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MICRO HEAT PIPES FOR STACKED 3D MICROELECTRONIC MODULES

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ABSTRACT

In context of a European Commission funded project, development of a standardized multifunctional stacked 3D package was envisioned for potential applications in aviation, space and telecommunication sectors. The standardization and modularity was aimed to integrate packages from different technologies and to allow mutual slice inter-changeability. Thermal management solutions to the proposed new stacked 3D package as per the project specifications (a total of three stacked substrate slices, each slice of size 55 × 55 × 1 mm^3 and total package height not exceeding 10.5 mm) are reported here. Three potential options were studied i.e. (a) module liquid cooling, (b) integration of miniature copper-water cylindrical heat pipes (OD 3.0 mm) with the 1.0 mm substrate slice and (c) development of flat plate heat pipes of 0.9 mm thickness. For options (a) and (b), initial tests have been performed taking aluminum as a representative material for AlSiC metal matrix composites which were to be employed in the final design. Further, copper based flat plate micro-structure conventional heat pipes have been developed and performance tested. Thermal interactions have been investigated with thermocouples coupled with infrared thermography. For safe operation up to 30W heating power (10W/slice), while thermal diffusion through the bare metallic substrate is sufficient for heat transfer from chip to the substrate, micro heat pipes should be employed to cool the substrate and transfer heat from it to an external cold plate. Flat plate heat pipes are advantageous for higher power levels per slice. Interlayer thermal interactions also affect the response of stacked 3D packages.

KEY WORDS

3D packaging, thermal management, miniature heat pipes

INTRODUCTION

Packaging technologies play a key role in microelectronics. Progress in the direction of creating compact, lightweight and multi-functional packages has resulted in the development of three-dimensional electronic modules. Modern day packaging trends are miniaturization, higher component density, higher power density and increased reliability. For these reasons high performance PCBs are being increasingly replaced by stacked 3D modules, especially using MCM technology.

In conjunction with this technology, 3D packaging offers a wide range of advantages over conventional planar packages. Some of the advantages include [1, 2]: (a) increase in electronics system density, miniaturization (b) increase in system speed, reliability and performance (c) reduction in costs etc. Since the development of integrated circuits, it is known that an increase in electronic density leads to performance improvements and cost reduction. In parallel, the thermal management of such highly integrated 3D packages faces considerable challenges. Many stringent demands of the foreseen potential applications of 3D technology are not met by the present standards. Consequently, to overcome these limitations, a research work was funded by the European Commission for the development of new stacked 3D packaging concept, involving technology end users from avionics, space and telecom sectors.

In the present paper, the thermal aspects of stacked 3D modules studied under the framework of the above referred project are reported. The thermal management was split up into different critical levels and various proposed cooling concepts i.e. liquid cooling, and integration of cylindrical and flat plate miniature heat pipes have been studied. The results of this study are not only relevant for the specific project targets but are generic in nature.

SYSTEM SPECIFICATIONS AND GENERAL DESIGN OUTLINE

The techno-scientific objective of the project was to develop high dissipative stacked 3D modules having the following characteristics:

- Total thermal power dissipation of 30 W in 3 stacked slices, i.e. 10 W per slice
- Minimum possible volume and weight (a total of three stacked substrate layers, each slice of size $55 \times 55 \times 1$ mm^3 and total package height not exceeding 10.5 mm)
- Modularity / standardized interchangeability
- Adaptability for liquid cooling
- Increase in reliability.

To achieve the target requirements of the project, a generic design, consisting of metallic frame substrate supports, with desired thermal dies, signal interconnection hardware, module housing or casing, module I/O pins and stacking system, was proposed. (see Fig. 1). The 'slices' as shown in the figure were either 'active' substrates (i.e. the slices are flat plate micro heat pipes) or 'passive' substrates (i.e. solid metallic plates made of either copper alloy or combination of aluminum alloy and AlSiC metal matrix composite inserts). The thermo-mechanical common demonstrator definitions included various configurations of active/passive substrates, thermal dies, interconnection strategy as per the end user requirements from avionics, space and telecom sectors. Thermal management of the stacked cubical module was divided into three levels [3]:

Level 1: At the substrate level; from chip to substrate
Level 2: From substrate to module casing
Level 3: From casing to the external ambient

The frames were designed to have the following vital functions [4]:

Mechanical: To allow the mounting of electronics, stacking inside the casing, overall integrity of the cubical module,

Thermal: to achieve successful thermal management at level 1 and 2,

Electrical: to integrate electrical interconnections and achieve mutual signal transfer within the stacked layers and external I/O pin matrix.

The typical 'slice' was designed in such a way so as to physically isolate the thermal passage and the signal routing/transfer functionality. Figure 2 shows the cut sections of the designed module structure and a typical substrate slice. The electrical interconnections between the stacked layers were required in the vertical and horizontal direction. The vertical interconnections were achieved by elastomeric flexible Zebra® strip connectors while the horizontal interconnections were achieved by tailor-made routing PCBs.

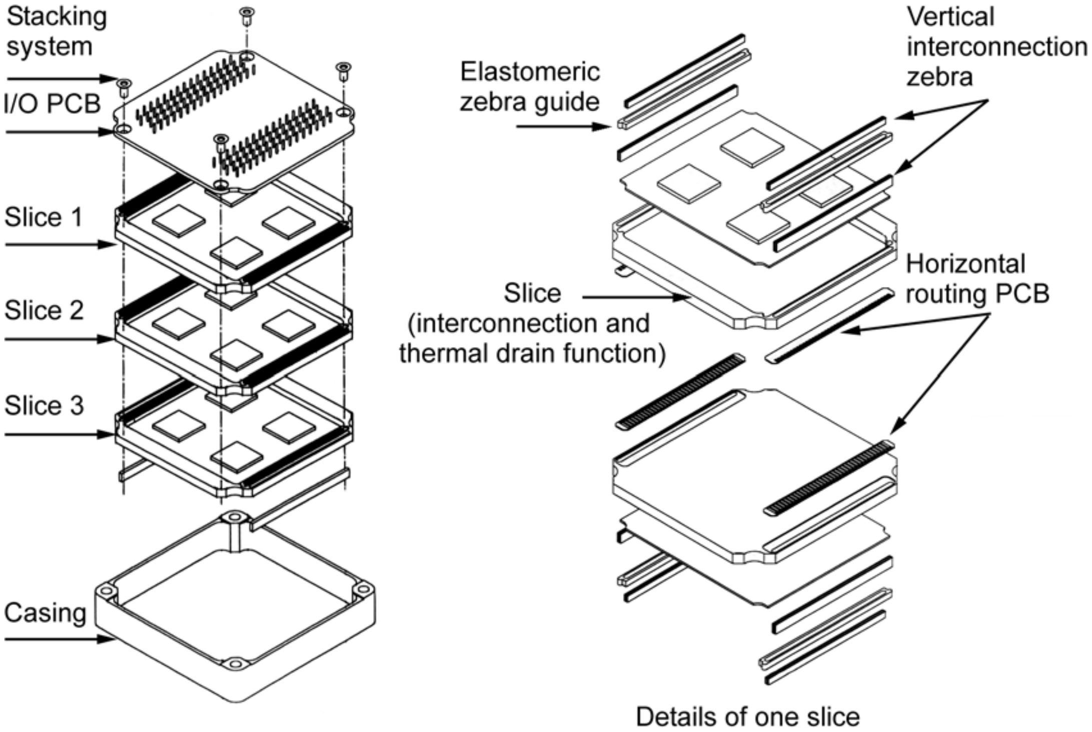
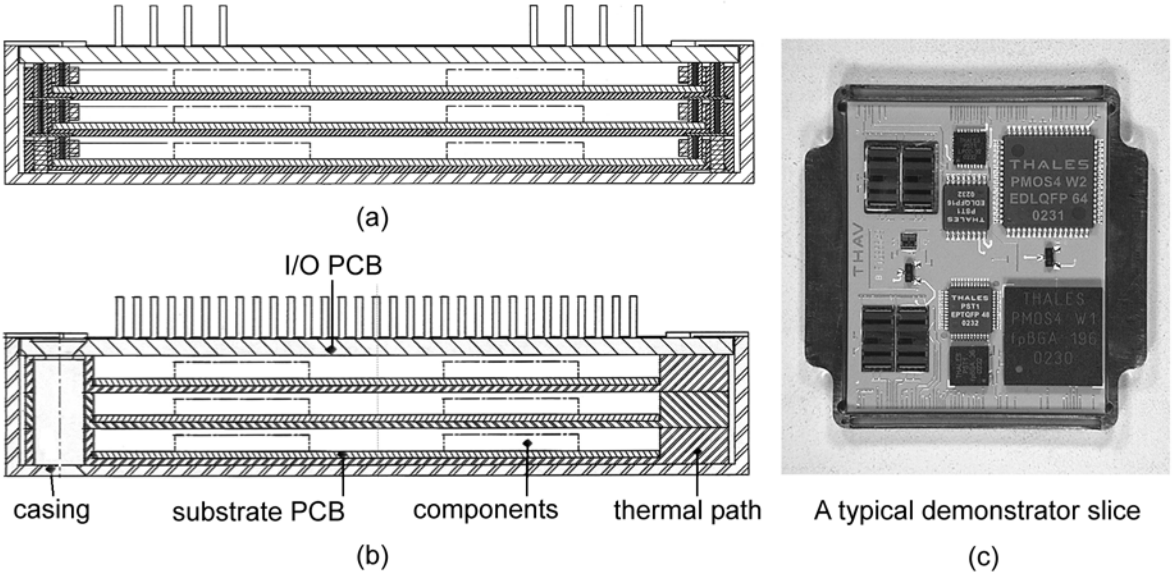


Figure 1: Design details of the proposed stacked 3D modular package



(a)

(b)

A typical demonstrator slice

(c)

Figure 2: Details of the package (a) Section showing electrical inter-connections, (b) Section showing the thermal path, and (c) a typical demonstrator slice

HEAT PIPE MANUFACTURING

For the final design, feasibility of two types of heat pipes was studied. For level 2/3 cooling, cylindrical copper-water miniature heat pipes and for level 1 cooling, flat plate heat pipes were considered as suitable options.

Miniature conventional wicked cylindrical heat pipes were made of copper with water as the working fluid. The heat pipes with OD/WT 4.0/0.5 mm were provided with sintered copper powder and had the vapor core diameter of about 2.3 mm. In case of heat pipes with OD/WT 3.0/0.25 mm, the capillary structure was formed from 48 pieces of copper thread supported at the internal tube wall. The wire and wall interface geometry provided the required capillary action. The vapor core diameter was approximately 1.4 mm. For heat pipes with OD/WT 2.5/0.25 mm, one layer of 200 screen mesh was employed. All cylindrical heat pipes were coated from outside with a 5 µm layer of electrolytic nickel. After filling the heat pipes with optimized fill charge, final sealing was done by TIG welding.

Schematic details and photograph of flat plate heat pipes are as shown in Fig. 3. The housing frame and the sealing lid were manufactured from copper alloy (Glidcop A115) coated with a 5µm layer of electrolytic nickel. A two layered 325 mesh screen (CuSn 6.3) was sintered to the frame bottom by placing in a graphite jig and running through conveyer belt furnace. To avoid hoop deflection of frame and sealing lid in case of high vapor pressure inside (likely to be encountered during curing of the glue while attaching the substrate/dies), four deflection preventing spacers of size 3 × 3 mm^2 were integrally machined to the housing frame. The housing frame and the sealing lid including the subparts, i.e. solder pre-forms AgCu 72/28 for all-around seal and spacers, the screen wick and lateral filling tube, were finally assembled together in one production step at about 780°C in a belt furnace under inert atmospheric conditions. The flat plate heat pipe cavity size was approximately 42 × 32 mm^2. The total outside thickness was 0.9 mm. The available vapor core thickness was about 0.25 mm.

Before the final design of thermo-mechanical demonstrator was frozen, flat plate heat pipes were fabricated with a slightly modified design, essentially similar to the ones described above. These heat pipes had an effective flat area of 40 × 40 mm^2. The overall outside thickness was also 0.9 mm. For comparative studies, one, two and three layered 325 mesh wick structured variations were fabricated. In this paper the performance data of these heat pipes is presented.

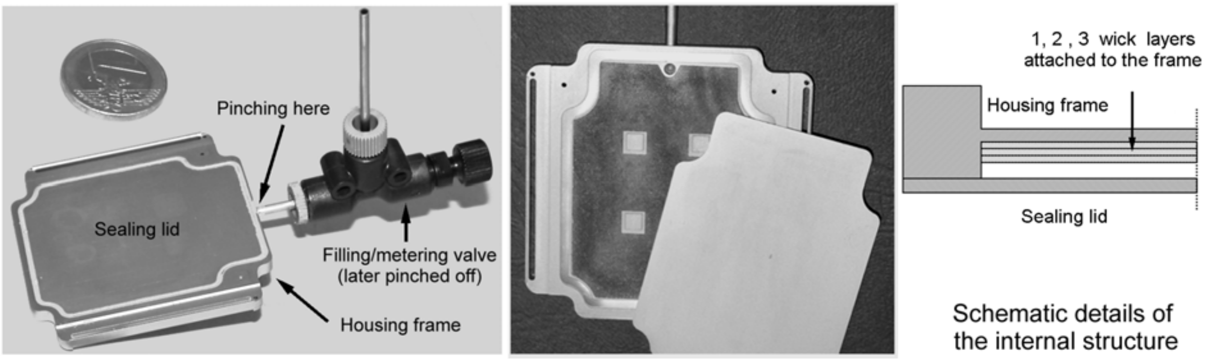


Figure 3: Details of the flat plate heat pipe designed for thermo-mechanical demonstrator

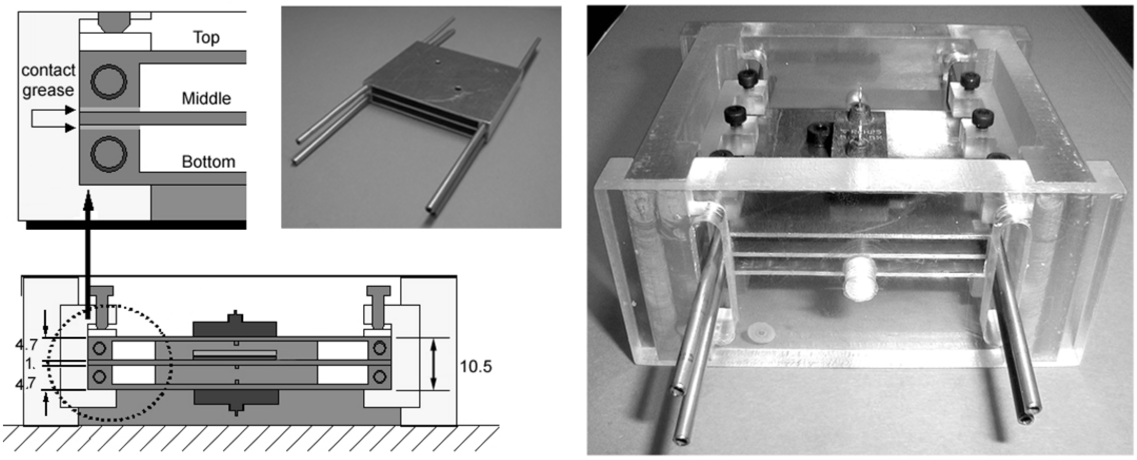


Figure 4: Details and photograph of the liquid cooling module mock-up

EXPERIMENTAL SET-UPS AND RESULTS

At the time of writing of this technical report, the final range of thermo-mechanical common demonstrators were being fabricated. The final results as per the specified test file will be reported at a later date. Before finalizing the demonstrator design, various mock-up tests were conducted as part of the feasibility study. In the following sub-sections results from these tests are presented.

LIQUID COOLED MODULE

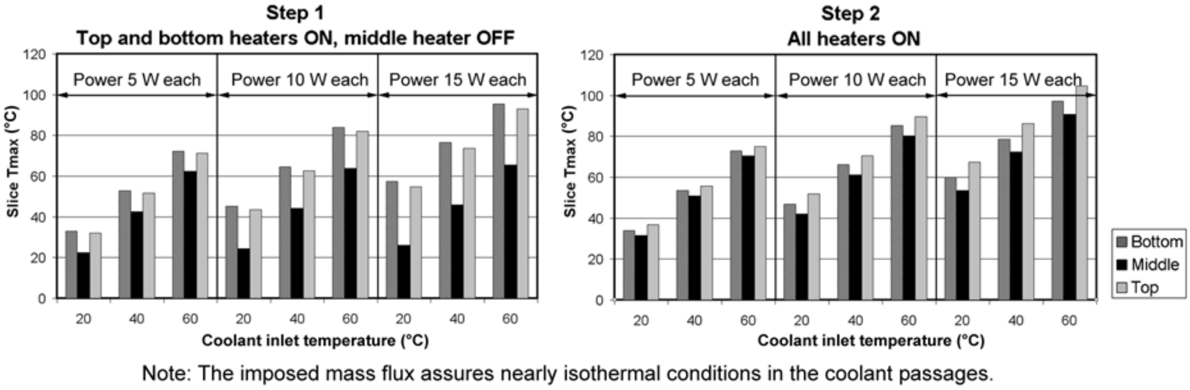
For testing the feasibility of liquid cooling concept, the mock-up module was fabricated with three aluminum plates representing the three slices of substrate support frames. The bottom and the top layer structures were exactly the same. The respective heaters of the top and the bottom plate were mounted onto the exterior side of the substrate as shown in Fig. 4. Water cooling was incorporated in drilled holes (internal diameter 3.0 mm) along the two longitudinal passages of the top and bottom substrates. The mass flow rate of coolant water was 0.25 l/min in each pipe. One thermocouple each was fixed on the geometric centers of the slices placed on the reverse side of that of the heater (which always correspond to the slice T_{max} for the specified configuration). The middle plate was only a simple flat plate without additional coolant channels along the edges as was done in the case of top and bottom plates. Cooling of this plate was due to a mechanical pressure contact (aided by thermal contact grease) between the three plates which was maintained by screws as shown. Thus a simple and symmetric structure could be achieved. This module was aimed to investigate:

- Transient variation of respective slice T_{max} at various heat powers / coolant temperatures.
- Evaluation of interlayer thermal interactions.

To quantify these interlayer mutual thermal influences the experiments were divided in 2 parts:

Step 1: start heating only top and bottom heaters at fixed power
Step 2: after steady state is reached for Step 1, start the middle heater also at the same power.

The tests were conducted at 5W, 10W and 15W per slice of input power. In Step 1, the heating of top and bottom layers resulted in an increase of the middle layer temperature. This state was continued till a quasi steady state temperature of all the slices was obtained. After this, Step 2 of the experiment commenced. Shortly after starting the middle slice heater, all the slices obtained their respective maximum temperatures and a steady state was once again reached. Simultaneously, the outer two layers warmed up due to the influence of additional heat of the middle layer. In all the trials, the layer T_{max} attained was lowest for the middle layer (refer Fig. 5).



Note: The imposed mass flux assures nearly isothermal conditions in the coolant passages.

Figure 5: Steady state T_{max} of respective slices for liquid cooling option

CYLINDRICAL HEAT PIPE INTEGRATED MODULE

Experimental studies for single substrate layer under different operating conditions with integrated copper-water micro heat pipes (OD/WT 3.0/0.25 mm) were designed as outlined in Fig. 6. The aluminum substrate structure of the heat pipe integrated module was exactly like the previous structure used for water cooled tests. Instead of coolant water flowing through the drilled channels, two heat pipes were used for cooling. These heat pipes were mechanically integrated in drilled channels along the longitudinal edges of the substrate. The remaining portion of the heat pipe was mechanically inserted into a standard finned air cooled aluminum heat sink. An axial fan with air velocity of 3 m/s was used for cooling. All experiments were conducted in horizontal position of the set up (and so also the heat pipes). For reference measurements, one type-K thermocouple was placed at the geometric center of the substrate and the whole set-up was viewed with an infra-red thermocamera. The infrared camera was properly calibrated with standard emitting surface before the experiment. The accuracy of temperature measurement was within ± 0.3°C.

The obtained results for layer T_{max} are shown in Fig. 7-a, where the improved cooling effect of the air cooled heat pipe solution as against the water cooling solution can be seen. A typical thermograph is also shown in Fig. 7-b.

HEAT PIPE PERFORMANCE EVALUATION

Cylindrical heat pipes

It was demonstrated by the previous tests that the 3.0 mm copper water micro heat pipes were able to meet the specified project boundary conditions. For a more broader outlook on the possible areas of applications, it was decided to carry out performance evaluation of a range of mini cylindrical copper-water heat pipes. In this study mini heat pipes with OD/WT 4.0/0.5 mm, 3.0 /0.25 mm and 2.5 mm/0.25 mm were tested.

The heat pipes were mechanically inserted into suitably sized copper blocks with application of thermal paste. Two surface mountable ceramic heaters were attached to the copper block to form the evaporator section. The condenser was made of Makrolon® (Plexiglass) with drilled passages for coolant water flow. Heat pipes were firmly located in this section by natural rubber stoppers. The entire set-up was well insulated. In all set-ups, three thermocouples were placed in the evaporator section, two in the adiabatic section and two in the condenser section. The entire set-up could be tilted at the desired angle.

The structures were tested with standard heat pipe performance testing procedures. The operating temperature, which corresponds to the adiabatic section temperature, was always maintained at a fixed value (by adjusting the condenser coolant temperature), as the heater input power was increased in small steps. A sudden surge in evaporator temperature corresponds to the dryout phenomenon inside the evaporator. The power step just before the dryout reflects the maximum performance at the fixed operating adiabatic temperature. This is shown in Fig. 8-a, b for vertical and horizontal configurations, for all the range of tested structures. It is seen from the figure that the maximum performance drastically reduces with decreasing capillary diameter. In addition, the manufacturing complexity associated with small diameter capillary wicked heat pipes also increases with decreasing tube diameter.

Flat plate micro heat pipe

As stated earlier, tests were conducted to evaluate the performance of flat plate heat pipes. The experimental set-up is shown in Fig. 9. A surface mountable ceramic DC heater (40×10 mm^2) provided the necessary input power while the cooling was achieved by pumping water through a 9 mm hole in a copper cold plate ($15 \times 15 \times 80$ mm^3) attached to the heat pipe. The effective length of the heat pipe was 27.5 mm. Thermographic profiles could be seen by an infrared camera from the exposed side as shown in Fig. 9. The heat pipes were tested in the vertical orientation (heater down).

Figure 10 shows the performance results for three layered wick (mesh 325) and two layered wick (mesh 325). An increase in the wick layers increases the liquid flow area but on the other hand decreases the available vapor volume. So, a trade-off has to be achieved between the liquid and vapor pressure drops vis-à-vis the available space. For the present design a two-layered structure gave best results as compared to one and three-layered wicked heat pipes.

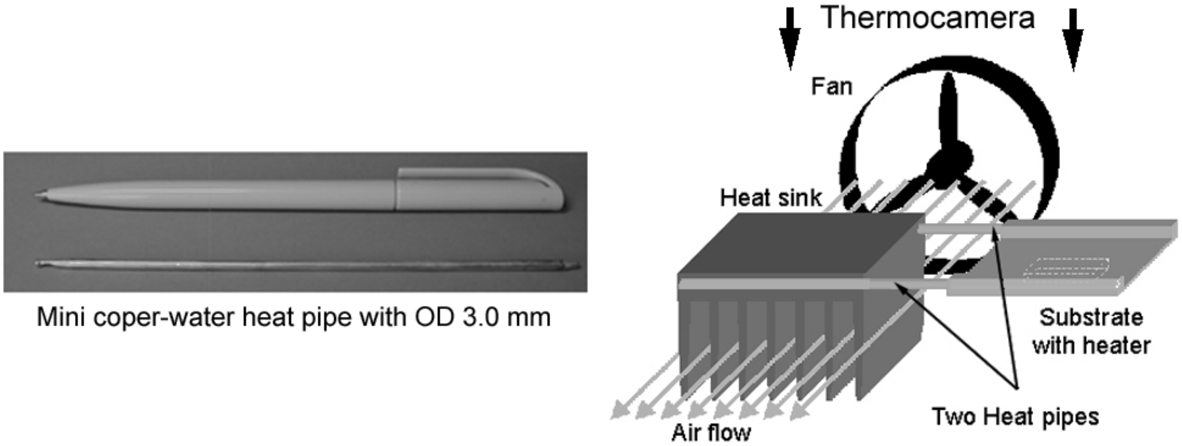
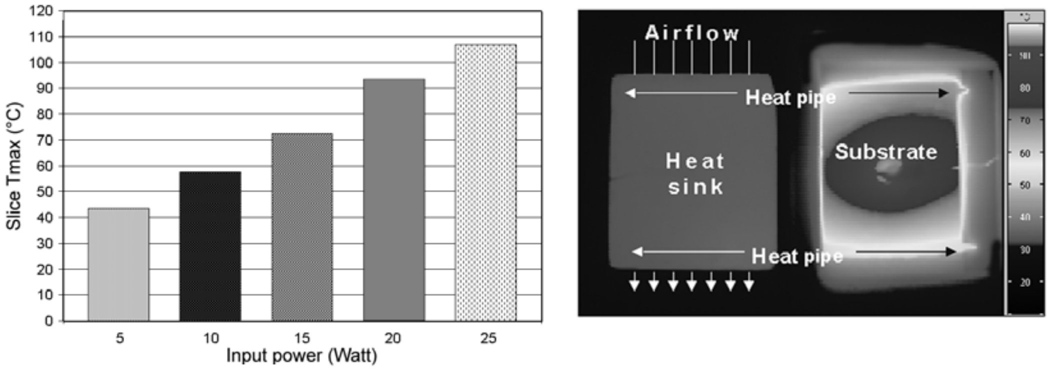
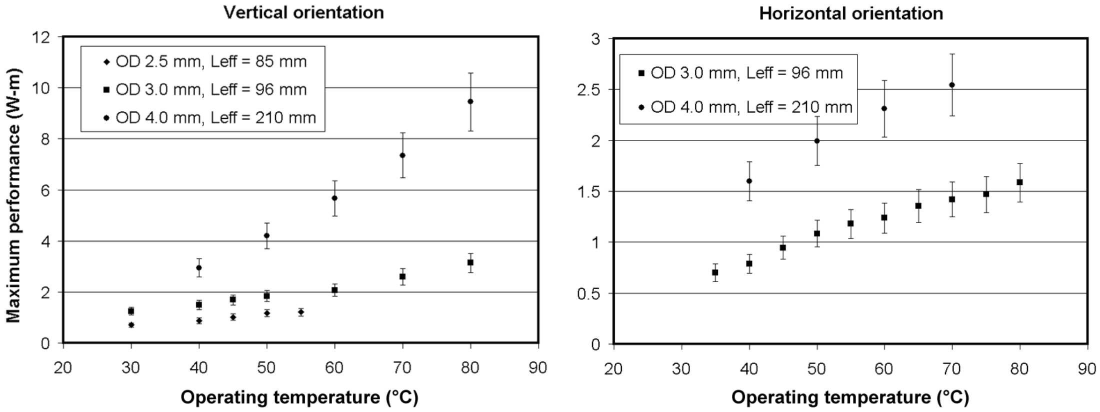

Mini coper-water heat pipe with OD 3.0 mm

Figure 6: Details of the cylindrical heat pipe integration set-up



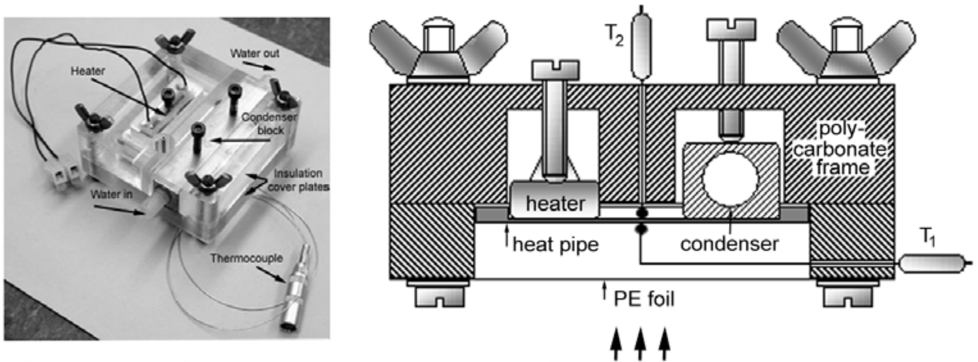
(a) (b)

Figure 7: (a) Steady state slice T_{max} for integrated heat pipe option, (b) Typical thermograph of the set-up



(a) (b)

Figure 8: Maximum performance of miniature cylindrical heat pipes (a) in vertical, (b) in Horizontal orientation



Photograph of the set-up

Figure 9: Details of the experimental set-up for performance testing of flat plate heat pipes

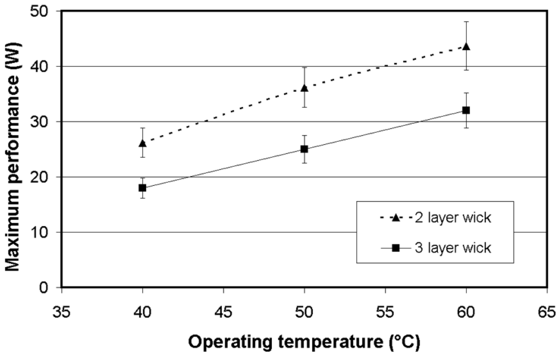


Figure 10: Performance of the flat plate heat pipes

CONCLUSIONS

A new concept for stacked 3D layers has been defined. The stacked layers are multifunctional and cater to die mounting and electrical interconnections, mechanical integrity and thermal requirements of the package. The thermal management has been successfully dealt with on various critical levels.

Flat plate heat pipes with maximum thickness of 0.9 mm have been successfully developed and preliminary performance tests have shown promising results. Although the thermal advantage is not substantial at relatively lower power inputs (10 W per slice as tested in the present experiments) as compared to solid copper plates of equivalent dimensions, the option is well suited for higher power dissipation levels.

Cylindrical miniature copper-water heat pipes in the diameter range of 2 mm to 4 mm have also been developed. These have been successfully integrated with the defined stacked 3D substrates. In the case of single substrate layer integrated with two mini heat pipes (OD 3.0 mm), the maximum power transmitted for safe operation at T_{max}<100°C was about 22 W for an air velocity of 3 m/s at about 25° C. The testing of such heat pipes has revealed that the maximum performance drops very fast with the decrease in internal diameter. Nevertheless, down to about 2.5 mm internal diameter copper-water conventional wicked heat pipes are quite promising. Below this diameter, limitations arise not only due to thermo-physical properties of the working fluid but also due to manufacturing constraints related to wick construction [5].

The option of cooling stacked modules with liquid circulation has also been tested. For 15 W per layer (heat flux = 6.5 W/cm²) and Tcoolant = 60°C (worst case), slice T_{max} ~100°C. For 10W per layer applied to the substrate (project specifications), following T_{max} were obtained in case of liquid cooling: coolant at 20°C: T_{max} = 52°C, coolant at 40°C: T_{max} = 70°C, coolant at 60°C: T_{max} = 88°C. Although the present project requirements were met with liquid cooling, integral cylindrical copper-water heat pipes achieved better results on a comparative basis.

Interlayer interactions also affect the thermal behavior of the 3D structure depending on the geometry of thermal interconnections and thermal bridges, if any [3].

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