Vibration-Induced Droplet Cooling of Microelectronic Components

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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. The condensed liquid is returned via gravity to the piezoelectric actuator where it is again atomized.

VIDA heat transfer cells ranging in diameter from 12 to 41mm, which generate spherical droplets between 50 and 100μm, have been constructed. Test data described in this study include the operating characteristics of the VIDA cell as well as preliminary cooling capabilities for a small-scale cell that is suitable for cooling a desktop microprocessor. 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 40W/cm^2 have been measured when a chilled water jacket is used as the external heat removal device.

KEY WORDS: two-phase cooling, vibration induced droplet breakup, droplet cooling, thermal management of microelectronics

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 also rises. 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 a large heat rate with a small temperature difference. Heat pipes and thermosyphons are examples of efficient heat transfer devices that exploit the benefits of two-phase heat transfer [3,4,5]. A cooling module based on the VIDA principle is a new technology capitalizing on the benefits of two-phase cooling while also seeking to improve 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 [6]. 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 thin film boiling in the evaporator section. The evaporation of a thin film prevents the formation of an insulating vapor blanket found 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, is limited to operating in a nearly horizontal orientation. Therefore the VIDA process creates a thin, evaporating liquid film that can provide high heat transfer rates and can minimize temperature gradients that cause potentially dangerous thermal stresses [7].

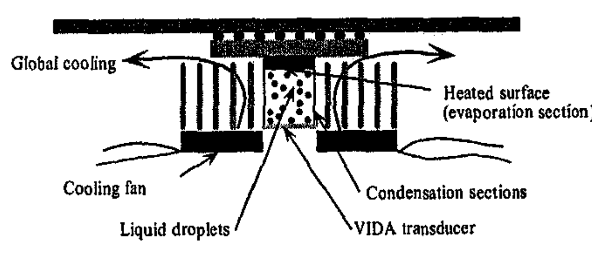
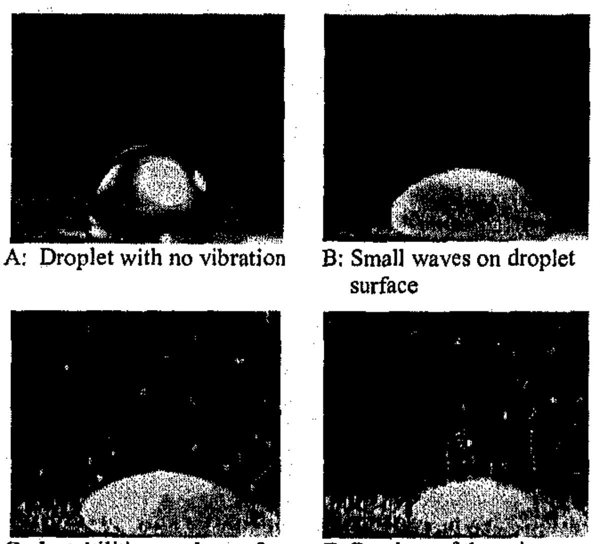


Figure 1: VIDA heat transfer cell with external fins and fans

A schematic of one type of VIDA cell is shown in Fig. 1. The cell consists of a vibrating driver that creates the small diameter secondary droplets by breaking up a larger primary drop. 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 cell with vapor. The interior surfaces of the cell are cooled via heat transfer to the ambient and the vapor condenses on the cool 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.

THE VIDA PROCESS

In order to design an efficient heat transfer cell, a major challenge is understanding the VIDA process. The VIDA process involves 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 the point 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 hitting 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.



A: Droplet with no vibration

B: Small waves on droplet surface

C: Instabilities on the surface generating small secondary droplets

D: Breakup of the primary droplet

Figure 2: Different stages of droplet atomization process for water at 5kHz

The four photographs in Fig. 2 illustrate the distinct phases of the VIDA process. This figure was obtained by using a single 10μL water droplet placed on a 15mm diameter brass vibrating driver. In frame A, the 3.5mm diameter droplet is shown on the stationary piezoelectric disk. Frame B shows the same droplet when the piezoelectric transducer is driven at a frequency of 5kHz. The droplet has a tendency to spread on the surface as the driver is vibrated and the normally smooth exterior surface of the drop begins to break down into small amplitude, short wavelength oscillations which form over the surface of the drop. In frame C the same droplet is vibrating at 5kHz, but the amplitude of the input sine wave signal has been increased. A few secondary droplets that are produced as a result of instabilities in the capillary waves are formed on the surface and are shown leaving the primary drop. Frame D shows a complete breakup of the primary drop into much smaller secondary droplets and atomization of the primary droplet as the amplitude of the driving signal was further increased.

Simply placing a drop of water on piezoelectric transducer and applying power to the transducer does not guarantee that the VIDA process will occur. The characteristics of the driver must be matched with both the driving frequency and with the mass of the liquid drop. Figure 3 shows different characteristic curves, which delineate three frequencies of vibration that will create the breakup of a water droplet placed on 12, 15 and 20mm drivers. For all three curves various volumes of water were placed on the piezoelectric transducer surface. The applied voltage to the transducer was held at a constant level of 25 Volts AC for all cases, which is the maximum operational voltage level recommended by the manufacturer. The volume of water was varied from 10μL to the maximum volume that the transducer could successfully atomize. After placing the primary drop on the transducer, the input frequency to the piezoelectric transducer was varied until the atomization process occurred. The areas between curves with like symbols in Fig. 3 represent the operational frequencies used to energize the drivers that produced the VIDA process.

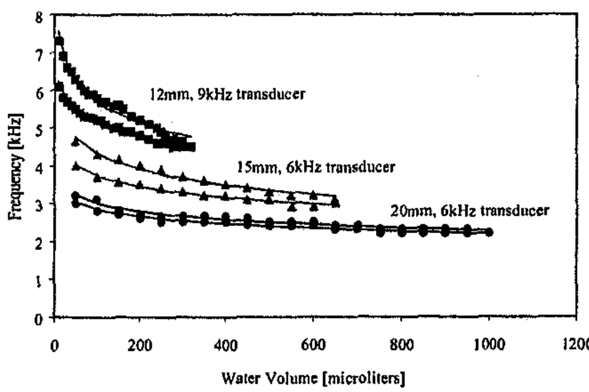


Figure 3: Operating characteristics of the VIDA phenomena

In all three curves of Fig. 3, the range of frequencies over which the breakup phenomena occurred was greatest for the small volume drops and it decreased to a narrow frequency range as the volume of the drop increased. The transducer used to obtain the results shown in the top curve was a 12mm diameter brass transducer with a free-air resonant frequency of 9kHz. The middle curve shows the VIDA results for a 15mm diameter brass transducer whose free-air resonant frequency was 6kHz. The results shown in the bottom curve are for a 20mm diameter brass transducer with a free-air resonant frequency of 6kHz. As the transducer increased in size, the frequency necessary to cause droplet breakup decreased, and the maximum volume of water that could be atomized increased. Also, as the volume of water on the transducer increased, the frequency required to produce the VIDA process decreased. For a given volume of primary drop, the range of acceptable input frequencies decreased as the piezoelectric transducer increased in size. While the operating bands of the VIDA process are narrow, they are not a strong function of temperature. Therefore, it is possible to generate a continual flow of liquid to the heater surface despite the normal changes in temperature that occur inside the VIDA cell.

Initial tests have shown that the VIDA breakup process is most efficient when the combination of the primary drop and driver operate close to their natural frequency. Therefore, as the mass of the drop on the driver and the diameter of driver increase, the frequency range at which the VIDA process provides reliable production of secondary droplets decreases. This conclusion is supported by the data shown in Fig. 3.

An important aspect of the design of a VIDA cell is a balance among the mass flow of secondary droplets, the rate at which the vapor is condensed on the cool interior surfaces of the cell, and the delivery rate of liquid back to the driver. The results shown in Fig. 3 are useful in determining the correct balance. They show that the smaller diameter drivers are more forgiving in the reliable production of secondary droplets. For example, the acceptable range of frequencies that will produce droplets is wider for low water volumes and for small diameter drivers.

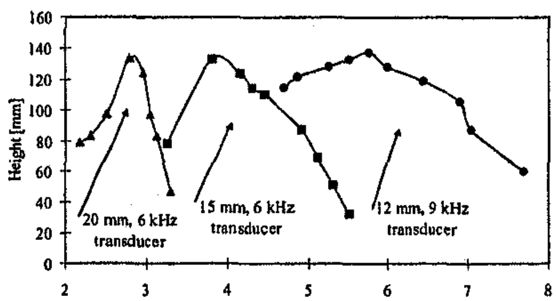


Figure 4: Maximum projection height of droplets as a function of driver frequency

In addition to understanding the input conditions that are required to create the VIDA process, the maximum height and diameter of the secondary droplets is needed in order to design a successful VIDA heat transfer cell. Figure 4 shows maximum height that the droplets are propelled for the same size transducers that were used for the test results shown in Fig. 3. The maximum height was recorded as a function of frequency while the applied voltage was held constant at 25 Volts AC for all cases. The primary droplet volume was varied to allow droplet atomization at different frequencies. For all three transducer sizes, the height curves varied with a similar pattern. The droplet height increased as the driving frequency was increased until a maximum level was reached and further increases in frequency caused a drop in height. All three transducers produced approximately the same maximum droplet height of about 135mm. Also, the maximum droplet height was not the same at the same frequencies for different transducers. As the transducer size decreased, the range of frequencies that produced droplets near the maximum height increased.

The results shown in Fig. 4 indicate that the droplets can be projected with sufficient energy to penetrate any vapor layer that may surround the heated surface. Experimental results support this conclusion, because in cases when the breakup of the primary drop occurs, the heater surface is always covered with a thin liquid layer.

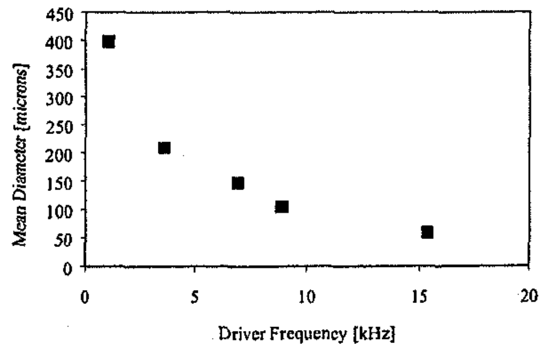


Figure 5: Secondary droplet mean diameter as a function of driver frequency

Measurements of the secondary droplet size distribution were carried out by means of image processing [8]. High-speed video equipment was used to capture the size distribution of the secondary droplets when a laser sheet illuminated the vertical plane through the center of the primary droplet. The primary droplet was then atomized, and videotape was used to record the event. Selected frames of the videotape were digitized so that the diameter of individual droplets could be measured. The thickness of the laser sheet varied from 1mm for the lowest frequency to 200μm for the highest frequency in order to capture the entire droplet diameter with the laser sheer. Software was used to determine the edge of the droplets as well as the number of pixels within droplet. The droplet size was calculated based on the resolution of the image. The mean diameter within the spray of secondary droplets was invariant during the atomization process. Also, the size of the primary droplet had no effect on the mean diameter of the secondary droplets that were produced during the atomization process. Experiments for the four volumes of *the primary droplet (20, 50, 100, and 150 μL) show that the* variation of the mean droplet size is smaller than the resolution of diameter measurement. The parameter that had the greatest influence on the size distribution within the spray was the applied frequency. Figure 5 shows the mean diameter of the spray droplets ranged from 390μm for primary droplets that were produced at a frequency of 1kHz, and the droplet diameter exponentially decreased to a diameter of 60μm for a driving frequency of 15kHz.

Further VIDA quantification tests were completed using a pump to supply water at a constant flow rate to the surface of the piezoelectric transducer. These experiments indicated that the VIDA process was capable of creating a continual spray on a flat surface located above the transducer, provided the applied frequency was capable of breaking the primary drop into a spray. Overloading of the piezoelectric driver with excess liquid can cause the VIDA process to cease operation. However, the VIDA process has continued successfully for up to 60 hours. At this point in the development of the VIDA process, the exact lifetime of a VIDA piezoelectric actuator is not known. The results of these endurance tests are important, because the success of a closed heat transfer cell depends upon the continual production of secondary droplets.

VIDA HEAT TRANSFER CELL

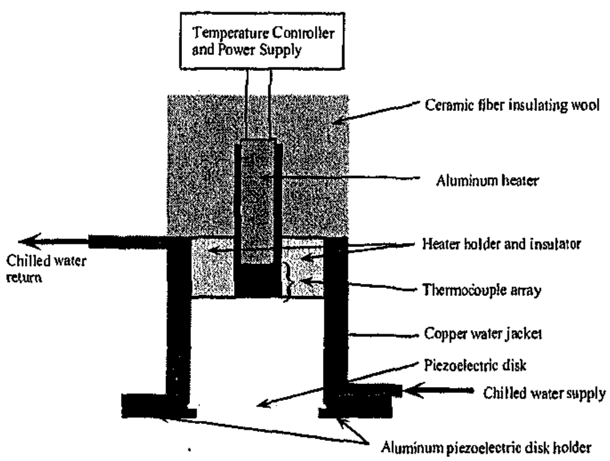


Figure 6: VIDA heat transfer cell with water jacket

Once the VIDA process was characterized, a closed heat transfer cell that incorporates a piezoelectric transducer was designed. A simplified version of an initial VIDA heat transfer cell is shown in Fig. 6. Two concentric copper tubes were used to create a water jacket. Cold water was continually circulated through the annular space to provide a low thermal resistance path between the condensing vapor on the inside of the tube and the circulating water on the outside of the tube. A 38mm diameter aluminum piezoelectric transducer was clamped to the bottom of the inner tube that was 35mm in diameter. A calibrated heat source was held in place with an insulating ring and was placed 25mm above the transducer. This heat source consisted of a cartridge heater placed in an aluminum cylinder with three sets of four equally spaced thermocouples inserted below the cartridge heater. By measuring the temperature distribution and assuming a one-dimensional conduction section within the heater, the surface temperature of the heater as well as the applied heat flux to the VIDA heat transfer cell were determined. The power into the heat source was controlled with a temperature controller to provide a constant heater surface temperature.

The VIDA heat transfer cell was filled with 5mL of water, the piezoelectric transducer was driven at 0.825kHz and 25 Volts AC, and the VIDA heat transfer cell was operated for over eight hours. During the experiment the heater surface temperature was varied, and the heat flux was measured as a function of surface temperature (see Fig. 7). The surface temperature varied from 105 to 130°C, while the heat flux on the heater surface remained close to 40W/cm^2. Standard uncertainty analysis determined the heat flux measurements were accurate to within 7% and the extrapolated surface temperature was within ±1°C of the value reported.

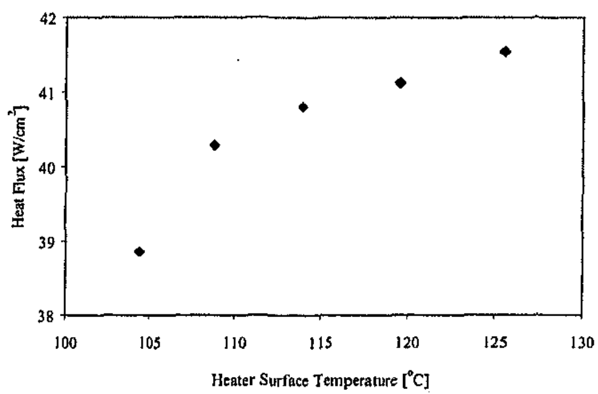


Figure 7: Heat transfer characteristics of a simple water-filled VIDA cell

Since this level of heat flux is in the range of heat removal expected of most modern microelectronic packages, a thermal management device based on the VIDA principle is a viable method to cool microelectronic packages. However, the surface temperatures measured in these initial tests are slightly above those that are acceptable for many microelectronic applications. Tests are currently being carried out with cells that operate at lower pressures. In these tests the saturation temperature of the water is reduced and the maximum temperature of the package can be likewise reduced to more acceptable levels.

CONCLUSIONS

A new heat transfer cell suitable for cooling small microelectronic packages is proposed which is based on a droplet atomization mechanism. A vibrating driver provides a continual generation 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 produced vapor condenses on the interior surfaces of the cell. The condensed liquid returns to the driver where it is re-atomized.

Initial tests with small piezoelectric actuators and water as the working fluid have produced continual sprays from mm sized primary drops such that the atomized droplets are in the range of 70 - 400μm in diameter. The generated droplets have sufficient energy to travel a vertical distance up to about 135mm. Therefore the driver that produces the droplets and the heated surface can be separated in a working cell. Initial heat transfer results utilizing water and a simple cell design have shown that a cell based on the VIDA process can provide a heat flux of about 40 W/cm^2. These preliminary tests have indicated that a VIDA-based heat transfer cell has a potential to provide inexpensive cooling of small-scale electronic devices and the cooling capabilities are within the range required for most modern package designs.

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