Substrate Embedded Heat Pipes Compatible With Ceramic Cofired Processing

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Abstract

A prototype miniature heat pipe has been fabricated that is compatible with MCM-C processing. The post-fired alumina heat pipe is constructed as a laminate structure using thick film dielectric (glass) paste to hermetically bond the layers together. An axially grooved wick fabricated in alumina by laser patterning provides capillary pumping action. The working fluid for the heat pipe was water. In addition, axially grooved heat pipe structures have been demonstrated in high and low temperature cofired green tape ceramic technology. The prototype heat pipe was found to have an effective thermal conductance of over 3000 W/m-K, which is more than 100 times higher than the alumina it replaced within the substrate.

Key words: Heat Pipes, Alumina, Cofired Processing, Green Tape, and Multichip Modules Ceramic (MCM-C).

1. Introduction

With increased packaging density and large integrated circuits having high power dissipation, the need to enhance thermal management at the packaging level becomes more critical. High temperature cofired ceramic (hereafter, HTCC) technology has been used in high power applications with the thermal conductivities ranging from 20 W/m-K for alumina (Al$_2$O$_3$) to 200 W/m-K for aluminum nitride (AlN) and beryllium oxide (BeO). Low temperature cofired ceramic technology (hereafter, LTCC) has not been used as frequently due to its very low thermal conductivity, which is an order of magnitude lower than alumina. With the projected power dissipation of the next generation of processors exceeding 200 W/per die, enhanced thermal management techniques will be needed for effective use with MCM-C technology.

Theoretically, an effective thermal conductance approaching 10,000 W/m-K can be produced using miniature heat pipes. Hence, the use of heat pipes embedded within a substrate can reduce the overall thermal resistance of an electronic package, and provide lower semiconductor junction temperatures and a more uniform temperature distribution over the entire substrate surface.

Current heat pipe construction typically uses a metal shell and wick structure, which would have to be inserted or attached to the ceramic substrates after the firing process. A goal of this research is to address the fabrication issues and develop miniature heat pipes that are compatible with cofired technology, such that an effective thermal management system can be fabricated integrally into the substrate which coexists with electrical interconnections.

For convenience of processing test samples and developing various wick structures, a glass sealed structure of fired Al$_2$O$_3$ layers were used to investigate the feasibility and performance of a ceramic heat pipe. Laser machining was used to create the necessary channels, grooves, and holes in the ceramic material. The stacked, post-fired structure, is also applicable with thick film or single sided structures which can be post-processed to the firing temperature of the hermetic glass used to seal the individual layers.

2. Heat Pipe Operation

Heat pipes are designed to transport heat over relatively long distances with no additional power input. A heat pipe generally
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consists of a sealed enclosure with three distinct regions of steady state operation: an evaporator, a condenser region, and an adiabatic region separating the evaporator and the condenser, as shown in Figure 1.

Figure 1. Axial cross section of a typical heat pipe showing operating regions and fluid flows.

The heat pipe contains a working fluid, which absorbs heat by evaporation at the evaporator and travels as vapor through the adiabatic region to the condenser where heat is removed, hence causing the vapor to condense back into liquid. The working fluid returns to the evaporator section through a wick structure by a thermocapillary pumping action. The amount of heat energy (W or J/s) that a heat pipe can transport relates to the heat of vaporization of the working fluid (J/gm) and the amount of material undergoing evaporation (gms/s). The design of the wick is the most critical aspect to insure high fluid transport and thus high heat transport capability. In this paper, the authors are focusing on two basic types of wicks compatible with cofired processing, the sintered (porous) wick and the axially grooved wick. The cross-section of these wicks is shown schematically in Figure 2.

Figure 2. Cross sections of an axially grooved heat pipe wick (top) and a sintered wick (bottom).

3. Fabrication Issues

The fabrication of a heat pipe within ceramic cofired materials requires an open channel to be built into the substrate. This leads to the primary concern of sagging of the green tape on the top and bottom layers of the substrate during the firing cycle. This would ultimately affect the flatness of the substrate. Hence, to optimize the potential for sagging or at least, to keep the flatness of the substrate acceptable, the width of the heat pipe should be minimized, with the width of heat pipes of 1.3 to 7.6 mm (0.050 to 0.300 in.). Furthermore, substrates by their nature are thin, hence, the thickness of the substrate dictates that the height of the heat pipe is on the order of 0.6 to 2.5 mm (0.025 to 0.100 in.).

The fabrication of an efficient wick structure must be compatible with ceramic materials and conventional manufacturing processes. Wick materials would have to adhere to ceramic materials, and not oxidize or burn-off during the firing cycle. Axially grooved wicks would require the patterning of very thin, long, and closely spaced slots into the green tape with the resolution of typical electrical interconnections. Additionally, these fine slots would have to remain intact during lamination and firing processes.

4. Design Issues

The design of an optimized miniature heat pipe for the thermal management of electronics involves a complex balance of system requirements. The thermophysics of a heat pipe involves capillary forces, phase change, two-phase flow interaction, and porous media and/or channel flow. The relevant issues will be discussed starting from the evaporator end of the heat pipe where the heat is generated, and concluding at the condenser end where heat is removed.

At the evaporator end of the heat pipe, it would be desirable for the heat pipe to handle heat fluxes up to 40 W/cm² (250 W/in²). This roughly equates to the capability of removing heat from a single device that dissipates 40 Watts or removing 100 Watts over its length from several devices. The most significant limiting factor in the power handling capability of miniature heat pipes is the capillary limit, which is the point at which the wick cannot deliver the working fluid at the same rate as that it is evaporated. This condition leads to evaporator dry-out, indicated by a rapid increase in the local temperature of the evaporator.

The capillary limit is a function of the surface tension of the working fluid and the frictional forces caused by the interaction of the working fluid with the wick material and with the opposing vapor flow. For axially grooved heat pipes, the capillary limitation is given² by Equation (1), which relates the pumping action of the working fluid due to the surface tension, σ, and the frictional forces, F_l and F_v, to the working fluid flow from the condenser back to the evaporator. The frictional forces are described by two components, F_l, which represents the interaction of the working fluid and the wick material (structure), and F_v, which represents the resistance to the vapor flow due to the geometry of the vapor space.

\[
Q_{\text{CAP}} = \frac{2\sigma}{w L_{\text{eff}} (F_l + F_v)}
\]  

(1)

The liquid and vapor frictional coefficients are given by Equations (2) and (3). Referring to Equation (2), it is seen that the permeability of the wick, K_w, is inversely proportional to the liquid frictional coefficient. Referring to Equation (3), it is seen that the vapor frictional coefficient is proportional to the friction factor, f(Re_w) which is given³ by Equation (5).
The permeability of the axial grooved wick is given by Equation (4), which is a ratio between the flow area and the friction to the flow. The friction factor, \( f(Re_{lh}) \), is determined using Equations (5), (6) and (7), which include the shear stress interaction between the vapor flow and the liquid:

\[
K_g = \frac{D_g^2 \phi}{2f(Re_{lh})}
\]  

\[
Re_{lh} = 24(1-1.35\alpha + 1.947\alpha^2 - 1.701\alpha^3 + 0.956\alpha^4 - 0.254\alpha^5)
\]  

\[
Re_{n0} = 8D_g^2 \left\{ \frac{w_g^2}{4} \left[ 1 + \frac{D_g}{w_g} \right] \left[ \frac{1}{3} - \frac{32w_g}{\pi^2D_g^3} \tan\left( \frac{\pi D_g}{w_g} \right) \right] \right\}^{-1}
\]  

\[
Re_{in} = \frac{Re_{n0}}{1 + N_e \frac{w_g^3}{6\pi D_{n0}} Re_\nu \frac{v_\nu}{v_l} \left[ 1 - 1.971 \exp\left( -\frac{\pi D_g}{w_g} \right) \right]}
\]  

Therefore, all the equations up to this point show the paradox of miniature heat pipe design, that is, to increase the heat transport capability, the flow rates of vapor and fluid must be increased, which in turn, leads to high frictional losses which decrease the heat transport capability. Hence, the optimization of the design parameters must be performed to provide the most effective design. Insight into an optimal design can be gained by showing the effect of the groove depth, \( D_g \), and width, \( w_g \), on the capillary limit as shown in Figure 3. From the Figure, it is clear that an optimal groove width exists which is approximately the same for various groove depths (all other parameters held constant), and as the groove depth increases, so does the capillary limit.

In an effort to minimize the thickness of the heat pipe, it is desirable to minimize the height of the vapor space. The effect of the vapor space height is shown in Figure 4, which shows that the capillary limit initially increases sharply with increasing vapor space height and then becomes relatively constant. Again, the effect of the groove depth is seen to follow the same trend as discussed for Figure 3. An important conclusion drawn from the Figure is that the minimum vapor space height is related closely to the depth of the grooves, and that additional vapor space height will not have any significant effect.

The effect of the interaction between the groove width and the vapor space height is made clearer by holding the depth of the grooves constant and varying the other two parameters as shown in Figure 5. The curves in the Figure show that for small vapor space heights, smaller groove widths provide the highest capillary limit. But, as the height of the vapor space increases, increases in the capillary limit are obtained with larger groove widths. The “crossing-over” effect shown by the curves indicates that there is a competition between the shear stress interaction between the vapor and liquid flows and the ability of the wick to provide adequate mass of working fluid.
Small vapor space heights cause greater shear stress interaction, hence, only smaller groove widths can minimize the surface area of the working fluid interacting with the vapor flow. However, at some point, the vapor height is large enough that the shear stress interaction becomes negligible and the capillary limit becomes strongly dependent on the cross-sectional area through which the working fluid can flow.

In concluding the discussion of the design issues for a miniature heat pipe, the conditions at the condenser end must be considered. As the goal is to cool electronics, the working temperature of the heat pipe needs to be between 25°C and 110°C. This range recognizes the typical design constraints used in the thermal management of typical electronic packages. The first constraint is that semiconductor junction temperatures must be below 150°C, however, for typical reliability requirements, derated temperatures typically are 110°C and 125°C. Also, additional thermal resistance will exist between the substrate and the semiconductor junction, hence the heat pipe’s operating temperature must be lower than the derated temperatures. Typical coldplate and thermal contact areas have temperatures of 50°C to 90°C. Due to these and other thermal design constraints, working fluids useful for the heat pipe would be water, ethanol-water, acetone, and methanol. For simplicity during this stage of the research, water was chosen as the working fluid.

5. Heat Pipe Fabrication

Heat pipe channels were fabricated in HTCC technology at Coors Electronic Packaging Inc. The channels had widths of 2.4 mm (95 mils) and 3.9 mm (155 mils). All channels had a length of 101.6 mm (4.0 in.). By varying the number of layers used in the substrate, the thickness (height) of the channels could be varied. All the substrates used a top and bottom layer with a thickness of 0.6 mm (24 mils). Channel heights of 0.36, 0.71, 1.07, 1.30, and 1.78 mm (14, 28, 42, 51, and 70 mils, respectively) were fabricated. A micrograph showing the cross section of a HTCC heat pipe is shown in Figure 6.

Figure 6. Micrograph of high temperature cofired heat pipe cross section used to evaluate sag of top and bottom substrate layers.

Since substrate flatness is required in most assembly operations, a critical parameter is the amount of sag in the ceramic upon firing. The amount of sag in the substrates was found to be minimal and acceptable for use with thick film applications. Axial grooved wick structures have been fabricated in the green tape using standard end-milling and routing techniques.

In a parallel effort, heat pipes are being developed in LTCC technology. Ceramic tape and inks from Ferro Corporation and Heraeus Corporation are currently being investigated. These pipes will be smaller in size to better match typical low temperature cofired applications. Current designs have heat pipe widths of 100 mils, heights of 25 to 50 mils, and lengths of two inches. A micrograph of the axial wick structure in an LTCC system heat pipe is shown in Figure 7.

Figure 7. Micrograph showing axial groove wick structure fabricated in low temperature cofired ceramic.

Prototype heat pipes have been fabricated using laser machined post-fired alumina. These heat pipes provide a rapid and relatively easy method of fabrication allowing for various heat pipe designs to be built and tested for performance. In this manner, optimum designs can be determined and then fabricated in cofired technology.

The post-fired heat pipe was fabricated using several pieces of Al₂O₃ which were laser machined by Lasereliance Technologies Inc. All the pieces had a length and width of 102 mm x 13 mm (4.0 in. x 0.50 in.) with a thickness of 0.6 mm (0.025 in.). Four types of patterns were used in the design to provide a top and bottom shell, axially grooved wicks, and spackers as shown in Figure 8.

Figure 8. Components of laser machined post-fired alumina heat pipe.

The layers of the heat pipe were bonded together using Heraeus SG-683K dielectric thick film paste that was stenciled onto the alumina with an approximate thickness of 0.25 mm (10 mils). To allow for soldering of a metal filling tube to the ceramic, a silver-platinum metallization (Heraeus C4740S conductor thick film paste)
was patterned around the fill hole in the top shell. The assembly was fired in two cycles, the first for the metallizations and the second for the glass. After firing, a 1.6 mm (0.0625 in.) O.D. copper tube and flange assembly was soldered to the heat pipe.

The heat pipe was then charged with approximately 0.50 cc of deionized, degasified water using a simple arrangement of a vacuum pump, a tee pipe section, and a gas chromograph syringe. The heat pipe, the syringe, and the vacuum pump are connected together using the tee section and short lengths of tubing. The charging process begins by evacuating the heat pipe to draw out condensible gases. Then, the desired amount of working fluid is drawn into the syringe. When the line to the syringe is opened, the working fluid is drawn into the heat pipe. Finally, the heat pipe is sealed by crimping and soldering the end of the filling tube.

6. Experimental Procedure

To evaluate the thermal performance of the heat pipe, a thermal load was placed at one end of the heat pipe using a Kapton™ foil heater adhered to the surface of the substrate. This end of the heat pipe (the evaporator section) was then insulated to prevent heat loss to the ambient conditions. The amount of heat dissipated by the foil heater was controlled using a variable transformer to adjust the AC voltage across the foil. The voltage (RMS) and the current drawn through the foil were monitored by a digital multimeter, which allowed the dissipated power to be determined.

Heat was removed from the heat pipe by exposing the surface of the substrate (excluding the evaporator region) to ambient conditions which was cooled by natural and forced convection. The temperature was monitored along the heat pipe by eight Type K thermocouples. The thermocouples were calibrated prior to the experiments and were found to provide ±0.1°C accuracy.

To assess the effects of gravity on the performance of the heat pipe, two orientations were tested. The first orientation was horizontal with the evaporator and the condenser at the same elevation. The second orientation was vertical with the evaporator lower than the condenser. This orientation is highly favorable for heat pipe operation, as gravity can assist in bringing the working fluid back to the evaporator.

7. Thermal Performance

A post-fired alumina heat pipe was tested to determine the thermal performance of the design. The heat pipe design parameters are given in Table 1 and shown in Figure 9. The derived design parameters described previously are given in Table 2. Additionally, the cross-sectional areas for thermal transport were: 1) substrate and heat pipe, 0.0685 in², 2) substrate only, 0.0478 in², and 3) heat pipe only, 0.0208 in². In determining the effective thermal conductivity of a heat pipe the following method was used. The temperature variation along the length of the heat pipe was determined using the maximum evaporator temperature and the mean temperature of the condenser region.

Table 1. Prototype alumina heat pipe dimensions (all in mm).

<table>
<thead>
<tr>
<th>Dg</th>
<th>Wg</th>
<th>Sg</th>
<th>L</th>
<th>Weff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.51</td>
<td>0.10</td>
<td>0.74</td>
<td>1.4</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Figure 9. Cross section of an axially grooved heat pipe showing the relevant dimensions.

Table 2. Derived design parameters for prototype alumina heat pipe.

<table>
<thead>
<tr>
<th>Ng</th>
<th>φ</th>
<th>A_e (mm²)</th>
<th>A_v (mm²)</th>
<th>K_g x10¹² (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.138</td>
<td>5.2</td>
<td>7.1</td>
<td>98.0</td>
</tr>
<tr>
<td>D_e (mm)</td>
<td>D_lhg (mm)</td>
<td>Re_lh</td>
<td>Re_vh</td>
<td>Q_cap (W)</td>
</tr>
<tr>
<td>2.0</td>
<td>0.17</td>
<td>23.4</td>
<td>17.9</td>
<td>32.5</td>
</tr>
</tbody>
</table>

The appropriate length scale used with the defined temperature variation is the distance between the mid-points of the evaporator and the condenser region. For the heat pipe presented, this would be approximately 2.25 inches. The temperature distributions along the heat pipe are shown in Figure 10 for thermal loads of 9.3, 12.0 and 13.0 W, in both the vertical and horizontal orientations. To provide a true baseline for measuring the performance of the heat pipe, the heat pipe was also tested without any working fluid, that is the heat pipe was not operational. In this manner, heat was transferred from the evaporator to the cooling jacket by conduction only through the shell material, which was alumina and glass. In this case, a thermal load of 5 W was used. The temperature distribution for the “conduction” mode is also shown in Figure 10.
Comparison of the temperature distributions in Figure 10 shows the clear difference when the heat pipe is functioning and when heat is only transferred by conduction. When the heat pipe is functioning, the temperature is relatively uniform along the length of the heat pipe, due to a high effective thermal conductance. Using the defined temperature variation and the length scale, the effective thermal conductances for the heat pipe are given in Table 3. For the horizontal orientation, the effective thermal conductivity of the heat pipe only was over 3000 W/m-K, and for the combined system of the substrate shell and the heat pipe, it was roughly 1000 W/m-K. It was found that at thermal loads above 12 W, the temperature at the evaporator began to rise rapidly, indicating that the capillary limit for the heat pipe had been reached. As given in Table 2, the capillary limit for the heat pipe was estimated to be 32.5 W. The reason for the lower performance of the heat pipe may be due to poor wetting of the working fluid on the alumina. The researchers are currently exploring ways to improve the wetting characteristics of the alumina surface coatings.

Table 3. Effective thermal conductivity of post-fired alumina heat pipe for various thermal loads, orientations, and thermal cross-sectional areas.

<table>
<thead>
<tr>
<th>Effective Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Watts)</td>
</tr>
<tr>
<td>9.3</td>
</tr>
<tr>
<td>12.3</td>
</tr>
<tr>
<td>13.0</td>
</tr>
<tr>
<td>5.0</td>
</tr>
<tr>
<td>Orientation</td>
</tr>
<tr>
<td>0°</td>
</tr>
<tr>
<td>60°</td>
</tr>
<tr>
<td>90°</td>
</tr>
<tr>
<td>0°</td>
</tr>
<tr>
<td>Substrate/pipe</td>
</tr>
<tr>
<td>1208</td>
</tr>
<tr>
<td>989</td>
</tr>
<tr>
<td>2181</td>
</tr>
<tr>
<td>32.5</td>
</tr>
<tr>
<td>Pipe Only</td>
</tr>
<tr>
<td>3922</td>
</tr>
<tr>
<td>3197</td>
</tr>
<tr>
<td>7133</td>
</tr>
<tr>
<td>n/a</td>
</tr>
</tbody>
</table>

In the vertical orientation, the heat pipe had a significant increase in performance with an effective thermal conductivity of over 7000 W/m-K. In addition, the capillary limit was not reached. In the vertical orientation, with the evaporator lower than the condenser, gravity assists the flow of the working fluid back to the evaporator, thus, the heat pipe can continue to operate even when the wick cannot produce the needed capillary pressure to transport the working fluid. Additionally, the orientation is favorable for the condenser making natural and forced convection more efficient. Hence, with increased transport of the working fluid and favorable external conditions, the performance of the heat pipe is enhanced producing a more uniform temperature distribution along its length. In the case where heat was transferred solely by conduction through the substrate, the temperature distribution was found to be highly linear with a slope of -1620°C/m. Using the cross-sectional area of the substrate without the heat pipe, the average effective thermal conductivity for the heat pipe’s shell was found to be 32.5 W/m-K. This value is in good agreement with the typical values found for alumina, which ranges from 21 to 29 W/m-K depending on manufacturer.

Conclusions

The data presented confirmed that a heat pipe can be fabricated using conventional ceramic technology and materials. The heat pipe provided a significant improvement to the thermal performance of the alumina substrate, with increases in the average effective thermal conductance of at least 100 times that of the heat pipe shell material. Due to its complex balance of many parameters, the optimization of a miniature heat pipe needs to be better understood. The heat pipe, presented in this paper, will allow for rapid experimentation to proceed for assessing the various issues in heat pipe design, due mainly to its capability to be rapidly produced. Further research in higher thermal loads and working fluid selection is needed. In addition, the wick of the heat pipe will continue to be improved. It is believed by the authors that an effective thermal conductances near 10000 W/m-K is attainable for ceramic heat pipes, and that optimization of the heat pipe’s design will provide a superior thermal management capability for advanced ceramic electronic packages.

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Nomenclature

- A: cross-sectional area, m²
- D: groove depth, m
- D_h: hydraulic diameter, m
- F: frictional coefficient
- h_L: latent heat of vaporization, J/kg
- L: effective heat pipe length, m
- K: wick permeability, m²
- N: number of grooves
- Q_cap: capillary limit, W
- Re: Reynold’s Number
- R_h: hydraulic radius, D_h/2
- s: groove spacing, m
- t_v: vapor space height, m
- w: width, m

Greek Symbols

- α: t/W
- μ: viscosity, kg/(m-s)
- ρ: density, kg/m³
- σ: liquid surface tension, N/m
- φ: wick porosity
Subscripts

g  groove
l  liquid
v  vapor

References


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