TESTING OF AN ELECTROMAGNETIC VALVE FOR TWO-PHASE COOLING OF MICROELECTRONICS

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Abstract: The paper presents the behavior of an electromagnetic valve designed for two-phase cooling of high power density microelectronic circuits. The valve shows sufficient reaction time, less than 10 ms, to be able to cope with the fast dynamics of bubble formation inside the heat sink. The size and actuation force of the main valve is reduced by making use of a pilot valve capable of controlling a flow rate though the main valve of up to 4 g/s (15 kg/h). This flow rate is sufficient to remove a heat input of 133 W equivalent with a heat flux of 500 W/cm^2 at a temperature difference of 20°C. Its equilibrated design allows a pressure drop control of up to 1 bar at maximum system pressures of 6 bar.

Keywords: electromagnetic valve, pilot valve, two-phase cooling, heat sink, microelectronics cooling

INTRODUCTION

The largest contribution on reducing the life time of microelectronic components is the failure due to fatigue and it is believed to be fully responsible for the 90% of all structural and electric failures [1]. Mismatch of the coefficient of thermal expansions between the Integrated Circuit (IC) and the printed circuit board during operation cycles causes thermal mismatches. This is the main cause of hardware induced failures due to thermo-mechanical stress [1,2]. In two-phase cooling the coolant is allowed to evaporate in the heat sink channels. Through this process energy is absorbed, increasing the heat transfer coefficient one order of magnitude above the single phase cooling [3, 4]. The greatest advantage of two-phase cooling is the near isothermal characteristic (less than 1 ^{o}C fluctuation) [5]. Thus, the heat removal at hot spots is increased, resulting in a more uniform temperature over the IC, significantly improving reliability. Despite the large number of designs and micro-valve prototypes [6], liquid cooling of micro-electronics is relatively new and up to now dedicated micro-valves for these systems have not been designed. To our knowledge this is the first valve designed to control the two-phase cooling of micro-electronics. Whereas the PowerMEMS 2011 paper [7] discussed the design and construction of the valve, this year's paper focuses on the tested performance and closed-loop control of temperature, flow, and pressure drop.

DESIGN REQUIREMENTS AND OPERATING PRINCIPLE

The main role of the valve is to cope with instabilities inherent to two-phase cooling systems [8, 9]. These instabilities are in fact cyclic oscillations between measured pressure drop, wall temperatures, inlet and outlet temperatures and mass flow rate [10]. For instance a too low flow rate results in drying up of the cooling channels and catastrophic overheating of the IC. A too high flow rate reverses the two-phase cooling to single phase, loosing efficiency.

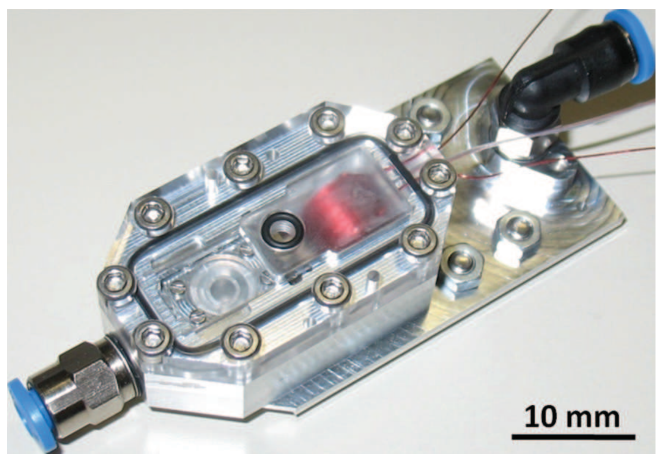

Fig. 1: Assembled electromagnetic valve on the heat sink.

To contribute to the space optimization, the valve is integrated in the heat sink on top of the IC to be cooled. It is driven by a pilot valve which reduces the overall dimensions of the valve as well as the forces to be generated by the electromagnetic actuation. Its planar design allows utilization in confined spaces.

The fast dynamics of bubble formation are the main source of instability for two-phase systems and sufficient change in pressure drop and flow has to be undertaken at very fast response times which are as low as 10 ms. The maximum flow rate the valve has to control is 4 g/s, sufficient to remove the imposed heat flux of 500 W/cm^2. For a more stable boiling control, the valve has to withstand system pressures up to 6 bar, aiming for a pressure balanced design. The valve has to control a maximum pressure drop of 1 bar and to alter a minimum 10 – 20% of this value in less than 10 ms.

The electromagnetic reluctance actuation is chosen for this valve because it provides a response time, stroke and force compliant with the requirements of two-phase systems and it can be produced with low manufacturing costs. To implement both the pilot valve and pressure equilibrated design, the main flow path is divided into two flow paths as illustrated in Fig. 2.

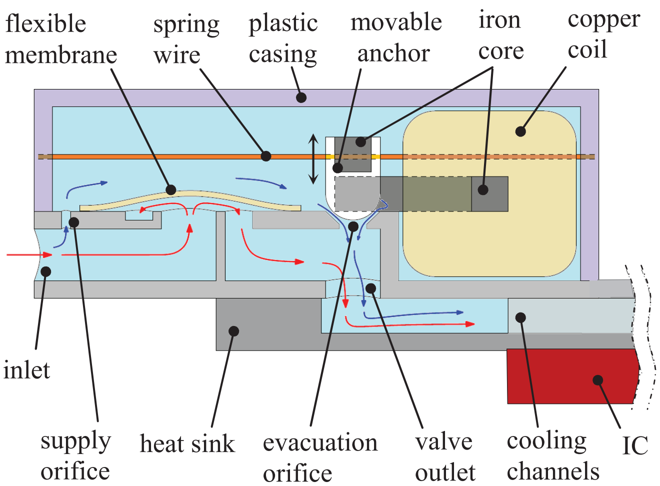

Fig. 2: Schematic of the valve operating principle.

The flow resistance on the secondary flow path which goes above the membrane is adjusted by a plunger controlled by the electromagnetic actuator. This modifies the pressure balance across the membrane which controls its position and by this the flow though the main flow path.

MEASUREMENT SETUP AND METHODS

As the IC's temperature has to be kept below 80°C, refrigerants are used to replace water because they have lower boiling point. For a better boiling stability, the system must be pressurised and therefore is not practical for testing and optimization of the valve. For this reason the valve has been tested with distilled water in single phase flow on a measurement setup schematically illustrated in Fig. 3.

The cooling fluid stored in reservoir (1) is driven through the system by pump (4). Manual valves (2) and (20) permit components interchange of the measurement setup without losing coolant. Valve (3) acts as a bypass for the pump. The coolant is continuously filtered by a 10 µm filter (6) and is releasing the stored heat through heat exchanger (21). The heater (12) plays the role of the IC with the generated power being controlled by the amplifier (19). The heat sink (11) is in direct contact with the heater and for space optimization is embedded on the electromagnetic valve (10). The valve is supplied by power amplifier (22) and controlled with a real time control system (23), cRIO, from National Instruments.

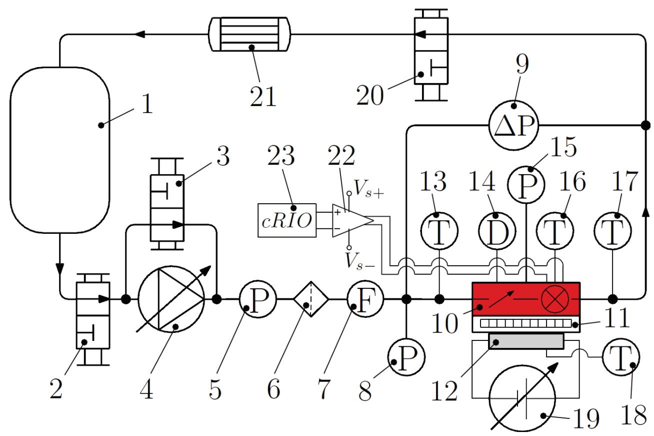

Fig. 3: Schematic representation of the measurement system.

It is based on current control implemented directly in a field programmable gate array on the cRIO for an increased control speed. With this technique control speed of 100 kHz and data logging at 1 kHz have been achieved. The flow control is based on the readings from the pressure sensors (5) and (8) who are measuring the pressure drop across the filter and flow meter (7). The flow meter is based on the Coriolis principle which gives high accuracy (<0.006 kg/h error) at the cost of large settling times (2 s). The pressure drop reading is much faster (10 µs) and thus the two sensors are calibrated to indicate a flow rate in function of pressure drop. The pressure drop across the valve is measured with pressure transducer (9), the absolute system pressure at the entrance of the valve with sensor (8) and the pressure at the valve chamber with sensor (15). The fluid temperature is measured with thermocouple (14) at valve inlet and with thermocouple (17) at the outlet. Thermocouple (18) measures the temperature at the junction between heater and heat sink and thermocouple (17) checks if the coil temperature of the valve remains within safe temperature limits. The valve plunger position is read by the laser measurement system (14).

TEST RESULTS AND DISCUSSIONS

The response at valve opening is displayed in Fig. 4. The plunger reaches the top position after just 2 ms and fully stabilizes after 20 ms. It has an influence on the pressure across the valve after 3 ms, where the pressure drop decreases from 140 kPa to 60 kPa in 8 ms and down to 10 kPa in 20 ms. These response times are sufficient for two-phase flow control.

For closing, the plunger speed is the same as for opening but the pressure build up is much longer due to compressibility of the air trapped inside the piping, the flexibility of the system and limited pump capacity. The valve is designed though to have the same response time for both closing and opening.

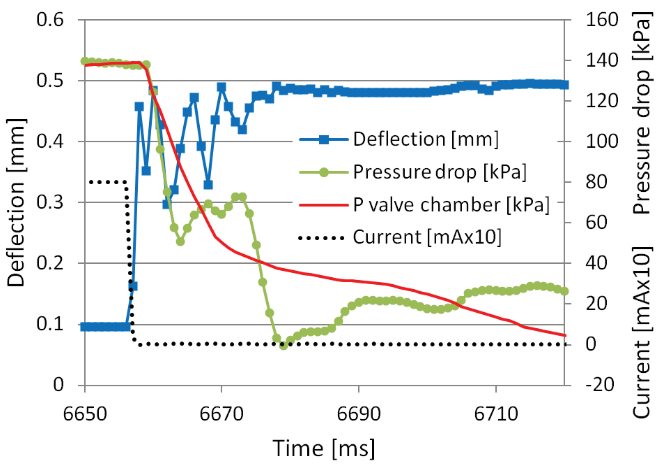

Fig. 4: Response time at valve opening.

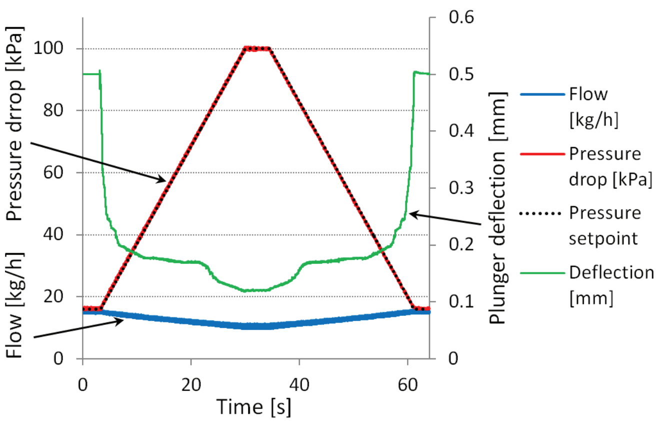

Fig. 5: Closed-loop pressure control: linearly increasing and decreasing pressure input.

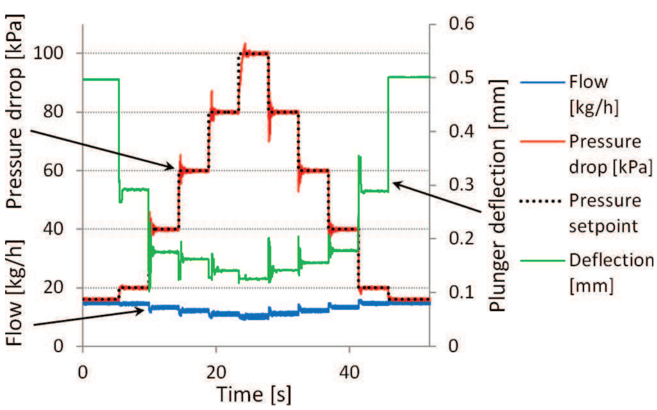

Fig. 6: Closed-loop pressure control: stepped increasing and decreasing pressure input.

The closed loop performance of the valve for a pressure drop is highlighted in Fig. 5 and Fig. 6. Fig. 5 shows this for a linearly increasing and decreasing pressure drop up to 100 kPa, while Fig. 6 shows the results for a stepped input. Along the pressure drop, plunger deflection and flow rate are displayed in function of time. Slight overshoot is allowed to reduce response time. The desired pressure drop across the valve at closing and thus at pressure drop increase, is reached in 36 ms the fastest. However, 715 ms are required to reach the highest step because of the previously mentioned flexibility of the hydraulic circuit. For opening, the step response is between 7 and 46 ms.

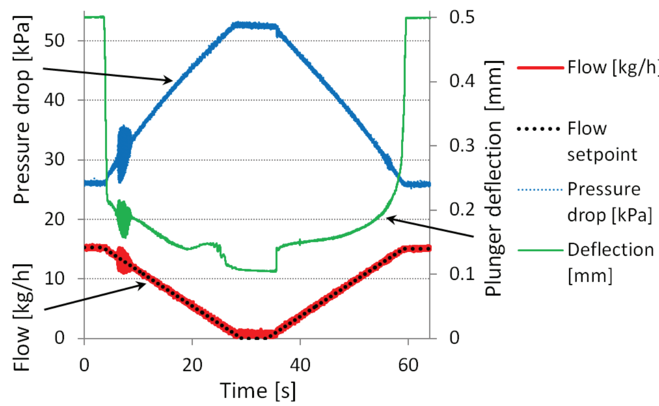

Fig. 7: Closed-loop flow control: linearly increasing and decreasing flow.

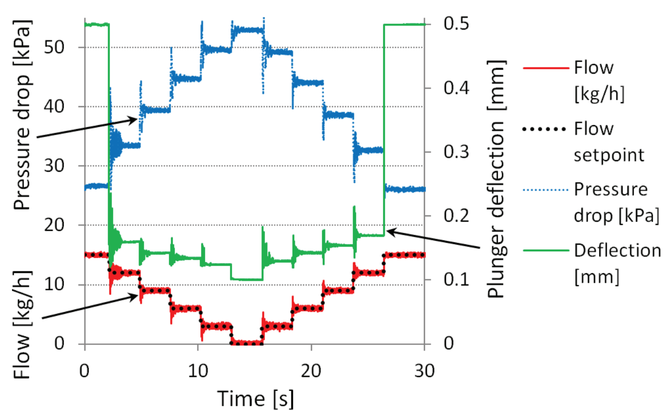

Fig. 8: Closed-loop flow control: stepped increasing and decreasing flow.

In Fig. 7 and Fig. 8 the controlled value is the flow rate. As mentioned in the previous chapter, the flow rate is calculated from pressure drop measurements. The pressure transducer measurements show high noise. This noise is a major source of instability in flow control. This effect can be observed in Fig. 7 where instabilities arise in the plunger position, pressure drop and flow rate for linearly increasing and decreasing flow input. For the stepped flow rate control shown in Fig. 8 the step height is 3 kg/h for a time interval of 3 s. The response time varies between 7 and 86 ms.

One of the most important characteristics of the valve if used in single phase systems is the ability to maintain the IC at a more uniform temperature. Figure 9 plots the closed-loop temperature control of the heater along with the flow rate without valve control (dotted line) and with valve control (continuous line). The desired IC temperature is set to 40ºC and a stepped increase and decrease of power input from 0 to 133 W is applied. After the setpoint is reached, the controller keeps the temperature within a band of a 1°C despite the variation of power dissipated by the IC. Without the controlling valve, the IC temperature varies between 20 and 40ºC.

The measurements in Fig. 10 display the same parameters as in Fig. 9 with the only difference that a sudden power variation is applied on the heater with a block wave of 50% duty cycle which is decreasing in time. As can be seen, the temperature is much more difficult to control because of the inertial effect from the large thermal mass of the heater and heat sink.

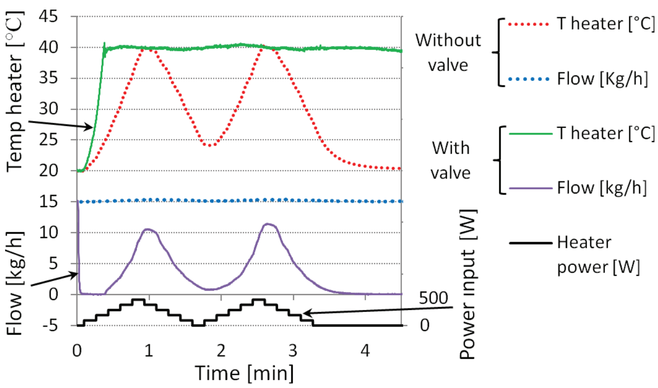

Fig. 9: Closed-loop temperature control vs. a system without control valve: gradual heat load.

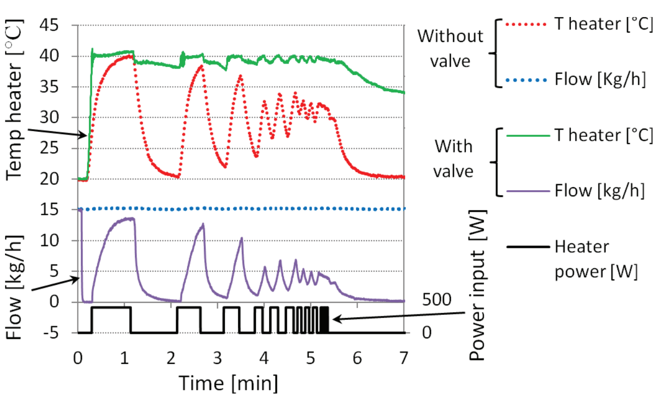

Fig. 10: Closed-loop temperature control vs. a system without control valve: sudden heat load.

Nevertheless the temperature variation is reduced from 20°C without valve to 2.5°C with valve control. Thus the valve has proven to stabilise the temperature and therefore prolong the IC's life by way of less thermal cycling.

CONCLUSION

Tests on the electromagnetic valve in single-phase flow show sufficient reaction time to cope with flow instabilities in two-phase systems. Closed-loop pressure drop, flow rate and temperature are effectively controlled through an FPGA control system. Temperature variations are significantly reduced which has a major benefit in lifetime extension of micro-electronic circuits. The next step is to stabilise the temperature in two-phase regime using sensors capable to detect vapour quality during boiling.

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