Micro Heat Spreader Enhanced Heat Transfer in MCMs DEC 27 1994

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Abstract

The peak thermal power generated in microelectronics assemblies has risen from less than 1 W/cm^2 in 1980 to greater than 40 W/cm^2 today, due primarily to increasing densities at both the IC and packaging levels. We have demonstrated enhanced heat transfer in a prototype Si substrate with a backside micro heat channel structure. Unlike conventional micro heat pipes, these channels are biaxial with a greater capacity for fluid transfer. Thermal modeling and preliminary experiments have shown an equivalent increase in substrate thermal conductivity to over $500 \text{ W/m}\cdot\text{K}$, or a four times improvement. Optimization of the structure and alternative liquids will further increase the thermal conductivity of the micro heat channel substrate with the objective being polycrystalline diamond, or about $1200 \text{ W/m}\cdot\text{K}$. The crucial design parameters for the micro heat channel system and the thermal characteristics of the system will be covered.

1. Introduction

The high power densities prevailing in today's assemblies cannot be adequately dissipated by conventional alumina MCM substrates, which only have thermal conductivity adequate to manage heating of approximately 1 W/cm^2 . Higher conductivity materials such as aluminum nitride ceramic, silicon crystal, tungsten copper alloy, or polycrystalline diamond improve upon traditional substrate materials but can be both expensive and difficult to implement. However, Si substrates with embedded micro heat pipes have the potential to couple the superior thermal characteristics of more expensive substrate technologies with the cost savings associated with IC batch processing techniques. This substrate would have the benefit of matching the IC's thermal expansion coefficient allowing high reliability during temperature cycling. The micro heat channels can also be fabricated using some of the same processes and technology from which the integrated circuit is made and assembled. The low expense of this all silicon, passive approach to thermal

management could have broad applications in the commercial electronics industry.

Micro heat spreaders, like micro heat pipes, transfer energy through the evaporation and condensation of an intermediate fluid, thus redistributing the fluid's heat of vaporization. As heat is applied to the evaporator region of the device, fluid in the channel vaporizes consequently removing the heat. The vapor travels through the vapor channels to the condenser region of the structure where the heat is released during condensation. The fluid is then transported back to the evaporator region by the capillary pumping action of the wick. This mechanism allows for the heat produced by the ICs to be more evenly distributed throughout the substrate and effectively transferred to a heat sink, thus improving the reliability and performance of the product.

Fig. 1. Conceptual design of a micro heat spreader.

A micro heat pipe, by convention, is a wickless, non-circular channel with a diameter of 10-500 micrometers and a length of about 10-20 millimeters, [1]. A fraction of the pipe is filled with a working fluid and the pipe is sealed. Since only the corners provide capillary pumping, the capillary force supplied may not be large enough to pump a sufficient amount of liquid back to the evaporator, [2]. However, unlike conventional micro heat pipe structures, a micro heat spreader utilizes an arrayed wick structure for fluid transport. The vapor returns via an

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independently etched channel, therefore differentiating the heat spreader from heat pipes, which utilize a single channel for fluid and vapor transport. The array structure allows for more efficient fluid transport by providing multiple paths for flow, while also increasing the surface area of the evaporator region. The separately etched wells provide large passages for vapor transport. Experiments are ongoing to determine the optimal substrate geometry for this technique. This system modifies a passive substrate into an effective heat spreader or channel regardless of heat sink location.

2. Fabrication

The focus of the work to date has been on investigating the wicking properties and thermal transfer characteristics of a Si wick structure. The processes described in this section have been developed and successfully demonstrated separately. Subsequent work will concentrate on integration of the steps into a single process for micro heat spreader production.

The module begins as two separate wafers. One wafer is prepared for the wick structure and the second for etching of vapor passages. After completion of the independent processes, the two wafers are bonded together. It is then necessary to seal the edges and charge the cavity through an evacuation and fill port. Later modules will be fabricated with confined wicking areas and will not require edge sealing. The final step is covering the port to provide a hermetic seal. The entire process is performed at the wafer level to leverage IC production equipment and processes. In subsequent designs, completed individual modules of typical size (1 in. x 1 in.; 1 in. x 2 in.) can then be cut out of the wafer. A more thorough description of the individual process steps follows.

2.1. The wick structure

Calculations and modeling based on standard heat pipe design formulas were applied in determining the wick structures, [3]. From these calculations it was learned that Si pillars with geometries in the 0.0015 to 0.003 in. range would provide the desired fluid flow and thermal transfer characteristics. However, the wicks need not be limited to this range to operate effectively. Several techniques for wick fabrication were then performed. The first process utilized IC fabrication techniques including photolithography and wet chemical etching. Since new photolithography masks can be fairly expensive, an existing mask using a 0.010 in. square pattern, spaced 0.010 in. apart (resembling a checkerboard), was patterned

onto CVD nitride. The wafers were then etched in KOH with the intention of forming uniform Si pillars. However, the nitride was undercut before the desired depth was reached, and the resulting pillars were unsuitable for wicking. Dry etch techniques were also investigated including reactive ion etching and deep etch x-ray lithography and subsequent etching, but proved to be prohibitively costly and complex. A second process investigated wick fabrication using a KOH etch in (110) Si with a 30° offset. This process provided deep, straight channels 0.0004 in. wide and approximately 0.003 in. deep, but due to the crystal orientation of the Si, it was not possible to etch perpendicular channels to create the necessary array.

The chosen technique for wick formation utilized a diamond saw to cut the necessary grooves into the wafer. A 0.0022 in. wide blade was chosen to provide a groove approximately 0.0028 - 0.003 in. wide. The depth of the cut was set to 0.003 in. as well. The wafer was sawed completely in one direction and then turned 90° to complete the array pattern. Fig. 2. To insure the cleanliness required for subsequent process steps, the wafers and wafer dicing equipment were treated and cleaned prior to each new wafer.

Fig. 2. SEM of sawed wick structure.

Wafers to be sawed are prepared by performing a piranha clean (5:1 sulfuric acid:hydrogen peroxide) followed by an oxidation process resulting in approximately 2000 Å of thermal oxide. The wafer dicing equipment is thoroughly cleaned using isopropyl alcohol, and a new saw blade is installed. Finally, to minimize contamination from the dicing stage, a second wafer and protective wafer mounting tape are placed between the wafer to be sawed and the stage.

2.2. The vapor return channels/wells

Unlike conventional micro heat pipes, the vapor return paths in this module are independent of the liquid carrying wicks. Because IC processing is utilized in the formation of the channels or wells, practically any geometry is attainable. Initial designs include long, narrow channels (4 in. x 0.3125 in. x 0.010 (deep)) to supplement earlier wicking experiments, Fig. 3., and square wells to approximate MCM geometry.

Fig. 3. Vapor return channel bonded to substrate.

Wafers first receive a piranha clean and then are deposited with 1400 Å of nitride. The wafers are photopatterned with the desired geometry, and the nitride is dry etched in the locations of the channels or wells. The photoresist is then stripped, and the wafers are placed in an 8M solution of KOH at 85 °C. The time in the etchant is dependent on the desired etch depth. The approximate etch rate of this solution is 75 μm/hour. After the wafer has been etched, the nitride is removed in a hydrofluoric acid solution and the wafers again receive a piranha clean.

2.3. Bonding

Once the array pattern is cut and the vapor passages are etched, the wafers are ready to be bonded. This bonding is achieved using boron-phosphorous-silicate glass (BPSG). The previously etched wafer (with vapor passages) is first deposited with 1 μm of 5/5 (5% boron, 5% phosphorous) BPSG in a LAM Integrity deposition system. Both wafers then undergo a piranha clean just prior to bonding to insure clean surfaces. The wafers are rinsed, dried, and then carefully positioned together polished side to polished side. The wafer pair is then placed in a VTR furnace at 800 °C in an O₂ environment

for approximately 30 minutes. This technique provides an excellent bond between the wafers.

Samples using etched patterns on one wafer and an etched well with an evacuation port on the other wafer were bonded and tested using a He leak detector. The samples were found to be hermetic down to the lowest limit of the detector (10^{-8} std cm³/s). Additional experiments were conducted to establish the bonding characteristics of the sawed arrays. A blank wafer and one with the sawed array were prepared. Again the bonding results were excellent, Fig. 4. Bonding will subsequently be performed between a wafer with the sawed array and one with vapor passages. The edges will be sealed using epoxies or other compatible materials utilized in assembly processes.

Fig. 4. Cross section of bonded wick structure.

3. Experimental setup

The structure described in the previous sections is the desired micro heat channel structure for MCM applications. However, prior to manufacturing a complete system, it was necessary to fabricate the individual portions (i.e. wick, well, bonding) to understand the fundamental workings of such a system. Our initial, and indeed primary, focus was on the wick structure. The wick structures were fabricated onto both 0.012 in. and 0.026 in. thick silicon wafers. The decision to examine two thicknesses was based on wafer availability and interest in the effect of Si thickness on heat transfer in this structure. To minimize heat transfer due to conduction in the Si, the 0.012 in. thick wafers were used in the experiments. These wafers were then cut into strips approximately 3.7 in. long x 0.5 in. wide. The length of the strips allowed analysis and measurement of the wick structure from a variety of distances to the fluid bath. The width was

chosen to accommodate the ATC03 (Assembly Test Chip) dimensions and to ease assembly of the test fixture. Control strips using bare, oxidized Si of the same dimensions were also cut from 0.012 in. and 0.026 in. wafers. An ATC03 was attached to one end of each of the strips using DuPont 5504 epoxy using a standard cure. The strips to be tested were then mounted to a test fixture as shown in Fig. 5. The test fixture consists of an epoxy resin PC board with narrow bands attached to the main board used to hold the silicon strips in place. Between the test strips and the test fixture are small brass pins that provide a moderate degree of thermal isolation. Cutouts in the board behind the Si strips allow for visual observation of the wicking action.

Fig. 5. Test fixture.

Measuring 0.25 in. per side, the ATC03 die, developed at Sandia, is used both as a heat source and a thermometer in this experiment, [4]. The ATC03 is a third generation chip used to measure a number of packaging and assembly related variables including mechanical stress, temperature, Al corrosion, in addition to providing chip self heating. Four 50 ohm polysilicon resistance heaters provide the heat source and a diode thermometer allows for convenient measurement of die temperature. A diode thermometer from the same lot and wafer as those mounted on the strips was calibrated at temperatures of 25, 50, 75, 100, 125 and 150 °C in a Delta model 9023 oven using a 10 uA current source. A linear approximation of diode voltage to temperature was assumed and this data

was then used to compute changes in die temperature during the experiment. A Luxtron fluoroptic temperature sensor with a 0.050 in. probe tip was also employed during this experiment to provide a reference temperature for the diode temperature calculations and to verify the calculations. Recently a FLIR IQ 325 Thermal Video System was added to the suite of diagnostics.

The electrical connections to the ATC03 die used in this experiment are shown in Fig. 6. The four polysilicon heaters on each ATC03 were connected in a series-parallel fashion, and a Hewlett-Packard 6627A system DC power supply, in remote sensing mode, was used to supply power to the heaters. A computer program was written to control the power output of the 6627A power supply. A Keithley model 220 programmable current source was used to provide the forward diode thermometer current (10 uA). The forward diode voltage was measured by a Fluke model 87 DVM. The entire setup was duplicated for each Si strip in the test fixture.

Fig. 6. Electrical Connections to ATC03

The test fixture was suspended, with the free ends of the strips down, into a fluid bath. The test fixture height was adjusted until the desired center-of-die to fluid distance (effective strip length) was obtained. The fluid provides both a fixed temperature heat sink and also allows saturation of the wick. The fluid was allowed to come to ambient temperature before any tests were begun. A large volume of fluid (approx. 750 ml) was used to minimize the change in fluid temperature during the course of any of the experiments to <2 °C.

The test fixture and experimental setup were designed to provide a comparative analysis between the wicked and control substrates. Therefore, the precise temperature differential between the bath and the end of the strips and convection to the surrounding air can be factored out in the experiment. The comparison between wicked and control

strips should have similar thermal and convective effects for each strip.

3.1. Wicking experiments

Initial tests, with no power applied to the strips, were performed to determine if the Si array would wick and if so, which fluid would provide the best wicking action. One end of each strip was immersed into a fluid bath and the resulting wicked height as a function of time was recorded, Fig. 7. The plateaus indicate the point at which the capillary pumping action of the wicks is overcome by the evaporation of the fluid. Given the test results, ESH (safety) concerns in the laboratory, and ease of handling during experimentation, deionized water proved to be the best choice for the wicking fluid. However, this will not necessarily be the case for an enclosed, hermetic micro heat channel. These tests will be repeated on subsequent designs. One problem observed with the wicks was an inability to wet up. Since Si is hydrophobic, it was necessary to oxidize (SiO_2 is hydrophilic) the strips to induce wetability after the grooves were cut. A 5 min. piranha clean resolved the wetting problem and also removed some of the silicon debris that was left by the wafer saw.

Fig. 7. Wicking of various fluids.

3.2. Effect of an applied heat source

The variation in die temperature for both wicked and control 0.012 in. silicon test strips with an effective strip length of 1.4 in. as a function of power is shown in Fig. 8. As chip power is increased in the control case, die temperature increases fairly linearly. In the wicked case however, evaporation of the working fluid (DI water) keeps the die below the boiling point of the working fluid until wick dryout begins between 4 and 4.5 W. At this

point, the die temperature suddenly increases and the slope of the curve begins to approach that of the control strip.

Fig. 8. Temperature vs. power for wicked and control substrates.

3.3. Effects of strip length and orientation

Due to the effects of gravity, the length of the heat spreader has less influence on the wicking action when operated in a horizontal orientation compared to a vertical orientation. All of the experiments to date have been performed in a vertical orientation which should produce the worst case wicking action. For a wicked test strip in a vertical orientation at a constant power, increasing the effective strip length increases the temperature of the strip, Fig. 9.

Fig. 9. Temperature vs. effective strip length at 4 W.

By shortening the effective strip length to reduce the effects of gravity and flow resistance, higher powers may be applied to the die before dryout occurs. An effective strip length of 1.0 in. at a power of 8.0 Watts gives an effective thermal conductivity of 570 W/m-K for the wicked strip. At the same power, an effective thermal conductivity of 161 W/m-K is calculated for the control strip. The effective thermal conductivity of the wicked

strip increases uniformly as heating power is increased due to increased wicked fluid flow and evaporation. Once the strip begins to dryout, however, it fails to provide as great a degree of cooling.

The angle of the test strips with respect to the fluid surface was varied to determine the effect of strip orientation on wicking action. Fig. 10 shows the effect of strip orientation using 0.012 in. strips with an effective strip length of 1.0 in. using methanol as the working fluid. Methanol was used instead of DI water for this test because the effects of changing the strip orientation in water were minimal. As predicted, when the strip is moved from a vertical position to a horizontal one, the heat removing properties of the wick structure are enhanced.

Fig. 10. Temperature vs. power for different strip orientations.

4. Modeling of the heat spreader

Two-dimensional fluid flow and heat transfer simulations were performed to determine the maximum allowed heat flux that can be imposed without exceeding the capillary pumping ability of the Si wick structure, [5]. A finite element computer program was developed to model the wick structure. The modeling was performed to simulate an enclosed, hermetically sealed wick structure. The computer model was developed assuming the wick structure would be operated in a vacuum, and that no heat would be lost to the test fixture. The actual experiments were performed under ambient conditions and some heat loss to the test fixture was assumed.

As hypothesized and later verified experimentally, the computer model predicted that the heat spreader would not perform well in a vertical position unless the effective wick length was decreased. The capillary pumping capability of the wick is insufficient to overcome the gravitational pressure drop without a reduction in the effective strip length. The computer model also predicted

that a test strip in a horizontal orientation provides greater heat flux levels than one in a vertical orientation.

Further simulations were performed to determine the effects of widening the test strips as well as eliminating the cross-cut grooves thus forcing the flow to be one dimensional (micro heat pipe). The model predicted that wider substrates enhance the performance of the wicks. It was also found that a large penalty is incurred from elimination of the cross-cut grooves. If the liquid is constrained to flow only in one direction, the area available for liquid flow decreases with a corresponding increase in liquid velocity and frictional pressure drop. Thus, eliminating the cross-cut grooves significantly degrades the performance.

5. Conclusions

Increasing densities at both the IC and packaging levels has led to thermal management problems. An all Si, passive micro heat spreader system has been proposed, and preliminary tests and modeling have shown a potential for efficient heat management using this approach. Subsequent work should further enhance the heat removal characteristics of this system. This approach has the potential to achieve the thermal characteristics of more expensive substrate technologies and utilize low cost IC processing techniques, while improving upon conventional micro heat pipe designs.

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