DYNEX SEMICONDUCTOR

AN4506

Calculation Of Junction Temperature

Application Note

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There are a number of ways of calculating the junction temperature of a device. These involve various levels of complexity from a quick hand calculation to a full three dimensional finite element analysis, with various shades of complexity between these two extremes. Examples of these various methods are spread sheets and simulation programs which use some form of mathematical model. When rating a device for a given application the designer must select an appropriate type and ensure that absolute maximum ratings are not exceeded. The device selected must be rated for the worst case conditions it is likely to see. If the device rating does not match the circuit requirements either a new type must be selected or the circuit design changed. Alternatively if the device is expected to fail the circuit must be designed to allow safe failure. Almost all power semiconductor ratings and characteristics are related to the junction temperature. Consequently reliable calculation of junction temperature, both transient and steady state is very important. For simple continuous current waveforms eg dc, 1/2 sinewave, rectangular waves etc, used with thyristors rectifiers and GTOs, standard equations given in textbooks can be used to determine the junction temperature for a given power loss and thermal impedance. These are easy to use to calculate T_j. For irregular shaped current waveforms the pulses can often be approximated to a series of equivalent energy rectangular pulses. The superposition theorem can then be used for calculating the junction temperature of a device. This theorem uses the power losses of a circuit in conjunction with the transient thermal impedance curve to calculate the junction temperature of a device.

Junction temperature calculations are extremely dependant on good thermal contacts from chip to heatsink. The chip to case characteristics are guaranteed by the manufacturer, but the case to heatsink characteristics are dependent upon the way in which the user mounts the device to the heatsink, surface flatness etc. The final operating conditions with in a given application, ambient temperature, heatsink thermal resistance etc all affect the final T_j of the device. In any mathematical model used for the calculation of junction temperature, variables such as these can only be guesstimated from worst case conditions, taking into account reasonable engineering compromises regarding heatsink flatness etc. In real life these values can never be known with 100% accuracy and when rating a device for a given application maximum tolerances should be taken into account. The only way of evaluating a system fully , is to build it using an approximately rated device, and test the thermal circuit.

1. POWER LOSSES:

The total power dissipation in a device is the sum of the switching losses(turn on and turn off), conduction losses, off state losses and the drive input losses. Only the first 2 of these quantities are generally significant, and at lower frequencies only the conduction losses are significant.

2. CALCULATION METHODS:

The superposition theorem is based upon rectangular pulses of power, non rectangular pulses are converted in rectangular pulses with the same peak power levels, but with reduced on periods fig 1. The transient thermal impedance for a given duty cycle can be derived from the transient thermal impedance single pulse curve fig 2.

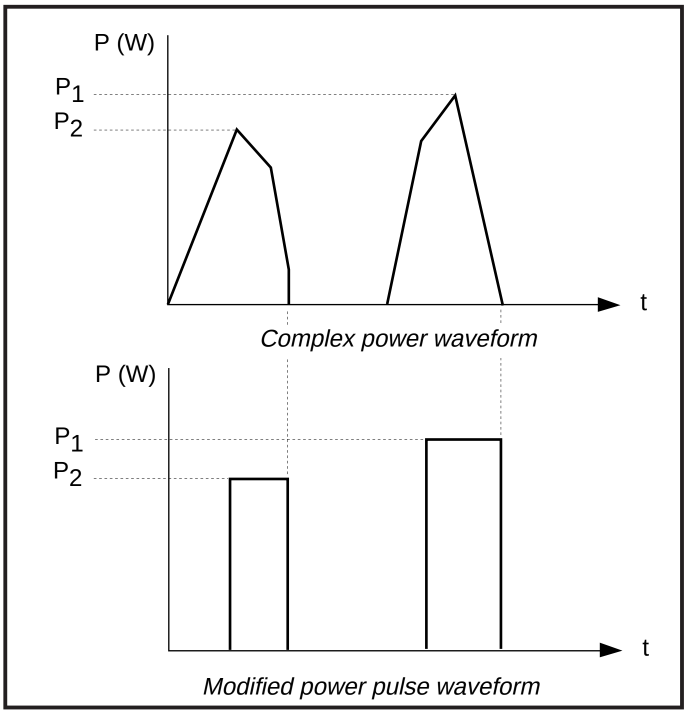

Fig.1

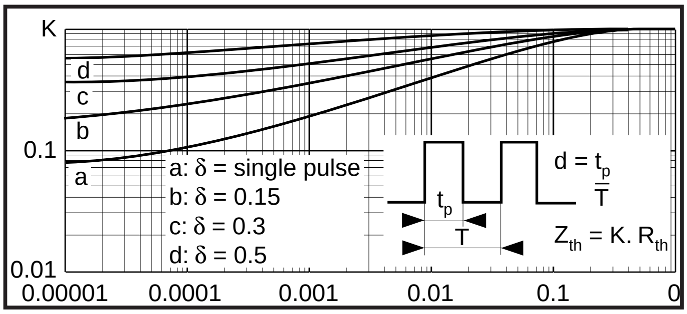

Fig.2 Typical transient thermal impedance

From the superposition theorem assuming that T_j is responding to the average power over a long pulse train the maximum junction temperature can be quickly derived as follows.

T_j-T_c = δ. P_{max}. R_{th} - δ. P_{max}. $r_{th}(t_p+T)$ + P_{max}. $r_{th}(t_p+T)$ - P_{max}. $r_{th}(T)$ + P_{max}. $r_{th}(t_p)$ [1]

The above is often simplified as follows

T_j-T_c = δ. P_{max}. R_{th} - δ P_{max}. $r_{th}(t_p)$ + P_{max}. $r_{th}(t_p)$ [2]

Rewriting the above

T_j-T_c = P_{max}. (δ + (1 - δ) $r_{th}(t_p)/R_{th}$) R_{th} [3]

Transient thermal impedance for different duty cycles is generally defined as shown below.

$Z(t_p,\delta) = (\delta + (1 - \delta)\, r_{th}(t_p)/R_{th})\, R_{th}$ [4]

Peak Power = $(T_j - T_c) / Z(t_p,\delta)$ [5]

The above equations are suitable for continuous power pulses but can be adapted for other wave forms. The power pulse train may include turn on losses, conduction losses and turn off losses. These can be added together to give the average power for the pulse and then the superposition theorem can be used for the pulses immediately following this period to determine the junction temperature at the end of each period.

$P_{av} = F\,(E_{on} + E_{cond} + E_{off})$ [6]

this equation takes a complex wave shape and approximates it to a single power pulse.

$E_{cond} = V \times I \times t_{on} = V \times I \times \delta \times T = P_{peak} \times \delta \times T$ [7]

$P_{av} = F\,(E_{on} + P_{peak} \times \delta \times T + E_{off})$ [8]

$T = 1/F$ [9]

$P_{av} = F\,(E_{on} + E_{off}) + P_{peak} \times \delta$ [10]

Using the same reasoning as above

For turn on T_{jmax}

$T_j - T_c = P_{av}. R_{th} - P_{av}. r_{th}(t_{on}) + r_{th}(t_{on}) \times E_{on}/t_{on}$ [11]

For T_j at end of conduction period

$T_j - T_c = P_{av}. R_{th} - P_{av}. r_{th}(t_{cond}) + P_{cond} \times r_{th}(t_{cond}) + r_{th}(t_{cond} + t_{on}) \times E_{on}/t_{on} - r_{th}(t_{cond}) \times E_{on}/t_{on}$ [12]

For T_j at end of turn off period

$T_j - T_c = P_{av}. R_{th} - P_{av}. r_{th}(t_{off}) + r_{th}(t_{off}) \times E_{off}/t_{off} + P_{cond} \times r_{th}(t_{cond} + t_{off}) + r_{th}(t_{cond} + t_{on} + t_{off}) \times E_{on}/t_{on} - r_{th}(t_{cond} + t_{off}) \times E_{on}/t_{on} - P_{cond}. r_{th}(t_{off})$ [13]

A further approximation often made to the above equations is of the following form whereby;

$P_{max} = F (E_{on} + E_{off}) + P_{peak}$ [14]

$T_j - T_c = P_{av}. R_{th} - P_{av}. r_{th}(t_p) + P_{max}. r_{th}(t_p)$ [15]

this is then rearranged to give

$T_{jmax} = P_{max} (D. R_{th} - D. r_{th}(t_p) + r_{th}(t_p)) + T_c$ [16]

or

$T_{jmax} = P_{max}. Z(t_p,D) + T_c$ [17]

3. HEAT SINKS:

Because of thermal capacitance, heat sinks generally only respond to average power except at low frequency. At low frequencies the delta T_j within a given device may be appreciable. This situation occurs in rail traction applications.

The thermal impedance of a heatsink is governed primarily by its mass, surface area, coolant flow-rate, and the material from which it is made (ie specific heat capacity, thermal capacitance and thermal resistivity. Some typical values are included in figure 3). Many other factors can affect a heatsinks performance such as the size of the heat source placed on the heatsink, the orientation of the heatsink etc.

$T_c - T_a = P_{av}. (R_{th(c-h)} + R_{th(h-a)})$ [18]

Combining the equations for heatsink and device the T_{jmax} can be approximated to

$T_{jmax} = P_{max}. Z(t_p,D) + P_{av}. (R_{th(c-h)} + R_{th(h-a)}) + T_a$ [19]

Material	Density (kg/m^3)	Specific Heat (kg/m^3)	Thermal Conductivity (W/m ˚C)
Alumina	800	3900	25
Aluminium	710		201
Copper	385	8930	394
Solder	175	9724	35
Silicon	750	2400	100
Water	998		0.59
Air	1.293		0.0241
Oil	800		0.17

Fig. 3

Specific Heat Capacity
= Specific Heat x Density x Volume

Thermal Resistance =
1/Thermal Conductivity x thickness/area

4. COMPUTER SIMULATION:

A more complete solution via a hand calculation method starts to become prohibitive at this level, and the use of simulation programs or spread sheets to calculate junction temperatures become useful.

5. ACCURACY OF CALCULATIONS-LIMITATIONS:

It should be noted at this stage that the actual junction temperature cannot be calculated accurately to within a couple of degrees under switching operations, due to it being extremely difficult to work out exactly how the current is distributed over the surface of the chip. To illustrate this statement if a device takes approximately 1µs to turn off and has switching losses of 30mJ this is equivalent to 30kW power pulse, which can raise a junction temperature by typically 5 to 20 degrees on a $(12x12)mm^2$ chip dependant on active chip volume, assuming uniform current distribution. The junction temperature is dependent upon the specific heat capacity of the active volume of the junction, under switching operations and more seriously under short circuit operations ie for periods of <10µs the majority of the heat generated does not escape the active volume of the chip. Under short circuit conditions the junction temperature can rise by as much as 100˚C in 10µs dependent upon gate drive levels. Gate drives are the subject of another application note.

The above method of calculating junction temperature is relatively accurate to within a few degrees and works well.

It can be seen from typical transient thermal impedance curves that as t_{on} increases to periods of >1 second Tjmax can be calculated directly from the steady state thermal impedance as $Z(t_p, \delta) \mapsto R_{th}$. as frequency increases T_j responds more to the average power than the peak power and peak junction temperature rise ≈ junction temperature rise, in many applications calculation of the average junction temperature is all that is necessary.

The methods described above are suitable for all different types of semiconductors i.e. Diodes, Thyristors GTOs , IGBTs, Bipolars, FETs etc.

6. NOMENCLATURE:

c-h	Case to heatsink
δ	Duty Cycle = t_{cond}/Period
D	Normalized Duty Cycle = P_{av} / P_{max}
E_{on}	Turn On Energy
E_{cond}	Conduction Energy
E_{off}	Turn Off Energy
F	Frequency
h-a	Heatsink to ambient
j-c	Junction to case
P_{av}	Average Power
P_{max}	Maximum Power
P_{peak}	Peak Power
R_{th}	Steady State Thermal Resistance
$r_{th}(t_p)$	Single Pulse Thermal Impedance
T	Period = 1/F
T_a	Ambient Temperature
T_c	Case Temperature
t_{cond}	Conduction Period
T_j	Junction Temperature
T_{jmax}	Maximum Junction Temperature
t_{off}	Turn Off Time
t_{on}	Turn On Time
t_p	Pulse Duration
$Z(\delta,t_p)$	Transient Thermal Impedance

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