AND9140/D

Thermal Calculations for IGBTs

ON Semiconductor®

http://onsemi.com

APPLICATION NOTE

Introduction

IGBTs generally require a more complex set of calculations to determine the die temperatures than do most power semiconductors. This is due to the fact that most IGBTs are co-packaged and include both an IGBT and a diode die in the same package. In order to know the temperature of each die, it is necessary to know the power dissipation, frequency, thetas and interaction coefficient for each die. It is also necessary to have the thetas for each device and the psi value for their interaction.

This application note will explain, in simple terms, how to measure the power and calculate the temperature rise of the diode and IGBT dice.

Loss Components

Depending on the circuit topology and operating conditions, the power losses between the two die can vary considerably. The losses in the IGBT can be broken down into the conduction and switching (turn-on and turn-off), while the diode losses are the conduction and turn off losses. Accurately measuring these losses generally requires the use of an oscilloscope with voltage and current probes to monitor the waveforms during operation of the devices. It will be necessary to utilize math functions to measure the energy. When the total energy for a switching cycle has been determined, it can be translated to power by dividing by the time of the switching period.

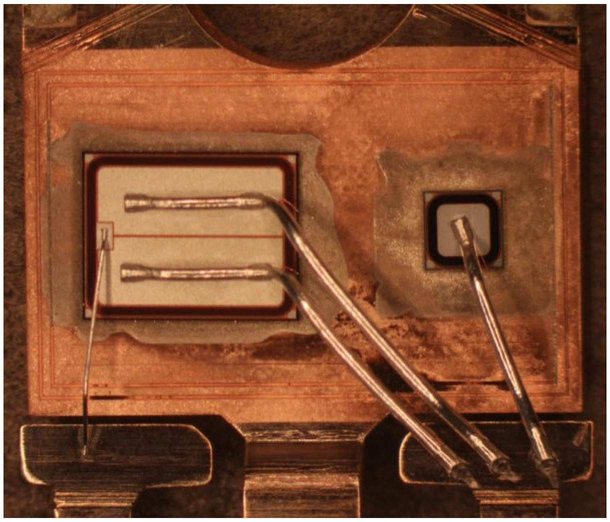


Figure 1. TO−247 Package Showing IGBT Die (Left) and Diode Die (Right)

IGBT Turn-on

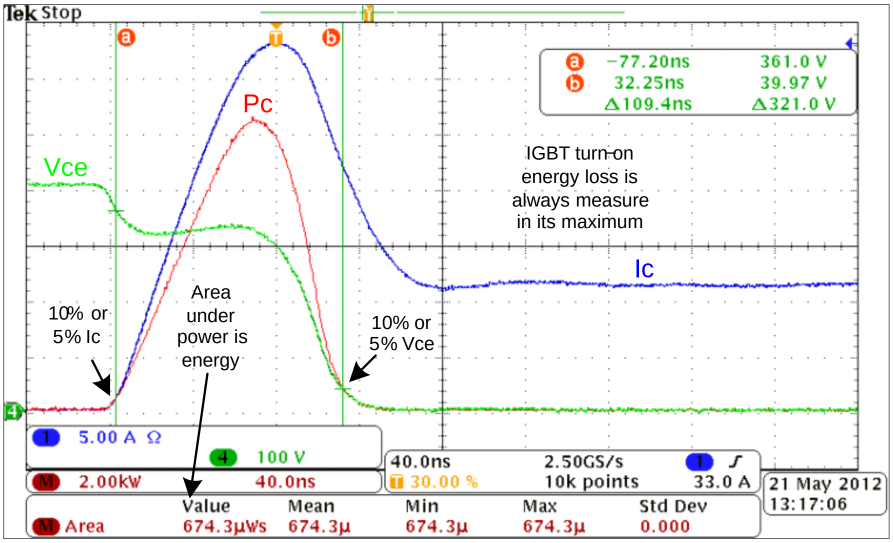


Figure 2. IGBT Turn-on Loss Waveforms

April, 2014 − Rev. 1

By multiplying the voltage and current of the turn-on waveforms, the power during this period can be calculated. The integral of the power waveform is shown at the bottom of the screen. This gives the energy for the turn-on losses of the IGBT.

The points at which the power measurement begins and ends are arbitrary, but once a set of criteria are selected, measurements should consistently conform to those criteria.

IGBT Conduction Loss

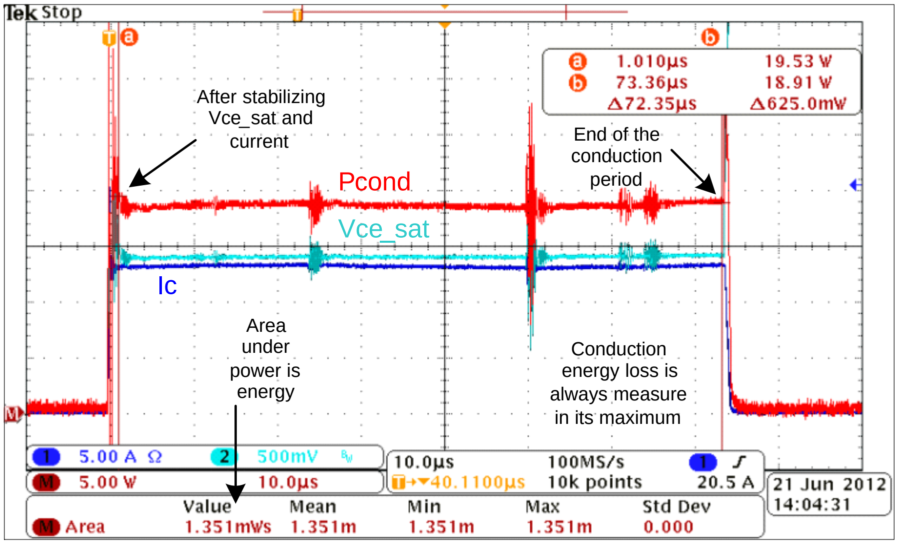


Figure 3. IGBT Conduction Loss Waveforms

Conduction losses occur between the turn-on and turn-off loss areas. Again the integral should be used since the power is not quite constant over this period.

IGBT Turn-off

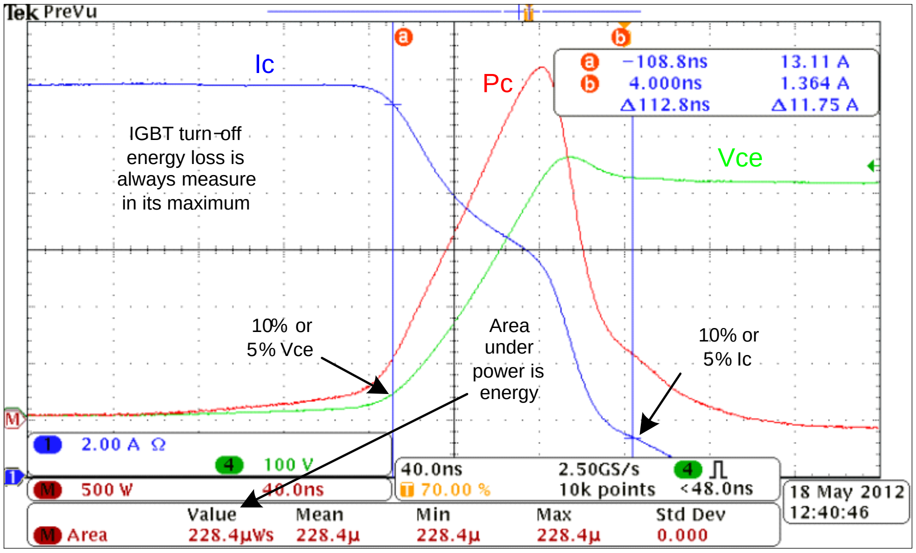


Figure 4. IGBT Turn-off Loss Waveforms

The turn-on, conduction and turn-off losses make up the sum of the losses for the IGBT die. The off-state losses are negligible and do not need to be calculated. To calculate the total power loss for the IGBT, the sum of the three energies must be multiplied by the switching frequency.

$$P_{IGBT} = (E_{on} + E_{cond} + E_{off}) \times f_{SW}$$

The IGBT losses must be measured with a resistive load or during a portion of the cycle where the load is consuming power. This eliminates the diode conduction.

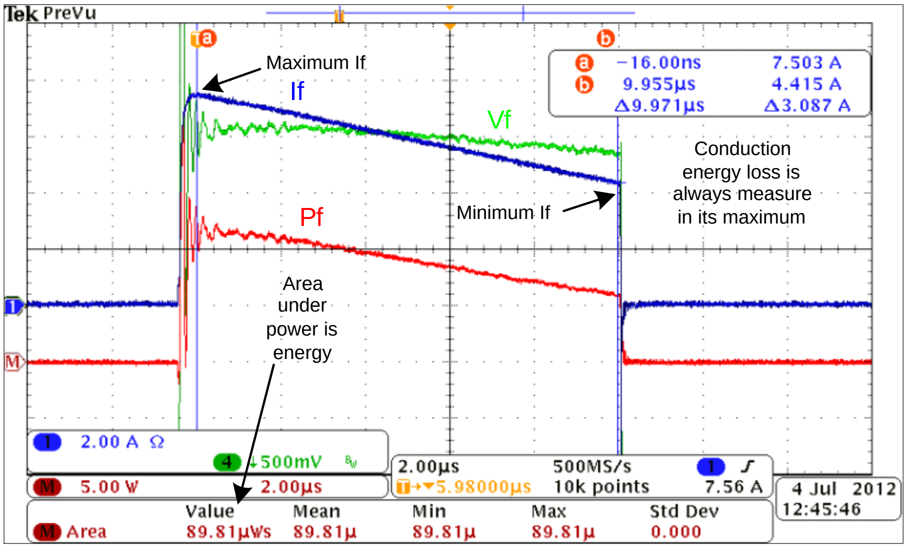


Figure 5. Diode Conduction Loss Waveforms

FWD Reverse Recovery

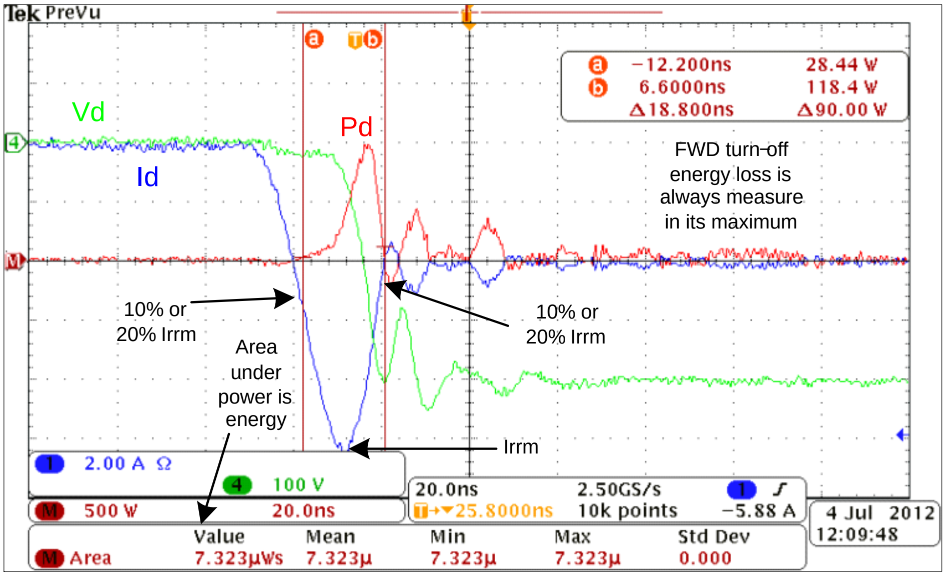


Figure 6. Diode Reverse Recovery Waveforms

Figures 5 and 6 show the diode current and voltage waveforms during operation in the rectifier or reactive mode. The diode losses are calculated similarly to the IGBT losses.

$$P_{DIODE} = \left(E_{cond} + E_{rev}\right) \times f_{SW}$$

It needs to be understood that the losses vary over the half-sine wave. The variation from the peak values to the zero crossing need to be taken into account to arrive at the average power dissipation in the device.

IGBT and Diode Power Calculations

When the five loss components have been measured, they need to be related to the conditions under which they were taken so that the total power in each can be calculated.

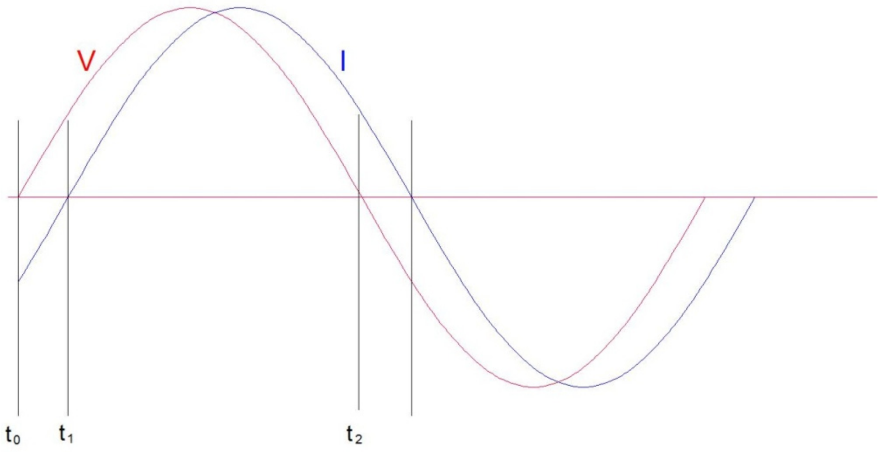


Figure 7. Inductive Load Waveforms

Figure 7 shows the typical voltage and current waveforms for an inductive load, such as a motor.

From t_0 to t_1 the current is reactive and the diodes are conducting current.

From t_1 to t_2 the current is resistive and the IGBTs are conducting current.

The power during these periods is the value of importance. Calculating the average power for each period based on a single pulse is very complex; however we can estimate it to a reasonable level of accuracy. To do this will require the calculation of the average power for that period of time.

In this situation it is necessary to calculate the average (or heating) equivalent. For voltage and current values, this is the rms value and for power it is the average.

Average Power

$$P_{avg} = \frac{P_{max}}{t_1 - t_0} \int_{t0}^{t1} \sin\left(\frac{2\pi t}{T}\right) dt$$

$$P_{avg} = -\frac{P_{max}}{t_1 - t_0} \times \frac{T}{2\pi} \left[\cos\left(\frac{2\pi t_1}{T}\right) - \cos\left(\frac{2\pi t_0}{T}\right)\right]$$

This equation would work for this power in a fraction of each quarter of the sine wave, so to correct for that we need to add a factor of 4 in the denominator. This is valid as long as the zero voltage crossing point is between 0 and 90° which it must be for an inductive load, so the equation becomes:

$$P_{avg} = -\frac{P_{max}}{t_1 - t_0} \times \frac{T}{8\pi} \left[\cos\left(\frac{2\pi t_1}{T}\right) - \cos\left(\frac{2\pi t_0}{T}\right)\right]$$

Diode

The diode is conducting during the interval from t_0 to t_1. Taking the waveforms at the zero crossing of the voltage will yield the peak power dissipation for the diode. Using this power level, we can use the average power formula during the period of t_0 to $t_1$to find the average power dissipation for the diode.

An example calculation for this period is shown below.

$P_{DIODEpk}$ = 50 W (at the voltage zero crossing point)

T = 20 ms (50 Hz sine wave)

$t_0 = 0$

t_1 = 2.5 ms

The 2 watt power level occurs at the time of 2.5 ms into the cycle. To calculate the equivalent power at the peak of the sine wave, we need to compare the amplitudes at these two points.

The peak amplitude will occur at 90° or $\pi/2$ radians, which equates to an amplitude of 1. The amplitude at 2.5 ms is sine ($\pi \times 2.5$ ms/10 ms) or 0.707, so the power at the peak of the sine wave is:

$$P_{pk} = \frac{50\text{ W}}{0.707} = 70.7\text{ W}$$

$$P_{DIODE} = -\frac{P_{max}}{t_1 - t_0} \times \frac{T}{8\pi} \left[\cos\left(\frac{2\pi t_1}{T}\right) - \cos\left(\frac{2\pi t_0}{T}\right)\right]$$

$$P_{DIODE} = -\frac{70.7}{2.5 - 0} \times \frac{20}{8\pi} \left[\cos\left(\frac{2\pi \times 2.5}{20}\right) - \cos\left(\frac{2\pi \times 0}{20}\right)\right]$$

$$P_{DIODE} = -22.5\,[0.707 - 1] = 6.60\text{ W}$$

IGBT

For the positive voltage half-cycle, the IGBT is conducting from t_1 to t_2. The average power for the IGBT is calculated similarly to the diode power. The example calculation for it is shown below.

$P_{IGBTpk} = 95$ W

T = 20 ms (50 Hz sine wave)

$T_1 = 2.5$ ms

$T_2 = 10$ ms (T/2)

For the IGBT analysis the IGBT power during the entire half sine wave ($t_0 - t_2$) will be calculated and then the IGBT power during the Diode conduction period ($t_0 - t_1$) will be calculated and subtracted from the full half sine wave.

$$P_{IGBT\,(t2-t0)} = P_{pk} \times 0.6366 = 95 \times 0.6366 = 60.48\text{ W}$$

Then we will calculate the power during the diode conduction period

$$P_{DIODE} = -\frac{P_{max}}{t_1 - t_0} \times \frac{T}{8\pi}\left[\cos\left(\frac{2\pi t_2}{T}\right) - \cos\left(\frac{2\pi t_1}{T}\right)\right]$$

Since t2 = T/2 the equation becomes

$$P_{DIODE} = -\frac{P_{max}}{t_1 - t_0} \times \frac{T}{8\pi}\left[1 - \cos\left(\frac{2\pi t_1}{T}\right)\right]$$

$$P_{DIODE\,(t1-t0)} = \frac{60.48}{2.5 - 0} \times \frac{20}{8\pi}\left[1 - \cos\left(\frac{2\pi \times 0}{20}\right)\right]$$

$$P_{DIODE\,(t1-t0)} = 19.25\,[1 - 0.707] = 5.64\text{ W}$$

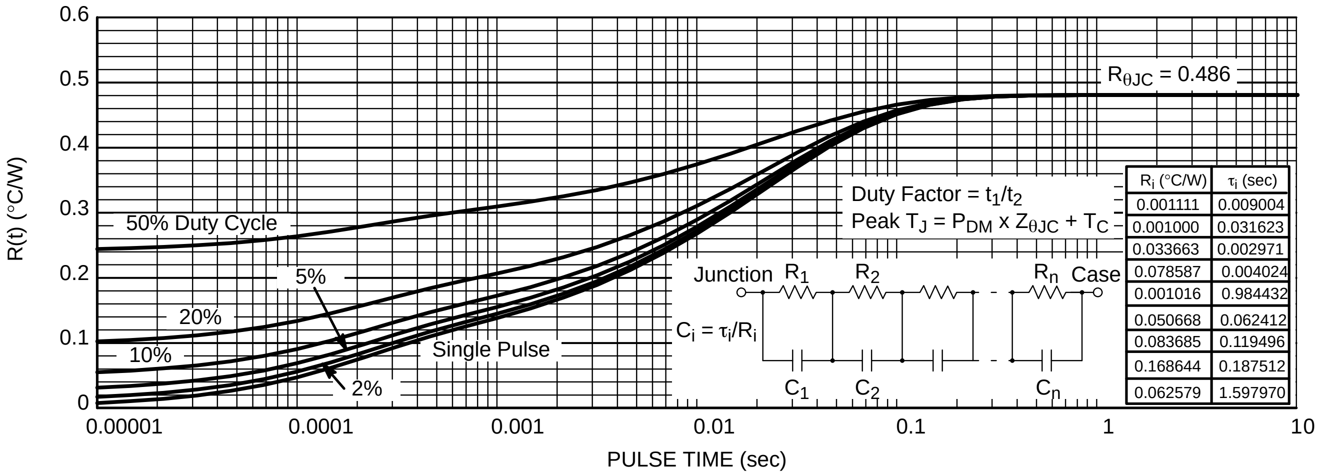
$$P_{IGBT\,(t2-t1)} = 60.48\text{ W} - 5.64\text{ W} = 54.84\text{ W}$$

Die Temperature Calculations

Once the power dissipation values for the two dice are completed, the die temperatures can be calculated by using the curves in the data sheets. Both die will not normally be at the same temperature. There is a theta for each die and a Psi-interactions.

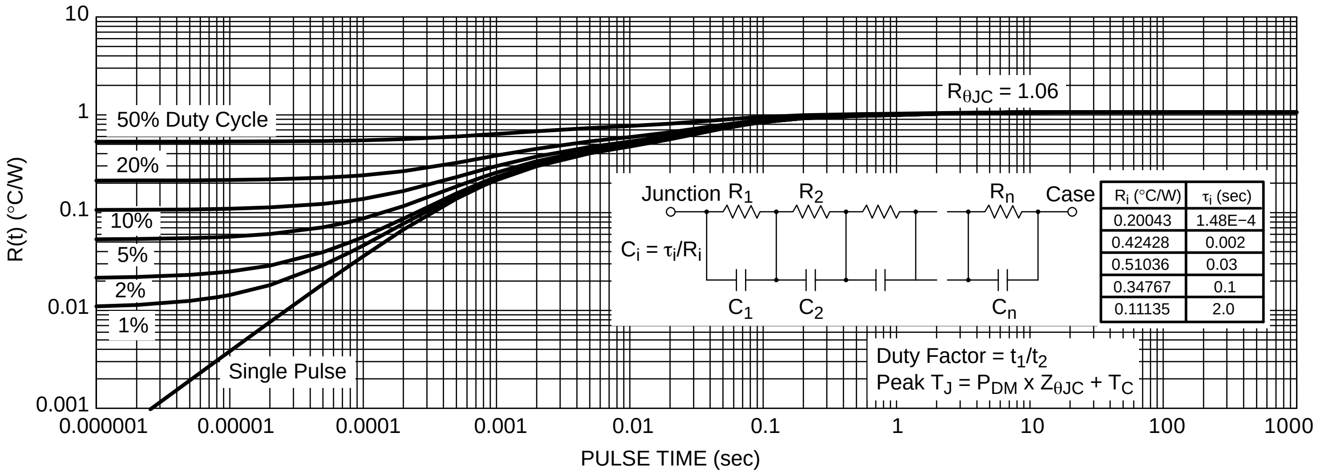
The theta is the thermal impedance from that die to the case or lead of the package, which will be called out in the variable name. e.g. $R\Theta_{JC}$ is the junction-to-case theta. The Psi-interaction is a constant that adds the thermal effect from the die that is not being calculated. It is based on the distance between the dice.

In general, for most of the TO−247 and TO−220 packages used for IGBTs, a value of 0.15°C/W is a good estimate.



R_i (°C/W)	τ_i (sec)
0.001111	0.009004
0.001000	0.031623
0.033663	0.002971
0.078587	0.004024
0.001016	0.984432
0.050668	0.062412
0.083685	0.119496
0.168644	0.187512
0.062579	1.597970

Figure 8. IGBT Thermal Curve



R_i (°C/W)	τ_i (sec)
0.20043	1.48E−4
0.42428	0.002
0.51036	0.03
0.34767	0.1
0.11135	2.0

Figure 9. Diode Thermal Curve

Figures 8 & 9 show the thermal response curves for the IGBT and diode in a typical package. The DC value is given on the curve. For the IGBT this is 0.486°C/W and for the diode is 1.06°C/W.

To calculate the steady-state temperature for a given power level, the power dissipation values, DC thetas and case temperature are all that are required. The calculations are as follows:

$$T_{J-IGBT} = \left(P_{IGBT} \times R\theta_{IGBT}\right) + \left(P_{DIODE} \times Psi\right) + T_{CASE}$$

$$T_{J-DIODE} = \left(P_{DIODE} \times R\theta_{DIODE}\right) + \left(P_{IGBT} \times Psi\right) + T_{CASE}$$

Example:

$T_C = 70°C$

$R\Theta_{JC\text{-}IGBT} = 0.486°C/W$

$R\Theta_{JC\text{-}diode} = 1.06°C/W$

$P_{D\text{-}IGBT} = 54.84\ W$

$P_{D\text{-}DIODE} = 6.60\ W$

Psi-interaction = 0.15°C/W

The steady-state junction temperature for the IGBT is:

$$T_{J-IGBT} = \left(P_{IGBT} \times R\theta_{IGBT}\right) + \left(P_{DIODE} \times Psi\right) + T_{CASE}$$

$$T_{J-IGBT} = (54.84 \times 0.486) + (6.60 \times 0.15) + 70$$

$$T_{J-IGBT} = 97.6^{o}C \quad \text{(Average Junction Temperature)}$$

The steady-state junction temperature for the diode is:

$$T_{J-DIODE} = \left(P_{DIODE} \times R\theta_{DIODE}\right) + \left(P_{IGBT} \times Psi\right) + T_{CASE}$$

$$T_{J-DIODE} = (6.6 \times 1.06) + (54.84 \times 0.15) + 70$$

$$T_{J-DIODE} = 85.2^{o}C \quad \text{(Average Junction Temperature)}$$

To calculate the peak junction temperature, we can add the pulse value to the steady-state (or average) temperature. This calculation requires the junction temperature from the previous set of calculations, and adds the instantaneous temperature change to it.

The only new constant that is needed is the one for the pulse value for the IGBT or diode for the pulse width required. At a line frequency of 50 Hz, the period for a half-cycle is 10 ms. The R_{IGBT} value for a 10 ms pulse, from Figure 8 and for a 50% duty ratio, is 0.375°C/W and the R_{DIODE} value from Figure 9, under the same conditions is 0.95°C/W.

The basic equations are:

$$T_{Jpk-IGBT} = T_{J-IGBT} + \left(P_{IGBT} \times R_{IGBT}\right)$$

$$T_{Jpk-DIODE} = T_{J-DIODE} + \left(P_{DIODE} \times R_{DIODE}\right)$$

So for the above conditions, the peak junction temperatures are:

$$T_{Jpk-IGBT} = 97.6^{o}C + \left(58.84\ W \times 0.375^{o}C/W\right) =$$

$$= 120^{o}C \quad \text{(Peak Junction Temperature)}$$

$$T_{Jpk-DIODE} = 85.2^{o}C + \left(6.6\ W \times 0.95^{o}C/W\right) =$$

$$= 91^{o}C \quad \text{(Peak Junction Temperature)}$$

Conclusion

Junction temperatures in multi-die packages can not accurately, be calculated with a single theta. Using waveforms and math obtained from a digital oscilloscope the power for each device can be calculated. Given the power dissipation, thetas and psi for the IGBT, the average and peak junction temperature values can be calculated.

PUBLICATION ORDERING INFORMATION

LITERATURE FULFILLMENT:
Literature Distribution Center for ON Semiconductor
P.O. Box 5163, Denver, Colorado 80217 USA
Phone: 303−675−2175 or 800−344−3860 Toll Free USA/Canada
Fax: 303−675−2176 or 800−344−3867 Toll Free USA/Canada
Email: orderlit@onsemi.com

N. American Technical Support: 800−282−9855 Toll Free USA/Canada
Europe, Middle East and Africa Technical Support:
Phone: 421 33 790 2910
Japan Customer Focus Center
Phone: 81−3−5817−1050

ON Semiconductor Website: **www.onsemi.com**

Order Literature: http://www.onsemi.com/orderlit

For additional information, please contact your local Sales Representative