Hotspot Liquid Microfluidic Cooling: Comparing The Efficiency between Horizontal Flow and Vertical Flow

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Abstract. This paper reports a novel cooling method for a local high-temperature block in an integrated circuit, which is called a "hotspot". The method is to cool the chip in out-of-plane (3-D) direction to overcome efficiency limit of traditional horizontal (2-D) cooling. Our result indicates that high-temperature (over 180 ℃) circuit block such as a phase-locked-loop (PLL), which is a performance limiting block in a modern CPU, can more efficiently be cooled by the vertical (3-D) cooling scheme.

1. Introduction

The more transistors are integrated to an LSI, the larger the power dissipation becomes. Due to the large power dissipation, especially of high-performance chips, chip-level cooling has become important today [1]. For effective cooling of a chip, several works focused on liquid cooling with integrated microfluidics since increasing the volume and the surface area of solid heat-sink is not always possible. While some studies such as Ref.[2] and Ref.[3] propose using microfluidics to replace the solid heat-sink, these methods need many external equipment like a pump, which leads to expand the size of the whole system.

To avoid increase of the size, some studies [4], [5] use both integrated microfluidics and solid heat-sink. In such a usage, the major role of an integrated microfluidics cooling system is as a heat spreader that reduce thermal non-uniformity of a LSI chip, which reduces in a performance of a microprocessor [6], caused by heavy loaded circuit block like a PLL.

To date, most of the previous research on microfluidics hotspot cooling systems has focused on improving the micro pump performance and characterization of in-plane micro-channels. A horizontal

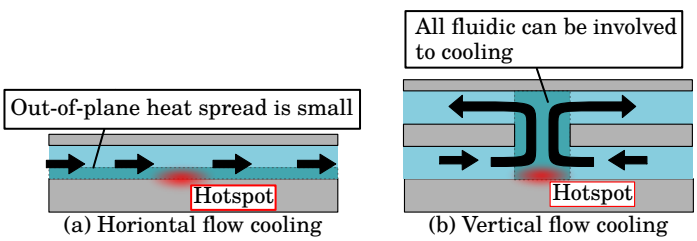


Figure 1. (a) Cooling a hotspot by horizontal flow. Out-of-plane heat spread is small due to laminar flow. (b) Cooling a hotspot by vertical flow. All flow can contribute cooling a hotpot over the hotspot.

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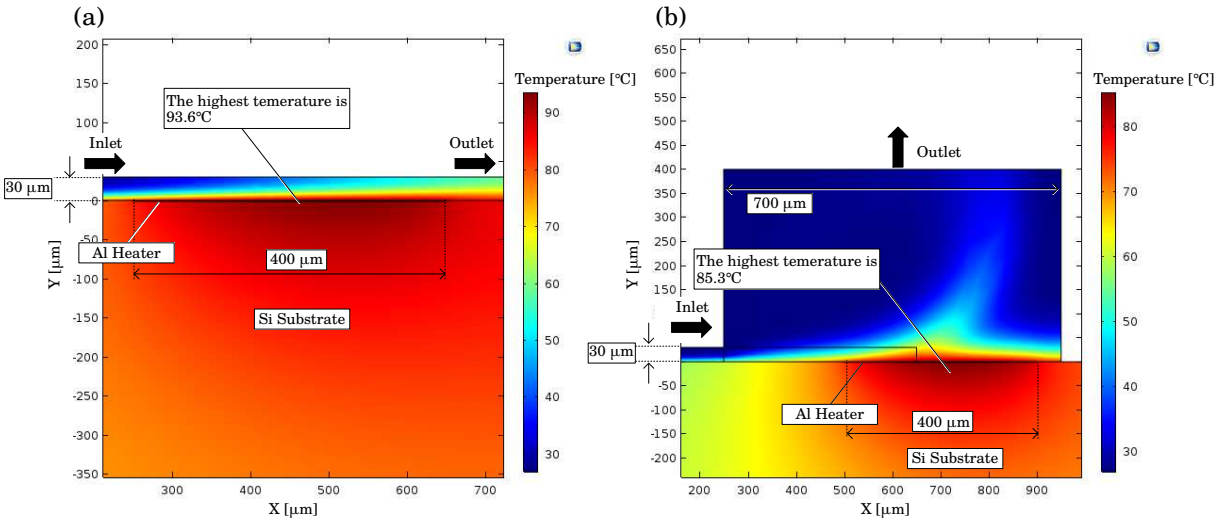


Figure 2. FEM simulation of (a) horizontal in-plane cooling (b) vertical out-of-plane cooling

in-plane micro-channel, however, can involve only the surface of the micro-flow as shown in Figure 1-(a). To involve all the liquid over the hotspot, the authors propose to make use of vertical flow (Figure 1-(b)). In this paper, we report the efficiency of vertical flow in order to cool down a hotspot with a micro aluminum a heater and a thermal sensor.

2. Experimental results

2.1. FEM simulation

Figure 2-(a) and (b) show the simulated temperature of a hotspot cooled with horizontal in-plane flow and vertical out-of-plane flow. In the simulation, 400 μm × 400 μm square Al heater is put on Si substrate as a hotspot and microchannel is placed on the Al heater. In the in-plane cooling simulation, a height of the channel is 30 μm, and the flow is made from left to right (Figure 2-(a)). In the case of the out-of-plane channel, the inlet is the 30 μm channel and the 750 μm outlet is above the hotspot (Figure 2-(b)). The input power is supposed to be 2 W and input liquid is supposed to be DI-water at a flow-rate of 500 μm/min. While the highest temperature with horizontal in-plane cooling is 93.6 ℃, the highest temperature with vertical out-of-plane coolingis 85.3 ℃. It means that the vertical flow can take out the heat from the hotspot thanks to the flow direction and the larger volume of cooling involved liquid.

2.2. Temperature measurement of in-plane cooling and out-of-plane cooling

To measure the temperature and to heat locally, we fabricated micro resistors as thermal sensors and an artificial hotspot as shown in Figure 3. The design of the device follows the simulated layout.

One micro heater was placed under the horizontal flow and the other was placed under the vertical flow. For fabricating a bottom plate, SiO_2 was sputtered by 500 nm as an insulator (Figure 4-(a-1)), and then Al was sputtered by 500 nm and patterned (Figure 4-(a-2)). After the patterning, 50 nm SiO_2 was sputtered again to avoid an electrolysis when liquid flowing (Figure 4-(a-3)). As a top plate with micro-channels, we patterned PDMS using a SU-8 mold (Figure 4-(b-1)). After peeling off the PDMS from the mold, inlet and outlet holes were made (Figure 4-(b-1)). Finally both of them were bonded after O_2 plasma activation (Figure 4-(c)).

The micro-channel was connected to an external pump, whose flow rate was 450 μL/min. The micro-heater as a hotspot was connected to a power source and the thermal sensor was connected to an LCR meter (HP 4284A) as shown in Figure 5. After the correspondence of the change of the resistance against

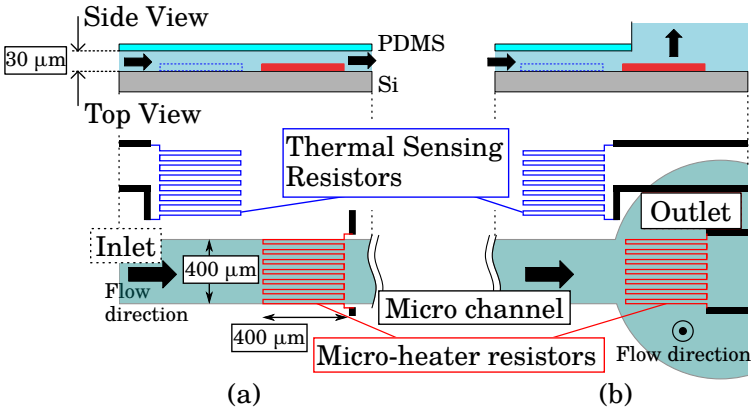


Figure 3. Schematic of the fabricated device to measure the impact of (a) horizontal flow and (b) vertical flow to cool the hotspot. A resistor is placed next to a micro-heater to measure the temperature .

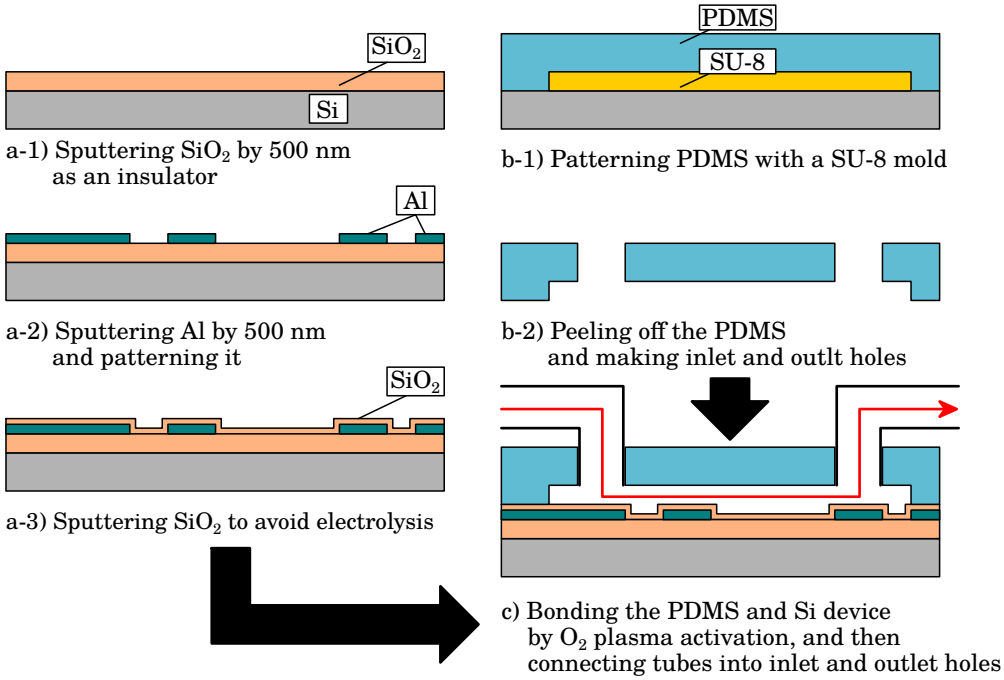


Figure 4. Process flow of the fabricated device

the temperature is measured, we calculated the temperature around a hotspot from the resister next to the hotspot as shown in Figure 6. After power consumption of a micro-heater reaches more than about 1 W, the temperature around the hotspot under the vertical flow becomes smaller than that of under the horizontal flow. It means that the heat which cannot spread to Si plate is spread by the water flow, and that the vertical flow can carry the heat more efficiently than the horizontal flow. When the power input to the hotspot is about 2.3 W, the difference of the temperature between with the horizontal flow and with the vertical flow reaches 10 ℃. This result is consistent with the simulated result, and the efficiency of vertical flow for cooling a hotspot in LSI is thereby confirmed.

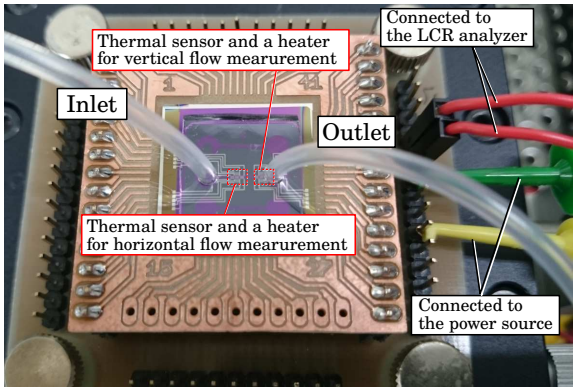


Figure 5. Setup of the experiment. The channel is connected to the external pump (450 µL/min). the resistor for a thermal sensor is connected to an LCR parameter analyzer and the resistor for a micro-heater is connected to a power source.

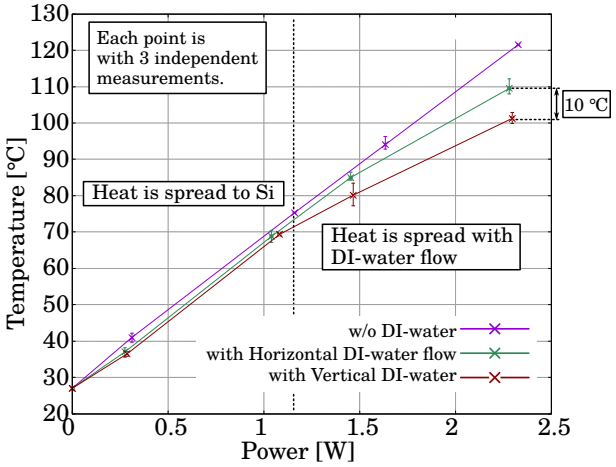


Figure 6. The temperature when the power is input to a micro-heater. When the input power is around 2.3 W is, the difference of the temperature between around the horizontal flow and with the vertical flow is 10 ℃

3. Conclusion

We propose a novel cooling method for a hotspot in an LSI with out-of-plane vertical cooling instead of in-plane horizontal cooling. The simulation results present that the vertical flow can involve much more liquid to cooling a hotspot. According to the measurement of the real fabricated thermal sensor and the micro-heater, we confirmed the higher cooling performance of vertical flow scheme for a hotspot.

Acknowledgments

The CAD patterns were designed with Cadence Virtuoso, accessible through the University of Tokyo, VLSI Design and Education Center (VDEC)'s academic program. The patterning for the device was directly performed by the VDEC's 8-inch EB writer F5112+VD01 donated by Advantest Corporation. The post-process was done using the open facilities of VDEC accessible through MEXT's Nanotechnology Platform Program. Part of this work is supported by KAKENHI No. 16H04345 and the three-dimensional integration development program of the WOW Alliance. The simulations were done with COMSOL Multiphysics™.

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