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LIQUID COOLED HEAT SINK WITH THROUGH VIAS
(FINAL REPORT)

Charles W. Eichelberger
J. Patrick Kusior

INTEGRATED SYSTEM ASSEMBLIES

1993

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REPORT SUMMARY

The objective of the Liquid Cooled Heat Sink (LCHS) Program was to produce a component which would provide the functions of heat removal and layer-to-layer interconnect in 3-D electronic assemblies. Specifically this component would solve the problem of interconnecting stacks of Multichip Modules (MCMs). A high performance Multichip Module is characterized by a large number of interconnects and a large amount of power both concentrated in a small area. Consequently a component which interconnects stacks of Multichip Modules must provide interconnects at high density while at the same time efficiently removing large amounts of power. In order to preserve electrical performance the thickness of the interconnect component must be minimized.

To achieve the above objectives a novel fabrication method for the Liquid Cooled Heat Sink was devised which combined semiconductor and printed circuit fabrication techniques. This allowed the MCM level densities to be achieved. The heat sink design was optimized by analysis supplemented with experimental verification.

The interconnect density, thermal performance and heat sink thickness goals of the program were determined by combining the most challenging requests in each area from potential ISA customers.

The actual measured performance results compared to the program goals are summarized in the Table 1. In addition to meeting or exceeding program goals, the resultant structure has capability for matched impedance interconnection. A costing analysis indicates that the Liquid Cooled Heat Sink would be economical to produce and cost effective in both Defense and commercial applications.

Parameter	Program Goal	Measured Result
Interconnect Density	100 Vias/cm ²	100 Vias/cm ²
Temperature Rise at 50W/cm ²	<25°C	15°C
Total Thickness	1.25mm	1.12mm

Table 1 Program Goals vs. Measured Results

INTRODUCTION

Several improvements to the Liquid Cooled Heat Sink have been made during this program. The first design consisted of continuous liquid channels. The best versions of this design could only dissipate $50\text{W}/\text{cm}^2$ with a temperature rise above ambient of 40°C . Subsequent designs have featured an array of copper plated columns through which liquid flows. The columns are staggered so that the water path is interrupted thereby creating turbulent flow. The best versions of this design have demonstrated temperature rises of 15°C above ambient at power densities of $50\text{W}/\text{cm}^2$.

Each column also contains a conducting via in the center which provides interconnection from pads on one side of the Liquid Cooled Heat Sink (LCHS) to pads on the other side. The revised version of LCHS which contains the columns will be referred to throughout this report as REV.LCHS.

The structure is fabricated by photo patterning solder mask to form the array of columns and subsequently copper plating the columns and base of the structure. The top and bottom of the structure is formed with Aluminum Nitride substrates which are pre drilled with appropriately sized via holes. The through vias are provided by drilling down through the columns with an Excimer Laser and subsequently metalizing the through holes and patterning the top and bottom pads. All processing steps are commercially used in either semiconductor or printed circuit processing.

The design methodology used to optimize the thermal performance involves providing a balance between maximum area of contact to the cooling liquid and providing enough of a flow path that sufficient liquid can be delivered to the array of columns.

METHODS AND PROCEDURES

The REV.LCHS is comprised of three materials: 1) two Aluminum Nitride (AlN) substrates, 2) photo definable solder mask and 3) plated copper. The solder mask is "sandwiched" between a top AlN substrate and a bottom one. Both substrates are identical with respect to the number and orientation of the holes.

Figure #1 is a top view of an AlN substrate. It is 2" x 2" x 0.015". In the center portion of the substrate, an array (26 columns x 26 rows) of 0.01" diameter holes were drilled with a CO₂ laser. Four 0.04" diameter alignment holes were drilled (one at each edge) and two 0.25" water input/output holes were drilled.

The idea of the REV.LCHS is to have water flow through an array of copper plated columns. These columns will have a greater diameter than the 0.01" diameter CO₂ laser drilled holes; the columns will also be centered on the holes and will have a height of 0.012".

REV.LCHS Fabrication Process

DuPont's Vacrel 8100 Photopolymer Film Solder Mask is laminated onto the AlN substrate. This substrate will be referred to as the bottom plate. The columns are made out of the solder mask. The solder mask is 0.003" thick; therefore, in order to achieve a column height of 0.012" it is necessary to laminate four times. The solder mask was designed to have good pattern resolution at a thickness of 0.003". It was possible to make columns that had a height of 0.003" without any distortion.

For example, one of the photolithographic masks we used had an array of 0.02" diameter circles. The photolithographic mask was brought in contact with the solder mask material and then the solder mask was exposed to UV light. After development the area of solder mask that was exposed to the UV light became the

columns while the area that was not exposed to UV light washed away in the developing solution. The column measured 0.02" across at the top and 0.02 across at the bottom. There was no distortion.

When this same procedure was tried with 0.012" thick solder mask; the top of the column had a diameter of 0.025" while the bottom had a diameter of 0.019". This degree of distortion (taper) was undesirable.

It was found that 0.006" of solder mask could be exposed and then developed with an acceptable taper. In order to achieve columns with a height of 0.012" we did the following:

1) Laminate 0.006" of solder mask, expose it, but, don't develop it; 2) laminate an addition 0.006" of solder mask, expose it, then, develop the 0.012" of solder mask all at once.

At this stage, there is an array of columns which are centered on the array of holes in the AIN. The next step is to copper plate the columns and the area of the bottom plate between the columns. The part is sputtered with titanium and copper. The tops of the columns are then covered with photoresist. This is done because it is not necessary to copper plate the top of the columns. After copper plating, the photoresist is stripped from the top of the columns; the underlying sputtered copper and titanium is etched, revealing the solder mask.

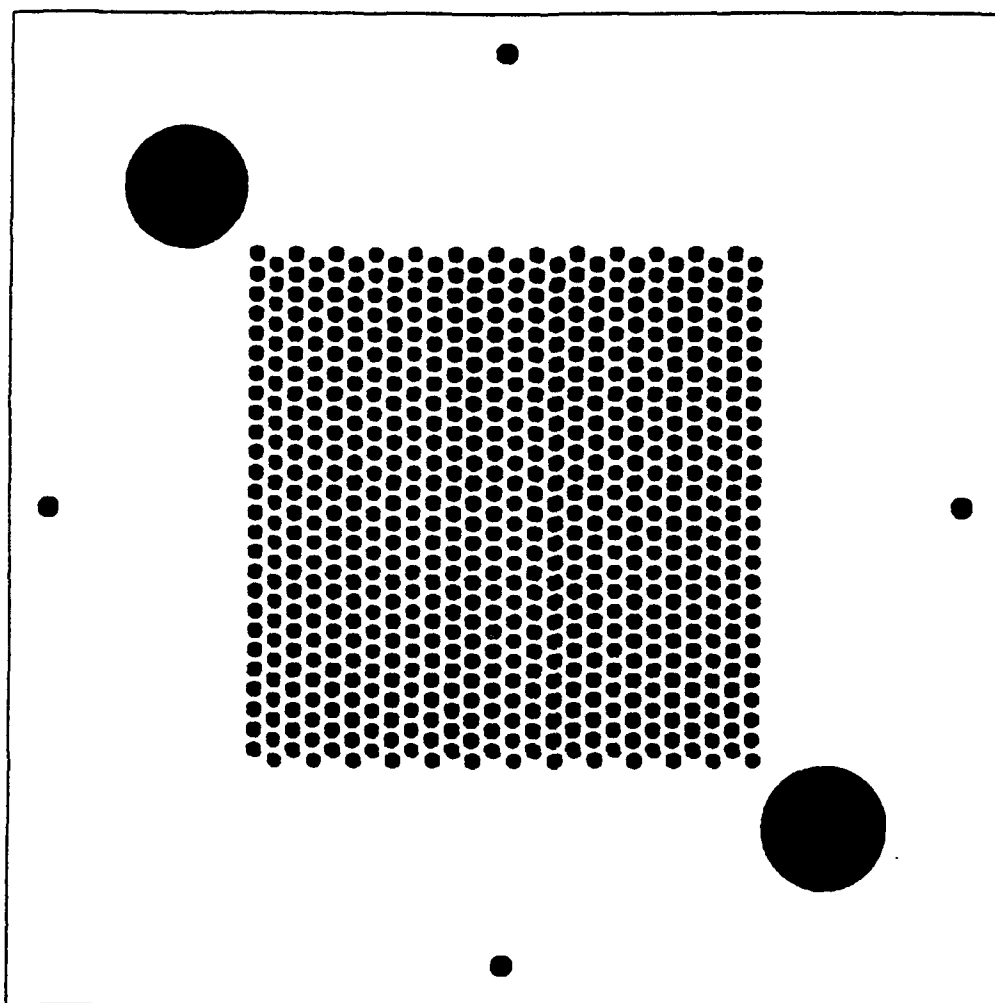


Figure #1 Top view of the Aluminum Nitride substrate
(not to scale).

Figure #2 is a top view of the REV.LCHS midway through processing. It shows the array of copper plated columns centered on the 10 mil holes in the AIN bottom plate. Figure #2a is an expanded view of Figure #2. This figure shows how water flows through the structure. The space between the columns is copper plated and the sidewalls of the columns are copper plated.

The next step in processing is to align the top plate to the bottom plate and secure the assembly. The bottom plate is placed in an alignment fixture. Guide pins stick up through the alignment holes. The bottom side of the top plate is laminated with solder mask. The solder mask is being used as a film adhesive. Using the guide pins, the top plate is brought in contact with the bottom plate. Heat and pressure is applied to ensure a good seal between the top and bottom plates. At this stage, the REV.LCHS is capable of having water flow through it.

The next step is to form electrically conducting vias through the structure. The part is placed on a X-Y translation table. An Excimer laser beam is directed unto the translation table. The table is set in motion and the part scans back and forth. When a hole in the ceramic passes beneath the laser beam, the beam penetrates the hole and ablates (removes) the solder mask; essentially coring the center of the column. When all of the material in the center portion of the columns has been ablated, the part is sputtered front and back with titanium and copper.

Both sides are coated with photoresist. Tiny bond pad sites on the top and bottom plates are defined in the photoresist. The part is then copper plated. After plating, the photoresist is stripped and the sputtered copper and titanium are etched.

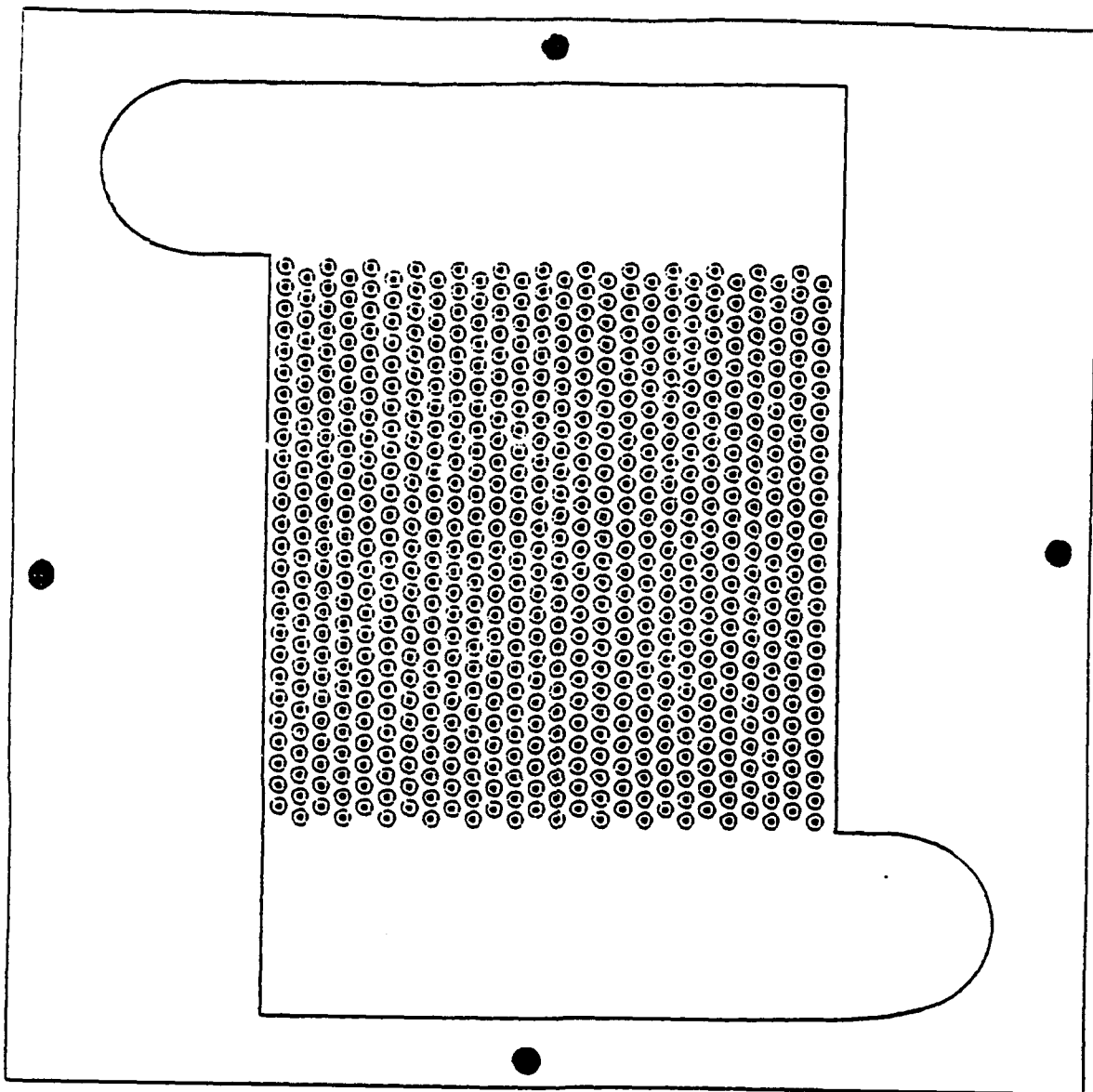
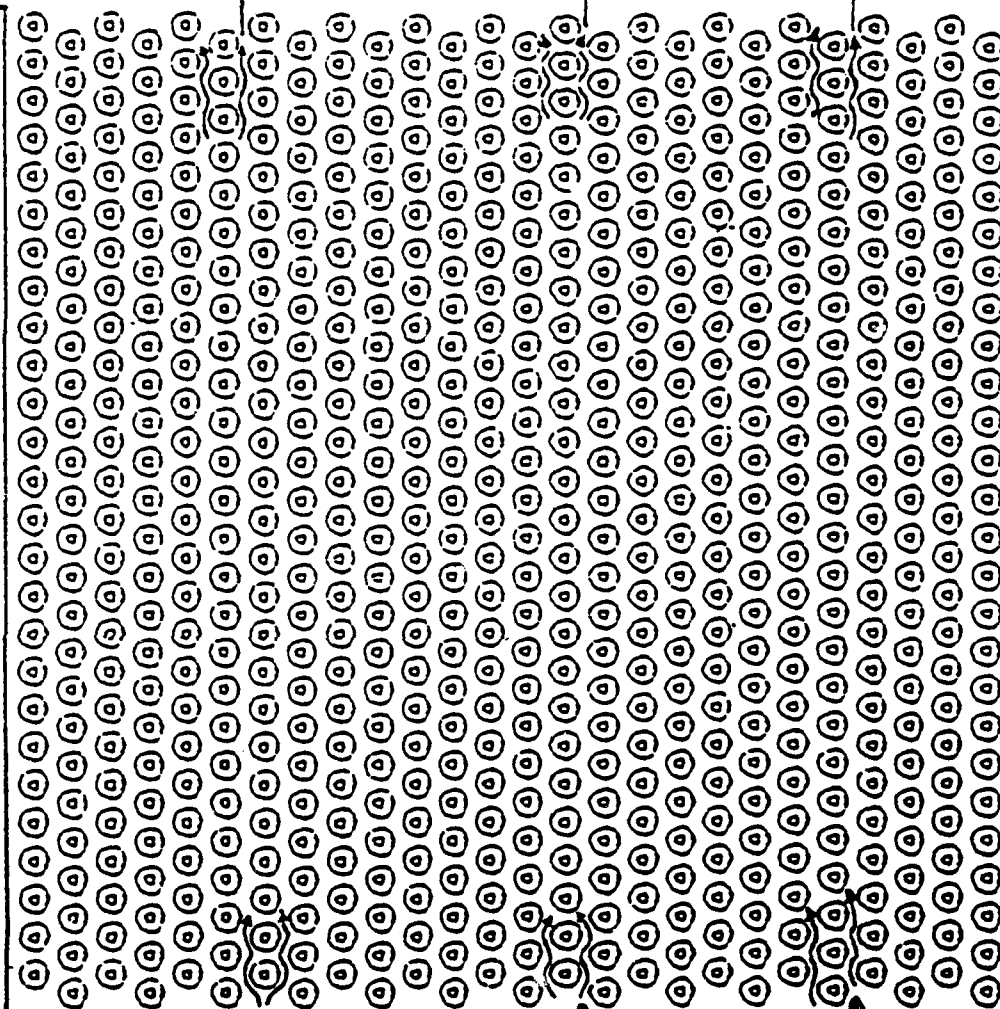


Figure #2 Top view of the bottom plate.

This shows the columns which are centered on the laser drilled holes.

Water Out



Water In

Figure #2a

Expanded view of Figure #2
This shows the passage of water through
the array of columns.

The part is nearly complete, all that remains is to connect flexible tubing to the water inlet/outlet holes of the top plate.

Figure #3 is an expanded cross-sectional view of the REV.LCHS. Looking at the part from top to bottom, we observe the following: on the top is the top plate with copper plated bond pads; below of this is 0.003" thick solder mask. This is the adhesive that connects the top plate to the rest of the part. Next are three columns. The columns are centered on the CO₂ laser drilled holes in the AIN. Between each column on the bottom plate is plated copper. The exterior side walls of the columns are also copper plated. Next is the bottom plate with bond pads. Water flows into the page.

RESULTS AND DISCUSSION

The REV.LCHS is 1.125 mm thick and has 100 through vias/cm². Also, it has a power removal capability of 50 W/cm² with no greater than a 15 °C rise above ambient.

Figure #4 is a cross sectional view of the REV.LCHS with an aluminum block and a heating element mounted on top. Note that the heating element/aluminum block combination is mounted on the bottom plate. Recall that this is the plate which has plated copper between the columns. Heat passes from the heating element, through the aluminum block, through the aluminum nitride and finally passes into the plated copper between the columns. Heat is then distributed down the sidewalls of the copper plated columns. Water, rushing past the columns, conducts the heat out of the REV.LCHS. The staggered formation of the columns, coupled with their saw toothed geometry ensures that the flow is not laminar. The amount of plated copper in contact with water and the lack of laminar flow are the

two primary reasons why the REV.LCHS has outstanding thermal properties. Figure #5 shows the actual size of a completed REV.LCHS.

LN

Solder Mask

Plated Cu

Post

Cu Plated through Hole

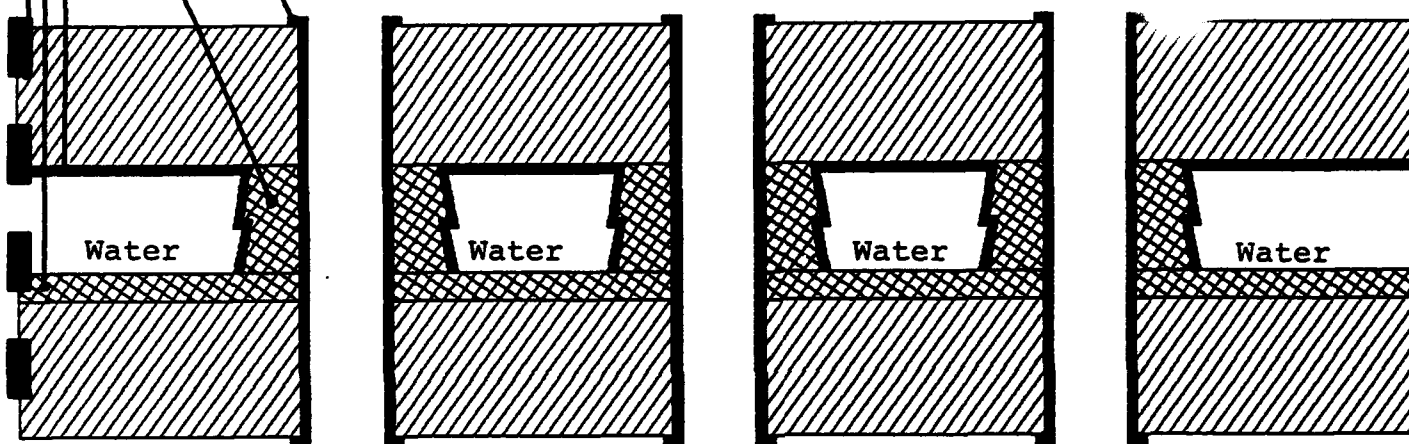


Figure #3 Cross sectional view of the REV.LCHS water flow into the page.

Thermal Paste

Aluminum Block

Heater

Thermocouple

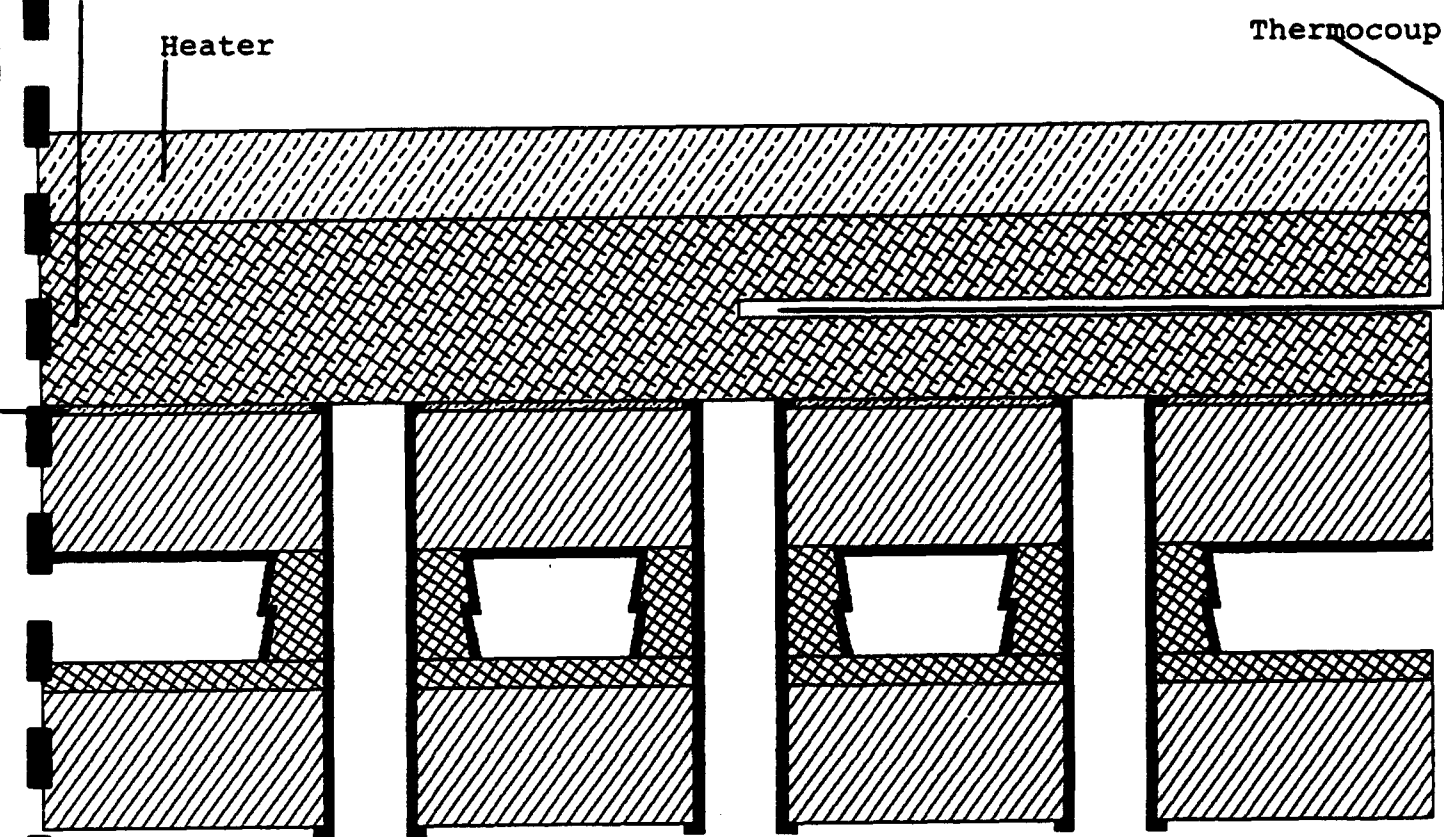


Figure #4 Cross sectional view of the REV.LCHS with attached heating element

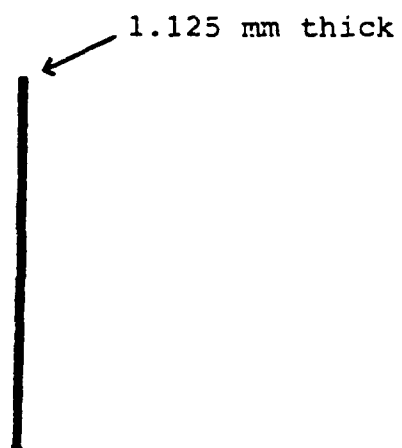
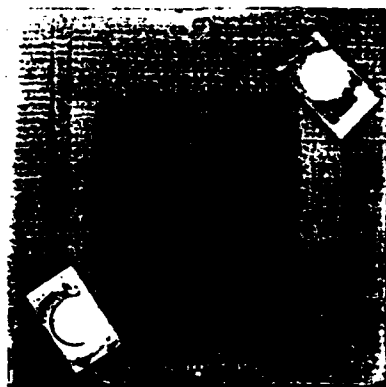


Figure #5 Actual size of the REV.LCHS

The surface area of copper in contact with water is determined by the following equation:

$$SA = L^2 + n \pi (Dh - r^2)$$

SA = copper plated surface area in contact with water (mils²)

L² = surface area of the bottom plate without columns (mils²)

n = number of columns

D = diameter of column (mils)

h = height of column (mils)

r = radius of column (mils)

For the REV.LCHS,

L = 1080 mils, n = 676, D = 25 mils, h = 12 mils, r = 12.5 mils

Therefore,

$$SA = 1.47 \times 10^6 \text{ mils}^2$$

The original LCHS had an SA = 7.2×10^5 mils²

The REV.LCHS has 2 times the copper plated surface area in contact with water.

As previously stated, the flow of the water through the structure also determines thermal performance. The volume of water in the REV.LCHS at a moment in time and the rate at which it passes through the structure has been analyzed. The volume of water is given by the following equation:

$$V = h(L^2 - n\pi r^2)$$

For the REV.LCHS, $V = 10.0 \times 10^6$ mils³. $V = 5.4 \times 10^6$ mils³ for the original LCHS. The REV.LCHS can "hold" 1.9 times more water than the original LCHS.

Let's address the water flow rate and its effect on temperature. Consider two structures, one has 21 mil diameter columns the other has 31 mil diameter columns. Using the above equations, the following is obtained:

$$SA (21 \text{ mils}) = 1.47 \times 10^6 \text{ mils}^2$$

$$SA (31 \text{ mils}) = 1.45 \times 10^6 \text{ mils}^2$$

$$V (21 \text{ mils}) = 11.2 \times 10^6 \text{ mils}^3$$

$$V (31 \text{ mils}) = 7.9 \times 10^6 \text{ mils}^3.$$

For both structures the copper plated surface area is nearly identical. The 21 mil diameter column structure has 1.4% more copper but, it has 42% more water volume! The 31 mil diameter columns have a larger "footprint", this greatly reduces the space which can be occupied by water. The larger diameter columns adversely effect the water flow rate through the structure.

Thermal Performance

An experiment was performed using two structures; one had 21 mil diameter columns the other 31 mil diameter columns. An aluminum block and heating element were attached to both structures. The area of the aluminum was 4.532 cm² Power corresponding to 54.4 W/cm² was applied to both structures. The results are shown below.

$$\text{Water Flow Rate (21 mil)} = 875 \text{ mL/min}$$

$$\text{Water Flow Rate (31 mil)} = 740 \text{ mL/min}$$

$$\text{Temperature of the aluminum block (21 mil)} = 68.6 \text{ }^{\circ}\text{C}$$

Temperature of the aluminum block (31 mil) = 83.6 °C

As expected, the results show that temperature is inversely proportional to flow rate. An 18% increase in flow rate (740 to 875) corresponds to an 18% decrease in temperature (83.6 to 68.6). Not only is the flow rate greater for the structure with 21 mil diameter columns; the flow is probably more turbulent.

Temperature Rise Calculation

The one dimensional heat flow equation will be used, i.e.:

$$\Delta T = P\Omega \quad (\Omega = x/kA)$$

ΔT = change in temperature (°C)

P = power (watts)

x = thickness (cm)

k = thermal conductivity (W/cm °C)

A = area (cm²)

For the REV.LCHS (Refer to Figure #4)

$$\Delta T = P (\Omega_{AL} + \Omega_{TP})$$

$$P = 8.5 \text{ amps} \times 28 \text{ volts} = 238 \text{ watts}$$

$$A = 4.532 \text{ cm}^2$$

Ω_{AL} = thermal resistance of the aluminum block

$$\Omega_{Al} = x/kA$$

$$X = 4.71 \times 10^{-1} \text{ cm}$$

$$K = 2.38 \text{ W/cm}^\circ\text{C}$$

$$= 4.71 \times 10^{-1} \text{ cm} / (2.38 \text{ W/cm}^\circ\text{C} \times 4.532 \text{ cm}^2)$$

$$= 4.367 \times 10^{-2} \text{ }^\circ\text{C/W}$$

Ω_{TP} = thermal resistance of the thermal paste

$$X = 5.08 \times 10^{-3} \text{ cm}$$

$$K = 2.38 \text{ W/cm}^\circ\text{C}$$

$$= 5.08 \times 10^{-3} \text{ cm} / (2.3 \times 10^{-2} \text{ W/cm}^\circ\text{C} \times 4.532 \text{ cm}^2)$$

$$= 4.874 \times 10^{-2} \text{ }^\circ\text{C/W}$$

Therefore,

$$\Delta T = 238 \text{ W} (4.367 \times 10^{-2} + 4.874 \times 10^{-2}) \text{ }^\circ\text{C/W}$$

$$= 22 \text{ }^\circ\text{C}$$

The equation for the temperature rise above ambient is:

$$T_R = T_{AL} - \Delta T - T_{amb.}$$

T_R = temperature rise above ambient

T_{AL} = temperature of the aluminum block

ΔT = temperature change due to thermal drop

$T_{amb.}$ = ambient temperature of cooling water = 22 $^\circ\text{C}$

Therefore,

$$T_f = (59 - 22 - 22) \text{ } ^\circ\text{C}$$

$$= 15 \text{ } ^\circ\text{C at } 52.5 \text{ W/cm}^2 \quad \text{or} \quad 0.29 \text{ (} ^\circ\text{C/W) cm}^2 \text{ !!}$$

Comparison with Diamond

A paper has been written [1] on the heat dissipating properties of diamond-based liquid cooled heat sinks. The next equations have been taken from that paper. Assumptions: uniform power density (P/A), conductive heat transfer, one dimensional heat flow (for equations (1) - (4)) and the thermal path is parallel to the plane of the substrate.

Consider a rectangular substrate with a heat source mounted and centered on the top. The substrate has a Length, L and a thickness, z . One edge is cooled and maintained at a constant temperature, T_0 . What is the maximum temperature, $T_{\max}$, at the uncooled edge provided that $L \gg z$?

$$\Delta T_{\max} = T_{\max} - T_0 = 0.5 [(P/A) L^2] / (kz) \quad (1)$$

k is the thermal conductivity in $\text{W/cm } ^\circ\text{C}$.

If both edges (opposite to one another) are cooled, the maximum temperature occurs along the center line. The equation for this case is give by:

$$\Delta T_{\max} = T_{\max} - T_0 = 0.125 [(P/A) L^2] / (kz) \quad (2)$$

If the substrate was a square, instead of a rectangle, such that $A=L^2$ then, equation (1) becomes:

$$\Delta T_{\max} = 0.500 [(P/kz)] \quad (3)$$

and equation (2) becomes:

$$\Delta T_{\max} = 0.125 [(P/kz)] \quad (4)$$

As stated in the temperature rise calculation subsection, the REV.LCHS was able to dissipate 238W with a maximum temperature rise of 15 °C.

Calculate $\Delta T_{\max}$ for diamond using equations (3) and (4) and the following parameters: $P = 238\text{W}$, $k = 16\text{W/cm } ^\circ\text{C}$ and $z = 0.1\text{cm}$.

For one edge cooled,

$$\begin{aligned}\Delta T_{\max} &= 0.500 (238\text{W}/[(\text{W/cm } ^\circ\text{C}) 0.1\text{cm}]) \\ &= 74.4 ^\circ\text{C}\end{aligned}$$

For two edges (opposite) cooled,

$$\Delta T_{\max} = 18.6 ^\circ\text{C}$$

For three edges cooled,

$$\begin{aligned}\Delta T_{\max} &= 0.113853 (P/kz) \\ &= 16.9 ^\circ\text{C}\end{aligned}\tag{5}$$

For four edges cooled,

$$\begin{aligned}\Delta T_{\max} &= 0.073672 (P/kz) \\ &= 10.96 ^\circ\text{C}\end{aligned}\tag{6}$$

The thermal conductivity, k , for diamond is not isotropic. k perpendicular to the plane of the substrate is greater than k parallel to the plane of the substrate. According to a recently published paper [2], k for diamond parallel to the substrate is 16 W/cm °C; while k perpendicular is 21.7 W/cm °C.

According to equations (3) - (6); a diamond substrate would have to be cooled on all four sides if it were to outperform the REV.LCHS.

Reynold's Number Calculation

The Reynold's number of a fluid flowing through a periodic array of columns is determined by the pore Reynold's number, Re :

$$Re = (U/\phi)D_h/\nu \quad \text{from [3]}$$

U = superficial velocity of the fluid (m/s)

ϕ = porosity = (volume occupied by fluid/total volume (water + columns))

D_h = hydraulic diameter = $(\phi/1-\phi) d$ (meters)

d = column diameter (m)

ν = kinematic viscosity (m^2/s)

By substitution and the elimination of terms, Re reduces to $Re = U d / ((1-\phi) \nu)$.

For the REV.LCHS:

$$U = 800 \text{ cm}^3/\text{min} \div 12 \text{ mils} \times 1080 \text{ mils} \times (2.54 \text{ mils/inch})^2$$

$$= 9567.92 \text{ cm/min}$$

$$= 1.59 \text{ m/sec}$$

$$d = 25 \text{ mils} \times (2.54 \times 10^{-2} \text{ m}/1000 \text{ mils})$$

$$= 6.35 \times 10^{-4} \text{ m}$$

$$\phi = (L^2 - n \pi r^2)/L^2$$

$$= 0.7155$$

$$\text{Therefore, } 1-\phi = 0.2845$$

$$\nu = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$$

$$Re = 3,560$$

Turbulent flow can occur over the range of 1,000 to 10,000. Engineers typically use 2,300 as the critical Re ; i.e. the transition point from laminar to turbulent flow[4].

Electrical Performance

The REV.LCHS has 100 Electrically Conducting through vias/cm². These vias have a very unique feature. Each one can be treated as a miniature coaxial cable.

The impedance equation for a coaxial cable is:

$$Z = ((138/\sqrt{k}) (\text{Log } D/d))$$

Z = impedance in ohms

k = dielectric constant of the coaxial material

D = outer diameter of coaxial cable

d = diameter of the inner cable

Disregarding the top and bottom AlN plates and using a k value, of the solder mask, of 3.8, D = 25 mils and d = 10 mils; the value of Z is 28 ohms. By reducing the via diameter to 5 mils and keeping the other parameters the same characteristic impedance of 50Ω could be obtained.

COST ANALYSIS

All of the process steps required to fabricate the REV.LCHS are in common use throughout the printed circuit board and semiconductor industries. Processes such as lamination, photolithography, metal etching, laser drilling and patterned copper plated through holes are routinely performed. When economies of scale are optimized, it costs approximately 10 cents a square inch to produce a patterned copper plated through hole printed circuit board. In volume, laser drilling 650 holes per square inch (100 holes/cm²), in AIN, would cost approximately \$8 per substrate.

The REV.LCHS is comprised of three materials: two aluminum nitride substrates, solder mask material and plated copper. The solder mask costs pennies a square inch as does the plated copper. Each aluminum nitride substrate costs \$12. Since the top AIN plate of the REV.LCHS is not used for cooling, it is possible to replace it with alumina. The cost of an alumina substrate is \$6. Compared with the cost of the AIN and alumina substrates, the cost of the solder mask and plated copper is negligible.

After the initial cost of tooling and when economies of scale are employed, the REV.LCHS will cost approximately \$35 per unit. This number represents a best case scenario. However, if one were to triple it to \$105 per unit, the REV.LCHS should be considered inexpensive when compared to diamond-based liquid cooled heat sinks. A recent quote from a diamond substrate manufacturer stated that a 2" x 2" x 1/2 mm diamond substrate costs \$13,700.

From start to finish, fabricating a REV.LCHS would take less than four, 8 hour, shifts (2 days). The REV.LCHS fabrication process is elegantly simple and straight forward. The yield will be high (>90%) therefore, activities which add to the cost of a product such as rework and scrap will be kept to a minimum.

CONCLUSION

As power densities continue to increase, the thermal management of both conventionally packaged integrated circuits and multichip modules will become more of an issue. Forced convection systems, i.e. fans, will be replaced by two-phased heat sink systems, immersion heat sink systems (direct cooling) and liquid cooled head sink systems (indirect cooling).

Integrated System Assemblies has designed, fabricated and tested a liquid cooled head sink . The REV.LCHS dissipates 50 W/cm². with a 15 °C rise above ambient; it also has 100 thru vias/cm² and is less than 1.25 mm thick.

It has been shown that the REV.LCHS performs better than diamond and could be produced in volume at a fraction of the cost of diamond-based systems.

The REV.LCHS would be well suited for use in a 3-D electronic assembly ("cube computer").

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