Topic 5 | Integrated Circuits

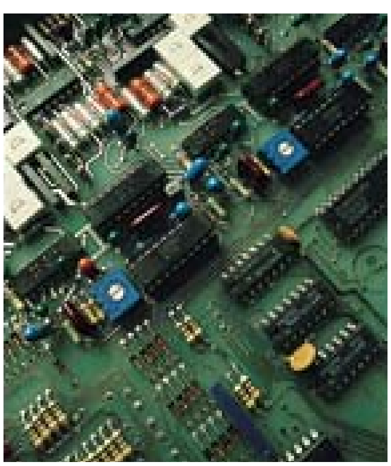
A Case Study in Heat Transfer

Integrated circuits (ic's) and VLSI (very large scale integration) chips are at the heart of most modern electronic devices, including computers, stereo systems, and fuel-injection systems in car engines (Fig. T5.1). The widespread use of these devices has posed new and interesting problems in heat transfer. Some of the electrical energy associated with the electric current in a chip is dissipated in the chip as heat; if a chip gets too hot as a result, the circuits become unreliable or are permanently destroyed. Keeping chips cool during operation is vitally important.

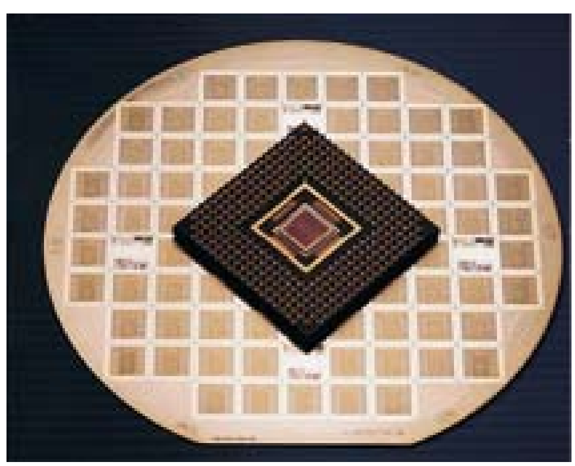
To introduce the problem, let's think about what happens when you turn on a light bulb. Electrical energy is dissipated as heat in the filament; the light bulb warms up until it reaches a temperature at which the rate of transfer of energy from the light bulb to its surroundings (by radiation as well as by conduction and convection to the surrounding air) just balances the rate of electrical energy input. A standard 60-W light bulb has a power input of 60 W and a surface area of about 120 cm^2. In equilibrium its power loss to its surroundings per unit surface area, or *power density,* is (60 W)/(120 cm^2) = 0.5 W/cm^2. The heating element on an electric range has a greater power loss relative to its surface area, so it has a larger power density of 2–3 W/cm^2.

Now consider the *much larger* power dissipation values that occur in microelectronics. Many thousands of electronic elements are packed tightly together on a silicon chip only a few millimeters on a side. Power densities for present-day VLSI chips range up to 40 W/cm^2. For comparison, the ceramic tiles that protect the space shuttle when it reenters the earth's atmosphere typically have to dissipate 100 W/cm^2.

For an ic chip in a plastic package, the maximum safe temperature is about 100°C. A chip in a ceramic package can operate reliably up to about 120°C. To see whether the temperature of an operating chip is within limits, we use the same principle as for a light bulb: power input equals power output. The power output H (the rate of heat transfer out of the chip) is approximately proportional to the difference $T_{ic} - T_{amb}$ between the temperature T_{ic} of the chip and the ambient temperature T_{amb} (temperature of the surroundings). Using a proportionality



(a)



(b)

T5.1 (a) Modern ic chips are usually placed in plastic or ceramic packages for protection. The packages contain conducting paths that lead from the chip to outside pins, which connect the circuit to the overall circuit board in the final product.
(b) This ceramic package was specifically designed to ensure r_{th} of less than 1 K/W.

constant r_{th} that depends on the shape and size of the ic, we express the rate of heat loss H as

$$H = \frac{T_{ic} - T_{amb}}{r_{th}} \tag{T5.1}$$

When the ic reaches its final operating temperature, the rate of heat loss must equal the electrical power P dissipated in the device. Equating H and P and solving for T_{ic}, we find

$$T_{ic} = T_{amb} + r_{th}P \tag{T5.2}$$

Values of r_{th} for common ic packages in still air vary from 30 to 70 K/W (30 to 70 C°/W). For example, one watt of electrical power ($P = 1$ W) into an ic will raise the temperature of a 40-pin plastic package to about 62 C° = 62 K above the surrounding air temperature. For this unit, $r_{th} = 62$ K/W.

Example T5.1

A 40-pin ceramic package has $r_{th} = 40$ K/W. If the maximum temperature the circuit can safely reach is 120°C, what is the highest power level at which the circuit can safely operate in an ambient temperature of 75°C?

SOLUTION

We use Eq. (T5.1), replacing H by P:

$$P = \frac{T_{ic} - T_{amb}}{r_{th}}$$

$$= \frac{120°\text{C} - 75°\text{C}}{40\,\text{K/W}} = 1.1\,\text{W}$$

This power level is adequate in many typical ic applications, but chips used in high-speed computing applications often require considerably higher power levels.

To remove heat from the chip more efficiently, we can force air past the circuit, improving the heat transfer by convection. Blowing air through the system at a rate of about 20 m^3/min can reduce the effective value of r_{th} for the chip and package by about 10 to 15 K/W. This is an improvement, but in many cases it is still not enough cooling for a high-performance ic.

One method of cooling that is currently being investigated is direct immersion of the ic package in a fluorocarbon fluid. These fluids are electrical insulators and are chemically inert, making them compatible with operation of electronic components. Their thermal transport properties are not very favorable because of small values of thermal conductivity and heat of vaporization. To improve heat transfer in these fluids, design engineers have tried forced convection, structural modification of packages, and boiling.

In forced convection, microscopic channels are cut into the back of the silicon base of the ic chip. Typical channel dimensions are 50 μm wide and 300 μm deep. Experiments with water (not suitable for cooling an actual ic) have achieved heat transfers as large as 790 W per square centimeter of surface area.

Adding fins to the basic cylindrical pin form of an ic package can increase the heated surface area of the package by a factor of 8 to 12. The larger surface area increases heat transfer by convection, conduction, and radiation, reducing the effective value of r_{th} by as much as a factor of 20.

Heat flow values of 45 W/cm^2 have been obtained by allowing the cooling liquid to boil so that heat transfer by convection involves both liquid and vapor at the same time. However, the sudden drop in temperature at the surface of the ic package when boiling begins results in thermal stress on the package. Further work in package design is underway to try to minimize this problem.

Chip packaging has become both an art and a science. Careful layout of electronic components on the circuit board can minimize the overall thermal resistance of the chip, allowing the heat generated to dissipate more readily. Much recent attention has been devoted to research and development of new packages, so there will be rapid changes over the next few years in the heat limitations of ic technology.