SCRs, Triacs, and AC switches,thermal management precautions for handling and mounting

Introduction

The behavior of a semiconductor device depends on the temperature of its silicon chip. This is why electrical parameters are given at a specified temperature.

To sustain the performance of a component and to avoid failure, the temperature has to be limited by managing the heat transfer between the chip and the ambient atmosphere. The aim of this note is to show how to calculate a suitable heatsink for a semiconductor device and the precautions needed for handling, mounting and soldering techniques.

1 Through-hole packages

1.1 Thermal resistance

1.1.1 Review

The thermal resistance of a semiconductor assembly is the parameter, which characterizes its resistance to the heat flow generated by the junction during operation. A temperature exceeding the maximum junction temperature curtails the electrical performance and may damage the device.

The maximum dissipated power capability is:

$$P_{\max} = \frac{T_{j\max} - T_a}{R_{th(j-a)}} \quad (1)$$

Where:

- T_{jmax} is the maximum junction temperature of the semiconductor in degrees (°C)
- T_a is the ambient air temperature in degrees (°C)
- $R_{th(j-a)}$ is the thermal resistance between the junction and ambient air in °C/W

The $R_{th(j-a)}$ takes into account all materials between the junction and ambient air.

An analogy between ohm's law and the thermal equivalent circuit can be made:

- Electrical resistance corresponds to thermal resistance
- Current corresponds to dissipated power
- Voltage corresponds to temperature

Thus:

$$V = R \cdot I \text{ correspond to } \Delta T = R_{th} \cdot P$$

1.1.2 Dissipated power for a thyristor or a triac

The maximum power dissipation versus average on-state current (for SCRs) or RMS onstate current (for triacs) is given in the datasheet for each product. However, a more accurate result is obtained by using the V_{to} and R_d values with the Eq. (2)

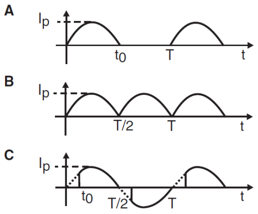
$$P = V_{to} \cdot I_{T(AV)} + R_d \cdot I^2_{T(RMS)} \quad (2)$$

Where:

- V_{to} is the threshold voltage specified in the datasheet
- R_d is the dynamic on-state resistance specified as R_d in the datasheet
- $I_{T(AV)}$ is the average on-state current
- $I_{T(RMS)}$ is the RMS on-state current

Figure 1 shows the RMS and average values for different waveforms of current.

Figure 1. RMS and average currents



$$I_{T(AV)} = \frac{1}{T}\int_0^T i(t)dt \qquad I^2_{T(RMS)} = \frac{1}{T}\int_0^T i^2(t)dt$$

A: $$I_{T(AV)} = \frac{2 \cdot I_p \cdot t_0}{\pi \cdot T} \qquad I^2_{T(RMS)} = \frac{I_p^2 \cdot t_0}{2 \cdot T}$$

B: $$I_{T(AV)} = \frac{2 \cdot I_p}{\pi} \qquad I^2_{T(RMS)} = \frac{I_p^2}{2}$$

C: $$I^2_{T(RMS)} = \frac{I_p^2}{2}\left(1 - \frac{2 \cdot t_0}{T} + \frac{1}{2 \cdot \pi} \cdot \sin\left(\frac{4 \cdot \pi \cdot t_0}{T}\right)\right)$$

$$I_{T(AV)} = 2 \cdot I_p \cdot \frac{\cos^2\left(t_0 \cdot \frac{\pi}{T}\right)}{\pi}$$

1.1.3 Dissipated power in a triac

A triac is made up of two thyristors connected back to back. This means we consider the sum of the dissipated power of both thyristors. The following Eq. (3) gives the total dissipated power versus $I_{T(RMS)}$ current through the triac (see Figure 1 (C) with t_0 = 0):

$$P = \frac{2 \cdot \sqrt{2}}{\pi} \cdot I_{T(RMS)} \cdot V_{to} + R_d \cdot I^2_{T(RMS)} \tag{3}$$

For a phase angle conduction the RMS current is given in Figure 1 (C).

1.1.4 Triac without external heatsink

Figure 2 shows the thermal equivalent diagram for a triac without external heatsink.

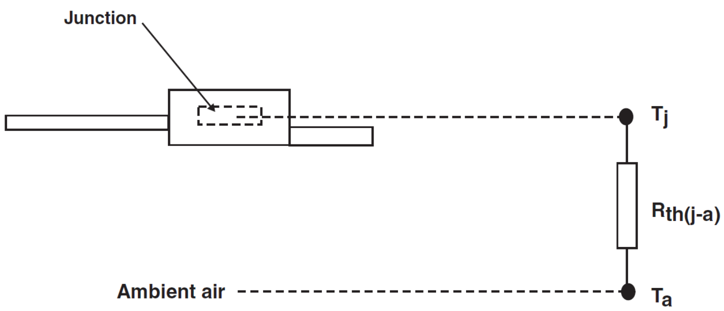
In practice the imposed parameters are:

- T_a: ambient air temperature where the triac is located
- $R_{th(j-a)}$: thermal resistance between junction and ambient air given in the datasheet
- P: dissipated power in the triac depending on the used triac and on the load current

The following Eq. (4) defines the junction temperature depending on these parameters:

$$T_j = P \cdot R_{th(j-a)} + T_a \tag{4}$$

Figure 2. Thermal equivalent diagram



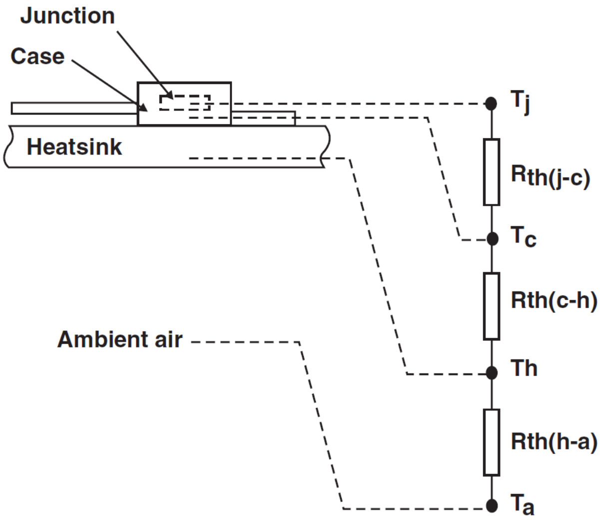
1.1.5 Triac with external heatsink

If the estimated junction temperature is higher than the maximum junction temperature specified in the datasheet, a heatsink has to be used.

Recommendation: this calculation has to be made in the worst case scenario i.e with the maximum dissipated power, load, and line voltage dispersions. We have to consider the maximum ambient temperature around the component that is, inside the box where the triac is located.

The same approach as presented in the previous section allows a suitable heatsink to be defined. Figure 3 shows the thermal equivalent diagram.

Figure 3. Thermal equivalent diagram with external heatsink



The Eq. (5) to calculate the thermal resistance between the heatsink and ambient air is the following:

$$R_{th(h-a)} = \frac{T_j - T_a}{P} - R_{th(j-c)} - R_{th(c-h)} \quad (5)$$

Where:

- T_j is the junction temperature in °C
- P is the maximum dissipated power in W
- $R_{th(j-c)}$ is the thermal resistance between junction and case in °C/W

$R_{th(c-h)}$ is the thermal resistance between case and heatsink in °C/W, depending on the contact case/heatsink. Since the current alternates in a triac, we have to consider the $R_{th(j-c)}$ in alternating current, which is different to the $R_{th(j-c)}$ in direct current.

This difference is due to the die of the triac. The first half of the silicon die works when the current is positive, the second when the current is negative. Because of the thermal coupling between these two parts, this gives the following Eq. (6):

$$R_{th(j-c)AC} = 0.75 \cdot R_{th(j-c)DC} \quad (6)$$

1.1.6 Choice of heatsink

Choosing a heatsink depends on several parameters; the thermal characteristic, the shape, and the cost.

However, in some applications a flat heatsink can be sufficient. Figure 4 shows the curve Rth(h-a) versus the length of a flat square heatsink for different materials and thickness.

Some applications need heatsinks with an optimized shape where the thermal resistances are not known.

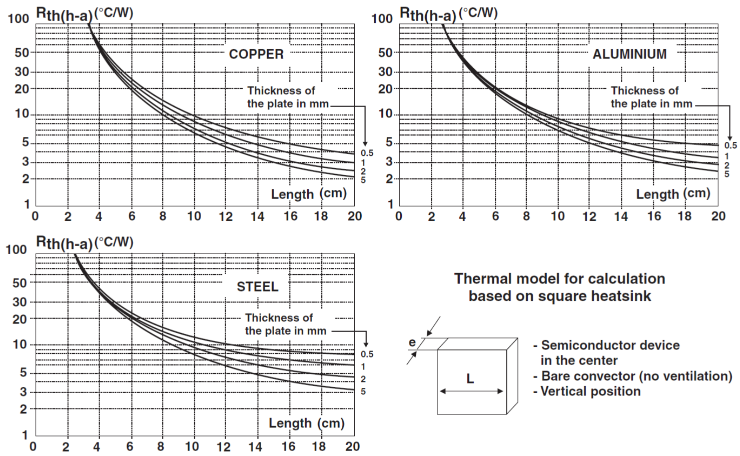
For this, the best solution involves measuring the case temperature of the component in the worst case scenario and keeping to the following Eq. (7):

$$T_C < T_{j\max} - P \cdot R_{th(j-c)} \tag{7}$$

Where:

- T_c is the case for temperature
- T_{jmax} is the maximum junction temperature
- P is the dissipated power in the component
- $R_{th(j-c)}$ is the thermal resistance between junction and case.

Figure 4. $R_{th(h-a)}$ versus the length of a flat square heatsink



1.1.7 Forced cooling

For high power or very high power applications, a forced-air or liquid cooling heatsink may be required. Heatsink manufacturers give a coefficient depending on the air or liquid flow.

However, in some applications like vacuum cleaners, dissipated power is only a few watts and air flow cooling is available. This allows a very small heatsink to be used, very often a flat aluminum heatsink. In this case it is necessary to measure the case temperature in the worst case scenario and to check the following formula:

$$T_C < T_{j\max} - P \cdot R_{th(j-c)} \tag{8}$$

1.2 Thermal impedance

In steady state, a thermal equivalent circuit can be made only with thermal resistances.

However, for pulse operation it can be useful to consider the thermal impedance, especially when the component is on during a time lower than the time to reach the thermal resistance.

The thermal impedance value versus pulse duration is given in the datasheets (see an example in Figure 5), in the form of the relationship Z_{th}/R_{th} plotted against pulse duration.

For example, BTA08-800SW is able to dissipate ≈ 27 W without heatsink during 1 s (see Eq. (9)):

$$P = \frac{T_{jmax} - T_{amax}}{Z_{th(j-a)(1s)}} \quad (9)$$

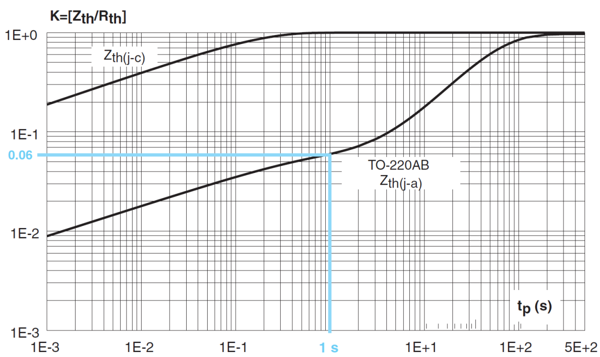
$Z_{th(j-a)}$ can be obtained from the datasheet by reading the value of the ratio Z_{th}/R_{th} from the curve (in the case of this product the ratio is 0.06 as seen in Figure 5) and multiplying the ratio by the value of $R_{th(j-a)}$ from the datasheet. For this example $R_{th(j-a)}$ is 60 °C/W (see Eq. (10)):

$$P = \frac{125 - 25}{60 \times 0.06} = 27.5W \quad (10)$$

In steady state, with the same ambient temperature, the same triac is able to dissipate (see Eq. (11)):

$$P = \frac{125 - 25}{60} = 1.7W \quad (11)$$

Figure 5. **Thermal transient impedance of a BTA08-800SW**



1.3 Insulating materials

We can classify them in 3 types as following:

Mica insulators

This has been the most commonly used insulator for many years. Its insulating quality is good, but due to its rigidity the thermal interface is not very good, and needs contact grease on both sides. Because of its rigidity it can be easily broken.

Ceramic insulators

More expensive than mica, their thermal resistances are lower. Due to their rigidity, they also need contact grease. However, they can be easily broken, as they are less fragile than mica.

Silicone insulators

These materials are not rigid and therefore do not need contact grease. They assume the shape of the component and of the heatsink if sufficient pressure is applied. The problems previously explained disappear. According to manufacturers, the stability in time is much better than with contact grease. However the thermal resistance is higher than the combination of the mica + grease.

Table 1. **$R_{th(c-h)}$ for different materials for TO-220AB package**

	Contact grease	Mica + grease thickness = 80 µm	Mica dry thickness = 80 µm	Silicone insulator
$R_{th(c-h)}$ °C	0.5	1.7	4	2.6

Table 1 shows the thermal resistance for different TO-220AB insulators and for a given pressure (F = 30 N).

1.4 Insulated components

Most of the thyristors and triacs manufactured by STMicroelectronics are available in insulated and noninsulated packages. For insulated packages, insulation can be achieved in two different ways:

- Ceramic between the die pad and the heatsink of the component (TO-220AB/TOP3/RD91 packages)
- Resin used for encapsulation (ISOWATT220AB/TO-220FPAB packages)

All insulated packages delivered by STMicroelectronics are in accordance with the UL1557 recognition applicable for "electrically isolated semiconductors". The added material increases the thermal resistance between the junction and the case, but the total thermal resistance ($R_{th(j-a)}$) is lower than the one when using a noninsulated component with an external insulating material. In addition, it simplifies assembly and reduces the cost.

For two 16 A triacs in the TO-220AB package, $R_{th(j-c)AC}$ values (°C/W) are shown in Table 2:

Table 2. Comparison of $R_{th(j-c)}$ for sample insulated and noninsulated products

BTA16-800CW (insulated version)	BTB16-800CW (noninsulated version)
2.1 device	1.2 device
+0.5 grease	+1.7 mica + grease
= 2.6 total	= 2.9 total

1.5 Handling and mounting techniques

The use of inappropriate techniques or unsuitable tools during handling and mounting can affect the long-term reliability of the device, or even damage it.

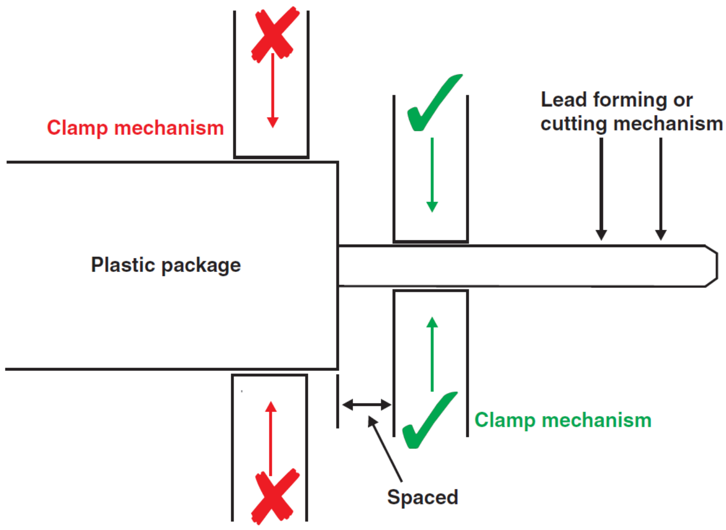
1.5.1 Bending and cutting leads

Lead bending must be done carefully. The lead must be firmly held between the plastic package and the bending point during lead operation. If the package / lead interface is strained, the resistance to humidity is impaired and in addition mechanical stress is inflicted on the die. This damage can affect the long-term reliability of the devices.

There are six basic rules to bear in mind:

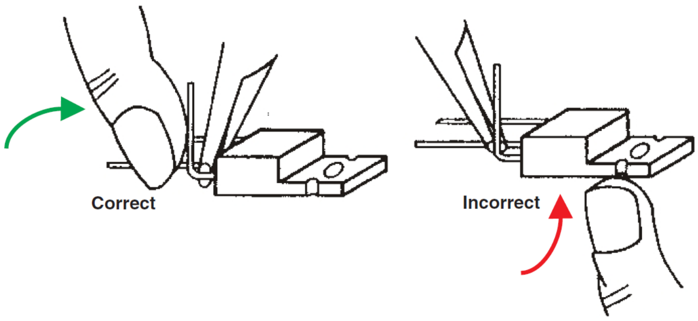
1. Never clamp the plastic package (Figure 6)

Figure 6. Clamping the lead not the package



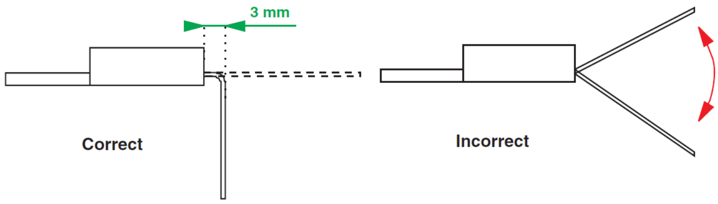
2. Clamp the leads firmly between the plastic package and the bend / cut point (Figure 7)

Figure 7. Clamping the lead between the package and the bend / cut point



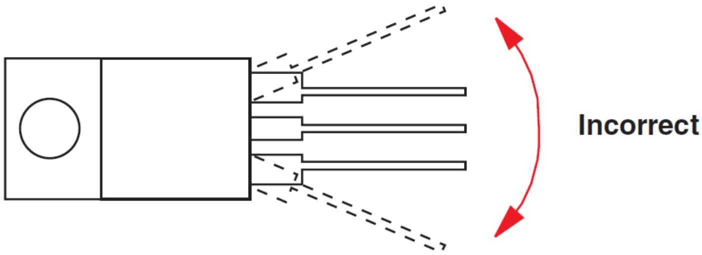
3. Bend the leads at least 3 mm from the plastic package (Figure 8)

Figure 8. Bending the lead at least 3 mm from the plastic package



4. Never bend the leads laterally (Figure 9)

Figure 9. Bending the lead laterally (not allowed)



5. Never bend the leads more than 90° and never bend more than once
6. Make sure that the bending / cutting tool does not damage the leads.

1.5.2 Using a heatsink

Mounting surface preparation

- The mounting surface should be flat, clean, and free of burrs and scratches
- The use of a thin layer of thermal silicone grease ensures a very low contact thermal resistance between the component and the heatsink. An excessively thick layer or an excessively viscous silicone grease may have the opposite effect and cause the deformation of the tab.
- The planarity of the contact surface between device and heatsink must be very low (less than 50 µm for TO-220AB).

Insertion

If the heatsink is mounted on the PC board, it should be attached to the component before the soldering process of the leads.

Mounting techniques

Mounting must be done carefully. Excessive stress may induce distortion of the tab and as a consequence mechanical damage on the die.

Soldering

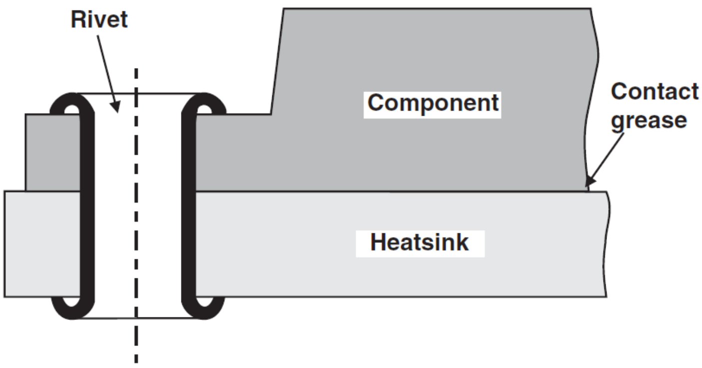
It is not recommended for through-hole packages.

With rivets: Pop rivets should never be used for the following reasons:

- A too rigorous expansion of the metal can lead to a distortion of the heatsink hole and induce mechanical stresses on the die
- High crimping shock can damage the die.

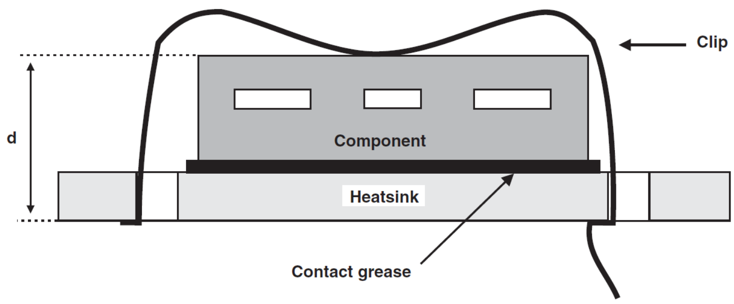
Press rivets can be used with caution provided they are of a soft metal like aluminum. The crimping force must be applied slowly and carefully to avoid shock and deformation of the heatsink.

Figure 10. Assembly with rivet



With clips: Care should be taken with the contact area between the plastic case and the clip: the maximum pressure allowed on plastic is 150 N/mm2. Over this value, cracks may be induced in the package. Therefore, the clips have to be round or smooth in the contact area to avoid concentrated loads on the plastic body. The force applied on the component depends on the heatsink and the component thickness, so they must be specially designed to take this value into account. Screw assembly is preferred to clip assembly for insulated packages.

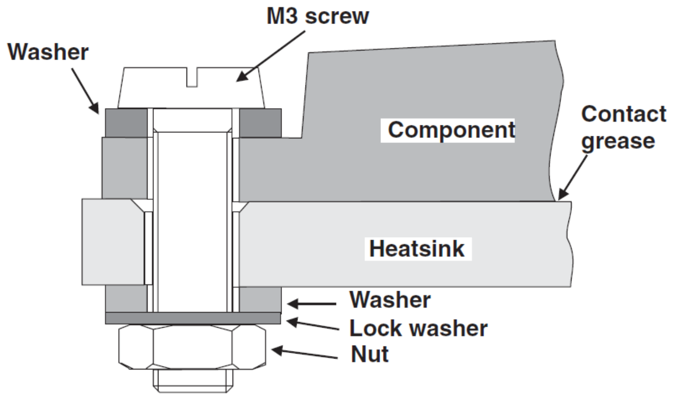
Figure 11. Clip assembly



With screws: The following precautionary measures should be taken:

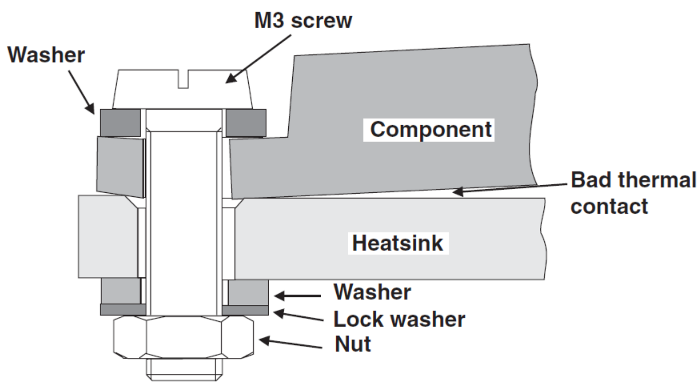
- To avoid tab distortion, a rectangular washer must be put between the screw head and the tab, and a compression washer must be put between the tab and the nut

Figure 12. Correct assembly



- Take care to avoid mechanical shock during screwing
- Keep the screw straight
- Appropriate screwing torque should be used, excessive screwing torque may cause the distortion of the tab and induce bad thermal contact. In addition it can generate cracks in the die.

Figure 13. Incorrect assembly



The thermal contact resistance depends on the force generated by the applied torque on the screw (see Eq. (12)):

$$F = \frac{2 \cdot T \cdot \pi}{P + r \cdot D \cdot \pi} \quad (12)$$

Where:

- T is applied torque on the screw in N.m
- P is pitch in m
- D is the screw diameter in m
- r is the rubbing factor: # 0.12 for steel-steel with grease and # 0.2 for steel-aluminium

The relative variation of the $R_{th(c-h)}$, compared with the value of $R_{th(c-h)}$ at 0.6 Nm versus the torque for an M3 screw used for the TO220AB is given in Figure 14.

Figure 14. **Relative variation of $R_{th(c-h)}$ compared with $R_{th(c-h)}$ at 0.6 Nm versus torque for TO-220AB**

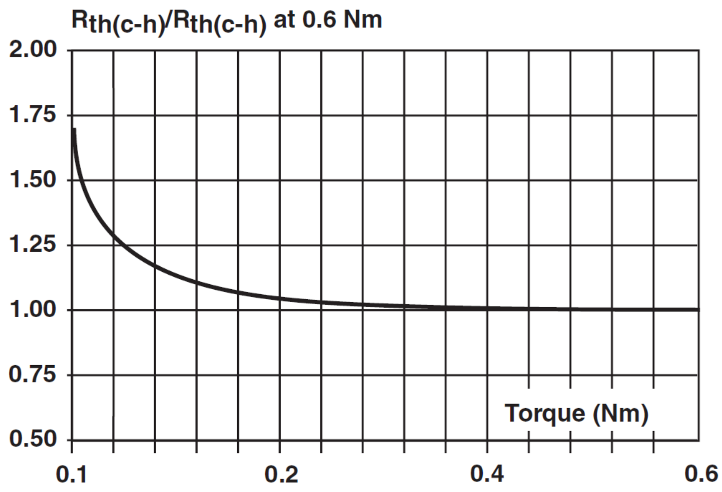


Table 3. **Recommended torque and thermal contact resistance**

Package	Torque (Nm)	Thermal contact resistance (°C/W)
TO-220AB / PENTAWATT	0.4 to 0.6	0.5
ISOWATT220 / TO-220FPAB	0.4 to 0.6	0.5
TOP3 / TOP3I	0.9 to 1.2	0.1
RD91	0.9 to 1.2	0.1

1. *For BTB20-xxx, BTB24-xxx and TYNxx40, the maximum torque is 0.5 Nm.*

1.6 Through-hole package wave soldering

The lead-free through-hole devices may be soldered with lead-free solder pastes or alloys (Sn-Ag-Cu based alloys). The typical soldering temperature is 260 °C. Alternatively these devices may be soldered with SnPb based solder pastes. The soldering temperature is then typically around 220 °C. Interface adherences on through-hole package structures are qualified to sustain only three consecutive dips of their connections in a solder pot at 260 °C (-0 °C/+5 °C).

- Immersion duration: 10 seconds each
- Delay between two dippings: 5 minutes
- Minimum distance solder to package plastic body: according to packages, by default 1 mm.

Lead-free devices are described in an internal specification defining:

- Their characteristics: lead-free connection coating, solderability, and identification features
- Their reliability such as soldering resistance, reliability performance, whiskers risk prevention.

This specification is available for STMicroelectronics customers upon request (title: ECOPACK components definition and characteristics). Consult that document for further information.

2 Surface mount packages

2.1 Thermal resistance

The thermal resistance of a semiconductor device characterizes the device’s capability to dissipate the heat generated by the chip during operation. This parameter allows us to calculate the junction temperature, taking into account the device environment (load current, ambient temperature, mounting conditions etc.).

For surface-mounted devices (SMDs), the thermal resistance between junction and ambient, called $R_{th(j-a)}$, depends on the copper surface used under the tab. Figure 15, Figure 16, and Figure 17 show curves giving the relation between $R_{th(j-a)}$ and the copper surface under the tab for an FR4 board - 35 µm copper thickness.

Figure 15. Thermal resistance junction to ambient versus copper surface under tab (typical values)

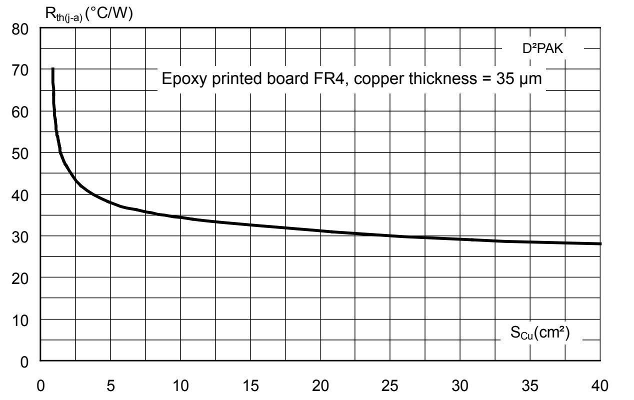


Figure 16. Thermal resistance junction to ambient versus copper surface under tab (DPAK)

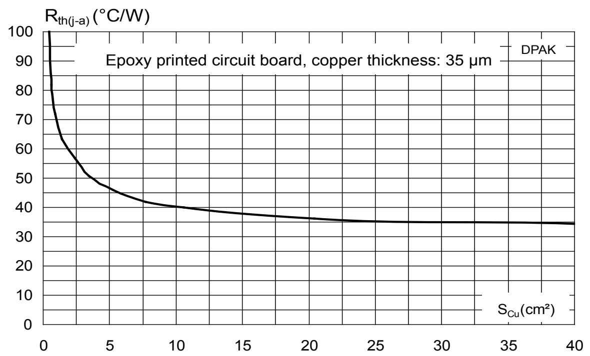
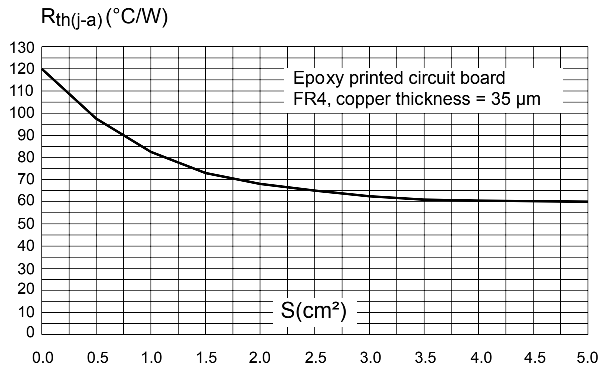


Figure 17. Thermal resistance junction to ambient versus copper surface under tab (SOT-223)



2.2 Thermal impedance

When dealing with short duration pulses, the thermal impedance must be considered to calculate the junction temperature. Depending on the time scale, the following elements are thermally prevalent:

- t_p < 10 ms: die influence
- t_p < 0.1 s: package influence
- t_p < 10 s: PCB influence
- Above 10 s: thermal exchange board-air (example: with / without forced cooling)

Figure 18 shows the Z_{th} / R_{th} ratio for SMD packages and Figure 19 shows $Z_{th(j-a)}$ for DPAK and D^2PAK.

Figure 18. Relative variation of thermal impedance junction to ambient versus pulse duration

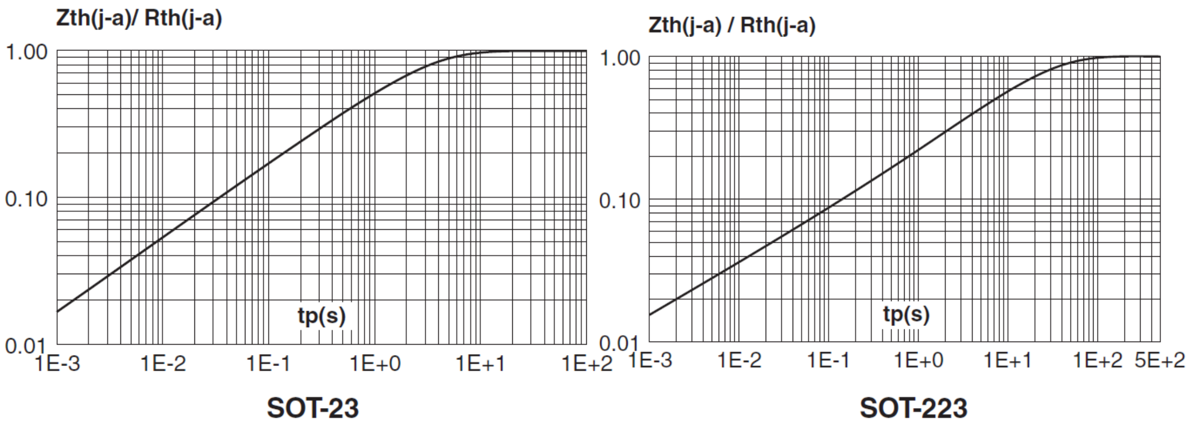
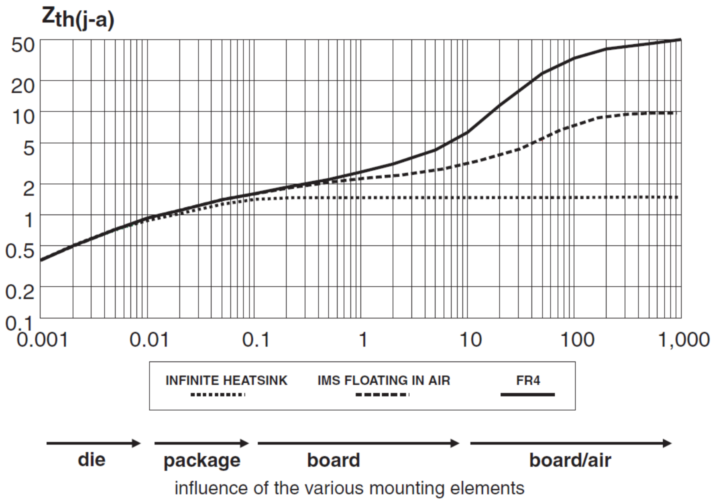


Figure 19. Typical $Z_{th(j-a)}$ for DPAK and D2PAK

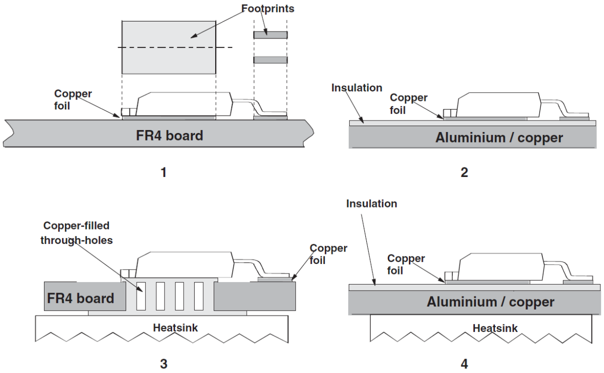


2.3 Mounting techniques for power SMDs

$R_{th(j-a)}$ varies based on the printed circuit board technology employed. Several technologies can be used depending on the performance required in the design. Four techniques are commonly used:

1. FR4 - copper
2. IMS (insulated metal substrate)
3. FR4 board with copper-filled through-holes + heatsink
4. IMS + heatsink

Figure 20. Mounting techniques for power surface mount packages



As the FR4 board is commonly used in surface mounting techniques, there are several ways of overcoming its low thermal performance:

- The use of large heat spreader areas (heatsink) at the copper layer of the PCB
- The use of copper-filled through-holes in addition to an external heatsink for even better thermal management

However, due to its power dissipation limitation, using the FR4 board with these techniques is only advisable for currents up to 8 A max.

Another technology available today is IMS - Insulated metal substrate. This offers greatly enhanced thermal characteristics for surface-mount components. IMS consists of three different layers:

1. Base material, which is available as an aluminum or copper plate
2. Thermal conductive dielectric layer
3. Copper foil, which can be etched as a circuit layer

Even if a higher power is to be dissipated, an external heatsink can be applied leading to an $R_{th(j-a)}$ of 4.5 °C/W (see Table 4). This is commonly applied in practice, leading to reasonable heatsink dimensions. Often, power devices are defined by considering the maximum junction temperature of the device. In practice, however, this is far from being fully exploited.

The designer should carefully examine the appropriate mounting method to be used based on the power dissipation requirements. The board type influences the thermal performance of the system.

Table 4 is an example of the $R_{th(j-a)}$ depending on the mounting techniques for DPAK and D2PAK.

Table 4. $R_{th(j-a)}$ for DPAK and D2PAK according to mounting method

Mounting method	$R_{th(j-a)}$	
	DPAK	D2PAK
FR4	70 °C/W	50 °C/W
FR4 with 10 cm² heatsink on board	40 °C/W	35 °C/W
FR4 with copper filled holes and external heatsink	13 °C/W	12 °C/W
IMS (40 cm²) floating in air	9 °C/W	8 °C/W
IMS with external heatsink	4.5 °C/W	3.5 °C/W

2.4 Reflow soldering information

The surface mount assembly is a 4-step process:

1. Solder paste printing
2. Component placement on the board
3. Reflow soldering
4. Cleaning (optional).

The soldering process causes considerable thermal stress to a semiconductor component. This has to be minimized to assure a reliable and extended lifetime of the device.

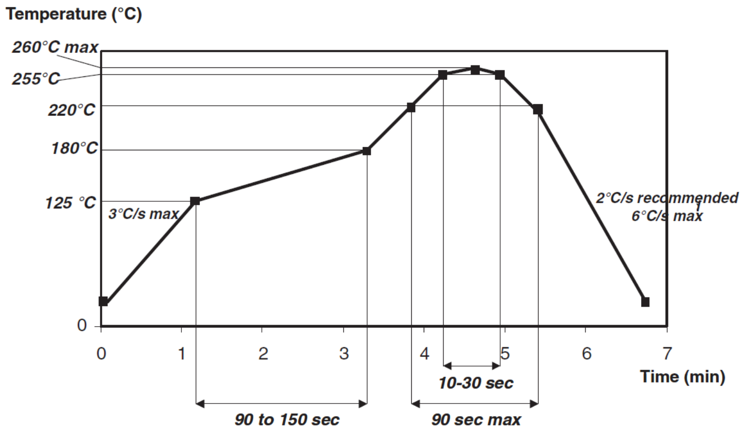
SOT-23, SOT-223, SO-8 and DPAK packages can be exposed to a maximum temperature of 260 °C for 10 to 30 seconds. For the D2PAK package, the maximum temperature is 245 °C. Overheating during the reflow soldering process may damage the device, therefore any solder temperature profile should be within these limits.

Reflow techniques are most common in surface mounting. Typical heating profiles for leadfree solder (STMicroelectronics ECOPACK) are given in Figure 21 for small packages (SOT-23, SOT-223, DPAK), either for mounting on an FR4 or on metal-backed boards (IMS). Refer to the IPC/JEDEC J-STD-020C standard for further information about “small” and “large” component definitions.

Note: The soldering profile defined in the IPC/JEDEC J-STD-020C standard is used for reliability assessment and typically describes the warmest profiles used for component mounting, not the necessary temperatures to achieve good soldering.

Wave soldering is not advisable for DPAK and D2PAK because it is almost impossible to contact the whole package slug during the process.

Figure 21. STMicroelectronics ECOPACK recommended soldering reflow profile for small packages



For each individual board, the appropriate heat profile has to be adjusted experimentally.

The current proposal is just a starting point. In every case, the following precautions have to be considered:

- Always preheat the device. The purpose of this step is to minimize the rate of temperature rise to less than 3 °C per second (recommended 2 °C/s) to minimize the thermal shock on the component.
- Dry out section, after preheating, ensures that the solder paste is fully dried before starting the reflow step. Also, this step allows the temperature gradient on the board to be evened out.
- Peak temperature should be at least 30 °C higher than the melting point of the solder alloy chosen to ensure the reflow quality. In any case, the peak temperature should not exceed 260 °C.

Lead-free devices are described in an internal specification defining:

- Their characteristics: lead-free connection coating, solderability, and identification features
- Their reliability such as soldering resistance, reliability performance, whiskers risk prevention.

This specification is available for STMicroelectronics customers upon request (title: ECOPACK components definition and characteristics). Please consult that document for further information about reflow and wave soldering. Voids pose a difficult reliability problem for large surface-mount devices.

Such voids under the package result in poor thermal contact and the high thermal resistance leads to component failures.

Coplanarity between the substrate and the package can be easily verified. The quality of the solder joints is very important for two reasons:

- Poor quality solder joints directly result in poor reliability
- Solder thickness affects the thermal resistance significantly. Thus, tight control of this parameter results in thermally efficient and reliable solder joints.

Revision history

Table 5. Document revision history

Date	Revision	Changes
Nov-1997	1	Initial release.
Oct-2000	2	Latest update.
10-Mar-2008	3	Reformatted to current standards. General update of all equations, and graphics.
25-Jan-2024	4	Replaced product BTA08-600SW by BTA08-800SW, product BTA16-600C by BTA16-800CW, and BTB16-600C by BTB16-800CW. Minor text changes.

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