

## FEATURE ARTICLE

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# Thermal Considerations in Electronics Design

Options for thermal management haven't been abundant for electronics designers in the past. Back before microprocessors, you were restricted in your choice of cooling. Today, it's a whole new story, as we see George detail some practical and reliable hard-data examples arrived at through the age-old method of measurement.

Until the first speedy microprocessors arrived, most electronics designers' experience with thermal management (that's the classy way of referring to cooling) was limited to power supplies and an occasional linear power output stage. Quite often, a rule of thumb was used to fit the few hot components with a heatsink and little further thought was given to the subject, unless problems arose. Things have changed drastically since those days and cooling of electronic components is (or should be) on everybody's mind.

The millions of transistors crowded within a minuscule space of a modern microprocessor chip, switching at continually higher clock frequencies, generate a great deal of heat. The power supplies, on the other hand, are expected to provide for these low-voltage, high-current

hungry circuits clean, rock-steady power. A common present-day 500-W switcher working with 90% (excellent, by today's standards) efficiency will turn 50 W into pure heat. Low-voltage, high-current regulators in particular struggle to achieve high efficiency.

There are two basic methods at your disposal to manage this sorry situation. First, the most obvious method is to address the cause and reduce the heat generation, whether it is as a result of the voltage drop in regulators, high saturation voltage, switching losses, or so forth. Unfortunately, 100% efficiency is merely a pipe dream, and there is only so far we can go with the laws of physics and the limits of technology. In the end, the majority of the effort will go to treating the symptom—to conducting the excess heat away from the device.

How can the heat the equipment generates be reduced? By circuit design, efficiency can be optimized. Switching instead of series regulators can be used. But, nothing is free, you pay for the high efficiency of switchers with EMI headaches. Digital, as opposed to analog processing affords better energy efficiency in most applications. Logic circuits and microprocessors, operating at lower voltage, dissipate less heat per transistor.

Starting with 5-V TTL levels many

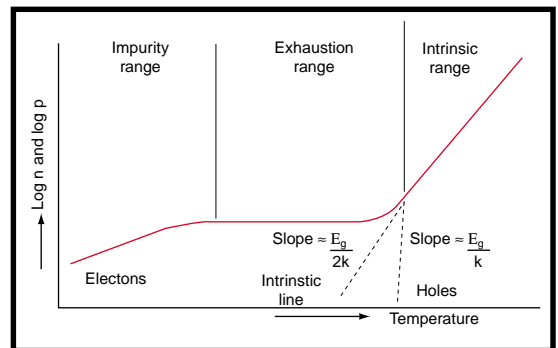


Figure 1—Here you can see the dependence of the carrier concentration of an N-type extrinsic semiconductor on temperature. When entering the intrinsic range (starting about 200°C for silicon devices) the semiconductor becomes unusable.

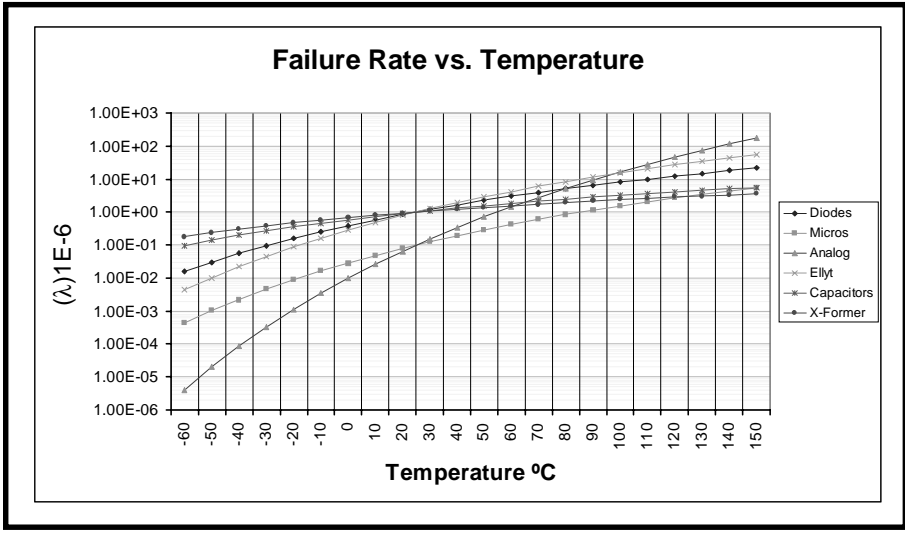


Figure 2—The normalized failure rate of various electronic components relative to their operating temperature can be seen here. Notice the steep slope for analog ICs and the logarithmic scale of the y axis.

years ago, 3-V devices came along, followed by lower voltages today. It is expected that in 10 years, the operating voltage will drop to 0.5 V, with gate thickness of a mere 10 atoms. However, the lower heat dissipation per transistor is always amply offset by increased functionality paid for by more, smaller transistors crowded inside the chip. Present-day microprocessors running with 1-GHz clocks easily put out 50 W in heat. The trend towards higher integration, smaller, more crowded cabinets, and higher clock speeds will only make the future heat dissipation problems worse.

**WHY WORRY?**

Why do you have to worry about the heat? Without getting too much into the theory of semiconductors, let's take a quick look at conduction characteristics of an N-type extrinsic semiconductor. Figure 1 shows how the carrier density is affected by temperature. This should be no surprise to you because conduction by electrons and holes, which is the underlying principle of semiconductors, is provided by their thermal excitation.

At normal temperatures, in an extrinsic semiconductor, electrons are excited from donor levels to the conduction band or from the valence band to the acceptor levels by a relatively small amount of energy. Direct excitation from valence to conduction level is practically nonexistent. As the temperature increases, the donor levels

become exhausted or the acceptor levels saturated. At this point, the carrier concentration becomes relatively insensitive to temperature. As you increase the temperature even more, electrons become excited from valence band to the conduction band in large numbers by the now abundant thermal energy. The equal numbers of electrons and holes that become liberated significantly exceed the limited number of the extrinsic carriers and the conduction becomes intrinsic.

What does that mean? At low and intermediate temperatures, conduction electrons are the majority carriers. The onset of the intrinsic conduction is related to the energy gap  $E_g$ , which for silicon semiconductors  $E_g = 1.1$  eV, corresponding to approximately 200°C (392°F). That is the upper temperature limit at which the semiconductor can operate. As the semiconductor junction approaches this temperature, the operating properties begin to degrade.

Leakage and slower operation are the most noticeable effects. Many silicon semiconductors on today's market are characterized for the maximum junction temperature,  $T_j = 125^\circ\text{C}$  (257°F). A few go as high as 170°C (338°F). If you know what you're doing, you can push devices to operate well above their rated temperature by judiciously derating the power and clock speed, so long as you stay below the intrinsic range. But remember, I am talking junction temperatures, not case or even ambient! As you will see later,

the junction temperature is usually many degrees higher than the case and ambient temperatures.

**RELIABILITY**

In a competent design, in the absence of gross misuse or badly rated power stages, it should be unusual to experience a failure caused by thermal breakdown. Common sense tells you that as long as you fit devices dissipating heat with some kind of a heatsink to keep them cool, you should be OK. There's an old saying—if you can keep your finger on the device without getting burned, there's nothing to worry about.

This is a good rule, although the old practitioners may not have necessarily understood why. The thermal breakdown or the performance degradation at high operating temperatures is not the only one, nor should it be the most important consideration in a reasonably competent design. Much more sinister (because it operates quietly in the background) is the loss of reliability and, therefore, the operating life. The old adage that temperature is the reliability killer rings true, although the effect of temperature on reliability has not always been fully appreciated in the commercial design. While at times addressed by designers instinctively, the engineering expertise and the associated cost of analysis have been prohibitive outside safety-related industries. This, however, changed when commercial manufacturers realized how much returned product, warranty repairs, and customers' unhappiness actually cost them in lost profits.

Understanding the temperature affect on product life may be used advantageously to arrive at a tradeoff between cost and life expectancy of a device to increase its cost competitiveness. I know of a microprocessor destined for use in cellular telephones whose smaller die allows its price to be extremely competitive. The fact that its higher operating temperature reduces its life expectancy to only three years is balanced out by the short life cycle of cellular telephones.

Figure 2 shows a plot of the normalized failure rates ( $\lambda$ ) against tempera-

ture for a number of different electronic components. The failure rate ( $\lambda$ ) expresses a number of expected failures per one million hours and is the reciprocal of the MTBF (mean time between failures).

The implications of this plot are revealing. It shows that a failure rate of a microprocessor operating at  $T_j = 50^\circ\text{C}$  will be only 10% of the same device operated at  $T_j = 120^\circ\text{C}$ . In other words, if the expected MTBF of the micro at  $120^\circ\text{C}$  is 200,000 hours, you can expect 2,000,000 hours MTBF if you keep the die at  $50^\circ\text{C}$ . The temperature effect is even more pronounced with analog integrated circuits, where the same operating temperature difference will result in the MTBF improvement by the factor of 65! The advantage of using digital processing as much as possible is clearly demonstrated by this example.

## DESIGN STEPS

A typical semiconductor cooling system is shown in Figure 3. Heat always transfers from a higher-temperature region to a lower-temperature region. The heat transfer is:

$$P = \frac{T_1 - T_2}{R}$$

where  $P$  is the power in watts,  $T_1$  and  $T_2$  are the regions' respective temperatures in  $^\circ\text{C}$ , and  $R$  is referred to as thermal resistance in units of  $^\circ\text{C}/\text{W}$ .

The heat flows from the semiconductor junction at temperature  $T_j$  to the case at  $T_c$ , the heatsink at  $T_h$ , and the ambient air at  $T_a$ . The thermal resistance between the junction and the air is:

$$R_{ja} = R_{jc} + R_{ch} + R_{ha}$$

In some situations the semiconductor is cooled by conduction directly from the case to the air without a heatsink. Manufacturers usually provide the  $R_{ca}$ , which replaces  $R_{ch}$  in the equation. The heatsink thermal resistance ( $R_{ha}$ ) is omitted.

During thermal design of a

system, some parameters are known at the beginning, others you'll have to determine. The semiconductor manufacturer specifies the junction-to-case thermal resistance ( $R_{jc}$ ) and the maximum junction temperature ( $T_j$ ). For devices that are intended to be fitted with a heatsink, the case-to-heatsink thermal resistance ( $R_{ch}$ ) is also specified. The maximum ambient operating temperature is known, also. Finally, there is the heatsink-to-ambient thermal resistance, which is usually the final variable that you can play with to tie it all together.

What leeway do you have in selecting parameters other than the heatsink ( $R_{ha}$ )?  $R_{jc}$  is a device characteristic you cannot affect. Maximum junction temperature ( $T_j$ ) is usually in the  $110^\circ\text{C}$  to  $175^\circ\text{C}$  range. As I mentioned previously, if you know what you're doing and are willing to pay the reliability and performance price, you can push a component outside its manufacturer-specified limits. However, unless absolutely necessary, I do not recommend this practice because the stress can induce irreversible damage. Some engineers recommend that the manufacturer's  $T_{jmax}$  be derated by at least  $25^\circ\text{C}$  for safe operation. In other words, the  $125^\circ\text{C}$  device be operated at

no more than  $T_j = 100^\circ\text{C}$ .

There may be some variation from the spec in the case-to-heatsink (or ambient, if the heatsink is not used) thermal resistance ( $R_{ch}$ ). Compounds and pads exist to improve the heat transfer. The pads also isolate the case from the heatsink. However, in some applications, such as military, thermal compounds are not permitted. Where the component case carries a potential, it may be thermally more efficient to isolate the entire heatsink than rely on the isolator pad. At any rate, read the specifications carefully and always verify your results by test.

After you have determined all the design parameters, you know what the heatsink has to do and can look for one. There is a wide selection of heatsinks available to satisfy just about any requirement. Wakefield, Aavid, and Kaiser (to name a few) offer a wide selection of ready-made heatsinks and extrusions to design your own. However, heat dissipation of modern microelectronic circuits is quickly reaching the point where regular convection heatsinks no longer suffice. One solution is to lower the heat generation by reducing the clock frequency. This is a common solution in some military and aerospace applica-

tions, but in many commercial situations, it would defeat the purpose. So, before you know it, you must turn to forced air cooling. After that, the sky's the limit. Water and oil cooled systems (even heat pumps), found only in the highest level systems until recently, are making appearances in commercial products. It is only a matter of time until their volume reaches critical mass with a subsequent drastic reduction in price and wide availability.

## PRACTICAL EXAMPLE

Let's look at a practical example. Using HEXFET IRC530 you drive a 28-V, 10-A DC load. The FET  $R_{DS(on)} = 0.16$  ohm, meaning that when saturated, a 1.6-V drain-to-source voltage drop at 10 A will cause

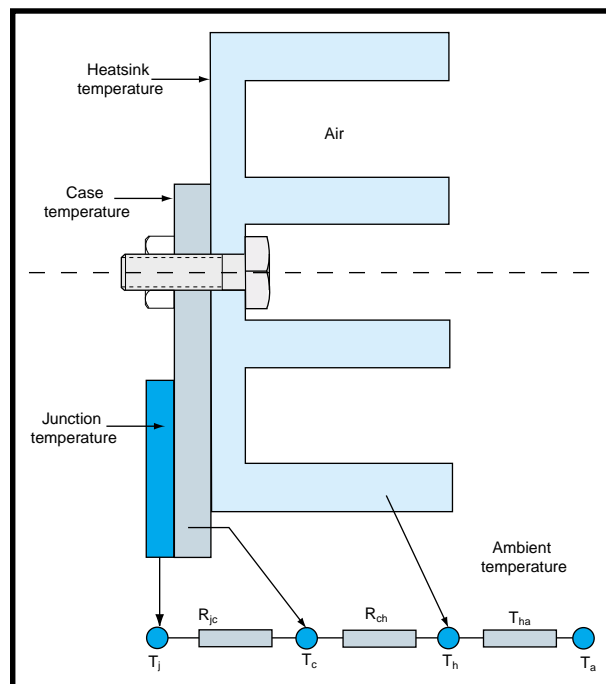


Figure 3—The heat generated by the junction is conducted through three thermal resistance regions to be dissipated in the air. The air can be replaced by another medium, such as water, oil, and such.

$P_D = 16$  W to turn into heat. The junction-to-case  $R_{jc} = 1.7$  °C/W and the case-to-heatsink  $R_{ch} = 0.50$  °C/W are specified in the datasheet. The maximum junction temperature is  $T_{jmax} = 175$ °C, but the specification also requires that it be linearly derated by  $0.59$  W/°C. This, when multiplied by the  $P_D = 16$  W dissipation, sets the maximum operating temperature,  $T_j = 175$ °C  $- 27.11$ °C =  $147.89$ . Following the reliability experts' recommendation for derating, use  $T_j = 120$ °C. The maximum ambient operating temperature is  $70$ °C. The thermal equation is:

$$T_j - (R_{jc} + R_{ch} + R_{ha}) \times P_D = T_a$$

Plugging in the above design requirements and solving for  $R_{ha}$  gives you:

$$R_{ha} = \frac{T_j - T_a}{P_D} - R_{jc} - R_{ch}$$

$$= \frac{120 - 70}{16} - 1.7 - 0.5 = \frac{0.925}{W}$$

$$T_h = T_j - (R_{jc} + R_{ch}) \times P_D$$

$$= 120 - (1.7 + 0.5) \times 16 = 84.8$$
 °C

The result means you need a heatsink with thermal resistance to air of  $0.925$  °C/W. The previous example was also calculated at  $70$ °C ambient temperature, so the heatsink temperature at the base is  $84.8$ °C. This is an important fact, as heatsink effectiveness is affected by the temperature difference. What remains now is to browse a heatsink manufacturer's catalog and find a suitable device. Some heatsinks may be unacceptable given your mechanical design constraints. Should this happen, you have to consider alternatives.

You can start by selecting a FET with lower  $R_{DS(on)}$  to reduce the  $P_D$ . You can also sacrifice some reliability and increase the junction temperature ( $T_j$ ), especially if the  $70$ °C ambient temperature is not a normal environment but a short-term exception. Or, if the design constraints are cast in stone, you have to look for a fan or even a liquid-cooled heat exchanger.

## HEATSINK SELECTION

The heatsink, or more accurately, the heat exchanger selection, is a sub-

ject in its own right. A wealth of design information can be found at heatsink manufacturers' web sites. Another excellent source of heatsink design information is the International Rectifier's Power Modules Designer Manual. The main problem is that the heatsink-to-ambient thermal resistance ( $T_{ha}$ ) depends on many factors, such as the orientation of the heatsink within the cabinet, exposure to air movement, and even color and the surface finish. For example, while polished aluminum heatsink radiation cooling efficiency is about 0.1, black anodized finish can achieve 0.9.

You will find heatsinks predominantly made out of aluminum. It has a volume heat storage capacity of  $40.5$  J/in.<sup>3</sup>°C. Although there are materials with higher storage capacity (i.e., brass,  $50.5$ ; copper,  $57.5$ ; or nickel,  $67.0$ ), aluminum wins hands down in heat storage capacity per weight, with  $413$  J/lb.°C. Brass, copper, and nickel are  $165$ ,  $178$ , and  $208$ , respectively. Although its thermal conductivity is not particularly high (gold, copper, and silver are higher), it is reasonably priced, easy to machine, and corrosion-resistant. Consequently, exchangers made of material other than aluminum are the result of specific design requirements.

## VERIFY BY TEST

I can't overemphasize the need to verify the calculations by test. Although the semiconductor manufacturer's catalog characteristics are worst-case, these conservative numbers should be taken at face value. There are two quantities you need to confirm by test because they can have a significant effect on the final result. The first one is the heat exchanger thermal resistance. As I stated, too many conditions that cannot be accurately forecast will affect the heat transfer efficiency. The only way out of the dilemma is to measure a prototype in the intended environment.

The second quantity that affects the result is the dissipated power ( $P_D$ ). As with the example, its worst-case scenario can be determined accurately for DC operation, but an AC or pulsed operation is a different matter. Al-

though the mathematics and the necessary data to plug into equations certainly exist, experience with thyristor and PWM drives taught me to accept the numerical results as guidelines at best. There is nothing more convincing than hard data obtained by measurement. ■

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## RESOURCES

International Rectifier, *Power Modules Designer's Manual*, IR, El Segundo, CA, 1991.  
C.W. Lander, *Power Electronics*, McGraw-Hill, New York, NY, 1993.

## SOURCES

### Heatsinks

AAVID Thermal Technologies, Inc.  
(603) 224-1117  
Fax: (603) 224-6673  
[www.aatt.com](http://www.aatt.com)

Kaiser Aluminum  
(831) 685-6056  
Fax: (831) 685-6058  
[www.metalsgroup.com](http://www.metalsgroup.com)

Wakefield Engineering, Inc.  
(781) 406-3000  
Fax: (781) 406-3224  
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