Improving Heat Transfer from a Flip-Chip Package

The lid of an ASIC package can significantly increase the temperature of the die by impeding heat transfer. In flip-chip packages the backside of a die can be exposed by eliminating the lid, thus allowing a heat sink to be attached directly. Numerical finite difference methods and experimentation were used to investigate the differences between lidded and lidless flip-chip designs. The results demonstrate that a lidless package is a superior design because of the increased thermal conductivity between the die and the heat sink.

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The cooling of electronic components has traditionally been considered as two separate problems: optimizing the internal thermal path within the package, and cooling the packaged component by optimizing the external thermal path. While this method has the advantage of being partitionable and therefore solvable independently by separate organizations or companies, it fails to engineer the thermally optimum solution. This is especially critical for high-power dice, which typically require custom heat sinks.

The electronics industry is moving in the direction of lidless flip-chip packages, which create new possibilities for cooling the dice. Processor chips from other major electronics suppliers are currently available in lidless packages because of their thermal and cost advantages.[1]

As an experiment to improve the design of a high-power processor package, the HP PA 8000 processor, a proposed design of a lidless package was compared to the traditional lidded package currently in use. An example of a lidless package using an air cooled heat sink has been discussed in an earlier paper.[2] In the present investigation, the proposed design uses the evaporator of a heat pipe assembly to contact the die, thus replacing the lid. This concept has the additional benefit of reducing the cost of the package by eliminating the relatively expensive lid.

The investigation began by constructing finite difference models of the lidded and lidless packages. The purpose of the models was not to correlate with measured results but to aid in understanding the magnitude of the relative improvements of the lidless design. After reviewing the results, laboratory measurements were made of the two designs and the relative improvements in thermal performance were recorded.

Two different methods were chosen to cool the packages. The heat pipe employed in the current HP PA 8000 design was a natural choice because of its practicality. Additionally, because of concerns about thermal gradients in the aluminum heat pipe evaporator and the difficulty of matching these to the boundary conditions in the finite difference model, a very efficient but impractical liquid cooled heat sink was chosen. The liquid cooled heat sink is highly efficient and behaves like an isothermal block, which is easily modeled.

For consistency throughout this paper, the term *aluminum evaporator heat sink* refers to the aluminum evaporator on the heat pipe assembly that directly sinks heat from the package. Likewise, the term *copper block heat sink* refers to the copper block on the liquid cooled heat sink that acts in the same capacity.

Package Construction

The lidded and lidless package designs are shown in Fig. 1 for the aluminum evaporator heat sink. Both packages are constructed identically between the printed circuit board and the die. Mounted on an FR-4 printed circuit board is a plastic socket containing 1089 contacts made from 0.025-mm gold plated molybdenum wire (see Fig. 2). A ceramic land grid array package rests on the socket, making electrical contact between the die and the board. The processor die is attached using flip-chip technology,[3] resulting in about 2500 solder bump connections encapsulated by an underfill material between the ceramic substrate and the silicon die. Fig. 3 shows the lidless package, plastic socket, and printed circuit board assembly. The aluminum carrier shown in the picture is used to support the assembly. The heat sink has been left off so that the assembly can be seen more clearly.

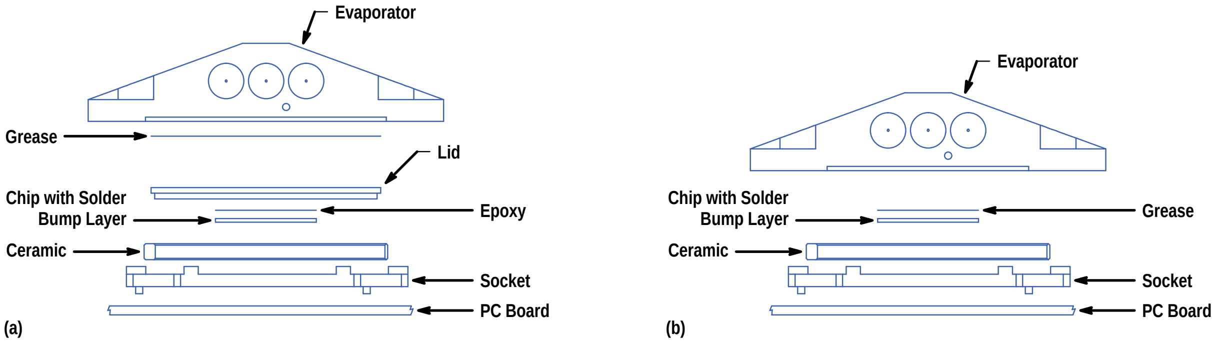

Fig. 1. *Package designs. (a) Lidded. (b) Lidless.*

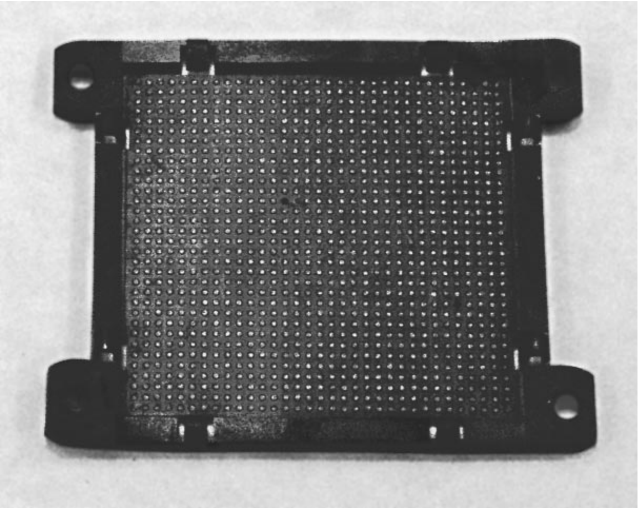

Fig. 2. *Plastic socket with 1089 gold plated molybdenum wire contacts.*

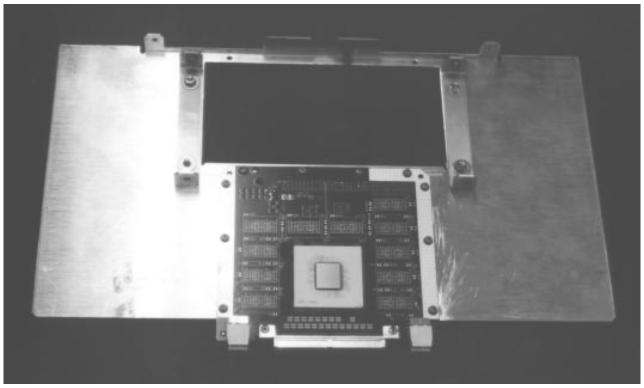

Fig. 3. *The experimental assembly without the heat sink, showing the printed circuit board, socket, and lidless package.*

The lidded design uses silver-filled epoxy between the die and the lid to enhance thermal performance. The lid is fabricated from a Kovar ring brazed to a sheet of tungsten copper. Fig. 4 shows the lidless and lidded packages side by side for comparison. A more detailed description of the lidded package can be found elsewhere in the literature.[4]

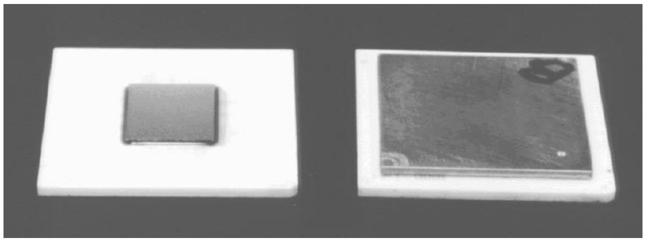

Fig. 4. *Lidless and lidded packages used in the experiment. The lidded package is on the right.*

The lidless design uses Dow Corning 340 thermal grease as the thermal interface above the die. This is a conservative choice considering that there are thermal greases available that have thermal conductivities more than three times that of Dow Corning 340.[5]

Measurement Technique

To compare the thermal performance of the two packages, a thermal test die with a temperature-sensitive resistor was placed into each package to allow direct measurement of the die temperature. The packages were each tested on the same socketed printed circuit board connected to an HP 75000 data acquisition system and a power supply. An HP 9000 Series 300 workstation with data acquisition software, HP VEE, displayed the die temperature as a function of time while the power supply provided the power to the die.

The two thermal test dice were calibrated in a Delta Design 9000 Series convective oven. Resistances were captured with the data acquisition system at four different temperatures ranging from 18 to 90 degrees Celsius. A least-squares fit was obtained for each package and the results were placed into HP VEE.

Four experiments were undertaken comparing each package—lidded and lidless—cooled by each of the heat sinks—the aluminum evaporator and the copper block.

Copper Block. The copper block heat sink was used to provide an isothermal surface to the package to which it was attached. This was accomplished via an efficient liquid cooled heat sink mounted to the backside of the highly conductive copper block as depicted in Fig. 5. The liquid cooled heat sink consists of a partially hollowed aluminum block through which water is cycled. The water is cooled by ambient air via a heat exchanger. Measurements showed that the surface of the copper block was kept isothermal to within 3°C, which indicated that the liquid cooled heat sink was functioning as intended.

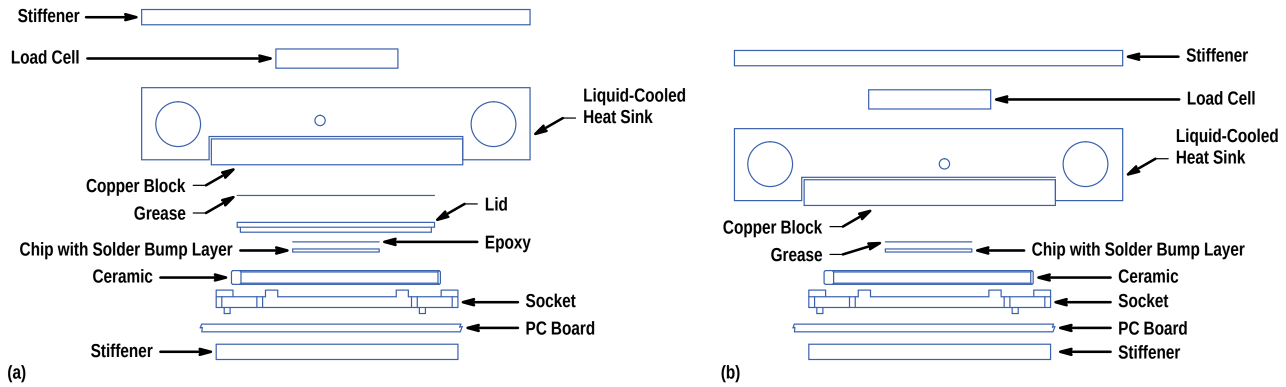

Fig. 5. *Liquid heat sink assembly. (a) Lidded package. (b) Lidless package.*

Each package was tested with the copper block heat sink by compressing it between the upper and lower stiffeners with a C-clamp. The setup was similar to Fig. 6 but with the heat pipe replaced by the liquid cooled heat sink. A load cell was employed to measure the compressive force being generated by the clamping assembly and stiffener plates were used to distribute the C-clamp load. Each assembly was compressed to 150 pounds to ensure comparable contact resistance between the two packages. Three thermocouples were placed within the copper block to record the heat sink temperature.

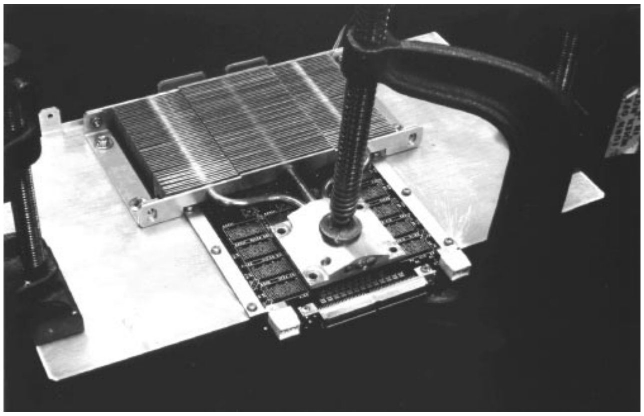

Fig. 6. *Experimental setup with heat pipe.*

Aluminum Evaporator. The aluminum evaporator is cooled by a heat pipe assembly. The assembly is constructed of three sintered copper pipes with water as the working fluid mounted planar to the evaporator, and thin aluminum fins are attached to the opposite end of the pipes. Heat from the aluminum evaporator enters the pipes, causing the water to vaporize. The steam is condensed at the other end of the pipes by air flowing over the fins. The water then returns to the evaporator via capillary action, thus completing the thermodynamic cycle. Upon measurement, it was discovered that the aluminum evaporator was indeed isothermal like the copper block, although at a higher temperature.

The aluminum evaporator was used to test the thermal performance of the packages in a manner similar to the copper block. A clamping assembly comparable to that used for the copper block was employed (the clamping assembly is shown in Fig. 6 with the heat pipe). The entire assembly was placed in a wind tunnel with a nominal velocity of 1.8 meters per second. A single thermocouple was placed near the evaporator plate/package interface to record temperature.

Data Comparison Methodology

Thermal resistance will be used throughout this paper as a means of comparing the data obtained from modeling and measurement. It is defined by equation 1 and frequently calculated using empirical data with equation 2:

$$R = L/(kA) \tag{1}$$

$$R = \Delta T/Q \tag{2}$$

where L is the thickness of the material, k is the material thermal conductivity, A is the cross-sectional area, ΔT is the measured temperature difference, and Q is the heat flow. By definition, thermal resistance is applicable for one-dimensional, steady-state heat transfer with no internal energy generation. In electronics packaging one rarely encounters one-dimensional heat transfer and there is significant internal energy generation in the silicon die. Additionally, it is rarely ever known explicitly how much heat is flowing into the heat sink relative to that being absorbed by the board. Typically, if no additional information is known it is assumed that all of the heat is dissipated into the heat sink. Nevertheless, with the restrictions on equations 1 and 2 and the unknowns involved, thermal resistance remains a useful quantity for the comparison of similar packages on similar printed circuit boards and will be used in that capacity in the interpretation of results.

Modeling Technique

A software tool employing a finite difference method was used to create models to represent the cooling of the packages under test.[6] One model was created for the lidded design and a second was created for the lidless design. With each model, either the copper block or the aluminum evaporator could be activated as the heat sink.

Two simplifications were made in modeling the packages. Components of the model that were thin layers, such as the epoxy and grease layers, were modeled as internal plates with only one-dimensional conduction, normal to the surface of the layer. Secondly, to simplify the model and reduce large grid aspect ratios and thus convergence time, geometry that was nearly coincident and thermally insignificant was spatially aligned. For example, the plastic socket housing is 0.7 mm larger than the ceramic but was modeled as the same overall size.

The FR-4/copper multilayer printed circuit board was modeled as a solid FR-4 block with a single layer of copper of thickness equivalent to the combined thicknesses of the copper layers in the board. The conductivity of the multilayer printed circuit board was calculated to be equivalent to the copper and FR-4 material in parallel, while the conductivity of the single copper layer placed within the modeled printed circuit board was made equivalent to the copper and FR-4 material in series. Only solid copper planes were included in the model since discontinuous signal planes have been determined to be inconsequential in conducting heat.[7]

To simplify the 1089 individual metallic contacts of the socket in the plastic housing, a block of equivalent conductivity to the 1089 individual 0.025-mm-diameter molybdenum wires was combined in parallel with the conductivity of the plastic housing.

Similarly, the solder bump layer with underfill was modeled as the area of 2500 solder bumps in parallel with the area of the underfill compound, with the conductivity of the internal plate appropriately weighted by the product of the thermal conductivity and the area of each material.

The copper block was modeled as an isothermal volume with a negative internal power source (i.e., a sink). The evaporator assembly, while more difficult to approximate, was modeled as an aluminum block with negative internal power sources that were of the same volume and in the same locations as the heat pipes used in the experiments. The actual cross sections of the heat pipes were modeled as squares because of the orthogonal limitations of the software tool.

The models were constructed to calculate conduction through the package to study the effects of various constructions and materials. To simplify and reduce convergence time, cooling from natural convection was not considered. This method allows good comparative results for small changes in materials but does not yield results that could be directly compared with measurements. Nevertheless, the purpose of the modeling was not to correlate numerical data with experimental data, but rather to determine whether experimentation would be worthwhile.

After the models were created, grid sensitivity calculations were done to ensure that the results were not affected by numerical computation errors induced by grid size or aspect ratios.

Modeling Results

Copper Block. The modeling results for the copper block are presented in Table I. These results show that the thermal resistance between the die and the heat sink of the two package styles was identical, within modeling error and for the assumptions made in the model.

Table I
Modeled Thermal Resistance for Copper Block

Package Type	Thermal Resistance (°C/W)
Lidded	0.21
Lidless	0.21

Aluminum Evaporator. The results for the aluminum evaporator are shown in Table II. Again, the thermal resistance between the die and the heat sink was nearly identical between the two designs. The model shows a small benefit in the lidded design.

Table II
Modeled Thermal Resistance for Aluminum Evaporator

Package Type	Thermal Resistance (°C/W)
Lidded	0.24
Lidless	0.26

Modeling Summary. Given the considerable assumptions and simplifications, it was difficult to draw a strong conclusion based solely on the modeling results. Considering the small differences between the two designs, it was very compelling to construct the packages and measure them.

Measurement Results

Temperature measurements were taken for each of the four package and heat sink combinations. The results are presented in Tables III and IV. Included in each table are the power dissipation, heat sink temperature, die temperature, and thermal resistance. The thermal resistance column refers to the thermal resistance between the die and the heat sink. It includes the separate resistances of the die, epoxy and lid (if applicable), thermal grease, and a portion of the heat sink through which the thermocouples were embedded.

Copper Block. Table III displays thermal data from each package using the copper block heat sink and Dow Corning 340 thermal grease at the heat sink/package interface. Note that the thermal resistance decreased by 50% with the removal of the lid.

Table III
Thermal Performance of Packages with Copper Block

Package Type	Power Dissipation (W)	Heat Sink Temperature (°C)	Die Temperature (°C)	Thermal Resistance (°C/W)
Lidded	93.3	40.2	55.1	0.16
Lidless	93.3	40.6	47.6	0.08

Aluminum Evaporator. Data from the two packages with the aluminum evaporator acting as the heat sink and Dow Corning 340 thermal grease at the interface is presented in Table IV. Note that both the packaged die temperatures and the heat sink temperatures increased using the aluminum evaporator because it is not as efficient as the copper block. The thermal resistance decreased slightly for each package type over that obtained in Table III. This is most likely because of differences in thermal grease application or thermocouple placement. Finally, the thermal resistance decreased 53% upon removal of the lid. As expected, the decrease in thermal resistance is independent of the type of heat sink used.

Table IV
Thermal Performance of Packages with Aluminum Evaporator

Package Type	Power Dissipation (W)	Heat Sink Temperature (°C)	Die Temperature (°C)	Thermal Resistance (°C/W)
Lidded	85.8	63.9	77.1	0.15
Lidless	85.3	66.2	72.2	0.07

Measurement Summary. The measured thermal resistance of the lidded package compares very favorably with measurements taken by other investigators.[4]

Table V displays the amount of power that can be dissipated by each heat sink/package combination at equivalent die and air temperatures. The heat sink thermal resistance refers to the thermal resistance between the heat sink thermocouples and the ambient air. The results indicate that the lidless package is a significantly better performer than its lidded counterpart. The lidless package attached to the copper block is able to dissipate 34% more power, or 62 watts more than the lidded version. Likewise, for the aluminum evaporator, the lidless package is able to dissipate 15% more power or 15 watts more. Note that a larger relative improvement is realized by using a more efficient heat sink. These calculations assume no losses other than through the heat sinks but clearly show the superiority of lidless package designs over lidded.

Table V
Allowable Power Dissipation for Equivalent Die Temperatures of 110°C and Air Temperature of 50°C

Package Type	Heat Sink Thermal Resistance (°C/W)	Interface Thermal Resistance (°C/W)	Calculated Power Dissipation (W)
Copper Block:			
Lidded	0.17	0.16	180
Lidless	0.17	0.08	242
Aluminum Evaporator:			
Lidded	0.46	0.15	98
Lidless	0.46	0.07	113

The superiority of the lidless package over the lidded, while expected, may not be as obvious to predict as it first appears. One of the main arguments for keeping the lid on the package is that it decreases the heat flux by increasing the surface area through which heat can leave the package to the heat sink. By a one-dimensional analysis, it can be shown that the thermal resistance of the lid is an order of magnitude less than that of the epoxy. This indicates that using the lid as a heat spreader to decrease the heat flux through the package is not necessarily a bad idea. Rather, it is the bonding of the lid to the die with a layer of epoxy that makes it a relatively poor thermal solution. If a lid must be used for reasons other than thermal performance, it is clear that an effort should be made to reduce as much as possible the thermal resistance of the bonding material by decreasing its thickness and/or increasing its thermal conductivity.

Summary and Conclusions

The results from the modeling showed that the thermal performances of the packages were very similar and the lidless design warranted further investigation through lab measurements.

Comparison of the thermal resistances of the two package styles was very consistent for both the copper block and the aluminum evaporator measurement methods. Both measurement methods showed about a 50% improvement in thermal resistance in the lidless design.

While impractical for low-cost computer systems, the liquid cooled copper block measurements determine some limits of cooling of the HP PA 8000 die. The lidded design could dissipate 180 watts of power while the lidless solution could dissipate 242 watts while maintaining the temperature of the die within the limits for reliable operation.

The measured results indicate that the lidless package is thermally superior to the lidded design. For the aluminum evaporator, 15 more watts could be dissipated while maintaining the same die temperature. This is of particular significance because a heat pipe assembly is one of the present cooling designs for the HP PA 8000 processor.

To obtain the thermal performance required in next-generation chips, the cooling design will need to be solved as a coupled problem, considering the complete thermal path originating from the surface of the die and ending in the cooling air. The lidless package is one possible solution.

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