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The Basics of Package/Device Cooling

Various cooling methods are available for keeping electronic devices within their operating temperature specifications.

Cooling Consumer Products

In the case of consumer products, such as kitchen appliances and telephones, the market will accept little increase in product size as a result of the addition of processing capability. In these cases, cooling is limited to the thermal conductivity of the packaging materials and whatever airflow is provided inside the system. As consumers demand more and more functionality from these products, and IC manufacturers increase the functionality available, the number of ICs tends to increase. Designers can reduce the heat generated by the electronics by integrating functions wherever possible. One IC providing two functions generates less heat than two separate ICs providing the same functions. In this case, miniaturization of the cooling solution is also miniaturization of the electronics themselves. The designer can maximize cooling of these ICs by placing them optimally in the air stream or adding a thermal spreader that moves the heat to the exterior packaging.

The most reliable and well-designed electronic device can malfunction or fail if it overheats. Considering thermal issues early in the design process results in a thermally conscious system layout and minimizes costs through the use of passive cooling and off-the-shelf components. When thermal issues are left until completion of the design, the only remaining solution may be a costly custom heat sink that requires all the space available. Incorporating a heat sink or a fan into a product after it is fully developed can be expensive, and still may not provide sufficient cooling of the device.

Electronic component suppliers estimate that for every 10°C rise of the junction temperature, the device failure rate doubles. If the waste heat generated inside a package or device is not removed, the reliability of the device is compromised.

There are many ways to remove heat from a device, from placing the device in a cool spot in the enclosure, to using a liquid-cooled plate connected to a refrigerated water chiller. The amount of heat generated by the device, the package configuration, and the expected lifetime of the product combine with many other factors to determine the optimum heat removal scheme.

Moore’s Law regarding semiconductor technology states that the logic density of silicon-integrated circuits closely follows the curve given by the equation: bits/in2 = 2(n-1962), where n = present year date. According to Moore’s Law, the amount of information storable in one square inch of silicon has roughly doubled yearly since the technology was invented.

Moore’s Law also applies to thermal management. As chip technology becomes increasingly smaller and more powerful, the amount of heat generated per square inch increases accordingly. Assembly and packaging technology changes make the situation more complex, driving new approaches to cooling.

Surface mounting, BGA packages, and the tight enclosures demanded by the shrinking notebook computer all require creative approaches to thermal management. Sometimes several cooling methods are required in the same device to create an effective thermal solution.

Thermal solutions range from the sublime to the complex. The simplest form of heat removal is the movement of ambient air over the device. In any enclosure, adding strategically placed vents will enhance air movement. The cooling of a critical device can be improved by placing it in the coolest location in the enclosure.
When these simple thermal solutions cannot remove enough heat to maintain component reliability, the system designer must look to more sophisticated measures, such as heat sinks, fans, heat pipes, or even liquid-cooled heat plates. Thermal modeling using computational fluid dynamics will help demonstrate the effectiveness of a particular solution.

Venting
Natural air currents flow within any enclosure. Taking advantage of these currents saves on long-term component cost. Using a computer-modeling package, a designer can experiment with component placement and the addition of enclosure venting to determine an optimum solution. When these solutions fail to cool the device sufficiently, the addition of a fan is often the next step.

Enclosure fans

The increased cooling provided by adding a fan to a system makes it a popular part of many thermal solutions. Increased airflow significantly lowers the temperature of any critical device, while providing additional cooling for all the devices in the enclosure. Increased airflow also increases the cooling efficiency of heat sinks, allowing a smaller or less efficient heat sink to perform adequately.

The decision to add a fan to a system depends on a number of considerations. Mechanical operation makes fans inherently less reliable than a passive system. In small enclosures, the pressure drop between the inside and the outside of the enclosure can limit the efficiency of the fan. In battery-powered applications, such as a notebook computer, the draw of the fan can reduce battery life, reducing the perceived quality of the product.
Despite these drawbacks, fans often are able to provide efficient, reliable cooling for many applications.

Passive heat sinks

Passive heat sinks use a mass of thermally conductive material to move heat away from the device into the air stream, where it can be carried away. Heat sink designs include fins or other protrusions to increase the surface area, thus increasing its ability to remove heat from the device.
Segmenting the fins further increases the surface area to get more heat removal in the same envelope, although often at the expense of a large pressure drop across the heat sink. Pin-fin and cross-cut fin heat sinks (Fig. 1) are examples of this solution. Passive heat sinks optimize both cost and long-term reliability.

Active heat sinks

When a passive heat sink cannot remove heat fast enough, a small fan may be added directly to the heat sink itself, making the heat sink an active component. These active heat sinks, often used to cool microprocessors, provide a dedicated air stream for a critical device (Fig. 2). Active heat sinks often are a good choice when an enclosure fan is impractical.

As with enclosure fans, active heat sinks carry the drawbacks of reduced reliability, higher system cost, and higher system operating power.

Heat pipes

Heat pipes, a type of phase-change recirculating system, use the cooling power of vaporization to move heat from one place to another (Fig. 3). Within a closed heat removal system, such as a sealed copper pipe, a fluid at the hot end (near a device) is changed into a vapor. Then the gas passes through a heat removal area, typically a heat sink using either air-cooling or liquid-cooling techniques. The temperature reduction causes the fluid to recondense into a liquid, giving off its heat to the environment.
A heat pipe is a cost-effective solution, and it spreads the heat uniformly throughout the heat sink condenser section, increasing its thermal effectiveness.

Metal backplanes
Metal-core printed circuit boards, stamped plates on the underside of a laptop keyboard, and large copper pads on the surface of a printed circuit board all employ large metallic areas to dissipate heat.

A metal-core circuit board turns the entire substrate into a heat sink, augmenting heat transfer when space is at a premium. While effective in cooling hot components, the heat-spreading of this technique also warms cooler devices, potentially shortening their life span. The 75 percent increase in cost over conventional substrates is another drawback of metal-core circuit boards.

When used with a heat pipe, stamped plates are a cost-effective way to cool laptop computers. Stamped aluminum plates also can cool power supplies and other heat-dissipating devices.
Large copper pads incorporated into the printed circuit board design also can dissipate heat. However, copper pads must be large to dissipate even small amounts of heat. Therefore, they are not real-estate efficient.

Thermal interfaces

The interface between the device and the thermal product used to cool it is an important factor in the thermal solution. For example, a heat sink attached to a plastic package using double-sided tape cannot dissipate the same amount of heat as the same heat sink directly in contact with a thermal transfer plate on a similar package.

Microscopic air gaps between a semiconductor package and the heat sink, caused by surface non-uniformity, can degrade thermal performance. This degradation increases at higher operating temperatures. Interface materials appropriate to the package type reduce the variability induced by varying surface roughness.

Since the interface thermal resistance is dependent upon applied force, the contact pressure becomes an integral design parameter of the thermal solution. If a package/device can withstand a limited amount of contact pressure, it is important that thermal calculations use the appropriate thermal resistance for that pressure.

The chemical compatibility of the interface materials with the package type is another important factor. Plastic packages, especially those made using mold-release agents, may compromise the adherence of tape-applied heat sinks.

Thermal options for different packages

Many applications have different constraints that favor one thermal solution over another. Power devices need to dissipate large amounts of heat. The thermal solution for microprocessors must take space constraints into account. Surface mount and ball grid array technologies have assembly considerations. Notebook computers require efficiency in every area, including space, weight, and energy usage. While the optimum solution for any one of these package types must be determined on a case-by-case basis, some solutions address specific issues, making them more suitable for a particular application.

Power devices

Newer power devices incorporate surface mount compatibility into the power-hungry design. These devices incorporate a heat transfer plate on the bottom of the device, which can be wave-soldered directly to the printed circuit board.

Metal-core substrates offer a potential solution to power device cooling, provided there are no other heat-sensitive devices in the assembly, and the cost of the board can be justified.

For some devices, such as the D-PAK (TO-252), D2-PAK (TO-263) and D3-PAK (TO-268), off-the-shelf, surface mount compatible heat sinks are available (Fig. 4), offering low procurement cost and negligible additional assembly cost.

Microprocessors

As microprocessor technology advances, the system designer struggles to keep ahead of the increase in the thermal output of both the voltage regulator and the microprocessor. The use of active heat sinks allows concentrated, dedicated cooling of the microprocessor, without severely impacting space requirements. For some applications, specially designed passive heat sinks facilitate the use of higher-powered voltage regulators in the same footprint, eliminating the need for board redesign.

BGAs

While BGA-packaged devices transfer more heat to the board than leaded devices, the type of package can affect the ability to dissipate sufficient heat to maintain high device reliability.

All-plastic packages insulate the top of the device, making heat dissipation through top-mounted heat sinks difficult and more expensive. Metal heat spreaders incorporated into the top of the package enhance the ability to dissipate power from the chip.

For some lower-power devices, flexible copper spreaders attach with pre-applied double-sided tape, offering a "quick fix" for borderline applications.

As the need to dissipate more power increases, the optimum heat sink becomes heavier. To prevent premature failure caused by ball shear, well-designed, off-the-shelf heat sinks include spring-loaded pins or clips that allow the weight of the heat sink to be borne by the PC board instead of the device.

Notebook computers

The multiple constraints of notebook computers demand consideration of nearly all types of heat-removing devices, separately and in combination. More than any other application, notebook computer design benefits from the use of thermal and airflow modeling during the initial design phase, with paybacks in cost, size, weight, and overall reliability.

Conclusion

Many thermal solutions exist to maintain high reliability of electronic components. Leaving thermal considerations until the end of the design process can result in the need for larger or more expensive thermal management components. The need to add an active thermal component may increase the system cost while compromising reliability. The choice of package type limits the options in interface materials and may affect the efficiency of a heat sink. By considering all the options during the initial board design, the system designer can reduce overall thermal management costs, optimize board layout, and maintain high system reliability.

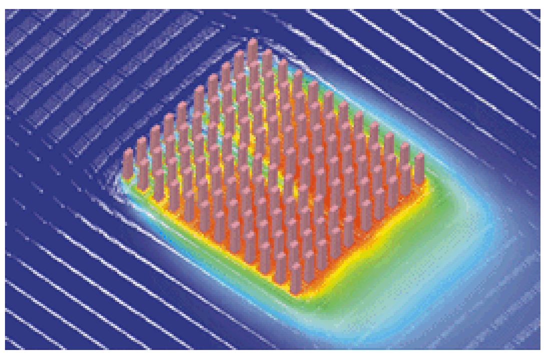

Figure 1. A pin-fin heat sink transfers heat to a flow of forced air.

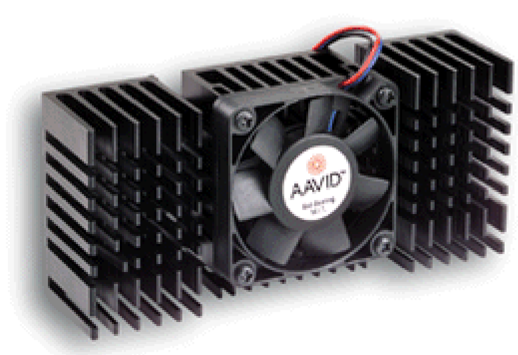

Figure 2. A fan is an integral part of this heat sink designed for cooling the Pentium II.

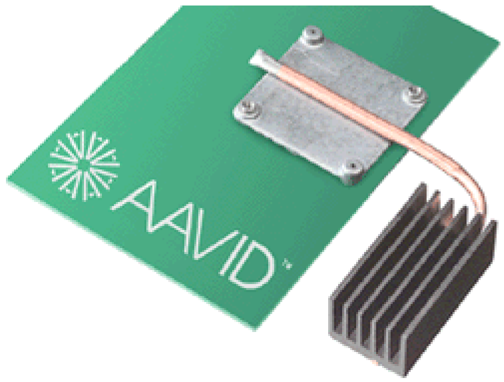

Figure 3. Heat is removed from a device mounting site by a small heat pipe assembly.

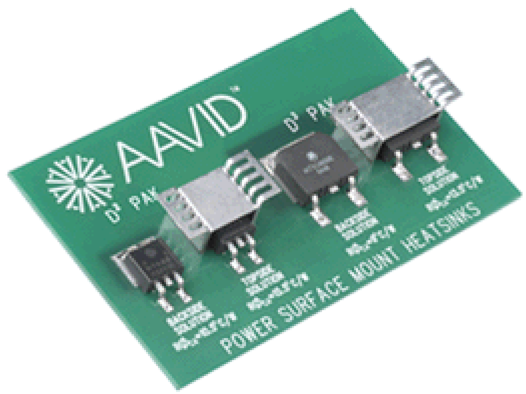

Figure 4. Power devices are fitted with low-profile surface mounted heat sinks.