electronic components and measurements

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checking the maximum temperature of semiconductor devices. They can be directly applied to the case of the component and thus the maximum operating temperature monitored directly in the actual circuit. The paints are useful when the temperature distribution over large surfaces is to be monitored.

20.3 thermal ratings of components

Most components are supplied by their manufacturers with one or more temperature and related power dissipation ratings. Virtually every device will have an upper and lower storage and operating temperature which is usually determined by the limits of thermal expansion and contraction and by the thermal limits of decomposition. Devices which generate significant amounts of heat internally, notably resistors and semiconductor devices, are also governed by power dissipation limits, which are related to the maximum permissible internal temperature at which the component can reliably operate. In the next section we will develop a simple model which describes the relationship between the maximum permissible temperatures and the internal power generation. We will, for the sake of clarity, consider the specific case of a transistor. However, the design techniques and conclusions are identical for power resistors and other semiconductor devices such as zener diodes, silicon controlled rectifiers, and power rectifiers.

20.3.1 thermal characteristics of transistors

As power is dissipated within the internal structure of a transistor, the temperature in that region increases until the heat flow through the transistor structure and outer case to the ambient surroundings just balances the internal power dissipation. The establishment of this steady-state balance is an example of the law of conservation of energy, since the power dissipation within a device is the rate of energy input (electrical) which in the steady-state must equal the rate of energy removal (thermal). The maximum power-dissipation rating of the transistor is then simply that rate of energy input which produces the maximum permissible internal operating temperature. Since the internal temperature will depend on the ambient temperature, the power-dissipation rating of a component is meaningless without some statement regarding ambient conditions.

Because the heat flow within a transistor is primarily by conduction, it is proportional to the temperature difference between the internal structure and the transistor outer case:

$$T_J = T_C + \theta_{JC} P_D \tag{20.1}$$

where T_J is the internal temperature (junction temperature in a transistor), T_C is the case temperature, and P_D is the internal power dissipation. The parameter θ_{JC} is called the *thermal resistance* with dimensions °C/watt, and the subscripts indicate that it relates the junction and case temperatures to the thermal heat flow. For a given transistor, $T_{J(\max)}$ and θ_{JC} are specified parameters. In silicon transistors $T_{J(\max)}$ is normally 200°C, while in germanium devices $T_{J(\max)}$ is usually 100°C. The value of θ_{JC} depends on the mechanical size of the structure and ranges from 0.5°C/watt in high-power units to 500°C/watt in miniature transistors intended for low-power applications.

Equation (20.1) also relates the maximum internal power dissipation to the corresponding maximum case and junction temperatures. This information is frequently presented in graphical form, known as the *power-temperature derating curve*, shown in Figure 20.5. The slope of this curve is called the *derating factor*, which is the reciprocal of θ_{JC}. Some data sheets give the derating factor rather than the thermal resistance. The maximum power dissipation in Figure 20.5 is shown constant below 25°C rather than the continued increase predicted by (20.1). This is a statement of the maximum permissible temperature difference between the junction and case which is governed by differential thermal expansion considerations rather than the absolute junction temperature.

The transistor described in Figure 20.5 would be called a 100-watt transistor in the advertising literature. But this dissipation level can only be achieved if the case temperature is held at 25°C or less—not an insignificant problem. For example, at a case temperature of 112°C the maximum dissipation is reduced to 50 watts. Thus, high-power dissipation levels require careful attention to the cooling of the transistor case.

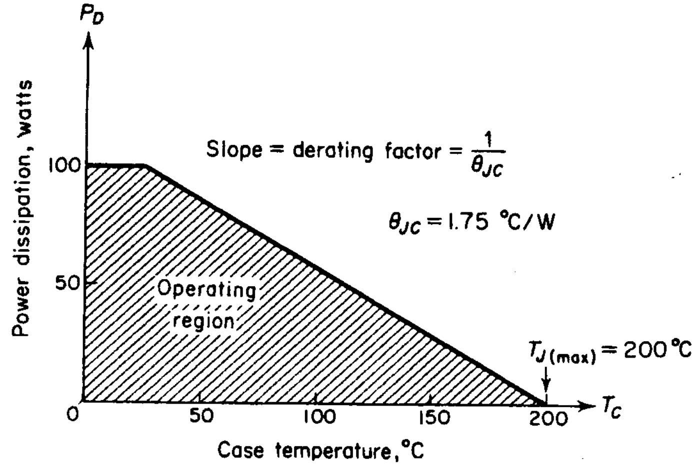


Figure 20.5. Typical power-temperature derating curve for a silicon power transistor.

For a transistor case to dissipate power to its surroundings, the case temperature must increase above the ambient temperature T_A. Since the heat rejection process involves conduction, convection, and radiation, it is in general a nonlinear function of the case-to-ambient temperature differential. However, in most practical situations, a linear approximation to the actual function is sufficiently accurate. Thus, we can relate the case temperature to the ambient temperature and power dissipation as follows:

$$T_C = T_A + \theta_{CA} P_D \tag{20.2}$$

where θ_{CA} is the thermal resistance between the transistor case and the ambient. For a transistor mounted in air, θ_{CA} is mainly a function of the case surface area, and typical values for some common transistor cases are given in Table 20.4. By combining (20.1) and (20.2) we obtain the relationship between T_J, T_A, and P_D,

$$T_J = T_A + (\theta_{JC} + \theta_{CA})P_D = \theta_{JA} P_D \tag{20.3}$$

where θ_{JA} is the total thermal resistance between the internal structure and the ambient, given by the sum of θ_{JC} and θ_{CA}.

Table 20.4 / Case to Ambient (Free Air) Thermal Resistance

Transistor Case	θ_{CA} (°C/watt)
TO-3	33
TO-5	125–200
TO-18	250–350

In a low-power transistor, θ_{JC} and θ_{CA} are usually the same order of magnitude. However, in a high-power transistor θ_{CA} may be much larger than θ_{JC}. For example, if the 100-watt silicon transistor, whose derating curve was shown in Figure 20.5, were mounted in a TO-3 case, then

$$\theta_{JA} = 1.75 + 33 = 34.75° \text{ C/watt} \tag{20.4}$$

for the transistor in free air. Thus the maximum power dissipation in free air for T_A = 25°C becomes, from (20.3),

$$P_D = \frac{200 - 25}{34.75} = 5 \text{ watts!!} \tag{20.5}$$

Thus we see that the 100-watt transistor has a much reduced power dissipation capacity when simply mounted in free air.

Exercise 20.4

From the thermal characteristics listed on the data sheet for a 2N5067 power transistor and the data in Table 20.4, determine the maximum power dissipation of the transistor in free air. Calculate the free air case temperature T_C when the transistor is operated at 80% of the maximum power dissipation.

Exercise 20.5

Solder the copper-constantan thermocouple previously constructed into the slot of a 6-32 × $\frac{1}{2}$ in. round-head brass screw. Mount this screw in one hole of a 2N5067 transistor which is in free air. Connect the thermocouple to a voltmeter and compensate for the reference junction. Using the circuit of Figure 20.6, adjust the collector current so that the power dissipation ($P_D = I_C V_{CE}$) is 80% of the maximum value. Measure the case temperature and compare it with the calculation of the previous exercise.

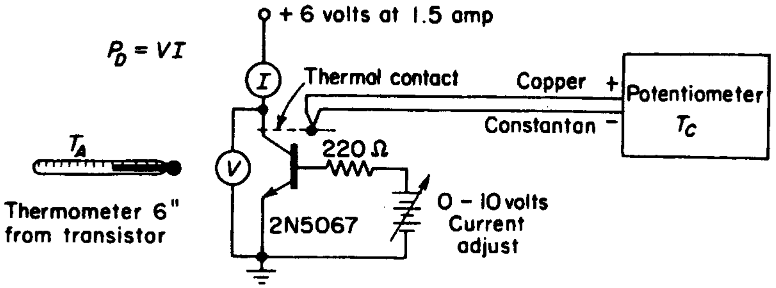


Figure 20.6. Measurement of transistor case temperature.

Exercise 20.6

Calculate the thermal resistance to ambient and maximum internal operating temperature for a 1-watt carbon composition resistor using the power derating curve shown in Figure 7.3.

20.4 heat sinks

We have seen in Section 20.3.1 that the major factor limiting transistor power dissipation capability is the high thermal resistance from the component case to the ambient surroundings. In order to increase the power-handling capability, the component case must be mounted in intimate thermal contact with a *heat sink*. A heat sink is simply a device with an improved heat-transfer capability and hence a low thermal resistance to the ambient surrounding. The heat sink may consist of a metal chassis, a finned structure with or without forced-air cooling, or even a liquid-cooled structure for maximum heat transfer in a minimum volume. The available shapes and sizes vary widely, with some typical examples illustrated in Figure 20.7.

The choice of a particular heat sink for a specific application begins by calculating from Equation (20.3) the required value for the net thermal resistance from the transistor case to the ambient, θ_{CA}, in terms of the required power dissipation P_D, the thermal characteristics of the transistor $T_{J(\max)}$ and θ_{JC}, and the maximum ambient temperature T_A. Note that the maximum expected ambient temperature must be used for this calculation in order that the maximum permissible junction temperature not be exceeded under the worst case ambient conditions. If the required net value of θ_{CA} is greater than about 2°C/watt, a forced air heat sink is indicated. For thermal resistances less than 0.2°C/watt a liquid-cooled heat exchanger will normally be required, although it probably would be better to consider an alternate transistor with a higher dissipation capability or a parallel combination of transistors in order to divide the power dissipation requirement among several devices.

Although there are heat sinks specifically designed for forced-air cooling, an air flow directed at a free-convection heat sink will substantially increase the heat dissipation capacity. This is illustrated in Figure 20.8, which shows the thermal characteristics of a Motorola MS-10 heat sink. We thus see that a small fan providing general ventilation for an instrument may improve free-convection heat-sink performance to the point that a specialized forced-air system is not required. It will also be noticed in Figure 20.8 that at the higher temperatures the heat flow improves somewhat over that calculated from the nominal θ_{SA} of 3°C/watt. This nonlinearity in the thermal characteristic is due to the effects of convection and radiation on the overall heat transfer from sink to ambient. However, for design purposes the low-temperature nominal value of θ_{SA} will provide a conservative calculation of junction temperature. In more demanding situations, the initial calculations can be corrected with the actual graphical data.

20.4.1 *heat sink mounting considerations*

The mechanical mounting of a transistor to a heat sink and of the heat sink to the chassis both influence the net heat rejection capabilities of the complete assembly. For convection-cooled heat sinks, mounting should provide a free air flow and be as far removed as possible from other heat-generating components. Also, mounting with cooling fins in a vertical plane will usually improve the heat rejection capacity through improved convection.

The method of mounting a transistor to a heat sink is an important factor in the net heat-rejection capability of the assembly. The manufacturer's specification for thermal resistance of a heat sink, θ_{SA}, is always

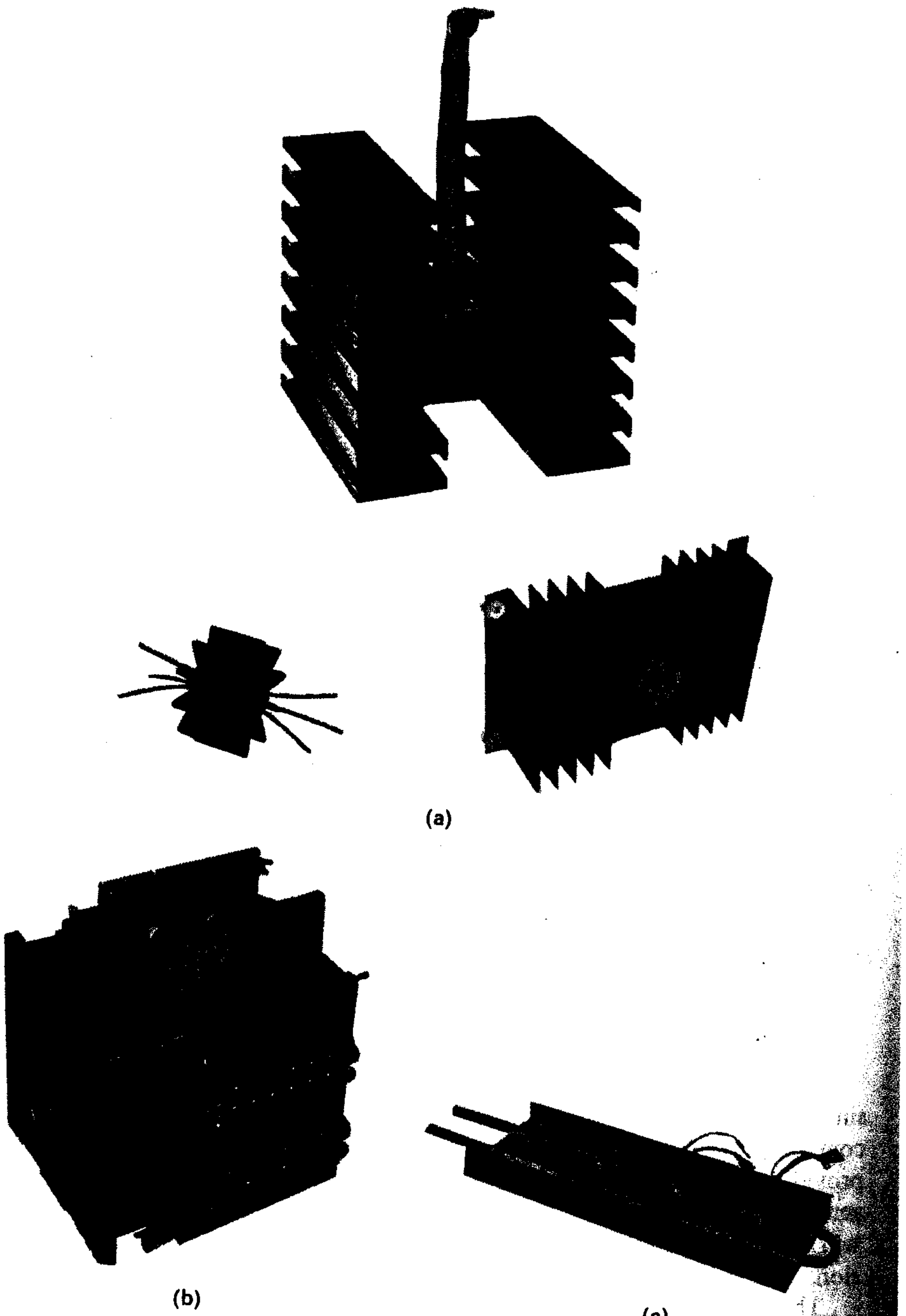
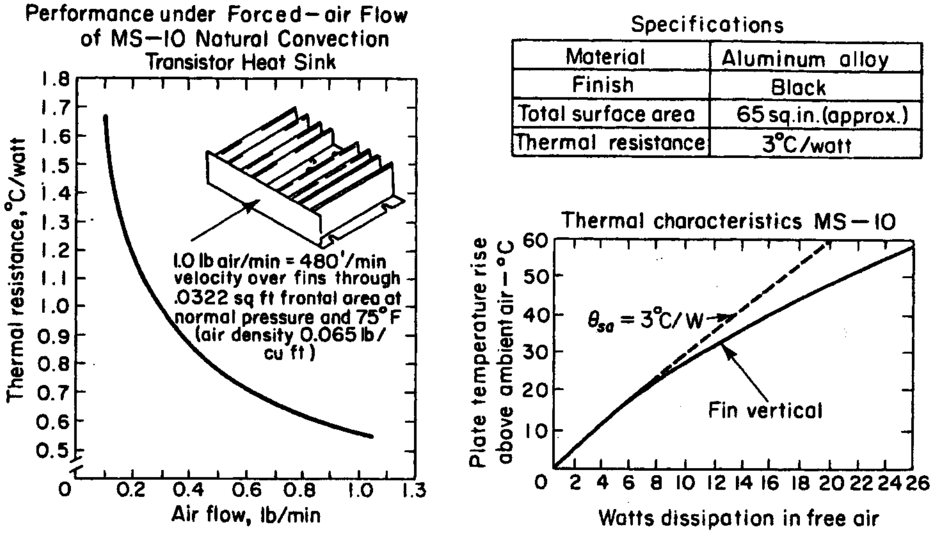


Figure 20.7. Typical heat sinks. (a) Natural convection. (b) Forced air. (c) Liquid cooled.



Specifications

Material	Aluminum alloy
Finish	Black
Total surface area	65 sq.in.(approx.)
Thermal resistance	3°C/watt

Figure 20.8. Typical thermal characteristics of a Motorola MS-10 heat sink.

measured between the heat-sink mounting surface and ambient. It does not include the additional component of thermal resistance θ_{CS} which exists at the case-to-heat sink interface. This additional component of thermal resistance, sometimes called the *thermal contact resistance*, is added to θ_{SA} to obtain the net thermal resistance from case-to-ambient:

$$\theta_{CA} = \theta_{CS} + \theta_{SA} \tag{20.6}$$

The specific value of θ_{CS} depends strongly on the properties of the mating surfaces, particularly smoothness and flatness, but is nominally 0.2°C/watt for a power transistor. In order to improve the thermal conduction at this interface, a thin coating of silicone lubricant, called *thermal joint* or *heat sink compound*, is applied to the mating surfaces, as shown in Figure 20.9. Typical examples of thermal joint compound are DC4 Silicone Lubricant and No. 340 Compound, manufactured by Dow Corning Co., and Thermacote, manufactured by the Thermalloy Company.

Since the minimum value of thermal contact resistance depends on intimate contact between case and sink, a secure mounting is important. However, overtightening of mounting screws and studs will often warp the mating surfaces and hence increase the contact resistance through decreased intimate contact area. Many specification sheets will include the maximum torque to be used in mounting a device in order to prevent mating-surface distortion.

Most power transistors have the collector junction electrically connected to the case in order to minimize θ_{JC}. Thus, the transistor case is at the

Figure 20.9. Application of thermal joint compound.

collector potential, which is not normally at zero volts or ground. Some electrical insulation is therefore necessary either between the heat sink and the chassis or between the transistor case and the heat sink. If the heat sink is protected by an enclosure, the fact that it may not be at ground potential may be of little consequence. However, heat sinks are often mounted on external surfaces in order to improve convection cooling. To prevent accidental short circuits in this situation the transistor itself should be insulated from the heat sink. Also, insulation of individual transistors may be required if more than one device is mounted on a single heat sink. Insulation from heat sinks is accomplished by placing an insulating washer between the transistor case and heat sink and by using insulating sleeves and washers with the mounting screws. This technique has the disadvantage that it may substantially increase the effective thermal contact resistance between the transistor case and heat sink. Typical insulating washer materials, along with their nominal values of θ_{CS}, are listed in Table 20.5. As in the case of no insulating washer, the use of a thermal joint compound will improve the heat transfer from case to sink. The choice of insulating washer is influenced not only by thermal resistance considerations, but also by dielectric strength, high frequency losses, and cost. In low-voltage applications, aluminum heat sinks with anodized coatings can provide sufficient insulation without the need for an insulating washer.

Exercise 20.7

Table 20.5 / Power Transistor Insulating Washers

Washer Material	Thermal Contact Resistance θ_{cs} (°C/watt) Dry Joint	 With Silicone Compound
Teflon-glass cloth	1.45	0.80
Mica	0.80	0.40
Beryllium oxide	0.70	0.50
Anodized aluminum	0.40	0.35
No insulating washer	0.20	0.10

Mount a 2N 5067 power transistor on a Motorola MS-10 (or equivalent) power transistor heat sink using the thermocouple-screw assembly from Exercise 20.5 for one mounting screw. Also attach the thermistor, previously calibrated, in one of the two holes near the edge of the heat-sink mounting surface. Use a thin coating of thermal joint compound, but do not use an insulating washer. (*Note:* For an accurate measurement of the thermal resistance of the heat sink, the temperature of the sink should actually be measured at the case-to-sink interface, not some distance away from the case.) From the thermal characteristics of the transistor, heat sink, and the nominal contact resistance, calculate the maximum permissible power dissipation for a 25°C ambient.

Using the circuit of Figure 20.10, adjust the power dissipation to 80% of the calculated maximum permissible value and measure the steady-state case temperature with the thermocouple. Monitor the heat sink temperature with the thermistor.

Compare the measured temperatures with calculated predictions and discuss the reasons for disagreement. Calculate the net thermal resistance from case-to-ambient from the measurement of T_C, T_A, and P_D.

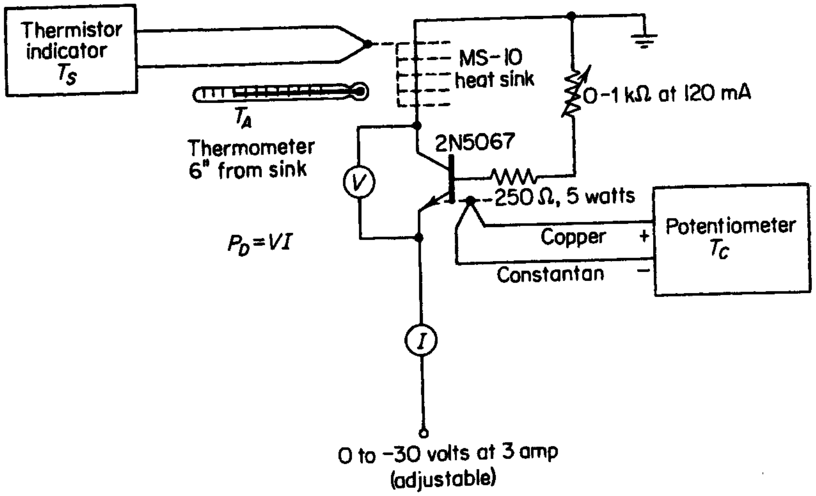


Figure 20.10. Evaluation of free-convection heat sink performance.

Exercise 20.8

With the transistor mounted as in the previous exercise and operating at 80% of the maximum power dissipation for free convection, direct the air flow from a fan onto the heat-sink assembly. From the new steady-state value of T_C, calculate net thermal resistance from case-to-ambient in the presence of the forced-air cooling. Compare this with the free-convection value obtained in the previous exercise.

20.5 references

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