APPLICATION REPORT

THERMAL DESIGN CONSIDERATIONS
FOR THE
CYRIX 5x86 MICROPROCESSOR

OCTOBER, 1995

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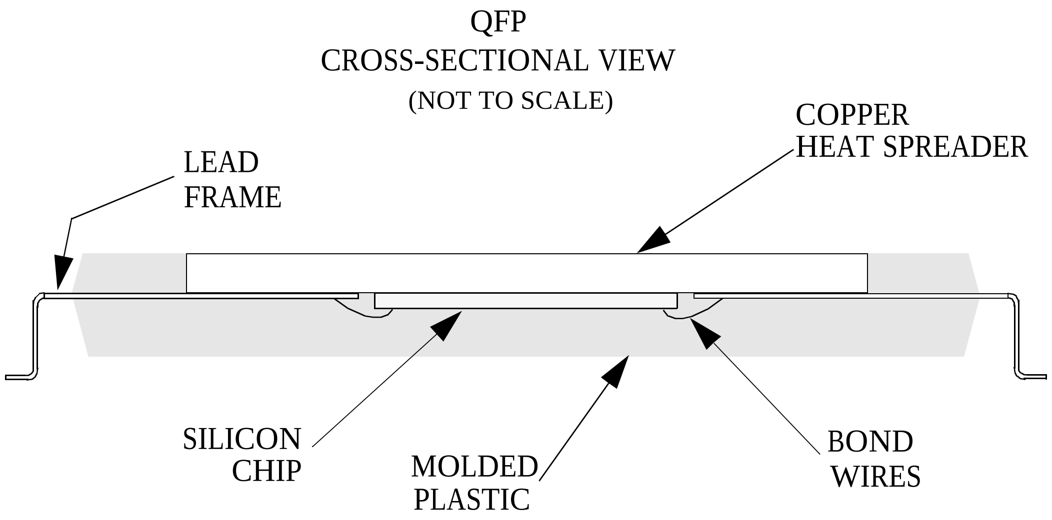

Figure 1. 5x86 QFP Cross-Sectional View

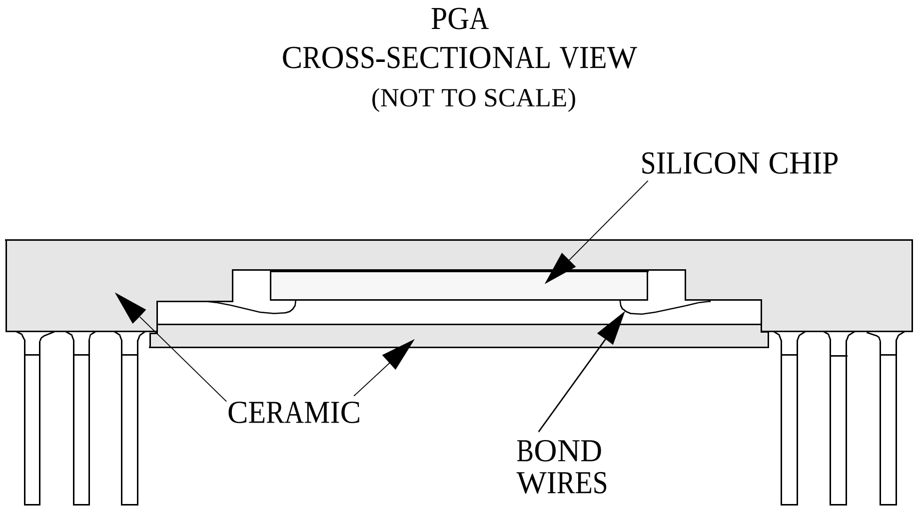

Figure 2. 5x86 PGA Cross-Sectional View

THERMAL DESIGN CONSIDERATIONS
FOR THE
CYRIX 5X86 MICROPROCESSOR

by Tim Shirey

Introduction

This report discusses some of the major aspects of thermal design for the engineer who is considering a personal computer design with the Cyrix® 5x86™ microprocessor. A simplified model of the thermal conduction paths is presented along with discussion of heatsinks and forced air flow as thermal management devices. The discussion also touches briefly on the subjects of thermal measurements and power management. Equations for calculating the temperatures at various points from thermal resistance values and ambient conditions are provided and illustrated by worked examples of several key calculations. Tables in the appendix expand on and update data presented in the 5x86 Microprocessor Data Book.

Thermal Model

The model for heat generation and heat flow in a large semiconductor device is a complex subject that requires some basic assumptions. The first is that all the heat generated by the electrical activity of the device is concentrated at the surface of the semiconductor chip. The second is that the heat is evenly distributed across the surface; no one spot is hotter or cooler than any other. The first assumption is based on the fact that semiconducting mechanisms are concentrated very near the interface between conducting silicon and the silicon dioxide surface insulation. For some older devices and those designed to handle large currents, this is not true. For these devices, there may be significant sources of heat in the bulk silicon (or the substrate) or in the chip mounting interface to the package. For semiconductors designed for logic functions, the first assumption is a good representation of reality.

The second assumption, that all points on the surface of the chip are at the same temperature, is generally true for well-designed, modern semiconductor chips in logic applications. There is the potential for “hot spots” in weak designs, but these are largely prevented by current semiconductor design practices.

There are three paths by which heat leaves the surface of the chip (see Figures 1 and 2) and flows out to its immediate surroundings: (1) through the bulk silicon and the chip mount interface to the package, (2) through the bond wires and package leads to the socket or circuit board, and (3) to the bottom of the package in some combination of radiation and conduction. The 5x86 QFP package construction puts molded plastic in contact with the chip surface, which provides a path for direct conduction to the surface of the package. The PGA package leaves a void between the surface of the chip and the bottom lid, which provides a path that combines radiation and conduction. Radiation, conduction, and convection then transport heat from the package and the circuit board into the air and out of the equipment enclosure.

Junction-to-Case Thermal Resistance

The thermal resistance between the surface of the chip (the semiconductor junction) and the package is represented by θ_{JC}. This thermal resistance is the ratio of (1) the temperature difference from the chip surface to the package and (2) the power applied to generate that temperature difference. It is expressed in °C/W and is entirely controlled by the package materials and geometry, and by the techniques used to mount the chip. There is no practical way for a system designer to change θ_{JC} for a semiconductor component. Junction temperature T_J is a fixed function of the case temperature T_C and the applied power P as shown in Equation 1. The system designer must control case temperature within a safe boundary, usually the recommended operating condition for the device.

$$T_J = T_C + P\,\theta_{JC} \qquad (1)$$

Definitions of Symbols

T_J = *junction (semiconductor chip surface) temperature in °C*

T_C = *case temperature (top dead center) in °C*

T_A = *ambient (free air) temperature in °C*

*P = power applied (Vcc * Icc) in W*

θ_{JA} = *thermal resistance from junction to ambient in °C/W*

θ_{JC} = *thermal resistance from junction to case in °C/W*

θ_{CA} = *thermal resistance from case to ambient in °C/W*

Junction-to-Air Thermal Resistance

Heat flow from the case is a function of infrared (IR) radiation and of characteristics of the medium in contact with the case. Specifications for semiconductor components are usually assumed to be with air at or near standard pressure as the medium. The temperature of the case can be controlled by controlling the temperature of the air in contact with the case through forced air flow or forced cooling. Even in nominally still air, there will be some air flow due the tendency for warmer air to rise from the case (natural convection), and natural flow can be impeded by physical layout around the component.

The thermal resistance between the surface of the chip and the air surrounding the case is represented by θ_{JA}. This value includes θ_{JC} plus the resistance (reciprocal of conduction) to heat flow provided by radiation, conduction, and convection to the air. The surface characteristics of the case are important in determining θ_{JA} and can be modified by the addition of a heat sink designed to maximize heat flow to air, but more about that later. θ_{JA} is expressed in °C/W, the same as θ_{JC}.

$$T_J = T_A + P\,\theta_{JA} \qquad (2)$$

$$T_C = T_A + P(\theta_{JA} - \theta_{JC}) \qquad (3)$$

Case-to-Air Thermal Resistance

The term $(\theta_{JA} - \theta_{JC})$ in Equation 3 represents the case-to-air thermal resistance θ_{CA}, describing the radiative, conductive, and convective characteristics of the case in parallel with the characteristics of the socket or board used for mounting the CPU. It is important to remember that a significant amount of heat flows into the connecting leads. From there it flows into the case itself and into whatever external structure the leads contact.

Semiconductor data sheets have traditionally specified θ_{JA}, but a combination of θ_{CA} and θ_{JC} specifications would probably be more appropriate for thermal design. Case temperature is directly measurable while junction temperature is not. Most manufacturers specify case temperature limits, not junction temperature limits, in their recommended operating conditions. Cyrix recommends a case temperature range for applications and warrants electrical parameters only over that range. Measurements on

5x86 CPUs to support θ_{JA} specifications in the QFP package were made with the devices soldered to a four-layer circuit board. Measurements on 5x86 CPUs to support θ_{JA} specifications in the PGA package were made with the devices in a standard 168-pin socket mounted on a four-layer circuit board.

Air Temperature

From the equations above, the maximum air temperature that corresponds to a maximum junction or case temperature (for given values of $\theta_{JC}$and θ_{CA}) can be calculated with Equations 4 and 5.

$$T_{A(MAX)} = T_{J(MAX)} - P_{(MAX)}\theta_{JA} \qquad (4)$$

$$T_{A(MAX)} = T_{C(MAX)} - P_{(MAX)}\theta_{CA}. \qquad (5)$$

Many semiconductor data sheets specify both the maximum junction temperature and the maximum case temperature. In these cases, the designer should calculate the maximum ambient (air) temperature for each condition and then take the lower resulting number as the effective maximum. Example 1 later in this paper illustrates this process. If the case temperature is the real limiting value, the ambient temperature calculated from that can be substituted into Equation 2 above to obtain the effective maximum junction temperature for reliability assessments. Example 1 also illustrates this calculation.

Forced Air Flow

Many semiconductor data sheets provide data for θ_{JA} versus air flow. Zero air flow actually refers only to forced flow, natural convection is always present when the heated air is free to rise. Equations 4 and 5 can be used for calculating the maximum air temperature corresponding to any forced air flow for which appropriate θ_{JA} or θ_{CA} data is provided. Example results of this calculation are shown in the Thermal Resistance tables in the appendix.

Heatsinks

The simplest way to reduce the case temperature is to remove heat from the case at a higher rate. Heatsinks are designed to improve θ_{CA} by providing a case-to-heatsink-to-air thermal resistance that is lower than case-to-air without a heatsink. The improvement in thermal resistance results from the efficiency of radiation and convection from the heatsink, but also depends on the goodness of fit between the case and heatsink. When a heatsink is used, the manufacturer's thermal resistance rating can be added to the θ_{JC} of the CPU along with the resistance between the case and heatsink to obtain the new, combined θ_{JA}. Then Equations 1 through 5 can be used in the same way as before. Most heatsink manufacturers provide extensive thermal resistance data versus air flow.

Measuring Thermal Resistance

Measuring the thermal resistance of semiconductor devices is thoroughly covered by industry measurement standards groups. Most chip manufacturers provide reliable data on their products and so do the heatsink manufacturers. But unusual applications sometimes require testing and development by individual designers. Notebook computer design provides one such application.

Notebook computers, small and operating from batteries, often do not provide space for convective air flow or power for a fan. These situations demand a creative approach to extracting heat from internal sources. The creative approach often involves custom heatsinks, and those require some non-standard techniques to measure their effectiveness.

The simplest approach is usually the best. In this case, measuring the thermal resistance of the custom heatsink is not necessary. Just monitoring the difference between the CPU case and an appropriate point in free air, with the heat sink installed and power applied to the CPU, is good enough. That temperature difference, subtracted from the maximum case temperature, will provide the means to estimate the maximum acceptable free-air temperature for the particular application.

Dynamic Power Management

The temperature of a CPU, such as the Cyrix 5x86 microprocessor, can also be managed through controlled reduction of the average or effective power dissipated. Many notebook computers make use of the Suspend Mode or clock-frequency reduction techniques to reduce the average current drain on their batteries, with the result that the case temperature is also reduced. It is beyond the scope of this report to go into those techniques, but some discussion of the effects is in order.

The thermal capacity of the CPU case and environment combines with the thermal resistance θ_{CA} to produce a *thermal time constant* similar to the time constant of a resistor and capacitor network. This time constant can be used to predict the case temperature transition from one power level to another, like the change from the full power condition for a CPU to the suspend-mode power. A designer can use suspend mode to reduce power during low demand periods for the CPU and reduce the case temperature. This technique can be extended to enforce periodic suspend time to maintain the case temperature at a lower value if the total period of full power and suspend mode is much smaller than the thermal time constant. Example 3 shows some calculations for the thermal time constant of the 208-lead QFP package.

Measurements of case temperature under selected conditions can be more informative than calculated values. Monitoring temperature stabilization time in the actual environment for the transition from one known power level to another can provide a very practical estimate of the thermal time constant. Then a program to enforce a certain duty cycle, the time at full power divided by the total period, can be run and the case temperature measured to verify compliance with recommended limits. It is important to make sure that compliance is verified under conditions that are the same as the worst-case environmental conditions expected.

Examples

Example 1

Calculating Maximum Ambient Temperature, Junction Temperature, and Case Temperature

This example will show the calculations for determining the maximum ambient temperature (at full power) based on maximum junction temperature and on maximum case temperature. It will then compare the two values, select the lower, and then calculate the junction temperature based on the selected case temperature. Finally, the case temperature for the suspend mode will be calculated. All these examples use conservative, worst-case design principles that require that the maximum power values represent the *maximum* V_{CC} and I_{CC} values. Using nominal values increases the risk of thermally generated errors in operation or CPU failure.

The equations below are for $T_{J(MAX)}$ = 100°C and other values as shown in Table 1 in the Appendix. The maximum ambient temperature for zero air flow and maximum junction temperature for a 5x86-100GP operating at a core clock frequency of 100 MHz is calculated by

$$P_{(MAX)} = V_{CC(MAX)}\, I_{CC(MAX)}$$

$$= 3.6\text{ V} * 1.2\text{ A} \quad = 4.32\text{ W}$$

$$T_{A(MAX)} = T_{J(MAX)} - P_{(MAX)}\, \theta_{JA}$$

$$= 100°\text{C} - 4.32\text{ W} * 11.0°\text{C/W}$$

$$= 100°\text{C} - 47.5°\text{C} = 52.5°\text{C}.$$

The maximum ambient temperature at the same conditions as above except at maximum case temperature is calculated by

$$T_{A(MAX)} = T_{C(MAX)} - P_{(MAX)} * \theta_{CA}$$

$$= 85°\text{C} - 4.32\text{ W} * 9.0°\text{C/W}$$

$$= 85°\text{C} - 38.9°\text{C} = 46.1°\text{C}.$$

As you can see, the maximum case temperature requires the lower no-air-flow maximum ambient temperature: 46.1°C versus 52.5°C (11.0°C/W and 9.0°C/W are zero-air-flow values and so the comparison is valid).

The highest junction temperature at an ambient temperature of 46.1°C is given by

$$T_J = T_{A(MAX)} + P_{(MAX)}\, \theta_{JA}$$

$$= 46.1°\text{C} + 4.32\text{ W} * 11.0°\text{C/W}$$

$$= 46.1°\text{C} + 47.5°\text{C} = 93.6°\text{C}.$$

The case temperature for the clock suspend mode at the maximum ambient temperature is given by

$$T_{C(Suspend)} = T_{A(MAX)} + P_{(Suspend)}\ \theta_{CA}$$

$$= 46.1°C + (3.6\ V * 75\ mA) * 9.0°C/W$$

$$= 48.5°C.$$

The results of these calculations are

- that the maximum case temperature of 85°C requires a lower ambient temperature than the maximum junction temperature of 100°C does,
- that the junction temperature at 85°C case temperature will be 93.6°C under the specified full-power conditions, and
- that the stable case temperature for suspend-mode conditions will be 48.5°C.

Use of the suspend mode to control case temperature is discussed in “Dynamic Power Management” on page 5.

Example 2

Calculating Required Thermal Resistance

Some cases arise where calculations like those in Example 1 show that the situation requires either a heatsink or a fan. In those cases, the designer must calculate the thermal resistance necessary to maintain the maximum case temperature at 85°C. The equation below shows how to calculate the combined thermal resistance of the package and heatsink required for an application.

$$\theta_{CA} = \frac{T_{C\,(MAX)} - T_{A\,(MAX)}}{V_{CC\,(MAX)}\, I_{CC\,(MAX)}} \qquad (6)$$

For a 5x86-100GP at

$V_{CC(MAX)} = 3.6$ V,

$I_{CC(MAX)} = 1.2$ A,

$T_{C(MAX)} = 85°C$, and

$T_{A(MAX)} = 40°C$,

the maximum combined thermal resistance of the package and heat sink should be

$$\theta_{CA(MAX)} = 10.42°C/W.$$

For a 5x86-120GP at

$V_{CC(MAX)} = 3.6$ V,
$I_{CC(MAX)} = 1.4$ A,
$T_{C(MAX)} = 85°C$, and
$T_{A(MAX)} = 40°C$,

the maximum combined thermal resistance of the package and heatsink should be

$$\theta_{CA(MAX)} = 8.93°C/W.$$

Example 3 Calculating Thermal Time Constant for the 208-Lead QFP

Thermal capacitance is a function of the mass and the specific heat of each component of the package and all those elements that are in contact with the package. This example will make the simplifying assumption that the thermal capacitance of the copper slug used as a heat spreader in the 5x86 Quad Flat Pack represents the total thermal capacitance of the package, an assumption that will produce small errors on the safe side. Then

$$\text{time constant} = RC = \theta_{CA} * \text{thermal capacitance}$$

$$= 18.0°C/W * 5.6\ J/°C = 100.8\ s$$

where J = 1 Joule, s = 1 second, and θ_{CA} is at zero air flow. Case temperature will, in theory, be at a long-term stable value after five time constants, or about 500 seconds in this example. Other components within the package will increase the time constant as will soldering the CPU to a circuit board. The conclusion to be reached here is that the duty cycle can be averaged over periods of several seconds without concern for the difference between peak case temperature and average case temperature when the suspend mode is used to dynamically manage power dissipation. Other power management techniques can use logic that is similar but adapted to the particular case.

Appendix

Thermal Data For Standard 5x86 CPUs

The data in this section represent devices that operate at a nominal supply voltage of 3.45 V as show in Table 1 below.

Table 1. 5x86 Specifications Related to Thermal Design

SYMBOL	DESCRIPTION	MIN	TYP	MAX	LOCATION IN DATA BOOK
V_{CC}	Supply Voltage	3.3 V	3.45 V	3.6 V	Table 4-4
	Absolute Maximum Operating Case Temperature			110°C	Table 4-3
T_C	Recommended Maximum Operating Case Temperature			85°C	Table 4-4
I_{CC}	Active I_{CC}				
	5x86-100 at f_{CLK} = 100 MHz, V_{CC} = 3.6 V		0.9 A	1.2 A	Table 4-5
	5x86-120 at f_{CLK} = 120 MHz, V_{CC} = 3.6 V		1.0 A	1.4 A	Table 4-5
I_{CCSM}	Suspend Mode I_{CC}				
	5x86-100 at f_{CLK} = 100 MHz, V_{CC} = 3.6 V		20 mA	75 mA	Table 4-5
	5x86-120 at f_{CLK} = 120 MHz, V_{CC} = 3.6 V		50 mA	75 mA	Table 4-5
I_{CCSS}	Standby I_{CC} (Suspend Mode and CLK Stopped)		15 mA	60 mA	Table 4-5

PGA Packages

Table 2 contains thermal resistance data and recommended maximum ambient temperatures for the standard parts as shown in Table 1. Recommended ambient temperature values are based on the *maximum* V_{CC} and I_{CC} values ($I_{CC(MAX)}$ at $V_{CC(MAX)}$ = 3.6 V). Using maximum values of supply voltage and current represents the worst-case thermal condition. In addition, T_C is as shown in Table 1.

Table 2. Thermal Data for PGA Packages Without Heatsink

AIR FLOW (feet per minute)	THERMAL RESISTANCE		RECOMMENDED MAXIMUM AMBIENT AIR TEMPERATURE	
	θ_{CA} (°C/W)	θ_{JC} (°C/W)	5x86-100GP (°C)	5x86-120GP (°C)
0	15.0	2.0	28.8	19.5
200	13.0	2.0	37.5	29.6
400	10.0	2.0	50.4	44.7
600	8.0	2.0	59.1	54.8
800	7.0	2.0	63.4	59.8

Table 3. Thermal Data for PGA Packages With Heatsink Provided

AIR FLOW (feet per minute)	THERMAL RESISTANCE		RECOMMENDED MAXIMUM AMBIENT AIR TEMPERATURE	
	θ_{CA} (°C/W)	θ_{JC} (°C/W)	5x86-100GP (°C)	5x86-120GP (°C)
0	9.0	2.0	46.1	40.0
200	5.0	2.0	63.4	59.8
400	3.2	2.0	70.0	68.9
600	1.8	2.0	77.2	75.9
800	1.4	2.0	79.0	77.9

QFP Packages

The thermal resistance values in Table 4 were obtained from measurements in a four-layer circuit board. Recommended ambient temperature values are based on the *maximum* V_{CC} and I_{CC} values ($I_{CC(MAX)}$ at $V_{CC(MAX)} = 3.6$ V). Using maximum values of supply voltage and current represents the worst-case thermal condition. In addition, T_C is as shown in Table 1.

Table 4. Thermal Data for QFP Packages Without Heatsink

AIR FLOW (feet per minute)	THERMAL RESISTANCE		RECOMMENDED MAXIMUM AMBIENT AIR TEMPERATURE	
	θ_{CA} (°C/W)	θ_{JC} (°C/W)	5x86-100GP (°C)	5x86-120GP (°C)
0	13.5	1.2	26.7*	17.0†
200	TBD	TBD	TBD	TBD

* This value can be adjusted to 40°C by the addition of a heatsink with θ_{CA} = 10.4°C/W as shown in Example 2.

† This value can be adjusted to 40°C by the addition of a heatsink with θ_{CA} = 8.9°C/W as shown in Example 2.

Thermal Data for Selected 5x86 CPUs at Higher Supply Voltage

The devices described in this section operate at a nominal supply voltage of 3.6 V as shown in Table 5 below. They require forced air flow and a heatsink.

Table 5. 5x86 Specifications Related to Thermal Design

SYMBOL	DESCRIPTION	MIN	TYP	MAX	LOCATION IN DATA BOOK
V_{CC}	Supply Voltage	3.45 V	3.6 V	3.75 V	NA
	Absolute Maximum Operating Case Temperature			110°C	Table 4-3
T_C	Recommended Maximum Operating Case Temperature			85°C	Table 4-4
I_{CC}	Active I_{CC} f_{CLK} = 100 MHz, V_{CC} = 3.75 V f_{CLK} = 120 MHz, V_{CC} = 3.75 V		 0.95 A 1.05 A	 1.3 A 1.5 A	 NA NA
I_{CCSM}	Suspend Mode I_{CC} f_{CLK} = 100 MHz, V_{CC} = 3.75 V f_{CLK} = 120 MHz, V_{CC} = 3.75 V		 50 mA 50 mA	 75 mA 75 mA	 NA NA
I_{CCSS}	Standby I_{CC} (Suspend Mode and CLK Stopped)		15 mA	60 mA	NA

PGA Packages

Table 6 below contains thermal resistance data and recommended maximum ambient temperatures for selected parts as shown in Table 5. The thermal resistance values shown with a * under air flow are representative of operation with a fan-heatsink combination manufactured by Sunon (part# KD1204PFS3) at 12 V and 0.9 W. The thermal resistance values for the air flow of 200 linear feet per minute represent operation with a heatsink like the one provided with the standard parts (0.35 inches high) and with forced air flow. The recommended maximum ambient temperatures are based on $V_{CC(MAX)}$ = 3.75 V, $I_{CC(MAX)}$ and T_C values from Table 5, and the thermal resistance shown. Using *maximum* values of supply voltage and current represents the worst-case thermal condition.

Table 6. Thermal Data for PGA Packages With a Fan Installed

AIR FLOW (feet per minute)	THERMAL RESISTANCE		RECOMMENDED MAXIMUM AMBIENT AIR TEMPERATURE	
	θ_{CA} (°C/W)	θ_{JC} (°C/W)	f = 100 MHz (°C)	f = 120 MHz (°C)
*	7.0	2.0	50.9	45.6
200	5.0	2.0	60.6	56.9

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94269-00 October 1995