Introduction

The thermodynamics of power semiconductor devices can be complex and confusing. The following article will present two sets of the most important specifications in this area, the thermal resistance (**R_θ**) and the power dissipation (**P_D**).

Thermal resistance and power dissipation each have several key specifications that are commonly used and essential in equipment system design.

The following is a list of the most important terms for power devices and how they are specified. All assume a maximum junction temperature as specified by the manufacture. At IXYS RF the maximum junction temperature is specified as $175^{O}C$.

P_{DC}: This is the maximum continuous power that the device is designed to dissipate. With the **case** temperature held at $25^{O}C$ and $T_J = 175^{O}C$.

P_{DHS}: This is the maximum continuous power that the device is designed to dissipate. With the **heat sink** temperature held at $25^{O}C$ and $T_J = 175^{O}C$.

P_{DAMB}: This is the maximum continuous power that the device is designed to dissipate in **free air, no heat sink**, Air temp=$25^{O}C$ and $T_J = 175^{O}C$.

In concert with these are the three thermal resistances of the device.

$R_{\theta JC}$: This is the thermal resistance from the device **junction** to the **case** of the device. **$R_{\theta JC}$** may be calculated in a very straightforward fashion to a reasonably good accuracy. Measurement of the value is difficult.

$R_{\theta JHS}$: This is the thermal resistance from the **junction** to the **heat sink**. Unlike **$R_{\theta JC}$** it is not calculated in a straightforward fashion. This specification is best measured.

$R_{\theta CHS}$: This is the thermal resistance from the **case** to the **heat sink**. It is also an essential specification. In addition the mechanics can be highly variable and very problematic.

$R_{\theta JAMB}$: This is the thermal resistance from the **junction** to **free air**, no heat sink. This specification is best measured.

In the following sections we will discuss in depth, the power dissipation ratings of devices, the thermal resistance specifications, how they are measured and their relevance to the designer.

Heat Flow and Thermal Resistance

Figure 1 illustrates the heat path and the thermal layers in the IXYS RF MOSFET. The layer thickness and materials can be changed to describe most power devices. The die utilized at IXYS RF has a maximum Junction Temperature (T_J) of 175^{0}C. The heat generated in the device is spread, in a uniform fashion, across the surface of the silicon die, layer 1.

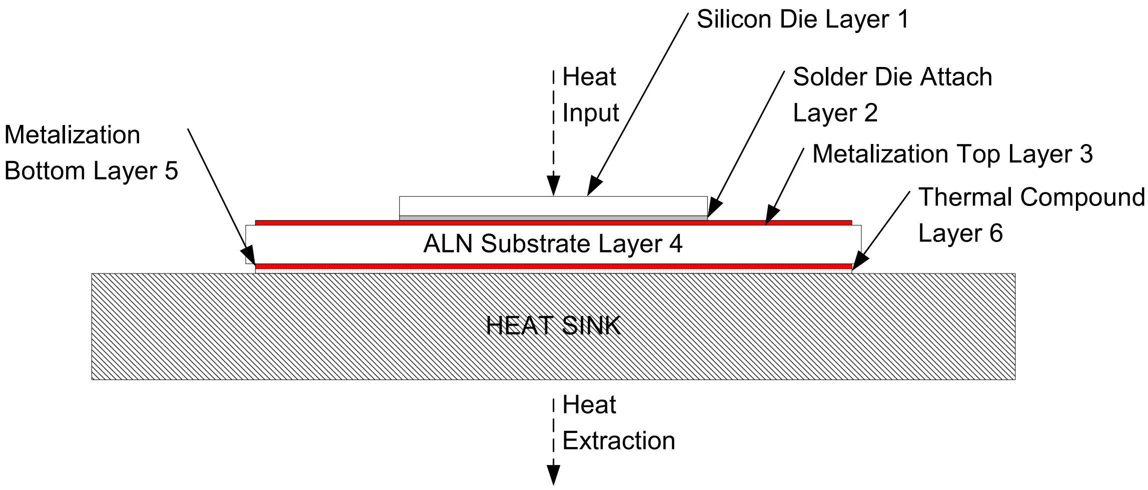
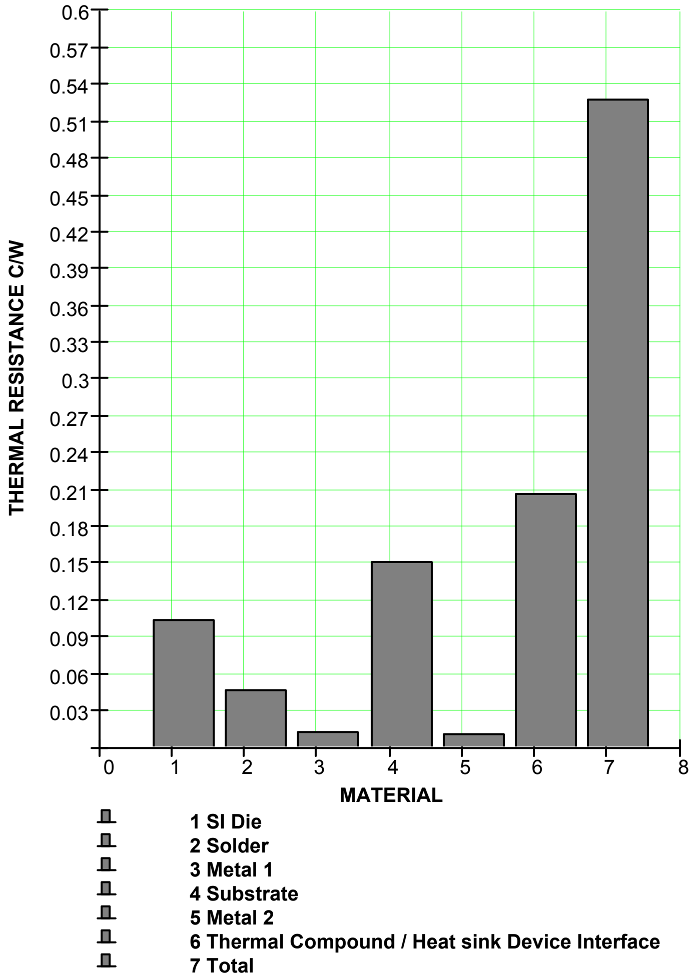


Figure 1 Thermal layers in the IXYS RF MOSFET

The heat flow path is from the surface of the die, as shown by the arrows labeled "Heat Input" to "Heat Extraction" at the heat sink. This path is therefore through the die (layer 1), solder die attach (layer 2), metalization top (layer 3), the aluminum nitride (ALN) substrate (layer 4), metalization bottom (layer 5), thermal compound/device interface (layer 6) and finally into the heat sink.

Components of R_θ

Figure 2 shows a bar graph of the R_θ by layer as found in the multi-layer configurations of modern high power devices and illustrated in Figure 1. The vertical scale is the R_θ and the horizontal scale is the layer, or material type.



$R_1 = 0.103$

$R_2 = 0.047$

$R_3 = 0.012$

$R_4 = 0.15$

$R_5 = 9.882 \times 10^{-3}$

$R_6 = 0.205$

$R\theta JHS := R_1 + R_2 + R_3 + R_4 + R_5 + R_6$

$R\theta JC := R_1 + R_2 + R_3 + R_4 + R_5$

$R\theta CHS := R\theta JHS - R\theta JC$

$R\theta JHS = 0.528$

$R\theta JC = 0.322$

$R\theta CHS = 0.205$

Figure 2 R_θ vs. Material

Layers 1 through 5 can be quantified through calculation in a fairly straightforward manner, however layer 6 (the thermal compound / device heat sink interface), is very difficult to quantify and can be highly variable. This is the interface layer between the device case and the system heat sink. Column 7 is the total R_θ. The MathCad program that was used to generate the graph of Figure 2 is provided in the appendix. Power measurements of devices are used to calibrate the software.

Thermal Resistance and Power

Using the power measurement data as a benchmark and MathCad software as a tool, Figure 2, the thermodynamic relationships can be probed for a better understanding of not only R_θ but power dissipation (P_D) as well.

$R_{\theta JC}$ and P_{DC}

Thermal Resistance Junction to Case, $R_{\theta JC}$, is the sum of layers 1 through 5. R_θ Junction to Case is used to specify the maximum theoretical power capability of the device P_{DC}.

Referring to Figure 2, $R_{\theta JC}$ is given as 0.322^{O}C/W. With this value and given Tjmax=175^{O}C and the case temperature held at 25^{O}C, we can calculate the P_{DC} as follows.

$R_{\theta JC}$ =0.322 ^{O}C/W

$$P_{DC} = \frac{Tj\max - Tc}{R_{\theta JC}} = \frac{175-25}{.322} = 465\,W$$

This specification requires that the **case** be maintained at 25^{O}C, with an input power of 465W in an area approximately 0.65cm^2. This is a very impractical cooling requirement. Therefore with only P_{DC} as a specification it is only useful as a figure of merit.

$R_{\theta JHS}$ and P_{DHS}

The Thermal Resistance Junction to Heat Sink, $R_{\theta JHS}$, column 7, is measured at maximum power with the heat sink maintained at 25^{O}C and the junction temperature at the device maximum.

$R_{\theta JHS}$ =0.528 ^{O}C/W (see Figure 2)

$$P_{DHS} = \frac{Tj\max - T_{HS}}{R_{\theta JHS}} = \frac{175-25}{.528} = 284\,W$$

This specification requires that the **heat sink** be maintained at 25^{O}C with an input power of 284W. The cooling requirement is nontrivial but obtainable. A more realistic approach would be to assume a heat sink temperature of 55^{O}C; the maximum power dissipation is then:

$$P_{DHS} = \frac{Tj\max - T_{HS}}{R_{\theta JHS}} = \frac{175-55}{.528} = 227\,W$$

This is quite removed from the P_{DC} of 465W specification. This shows us that the complete R_θ term is essential. $R_{\theta JHS}$ and P_{DHS} are the only complete terms; $R_{\theta JC}$

and P_{DC} both lack the device heat sink interface term. At minimum the $R_{\theta CHS}$, or a de-rating value, is required in a complete specification and to obtain practical and relevant application results.

$R_{\theta CHS}$ Device Heat Sink Interface

The bottom surface of the device and the top surface of the heat sink appear flat and smooth to the eye and to the touch, however, from a heat transport perspective, they are not. For a near perfect thermal contact the two surfaces would need to be match ground and polished to better than mirror quality. When then pressed together there would be near 100% contact and almost no air. This is not a practical implementation. Therefore a thermal compound is used to improve the thermal resistance of the interface between the standard device surface and the standard heat sink surface. The variability of this interface is often problematic for production and when attempting to arrive at a value for $R_{\theta CHS}$. The straightforward solution is to indirectly measure the term, given a mounting technique that in highly reproducible. This can be done to a reasonable degree of accuracy.

The R_{θ} of the heat sink device interface, layer 6, is the largest single component of layers 1 through 6, as shown in Figure 2.

$$R_{\theta CHS} = R_{\theta JHS} - R_{\theta JC}$$

$R_{\theta JC}$ is calculated and $R_{\theta JHS}$ is measured.

R6 =0.205 ^{O}C/W (see Figure 2)

$R_{\theta JC}$ and P_{DAMB}

The P_{DAMB}, or free air power dissipation, is the lowest power level and is measured in a still but free air environment at Standard Temperature and Pressure (STP). The air temperature is specified to be 25^{O}C. Power is applied to the device until the junction of the device reaches 175^{O}C. A cautionary note at this point is necessary. Given that the $R_{\theta JC}$ of the IXYS RF devices is low, the resulting surface temperature of the bottom metalization can easily be above 100^{O}C, therefore caution is advised.

$$R_{\theta JAMB} = \frac{Tj\max - T_{AMB}}{P_{DAMB}} = \frac{175 - 25}{3} = 50^{O}C/W$$

It is obvious that the power rating for this mounting scheme implies a low average power application.

Conclusion

Figure 2 shows us that the weak link in layers 1 through 6 is the device to heat sink interface. A reduction in the $R_{\theta CHS}$ by a factor of two increases the P_{DHS} by 24% while reducing the die thickness (a common practice for high power RF devices) by a factor of two only increases the P_{DHS} by 5%. This suggests that the first place to attempt to improve the power capability is in layer 6.

Layer 6 is also the only layer under the user's control. Poor mounting results in poor performance if not damage to the device. The DE-Series devices are designed to have a very reproducible mounting interface.

IXYS RF has provided a technical note, "*DE-Series MOSFET and DEIC420 Device Installation and Mounting Instructions*" that may be downloaded from www.ixysrf.com. This document provides detailed mounting information. All data in this technical note is based on the mounting procedure described in that document.

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Appendix – MathCad Program:

DE-SERIES-R-THETA REV 3.MCD

$j := 1..6$ $C := 2.54$ $K := 0..8$

DIE	DIE ATTACH WETTING	HEAT SINK	PD MEASURED VALUE	Set DIE and DIE attach parameters
$H := .016$	$DAW := .95$	$THS := 25$	$PDmv := 284$	
$L := .233$		$TJ := 175$		
$W := .289$				

THERMAL CONSTANTS W / cm C

Tc(Zink-oxide)	Silver=4.18	Beo=2.6	Air=.00024	IXYS std
	Copper=3.98	AIN=1.3 (.67-2.0)	Mineral Oil=.0015	Solder Thickness = 2-4mil.
Mica=.050	Gold=2.9	Al2O3=.26	Water=.006	Voiding Area = 95% DWA
Kapton=.03	Solder(Tin-Lead)=.34	Metalizition=2.0	Si= 1.16 (.85-1.48)	Die Thickness = .016
			GaAs= .105 (.07-.14)	

LAYER 1 (Si Die)	LAYER 2 (Solder Die attach)	LAYER 3 (Metal 1)	LAYER 4 (Substrate)	LAYER 5 (Metal 2)	LAYER 6 (Thermal Comp.)	LAYER 6 The values for this layer are highly variable
$K1 := .85$	$K2 := .34$	$K3 := 4.0$	$K4 := .7$	$K5 := 4.0$	$K6 := .038$	ADJUST K6 and D6 TO SET PD = MEASURED VALUE
$D_1 := H$	$D_2 := .003$	$D_3 := .010$	$D_4 := .025$	$D_5 := .010$	$D_6 := .002$	

Assume 45deg. spreading angle for all materials.

$$Aa1 := (L + D_1)\cdot(W + D_1)\cdot C^2\cdot DAW$$ **DIE** $Aa1 = 0.465$

$$Aa2 := [(L + D_1 + D_2)\cdot(W + D_1 + D_2)]\cdot C^2\cdot DAW$$ **DIE ATTACH** $Aa2 = 0.476$

$$Aa3 := [(L + D_1 + D_2 + D_3)\cdot(W + D_1 + D_2 + D_3)]\cdot C^2\cdot DAW$$ **METAL 1** $Aa3 = 0.511$

$$Aa4 := [(L + D_1 + D_2 + D_3 + D_4)\cdot(W + D_1 + D_2 + D_3 + D_4)]\cdot C^2\cdot DAW$$ **SUBSTRATE** $Aa4 = 0.603$

$$Aa5 := [(L + D_1 + D_2 + D_3 + D_4 + D_5)\cdot(W + D_1 + D_2 + D_3 + D_4 + D_5)]\cdot C^2\cdot DAW$$ **METAL 2** $Aa5 = 0.643$

$$Aa6 := [(L + D_1 + D_2 + D_3 + D_4 + D_5 + D_6)\cdot(W + D_1 + D_2 + D_3 + D_4 + D_5 + D_6)]\cdot C^2\cdot DAW$$ **THERMAL COMPOUND** $Aa6 = 0.651$

R Theta by Layer

$$R_1 := \frac{D_1\cdot C}{K1\cdot Aa1} \quad R_2 := \frac{D_2\cdot C}{K2\cdot Aa2} \quad R_3 := \frac{D_3\cdot C}{K3\cdot Aa3} \quad R_4 := \frac{D_4\cdot C}{K4\cdot Aa4} \quad R_5 := \frac{D_5\cdot C}{K5\cdot Aa5} \quad R_6 := \frac{D_6\cdot C}{K6\cdot Aa6}$$

$R_1 = 0.103$ $R_2 = 0.047$ $R_3 = 0.012$ $R_4 = 0.15$ $R_5 = 9.882\times10^{-3}$ $R_6 = 0.205$

R theta and POWER J to HS

$R\theta := R_1 + R_2 + R_3 + R_4 + R_5 + R_6$

$R\theta = 0.528$ $PD := \frac{(TJ - THS)}{R\theta}$

$PD = 284.097$ $PDmv = 284$

R theta and POWER J to CASE

$R\theta C := R_1 + R_2 + R_3 + R_4 + R_5$

$R\theta C = 0.322$

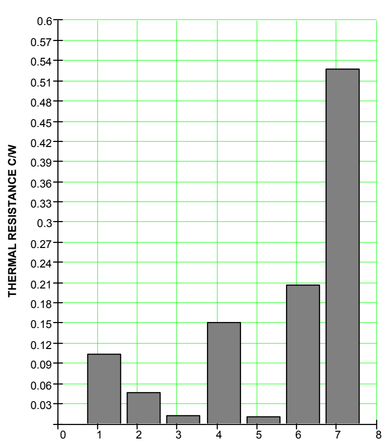
$PDC := \frac{(TJ - THS)}{R\theta C}$ $PDC = 465.118$

$R\theta CASE := R_1 + R_2 + R_3 + R_4 + R_5$ $R\theta CASE = 0.322$

$R\theta CASEtoHS := R_6$ $R\theta CASEtoHS = 0.205$

$R\theta = 0.528$

$R\theta 1 := R_1 + R_2 + R_3 + R_4 + R_5 + R_6$



1 SI Die
2 Solder
3 Metal 1
4 Substrate
5 Metal 2
6 Thermal Compound / Heat sink Device Interface
7 Total

$R_1 = 0.103$

$R_2 = 0.047$

$R_3 = 0.012$

$R_4 = 0.15$

$R_5 = 9.882\times10^{-3}$

$R_6 = 0.205$

$R\theta JHS := R_1 + R_2 + R_3 + R_4 + R_5 + R_6$

$R\theta JC := R_1 + R_2 + R_3 + R_4 + R_5$

$R\theta CHS := R\theta JHS - R\theta JC$

$R\theta JHS = 0.528$

$R\theta JC = 0.322$

$R\theta CHS = 0.205$