Heat Transfer Challenges in Semiconductors Processing and The Applications of Heat pipes for Efficient Heat Removal

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Abstract. The rapid developments in electronics and semiconductors processing led to the use of very compact and precise units with relatively large power and excellent performance. But still the temperature sensitivity and control of such special materials are pronounced and hence its cooling is essential for better performance and smooth operation. Moreover, the dimensions of these electronic components are small and the surface available for heat transfer is also small. Hence, compact cooling means are necessary for effective heat removal from these sensitive materials. In the present work, various cooling technologies applied in electronic systems are analysed and discussed in view of their cooling potentials and compactness necessary by semiconductor systems. The heat pipe technology was selected in the present work as an efficient tool for heat removal from electronic chips due to its direct cooling via phase change of the working fluid inside and without any external pumping power. Simplified design calculations are given in the paper for the selected copper-water heat pipe for themal cooling of an electronic system.

Introduction

The invention of the transistor in 1947 and subsequent innovations of integrated circuits triggered the development of today's huge industrial base. The influence brought by the integrated circuit technology is not limited to the industry.

As condensed in the term – information age – all aspects of our life are touched by this new wave of technology.

In fact, electronics and semiconductors have developed to surround all faces of modern life. At the same time with increasing number of applications, reliability has become a real cruciable problem.

No doubt that; for large scale computers, the heat removal from the electronic chips is the major technical problem in achieving higher data processing speeds.

The thermal power dissipation from the electronic chip is about 100 watt/cm^2 and from the module, this value is about 25 watt/cm^2(1). The longer term projects suggest a value of 125 watt/cm^2 for 50 million or a billion components depending upon the compromise between the switching power and the speed. This heat dissipation level is in the range of thermal loading associated with nuclear blast(1). However in that case, the temperature are in excess of 1000 ^{0}C, whereas in electronic system the surface temperature should be maintained between 50- 100 ^{0} C for successful and reliable operation of these systems. This must also be maintained uniformly over the board and considering cost and reliable life restrictions as well. Hence for fast developing electronic technology, it becomes a must for expert people in heat transfer, fluids and control to involve themselves to meet the requirements of the microelectronic technology.

Main problems and challenges in cooling semiconductors and electronic systems

All electronic components from microprocessors to high power converters, generate heat and the rejection of this heat is necessary for their optimal and reliable operation. Thermal control of semiconductors and electronics has been, for the past 50 years, one of the primary areas of application of advanced heat transfer techniques. The growing use of semiconductors and electronics in both military and civilian sectors has led to widespread recognition of the need for thermal packaging and design of these systems and again the benefits of thermal control technology(2).

The main goal of thermal control is to maintain the temperature of the individual elements within their functional and allowable limits. If the operational temperature goes over the design limits, degraded electrical performance and logic errors are very likely to occur.

In order to meet the cooling requirements of microelectronics, we have to find the most efficient thermal paths from heat sources to the ultimate heat sinks. For this purpose, emphasis must be given to find ways of reducing both internal and external resistance. It is worth mentioning that; the dimensions of these electronic components are small as the surface available for heat transfer is also small ; hence compact cooling means are necessary for efficient heat removal form these sensitive materials.

Form the heat transfer point of view, the heat load to be removed from an electronic chip is as much as 500 watt. This load has to be removed at a heat flux of about 50- 100 watt/cm^2 . While for a multi chip module the heat load can reach a large value of 10 kwatt at a heat flux of about 25 watt/cm^3 (due to available of more area for heat transfer in such multi chip modules).More over, the volumetric rate of heat release from these modules can be expected to increase dramatically and approach a value of 10 watt/cm^2 at the same time the surface temperature of silicon chips has to be maintained traditionally at about 65^0 C for commercial computers and at about 110 - 125^0 C for military equipment(3).

In all these environments, the average cooling temperature is at about 30^0 C.Combining all these factors, it would appear that, future thermal control systems will require chip –to- coolant thermal resistance of less than 0.1 k/W, and overall heat transfer coefficient of approximately 10,000 to 30,000 watt/m^2 k (1-3 watt/ cm^2 k) with volumetric heat transfer coefficient greater than 200,000 watt/m^3 k (0.2 watt/cm^3 k).

It is worth mentioning that in developing a thermal management strategy for an electronic product, it is not sufficient to merely limit its temperature as dictated by functions and reliability requirements, but also to eliminate or control the thermally induced failure at work throughout the electronic system.

From the heat transfer point of view, the following questions have to be considered before developing a certain cooing device for electronic equipment or computers.

(a) what geometry has to be assumed for the heat source and the cooing flow path.
(b) How high heat flux is reasonable for the target of research?
(c) Are the currently adopted criteria, namely 85^0 C for the maximum junction temperature and 15^{0}c for the maximum temperature difference in the system, bound to be applied in the future?
(d) What constraints on the selection of coolant and other packaging materials need to be assumed?

It is Important to mention that, heat transfer research “in the area of electronics and computers”, needs to be planned and conducted with a view on such generic questions as “ why does information processing require energy”? and how can we increase the speed and capacity of information processing by hardware design?(4).

In brief cooling electronic equipment is now one of the popular research areas of heat transfer and the number of technical papers is rapidly increasing reflecting the needs of the computer industry.

Cooling Techniques of Electronic Equipments

Various techniques have been used to remove heat from individual electronic devices and electronic systems. These techniques include free and forced gaseous and liquid convection as well as conduction and radiation or any combinations of these means.

Several cooling strategies have been developed for controlling and removing the heat generated in these electronic devices and systems. These include advanced air cooling schemes as the one in the IBM 4381 midrange processor and he Mitsubishi high thermal conduction module(5). Direct cooling without phase change is also used as that applied in the cray–2 super computer while direct cooling with phase change, “in which the electronic package is submerged in a liquid pool”, is also used(5).

From the technical point of view, air cooling is most traditionally used due to its simplicity and its lower cost as well as its ease maintenance. However, it is not capable of high heat removal, especially from large scale equipment.

Form the practical point of views, main cooing techniques of electronics and computer systems are summarized below :

[A] Air cooling – natural convection.

[B] Air cooling – forced convection.

[C] Liquid cooling – direct and indirect devices (using immersion means)

[D] Heat pipes.

Table (1) gives brief information’s about these cooling methods.

Although air cooling is best understood and most frequently used, it is limited in the heat removal rate by the convection coefficient . Moreover direct cooling methods are capable of attaining high heat flux levels, but they present problems with contamination and are extremely expensive .

On the other hand, heat pipes because of their high thermal conductivity provide an essentially isothermal environment with very small temperature gradients between the individual components. Hence, they are an acceptable alternative to the large bulky aluminum or copper fin structures of complex geometric that are currently used in these electronic cooling systems(5).

The high heat transfer characteristics, the ability to maintain constant evaporator temperatures under different heat flux levels and the diversity as well as the variability of evaporator and condenser sizes make the heat pipe an effective device for the thermal control of electronic systems. Hence heat pipes have been proposed and selected as an efficient heat removal tool for semiconductors and electronic equipment.

Heat pipe Operation

A heat pipe is a device that utilizes high latent heat of evaporation or condensation to transfer high heat flux without the addition of an external work. As show in fig.2, the heat pipe is composed of three sections, an evaporator, an adiabatic section and a condenser. A porous capillary wick covers the inside surface and extends over the surface of the pipe. The heat pipe chamber may take on almost any shape “round, square or rectangular” and the wick is designed to be saturated with the liquid phase of the working fluid. The remaining volume of the chamber contains the vapor phase of the working fluid.

At one end, heat is added to the evaporator section, where fluid vaporizes transferring to the other end, condenser, where vapor condenses losing its latent heat to the surroundings. The liquid is then pumped by the action of surface tension through the capillary wick back to the evaporator. The condenser is seperated from the condenser by the adiabatic section. Heat pipes can be called “ super conductors”, where its effective thermal conductance is hundred times greater than those of copper pipe having the same dimensions(2,6,7).

From the heat transfer point of view heat pipes can be designed to operate over a wide range of temperature from cryogenic applications (below 30^0 k) utilizing titanium alloy /nitrogen heat pipes to high temperature applications (above 2000^0 c) using tungsten/silver heat pipes(9).

In electronic cooling applications where it is desirable to maintain junction temperature below 125 - 150 ^{0} C, copper/water heat pipes are typically used(2,5,8).

Heat pipes Design

There are many factors to consider when designing a heat pipe, i.e. compatibility of materials, operating temperature range, diameter of the pipe, power limitations, thermal resistance and operation orientation.

According to various design strategies appeared in literature for heat pipes four types of heat transfer limitations have to be checked for successful design and operation of heat pipes as follows(2,5,6,7,8):-

(A)The capillary limitation ,which is linked to the capillary pumping capability.

(B)The sonic limitation, which is due to the choking of the vapor flow.

(C)The entrainment limitation , which is due to the tearing of the liquid off the liquid vapor interface by the vapor flowing at a high velocity.

(D)The boiling limitation , which deals with the disruption of the liquid flow at the evaporator by nucleate boiling in the wick.

The following expressions are given in literature for these critical limitations :-(2,6,7)

(1) The capillary limitation q_c is given by:-

$$q_c = -\frac{(qL)_c}{(1/2)\,L_c + L_a + (1/2)\,L_e}$$

Where:

$(qL)_c$ = the capillary heat transfer factor defined by(2).

L_c = length of the condenser section.

L_a = length of adiabatic section.

L_e = length of evaporation section.

(2) The sonic limitation q_s is given by

$$q_s = A_v \rho_v \lambda \left[\frac{1}{2(\gamma_v + 1)} \gamma_v R_v T_v \right]^{1/2}$$

Where :

Aυ = area of vapour, m^2

ρ_v = density of vapour, kg/m^3.

λ = Latent heat of vaporigation

γ_v = specific heat ration for vapour

R_v = universal gas constant

T_v = Temperature of v vapour.

(3) the entrainment limitation, q_e is given by

$$q_e = A_v \lambda \left(\frac{\sigma \rho_v}{2r_h} \right)^{1/2}$$

Where:

σ = surface tension, N/m

ρ_v = vapor density, Kg/m3

r_h = the hydraulic radius of the wick pores.

(4) The boiling limitation q_b is given by:

$$q_b = \frac{2\pi l_e k_e T_v \left[2\sigma / r_n - P_{cm}\right]}{\lambda \rho_v \ln\left(r_i / r_v\right)}$$

Where:

k_e = the effective thermal conductivity for liquid saturated wicks.

r_n = the nucleation radius which has a value between 2.54x 10^{-5}m and 2.54x10^{-7}m " as given by Ref (2).

r_i = inner radius for the liquid.

r_v = radius of vapors flow.

P_{cm} = maximum capillary pressure.

It is worth mentioning that, the design issue of heat pipes can be reduced to two major considerations by limiting the selection to copper/water heat pipes for cooling electronic system as recently reported in literature. (8 ,9). These two considerations are the amount of thermal load which can be carried out by the heat pipe and the effective thermal resistance of the considered pipe. Various design limitations of heat pipes are given in Figs 3,4 for the copper/water type which is now recommended for cooling of electronic systems as reported in reference(9).

The Equivalent circuit of Heat Pipes

The temperature drop between the evaporator and the condenser of the heat pipe is of particular importance to the designer especially in the thermal control of electronic systems. This temperature drop can be readily obtained by considering the equivalent circuit (or the electrothermal analoge) of the heat pipe.

The electrothermal circuit is given below in fig. (5) according to the thermal performance analysis given in (2) and (5). As shown in this figure, there are six resistance to the flow of heat from evaporator to the environment as follows:

(1) The resistance of the pipe wall at the evaporator (Rpe).
(2) The resistance of the wick at the evaporator (Rwe).
(3) The resistance of the adiabatic section of the pipe (Ra).
(4) The resistance of the wick at the condenser, (Rwc).
(5) The resistance of the pipe at the condenser (Rpc).
(6) The resistance between the condenser section and the environment, (Rs).

These resistances are usually expressed by the following mathematical formulas .

(1) The wall pipe resistance's at evaporator, Rpe.

$$Rpe = \frac{\mathrm{Ln}\ (do/di)}{2\pi L_e K_m}$$

Where: do = outside diameter of the pipe
di = inside diameter of the pipe.
L_e = length of evaporator section.
K_m = thermal conductivity of pipe wall.

(2) The wick resistance at evaporator, Rwe

$$Rwe = \frac{\mathrm{Ln}\ (di/do)}{2\pi L_e K_e}$$

Where: K_e is the effective conductivity of the wick material.

(3) The adiabatic resistance Ra;

$$Ra = \frac{T_v[P_{ve}-P_{vc}]}{P_v \lambda\ J\ q}$$

Where:
T_υ = Temperature of the vapor.
$P_{\upsilon e}$ = vapor pressure at the evaporator.
$P_{\upsilon c}$ = vapor pressure at the condenser.
ρ_v = density of vapor.
λ = latent heat of vaporization
J = mechanical equivalent of heat « joule constant»

Q = heat flow

(4) The wick resistance at the condenser Rwc

$$Rpe = \frac{Ln\ (di/do\ )}{2\pi L_c K_c}$$

Where L_c = length of condenser section.

(5) The pipe wall resistance at the condenser section, Rpc:

$$Rpc = \frac{Ln\ (do/di\ )}{2\pi L_c K_m}$$

(6) The resistance between the condenser section and the environment :

$$Rs = 1/hS_t$$

Where :

h = heat transfer coefficient between the pipe outer wall and the environment.

S_t = the total surface at the condenser section.

Simplified Design procedure for a selected Heat Pipe Application in cooling an electronic system

In this application a copper-water heat pipe is to be used for the removal of a heat load equal to 75 watt from an electronic system in which the surface temperature of its chips does not exceed 50˚c, while the ambient air temperature is about 40˚c.

The available heat pipe dimensions are 1.27 cm, outside diameter, the vapor diameter is 1 cm, and 30.5 cm length with an evaporation section 5 cm long and similar condensation section of 5 cm length. The wick structure of this pipe is of the powder metal type.

Solution

In order to decide for the feasibility of this heat pipe, we have to calculate its thermal resistance and from it we will find the required ΔT for this pipe to remove the heat load.

Based on the achieved value of ΔT we decide for the surface temperature of the electronic chip.

As reported in literature(9) for the copper water heat pipe of the given dimensions a design value for its specific resistance of the evaporation section can be estimated to be equal to 0.20˚C/(w/cm ^{2}) , while for the axial specific resistance " of the adiabatic section" the design value is about 0.020˚C/(w/cm ^{2}). For the condensation section a similar value of 0.20˚C/(w/cm ^{2}) is also reported for its specific resistance.

The total driving force for this pipe is given by:

$$(\Delta T)_{total} = (\Delta T)_{evap} + (\Delta T)_{cond} + (\Delta T)_{axial}$$

$$= R_{evap}.q_{evap} + R_{cond}.q_{cond} + R_{axial}.q_{axial}$$

$$q_{evap} = \frac{75}{\pi \text{ x } 1.27 \text{ x } 5}$$

$$q_{cond} = q_{evap} = 3.8 \text{ w/cm}^2$$

$$q_{axial} = \frac{75}{(\pi/4) \text{ x } (1)^2}$$

$$= 95.5 \text{ w/cm}^2$$

$$(\Delta T) \text{ total} = (0.20)(3.8) + (0.20)(3.8) + (0.020)(95.5)$$

$$(\Delta T) \text{ total} = 3.43 \text{ ˚C}$$

$$T_h = T_a + (\Delta T)_{total}$$

$$= 40 + 3.43 = 43.43 \text{ ˚C}$$

Hence the surface temperature of the chips will be 43.43 < 50°C, and hence the selected heat pipe will be used effectively for the required thermal controlling of the present electronic chips and its surface temperature will not exceed the design limit.

It is worth mentioning that the copper water heat pipes are recently applied in cooling the pentium processors of the notebook computers(9). The heat pipes are considered the optimum selection as thermal control for these computers due to its small dimensions and its low thermal resistance .

In addition to notebook computer application ,other high power electronics like silicon controlled rectifiers “SCRs” ,insulated gate bipolar transistors “IGBTs” and Thyristors are now utilizing heat pipe devices for cooling. In these high power electronics, heat pipes can remove a heat load up to 5 kW and its typical thermal resistance range from 0.1°C/watt as recently reported (3,4,5,9). Fig.6 indicates a schematic diagram for the utilization of heat pipes in cooling high voltage electronic components as reported in literature(2).

Conclusions

The present work led to the following conclusions :-

(1) The fast developing rate of computers and electronic systems dictates large potential in heat transfer research and innovations to solve its thermal bottleneck problems and to avoid any thermal failure during its processing .

(2) Heat pipes with its small dimensions and efficient thermal performance can be considered among the optimum and reliable cooling devices for semiconductors and electronic systems to enhance the reliability of these components.

(3) The copper - water heat pipes are promising cooling devices for both low and high power electronics and computers especially for relatively hot climate areas like Saudi Arabia; but for other cold environments like western countries other fluids have to be applied like methanol or other low boiling point liquids.

(4) More research work is required especially in materials area to avoid both corrosion and fabrication problems in heat pipe design and installation.

(5) The enhancement tools of heat transfer like use of rough or finned surfaces and forced convection techniques have to be utilized and improved to be suitable and compatible with the electronic devices.

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تحديات عمليات انتقال الحرارة في اشباه الموصلات وتطبيقات الأنبوب الحراري للتخلص من الحرارة

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الملخص

أدى التطور في صناعة أشباه الموصلات إلى استخدام قطع صغيرة جداً تستهلك طاقة عالية كي تقدم أداءاً رفيعاً . ومازالت الحرارة عقبة رئيسية لابد من حسن التحكم بها لتحسين أداء القطع الإلكترونية. من العقبات أيضا صغر سطح انتقال الحرارة بسبب صغر القطع أصلاً لذلك لابد من تقنيات تبريد مناسبة وذات كفاءة عالية . في البحث الحالي هناك استقصاء لطرق تبريد المكونات الإلكترونية . وتم اقتراح نظام الأنبوب الحراري للتبريد نظراً لكفاءته العالية دون الحاجة إلى طاقة خارجية . تم تحليل المعادلات اللازمة واقتراح التصميم المناسب لهذا النظام باستخدام أنبوب نحاسي - مائي .