PCB-Integrated Heat Exchanger for Cooling Electronics using Microchannels Fabricated with the Direct-Write Method

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***Abstract*—The electronic industry has a growing need for efficient heat dissipation mechanisms such as micro heat exchanger systems. This active cooling approach requires the integration of microfluidic components near the main heat sources of the electronic devices. Despite the investigation of several micro-cooling configurations, their commercial utilization by the electronic industry is rather limited due to complex fabrication and integration methods. Here we present the integration of cylindrical microchannels fabricated by direct-write assembly in printed circuit board layouts for a micro heat exchanger application. The thermal performance of the manufactured prototype was characterized with respect to the fluid flow rate. The original fabrication and integration approaches presented here show high potential for efficient, compact, and low-cost micro heat exchangers for the electronic industry.**

Index Terms— **Direct-write assembly, micro heat exchanger, electronic cooling, printed circuit board**

NOMENCLATURE

D_h	Hydraulic diameter
f	Darcy friction factor
L	Length of channel
ΔP	Pressure drop
Re	Reynolds number
T	Temperature
u	Average velocity
η	Dynamic viscosity
ρ	Density
υ	Kinematic viscosity

I. INTRODUCTION

Thermal management has become a major limitation for the electronic industry. The utilization of extremely small transistors at high operating frequencies (~ GHz) generate a significant amount of heat which is exceeding the capacity of conventional heat removal techniques. The lack of heat dissipation yields higher operating temperatures that increase the risk of electrical failures in the device. This concern is not only problematic for the electronic industry [1] but also for the development of miniaturized robots [2] and the design of aerospace structures [3]. For many applications, air cooling mechanisms are not sufficient or simply impossible and other cooling technologies have to be used. Fluid cooling (e.g., water) offers a thermal conductivity and a specific heat capacity 25 and 4 times superior than air, respectively. The passive or active circulation of liquid could be used to transfer the heat from a specific location to another location where heat dissipation becomes more effective. For example, the heat generated by all the main electronic components of a computer could be transferred to a fluid and then transported to a single heat dissipation system, reducing the number of fans while lowering the noise level. Thus, electronic manufacturers have an increasing interest in passive micro heat pipe [4,5] and active micro heat exchanger technologies since they enable the creation of compact and efficient heat removal systems located close to the heat source.

The cooling of electronic components using micro heat exchangers is a promising approach [6-9]. A micro heat exchanger is an active system where the heat is transferred to a fluid circulating inside a microchannel (i.e., channel with a hydraulic diameter smaller than 1 mm). The system is usually composed of a pump for fluid circulation, a heat source, a heat sink and a network of microchannels. Previous work demonstrated an efficient micro heat exchanger cooling system with a low thermal resistance and a high heat dissipation capacity reaching 750 W/cm^2 [10]. The cooling efficiency of the micro heat exchanger strongly depends on the fluid flow rate, the thermal properties of the cooling fluid, the hydraulic diameter of the microchannel and the surface and the distance of the microchannel network to the heat sources. In addition, the utilization of integrated microchannels inside a printed circuit board (PCB) will enable a tight coupling with the heat source while minimizing the thermal resistance. Exposed paddle packages (i.e., packaging technique where metallic die paddles are exposed on the die) exhibit better thermal characteristics compared to other packaging techniques but the heat flux absorbed by the ground planes is not removed. This heat flux in the board may lead to an increase of temperature over time leading to malfunctions or failures of the device. Thus, the heat removal of conventional PCB such as copper/FR4 requires enhancement in order to facilitate the

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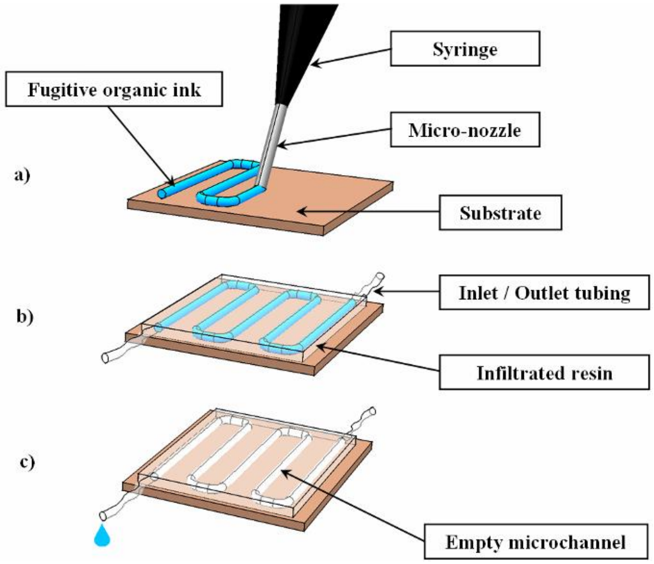

Fig. 1. Schematic representation of the fabrication process of a two dimensional microchannel by direct-write assembly: a) Extrusion of ink through a micro-nozzle and robotic deposition on substrate; b) Fluidic connection and epoxy infiltration; c) epoxy solidification and removal of fugitive organic ink.

fabrication of high power electronic devices.

The main manufacturing processes used to build microchannels for micro heat exchanger are LIGA (i.e., German acronym for RontgenLIthographie Galvanik Abformung meaning X-ray lithography electrodeposition and molding), chemical etching, stereolithography and micromachining [11]. Silicon etching is the most reported technique for the fabrication of microchannels with rectangular, trapezoidal or triangular cross-section. However, the integration of microfluidic components fabricated by chemical etching, LIGA, and stereolithography is not compatible with FR4 PCB manufacturing. The main challenges are the materials and chemical used and the required process for bonding between the micro heat exchanger and the electronic device. Micromachining of copper was successfully used [12] for the fabrication of microchannel on copper/FR4 boards and is occasionally used by the electronic industry. Though, the micromachining process is limited regarding the possible microchannel cross-section geometry.

This paper presents the fabrication of circular cross-section microchannels (~ 200 and 500 µm in diameter) and their integration inside the layers of a PCB for micro heat exchanger applications. The fabrication of the microchannels by direct-write assembly inside PCBs enables a tight thermal coupling to the heat sources. This customizable approach can use the Gerber files to define the microchannel path and avoid the vias. The thermal efficiency of a prototype with a 500 µm diameter microchannel was experimentally characterized and showed promising performance at high flow rates.

II. Experimental Procedure and Materials

A. *Substrate preparation*

A double layered Cu/FR4 sheet of 350 µm of thickness (Cu = 75 µm, FR4 = 200 µm) was used for the prototype fabrication. Copper was etched from the substrate on one side of the sheets using a PCB milling (Protomat S95, LPKF) to form heating circuits. Two prototypes were made with lines width of 200 µm and 500 µm, respectively. A thin resin film (~ 40-200µm) was then deposited and polished on the circuit for electrical isolation. Note that this insulation layer is not necessary if the microchannels are directly built over the ground plane and are not crossing electrical lines, and the cooling fluid used is a dielectric.

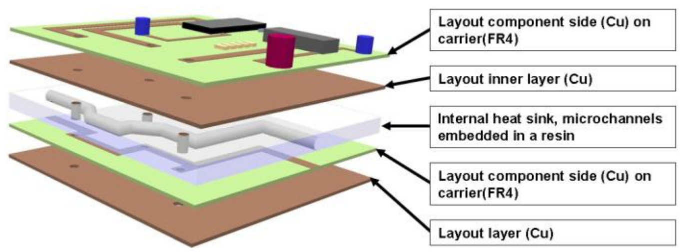

Fig. 2. Exploded view of a four layer PCB with an embedded microchannel.

B. *Microchannel fabrication*

Microchannels were directly built over the traces of copper by direct-write assembly. This approach consists of the robotic deposition of an ink for the freeform fabrication of various structures such as periodic ceramics structures [13] or fluidic 3D micromixers [14]. The direct-write procedure for the creation of microchannels is based on the robotic deposition of a fugitive organic ink [15] on a substrate as illustrated in Fig.1.

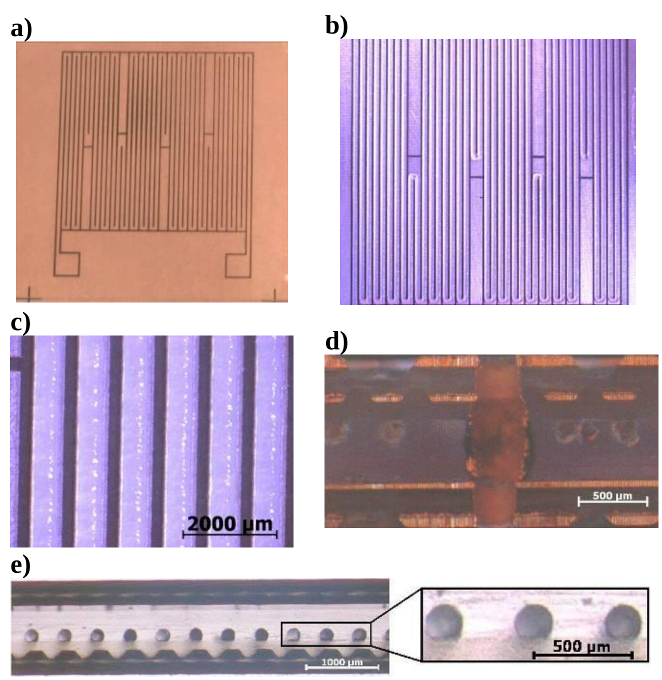

Fig. 3. a) Internal copper layout used for microfabrication and thermal testing of micro heat exchanger; b) Ink pattern deposited over copper trace following circuit drawings (500 µm filament diameter); c) Larger view of ink the filaments over the layout; d) Electroplating of a via of 300 µm of diameter on a resin/FR4/copper sheet; e) Side view of 200 µm of diameter channels embedded between two FR4/copper sheets.

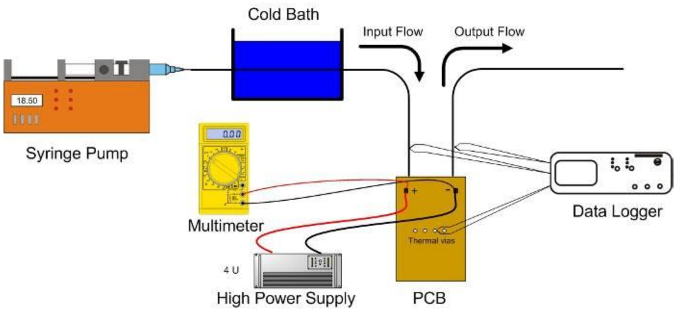

Fig. 4. Schematic representation of the thermal setup used to characterize the thermal efficiency.

The ink is contained in a syringe barrel and consists of a mixture of 40% by weight of microcrystalline wax and 60% by weight of petroleum jelly. The paste-like material was extruded through a cylindrical micronozzle (200 or 500 µm in diameter, Stainless-steel precision tips, EFD) under constant pressure. The ink deposition pattern was performed at constant velocity according to the circuit drawings Alignment marks were etched on the copper in order to position the tip of the nozzle relative to the circuit prior to the ink deposition. The deposited ink pattern was then infiltrated (Fig.1b) with a low-viscosity resin (ratio 2.5:1, Epon-828 and Epi-cure 3274, Shell Chemicals) at ambient conditions.

C. Micro heat exchanger assembly

Upon curing, a second laminated sheet of Cu/FR4 was glued to the circuit using the same epoxy resin for the assembly of the multilayer PCB (Fig.2). Holes of 300 µm and 2 mm in diameter were drilled on the board for the creation of thermal and electrical vias. The fully-assembled micro heat exchangers (microchannel diameter of 200 or 500 µm) are depicted in Fig.3. Fig.3a presents the outlines etched on the internal layout of the PCBs. The channel used was 1.45 m long and covered a planar area of 7.25 cm^2. A chemical electroplating (Contact II, LPKF) was performed for a successful coating of copper over the resin/FR4 layers as shown in Fig.3d. Fig. 3e is a side view of the middle of the PCB showing that the circularity of the microchannel cross-section was maintained during the fabrication and integration processes. The inner wall surface of the microchannel had a root-mean-square roughness of 13.3 ± 6.5 nm [14].

D. Fluidic connections

After the board assembly, the two extremities of the encapsulated ink pattern were glued to micro-tubes (S-54-HL, Tygon) with either an inner diameter of 200 µm or a 500 µm. Then, the board was heated at moderate temperature (~ 348 K) and the melted ink was removed under a vacuum at one end of the micro-tubing. Finally, hot water was injected for a few seconds in the microchannel in order to completely remove the ink (Fig.1c).

E. Thermal setup

Thermal experiments were performed on a four layer PCB containing a 500 µm of diameter microchannel in order to demonstrate the novel fabrication and integration processes and characterize the thermal efficiency of our micro heat exchanger.

The thermal testing setup is shown in Fig.4. The inside etched copper layer is electrically connected through vias and is used to generate the heat flux. In the present case distilled water is used as the cooling fluid. The circuit has been embedded in a polymer matrix to minimize the heat dissipated by convection during the experiment. The temperature reading was done with type-T thermocouples connected to the inlet/outlet of the channel and to a via located at the center of the circuit to measure its average temperature. The water was injected at a temperature of 284 ± 1 K in order to reach the desired temperature gradients between the circuit and the input fluid temperature.

The following procedure was used during the thermal experiments. First, a high current (DCS12-250E, Sorensen) was applied while the voltage was monitored at the terminals of the circuit. A syringe pump (NE-1000, Pump Systems inc.) was used to flow the cooling water at desired flow rate. The temperatures were monitored and recorded using the thermocouples linked to a data acquisition system (HH506R, Omega). The thermocouples measured the fluid temperature at the entrance and exit of the embedded microchannel, and the temperature of the circuit located in the center of the board. Finally, the flow rate imposed by the syringe pump was manually adjusted and maintained constant in order to achieve the specific temperature gradients (i.e., 15 K, 20 K and 25 K) between the input fluid temperature and the circuit (ΔT). The adjusted flow rates were recorded after a few minutes when the steady state condition was reached.

III. Results and Discussion

A. Thermal results

The current of the power supply was set to generate a power of 3 W, 4W, 5 W and 6 W in the internal circuit having an area of 7.25 cm^2. Fig.5 presents the adjusted fluid flow rates required to keep a temperature gradient between the circuit and the input fluid at 15 K, 20 K and 25 K. Fluid flow rates ranging from 0.75 ml/min to 3 ml/min were necessary to reach

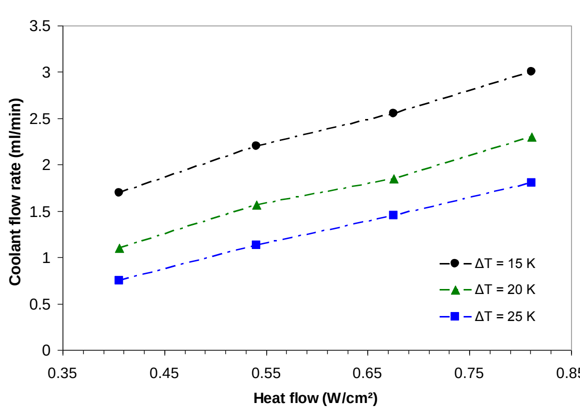

Fig. 5. Experimental results of water flow rates needed to dissipate heat flux for different temperature gradients in a 500 µm diameter channel.

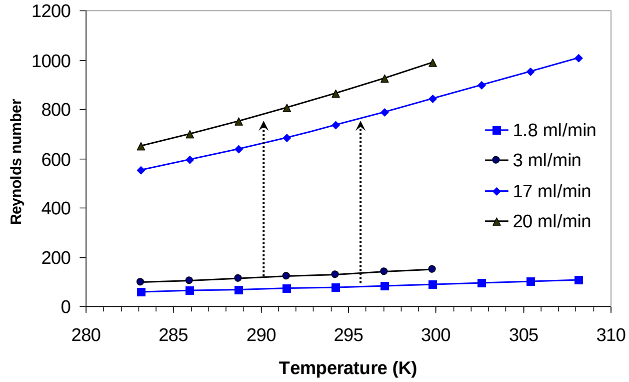

Fig. 6. Calculated Reynolds number versus the average fluid temperature in a 500 µm diameter channel for a flow rate of 1.8ml/min (Δ 25 K) and 3ml/min (Δ 15 K) and their extrapolation at the maximum flow rate prior to turbulent behavior.

the desired temperature gradients with a linear dependence. Assuming that this linear regime is maintained at higher flow rates, the thermal performance of the prototype could be extrapolated before turbulent flow occurs (i.e., when the linear regime was lost).

The Reynolds number is the dimensionless ratio of inertial to viscous forces and is calculated using

$$\mathrm{Re} = \frac{\rho D_h u}{\eta} = \frac{D_h u}{\upsilon} , \qquad (1)$$

Where D_h is the hydraulic diameter; u is the average velocity of the fluid inside the channel; ρ is the density of the fluid; η is the dynamic viscosity; and υ is the kinematic viscosity of the fluid which is temperature dependent.

At the highest flow rate used during the experiments (i.e., 3ml/min), the Reynolds number reached a value of only 178 and laminar flow was maintained. Fig. 6 shows the Reynold numbers with respect to the average fluid temperature for two different flow rates (i.e., 1.8 and 3 ml/min). The thermal performance can then be extrapolated for a flow rate of 17 and 20 ml/min, where turbulent flow is expected to occur (i.e., Re ~ 1000 for most situations [16]). With a flow rate of

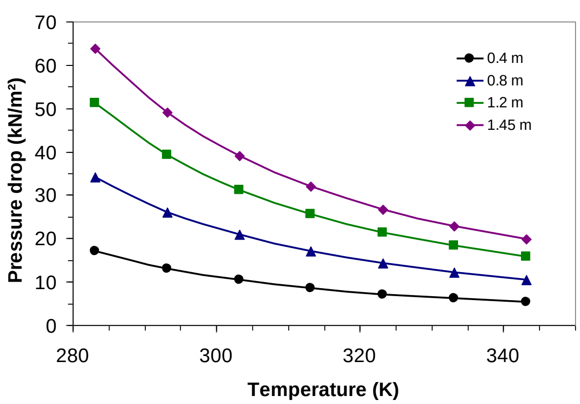

Fig. 7. Calculated pressure drop versus the average fluid temperature for different microchannel length (coolant fluid: water, flow rate = 3ml/min).

17ml/min and a temperature gradient of 25 K, an heat flow dissipation of 6.73 W/cm^2 using the linear relation measured from the thermal experiments (Fig. 5) is predicted. At a flow rate of 20 ml/min and a temperature gradient of 15 K, the predicted heat dissipation is 6.23 W/cm^2. As expected, the higher temperature gradient will dissipate more heat at a lower coolant flow rate. However, higher operating temperatures will also increase the Reynolds number and the risk of turbulent flows.

B. *Pressure drop*

The pressure drop along a channel needs to be within the capacity the micro-pump used with the micro heat exchanger system. During our thermal experiments, leakage was observed at flow rates > 6ml/min due to fluidic connection problems and high pressure at the fluid inlet. Considering the operating temperature range and the desired flow rate for a given heat dissipation, the pressure drop can be estimated. For circular microchannels, the pressure drop is given by

$$\Delta P = \mathrm{Re}\, f \,\frac{\eta L}{2 D_h^{\,2}} u , \qquad (2)$$

where L is the length of the channel and f is the Darcy friction factor. This factor for laminar flows is defined by

$$f = 64 / \mathrm{Re} . \qquad (3)$$

Substituting (3) into (2) give

$$\Delta P = 32 \frac{\eta L}{D_h^{\,2}} u \quad . \qquad (4)$$

As described by (4), this estimation of the pressure drop is a function of the length of the channel, its hydraulic diameter, the dynamic viscosity and the velocity of the fluid. At constant temperature, the pressure drop increases linearly along a channel and the slope depends on the fluid flow rate. For a flow rate of 3 ml/min and an average fluid temperature of 298K, the pressure drop reaches a value as high as ~ 42 kN/m^2 at the end of the channel (diameter = 500 µm). The dynamic viscosity of water is temperature dependent [17] and this variation affects the pressure drop along a channel as shown in Fig.7. For a temperature gradient of 15 K, the pressure drop at the end of the microchannel during our experiments is estimated at ~ 41 kN/m^2 as opposed to ~ 33 kN/m^2 for a gradient of 25 K. Fig.7 also shows that the length of the channel has less effect on the pressure drop as the temperature increases. This diminution of the pressure drop promotes the operation of the cooling system at the highest possible temperature while staying below the junction temperature and turbulent flow transition.

IV. Conclusion

We have successfully used a new microfabrication technique based on direct assembly of a fugitive organic ink to build circular microchannels inside PCBs. The fabrication process is compatible with PCBs manufacturing process or requires minor modifications. This process could be combined to exposed paddles packages, for instance, for higher heat dissipation with low thermal resistance. The routing of the channels is customizable and can be adjusted to the specifications of a circuit design to achieve the best thermal coupling with high power components. Direct writing is a relatively low cost production technique and recent work [19] has already enhanced the manufacturing capability of the direct write process with a writing speed of up to 100 mm/s for two dimensional microchannels. Experiments have been conducted with one channel with a diameter of 500 µm using low flow rates. The results show promises for this technique with a heat dissipation of 0.81 W/cm^2 at only 3 ml/min. Under laminar flow, the extrapolated heat dissipation is estimated at 6.7 W/cm^2 for a flow rate of 17 ml/min and a temperature gradient of 25 K. The diameter, length and number of channel deployed need to be adjusted according to the heat sink and the micropump used and the desired operating temperature for an efficient cooling.

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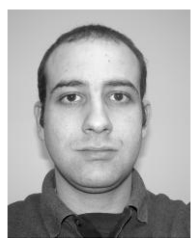

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