

# AN ELECTROMAGNETIC VALVE FOR TWO-PHASE COOLING OF MICROELECTRONIC CIRCUITS

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**Abstract:** This paper reports on the design, optimization and testing of an electromagnetic valve for controlling two-phase cooling through heat sinks for microelectronic circuits. A response time below 10 ms makes it suitable for the fast dynamics of bubble formation inside heat sinks. The main valve is driven by a pilot valve to reduce the required actuation force. It is designed to cope with up to 6 bar absolute system pressure and up to 1 bar differential pressure at maximum flow rates of 4 g/s (15 kg/h) required to remove a heat flux of 500 W/cm<sup>2</sup>.

**Keywords:** electromagnetic valve, pilot valve, two-phase cooling, heat sink, microelectronic circuits

## INTRODUCTION

Thermal fluctuation is one of the main issues in lifetime shortening of microelectronic components [1, 2, 3] due to repeated thermal expansion and contraction. Therefore, one of the main advantages of two-phase cooling is the nearly isothermal characteristic (less than 1 °C fluctuation) [4, 5] which significantly improves the microelectronic circuit's lifetime.

This paper reports on the design, optimization and testing of an electromagnetic valve (Fig. 1) for two-phase flow control through heat sinks for microelectronics. In two-phase cooling, the coolant is allowed to evaporate in the heat sink (boiling), increasing the heat transfer with an order of magnitude with respect to single-phase liquid cooling [6, 7]. The goal is to absorb a heat flux of 500 W/cm<sup>2</sup> at a maximum temperature difference of 30-40 °C [8].

This valve differs from the thermopneumatic valve for single phase cooling presented at PowerMEMS 2010 [9], which aims at reducing pumping power and at maintaining a more uniform IC temperature. As the temperature is constant in the two-phase regime, the thermopneumatic principle could no longer be used and an actively controlled valve is needed.

## DESIGN AND OPERATING PRINCIPLE

The valve introduced in this report is integrated in the heat sink on top of the IC to be cooled. It is essential for stability: a too low flow rate causes the heat sink to boil dry resulting in catastrophic overheating of the IC; a too high flow rate keeps the cooler in the single-phase regime where cooling is less effective. To our knowledge this is the first time that a valve is designed and used for this purpose.

The valve requirements have to be based on the following considerations:

- The dynamics of systems based on two-phase flow are very fast and to maintain a stable boiling condition, very fast response times are required which are as low as 10 ms.
- A maximum flow rate of 4 g/s is required to pass through the valve, sufficient for the proposed heat removal (500 W/cm<sup>2</sup>).

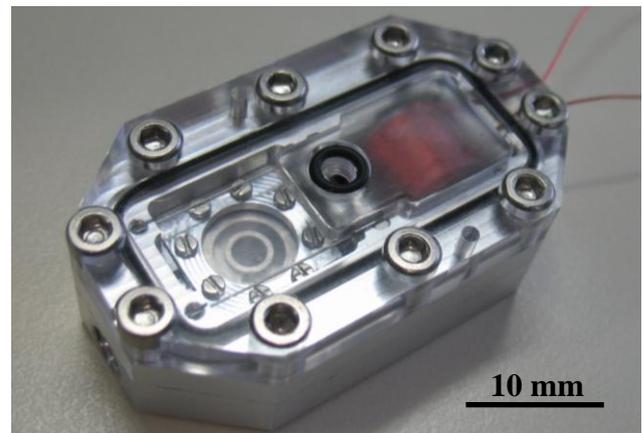


Fig. 1: Assembled electromagnetic valve.

- The maximum pressure drop the valve needs to control is 1 bar while the minimum is 10 – 20 % of that value. For a more stable boiling control, system pressures up to 6 bar have to be used in the cooling system. This high pressure is required to maintain the refrigerant at the desired operating temperature. The valve benefits from an equilibrated design to cope with these pressures.

The actuation principle chosen for this valve is electromagnetic actuation because it provides a response time, stroke and force compliant with the requirements. The operating principle is depicted in Fig. 2. To reduce the required actuation force, the main valve is driven by a pilot valve. The flow entering the valve is therefore divided into the main flow below the membrane (marked with red arrows) and a secondary flow above the membrane (marked with blue arrows). The resistance of the secondary flow is adjusted by a plunger controlled by the electromagnetic actuator. The resulting pressure difference across the membrane adjusts the position of this membrane, changing the flow through the main flow path.

The advantage of this operating principle is that it is able to fully block the flow, even at very high pressures, which is highly advantageous for parallel chip cooling.

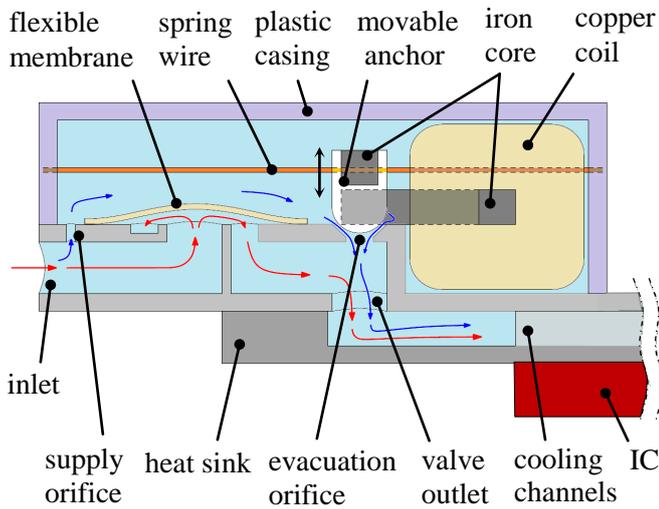


Fig. 2: Schematic of the valve operating principle.

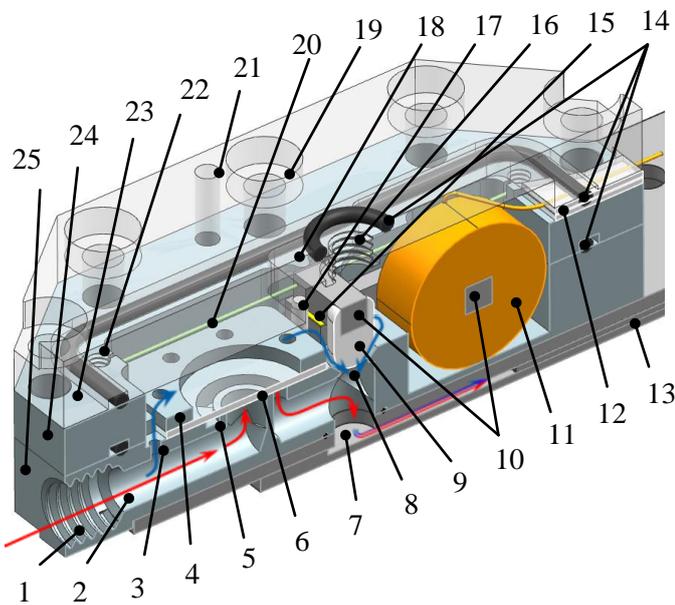


Fig. 3: 3D model of the electromagnetic valve.

The valve features a very compact planar design such that it can be fitted directly on top of the IC. The valve outlet is in direct contact with the heat sink inlet to improve compactness and minimise pressure losses.

A 3D model of the valve is displayed in Fig. 3. The cooling fluid is entering the valve through the inlet (2) which can be connected to the supply tube through a M5 thread (1). As outlined above, the cooling fluid is divided in two paths: one above the membrane (6) through the supply orifice (3) and the other one (the main flow) under the membrane through a circular groove (5) that is communicating with the valve outlet (7). The membrane is being kept in position by a pre-stressing element (4), fixed with 8 M1 screws on the valve body (25). The secondary flow above the membrane is reaching the valve outlet through the evacuation orifice (8). The opening of this orifice is controlled by the position of a ball shaped plunger (9). When the plunger is closing the evacuation orifice, the pressure is increasing above the membrane, pressing it against the circular groove borders, stopping the flow. Although the pressure equalises on the two flow paths

at the valve inlet immediately after valve closing, the pressing force above the membrane is maintained higher than under it because of the area difference of the liquid in contact with the membrane.

The actuation mechanism of the plunger is provided by an electromagnetic reluctance actuator formed by the copper coil (11), wrapped around an iron core (10). The plunger is fixed on the movable iron anchor which is prevented from touching the metal core by epoxy spacers (15) applied onto it. The driving force to return the plunger back to the open position is delivered by two spring wires (20) supported on 4 adjustment screws (22). The aim of these screws is to control the pre-tensioning and position of the spring wires. The plunger is self-centring on the evacuation orifice for a perfect sealing. Rough alignment is however required to position the plunger on the desired starting position. Vertical and horizontal alignment is provided by the extrusions (18) milled on the spring support (24) and 2 centring pins (17) fixed on the valve body. The coil wire is exiting the valve cover (24) through a slot on which PDMS seals (12) are preventing leakage and allow reassembly. The threaded hole (16) is providing direct access to the actuator (plunger) after the valve is assembled. For a leak free valve, O-rings are used (14). The fixation of the 3 valve layers is realised with 10 M2.5 screws placed around the valve (19). The alignment with the heat sink (13) is secured by a centre pin going through all layers (21).

## FABRICATION TECHNOLOGY

The entire assembly is fabricated using micro-milling and micro-turning. The material chosen for the metallic components is aluminum Al7075. Besides its excellent thermal conductivity, its superior hardness compared to other aluminum grades makes it one of the best machinable materials (by milling) on the market. The iron core is machined from steel 430F which is specially developed for solenoid core applications in corrosive environments. It features optimum machining and magnetic properties. The material used for the flexible membrane is PDMS (silicone rubber) with a thickness of 0.5 mm. It was chosen because of its exceptional mechanical properties like low modulus (<1 MPa), which reduces the required actuation force, high flexibility, high tear strength, good sealing and stability over time.

The manufactured valve components are shown in Fig. 4.

## MEASUREMENTS AND RESULTS

To determine the optimal dimensions of the flow path, analytical calculations and finite element simulations were performed. Although refrigerants will be used on the final cooling system, the valve modelling has been done for both refrigerants and water. The results presented here represent validation experiments with water.

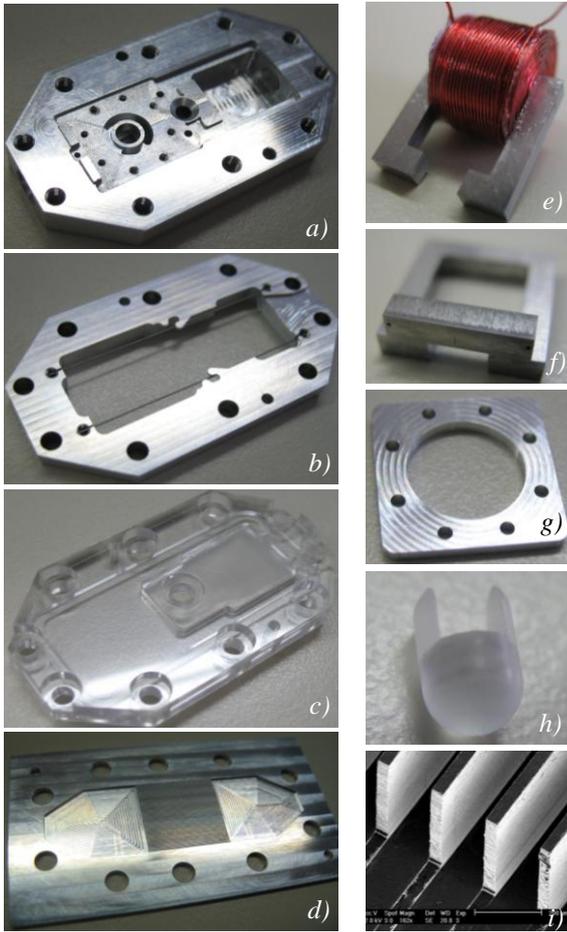


Fig. 4: Main valve components: a) Body; b) Spring support; c) Cover; d) Heat sink; e) Coil; f) Iron core; g) Membrane pre-stressing element; h) Plunger; i) Heat sink channels.

Fig. 5 is plotting the pressure drop across the valve versus flow rate when the pilot valve is not actuated, taking into account the membrane deflection given by the pressure difference between the two flow paths. The analytical calculations and FEM simulations agree very well and are successfully validated by measurements. The hysteresis shown in the measurements is probably caused by material hysteresis in the membrane rubber or initial stresses and deformations in the membrane due to pre-tensioning. It can be observed that the pressure losses across the valve in open position are very low.

The electromagnetic pilot valve properties are depicted in Fig. 6: magnetic forces are plotted as a function of gap height for different currents, along with the counteracting spring force for two different spring stiffnesses. A logarithmic scale is applied for the force to accommodate for the sharply rising magnetic force when the gap closes.

In case the soft spring is used, the response time of the membrane valve is estimated at maximally 3.6 ms, resulting in a total response time around 6.6 ms.

For small gaps, the actuator force rises faster than the spring force causing pull-in or bi-stable behavior. This is illustrated in Fig. 7 where the plunger deflection is plotted as a function of current.

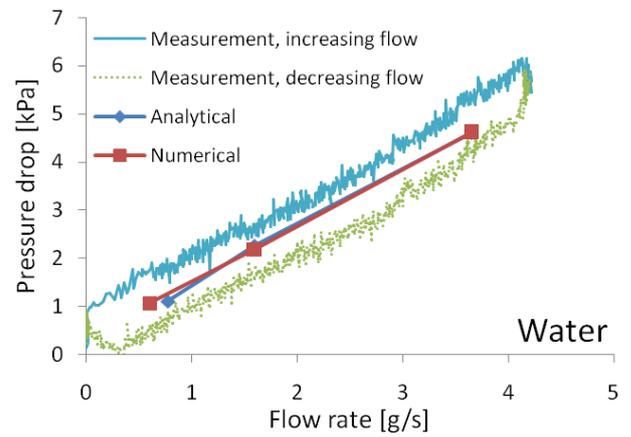


Fig. 5: Pressure drop across the valve in function of flow rate for an open valve.

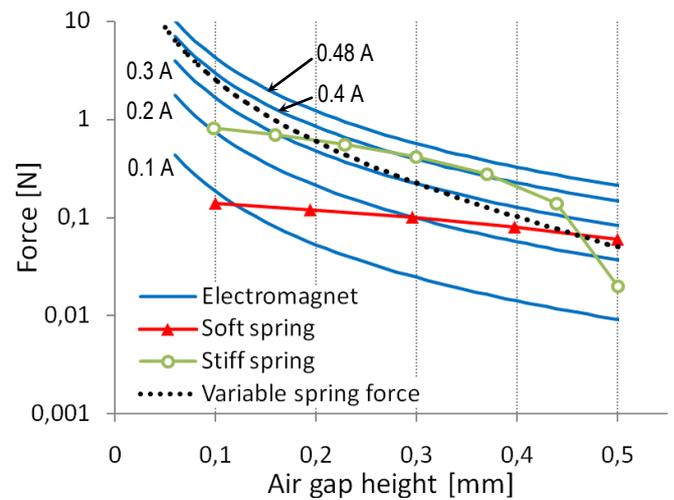


Fig. 6: Electromagnetic pilot valve properties: force developed by the actuator versus gap between poles.

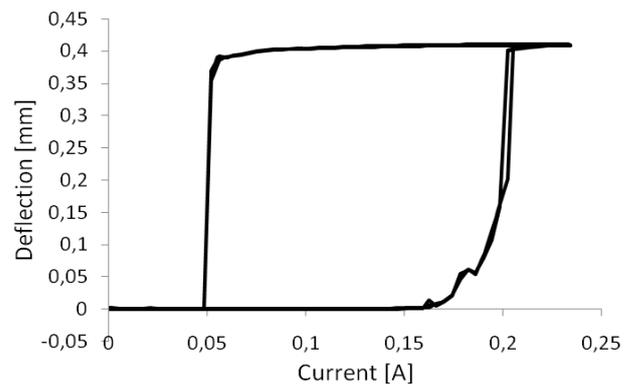


Fig. 7: Plunger deflection in function of current.

Fig. 8 shows more clearly that the current has to decrease significantly to maintain the plunger in equilibrium with the spring towards smaller air gaps. Thus each current value corresponds to two air gap positions, with only the larger gap being stable. Experiments with a stiffer spring (thinner lines) indicate a wider stable operating range, but instability still exists for small gaps. In the stable range, the plunger position was measured in function of current, and these measurements appear in good agreement with the analytical results, as can be seen on the graph.

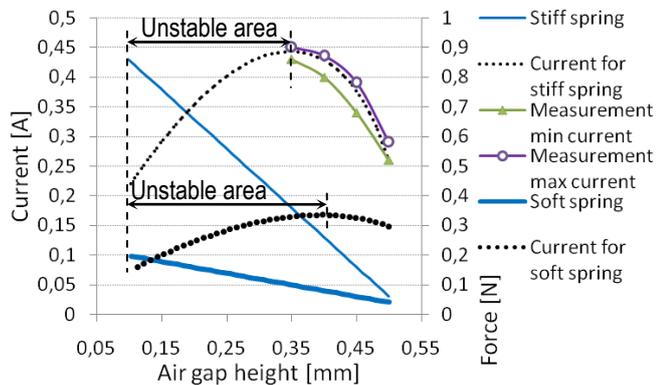


Fig. 8: Required current in function of air gap, for two different linear springs.

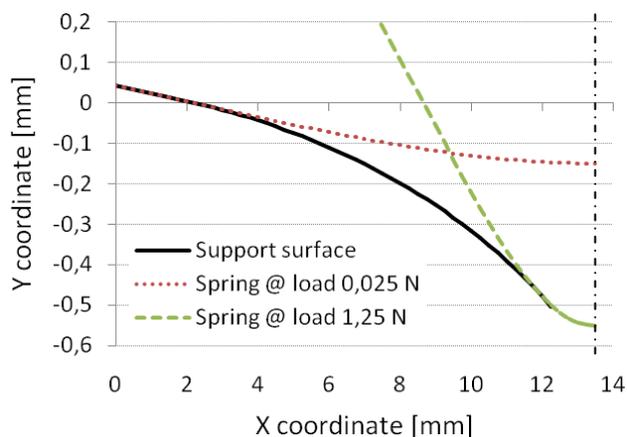


Fig. 9: Spring support geometry for the nonlinear spring. Only left half of the symmetric design is shown.

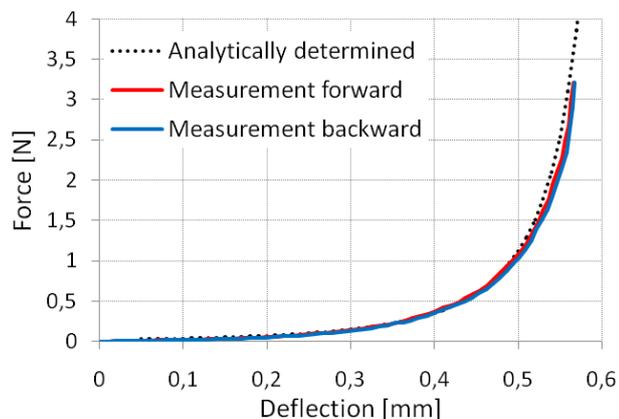


Fig. 10: Calibrated spring force in function of deflection.

As pull-in occurs in the timeframe of around 1 ms, it is not realistic to stabilize the valve with electronic control, especially in view of the intended application. Therefore it is desired to mechanically balance the actuator with a non-linear stiffening spring. For this purpose a surface has been modeled (Fig. 9) on which the supported spring length shortens while the spring deforms. The input values are the forces developed by the electromagnetic actuator driven by currents ranging from 0.2 to 0.4 A along the plunger stroke. The zero value on the Y coordinate is the spring support point for a preload on the spring of 0.025 N. The X coordinate represents the length for half a spring while

the Y coordinates give the support surface (continuous line) and deformed spring for two different loads (dashed and dotted lines). To validate the model, a test surface has been machined on which the spring force is measured in function of deflection (Fig. 10). The agreement between the model and the experimental results is very high.

## CONCLUSION

Analytical calculations and FEM simulations predict a response time of the electromagnetic valve of less than 10 ms, in line with the specifications for two-phase systems. A pilot valve is used to drive the main valve, to reduce the size and power of the electromagnetic actuator. The complete valve features a compact planar design, making it easier to implement in portable devices. The equilibrated design allows operation at high pressures, and even to fully block the flow at high pressures. The first measurements are in good agreement with the valve modelling. The valve has been mechanically equilibrated and more tests are going on to characterise its ability to control boiling in two-phase heat sinks.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] Kraus A D, Bar-Cohen A 1983 *Thermal Analysis and Control of Electronic Equipment* (Washington DC, Hemisphere Publishing Corp.)
- [2] Bar-Cohen A, Kraus A D 1988 *Advances in Thermal Modelling of Electronic Components and Systems* (New York, Hemisphere Publishing Corp.)
- [3] Yeh L Y, Chu R C 2002 *Thermal management of Microelectronic Equipment* (ASME Press)
- [4] Saums D, Levett D, Howes J 2008 Cooling of IGBT Modules with Vaporizable Dielectric Fluid (VDF) *Int. Microelectronics and Packaging Society France 4<sup>th</sup> Annual Adv Tech. Workshop on Thermal Management (La Rochelle, France, 30-31 January 2008)*
- [5] Saums D, Levett D, Howes J, Marsala J 2008 Vaporizable Dielectric Fluid Cooling for IGBT Power Semiconductors *European Center for Power Electronics Workshop on Adv. Cooling (Delft, The Netherlands, 20 November 2008)*
- [6] Garimella S V 2002 Thermal Challenges in Next Generation Electronic Systems- Summary of Panel Presentations and Discussions *IEEE Transactions on Components and Packaging Techn.* **25** 4 569-575
- [7] Mudawar I 2001 Assessment of High-Heat-Flux Thermal Management Schemes *IEEE Transactions on Components and Packaging Techn.* **24** 2 122-141
- [8] High Performance Micro-Cooling for Electronic Components 2006 *Project proposal SBO “HyperCool-IT”, [www.hypercool-it.be](http://www.hypercool-it.be)*
- [9] Donose R, Peirs I, Reynaerts D 2010 A Thermopneumatic Valve for Single Phase Cooling for Microelectronics *Technical Digest PowerMEMS 2010 (Leuven, Belgium, 1-3 December 2010)* 161-164