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## SCRs, TRIACs and AC switches: Thermal Management Precautions for Handling and Mounting

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### INTRODUCTION

The behaviour 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 and mounting techniques.

### THROUGH - HOLE PACKAGES

#### I - THERMAL RESISTANCE

##### 1- Review

The thermal resistance of semiconductor assembly is the parameter which characterizes its resistance to the heatflow 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 :

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

Where:

- $T_{j\max}$  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 junction and ambient air in °C/W

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

##### 2- Dissipated power in a thyristor

The maximum mean power dissipation versus the average on-state current curve is given in the datasheet. However, a more accurate result is obtained by using the  $V_{to}$  and  $R_d$  values with the following calculation:

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

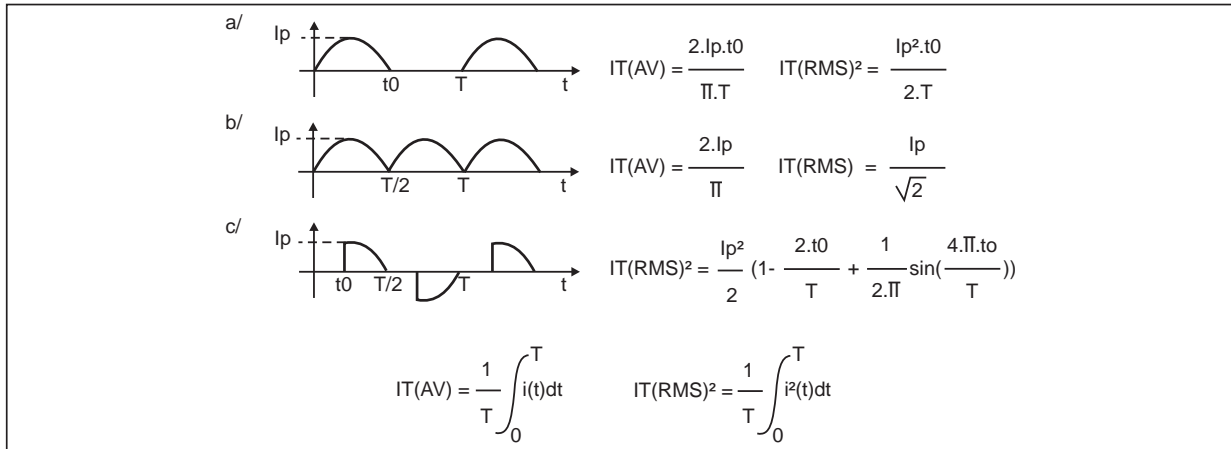
Where:

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

Figure 1 shows the  $R_{MS}$  and average values for different waveforms of current.

## APPLICATION NOTE

**Fig. 1: RMS and average current.**



### 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 formula gives the total dissipated power versus  $I_{T(RMS)}$  current through the triac :

$$P = \frac{2 \cdot \sqrt{2}}{\pi} \cdot I_{T(RMS)} \cdot V_{t0} + R_d \cdot I_{T(RMS)}^2$$

For a phase angle conduction the RMS current is shown in figure 1 c.

Depending on the dissipated power in the component, two types of assembly are possible:

- In the air without external heatsink
- With heatsink

### 4- Triac without external heatsink

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

In practice the imposed parameters are:

- **Ta**: ambient air temperature where the triac is located
- **Rth(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

The following equation defines the junction temperature depending on these parameters:

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

If this 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 i.e. inside the box where the triac is located. The most rigorous way is to determine the thermal resistance between ambient air and the triac location.

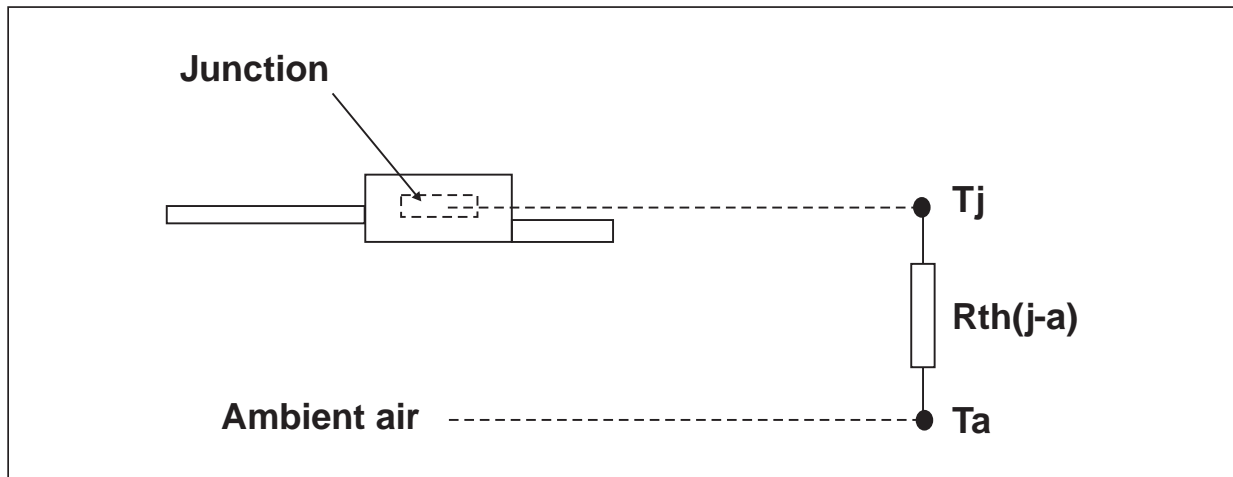
In most cases, the ambient temperature is considered as the temperature around the triac which is the box temperature. This has been done in this paper.

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:  $U = R \cdot I$  corresponds to  $T = R_{th} \cdot P$

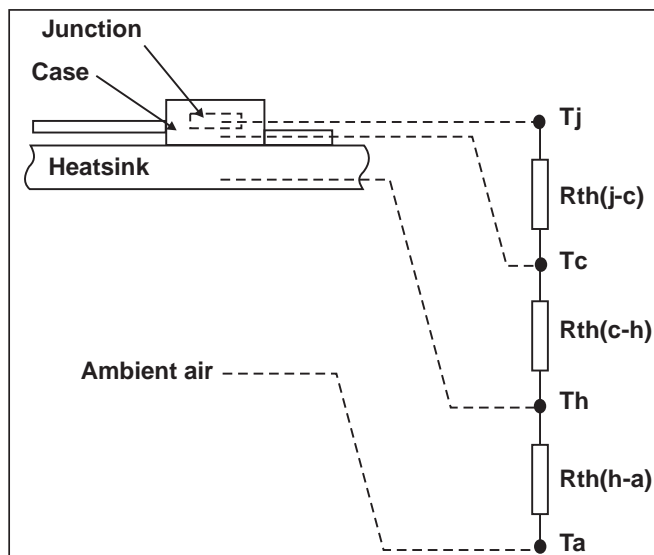
Fig. 2: Thermal equivalent diagram.



### 5- Triac with external heatsink.

The same approach allows a suitable heatsink to be defined. Figure 3 shows the thermal diagram.

Fig. 3: Thermal equivalent diagram with external heatsink.



## APPLICATION NOTE

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The formula to calculate the thermal resistance between heatsink and ambient air is the following :

$$R_{th(h-a)} = (T_j - T_a) / P - R_{th(j-c)} - R_{th(c-h)}$$

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 AC which is different to the  $R_{th(j-c)}$  in DC.

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, we use the following equation.

$$R_{th(j-c)} AC = 0.75 \times R_{th(j-c)} DC$$

### 6 - Choice of heatsink

Choosing of 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 on the following page shows the curve  $R_{th(h-a)}$  versus the length of a flat square heatsink for different materials and thickness.

Some applications need heatsinks with a very optimised shape where the thermal resistances are not known.

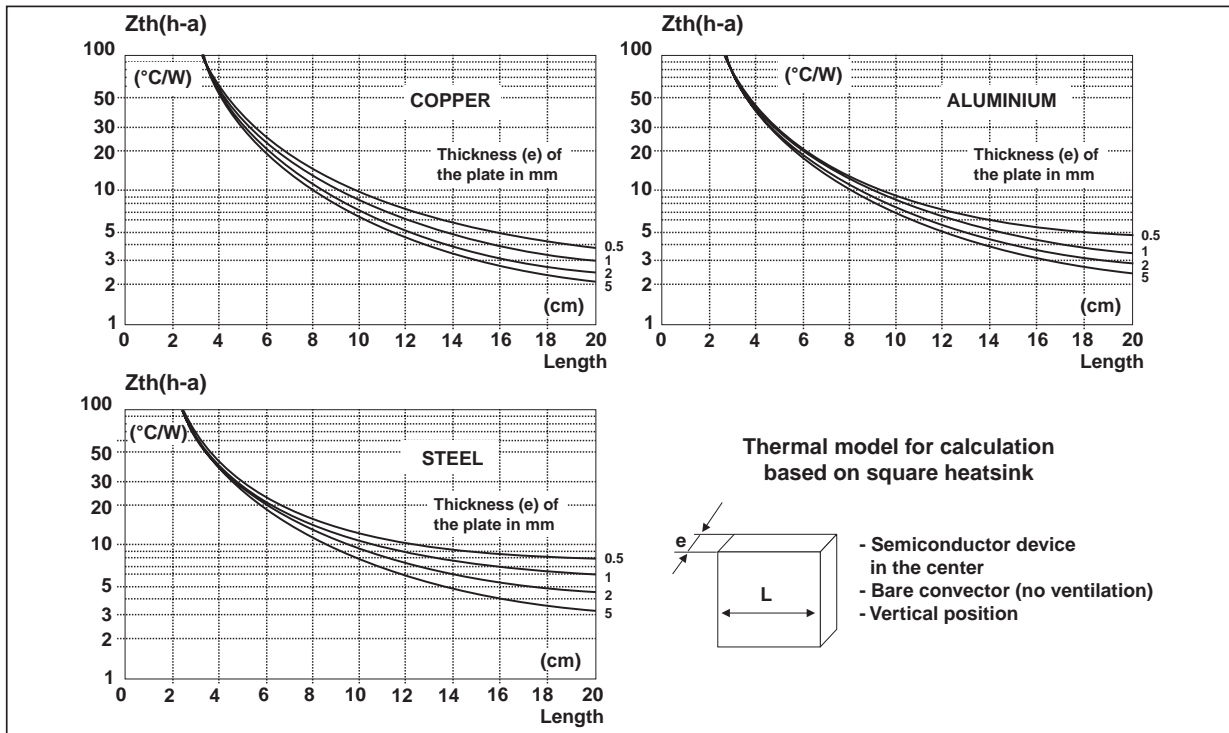
For this, the best solution involves measuring the case temperature of the component in the worst case scenario and keeping to the following formula:

$$T_c < T_{j_{max}} - P \cdot R_{th(j-c)}$$

Where:

- $T_c$  is the case temperature
- $T_{j_{max}}$  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.

Fig. 4: Rth(h-a) versus the length of a flat square heatsink.



7- Forced cooling

For high power or very high power, an air-forced or liquid cooling may be needed. 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 there is air flow. This allows a very small heatsink to be used, very often a flat aluminium heatsink. In this case it is necessary to measure the case temperature in the worst case scenario and to check the following formula:

$$T_c < T_{j_{max}} - P \cdot R_{th(j-c)}$$

II - 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 capacitance, especially when the component is on during a time lower than the time to reach the thermal resistance. The thermal impedance value versus duration is given in the datasheet (see an example on fig.5), in relation with Zth/Rth relation variation.

For example, BTA08-600SW is able to dissipate 21 W without heating during 1s :

$$P = \frac{T_{j_{max}} - T_{a_{max}}}{Z_{th(j-a)}}$$

$$P = \frac{125 - 25}{60 \times 0.06}$$

$$P = 27.5 \text{ W}$$

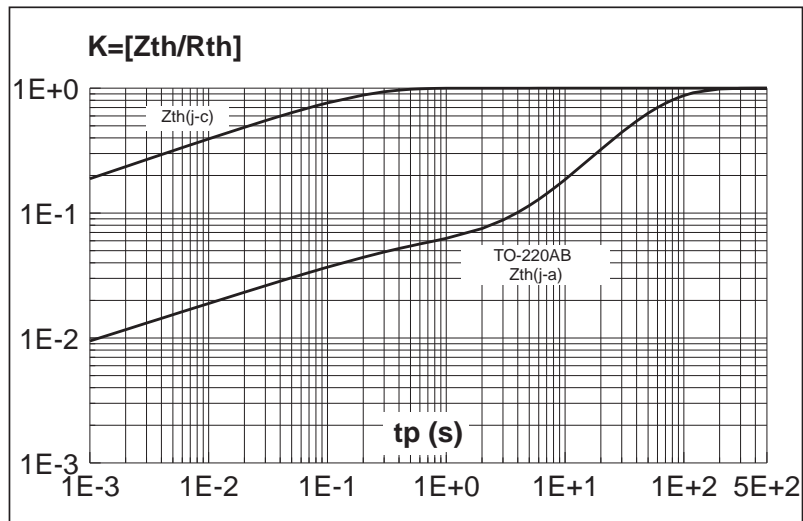
In steady state, with the same ambient temperature, the same triac is able to dissipate :

$$P = \frac{125 - 25}{60}$$

$$P = 1.7 \text{ W}$$

## APPLICATION NOTE

Fig. 5: Thermal transient impedance of a BTA08-600SW.



### III - INSULATING MATERIALS

We can classify them in 3 types as follows :

#### **a - 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.

#### **b - 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.

#### **c - Silicon 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.

Fig. 6:  $R_{th}(c-h)$  for different materials for TO-220AB package.

	CONTACT GREASE	MICA + GREASE $e=80\mu\text{m}$	MICA DRY $e=80\mu\text{m}$	SILICONE INSULATOR
$R_{th}(c-h)$ $^{\circ}\text{C}/\text{W}$	0.5	1.7	4	2.6

Figure 6 shows the thermal resistance for different TO-220AB insulators and for a given pressure ( $F = 30\text{N}$ ).

**IV - INSULATED COMPONENTS**

Most of the thyristors and triacs manufactured by STMicroelectronics are available in insulated and non-insulated packages. For insulated packages, insulation can be achieved in two different ways, either with a ceramic between the die pad and the heatsink of the component (TO-220AB/TOP3/RD91/ISOTOP packages), or by the resin used for encapsulation (ISOWATT220AB). All insulated packages delivered by STMicroelectronics are in accordance with 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 (Rthj-a) is lower than the one when using a non insulated component with an external insulating material. In addition, it simplifies assembly and reduces the cost.

For two 16 Amps triacs in TO-220AB package, Rth(j-c) AC are the following (in °C/W):

BTA16-600C (insulated version)	BTB16-600C (non insulated version)
2.1 device + 0.5 grease ----- 2.6	1.2 device + 1.7 mica + grease ----- 2.9

The use of an insulated component results in low thermal resistance between junction and heatsink and reduced assembly costs.

**V - 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.

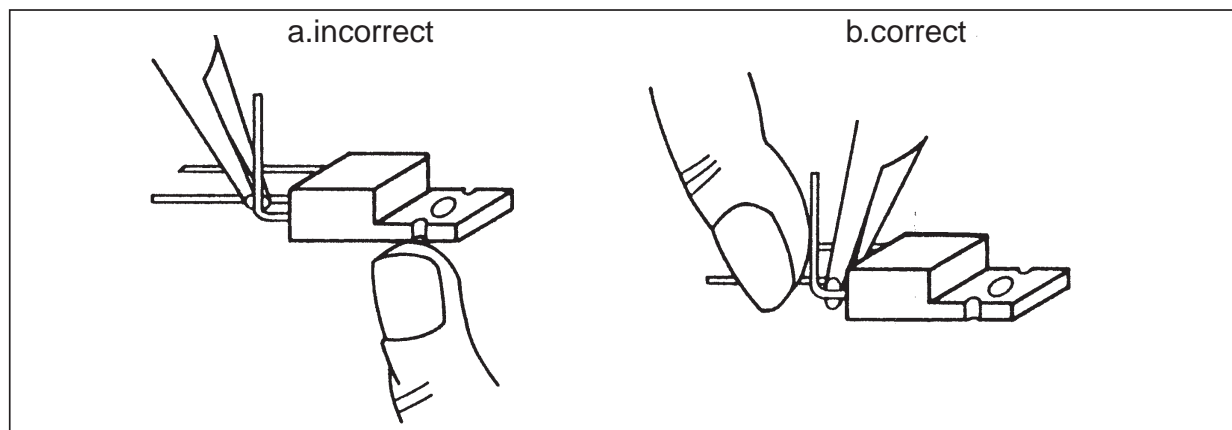
**1- Bending and cutting leads.**

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 :

- a. Never clamp the plastic package (figure 7a - 7b)

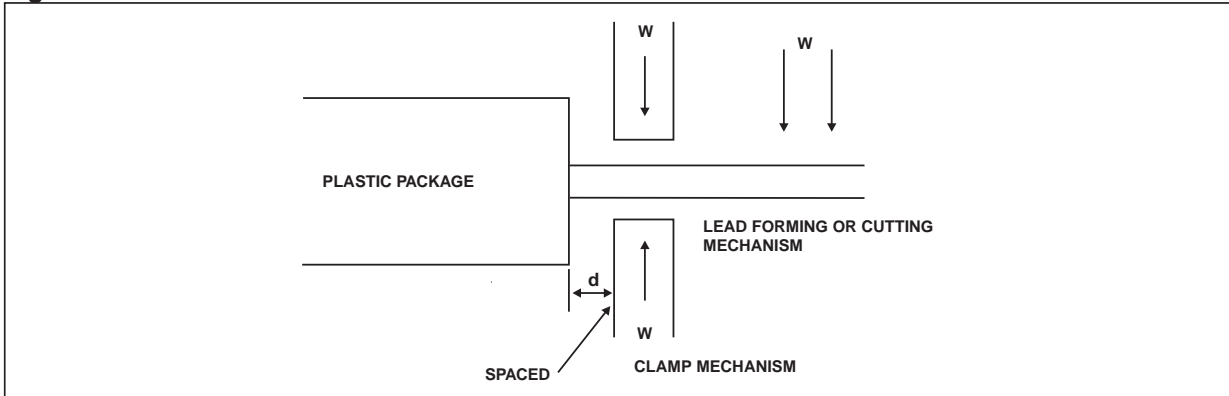
**Figure 7a - 7b**



**APPLICATION NOTE**

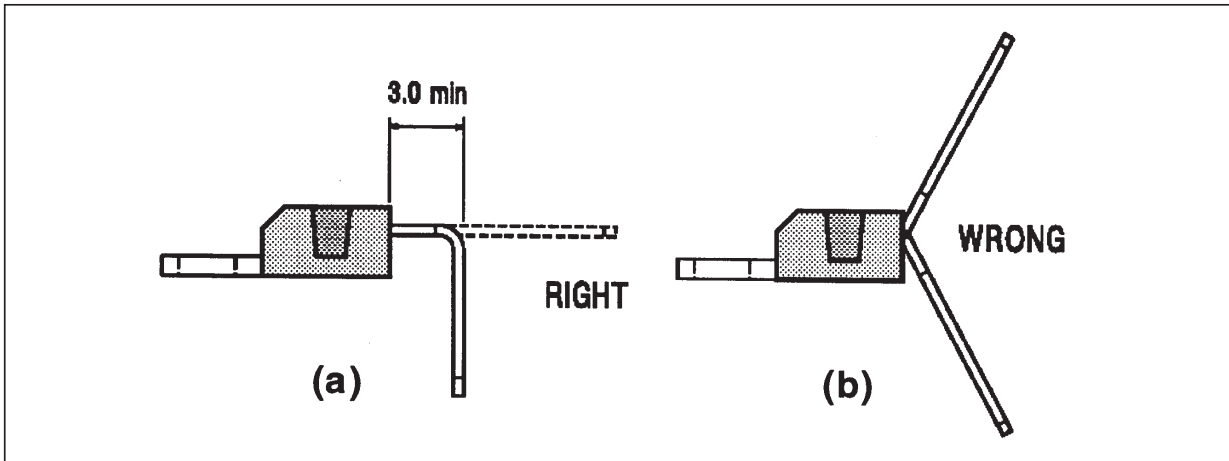
b. Clamp the leads firmly between the plastic package and the bend / cut point (figure 7c).

**Figure 7c:**



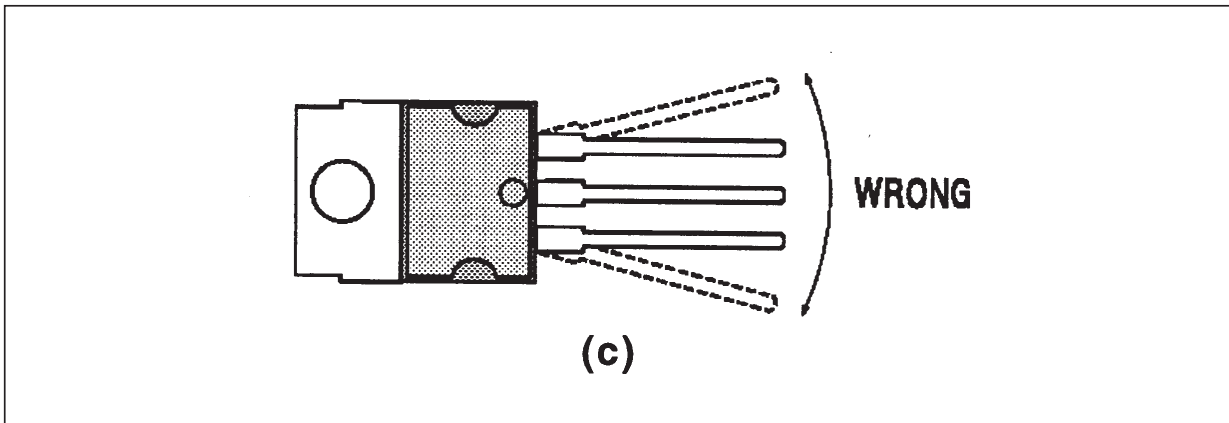
c. Bend the leads at least 3mm from the plastic package (figure 8a -8b).

**Figure 8a - 8b**



d. Never bend the leads laterally (figure 8c).

**Figure 8c**



e. Never bend the leads more than 90° and never bend more than once

f. Make sure that the bending / cutting tool does not damage the leads.



## 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 silicon grease ensures a very low contact thermal resistance between the component and the heatsink. An excessively thick layer or an excessively viscous silicon 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 more than 50µm 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.

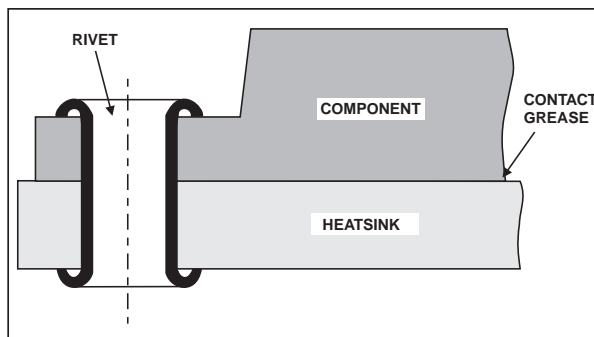
Soldering: It is not recommended for through-hole packages.

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.

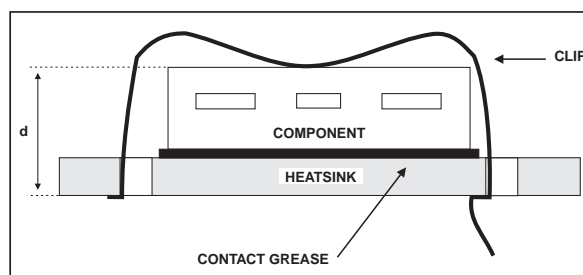
Press rivets can be used with caution provided they are of a soft metal like aluminium. The crimping force must be applied slowly and carefully in order to avoid shock and deformation of the heatsink.

**Fig. 9:** 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 150N/mm<sup>2</sup>. 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 concentrate 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 in to account:

**Fig. 10:** Clip assembly.

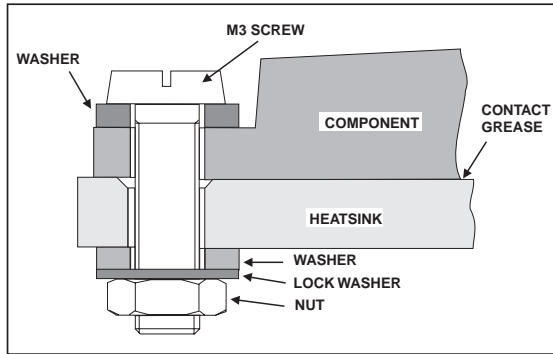


## APPLICATION NOTE

With screws: The following precautionary measures should be taken:

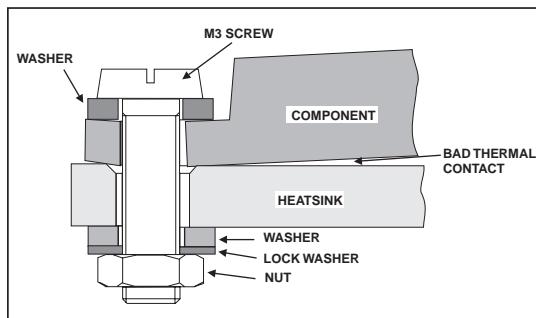
- In order to avoid tab distortion, a rectangular washer must be put between the screw head and the tab, and a compression washer must be put between the tab and the nut.

**Fig. 11:** 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:

**Fig. 12:** Incorrect assembly.



The thermal contact resistance depends on the force generated by the applied torque on the screw:

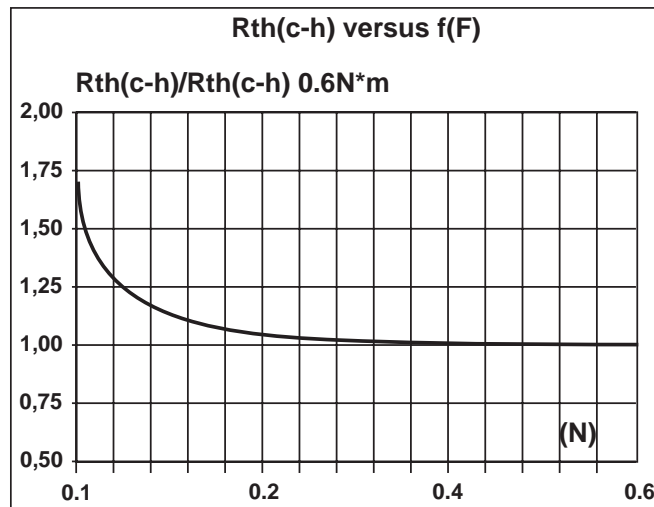
$$F = \frac{2 \cdot T \cdot \pi}{P + r \cdot D \cdot \pi}$$

Where:

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

The relative variation of the Rth(j-c) versus the torque for M3 screw used for the TO220AB is:

**Fig. 13:** Relative variation of  $R_{th}(c-h)$  versus pressure force for TO-220AB.



The table below gives the recommended torque and the thermal contact resistance:

Package	Torque (N*m)	Thermal Contact Resistance (°C/W)
TO202-3	0.5 to 0.7	0.5
TO-220AB	0.4 to 0.6 (*)	0.5
ISOWATT220	0.4 to 0.6	0.5
TOP3	0.9 to 1.2	0.1
RD91	0.9 to 1.2	0.1
ISOTOP™	0.9 to 1.2	0.05

Note (\*): For BTB20-xxx, BTB24-xxx and TYNxx40, the maximum torque is 0.5N\*m.

## APPLICATION NOTE

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### VI - SUMMARY

To sustain the performance of a component, the temperature has to be limited by applying simple rules.

#### 1- Dissipated power:

$$\text{Thyristor : } P = I_{T(AV)} \cdot V_{to} + R_d \cdot I_{T(RMS)}^2$$

$$\text{Triac : } P = \frac{2 \cdot \sqrt{2}}{\pi} \cdot I_{T(RMS)} \cdot V_{to} + R_d \cdot I_{T(RMS)}^2$$

#### 2- Junction temperature:

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

#### 3- External heatsink:

needed if :  $T_j > T_{j_{max}}$

#### 4- Thermal resistance between case and heatsink:

This thermal contact resistance has to be as small as possible. This is done by adding contact grease between the case and heatsink.

#### 5- Insulation:

If insulation is needed, we recommend an insulated component instead of external insulation.

#### 6- Heatsink thermal resistance:

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

#### 7- Handling:

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.

#### 8- Mounting with a screw, rivet or clip:

##### Screw :

- Advantages:
  - Possibility to insulate and easy and fast to disassemble
- Disadvantages:
  - Slow assembly for mass production, high cost
  - Master control the tightening torque

##### Rivet :

- Advantages:
  - Fast assembly for mass production
- Disadvantages:
  - Difficult to disassemble
  - Difficult to control the force applied to the rivet

##### Clip :

- Advantages:
  - Fast assembly and disassembly
  - Easy to control the applied pressure
- Disadvantages:
  - Difficult to place the component

## SURFACE MOUNT PACKAGES

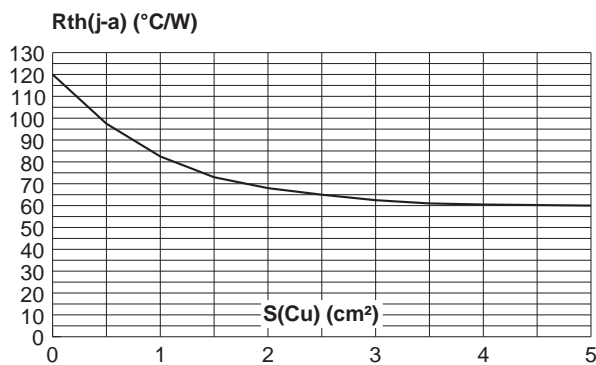
### I - THERMAL CHARACTERISTICS

#### 1- Thermal resistance

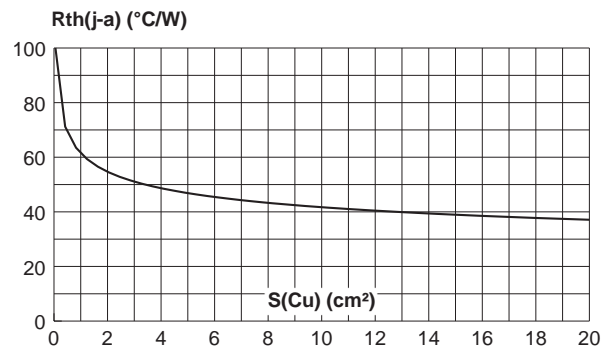
The thermal resistance of a semiconductor device characterizes the device capability to dissipate the heat generated by the chip during operation. This parameter allows us to calculate the junction temperature, taking into account the device environment (load current, ambient temperature, mounting conditions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

For SMDs, the thermal resistance between junction and ambient, called  $R_{th(j-a)}$ , depends on the copper surface used under the tab. Below, are the curves giving the relation between  $R_{th(j-a)}$  and the copper surface under the tab for a FR4 board - 35 $\mu$ m copper thickness:

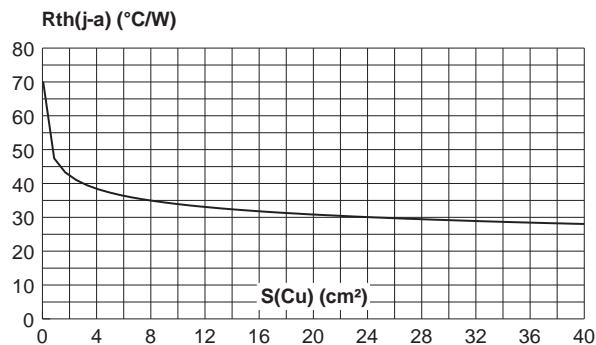
#### SOT-223



#### DPAK



#### D<sup>2</sup>PAK



#### 2- Thermal impedance

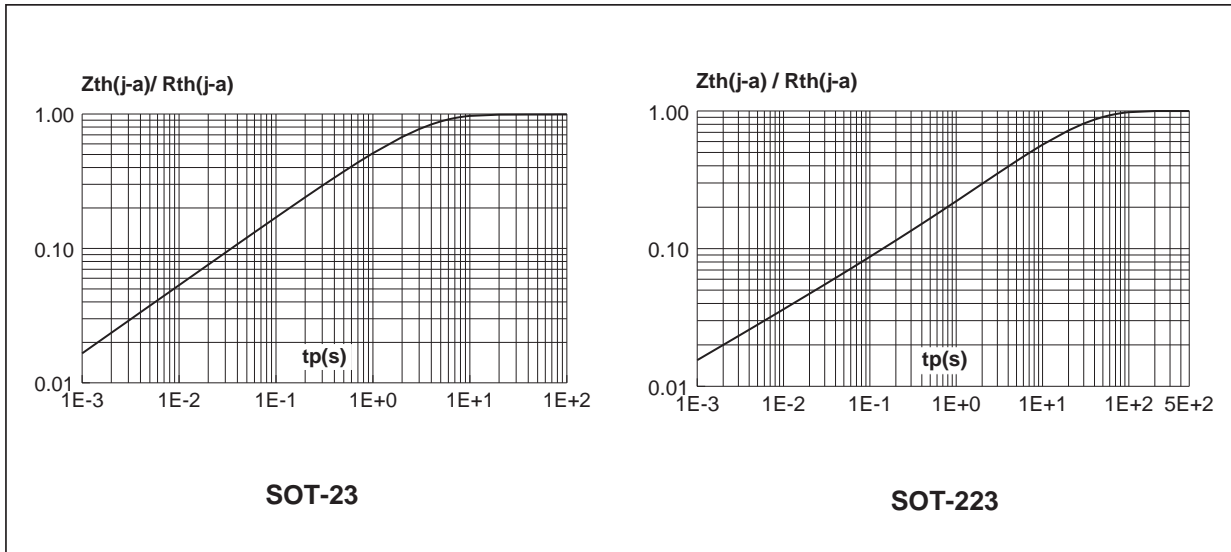
When dealing with short duration pulses, the thermal impedance must be considered to calculate the junction temperature. Depending on the time scale, the following elements are thermally prevalent:

- $t_p < 500\text{ms}$  : die influence
- $t_p < 0.1\text{s}$  : package influence
- $t_p < 10\text{s}$  : PCB influence
- above 10s : thermal exchange board-air (example: with / without force cooling)

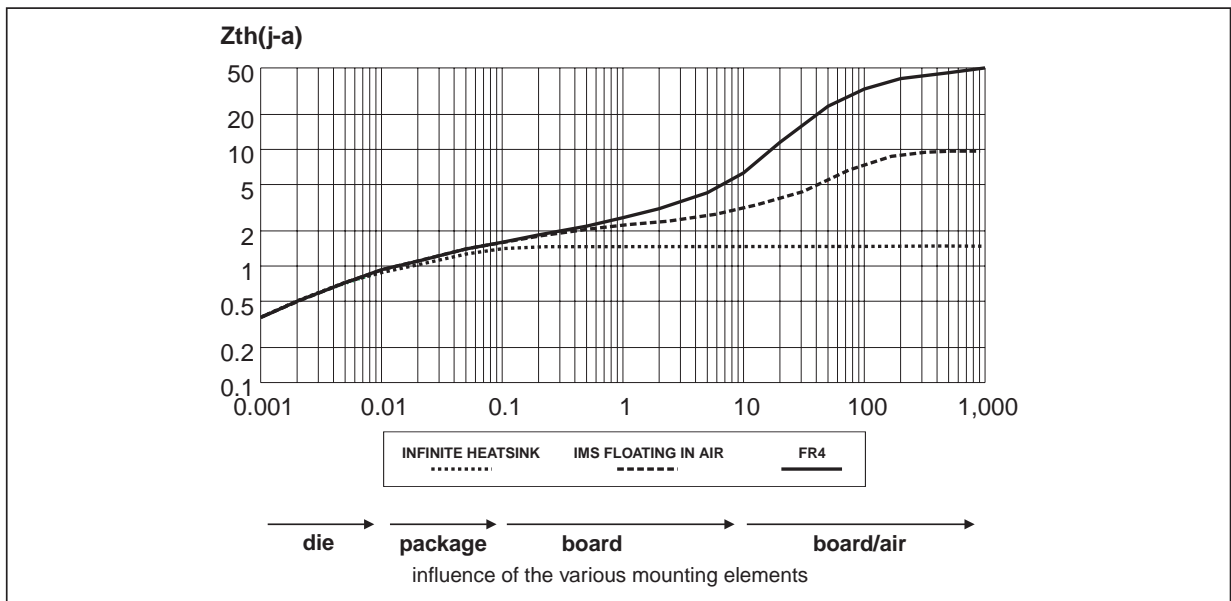
The figures on next page show the  $Z_{th} / R_{th}$  ratio for SMD packages

# APPLICATION NOTE

## Relative variation of thermal impedance junction to ambient versus pulse duration



## Typical $Z_{th}(j-a)$ for DPAK and D<sup>2</sup>PAK

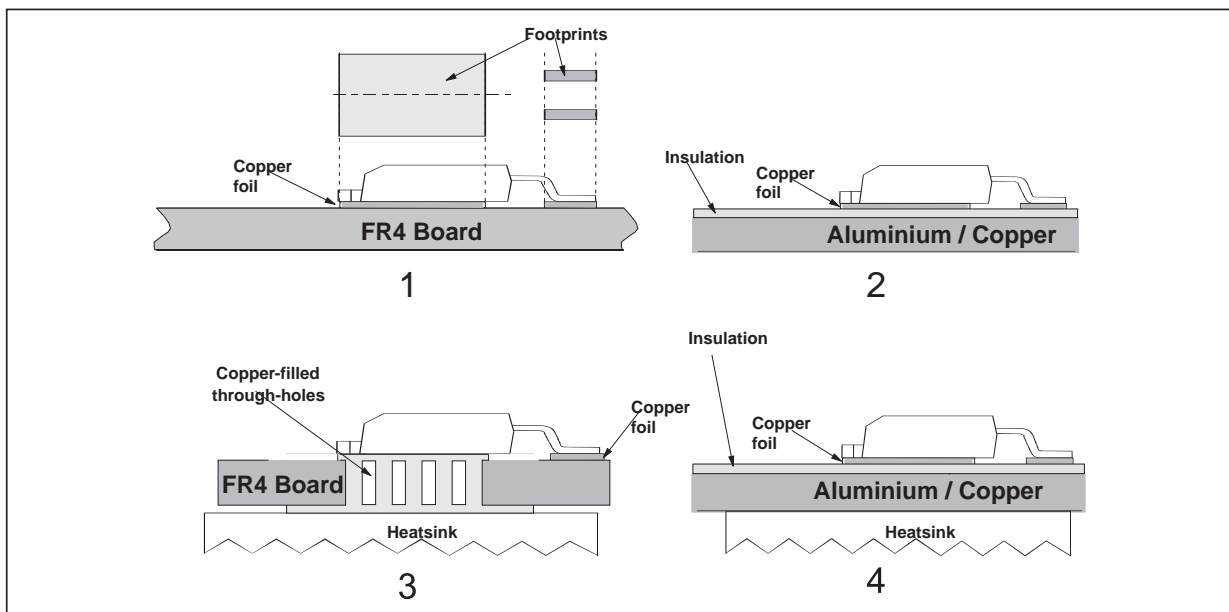


### 3- Mounting Techniques and $R_{th(j-a)}$

$R_{th(j-a)}$  varies with the mounting technique. Several can be used depending on the performance required in the design. Four techniques are commonly used:

- FR4 - Copper
- IMS (Insulated Metal Substrate)
- Aluminum
- FR4 board with copper filled through holes + HEATSINK
- IMS + HEATSINK.

#### Mounting techniques for power SMDs



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 (heat sink) at the copper layer of the PCB.
- The use of copper-filled through holes in addition to an external heatsink for an 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 Amps max.

A new technology available today is IMS - an Insulated Metallic Substrate. This offers greatly enhanced thermal characteristics for surface mount components. IMS is a substrate consisting of three different layers :

- (I) the base material which is available as an aluminum or a copper plate
- (II) a thermal conductive dielectric layer
- (III) a copper foil, which can be etched as a circuit layer.

## APPLICATION NOTE

Even if a higher power is to be dissipated, an external heatsink can be applied leading to an  $R_{th(j-a)}$  of  $4.5^{\circ}\text{C/W}$  (see table 1 below) assuming that  $R_{th}$  (heatsink-air) is equal to  $R_{th}$  (junction-heatsink). 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 exploited.

The designer should then carefully examine the appropriate mounting method (see table 1) to be used according to the dissipated power. The type of board will influence the thermal performance of the system. Table 1 shows the  $R_{th(j-a)}$  depending on the mounting techniques for DPAK and D<sup>2</sup>PAK.

**TABLE 1:  $R_{th(j-a)}$  for DPAK and D<sup>2</sup>PAK**

MOUNTING METHOD	$R_{th(j-a)}$	
	DPAK	D <sup>2</sup> PAK
FR4	$70^{\circ}\text{C/W}$	$50^{\circ}\text{C/W}$
FR4 with 10cm <sup>2</sup> heatsink on board	$40^{\circ}\text{C/W}$	$35^{\circ}\text{C/W}$
FR4 with copper filled holes & external heatsink	$13^{\circ}\text{C/W}$	$12^{\circ}\text{C/W}$
IMS (40cm <sup>2</sup> ) floating in air	$9^{\circ}\text{C/W}$	$8^{\circ}\text{C/W}$
IMS with external heatsink	$4.5^{\circ}\text{C/W}$	$3.5^{\circ}\text{C/W}$

## II - SOLDERING INFORMATION

The Surface Mount assembly is a 4-step process :

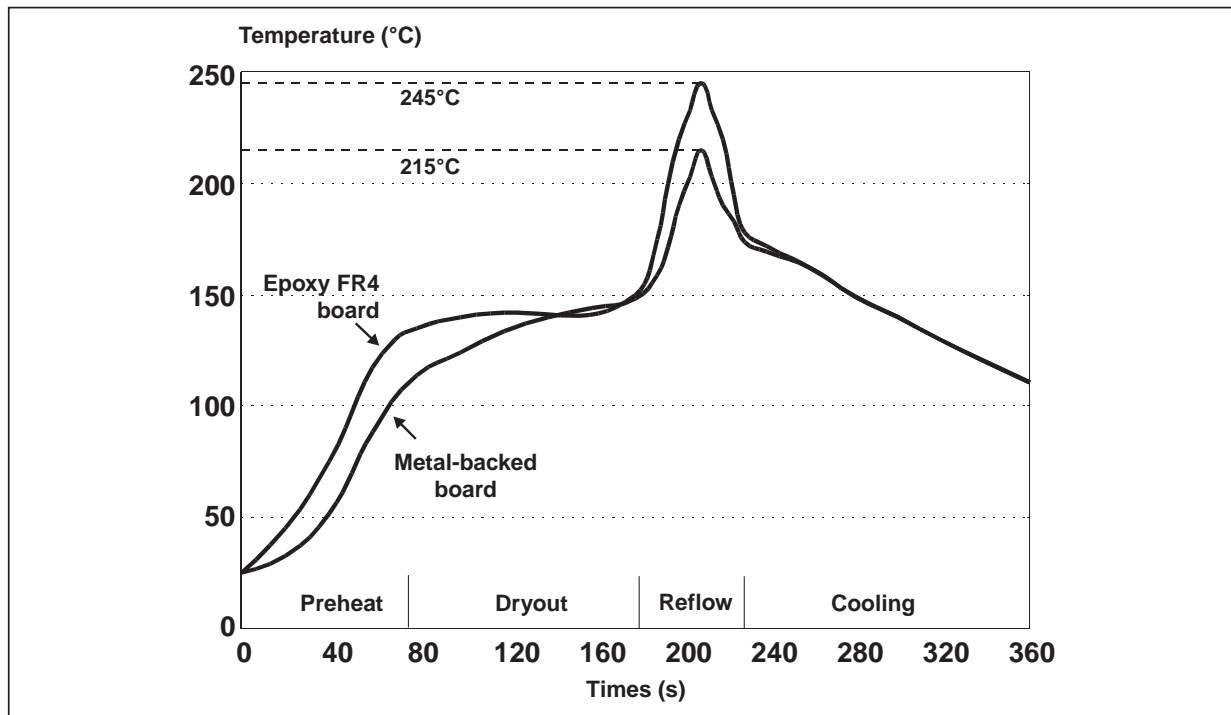
- solder paste printing
- component placement on the board
- reflow soldering
- cleaning (optional)

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, DPAK and D<sup>2</sup>PAK packages can be exposed to a maximum temperature of *260°C for 10 seconds* . Overheating during the reflow soldering process may damage the device, therefore any solder temperature profile should be within these limits. As reflow techniques are most common in surface mounting, typical heating profiles are given in Figure 14 for SOT-23, SOT-223, DPAK and D<sup>2</sup>PAK package family, either for mounting on a FR4 or on metal-backed boards (IMS).

**Wave soldering is not advisable for DPAK and D<sup>2</sup>PAK because it is almost impossible to contact the whole package slug during the process.**



Fig. 14: Reflow soldering heat profile temperature



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 2°C per second in order to minimize thermal shock on the component.
- Dryout sections ensure that the solder paste is fully dried before starting 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 quality reflow. In any case the peak temperature should not exceed 260°C.

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 :

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

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