# THEORETICAL ASPECTS RELATED TO JUNCTION TEMPERATURE AT POWER SEMICONDUCTORS

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## INTRODUCTION

Power devices may fail catastrophically if the junction temperature becomes high enough to cause thermal runaway and melting. A much lower functional limit is set by temperature increases that result in changes in device characteristics, such as forward breakover voltage or the recovery time, and failure to meet device specifications. Heat generation occurs primarily within the volume of the semiconductor pellet. This heat must be removed as efficiently as possible by some form of thermal exchange with the ambient, by the processes of conduction, convection or radiation.

Heat loss to the case and heat-sink is primarily by conduction. Heat loss by radiation accounts for only 1-2% of the total and can be ignored in most situations. Finally, loss from the heat-sink to the air is primarily by convection. Heat transfer by conduction is conveniently described by means of an electrical analogy.

## 1. TRANSIENT THERMAL OPERATING CONDITIONS

The concept of thermal resistance can be extended to thermal impedance for time-varying situations. For a step of input power the transient thermal impedance, $Z_{thjCDC}(t)$, has the expression,

$$Z_{thjCDC}(t) = \frac{\Delta\theta_{jC}(t)}{P} \tag{1}$$

where:
$Z_{thjCDC}(t)$ means junction-case transient thermal impedance;
$\Delta\theta_{jC}(t)$ – difference of temperature between junction and case at a given time t;
P – step of input power.

The transient thermal impedance can be approximated through a sum of exponential terms, like in expression bellow,

$$Z_{thjCDC}(t) = \sum_{j=1}^{k} r_j \left(1 - e^{-\frac{t}{\tau_j}}\right), \tag{2}$$

where $\tau_j = r_j C_j$ means thermal time constant.

The response of a single element can be extended to a complex system, such as a power semiconductor, whose thermal equivalent circuit comprises a ladder network of the separate resistance and capacitance terms. The transient response of such a network to a step of input power takes the form of a series of exponential terms. Transient thermal impedance data, derived on the basis of a step input of power, can be used to calculate the thermal response of power semiconductor devices for a variety of one-shot and repetitive pulse inputs. Further on, the thermal response for commonly encountered situations have been computed and are of great value to the circuit designer who must specify a power semiconductor device and its derating characteristics.

### 1.1. Step input power

The thermal step input power is shown in figure 1. The expression for the thermal step is given by equation (3) below.

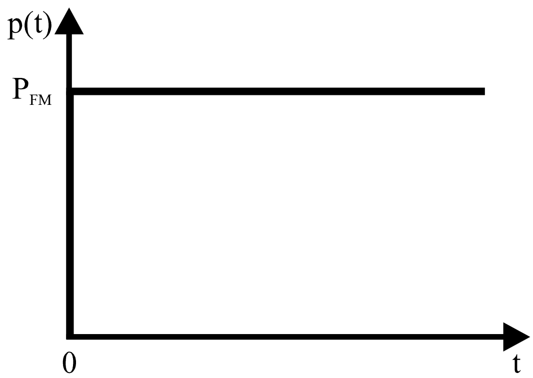


**Figure 1.** Step input power.

$$P(t) = \begin{cases} P_{FM} & if \quad t \geq 0, \\ 0 & if \quad t < 0 \end{cases} \tag{3}$$

It gets the thermal response:

$$\Delta\theta_{jC}(t) = P(t) Z_{thjCDC}(t) = P_{FM}\sum_{i=1}^{k} r_i\left(1 - e^{-\frac{t}{T_i}}\right) \quad (4)$$

## 1.2. Slope input power

Figure 2 shows the thermal slope input power and it has the expression from equation (5).

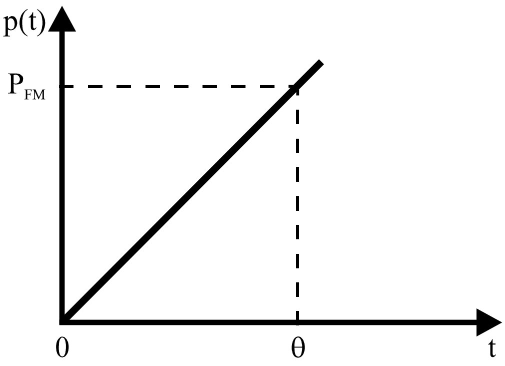


**Figure 2.** Slope input power.

$$P(t) = \begin{cases} \dfrac{P_{FM}}{\theta} t & if \quad t \geq 0, \\ 0 & if \quad t < 0 \end{cases} \quad (5)$$

The relation to establish the junction temperature is,

$$\Delta\theta_{jC}(t) = \frac{P_{FM}}{\theta}\left[t\sum_{i=1}^{k} r_i + \sum_{i=1}^{k} r_i T_i\left(1 - e^{-\frac{t}{T_i}}\right)\right] =$$
$$\frac{P_{FM}}{\theta} t\sum_{i=1}^{k} r_i\left[1 + T_i\left(1 - e^{-\frac{t}{T_i}}\right)\right] \quad (6)$$

## 1.3. Rectangular pulse input power

The time variation of the rectangular pulse input power is shown in figure 3 and its expression is given by the equation (7).

$$P(t) = \begin{cases} P_{FM} & if \quad 0 < t \leq \theta, \\ 0 & if \quad t > \theta \end{cases} \quad (7)$$

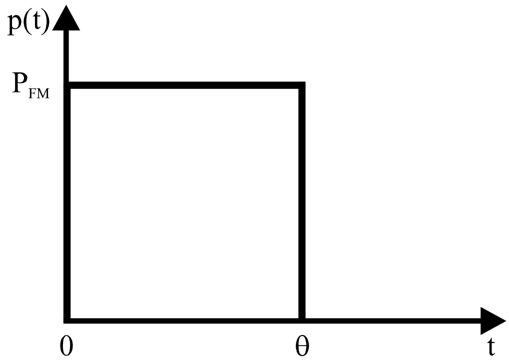


**Figure 3.** Rectangular pulse input power.

The junction temperature is given by,

$$\Delta\theta_{jC}(t) = \begin{cases} P_{FM}\sum_{i=1}^{k} r_i\left(1 - e^{-\frac{t}{T_i}}\right) & if \quad 0 < t \leq \theta, \\ P_{FM}\left[\sum_{i=1}^{k} r_i e^{-\frac{t-\theta}{T_i}}\left(1 - e^{-\frac{t}{T_i}}\right)\right] & if \quad t > 0 \end{cases}$$

(8)

## 1.4. Rectangular pulse series input power

Figure 4 shows the rectangular pulse series and the equation (9) describes this kind of input power.

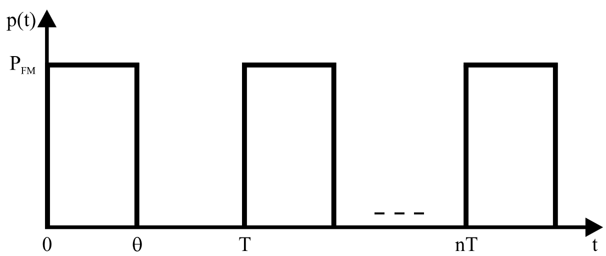


**Figure 4.** Rectangular pulse series input power.

$$P(t) = \begin{cases} P_{FM} & if \quad nT \leq t \leq nT + \theta, \\ 0 & if \quad nT + \theta < t \leq (n+1)T \end{cases} \quad (9)$$

The thermal response is given by the following equation (10).

For a very big number of rectangular pulses, actually $n \to \infty$, it gets the relation (11).

$$\Delta\theta_{jC(n+1)}(t)=\begin{cases} P_{FM}\sum_{i=1}^{k} r_i\left[1-\dfrac{e^{-\frac{t-nT}{T_i}}\left(1-e^{-\frac{(n+1)T}{T_i}}\right)-\left(1-e^{-\frac{nT}{T_i}}\right)e^{-\frac{T-\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}\right] & if \quad nT\le t\le nT+\theta,\\ P_{FM}\sum_{i=1}^{k} r_i e^{-\frac{t-nT-\theta}{T_i}}\dfrac{1-e^{-\frac{\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}\left(1-e^{-\frac{(n+1)T}{T_i}}\right) & if \quad nT+\theta<t\le(n+1)T\end{cases} \tag{10}$$

$$\Delta\theta_{jC\infty}(t)=\begin{cases} P_{FM}\sum_{i=1}^{k} r_i\left(1-e^{-\frac{t}{T_i}}\right)\dfrac{1-e^{-\frac{T-\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}} & if \quad nT\le t\le nT+\theta,\\ P_{FM}\sum_{i=1}^{k} r_i e^{-\frac{t-\theta}{T_i}}\dfrac{1-e^{-\frac{\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}} & if \quad nT+\theta<t\le(n+1)T\end{cases} \tag{11}$$

Therefore, the junction temperature variation in steady-state conditions will be,

$$\begin{aligned}\Delta\theta_{jC\infty} &= \left(P_{FM}-\frac{\theta}{T}P_{FM}\right)\sum_{i=1}^{k} r_i - \\ &- P_{FM}\sum_{i=1}^{k} r_i e^{-\frac{\theta}{T_i}}\frac{1-e^{-\frac{T-\vartheta}{T_i}}}{1-e^{-\frac{T}{T_i}}} = \\ &= P_{FM}\sum_{i=1}^{k} r_i\left[1-\frac{\theta}{T}-e^{-\frac{\theta}{T_i}}\frac{1-e^{-\frac{T-\vartheta}{T_i}}}{1-e^{-\frac{T}{T_i}}}\right] = \\ &= P_{FM}\sum_{i=1}^{k} r_i\left(\frac{1-e^{-\frac{\vartheta}{T_i}}}{1-e^{-\frac{T}{T_i}}}-\frac{\theta}{T}\right)\end{aligned} \tag{12}$$

## 1.5. Increasing triangle pulse series input power

A series of increasing triangle pulses is shown in figure 5 and the equation which describes this series is given in (13)

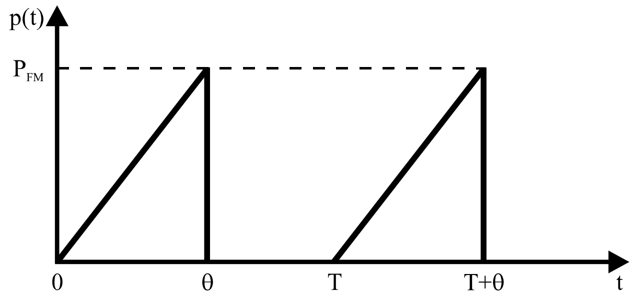


**Figure 5.** Increasing triangle pulse series input power.

$$P(t)=\begin{cases} t\dfrac{P_{FM}}{\theta} & if \quad nT\le t\le\theta+nT,\\ 0 & if \quad \theta+nT<t\le(n+1)T\end{cases} \tag{13}$$

In the case when $n\to\infty$, the thermal response will be,

$$\Delta\theta_{jC\infty}(t)=\begin{cases} \dfrac{P_{FM}}{\theta}\sum_{i=1}^{k} r_i\left\{t-T_i\left[1-\dfrac{1-\left(1-\frac{\theta}{T_i}\right)e^{-\frac{T-\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t}{T_i}}\right]\right\}\\ if \quad nT\le t\le\theta+nT,\\ \dfrac{P_{FM}}{\theta}\sum_{i=1}^{k} r_i T_i\dfrac{\frac{\theta}{T_i}+e^{-\frac{\theta}{T_i}}-1}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t-\theta}{T_i}}\\ if \quad \theta+nT<t\le(n+1)T\end{cases} \tag{14}$$

## 1.6. Decreasing triangle pulse series input power

Figure 6 shows a decreasing triangle pulse series with its equation (15).

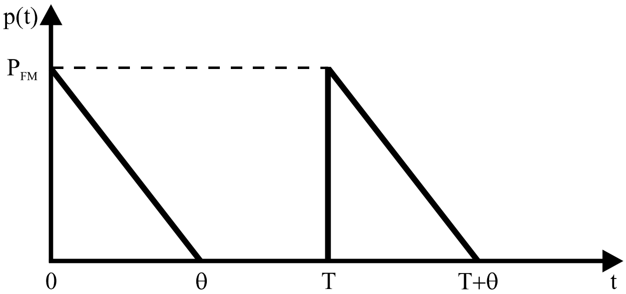


**Figure 6.** Decreasing triangle pulse series input power.

$$P(t)=\begin{cases}1-t\dfrac{P_{FM}}{\theta} & if \quad nT\le t\le \theta+nT,\\ 0 & if \quad \theta+nT<t\le (n+1)T\end{cases} \qquad (15)$$

At limit, when $n\to\infty$, the thermal response will be:

$$\Delta\theta_{jC\infty}(t)=\begin{cases}\dfrac{P_{FM}}{\theta}\displaystyle\sum_{i=1}^{k} r_i\left\{\begin{aligned}&(\theta-t)-\\ &-T_i\left[1+\dfrac{1+\dfrac{\theta}{T_i}-e^{-\frac{T-\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t}{T_i}}\right]\end{aligned}\right\}\\ if \quad nT\le t\le\theta+nT,\\ \dfrac{P_{FM}}{\theta}\displaystyle\sum_{i=1}^{k} r_iT_i\,\dfrac{1-\left(1+\dfrac{\theta}{T_i}\right)e^{-\frac{\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}\\ if \quad \theta+nT<t\le(n+1)T\end{cases}$$

(16)

## 1.7. Triangle pulse series input power

A series of triangle input power is shown in figure 7. The equation which describes this kind of series is given in (17).

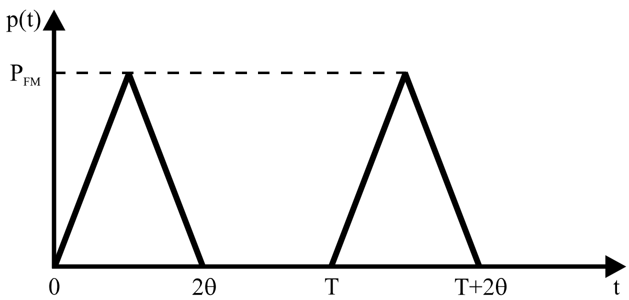


**Figure 7.** Triangle pulse series input power.

$$P(t)=\begin{cases}t\dfrac{P_{FM}}{\theta} & if \quad nT\le t\le\theta+nT,\\ \left(2-\dfrac{t}{\theta}\right)P_{FM} & if \quad \theta+nT<t\le 2\theta+nT,\\ 0 & if \quad 2\theta+nT<t\le(n+1)T\end{cases}$$

(17)

For junction temperature computation when $n\to\infty$, the following relation will be used:

$$\Delta\theta_{jC\infty}(t)=\begin{cases}\dfrac{P_{FM}}{\theta}\displaystyle\sum_{i=1}^{k} r_i\left[\begin{aligned}&T_i\dfrac{1-2e^{-\frac{T-\theta}{T_i}}+e^{-\frac{T-2\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t}{T_i}}\\ &+(t-T_i)\end{aligned}\right]\\ if \quad nT\le t\le\theta+nT,\\ \dfrac{P_{FM}}{\theta}\displaystyle\sum_{i=1}^{k} r_i\left\{\begin{aligned}&-T_i\dfrac{2-e^{-\frac{\theta}{T_i}}-e^{-\frac{T-\theta}{T_i}}}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t-\theta}{T_i}}\\ &+[(2\theta-t)+T_i]\end{aligned}\right\}\\ if \quad \theta+nT<t\le 2\theta+nT,\\ \dfrac{P_{FM}}{\theta}\displaystyle\sum_{i=1}^{k} r_iT_i\dfrac{\left(1-e^{-\frac{\theta}{T_i}}\right)^2}{1-e^{-\frac{T}{T_i}}}e^{-\frac{t-2\theta}{T_i}}\\ if \quad 2\theta+nT<t\le(n+1)T\end{cases}$$

(18)

## 1.8. Trapezoidal pulse series input power

Figure 8 shows a trapezoidal pulse series with the equation from (19).

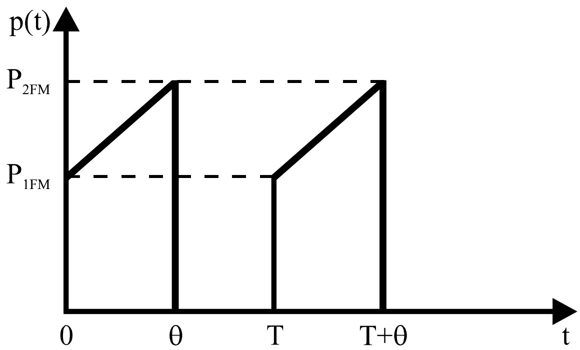


**Figure 8.** Trapezoidal pulse series input power.

$$P(t)=\begin{cases}P_{1FM}+(P_{2FM}-P_{1FM})\dfrac{t}{\theta} & if \quad nT\le t\le\theta+nT,\\ 0 & if \quad \theta+nT<t\le(n+1)T\end{cases}$$

(19)

At limit, $n \to \infty$, the thermal response is given by,

$$\Delta\theta_{jC\infty}(t)=\begin{cases}\dfrac{1}{\theta}\sum_{i=1}^{k} r_i\left[T_i \dfrac{F_{P_1P_2}}{1-e^{-\frac{T}{T_i}}} e^{-\frac{t}{T_i}} + P_{1FM} + \dfrac{P_{2FM}-P_{1FM}}{\theta}(t-T_i)\right] \\ \quad if \quad nT \le t \le \theta + nT, \\ \dfrac{1}{\theta}\sum_{i=1}^{k} r_i T_i \dfrac{G_{P_1P_2}}{1-e^{-\frac{T}{T_i}}} e^{-\frac{t-\theta}{T_i}} \\ \quad if \quad \theta + nT < t \le (n+1)T \end{cases} \tag{20}$$

where:

$$\begin{aligned} F_{P_1P_2} &= P_{2FM} - P_{1FM}\left(1+\frac{\theta}{T_i}\right) + \\ &+ \left[P_{1FM} - P_{2FM}\left(1-\frac{\theta}{T_i}\right)\right] e^{-\frac{T-\theta}{T_i}}, \\ G_{P_1P_2} &= P_{1FM} - P_{2FM}\left(1-\frac{\theta}{T_i}\right) + \\ &+ \left[P_{2FM} - P_{1FM}\left(1+\frac{\theta}{T_i}\right)\right] e^{-\frac{\theta}{T_i}} \end{aligned} \tag{21}$$

## 1.9. Partial sinusoidal pulse series input power

A partial sinusoidal pulse series waveform is shown in figure 9. The equation which describes

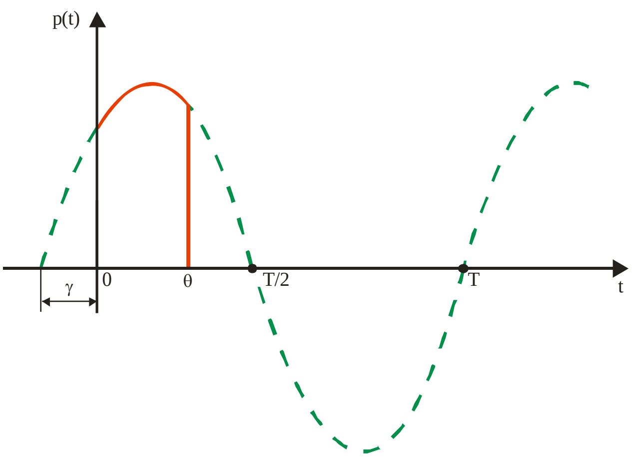


**Figure 9.** Partial sinusoidal pulse series input power.

this kind of waveform is given b (22).

$$P(t)=\begin{cases} P_{FM}\sin(\omega t+\gamma) & if \quad nT \le t \le \theta + nT, \\ 0 & if \quad \theta + nT < t \le (n+1)T \end{cases} \tag{22}$$

In order to establish the junction temperature when $n \to \infty$, it will use the relation (23),

$$\Delta\theta_{jC\infty}(t)=\begin{cases} P_{FM}\left\{Z\sin(\omega t+\gamma-\delta) - \sum_{i=1}^{k} r_i\left[\sin(\gamma-\varphi_i) - \sin(\gamma-\varphi_i+\omega\theta)e^{-\frac{T-\theta}{T_i}}\right]\dfrac{e^{-\frac{t}{T_i}}}{\left(1-e^{-\frac{T}{T_i}}\right)\sqrt{1+(\omega T_i)^2}}\right\} \\ \quad if \quad nT \le t \le \theta + nT, \\ P_{FM}\sum_{i=1}^{k} r_i\left[\sin(\omega\theta+\gamma-\varphi_i) - \sin(\gamma-\varphi_i)e^{-\frac{\theta}{T_i}}\right]\dfrac{e^{-\frac{t-\theta}{T_i}}}{\left(1-e^{-\frac{T}{T_i}}\right)\sqrt{1+(\omega T_i)^2}} \\ \quad if \quad \theta + nT < t \le (n+1)T \end{cases} \tag{23}$$

where:

$$\begin{aligned} ctg\varphi_i &= \frac{1}{\omega T_i}; \\ Z^2 &= \sum_{i=1}^{k}\left(r_i \cos^2\varphi_i\right)^2 + \sum_{i=1}^{k}\left(\frac{r_i}{2}\sin 2\varphi_i\right)^2; \\ tg\delta &= \frac{\sum_{i=1}^{k}\frac{r_i}{2}\sin 2\varphi_i}{\sum_{i=1}^{k} r_i\cos^2\varphi_i} \end{aligned} \tag{24}$$

Extremely short overloads of the type that occur under surge or fault conditions are limited to a few cycles in duration. Here the junction temperature exceeds its maximum rating and all operational parameters are severely affected. However the low transient thermal impedance offered by the device in this region of operation, is often sufficient to handle the power that is dissipated.

## 2. CONCLUSIONS

Thermal response of power semiconductor devices for a variety of one-shot and repetitive pulse inputs have been computed with the aim to offer valuable formulae for power circuit designers. A transient thermal calculation even using the relation (2), is very complex and difficult to do. So, a more exactly and efficiently thermal calculation of power semiconductors at different types of input power, can be done using specific modelling and simulation software.

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