A THERMOPNEUMATIC VALVE FOR SINGLE PHASE LIQUID COOLING FOR MICROELECTRONICS

Radu Donose*, **Jan Peirs, Dominiek Reynaerts**
Departement Werktuigkunde, Katholieke Universiteit Leuven, Leuven, Belgium
*Presenting Author: Radu.Donose@mech.kuleuven.be

Abstract: This paper reports on the design, optimization and testing of a thermopneumatic valve for single phase liquid cooling for microelectronics. Its purpose is to maintain the Integrated Circuit (IC) at constant temperature and to reduce the power consumption by diminishing the flow actuated by the pump in function of the cooling requirements. It uses a thermopneumatic actuation principle that combines the advantages of zero power consumption, small size in combination with a high flow rate, and low manufacturing costs. A maximum flow rate of 38 kg/h is passing through the valve for a heat load up to 500 W.

Keywords: thermopneumatic valve, single phase, microelectronics liquid cooling, heat sink

INTRODUCTION

This paper reports on the design, optimization and testing of a thermopneumatic valve (figure 1) for cooling of microelectronics. Thermal fluctuation is one of the main issues for electronics lifetime [1,2,3]. Cycles of alternating temperatures lead to repeated changes in dimension of electronic components which lead to the shortening of their lifetime. However, most electronics cooling solutions [4,5] consume power. In many cases this energy consumption is not optimized being wasted on excess of cooling [6].

In the design of this thermopneumatic valve, we target these issues. Its purpose is to maintain the Integrated Circuit (IC) at constant temperature and to reduce the power consumption by diminishing the flow delivered by the pump in function of the cooling requirements.

The dimensioning meets the cooling requirements of an IC of 1 cm^2 by absorbing up to 500 W/cm^2 at a temperature difference of 30 - 40 °C [7]. To achieve these high performances, conventional air cooling is not sufficient and therefore liquid cooling is used.

DESIGN AND OPERATING PRINCIPLE

The design of the valve is based on the following ideas:

1. To reduce the actuation force, the knife-gate principle is adopted [8]: the flow is obstructed by a thin blade moving perpendicularly to the flow direction, such that the pressure difference across the valve has a minimal effect on the actuation force.
2. The response of the valve to the IC temperature is provided by the thermal expansion of a liquid that is heated by the IC. This results in a passive valve which requires no control or external power supply.

Silicone oil is chosen as expansion fluid because it possesses the highest expansion coefficient among the non-toxic, inflammable and safe liquids. The silicone oil used (Dow Corning 200 fluid 500 CS) has a volumetric expansion coefficient of 0.96 x 10^{-3}/K at 20°C, which is 4.7 times higher than the expansion of water and 28 % higher than the expansion of ethanol.

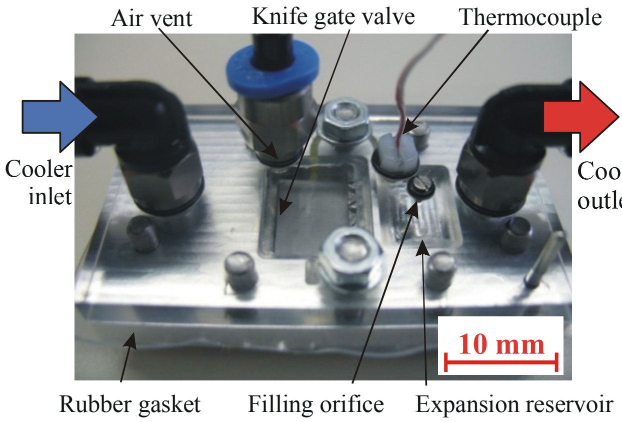

Figure 1: Assembled thermopneumatic valve.

A schematic representation of the valve mechanism is shown in figure 2. A heat sink is placed over an IC to remove the heat. During functioning, the heat is transmitted to a reservoir filled with silicone oil which expands into a tube that is pressing against a beam, moving it upwards. The beam is opening the cooling channels reducing the IC temperature by increasing the flow rate.

Figure 3 depicts a cross-sectional view of the valve design. The heat generated by the IC (1) is transmitted to the silicone oil in the reservoir (2). The silicone oil

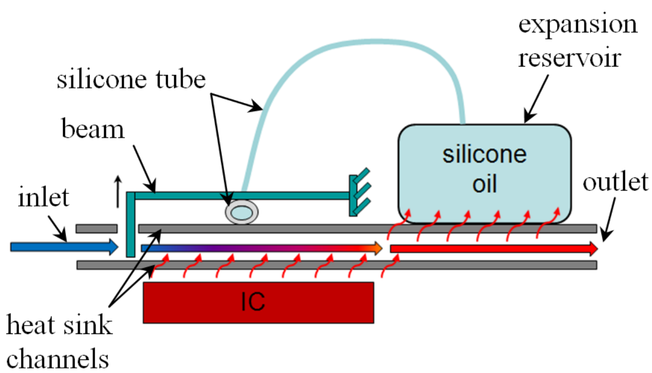

Figure 2: Valve mechanism.

expands into a silicone tube (3) through a connection channel (4). When the silicone tube is pressing against the beam (5) fixed on the frame by screws (6), the beam moves upwards and allows the cooling fluid to enter the heat sink (7) at an increased rate. The heated fluid is leaving the system through the outlet (8) while cold fluid is getting in through the inlet (9).

The temperature range in which the valve is sensitive is adjusted by caliber plates (10) of different thicknesses that are inserted in the reservoir replacing a specific quantity of silicone oil. The reservoir is filled through orifice (11). Orifice (12) is used as a port for a temperature or pressure sensor and orifice (13) to remove the air trapped in the beam enclosure. A silicone membrane (15) provides sealing between the main valve body (14) and the transparent cover (16).

To amplify the stroke, the tube is placed halfway the beam. The cross-section of the beam (figure 4) is carefully chosen to maximize the deflection range: a thinner section close to the fixation area to increase the upward flexing of the beam, and a thicker section for the front part to minimize downward bending due to flow pressures exerted at the tip of the beam.

The cooling fluid is controlled at the entrance of the channels for better hydrodynamic stability. To obtain maximal sensitivity to temperature change, the reservoir is placed over the heat sink at the end of the channels, as close as possible to the IC. This way it can detect the heat coming from the IC and the heat that is absorbed by the cooling fluid.

The volume of silicone oil required for actuation was calculated in function of the volumetric change of the tube, as it goes from a flattened to a round shape

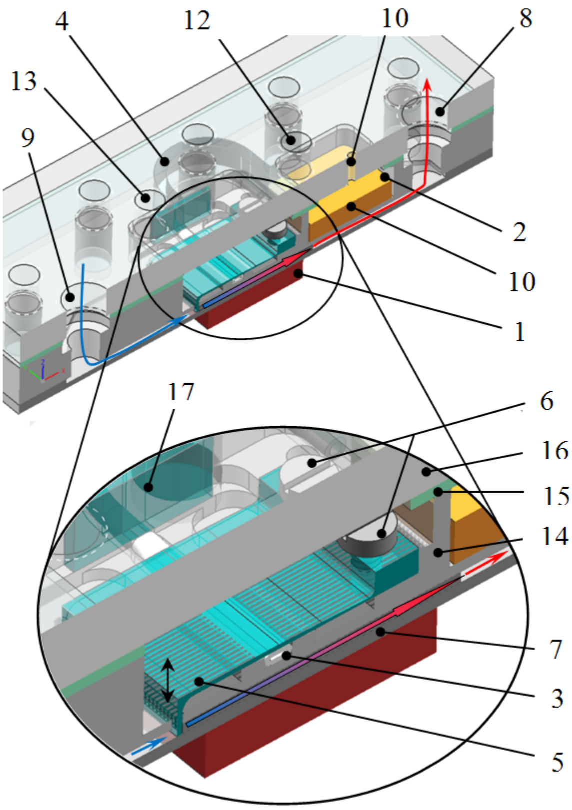

Figure 3: Section view of the thermopneumatic valve.

when actuating the beam. Also the thermal expansion of the tube itself is taken into account. The required reservoir volume V to lift the beam as a function of the temperature difference ΔT is listed in table 1.

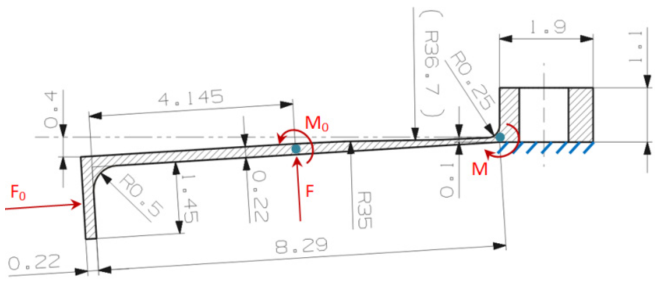

Figure 4: Cross-section of the designed beam.

ΔT [°C]	10	20	30	40	50	60
V [mm^3]	350	175	117	88	71	59

Table 1: Required reservoir volume as a function of temperature difference.

FABRICATION TECHNOLOGY

The entire assembly is fabricated using micro-milling and micro-EDM technology. The material chosen for the metallic components is aluminum Al7075. Besides its excellent thermal conductivity, its superior hardness makes it one of the best machinable materials (by milling) on the market, and allows aspect ratios up to 15 for heat sink fins.

The material used for the tube is Silastic Rx 50 medical grade tubing with an internal diameter of 0.51 mm and an external diameter of 0.94 mm. It was chosen because of its excellent flexibility (815 % strain at failure) and tear strength (46 kN/m).

Perfect sealing between the beam and the heat sink would mean perfect contact between them. This is not desirable because they need to have some play to avoid friction. Based on machining and aligning accuracy, this gap is considered to be 40 µm.

The temperature needed to open the valve is adjusted by heating up the reservoir to the required temperature with the filling orifice open so the excess of silicone oil can leave the reservoir. Before cooling down, the filling orifice is closed and sealed with a rubber o-ring around the M1 screw to avoid air entering the reservoir.

Figure 5 shows the main valve components. The cooling channels in the heat sink are 150 µm wide and 450 µm deep. The walls in between the channels are 40 µm wide. The cover plate is made from polycarbonate to provide visual access to the inner working of the valve. The tube is closed on one end with a silicone plug while the other end is inserted in the reservoir via a circular groove. The circular groove is filled with glue to secure the tube and seal the groove. A silicone rubber gasket is placed between the valve body and the cover plate to avoid leakage.

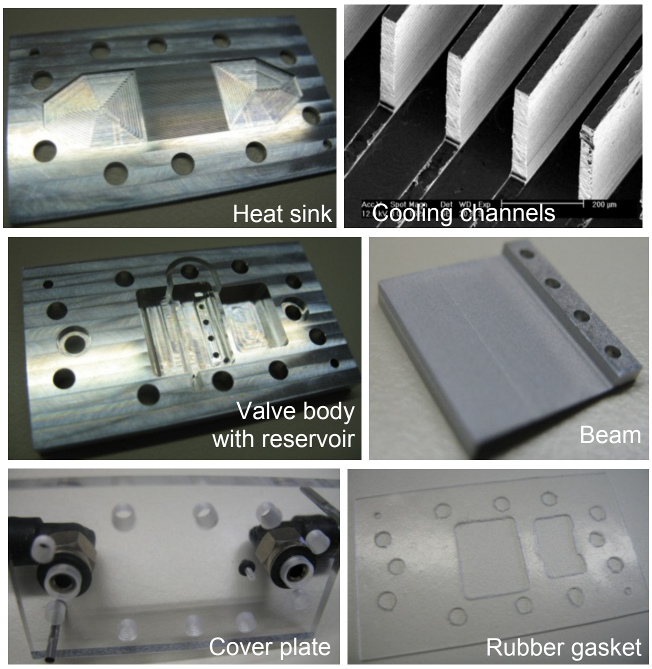

Figure 5: Thermopneumatic valve components.

MEASUREMENTS AND RESULTS

As the actuation of the beam is central to the operation of the valve, beam deflection was measured as a function of temperature. Figure 6 shows that for an ambient temperature of 23 °C and a dry valve, a stroke of 750 µm is obtained for a temperature change of 16°C. The response is linear with insignificant hysteresis. The plotted temperature is the average between the temperature measured in the reservoir and the temperature measured at the junction between the resistor and the heat sink. The measured stroke is more than sufficient compared to the 450 µm channel height.

In the next measurements the valve is placed in the cooling system using distilled water as coolant. The ambient temperature is maintained at 20.5 °C. The pump regulates the flow in function of the valve behavior in such way that the pressure difference between inlet and outlet is kept constant. In a first experiment, a sudden power input of 490 W is applied to the heater for 6 minutes, followed by another 6 minutes of cooling at zero power input. In a second experiment, the heat is applied stepwise: 0, 13, 50, 113, 202, 315 and 450 W with time intervals of 2 minutes. The same procedure is used during cooling. Figure 7 shows the resulting flow rate and beam deflection as a function of heater temperature, when maintaining a pressure drop of 0.5 bar. The experiments with sudden heating indicate a reaction time of 10 s, due to the time required to heat the oil in the reservoir. A similar response is observed for the stepwise heating, but with smaller hysteresis in figure 8, as the system gets time to adapt to the new temperature at each step.

Figure 8 displays the flow rate as a function of time as the heat load changes stepwise, and this for pressure drops of 0.05, 0.2 and 0.5 bar.

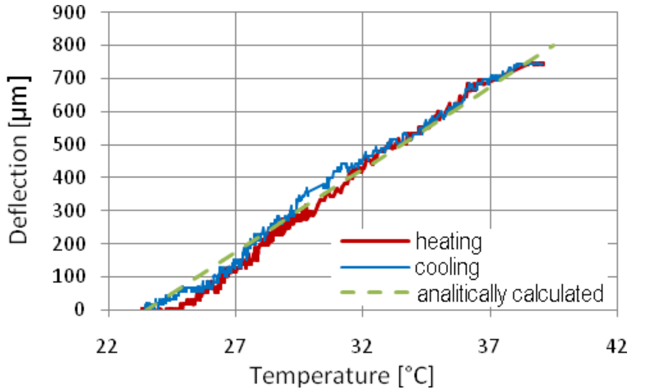

Figure 6: Beam deflection versus temperature at atmospheric pressure.

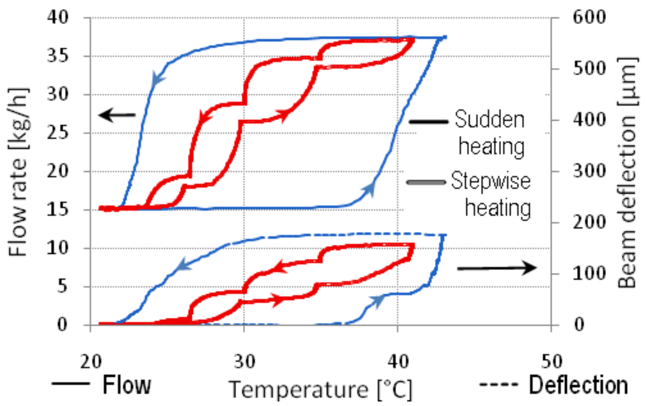

Figure 7: Flow rate and beam deflection vs. temperature at a ΔP of 0.5 bar.

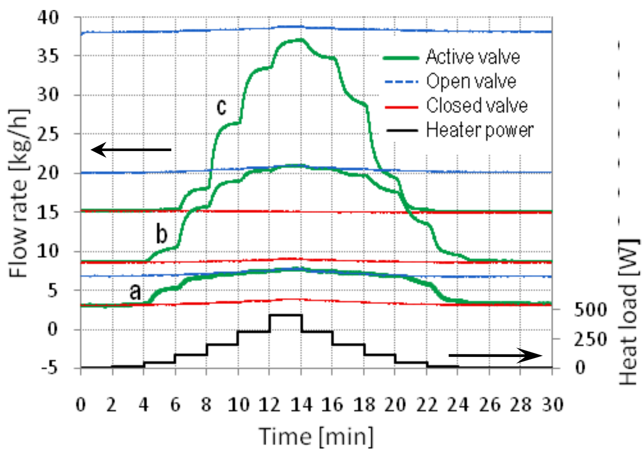

Figure 8: Flow rate in function of time for a stepped heat input at ΔP 0.05 (a), 0.2 (b) and 0.5 bar (c).

For comparison, the same measurement was performed on the valve in the closed state and in the fully opened state. It can be observed that the valve was able to regulate the flow over the full range and to completely close every time. At the highest flow rate however, when ΔP equals 0.5 bar, the maximum flow rate couldn't be achieved by a small margin due to the too strong cooling that prevented the silicone oil to heat up enough. It has been observed that the heat sink resistance is increasing with the flow such that above a certain flow rate, the pressure drop caused by the beam is negligible in comparison to the total pressure drop.

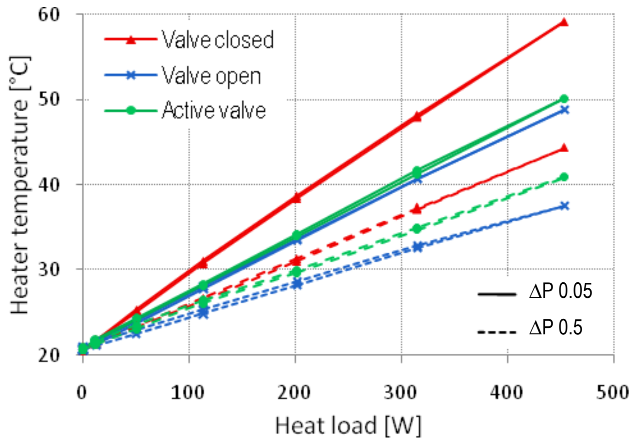

Figure 9: Heater temperature versus heat load.

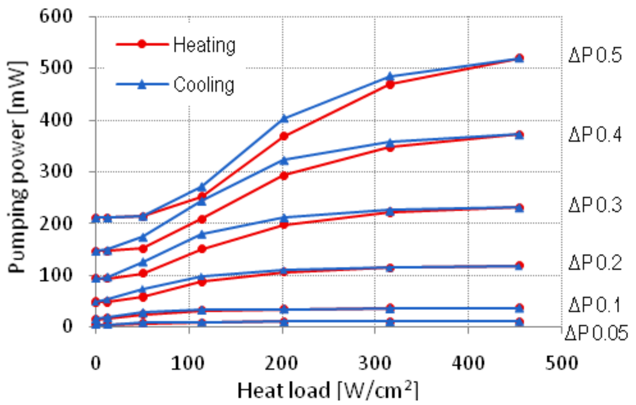

Figure 10: Pumping power versus heat load.

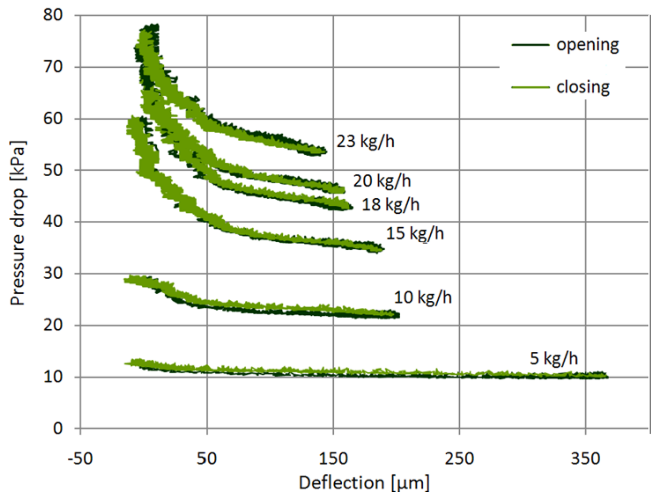

Figure 11: Pressure drop versus deflection.

For a flow rate of 38 kg/h, occurring at a pressure drop of 0.5 bar when the beam is in open position, the stroke required is just 170 µm, compared to the 450 µm of the channel height.

In figure 9, the heater temperature at the junction with the heat sink is plotted in function of the heat load applied to it for pressure drops of 0.05 and 0.5 bar through closed, open and active valves. At smaller flow rates, the heat removal is lower and thus the heater temperature is higher. For the low pressure drop of 0.05 bar (corresponding to low flow rates), the temperature of the active valve follows very closely the characteristic of the constantly open valve for almost the entire range. This is very logic as the overheated valve is craving for cooling fluid and will open completely. For high flow rates (ΔP = 0.5 bar), the active valve follows the trend of the closed valve at heat inputs up to 100 W, and then acts halfway the open and closed characteristics.

An interesting characteristic and decisive factor for using valves in single phase cooling is the pumping power presented in figure 10. Depending on the pressure drop set across the valve, the saved pumping power amounts to up to 320 mW, corresponding to 60 % power savings. The hysteresis is a measurement artifact caused by insufficient settling time (2 min.) preceding the individual measurements.

Figure 11 presents the pressure drop across the valve as a function of deflection for different flow rates. For high flow rates, the beam deflection is limited because the cooling becomes too strong for the current heater. For low flow rates, beam deflection seems to have almost negligible effect on the pressure drop, while for high flow rates, more variation in pressure drop is observed.

CONCLUSION

The thermopneumatic valve shows a novel actuation principle that combines the advantages of zero power consumption, small size versus high flow rate, and low manufacturing costs. Its independence from external energy makes it suited for portable devices. Its passive operation increases the simplicity and reliability. This valve can be used together with any heat sink used for microelectronics cooling. It has the capability of maintaining a more uniform IC temperature and save up to 60 % pumping power.

ACKNOWLEDGEMENTS

This research is sponsored by IWT, the Institute for the Promotion of Innovation by Science and Techn. – Flanders, Belgium; project SBO "HyperCool-IT".

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