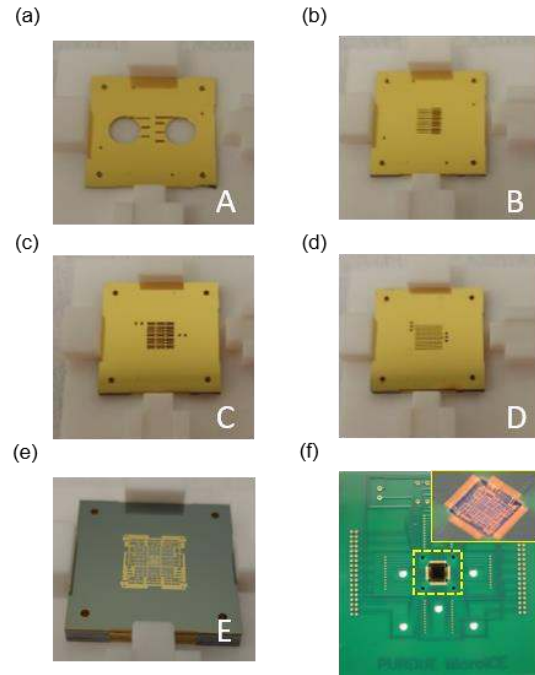

Figure 6. (a-d) Top view of the metallized manifold dies and (e) microchannel die after stacking. (f) Photograph of the fully assembled hierarchical manifold microchannel heat sink array test vehicle, with inset showing the wirebonded chip.

visual inspection, thermocompression bonding was selected as the sealing method for the test samples used in this work.

Prior to bonding, the microchannel and manifold wafers are cleaned using piranha solution. After cleaning, 50 nm of Ti and 500 nm of Au are deposited on both sides of the manifold wafers using a magnetron sputtering system (MANTIS Deposition CUSP-Series); the Ti layer is used to increase adhesion of the subsequent Au layer. The sputtering system pressure during deposition is held at 7.3×10^{-3} Torr and the DC deposition current is 0.1 A. The sample is rotated during deposition to improve uniformity across the wafer. The microchannel wafer is coated using the same deposition process on the channel side. The wafers are then diced into 20 mm × 20 mm dies for bonding (Disco DAD-2H/6 Dicing Saw). Figure 6(a-e) shows the metallized and diced dies.

A custom-made, Macor ceramic assembly fixture is used to align the microchannel die and manifold dies during thermocompression bonding. The assembly and alignment is completed in a cleanroom to prevent any contamination at the interfaces. Once the manifold and microchannel dies are stacked in order, as shown in Figure 6(a-e), the fixture is installed in the vacuum chamber of a bonding facility. Bonding is performed by heating the assembly stack to 350 °C while compressing at a pressure of 500 kPa for 1 h. The assembled fluid features, including the hierarchical manifold (dies from Wafers B-E), are confined to a 5 mm × 5 mm × 2.3 mm working envelope. After thermocompression bonding, the die assembly is attached to the underside of a custom-designed PCB using adhesive tape. The heaters and RTDs are then electrically connected to the PCB bond pads using gold wire bonds as shown in Figure 6(f). Each of the background heaters and RTDs are wirebonded (West Bond 7400A Ultrasonic Wedge Bonder) separately such that they can be addressed and monitored individually. A dummy chip is prepared to confirm the reliability of the custom heaters and RTDs at the maximum

operating temperature. A constant current density (4.8×10^6 A/cm^2) was applied to the base heater and the chip temperature was monitored by the central RTD. The temperature recorded by the RTD was initially at 155 °C but decreased rapidly within the first few hours as the heater resistance decreased. Because the heater resistance would be expected to increase if degraded by electromigration, this reduction in the heater resistance is attributed to an annealing effect caused by Joule heating. Afterward, the temperature remains stable at 138 ± 2 °C and the resistance of heater slowly increases by 1% over a period of 378 h, which causes a slight temperature increase due to the increased heating power at constant current density; no failure was observed. To calibrate the heater resistance before testing, heaters are annealed at 180 °C in a laboratory oven for 24 h.

To characterize the manifold feature alignment, one sample was diced normal to the flow direction in the microchannels, polished, and imaged using a microscope, as shown in Figure 7. The arrows indicate the inlet fluid path through the manifolds. The results reveal that there are no gaps between the plates and that the flow features are aligned within a few microns.

III. EXPERIMENTAL METHODS

A. Electrical measurement and calibration details

A wiring diagram of the electrical components used to measure the voltage and current to each of the heaters, and to adjust the power to each of the heaters, is shown in Figure 8. A single DC power supply (Sorensen XG100-8.5) is used to power all of the heaters. While the design of each individual heater element on the test chip is identical, slight differences in metal deposition thickness, trace length, wire bond resistance, lead wire length, and operational temperature can
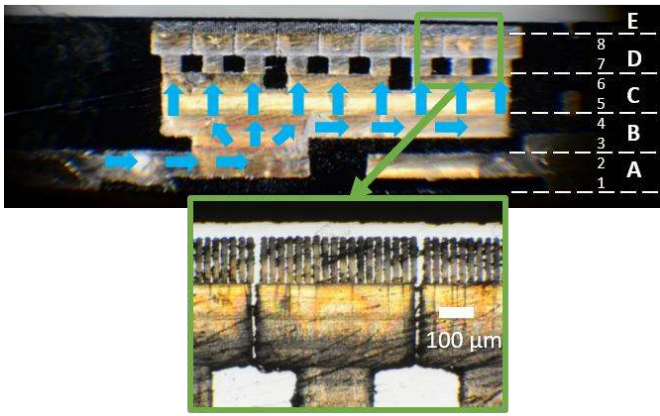
Figure 7. Cross-section image of the bonded manifold and microchannel test chip assembly with a magnified inset image of the top plenum and microchannel features (refer to Figure 1(b) for wafer labels A-E and level numbers 1-8).
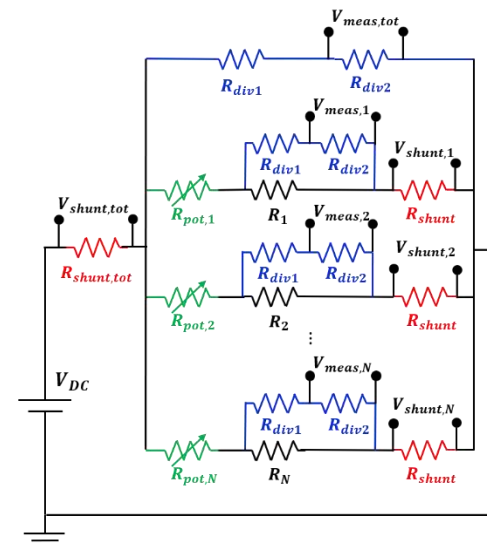

Figure 8. Electrical wiring diagram showing the components used to measure heater power to the test vehicle. The voltage divider circuits (blue) consist of two resistors (R_{div1} = 499 kΩ, R_{div2} = 10 kΩ) and each shunt resistor (red, R_{shunt} = 0.1 Ω, $R_{shunt,tot}$ = 0.2 Ω) is used for current measurement. The potentiometers (green, R_{pot} = 0-25 Ω) are added to adjust and equalize power to each heater.

lead to small differences in their resistance. To ensure uniform heat flux across the chip surface throughout testing, a potentiometer (Ohmite RES25RE) is added in series with each of the heaters; this provides a variable resistance that is used to adjust the voltage drop of each parallel branch and thus equalize the power applied by each heater. A voltage divider circuit (TE Connectivity 1622796-6, 10 kΩ ± 0.1%; TE Connectivity 8-1879026-9, 499 kΩ ± 0.1%) is wired in parallel to each heater of the test chip, which is used to step down the voltage below the 10 V limit of the data acquisition hardware (National Instruments cDAQ-9178). For instance, as shown in the Figure 8, the voltage across R_1 (V_1) is calculated using $V_1 = V_{meas,1} * ((R_{div1} + R_{div2})/R_{div2})$, where $V_{meas,1}$ is acquired from the data acquisition hardware and R_{div1} and R_{div2} are known. The voltage drop (V_{shunt}) across a shunt resistor (R_{shunt}) (Vishay Y14880R10000B9R, 0.1 Ω ± 0.1%) wired in series to each heater is used to calculate the current through each heater: $I_N = (V_{shunt,N}/R_{shunt})$. The total voltage drop and current are measured using the same techniques and are used to verify the individual measurements.

To calibrate the on-chip RTDs, the test chip is placed in a laboratory oven along with a Pt100 RTD (PR-10-3-100, Omega) that is used as the known reference temperature. The electrical resistance of the on-chip RTDs was measured at two different temperature levels: 50 °C and 100 °C. A linear fit is used to determine the relationship between electrical resistance and temperature for each of the 18 RTDs across the chip surface.

B. Thermal and hydrodynamic testing procedure

Prior to testing, the working fluid HFE-7100 is degassed via vigorous boiling and subsequent capture of the vapor; noncondensable gases escape during this process, leaving pure working fluid to be used for testing. HFE-7100 was chosen because of its high dielectric strength and low attenuation of RF signals; its boiling point is 61 °C at 100 kPa . A two-phase flow loop is used to deliver fluid to the test section at a constant and known flow rate, inlet temperature, and outlet pressure. The magnetically-coupled gear pump (GB-P23, Micropump) provides a constant flow rate that is independent of the system

pressure drop; the flow rate is measured using a Coriolis mass flow meter (CMF010M, Micromotion). The differential pressure drops across the entire chip and across the microchannels are measured (PX2300, Omega) using pressure taps located in the inlet/outlet of manifold and microchannels, respectively. A detailed description of this flow loop is available in Ref. [41]. To characterize the two-phase heat sink performance under boiling conditions, the fluid temperature at the inlet to the test section was set to achieve a constant, relatively small subcooling below the saturation temperature. Experimental testing was performed at a fixed inlet temperature of 59 °C (~6 °C below the saturation temperature at the outlet pressure), fixed absolute outlet pressure of 121 kPa, and fluid flow rates ranging from 150 to 350 g/min. During testing, the heat input to the test chip heaters begins at 0 W and is incremented in steps until a maximum chip temperature of 120 °C is reached, with the steady-state data (temperatures, pressures, voltages, currents, and flow rate) being recorded at each heat input level. The fluid pressure drop is measured between the inlet and outlet streams at Level 1 and Level 8 (Figure 1(b)); the measurement at Level 1 provides the total pressure drop while the measurement at Level 8 provides the channel pressure drop.

C. Data reduction

Electrical power supplied to each heater is calculated using $P = V \times I$, where V is electrical voltage and I is electrical current. The total power supplied to the heaters, P_{total}, is then calculated by summing the power to each of the heaters. Most of the applied heat is absorbed into the fluid via convective and boiling heat transfer; however, some of the heat is conducted into the test fixture and lost to the ambient. This heat loss was estimated prior to testing using the method outlined in Ref. [38] and was found to be $Q_{loss} = 0.02768 * (T_{chip,avg} - T_{amb})$. The net heat input is calculated by subtracting the calibrated heat loss, Q_{loss}, from the supplied
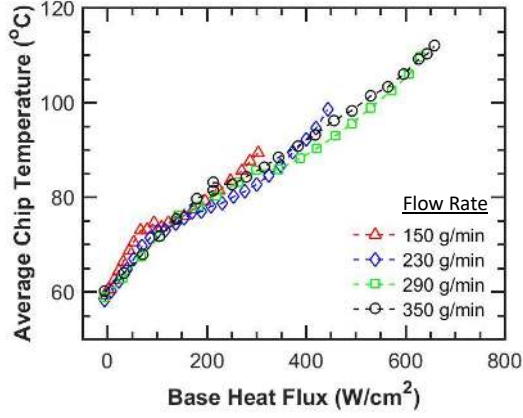
Figure 9. Average chip temperature as a function of base heat flux at flow rates of 150, 230, 290, and 350 g/min.

electrical power as $Q_{in} = P_{total} - Q_{loss}$. The base heat flux is calculated by dividing the net heat input by the base footprint area, A_b. Pressure drop is measured at the inlet and outlet to the manifold as well as the inlet and outlet to the channels.

IV. Results

A. Thermal performance

Figure 9 shows the average chip temperature as a function of base heat flux at four different fluid flow rates. Fluid enters the test chip at 59 °C and is heated as it flows along the length of the channels. At low heat fluxes (< 100 W/cm² approx.), the surface temperature rise is not sufficient to initiate boiling of the liquid. In this single-phase region, convective heat transfer results in a linear chip temperature increase with heat flux at each flow rate. At higher heat fluxes, the fluid transitions to boiling, resulting in a lower temperature rise for a given increase in heat flux in the two-phase region compared to the single-phase regime; the slope of the curves in the two-phase regime is insensitive to flow rate, indicating that the boiling process governs heat transfer to the fluid. At some critical heat flux, the surface temperature experiences a sudden increase past the 120 °C limit and the heater power is cutoff; the last steady-state data point before this threshold terminates each curve in Figure 9. There is a slight degradation in performance (increasing slope) in each curve as the critical heat flux is approached. The critical heat flux is highly dependent on the fluid flow rates and as flow rate increases, higher heat fluxes can be dissipated before critical heat flux is encountered. The highest heat flux dissipated at a flow rate of 150 g/min is 305 W/cm² and at 350 g/min is 660 W/cm², an increase of 116%. A more thorough analysis of performance trends in MMC heat sinks during two-phase operation is available in [38], [41].

B. Pressure drop

Figure 10(a) shows the measured total pressure drop across the entire test chip, which includes pressure drop in the inlet and outlet manifold as well as the microchannels. For each flow rate, the pressure drop is relatively constant in the single-phase region. Upon boiling incipience, the bulk fluid density decreases causing an increase in fluid velocity and hence
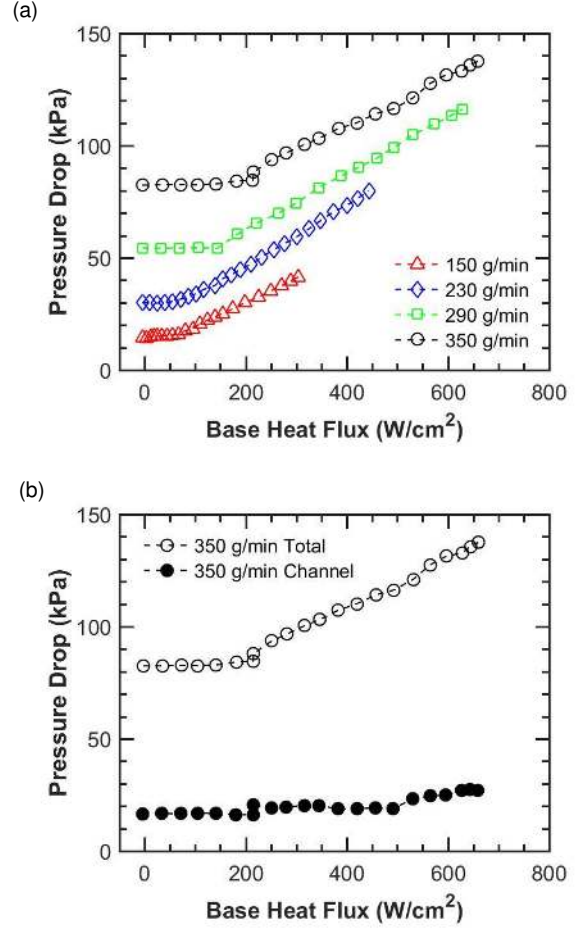

Figure 10. (a) Total pressure drop as a function of base heat flux at flow rates of 150, 230, 290, and 350 g/min and (b) comparison of the total pressure drop (open symbols) versus microchannel pressure drop (closed symbols) at a flow rate of 350 g/min.

pressure drop. The two-phase pressure drop increases with heat flux due to the increase in vapor generation with increasing heat flux at a given flow rate. The pressure drop increases with increasing flow rate in both the single- and two-phase regions, as expected. Figure 10(b) plots both the total pressure drop across the test chip and the pressure drop across the microchannels for the highest flow rate of 350 g/min. A majority of the total pressure drop occurs in the manifold flow features; the channel pressure drop accounts for only 20% to 27% of the total pressure drop, depending on the heat flux. This is important to note because thermal performance is governed by the channel size; due to the discretization of the heat sink into a 9 × 9 array with very short flow paths, the pressure drop across the channels can be maintained at only 27 kPa for the maximum heat flux dissipation of 660 W/cm². In the current design, the large maximum total pressure drop of 138 kPa is caused by the restriction of the manifold flow features to a compact envelope of only 5 mm × 5 mm × 2.3 mm such that the observed volumetric heat dissipation of 2870 W/cm³ can be achieved.

C. Discussion

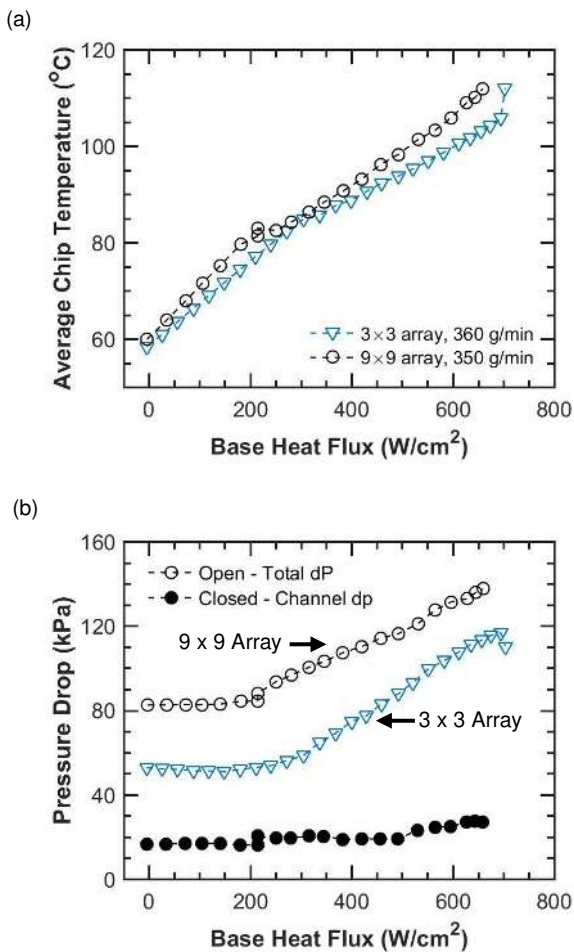To illustrate the compactness of the 9 × 9 heat sink array, its

(a)

(b)

Figure 11. (a) Average chip temperature and (b) pressure drop for the 3 × 3 array and the 9 × 9 array. A similar nominal microchannel size of approximately 15 μm × 150 μm was used in both array designs. (Channel pressure drop for 3 × 3 array test vehicle was not available.)

thermal and hydraulic performance are compared with our previous work. Figure 11(a) shows the 350 g/min data from the current test vehicle having a 9 × 9 heat sink array compared to data from Drummond *et al*. [41] for a 3 × 3 array at a similar flow rate of 360 g/min. The samples have similar nominal channel geometries of approximately 15 μm × 150 μm. Overall, the thermal performance is very similar for the two different test vehicles. While the flow length and number of parallel flow paths differ significantly, thermal performance is known to be largely governed by channel size and fluid quality during two-phase operation in confined microchannels, which are essentially the same across these data sets. Even though the thermal performance is very similar between the designs on a heat flux basis, the primary advantage of the 9 × 9 heat sink array is the small volumetric envelope of the compact integrated manifold, which is significantly reduced compared to the 3 × 3 array manifold. All functional flow features could be confined into a 5 × 5 × 2.3 mm³ for the 9 × 9 manifold in the current work compared to an envelope of 25 × 8 × 10 mm³ for the 3 × 3 manifold in our prior work. This translates to a maximum volumetric heat dissipation of 2870 W/cm³ for the 9 × 9 array compared to a maximum of only 285 W/cm³ for the 3 × 3 array. However, this compact manifold design requires smaller manifold flow features that increase the total pressure

drop; Figure 11(b) shows the total pressure drop for the 9 × 9 array compared to that the 3 × 3 array. The channel pressure drop for the 9 × 9 array is also shown for reference. Even though the 3 × 3 array would be expected to have a higher channel pressure drop (it was not measured), the 9 × 9 array still has a notably higher total pressure drop at a given heat flux, due to the dominant contribution of the manifold flow resistance to the overall pressure drop.

V. CONCLUSION

A compact hierarchical manifold microchannel heat sink was fabricated and tested. The hierarchical manifold consists of 8 fluid routing levels which distribute fluid uniformly to a dense 9 × 9 array of embedded microchannel heat sinks. All fluid features are fabricated using photolithography and DRIE processes. The individually addressable heaters and 4-wire RTDs are patterned directly on top of the microchannel wafer to provide heating and local temperature sensing. The fabricated dies are aligned using a custom-designed assembly fixture and thermocompression bonded. With stringent size constraints on most heat sinks, this compact, robust manifold design provides a functional manifold within a total envelope volume of 5 × 5 × 2.3 mm³.

The thermal performance of the 9 × 9 array heat sink at a given flow rate is very similar to previous work that investigated 3 × 3 arrays. However, due to the integration of a compact manifold, a volumetric heat density of up to 2870 W/cm³ is dissipated from the 9 × 9 array, an order of magnitude higher than that with the 3 × 3 array. While the microchannel pressure drop was only 27 kPa for the maximum heat flux dissipation of 660 W/cm², a majority of the pressure drop (80% of the total) occurs in the manifold for these extremely small fluid flow features, resulting in a total pressure drop of 138 kPa at this heat flux.

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