THERMAL CONSIDERATIONS - TRANSISTORS

Thermal resistance

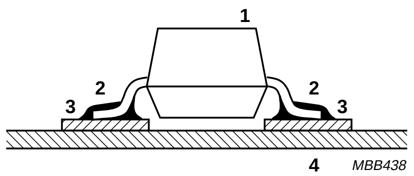
Circuit performance and long-term reliability are affected by the temperature of the transistor die. Normally, both are improved by keeping the die temperature (junction temperature) low.

Electrical power dissipated in any semiconductor device is a source of heat. This increases the temperature of the die about some reference point, normally an ambient temperature of 25 ºC in still air. The extent of increase in temperature depends on the amount of power dissipated in the circuit and the net thermal resistance between the heat source and the reference point.

Devices lose most of their heat by conduction when mounted on a printed-circuit board, a substrate or heatsink. Referring to Fig.1 (for surface mounted devices mounted on a substrate), heat conducts from its source (the junction) via the package leads and soldered connections to the substrate. Some heat radiates from the package into the surrounding air where it is dispersed by convection or by forced cooling air. Heat that radiates from the substrate is dispersed in the same way.

The elements of thermal resistance shown in Fig.2 are defined as follows:

- $R_{th(j-mb)}$ thermal resistance from junction to mounting base
- $R_{th(j-c)}$ thermal resistance from junction to case ($R_{th(j-mb)}$ and $R_{th(j-c)}$ are the same for most packages
- $R_{th(j-s)}$ thermal resistance from junction to soldering point
- $R_{th(s-a)}$ thermal resistance from soldering point to ambient
- $R_{th(c-a)}$ thermal resistance from case to ambient ($R_{th(s-a)}$ and $R_{th(c-a)}$ are the same for most packages)
- $R_{th(j-a)}$ thermal resistance from junction to ambient.



Heat radiates from the package (1) to ambient.
Heat conducts via leads (2), solder joints (3) to the substrate (4).

Fig.1 Heat losses.

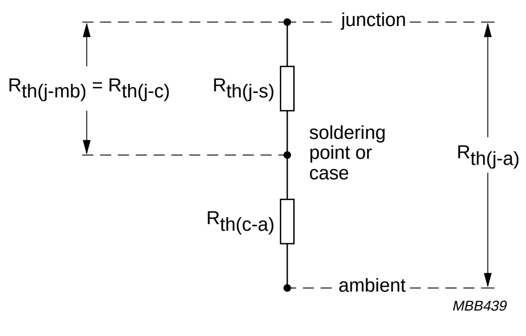


Fig.2 Representation of thermal resistance paths of a device mounted on a substrate or printed-circuit board.

The temperature at the junction depends on the ability of the package and its mounting to transfer heat from the junction region to the ambient environment. The basic relationship between junction temperature and power dissipation is:

$$T_{j(max)} = T_{amb} + P_{tot(max)} (R_{th(j-s)} + R_{th(s-a)})$$
$$= T_{amb} + P_{tot(max)} (R_{th(j-a)})$$

where

$T_{j(max)}$ is the maximum junction temperature

T_{amb} is the ambient temperature

$P_{tot(max)}$ is the maximum power handling capability of the device, including the effects of external loads when applicable.

In the expression for $T_{j(max)}$, only T_{amb} and $R_{th(s-a)}$ can be varied by the user. The package mounting technique and the flow of cooling air are factors that affect $R_{th(s-a)}$. The device power dissipation can be controlled to a limited extent but under recommended usage, the supply voltage and circuit loading dictate a fixed power maximum. The $R_{th(j-s)}$ value is essentially independent of external mounting method and cooling air; but is sensitive to the materials used in the package construction, the die bonding method and the die area, all of which are fixed.

Values of $T_{j(max)}$ and $R_{th(j-s)}$, or $R_{th(j-c)}$ or $R_{th(j-a)}$ are given in the device data sheets. For applications where the temperature of the case is stabilized by a large or temperature-controlled heatsink, the junction temperature can be calculated from:

$T_j = T_{case} + P_{tot} \times R_{th(j-c)}$ or, using the soldering point definition, from $T_j = T_{solder} + P_{tot} \times R_{th(j-s)}$.

$R_{th\ s\text{-}a}$ for SMDs

The thermal resistance $R_{th(s-a)}$ for SMDs mounted on a ceramic substrate (Al_2O_3) is a function of the substrate area as shown in Fig.3.

The thermal resistance $R_{th(s-a)}$ for SMDs mounted on a FR4 printed-circuit board is a function of the board type (single-sided or double-sided), track area and plated or unplated tracks as shown in Fig.4.

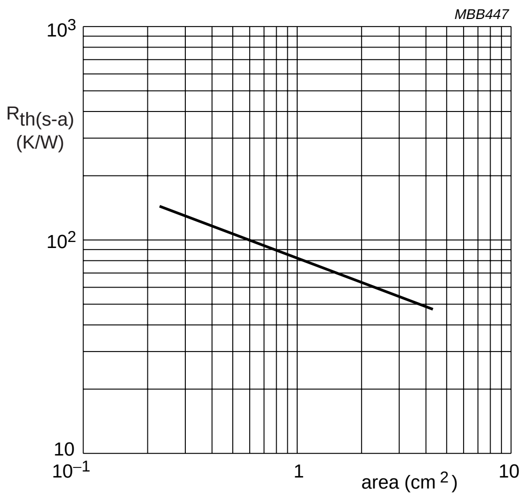
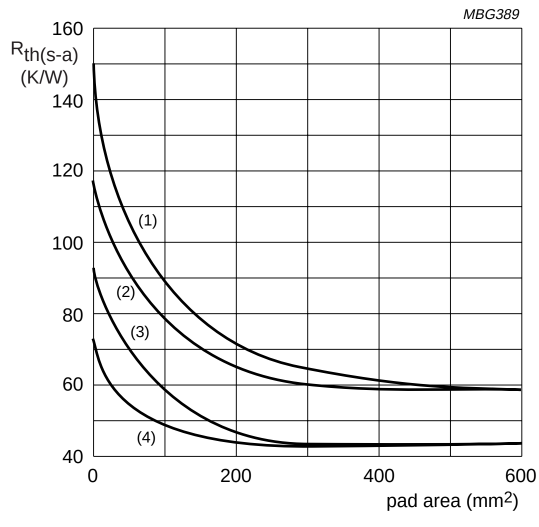


Fig.3 Thermal resistance ($R_{th\ s\text{-}a}$) as a function of area of ceramic substrate.



(1) Single-sided, unplated.
(2) Single-sided, plated.
(3) Double-sided, unplated.
(4) Double-sided, plated.

Fig.4 Thermal resistance ($R_{th(s-a)}$) as a function of pad area on different configurations of FR4 printed-circuit board.

Temperature calculation under pulsed conditions

In pulsed power conditions, the peak temperature of the die depends on the pulse time and duty factor as well as the ability of the package and its mounting to disperse heat.

When power is applied in repetitive square-wave pulses with a certain duty factor (δ), the variation in junction temperature has a sawtooth characteristic.

The average steady-state junction temperature is:

$T_{j(av)} = T_{ref} + \delta \times P_d \times R_{th(j\text{-}ref)}$

The peak junction temperature, however, is the most relevant to performance reliability. This can be calculated by heating and cooling step functions that result in heating and cooling curves shifted in time as shown in Fig.5.

The peak value of T_j is reached at the end of a power pulse and the minimum value immediately before the next power pulse. The thermal ripple is the difference between $T_{j(peak)}$ and $T_{j(min)}$.

Calculation of $T_{j(peak)}$ after n pulses:

$$T_{j(peak)} = T_{ref} + P_d \times \sum_{a=0}^{a=n-1} [Z_{th(at+w)} - Z_{th(at)}]$$

where ‘a’ is an integer number.

Approximation method of finding $T_{j(peak)}$

With this method it is assumed that the average load is immediately followed by two square power pulses as shown in Fig.6. This two-pulse approximation method is accurate enough for finding $T_{j(peak)}$.

The junction temperature at the end of the second pulse is:

$$T_{j(peak)} = T_{ref} + P_d \times [\delta \times R_{th(j\text{-}ref)} + (1 - \delta) \times Z_{th(t+w)} + Z_{th(w)} - Z_{th(t)}]$$

The junction temperature immediately before the second power pulse is:

$$T_{j(min)} = T_{ref} + P_d \times [\delta \times R_{th(j\text{-}ref)} + (1 - \delta) \times Z_{th(t)} - Z_{th(t-w)}]$$

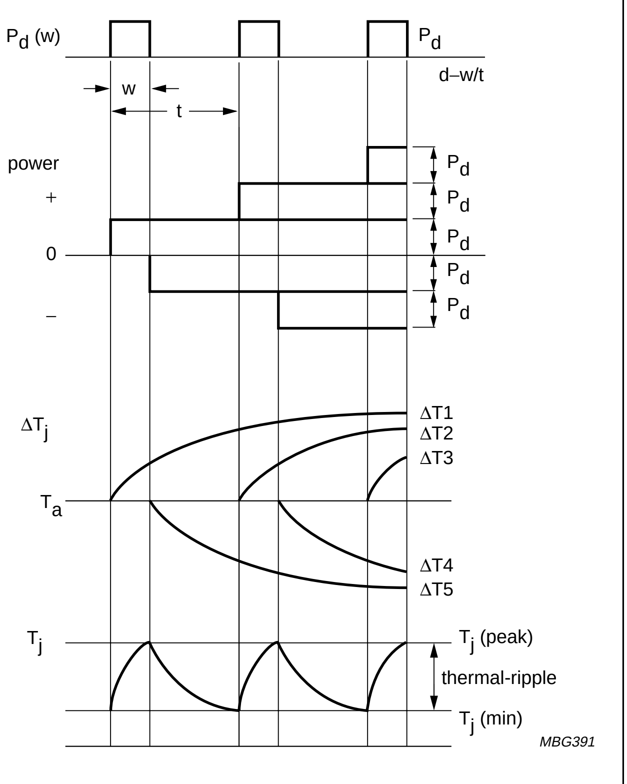


Fig.5 Heating effect of three identical power pulses after thermal stabilization.

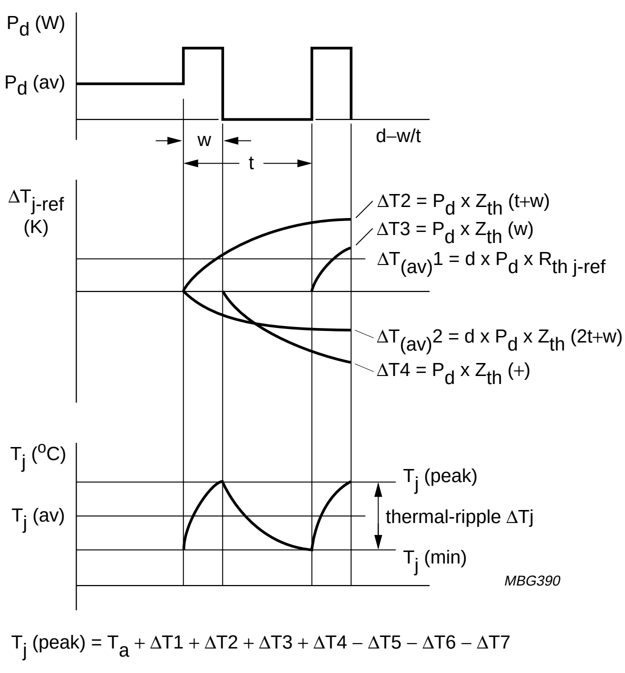


Fig.6 Two-pulse approximation method of finding peak steady-state junction temperature ($T_{j(peak)}$).

The thermal ripple is:

$\Delta T_j = T_{j(peak)} - T_{j(min)}$

$\Delta T_j = P_d \times [\delta \times (Z_{th(t)} - Z_{th(t+w)} - 2 \times Z_{th(t)} + Z_{th(w)} + Z_{th(t-w)}]$

Reducing calculation time

To be able to point out the junction peak temperature at a certain pulse time and duty cycle, a graph similar to that shown in Fig.7 is included in relevant data sheets. In this example, the curves have been derived using the formula $T_{j(peak)} = T_{ref} + P_d \times [\delta \times R_{th(j\text{-}ref)} + (1 - \delta) \times Z_{th(t+w)} + Z_{th(w)} - Z_{th(t)}]$, with typical values inserted.

The pulse width along the X-axis meets a particular duty cycle curve, indicating the Z_{th} value in K/W along the Y-axis.

$T_{j(peak)} = P_{d(peak)} \times Z_{th(j\text{-}s)} + P_{d(av)} \times R_{th(s\text{-}a)} + T_{amb}$ (°C)

Soldering point temperature provides a better reference point than ambient temperature as this is subject to many uncontrolled variables. Therefore, the thermal resistance from junction to soldering point [$R_{th(j\text{-}s)}$] is becoming a more relevant measurement path.

For transistors in small SMD packages which are usually mounted on FR4 epoxy fibre-glass printed-circuit boards, only the thermal resistance from junction to ambient [$R_{th(j\text{-}a)}$] is published. In this case, the junction temperature can be calculated by:

$T_{j(peak)} = P_{d(peak)} \times Z_{th(j\text{-}a)} + T_{amb}$ (°C)

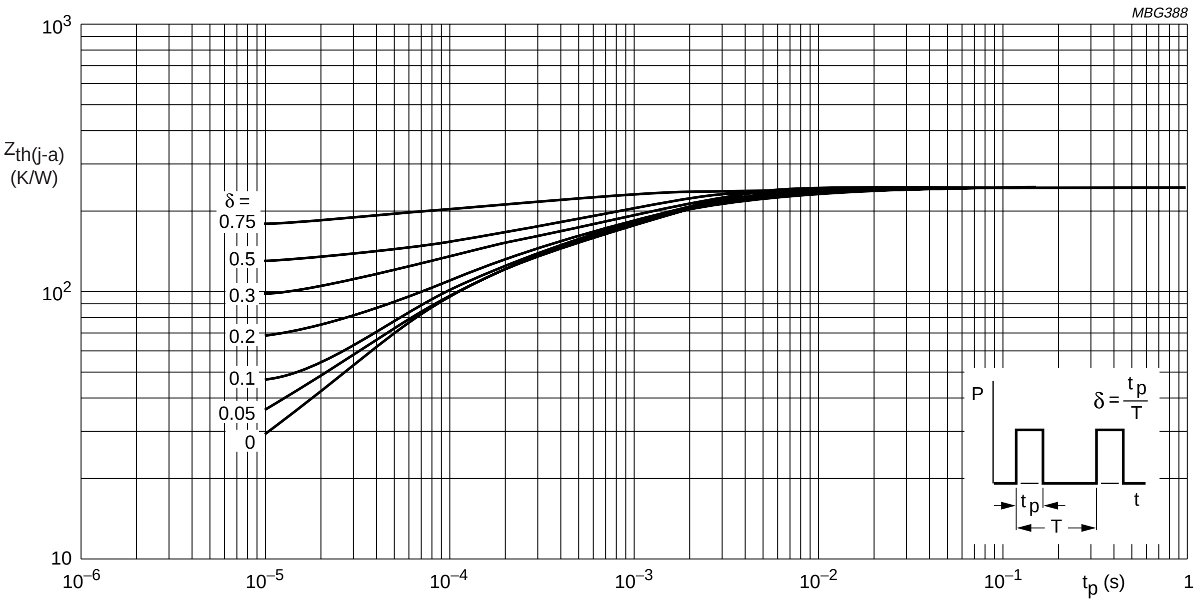


Fig.7 Direct reading of thermal impedance from junction to soldering point for calculation of junction temperature at pulsed power conditions.