VIBRATION-INDUCED DROPLET ATOMIZATION HEAT TRANSFER CELL FOR HIGH-HEAT FLUX APPLICATIONS

S.N. Heffington, W.Z. Black & A Glezer
Woodruff School of Mechanical Engineering
Georgia Institute of Technology,
771 Ferst Dr. Love Bldg.
Atlanta, GA 30332
Phone: (404) 385-2142
Fax: (404) 894-8496
Email: sam.heffington@me.gatech.edu

ABSTRACT

This paper describes a unique two-phase cooling method that includes a closed heat transfer cell, similar to a thermosyphon that can be used to cool microelectronic packages. The cooling method is based upon a Vibration-Induced Droplet Atomization, or VIDA, process that can generate small liquid droplets inside a closed cell and propel them onto a heated surface. The VIDA technique involves the violent break-up of a liquid film into a shower of droplets by vibrating a piezoelectric actuator and accelerating the liquid film at resonant conditions. The droplets continually coat the surface with a thin liquid film, which evaporates on the heated surface, and the vapor is condensed on the internal surfaces of the heat transfer cell as well as the liquid working fluid. The condensed liquid is returned via gravity to the piezoelectric actuator where it is again atomized.

A VIDA heat transfer cell 50 mm in diameter and 20 mm thick was constructed. Test data described in this study include the heat transfer characteristics and cooling capabilities for a small-scale cell that is suitable for cooling a desktop microprocessor during the burn-in portion of the manufacturing process. The VIDA process produces droplets of relatively uniform diameter, and the droplets have sufficient momentum to reach the remotely located heated source. Heat fluxes as high as 200 W/cm^2 have been measured when a chilled water heat exchanger is used as the external heat removal device.

KEY WORDS: two-phase liquid cooling, high heat flux, vibration-induced droplet atomization, burn-in

INTRODUCTION

In the microelectronics industry, advances in technology have brought about an increase in transistor density and faster electronic chips. As electronic packages increase in speed and capability, the level of heat flux that must be dissipated to maintain reasonable chip temperatures has also risen. Cooling levels are projected to reach the 100 – 150W range according to the SIA Packaging Technology Roadmap [1]. To provide reliable cooling for this expected level, the single level integrated module under development by the Packaging Research Center at the Georgia Institute of Technology is expected to dissipate between 20 and 100W/cm^2 [2].

Two-phase heat transfer, involving the evaporation of a liquid in a hot region and the subsequent condensation of the resulting vapor in a cold section, can provide the large heat fluxes needed for microelectronic packages to operate at acceptable temperature levels. By changing the phase of the working liquid, a two-phase heat transfer cooling scheme can transport high heat transfer rates across moderately small temperature differences. Heat pipes and thermosyphons are examples of efficient heat transfer devices that exploit the benefits of two-phase heat transfer [3-5]. Immersion cooling involving pool boiling of a dielectric working fluid on the surface of the package is another example of two-phase cooling technology useful for microelectronic applications [6]. A cooling module based on the VIDA principle is a new technology capitalizing on the benefits of two-phase cooling while improving on heat pipe performance by eliminating the wicking structure and employing a more active means to transport the liquid phase back to the heat source [7]. Without a wick structure, the operation of a VIDA cell is not limited by the capability of the wick to continually supply the boiler section with liquid. Furthermore, the VIDA cell has the potential to improve upon the performance of a thermosyphon, because it creates a condition of thin film boiling in the evaporator section and it can minimize temperature gradients that cause potentially dangerous thermal stresses. The evaporation of a thin film prevents the formation of an insulating vapor blanket that can exist in pool boiling situations. Also, the atomized droplet momentum is sufficient to propel the liquid droplets through the vapor layer and to spread the impinging liquid into a thin film on the heated surface. While the VIDA cell has advantages over heat pipes and thermosyphons due to the production of a thin evaporating film, the VIDA cell, like a thermosyphon, has one limitation because it must be operated in a nearly horizontal orientation [8].

A schematic of one type of VIDA cell is shown in Figure 1. The cell consists of a vibrating driver that creates a shower of small diameter secondary droplets by breaking up a larger primary drop that forms on the driver and improve the efficiency of the breakup process. An optional orifice plate can be placed over the driver to regulate the thickness of the liquid film on the driver. In this type of design, the driver ejects small secondary droplets through the holes in the orifice plate. The secondary droplets are propelled toward the heated surface where they form a thin film of liquid on the heater. The liquid film evaporates and fills the interior cavity of the cell with vapor. The exterior surfaces of the cell are cooled via heat transfer to the ambient and the vapor condenses on these surfaces. The condensed liquid is then returned via gravity to the driver where it once again is atomized and the process is repeated. The entire cell can be very small and the driver requires only milliwatts of energy to operate.

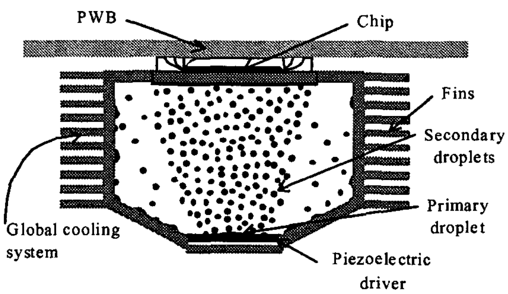

Fig. 1 Schematic of VIDA heat transfer cell

Several VIDA heat transfer cells that use forced air convection as the global cooling method have been constructed and tested [9-11]. Heat fluxes over 100W/cm^2 are dissipated while keeping the heater temperature below 100°C while using standard cooling fans. These VIDA heat transfer cells have used both water and FC-72 as the working fluid, and they have proven more effective than solid metallic conductors of equal volume [12].

This research investigates a different VIDA heat transfer cell design that uses a circulating chilled water loop, instead of a fin array and fan, for the global cooling method. This liquid cooled cell is primarily designed for controlled cooling of microprocessor packages during the burn-in process associated with microelectronic package production.

THE VIDA PROCESS

In order to design an efficient heat transfer cell, it is important to understand the VIDA process. The VIDA cell includes a metallic disc coated with a piezoelectric material that is energized with a sinusoidal varying voltage. The resulting vibrations are capable of accelerating a single liquid droplet or liquid film to an extent that the fluid has sufficient velocity to break-up or atomize into numerous smaller secondary droplets. The secondary droplets are propelled upward and they are capable of impacting a remotely located heated surface. The frequency and amplitude of the voltage used to energize the piezoelectric transducer are important parameters that must be properly controlled in order to achieve the liquid breakup phenomena that is essential to the VIDA process. Operating the piezoelectric driver over a narrow range of frequencies produced a reliable spray of drops, while at other frequencies atomization was inhibited creating a dangerous dry out of the heated surface inside the cell. The frequencies that were acceptable were determined by experimentation.

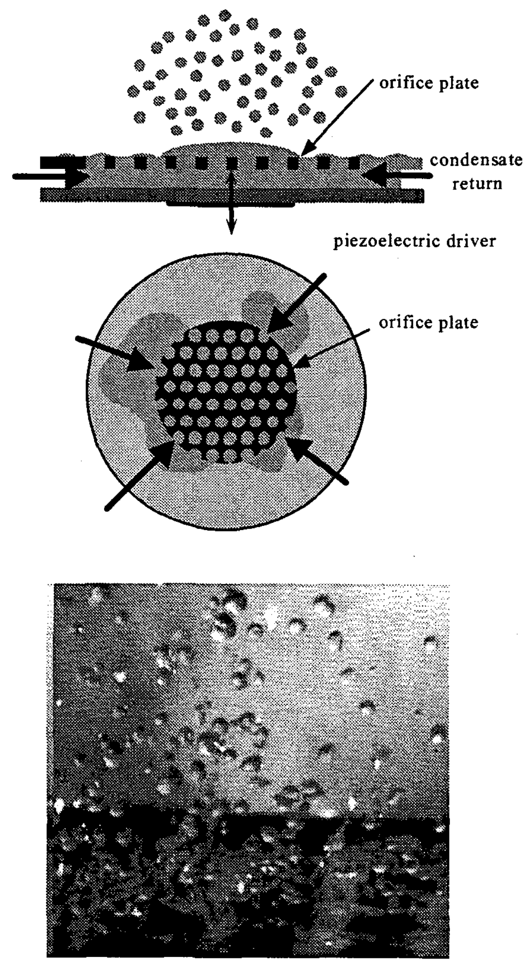

Fig. 2 VIDA process schematic and photograph of ejected secondary droplets from the orifice plate

The schematic and photograph in Figure 2 illustrate the VIDA atomization process used in this research investigation. An aluminum piezoelectric driver that was 31 mm in diameter was placed below a brass perforated plate. This perforated orifice plate contained holes 1.59 mm in diameter spaced on 3.18 mm centers in a square grid. The dimensions and spacing of the holes in the orifice plate were selected to optimize the production of secondary droplets from the holes in the orifice plate. The thin vertical spacing between the orifice plate created surface tension forces that were sufficient to pump water onto the driver surface from a reservoir surrounding the driver. This liquid layer was accelerated by the motion of the driver which resulted in atomization of the liquid through the holes in the orifice plate. Secondary droplets were produced that were much smaller than the diameter of the holes in the orifice plate. The orifice plate provided a robust continuous VIDA process by regulating the mass of water on the driver surface while not allowing the driver to become overloaded or starved for water. This droplet atomization procedure ensured a continual supply of liquid droplets to the heater surface.

VIDA HEAT TRANSFER CELL

Several different VIDA cells that used a fan and fin array for transferring heat to the environment have been built and tested to evaluate their heat transfer characteristics [10-12]. In order to remove the higher heat fluxes associated with the burn-in manufacturing process, a heat transfer cell was designed that replaced the fan and fins with a chilled water loop for the global cooling system. The burn-in process provides several luxuries that do not exist when designing a cooling scheme for a desktop application. Even though heat fluxes during the burn-in process are higher than those that exist during the operation of a typical microprocessor, a cooling scheme for the burn-in process is not as restricted by economic and size constraints. Thus, a chilled water loop maintaining a cool condenser surface is a viable design option.

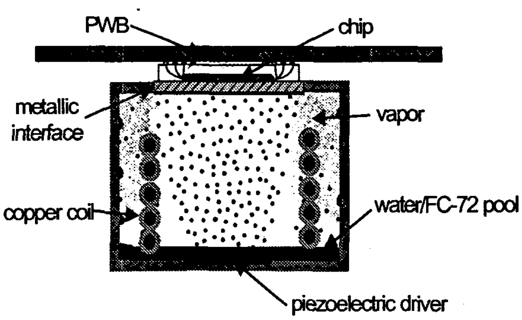

Fig. 3 Schematic of a VIDA heat transfer cell designed for the burn-in process of microprocessor packages

A schematic of the VIDA heat transfer cell using a liquid chilled loop is shown in Figure 3. The cell has an overall diameter of 50 mm and the height is 20 mm. A copper coil containing circulating chilled water was located inside the cell. The copper tubing has an outside diameter of 3.2 mm and an inner diameter of 2 mm. The piezoelectric driver was located 6.35 mm above the bottom of the cell leaving a small backing cavity behind the driver. Three stainless steel tubes with an outer diameter of 2 mm were used to connect the backside of the driver to the topside. These tubes were used to equalize the pressure on both sides of the driver when the cell was operated under vacuum conditions. The cell consisted of two sections connected with an O-ring. The bottom section contained the driver and coil assembly, and the top allowed for the thermal test vehicle connection. After the aluminum cell was machined, it was black anodized to prevent the aluminum surface from corroding where it was in contact with water. The cell was instrumented with eight thermocouples making it possible to measure temperatures within the cell even under vacuum conditions. A pressure transducer was also connected to the cell to measure the internal gage pressure during the heat transfer experiments.

The cell was charged with water or FC-72 to provide a liquid reservoir in the bottom of the cell. This liquid pool also provided a uniformly thick layer of fluid over the top of the driver. The piezoelectric driver was 31 mm in diameter, and it was activated by a 25 V_{rms} sinusoidal source. A perforated orifice plate with uniformly spaced holes was centrally located over the driver. The small spacing between the driver and orifice plate assured a reliable flow of liquid to the surface of the driver. The frequency and amount of liquid inside the cell were varied until a continuous VIDA process was observed on the driver. For the VIDA cell shown in Figure 3, a strong VIDA process was experienced when the cell was charged with 12 to 15 mL of liquid and it was vibrated at a frequency between 0.5 and 1.2 kHz.

HEAT TRANSFER RESULTS

Several heat transfer experiments were conducted with two different heat sources. Both heaters were thermal test vehicles provided by the Intel Corporation. The smaller heater had a die area of 1.18 cm^2 while the die of the larger heater had a surface area of 4.72 cm^2. The procedure for completing a heat transfer test was the same for both heaters. After the heater had been attached to the top section of the cell with a silicon sealant, the cell was charged with 12-15 mL of working fluid. The capillary pumping action provided by the location of the orifice plate above the piezoelectric driver allowed for atomization at a wide range of working liquid volumes. If water was the working fluid, the cell was then evacuated until the pressure in the cell reached approximately 2.5 kPa. The pressure inside the cell was initially one atmosphere if FC-72 was the working fluid. After charging the cell, the chilled water supply was activated and allowed to reach steady-state. The piezoelectric driver was first energized to form droplets followed by activation of the heater. Power was supplied to the die surface that was uniformly heated by means of a direct current power supply. Temperature sensing diodes embedded in the silicon die were used to measure and record the temperature of the die as the power level to the heater was varied.

In the first experiment, the flow rate of the chilled water through the copper coil was changed while maintaining the temperature of the liquid at a constant 20°C. Figure 4 shows the effect of changing the water flow rate from 1.5 to 25 mL/sec on the die temperature and heat transfer rate from the die. The working fluid inside the VIDA heat transfer cell for both of these tests was water. For both flow rate conditions the pressure inside the cell varied from 2.8 to 6.9 kPa, and the temperature inside the cell increased from 22 to 41°C. The results indicate identical die performance when the die temperature is less than about 50°C, regardless of the cooling water flow rate. However, as the die temperature increases, it is able to dissipate a greater amount of heat at the larger water flow rates. When the die temperature is 100°C, it is able to dissipate 17% more heat at the higher water flow rate.

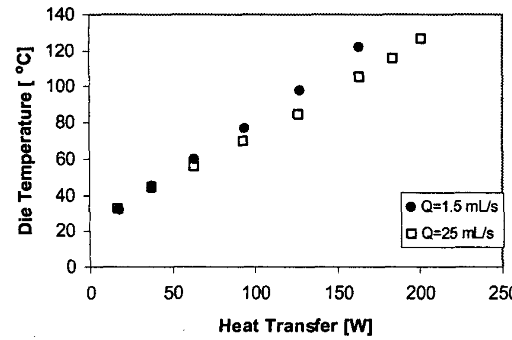

Fig. 4 Effect of chilled water flow rate for liquid cooled VIDA heat transfer cell

The effect of changing the circulating bath temperature in the copper coil on the die temperature and heat transfer rate is shown in Figure 5. Three different bath temperatures (20, 40 or 60°C) are plotted, and the flow rate for all three tests was held constant at 25 mL/sec. As the temperature of the cooling water increased, the pressure inside the cell increased and the heat dissipated decreased for a given die temperature. At a bath temperature of 20°C, the pressure increased from 2.8 to 6.9 kPa and the temperature increase from 22 to 41°C. The pressure increased from 9.0 to 18.7 kPa and the temperature increase from 47 to 60°C when the bath temperature was 40°C. When the bath temperature was 60°C, the pressure increased from 26.2 to 36.5 kPa and the temperature increase from 67 to 74°C. Since the heat transfer goal during the burn-in process was 100W at a die temperature of less than 100°C, these results indicate that the VIDA heat transfer cell is capable of meeting the thermal requirements of the burn-in process. The cell is capable of dissipating 150W while keeping the die at 100°C for a conservative chilled water flow rate of 25mL/sec and a bath temperature of 20°C.

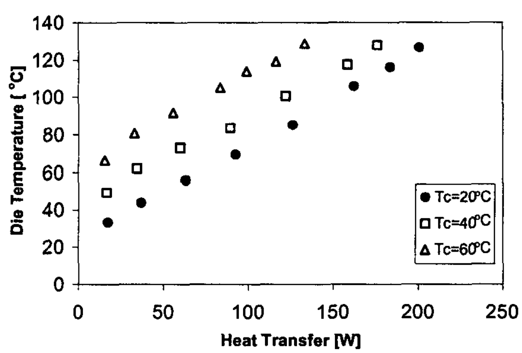

Fig. 5 Effect of cooling water temperature for liquid cooled VIDA heat transfer cell

For the previous two figures, the VIDA spray impacted directly on the copper integrated heat spreader (IHS) that covered the die. The results in Figure 6 indicate the effect of removing the IHS and spraying directly on the die surface. For the test results shown in Figure 6, the water in the chilled loop circulated at 25 mL/sec and was maintained at 20°C, and the small thermal test vehicle was used. The pressure inside the cell increased from 2.8 to 6.9 kPa, and the internal temperature also increased from 22 to 41°C. The IHS surface area for the smaller die was 9.61 cm^2, and difference in area between the bare die and the IHS was nearly 8.5 cm^2. The bare die temperature increases with increasing heat power until a critical heat transfer rate is reached at approximately 50W. Beyond this level, large increases in die temperature are experienced for slight increases in power. The critical heat transfer rate in which the IHS was in place could not be determined with the smaller die because the maximum operating temperature of 120°C was exceeded before the critical heat transfer rate was reached. These results indicated that the added area associated with the IHS plays a larger role than the reduction in thermal contact resistance that can be achieved by removing the IHS.

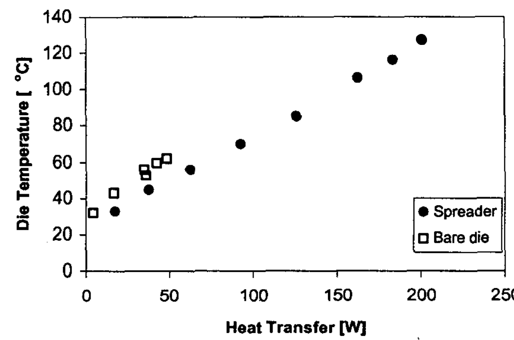

Fig. 6 Effect of integrated heat spreader for liquid cooled VIDA heat transfer cell

Some tests were also conducted with the larger thermal test vehicle, and these results are presented in Figure 7. These tests were completed with the IHS removed, the chilled water was maintained at a flow rate of 25mL/sec and a temperature of 20°C. Water and FC-72 were used as the working fluids and the initial pressure in cell was 4.1kPa for water, and 101.3 kPa for FC-72. When water was used, the pressure in the cell increased from 4.1 to 11.7 kPa, and for FC-72 the pressure in the cell increased from 10.5 to 12.5 kPa. The data plotted in Figure 7 obviously shows that water has superior heat transfer properties, and it is a better choice for a working fluid in a VIDA heat transfer cell. The critical heat transfer rate when FC-72 was used as a working fluid was 60W when the die reached 100°C. The critical heat transfer rate could not be reached for the case when water was used as a working fluid before the die reached its upper temperature limit of 120°C. With water as the working fluid, over 300W was dissipated while keeping the die at a temperature of 118°C. Standard uncertainty analysis determined the heat transfer measurement accurate to within 4.5% and the die temperature was within ±1°C of the value reported.

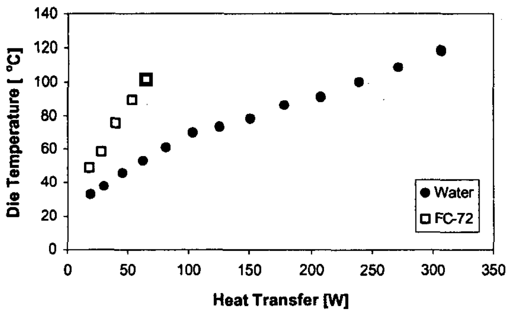

Fig. 7 Effect of working fluid for liquid cooled VIDA heat transfer cell

CONCLUSIONS

A new heat transfer cell based on a droplet atomization mechanism and suitable for cooling small microelectronic packages during the burn-in manufacturing process is proposed. A vibrating driver provides continual supply of small diameter droplets that are propelled toward the heated surface where they form a thin liquid film. The liquid evaporates on the heater and the vapor condenses on the secondary droplets and on the cool inner surfaces inside the cell. The condensed liquid returns to the driver where it is re-atomized.

Initial heat transfer results utilizing water as a working fluid and a simple cell design have shown that a cell based on the VIDA process can provide a heat transfer rate over 300 W. Reducing the flow rate inside the chilled loop inside the cell slightly reduced the heat flux at a given heater die temperature. In addition, for a given heat transfer rate, the die temperature was increased as the temperature of the water in the cooling loop was increased. Removal of the integrated heat spreader placed on top of the die does not increase the heat transfer performance because the benefit of the additional area of the heat spreader outweighs the drawback of the added thermal contact resistance between the die and heat spreader. Comparative tests using water at reduced pressures and FC-72 at atmospheric pressure show the clear advantages of utilizing water as a working fluid inside the VIDA heat transfer cell. These preliminary tests have indicated that a VIDA-based heat transfer cell has a potential to cool small-scale electronic devices during the burn-in process, and VIDA cells can provide cooling capabilities that are within the range required for most modern microprocessor package designs.

ACKNOWLEDGEMENTS

This work was supported by DARPA through BAA 98-32.

REFERENCES

[1] SIA Semiconductor Industry Association, 1994, The National Technology Roadmap for Semiconductor: Technology needs – 1997", Semiconductor Industry Association, Washington DC.

[2] Georgia Institute of Technology, 1995, Packaging Research Center, Third Annual Review, Atlanta Georgia, pp. 4.1-4.5.

[3] Peterson, G. P., 1994, An Introduction to Heat Pipes, John Wiley & Sons, Inc.,, New York, pp. 285-326.

[4] Kiewra, E. W., and P. C. Wayner, 1986. "A Small Scale Thermosyphon for Immersion Cooling of a Disc Heat Source," *Heat Transfer in Electronic Equipment,* ASME Symposium HTD-Vol. 57, Bar-Cohen, A. (Ed.), American Society of Mechanical Engineers, New York, pp.77-82.

[5] Mudawar, I., T. A. Incropera, and F. P. Incropera, 1987, "Microelectronic Cooling by Fluorocarbon Liquid Films," *Proc. Int. Symposium of Cooling Technology for Electronic Equipment.*

[6] Arik, M. and A. Bar-Cohen, 1998, "Immersion Cooling of High Heat Flux Microelectronics with Dielectrid Liquids", 4th Int. Symposium and Exhibition on Advanced Packaging-Materials-Processes-Properties, Atlanta, pp. 229-247.

[7] Smith, M. K., A. James, B. Vukasinovic, and A. Glezer, 1998, "Vibration-Induced Droplet Atomization," submitted for publication.

[8] Denney, D. L., W. Z. Black, J. G. Hartley, and A. Glezer, 1996, "High Heat Flux Boiling with Monodisperse Water Droplets," Process, Enhanced, and Multiphase Heat Transfer, R. M. Manglik and A. D. Krause, eds., Begel House, Inc., New York, pp. 175-182.

[9] Heffington, S.N., W.Z. Black, and A. Glezer, 2000, "Vibration-Induced Droplet Cooling of Microelectronic Components," *ITHERM 2000 Proceedings,* Vol. 2, Las Vegas, NV, pp.328-332.

[10] Heffington, S.N., W.Z. Black, and A. Glezer, 2001, "Vibration-Induced Droplet Atomization Heat Transfer Cell for Microelectronic Thermal Management," *13th European Microelectronics and Packaging Conference & Exhibition,* Strasbourg, France.

[11] Heffington, S.N., W.Z. Black, and A. Glezer, 2001, "Vibration-Induced Droplet Atomization Heat Transfer Cell for Cooling of Microelectronic Components," *The Pacific Rim/ASME International Electronic Packaging Technical Conference & Exhibition,* Kauai, Hawaii.

[12] Heffington, S.N., W.Z. Black, and A. Glezer, 2002, "Vibration-Induced Droplet Atomization Heat Transfer Cell for High-Heat Flux Dissipation," *Thermal Challenges in Next Generation Electronic Systems (THERMES-2002),* Santa Fe, NM.