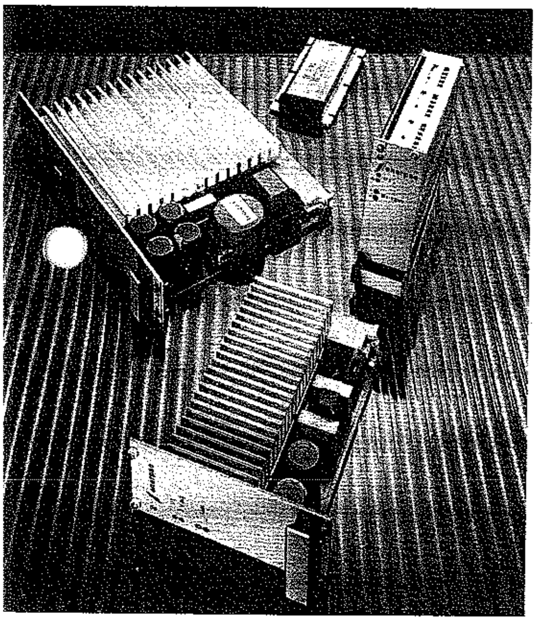
Designer heat sinks

Using two worked examples, Ray Fautley shows how quick and easy it is to determine heat sink size for any transistor or diode using a design table.

Semiconductor devices need to be mounted on metal panels of sufficient size and thermal conductivity to be able to conduct excessive heat away from the junction of the transistor or diode. This is necessary to prevent the temperature of the device's junction from exceeding its maximum rating.

The total thermal path between the device junction and the ambient temperature existing inside the case of the equipment is measured as a thermal resistance. It is referred to as $R_{th(j\text{-}amb)}$, or as $\theta_{(j\text{-}a)}$. This term that is easy to assess. You only need to know three things. One is the maximum allowable junction temperature – which for most discrete silicon devices may be assumed to be about 200°C. Secondly you need to know the ambient temperature, which, inside electronic equipment is usually about 50°C, and finally you need to know the power dissipated in the semiconductor.



This total thermal path $R_{th(j\text{-}amb)}$ comprises three parts,

- The thermal path from device function to its case, $R_{th(j\text{-}c)}$, also called $\theta_{th(j\text{-}c)}$ or $R_{th(j\text{-}mb)}$.
- The thermal path between the case of the device and the heat-sink to which it is fitted, $R_{th(c\text{-}hs)}$, also called $\theta_{th(c\text{-}hs)}$.
- The thermal path between the heat-sink and the ambient temperature inside the equipment, $R_{th(hs\text{-}amb)}$, or $\theta_{(h\text{-}a)}$.

All of these three paths – and of course, the total path $R_{th(j\text{-}amb)}$ are measured in °C/W. This makes the total thermal path $R_{th(j\text{-}amb)}=R_{th(j\text{-}c)}+R_{th(c\text{-}hs)}+R_{th(hs\text{-}amb)}$.

The first of the three terms, $R_{th(j\text{-}c)}$, can be found in the data sheets provided by the manufacturer of the semiconductor device.

Path $R_{th(c\text{-}hs)}$ depends on the method used to mount the transistor or diode to the heat-sink. In some cases the device may be mounted directly on to the heat-sink, but in others it may be necessary to provide some form of electrical insulation between the device and the heat-sink.

Unfortunately, electrical insulation also means some degree of heat insulation so a compromise is necessary. A thin mica washer can provide the electrical insulation. As the semiconductor's working voltage does not exceed a few tens of volts, a thick insulator is unnecessary.

Heat conduction is assisted by the use of silicon grease between the surfaces. Path $R_{th(c\text{-}hs)}$ can be considered to be between 0.1 and 0.7°C/W. In practice, a value of 0.4°C/W is usually acceptable for this term. This leaves the third term, $R_{th(hs\text{-}amb)}$, which needs to be evaluated.

Ray Fautley, C Eng, MIEE

Heat sink design steps

1. From the semiconductor data sheet, find $R_{th(j\text{-}c)}$ in °C/W.
2. Determine $R_{th(c\text{-}hs)}$ in °C/W. This value depends on the effectiveness of the thermal contact between the case of the semiconductor and the surface of the heat-sink. A value of 0.4°C/W will be a good enough approximation if the actual value is unknown.
3. Determine the power dissipated in the device,

   (a) For power-amplifier transistors the power dissipated is,

   $$P_D=P_{in}-P_{out}.$$
   $$=V_{ce}\times I_c-P_{ac}$$

   (b) For rectifier diodes,

   $$P_D=V_D-I_{ave}.$$

4. Find,

   $$R_{th(j-amb)}=\frac{T_j-T_{amb}}{P_D}\text{ in °C/W}$$

For silicon devices, maximum junction temperature T_j is usually 200°C, but to be safe it is better to design around 150°C. In some cases T_j may be specified lower than 200°C, so always check with the manufacturer's data before proceeding with the heat-sink design. Inside the equipment, the ambient temperature T_{amb} can be assumed to be 50°C.

Heat sink terms

Term	Description	Units
I_{ave}	Average current through diode	A dc
I_c	Transistor collector current	A dc
P_D	Power dissipated in transistor	W
P_{in}	Power input to device, dc	W
P_{out}	Output power – rf or af from transistor	W
$R_{th(c\text{-}hs)}$	Thermal resistance between device case and heat-sink	°C/W
$R_{th(hs\text{-}amb)}$	Thermal resistance between heat-sink and T_{amb}	°C/W
$R_{th(j\text{-}amb)}$	Thermal resistance between device junction and T_{amb}	°C/W
$R_{th(j\text{-}c)}$	Thermal resistance between device junction and case	°C/W
T_{amb}	Ambient temperature inside equipment	°C
T_j	Maximum temperature of device junction	°C
V_{ce}	Potential between collector and emitter of device	V
V_d	Voltage drop across diode at stated current	V dc

5. Determine,

   $R_{th(hs\text{-}amb)}=R_{th(j\text{-}amb)}-R_{th(j\text{-}c)}-R_{th(c\text{-}hs)}$

6. The surface area of the heat-sink required to provide the necessary $R_{th(hs\text{-}amb)}$ can be found from **Table 1**.

A variation of the thickness of the heat-sink between 1mm and 5mm does not have very much effect. It is surface area that counts. These figures should provide adequate design margins.

Note that the surface areas in the table are for one side of the heat-sink only, the total surface area is thus twice the table figure – plus twice the thickness of the metal.

All heat-sink surfaces are assumed to be painted matt-black and mounted horizontally. Vertical mounting increases the cooling effect and adds a further margin of safety. But bright metal surfaces will need the figures of Table 1 to be increased by some 33%.

Note that the figures were arrived by experimentation. After comparing various results using different methods for arriving at the necessary surface area for the same value of $R_{th(hs\text{-}amb)}$, agreement was not 100%.

Design examples

These two worked examples should help clarify the design procedure for you.

Example 1. A rectifier diode, for which the manufacturer's data gives $R_{th(j\text{-}c)}$=5°C/W, has a forward voltage drop 1.0V when the average current through it – or dc load – is 5A. The maximum junction temperature T_j of the diode is given as 100°C. Inside the equipment that the rectifier is to be used in, the ambient temperature will be assumed to be 50°C.

Design procedure

1. $R_{th(j\text{-}c)}$ is known to be 5°C/W.
2. Assume that $R_{th(c\text{-}hs)}$ will be 0.4°C/W.
3. Power dissipated in the diode is,

   $P_d=V_d\times I_{ave}$

   $=1.0\times5=5$W for a T_j of 100°C

4. $$R_{th(j-amb)}=\frac{T_j-T_{amb}}{P_D}$$

   $$=\frac{100-50}{5}=\frac{50}{5}=10°C/W$$

5. $R_{th(hs\text{-}amb)}=R_{th(j\text{-}amb)}-R_{th(j\text{-}c)}-R_{th(c\text{-}hs)}$

   $=10-5-0.4=4.6$°C/W

6. Referring to Table 1 gives the following dimensions for a suitable heat-sink.

   For copper, 84cm^2 or 9.2cm×9.2cm
   For aluminium, 100cm^2 or 10cm×10cm
   For brass, 113cm^2 or 10.6cm×10.6cm
   For steel, 128cm^2 or 11.3cm×11.3cm

Example 2.
A *BLW81* transistor is to be used as a vhf power amplifier to provide a cw output of 10W.

Design procedure

1. The thermal resistance from junction to case $R_{th(j\text{-}c)}$ is given by its manufacturer as 4.3°C/W.
2. Say R_{th} is 0.4°C/W.
3. Efficiency of the *BLW81* is given as about 60% as a cw amplifier, so the input power for 10W output will be,

   $$P_{in}=\frac{P_{out}}{0.6}=\frac{10}{0.6}=16.7W$$

   So,

   $P_D=P_{in}-P_{out}=16.7-10=6.7$W.

4. $$R_{th(j-amb)}=\frac{T_j-T_{amb}}{P_D}$$

   $$=\frac{150-50}{6.7}=14.9°C/W$$

5. $R_{th(hs\text{-}amb)}=R_{th(j\text{-}amb)}-R_{th(j\text{-}c)}-R_{th(c\text{-}hs)}$

   $=14.9-4.3-0.4=10.2$°C/W

6. From Table 1, suitable heat-sinks are,

   For copper, 29cm^2 or 5.4cm×5.4cm
   For aluminium, 35cm^2 or 5.9cm×5.9cm
   For brass, 37cm^2 or 6.4cm×6.4cm
   For steel, 130cm^2 or 11.4cm×11.4cm

My thanks to Anglia Microwaves of Billericay, Essex for their help in providing semiconductor data. ■

Table 1. These figures give you the surface area in cm^2 for one side of the heat sink for a known value of $R_{th(hs\text{-}amb)}$.

$R_{th(hs\text{-}amb)}$ °C/W	Material Copper	Aluminium	Brass	Steel
1	734	—	—	—
1.5	342	—	—	—
2	220	376	477	—
2.5	175	277	302	711
3	135	187	210	338
3.5	116	149	175	222
4	94	120	150	165
4.5	85	102	115	132
5	70	83	90	109
6	53	68	72	82
7	41	61	63	66
8	37	55	58	61
9	33	39	44	47
10	29	35	37	41
11	26	30	33	36
12	24	29	30	32
13	22	27	29	30
14	20	25	26	27
20	14	17	18	20