Development of Thermal Spreading Technology Nowadays

Shung-Wen Kang[a], Meng-Chang Tsai[a], Ming-Tai Weng[b], Chao-Hsiang Hsu[b]

[a]Department of Mechanical and Electro-mechanical Engineering, Tamkang University, 151 Ying-Chuan Rd., Tamsui, 25137, Taiwan.
[2] Foretherma corporation,286 Shihyuan Rd., Dasi Town ship, Taoyuan Conuty, 33551, Taiwan.

Abstract

Thermal spreading is a technology of decreasing the hot spot for electronic cooling and other high heat flux applications, and is characterized by high heat transfer, uniformity of heat removal. Vapor chamber is one of the Thermal spreading technologies which depend on two phase heat pipe technology. This paper provides an introduction to vapor chamber for electronic cooling, high power LEDs, multi heat sources, communication devices, and bio technology applications, reviews the development of thermal spreading technology nowadays, and summarizes the data regarding effects of vapor chamber inside thermal module, future applications, and suggestion. Some models of multi heat sources cooling were also presented.

Introduction

The 30-year-long trend in microelectronics has been to increase both compute speed and power density by scaling of device components (e.g., CMOS switch) [1]. However, this trend will end as we approach the energy barrier due to limits of heat removal capacity. Future electronic systems and power electronics have a large technological change. We believe that in next ten years, the impact of heat removal research will be a key technology in the evolution of the CMOS technology. Thermal management and high heat flux removal technologies will widely use in a system design. High heat flux thermal designs are necessary to maintain lower operating temperatures, which increases the reliability of components and can results in higher performance. Some required characteristics of heat transfer technologies are low cost, minimal and high power input, multi heat sources, and adaptability to a wide range of heat flux. Use of two phase heat transfer technology will become unavoidable as the power dissipation levels increase in future electronic systems.

Possible liquid cooling technologies include single-phase liquid cooling in microchannels, immersion flow boiling, spray cooling, jet impingement cooling, heat pipes, thermosyphons, loop heat pipes, pulsating heat pipes and vapor chamber. Each of the above has advantages and drawback which must be carefully weighed when selecting a system. Of the above cooling technologies, vapor chamber appears to offer the best balance in heat spreading research of high heat removal capability, spreading the hot spot problems, and let the base isothermal of a heat sink. Vapor chamber such like a flat-plate heat pipe used to enhance heat spreading for microelectronic applications. The idea of vapor chamber technology is from micro channel heat spreader. The micro heat pipe (MHP), which was first proposed by T. P. Cotter in 1984 [2], was built to solve the cooling problem of electronic components. Babin et al. (Texas A&D University) presented the triangle microchannel micro heat pipe arrays on silicon wafer to solve the heat problem on semiconductor cooling in 1989 [3]. Shung-Wen Kang's group in Tamkang University also fabricated of star grooves and rhombus grooves micro heat pipe on silicon wafer in 1999 and 2000 , and publish on Journal of Micromechanics and Microengineering in 2002 [4].

A detailed mathematical model of low-temperature axially grooved heat pipes (AGHP) is developed in which the fluid circulation is considered along with the heat and mass transfer processes during evaporation and condensation by Khrustalev, D. and Faghri, A. in 1995 [5]. Cao et al. presented two flat copper-water axially-grooved miniature heat pipes filled with water to be working fluid in 1997 [6]. Benson et al. and Peterson fabricated a number of different wicking structures using silicon dicing saw, conventional anisotropic etching, and deep plasma etching technique (Figure 1) [7-8] in 1998 to 1999.

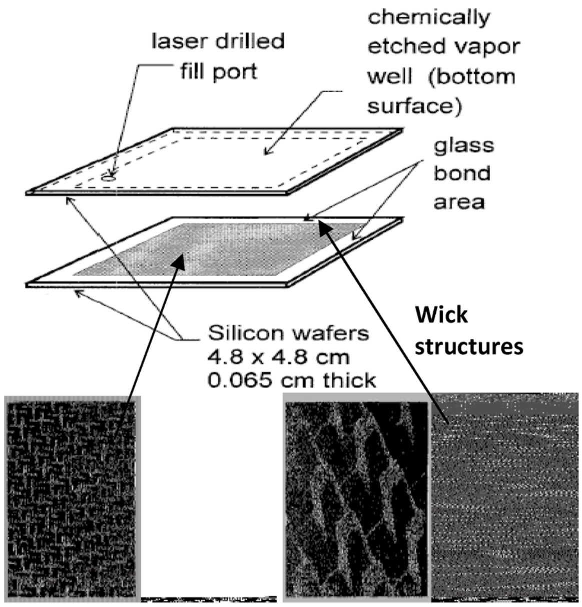

FIGURE 1. Flat plate micro heat spreader [7-8]

Sandia National Laboratories used Kover alloy of iron, cobalt and nickel, and micromachining methods to produce µm scale patterns that act as a wick in these small scale heat pipes. They design and Test of the high performance micro radiation phase change silicon heat spreaders as shown in figure 2 [9]. Shung-Wen Kang et al. used micro channel to make a mini size spreader on silicon named radial grooved micro heat pipes (MHPs) as shown in figure 3 [10].

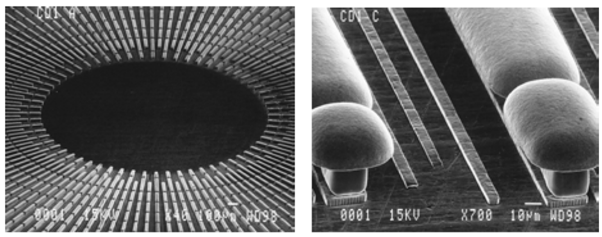

FIGURE 2. Fabrication of micro heat spreader by Kovar metal [9]

978-1-4244-4342-0/09/$25.00

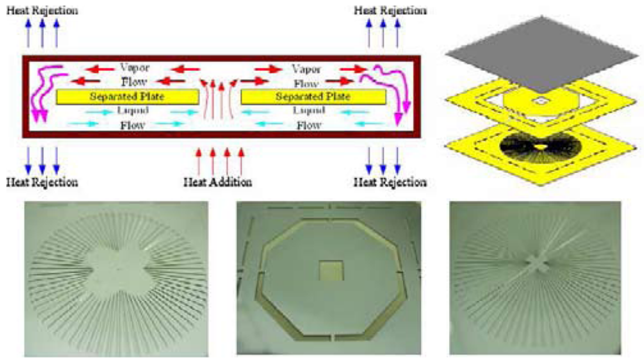

FIGURE 3. Radial grooved micro heat pipes (MHPs) [10]

Novel Concept, Inc. is the earliest company that used fully metal to make a vapor chamber. The vapor chamber is fabricated by traditional machining and chemical etching [11]. The team of D. Khrustalev presents a detailed experimental and theoretical analysis on maximum heat transfer capabilities of two copper-water Flat miniature heat pipes with diagonal trapezoidal micro capillary grooves and one copper-water FMHP with axial rectangular micro capillary grooves shown in [12].

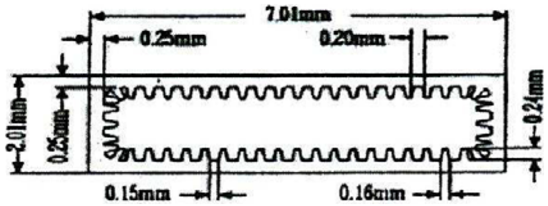

FIGURE 4. Flat miniature heat pipes with diagonal trapezoidal micro capillary grooves

In 2000, Take et al. present a roll bond heat pipe (RBHP) used on notebook computers. This study presents prediction data on maximum capillary limit obtained for the RBHP with 7.8 mm wide flow channel [13]. This is the first metal heat spreader fabricated by aluminum metal, and used 4, 8 and 24 channels which wide by 3 or 7 mm. The size is 270 × 110 mm2 and 0.8 mm thickness, shown in figure 5. The same year, Wang tested a vapor chamber heat spreader which fabricated by copper, and the size is 190.5 × 139.7 × 34.93 mm^3. It used a sinter copper wick, thickness 1.651 mm, to transfer the working fluid [14]. C. B. Sobhan, S. V. Garimella, and V. V. Unnikrishnan simplify the heat pipe model to three parts, core, wick and wall. Used continuum, momentum, energy and conduction equations solve the temperature, pressure and velocity gradient [15]. In 2002, Lin et al. used thin copper bended to be a channel as wick structure, and fabricated a high performance miniature heat pipe which wick structure thickness is 0.1 mm [16], shown in figure 6. In 2003, Kang et al. fabricated a film type heat pipe (FTHP) the size of the undergone research is composed of a single-layer copper net using 65mm×40mm×0.31mm whereas the size of a double-layer copper net using 65mm×40mm×0.51mm [17], shown in figure 7. In 2004, Kang et al. used three layer mesh and grooves structures to fabricated a metallic micro heat pipe heat spreader [18] shown in figure 8. Kang et al. also try to build the obserable envirnment to understand the phenomena inside a vapor chamber heat spreader, shown in figure 9. In 2005, Kang et al. bulid a high performance vapor chamber with triangular grooves [19], shown in figure 10.

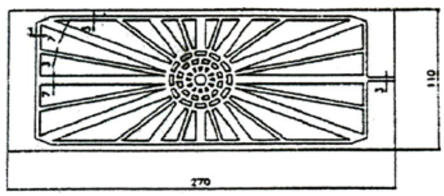

FIGURE 5. A roll bond heat pipe (RBHP) which have 24 capillary grooves [14]

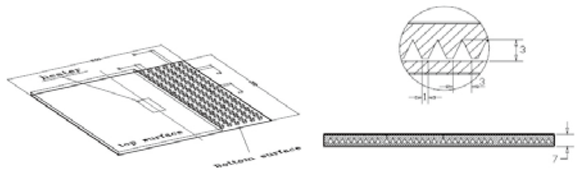

FIGURE 6. A roll bond heat pipe with 24 capillary grooves [16]

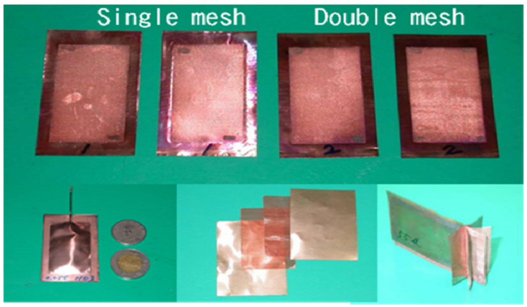

FIGURE 7. FILM TYPE HEAT PIPE (FTHP) [17]

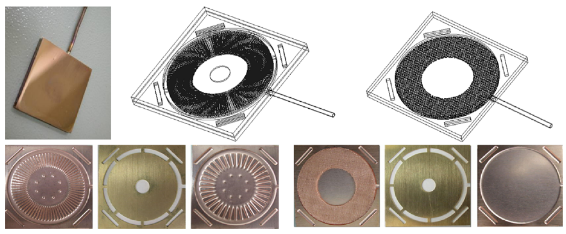

FIGURE 8. MACH SCREEN AND MICRO CHANNELS HEAT SPREADER [18]

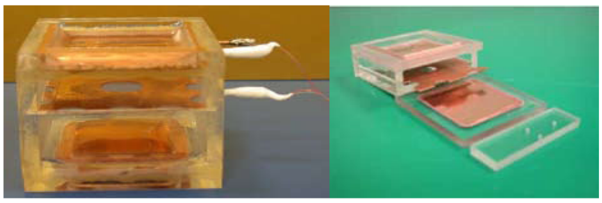

FIGURE 9. Obseration of three layer vapor chamber

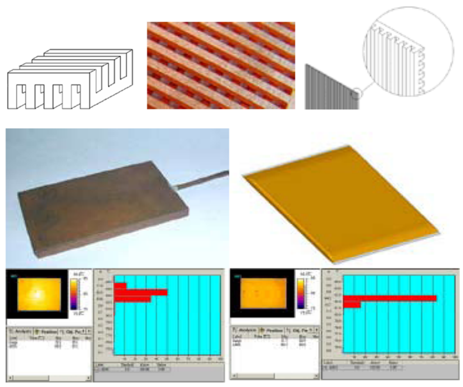

FIGURE 10. High performance vapor chamber with triangular grooves

About other research of vapor chamber such like Jie Wei determined an experiment by a vapor chamber with water as working fluid and sintered metal particles for wick structure. The maximum heat flux measured is approach to 80 W/cm^2 [20]. Koito et al. describes the fundamental experiments on heat transfer characteristics of the heat sink with the vapor chamber [21]. Jeung Sang Go evaluates the thermal performance of an acetone-charged vapor chamber heat sink containing new micro wick structures for cooling microprocessors in PC desktop applications [22]. It also worked successfully for a high heat input of 140W. Mochizuki et al. make many types of vapor chambers having different shapes and sizes used on PC or notebook [23] [24]. Koito et al. carried out a numerical analysis on vapor chamber [25]. From the numerical results, the capillary pressure head necessary to circulate the working fluid is estimated and the temperature drop inside the vapor chamber is determined. Vadakkan et al. used the novel concept of using carbon nanotubes (CNTs) based wick structures for high performance heat pipes and vapor chambers [26]. Individual carbon nanotubes possess extremely high thermal conductivities of the order of 2000 - 3000 W/mK. Wu et al. used vapor chamber on High-Density Blade Servers (HDS) [27]. Koito and Imura try to build the three-dimensional heat transfer mathematical model inside the vapor chamber and the heat sink base plate is computed [28]. Alexandre et al. also finned a heat sink with vapor chamber to test with filling ratios ranging from 10 to 40% of the vapor chamber volume and heat power input from 25 to 200 W [29]. Kang et al. build a vapor chamber and test the performance with different condenser devices of air cooling and water cooling [30]. The other used pulsating/oscillation heat pipe to be a heat spreader idea shown in figure 11 [31].

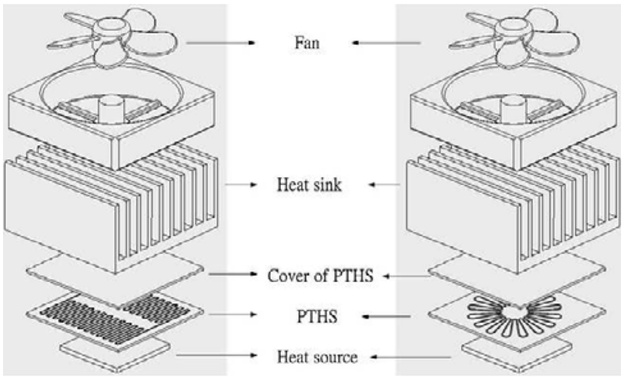

FIGURE 10. Schematic of pulsating/oscillation heat spreader

SCHEMATIC AND EXPERIMENT SETUP OF VAPOR CHAMBER HEAT SPREADER

The most popular heat spreading technology in recent year is the vapor chamber technology. The vapor chamber is divided into three components: closed metal wall, wick structure, and heat sink, respectively. Some time it will put in some support columns to enhance the strength to avoid the deformation by pressure or thermal expand. For example, figure 12 shows the schematic of a vapor chamber which have two different type of column. The wick column is a porous copper wick structure, which can support that working fluid go back to evaporator more easily. Wick columns made by small copper particles are used as the parts of wick structure. The solid column made by copper which can support the mechanical strength of the vapor chamber. The heat power evaporates fluid in the evaporator section. Vapor flows to the condenser as a result of condensation heat transfer. Working fluid flows back to evaporator from the wick structure channel due to capillary pumping. The fluid flow compensates the deletion of mass due to vaporization in the evaporator section. In general, the vapor chamber is a flat-plate heat pipe which offers a thermal management solution for cooling of high performance electronic devices. The top view of the wick structure inside the vapor chamber shows in Figure 12.

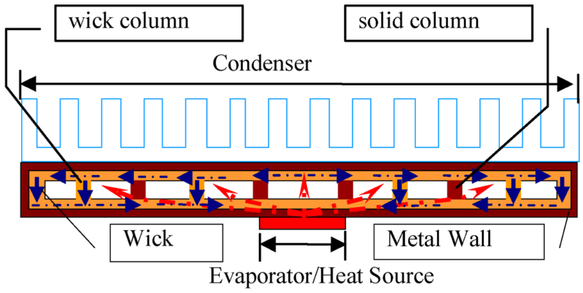

FIGURE 11. Simplified schematic diagram of the vapor chamber-heat sink cross section

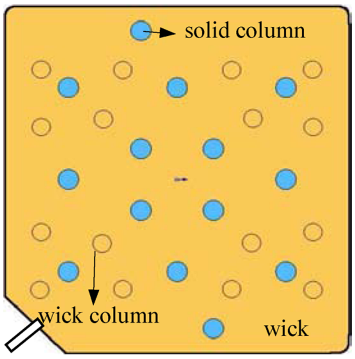

FIGURE 12. The top view of the vapor chamber

The experiment standard of a vapor chamber is very important. What kind factor can symbolize the performance of a vapor chamber? Figure 13 is the cross-section view of the vapor chamber testing. Figure 14 point out the measurement points.

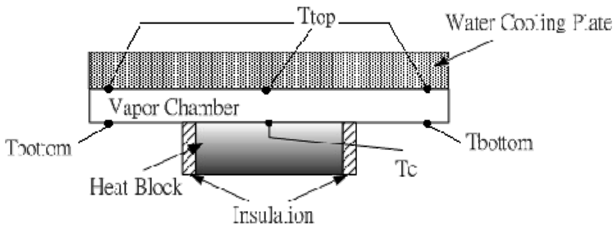

FIGURE 13. Cross-section view of the vapor chamber

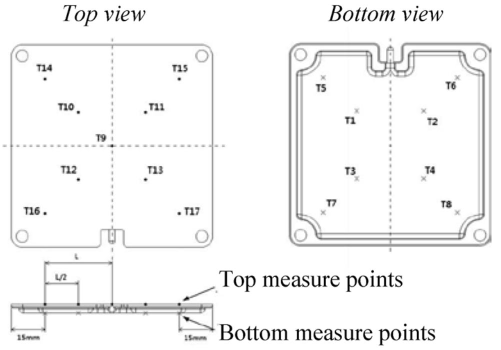

FIGURE 13. The measurement points of the vapor chamber

In a vapor chamber system with adiabatic edges, the total thermal resistance is composed of two terms: one-dimensional resistance and a spreading resistance that vanishes as the source area approaches the vapor chamber size area. Yovanovich et al. obtained a solution for a centrally located heat source on a compound rectangular flux channel [32]. The general solution will depend on several dimensionless geometric and thermal parameters. In general, the total resistance is given by

$$R_T = R_{1D} + R_s \qquad (1)$$

Where R_s is the thermal spreading resistance and R_{1D} is the one dimensional resistance of the system given by

$$R_{1D} = \frac{t}{hA_b} + \frac{1}{hA_b} \quad \text{and} \quad R_s = \frac{\overline{T}_c - \overline{T}_b}{Q} \qquad (2)$$

Which A_b is vapor chamber size area, h is the coefficient of heat convection in the ambient, t is the vapor chamber thickness, $\overline{T}_c$ is the average temperature of the heat source, $\overline{T}_b$ is the average temperature of the vapor chamber bottom area, Q is the heat transfer rate.

From the definition of the spreading resistance, we can definite the resistance of a vapor chamber from figure 14 to 15 given by

$$R_{1D} = \frac{T_b - T_t}{Q} = \frac{\frac{1}{8}\sum_{T1}^{T8} T_b - \frac{1}{9}\sum_{T9}^{T17} T_t}{Q} \qquad (3)$$

$$R_s = \frac{\overline{T}_c - \overline{T}_b}{Q} = \frac{\overline{T}_c - \frac{1}{8}\sum_{T1}^{T8} T_b}{Q} \qquad (4)$$

$$R_{vc} = R_{1D} + R_s = \frac{\overline{T}_c - \frac{1}{9}\sum_{T9}^{T17} T_t}{Q} \qquad (5)$$

A measure of the relative importance of thermal resistance win in a solid body is Biot number Bi, the ratio of the internal to the external resistance, which is defined by the equation

$$Bi = \frac{R_{internal}}{R_{external}} = \frac{\overline{h}L}{k_s} = \frac{\overline{h}t}{k_s} \qquad (6)$$

Where $\overline{h}$ is the average heat transfer coefficient, L is a significant length dimension obtained by dividing the volume of the heat source by its surface area, in a heat spreader is mean the thickness t. ks is the thermal conductivity of the heat source. The error introduced of heat source by the assumption that the temperature at any instant is uniform will be less than 5% when the internal resistance is less than 10% of external surface resistance, that is, when Biot number small than 0.1. The heat source area is thermally simple can be a lump. The average heat source temperature $\overline{T}_c$ is equality to the highest temperature T_c. If Bi large than 0.1, the average heat source temperature $\overline{T}_c$ given by

$$\overline{T}_c = \frac{1}{A_s}\iint_{A_s} T(x,y,0)\,dA_s \qquad (7)$$

FACTORIES

There are many factories are interesting in the vapor chamber technology. Today, many people looking at vapor chamber to solve their problems on server, LEDs, high power density electronic devices and other application which need a uniform surface temperature. The most famous we know as Thermacore Inc., which is the earliest factory can support vapor chamber product named Therma-Base shown in figure 14.

Figure 15 is the largest heat pipe factory, Fujikura Ltd., in Japan. Fujikura Ltd. has cooperation for a long time with Prof. Imura in Kumamoto University. Figure 16 Nanospreader™ fabricated by Celsia Technologies Inc. The ultra thin and flat is the characteristics of Nanospreader™. VAPRO Inc. developed the high performance Liquid Chamber® Technology shown in figure 17. Acmecools Electronic Technology Inc. introduces the tail-free Vapor Chambers shown in figure 18. The main features of vapor chamber in Taiwan have Microloops Corp. and Foretherma Advanced Technology Co. Ltd. Taiwan Microloops Corp. used diffusion bonding technology to welding the single or multi mesh screen to copper base shown in figure 19. Foretherma Advanced Technology Co. Ltd. has their own unique welding technology can fabricated large size flat type vapor chamber and complex steps vapor chamber. Their products named vapor spreader® and shown in figure 20. The other thermal module factories such like Foxconn Technology Co., Ltd., Chaun Choung Technology Corp. (CCI), Yeh-Chiang Technology corp., and ASIA Vital components Co., Ltd. (AVC) etc., also developed vapor chamber used on their thermal modules.

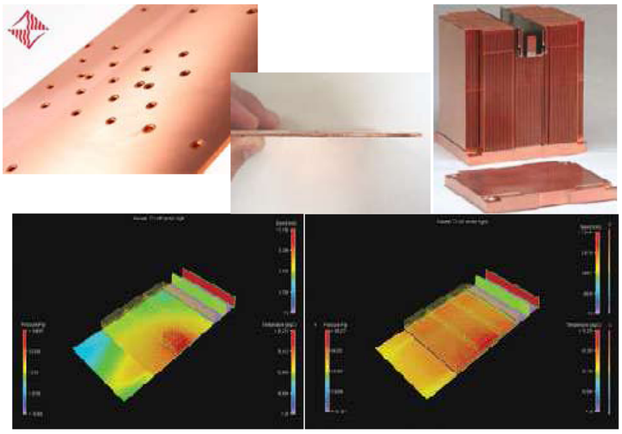

FIGURE 14. Therma-Base™ heat sinks (Thermacore, Inc.) (http://www.thermacore-europe.com)

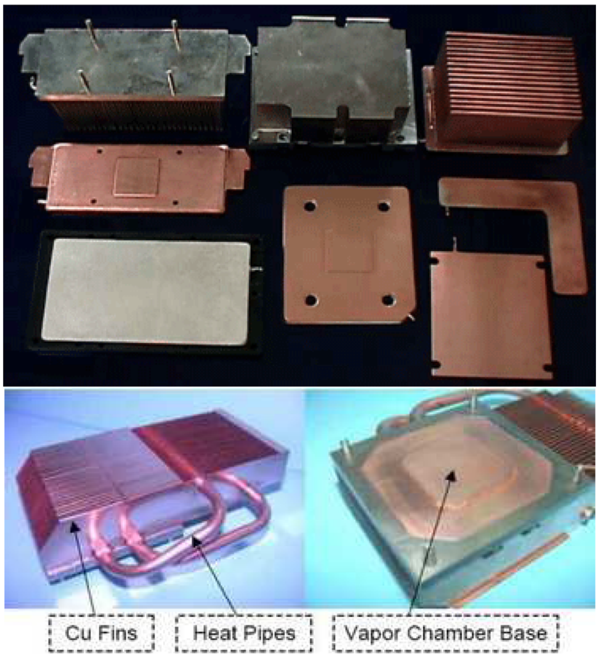

FIGURE 15. Vapor Chamber products (Fujikura Ltd.) (http://www.Fujikura.com)

» Main Memu » Full Papers » Back

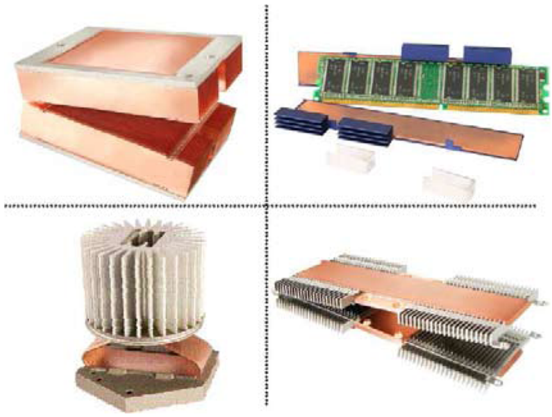

FIGURE 16. Nanospreader™ (Celsia Technologies Inc.) (http://www.celsiatechnologies.com)

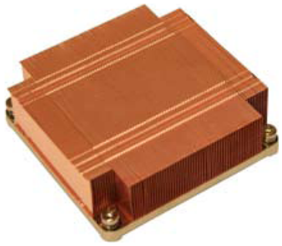

FIGURE 17. Liquid Chamber® (Vapro Inc.) (http://www.vaproinc.com/)

FIGURE 18. Tail-free vapor chamber (Acmecools Electronic Technology Inc.) (http://www.acmecools.com/)

FIGURE 19. Vapor Chamber products (Taiwan Microloops Corp.) (http://www.microloops.com)

FIGURE 20. Vapor Spreader™ Foretherma Advanced Technology Co. Ltd. (http://www.foretherma.com.tw/)

APPLICATION & TEST RESULT

Vapor chamber technology such like a planar heat pipe, or vapor spreader, used as the base of a heat sink, which delivers higher thermal performance than a traditional heat sink by alleviating spreading resistance found in solid heat sink construction. In primarily study, vapor chamber can help to decrease of 42% heat sink total thermal resistance in a cooling system [33]. Simultaneously, vapor chamber can help to decrease the ambient temperature in a multi heat source system effectively. Follows shows applications and results in many different devices supported by Foretherma corp.:

(A) Electronic Cooling (CPU, GPU, and Server)

A common application of vapor chambers in electronics cooling is to place the vapor chamber heat spreader between a small, high heat flux device and a conventional air-cooled heat sink. Without the vapor chamber, only the heat sink area local to the heat source is efficiently utilized because the conduction gradient through the base of the heat sink is very large. With a vapor chamber, the heat from the small heat source is delivered to the entire base of the heat sink with minimal temperature gradients. The isothermal base raises the fin efficiency of the entire heat sink. In primarily study, the smallest bulk thermal resistance will decrease of 42% in an electronic system [34]. The bulk thermal resistance of the vapor chamber unit and heat sources were calculates as follows, which equal to the total resistance present a moment ago [35]:

$$R_b = \frac{T_H - T_{Cond}}{\dot{Q}} \quad (8)$$

Where the heater-evaporator surface interface, T_H, the condenser temperature, T_{cond}, and the heat input, $\dot{Q}$, are all measured quantities.

The experimental cooling tests focus on rectangular vapor chamber and square heater area. Thermal resistance as a function of vapor chamber surface area shows in figure 21. The test used water cooling system, and measured by T type thermocouples (PT-100) setup as figure 13. The input power is 130 watt by 30 mm square, and the cooling water flow rate as 0.5 LPM at 35°C ambient cooling temperatures. From the conclusion of results we can understand the relationship between thermal spreading resistance and surface area. The thermal spreading resistance calculated by equation 4. The engineer can use these results to design CPU, GPU, and Server more easily. Some designs from Foretherma Company of CPU, GPU, and Server shown in figure 22 and 23. Foretherma Company submitted the first one general type vapor chamber module of CPU LGA 1366 standard by Intel at Aug. 2009. This is a nice achievement of vapor chamber used on high performance CPU system.

» Main Memu » Full Papers » Back

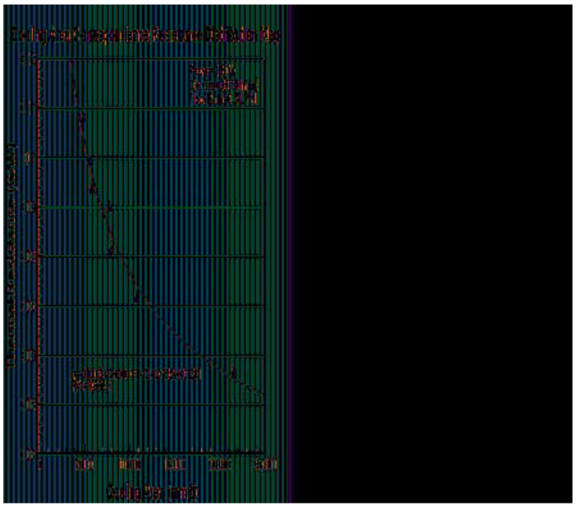

FIGURE 21. Thermal resistance as a function of vapor chamber surface area

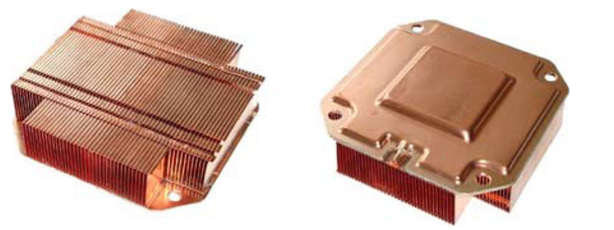

FIGURE 22. The design of vapor spreader™ used on a Server system

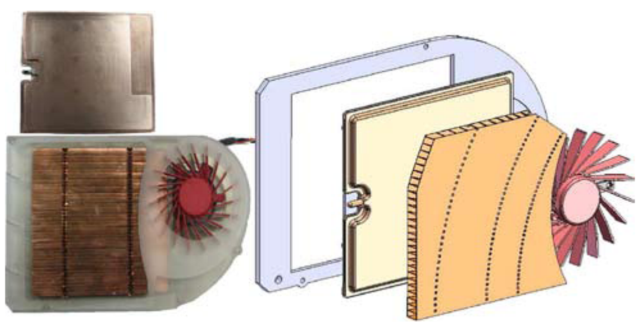

FIGURE 23. The design of vapor spreader™ used on a graphics processing unit (GPU)

(B) Multiple Heat Sources Cooling System (LEDs and Blade Server)

In recent years, with increasing functions of electrical manufactures, we need perfect cooling systems to solve the high temperature problems resulted from interior concentrative power consumption of electrical devices. Especially on multiple heat sources devices such like high power LEDs and multiple cores CPU use on Blade Server system. The vapor chamber heat spreader technology seems to be the best solution to uniform multiple heat sources system with a flat. Figure 24 shows a simulation results by 25 chips high power LEDs used on different base. On the same cooling condition, vapor chamber presented a better performance and uniform temperature description. Figure 25 shows an application design used on a 12core 4chip Blade Server system. The figure 25 is a thermal solution just for one chip of CPU. In a 12core 4chip Blade Server system need 4 unit of thermal solution. There is a special study is used a large space vapor chamber covered on both of two CPU chip directly. The experimental results show that it can average the die and ambient temperature effectively. Figure 26 shows that special application by used one vapor chamber cooler unit to solve two CPU used on 12Core 4Chip Blade Server.

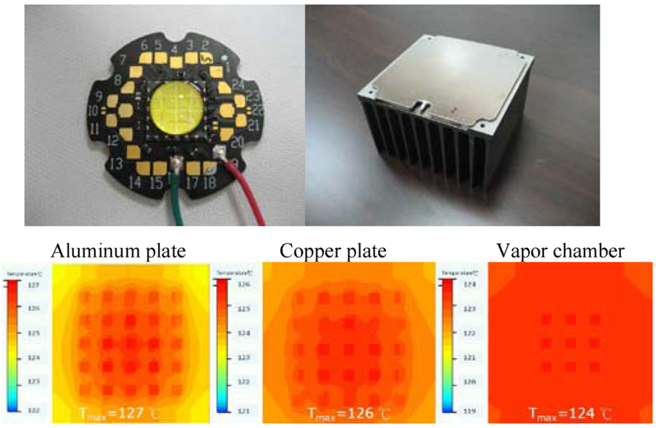

FIGURE 24. Simulaion of Multiple LEDs Cooling solution

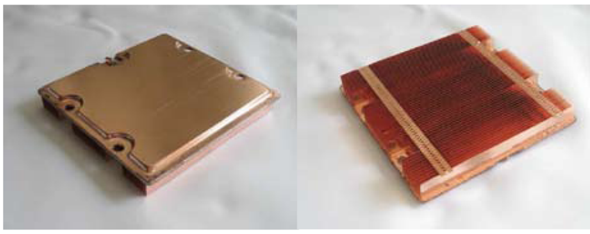

FIGURE 25. One vapor chamber cooler unit used on 12Core 4Chip Blade Server Cooling solution

FIGURE 26. One vapor chamber cooler unit to solve two CPU used on 12Core 4Chip Blade Server Cooling solution

(C) Large size (Industry Computer or Communication devices)

An Industrial PC or A Communication device is an x86 PC-based computing platform for industrial applications. They need handle many different works on one board. The thermal module always base on a large skived or extension fin to solve the heat problems. In order to support larger function in future, Industry Computer and Communication devices need a big vapor chamber to spreader heat problems on a large skived or extension fin plate. The large size skived or extension fin to be a cover on vapor chamber unit is a design rule. Figure 27 shows a Complex Vapor Chamber Communication devices application. It is not only with multiple heat sources but also with complex shape and step layer. The primarily simulation results showed this special device can let temperature spreader quickly, and the temperature under 80 °C with total 84 watt power input. One kind of this type vapor chamber simulation temperature description as figure 28.

» Main Memu » Full Papers » Back

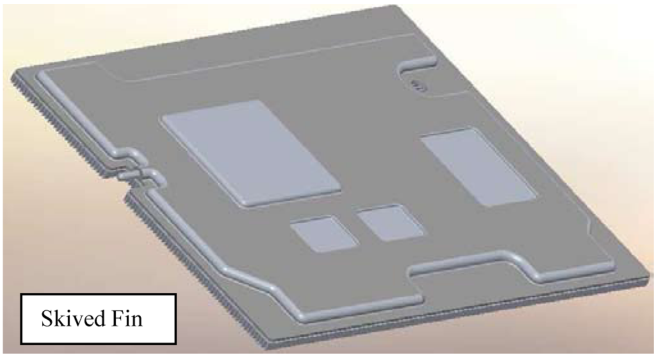

FIGURE 27. Complex Vapor Chamber Communication devices

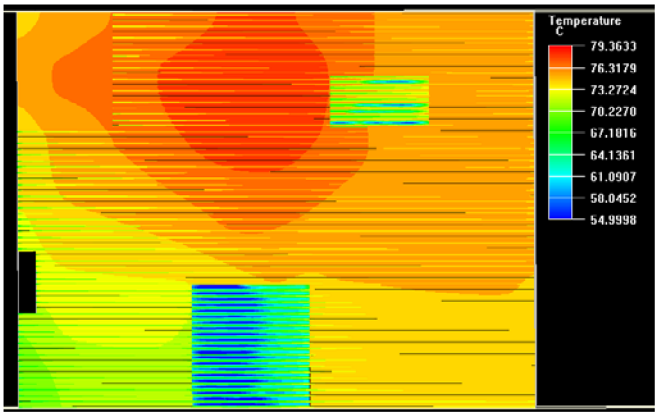

FIGURE 28. Simulation of the temperature of Complex Vapor Chamber Communication devices

(D) Uniform temperature needed (Medical or Biochemical devices)

In some medical or biochemical devices, they need a highly uniform temperature to nurture germs steady and quickly. Sometimes they need to solve instant large power input and make sure the device without broken. At this moment, a vapor chamber unit to make a uniform surface and with highly thermal responds time is very important. Figure 29 shows one kind electronic device by 40 W/cm^2 power input, and use a flat plate heat pipe (vapor chamber) to get a uniform temperature [36].

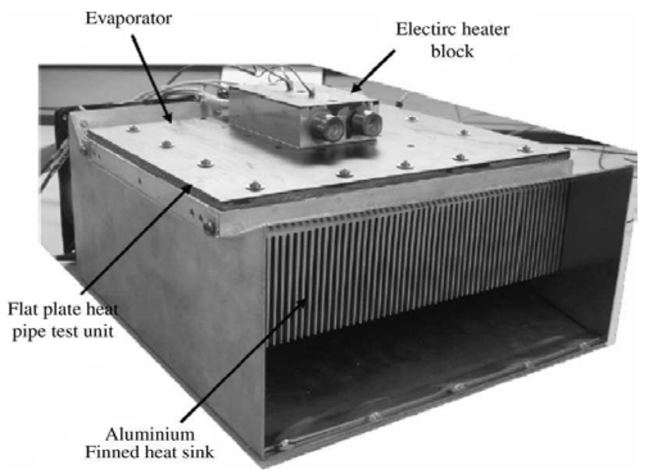

FIGURE 29. The assembly of the flat plate heat pipe[36]

(E) Low power fan-less design

Vapor chamber technology can improve heat sink effectively which has a special application on low power fan-less system. The fan-less design with low power consumption enhances system reliability while reducing both component failure and maintenance. The compact size, rich functionality and power efficiency make PC boards perfect for a broad range of end user embedded applications, such as transportation, surveillance, medical and outdoor applications. Figure 30 shows a fan-less design on high power LEDs application.

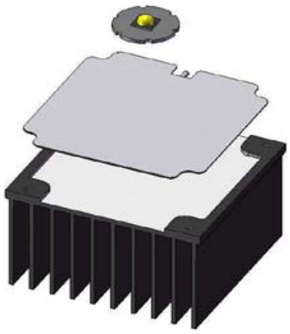

FIGURE 30. Fan-less Design on high power LEDs application

(F) Pulsating spreader (IHS)

An Integrated Heat Spreader (IHS) is the surface used to make contact between a heat sink or other thermal solution and a CPU or GPU processor. IHS size is about 10 times of the processor size base on the assumption that the die size is 10 mm × 10mm. The average thermal spreading resistance between processor chip surface and the HIS is a significant ratio to overall thermal resistance. The mechanical strength and spreading speed is very important to protect CPU or GPU processor without breakage, and spread heat quickly. A disappointing IHS may drop your temperatures that few degrees. The thing we want to gain perfect stability by a new type pulsating spreader.

CONCLUSION

The development of heat spreading technology has not yet exhausted its potentialities. At present five main trends of this development can be distinguished.

1. Thermal reaction time will be an issue for hot spot problem.
2. Multiple heat sources and large size design will be a challenge in different application.
3. Low cost and high performance VC will be two functions in future thermal design.
4. The hybrid vapor chamber witch combines mesh and sinter wick to enhance performance can make a breakthrough in the development of vapor chamber.
5. Fabrication in cold process to get a high mechanical strength heat spreader device will be an issue.

ACKNOWLEDGMENTS

The work was supported by National Science Council of Taiwan, Republic of China under contract no. NSC 98-2622-E-032-004-CC3. Prof. Kang and Mr. Tsai would like to acknowledge the generous support in machining of the vapor chamber free samples supported by Foretherma Advanced Technology Co. Ltd.

REFERENCES

[1] V. V. Zhirnov, R. K. Cavin, J. A. Hutchby, G. I. Bourianoff, *Limits to binary logic switch scaling – a Gedanken model.* Proceedings of the IEEE 91 (11), 2003, pp. 1934-1939.

[2] T. P. Cotter, *Principles and prospects for micro heat pipe*, Proceedings of the 5th International Heat Pipe Conference, Tsukuba, Japan, 1984, pp. 328 – 335.

[3] Babin B. R., Peterson G. P., Wu D., *Analysis and Testing of a Micro Heat Pipe During Steady-State Operation*, Journal of Heat Transfer, 1989, vol. 110, pp. 655-665.

[4] Shung-Wen Kang, Derlin Huang, *Fabrication of star grooves and rhombus grooves micro heat pipe*, Journal of Micromechanics and Microengineering, 2002, 12 (5), pp. 525 – 531.

[5] Khrustalev, D. and Faghri, A., *Thermal Characteristics of Conventional and Flat Miniature Axially Grooved Heat Pipes*, Journal of Heat Transfer, 1995, Vol. 117, pp. 1048–1054.

[6] Cao, Y., Gao, M., Beam, J. and Donovan, B., *Experiments and analyses of flat miniature heat pipes*, J. Thermophysics & Heat Transfer, 1997, vol. 11 , pp. 158-164.

[7] Benson, D.A., Mitchell, R.T., Tuck, M.R., Adkins, D.R., and Palmer, D.W., *Micro-machined Heat Pipes in Silicon MCM Substrates*, Proc. IEEE Multichip Module Conference, 6–7 February, Santa Cruz, CA.

[8] David A. Benson, R. T. Mitchell, M. R. Tuck, D. W. Palmer, and G. P. Peterson, *Ultrahigh-capacity micro machined heat spreaders*, Microscale Thermophys. Engin., 1998, vol. 2, pp. 21–30.

[9] David A. Benson, Charles V. Robino, *Design and testing of metal and silicon heat spreaders with embedded micromachined heat pipes*, 1999, vol. 26-2 , pp.1957-1964.

[10] Shung Wen Kang, Sheng-Hong Tsai, Hong-Chih Chen, *Fabrication and test of radial grooved micro heat pipes*, Applied Thermal Engineering, 2002, vol. 22, issue 14, pp. 1559-1568.

[11] Novel Concepts, Inc. 2240 Union Street, Suite 302 San Francisco, CA 94123 .

[12] Hopkins, R., Faghri, A., Khrustalev, D.,"*Flat miniature heat pipes with micro capillary grooves*," J. of Heat Transfer, 1999, vol. 121, pp. 102-109.

[13] Take, K., Furukawa, Y., Ushioda, S., *Fundamental investigation of roll bond heat pipe as heat spreader plate for notebook computers*, IEEE Trans on components and packaging technologies, 2000, vol. 23, pp. 80-85.

[14] Wang, Y., Vafai, K., *An experimental investigation of the thermal performance of an asymmetrical flat plate heat pipe*, Int J Heat Mass Transfer, 2000, vol. 43, pp. 2657-2668.

[15] C. B. Sobhan, S. V. Garimella, V. V. Unnikrishnan, *A computational model for the transient analysis of flat heat pipes*, 2000, IEEE Thermal and Thermomechanical Phenomena in Electronic Systems, vol. 2, pp. 106-113.

[16] Y. Cao, M. Gao, *Wickless network heat pipes for high heat flux spreading applications*, International Journal of Heat and Mass Transfer, 2002, vol45, pp. 2539-2547.

[17] Shung-Wen Kang, Meng-Chang Tsai, Yu-Hsing Lin, *Fabricationof Film Type Heat Pipe*, The 7th International Heat Pipe Symposium, 2003, October, pp. 294-299.

[18] Shung-Wen Kang , Sheng-Hong Tsai , Ming-Han Ko, *Metallic Micro Heat Pipe Heat Spreader Fabrication*, Applied Thermal Engineering, 2004, Volume 24, pp.299-309.

[19] Sheng-Hong Tsai, Shung-Wen Kang, Y. T. Chen, *A comparison between Triangular Grooves, Star Grooves and Rhombus Grooves in Micro Heat Pipe*, Journal of Chinese Society of Mechanical Engineer, 2006, vol.27, pp. 1– 5.

[20] Jie Wei, *Measurement of Vapor Chamber Performance*, Proc. of 19th IEEE SEMI-THEW Symposium, 2003, pp. 191-194.

[21] Y. Koito, K. Motomatsu, H. Imura, M. Mochizuki, Y. Saito, *Fundamental Investigations on Heat Transfer Characteristics of Heat Sinks with a Vapor Chamber*, Proc. of 7th International IHPS, Korea, 2003, pp.247-251.

[22] J. Sang Go, *Quantitative thermal performance evaluation of a cost-effective vapor chamber heat sink containing a metal-etched microwick structure for advanced microprocessor cooling*, Sensors and Actuators , A 121, 2005, 549–556.

[23] F. Kiyooka, Y. Saito, M. Mochizuki, T. Nguyen, Y. kawahara, *A novel thermal solution using vapor chamber technology for cooling high performance desktop CPU in notebook PC*, Proc. of 8th IHPS, Kumamoto, 2006, pp. 222-225.

[24] Y. Koito, H. Imura, M. Mochizuki, S. Torii, F. Kiyooka, *Thermal management of high-power microprocessor units using vapor chamber technology*, Proc. of 13th IHTC, Syendy, 2006b, HEX-31, 11 pages.

[25] Y. Koito, H. Imura, M. Mochizuki, Y. Saito, S. Torii, *Numerical analysis and experimental verification on thermal fluid phenomena in a vapor chamber*, Applied Thermal Engineering, 2006, Vol. 26, pp. 1669 – 1676.

[26] U. Vadakkan, G. M. Chrysler, J. Maveety and M. Tirumala, A *Novel Carbon Nano Tube based Wick Structure for Heat Pipes/Vapor Chambers*, Proc. of 23rd IEEE SEMI-THERM Symposium, 2007, pp.102-104.

[27] X. P. Wu, M. Mochizuki, T. Nguyen,Y. Saito, *Low Profile-High Performance Vapor Chamber Heat Sinks For Cooling High-Density Blade Servers*, Proc. of 23rd IEEE SEMI-THERM Symposium, 2007, pp.174-178.

[28] Y. Koito, H. Imura, *Transient Thermal Characteristics of a Vapor Chamber*, Proc. of 14th International IHPC, Brazil, 2007, pp.233-238.

[29] S. Oliveira Alexandre, B. H. Mantelli Márcia, H. Milanez Fernando, *Use of Vapor Chamber on Electronic Devices to Eliminate Hot Spot Under Fin Heat Sink*, Proc. of 14th International IHPC, Brazil, 2007, pp.239-244.

[30] Meng-Chang Tsai, Kun-Cheng Chien, Chi-Yao Huang, and Shung-Wen Kang, *Thermal Performance of a Vapor Chamber*, The 9th International Heat Pipe Symposium, November, 2008 , Malaysia, pp.86-89.

[31] Yu-Hsing Lin, Kuan-Ting Chen, Po-Hsuan, Shung-Wen Kang, *PCP Pulsating Heat Pipe*, The 9th International Heat Pipe Symposium, 2008, November, Malaysia, pp. 121-125.

[32] Yovanovich, M. M., Muzychka, Y. S., and Culham, J. R., 1999, ''Spreading Resistance of Isoflux Rectangles and Strips on Compound Flux Channels,'' J. Thermophys. Heat Transfer, 13, pp. 495–500.

[33] Meng-Chang Tsai, Kun-Cheng Chien, Chi-Yao Huang, and Shung-Wen Kang, *Thermal Performance of a Vapor Chamber*, The 9th International Heat Pipe Symposium, 2008, November, Malaysia, pp.86-89.

[34] Meng-Chang Tsai, Kun-Cheng Chien, Chi-Yao Huang, and Shung-Wen Kang, *Thermal Performance of a Vapor Chamber*, The 9th International Heat Pipe Symposium, 2008, November, Malaysia, pp.86-89.

[35] M. Adami, B. Yimer, *Development and evaluation of a planar heat pipe for cooling electronic systems*, Chemical Engineering Communications, 1990, vol. 90, pp.57-74.

[36] R. Boukhanouf, A. Haddad, M.T. North, C. Buffone, *Experimental investigation of a flat plate heat pipe performance using IR thermal imaging camera*, Applied Thermal Engineering, 2006, vol. 20, pp. 2148 – 2156.