International
IR Rectifier

Application Note AN-1059

DirectFET™ Thermal Model and Rating Calculator

By Doug Butchers

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DirectFET™ Thermal Model and Rating Calculator

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Introduction

Industry-standard, encapsulated power semiconductors in packages such as the TO-220 or D-Pak, have traditionally been fairly easy to model thermally, using just one thermal parameter.
The assumption has been that most of the power generated in the silicon chip has travelled in one direction. This is entirely reasonable, as the construction involves the silicon chip soldered (or epoxy-attached) to a lead frame with this surface providing the significant cooling path to the environment.
In the diametrically opposite direction to this heat flow, the die is insulated with a layer of encapsulation "plastic", so limiting heat flow.
Consequently by far the majority of the power flow is from the silicon, through the lead-frame and out to the ambient via this path, often then via a further cooling medium like an attached heat sink.
The DirectFET™ however, is fundamentally different. The DirectFET™ encourages the removal of heat in opposing directions away from the die, so that cooling will occur both though the substrate pad connections (source/gate) **and** through the surrounding "Can". The "Can" then dissipates heat to the ambient through the "Can"-to ambient thermal interface, which is maximised where a heat sink is used.
The "Can" construction additionally provides a parallel or shunt thermal path from the "Can" to substrate- see figure 1a.

Thermal circuit for DirectFETs in application

The DirectFET™ and its heat flow paths:-

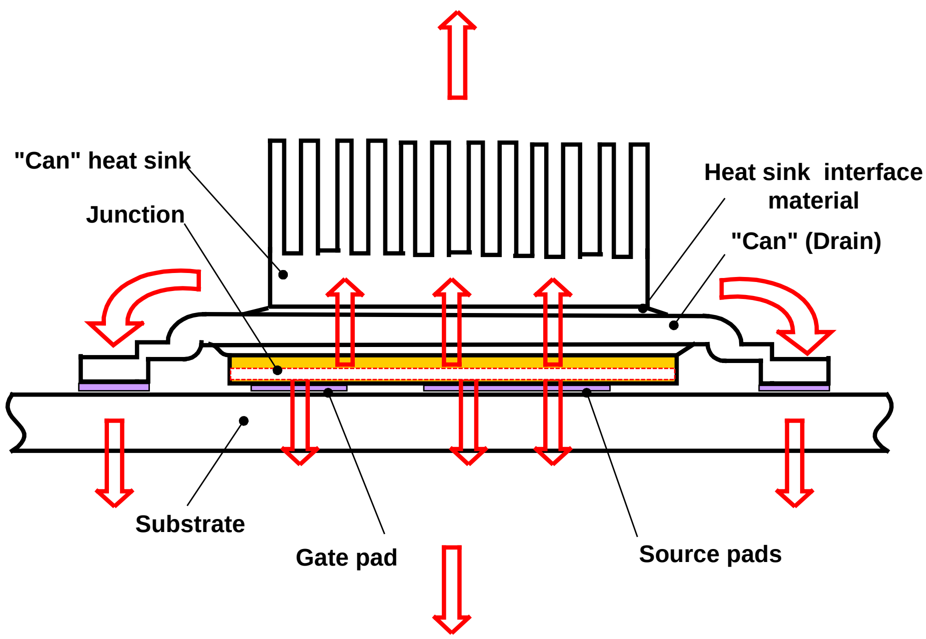

Figure 1a. The DirectFET™ showing the heat flow directions (red arrows)

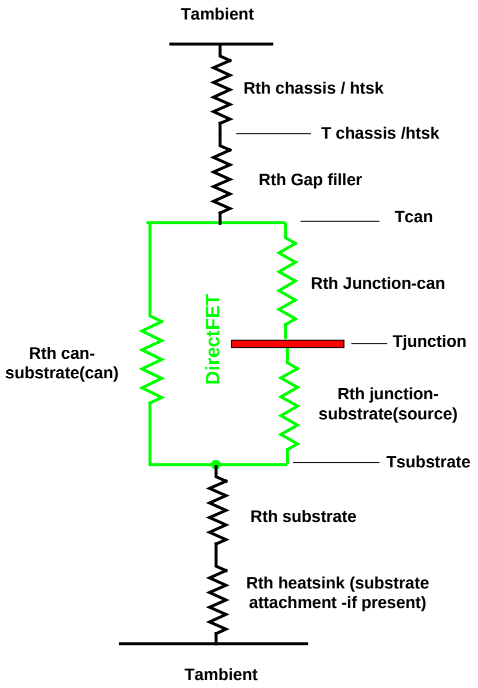

Figure 1b. An approximate thermal equivalent circuit

Power flow

Thermal resistance measurements carried out on DirectFETs inevitably produce a composite result based upon measured temperatures at the junction, "Can", or the substrate using the **total** power dissipated by the silicon.
Whilst this does represent the effective value of thermal resistance under those particular sets of cooling conditions, it will not adequately represent the situation for other sets of cooling conditions. Under dual-sided cooling conditions, the most significant factors in determining ratings are the heat sink and substrate thermal values and for those to be correctly assessed, the power flow through each of these paths must be known. What is required is a method of predicting the proportion of power flow through these resistances. "Can" and substrate temperatures will change with different levels of "Can" and substrate cooling and indeed it is just this feature of the DirectFET™ which allows cooling to both sides of of the silicon die, that brings particular benefits to the part.

The purpose of this note is to provide an easy method of assessment for the proportion of power flow from each of the DirectFET's surfaces so that the appropriate thermal resistance figures are used and the true rating accurately determined.

Equivalent circuit values for the DirectFET™ component

With thermal modelling packages available today, it is possible to solve for entire cooling systems, predicting temperatures at any chosen point within that system. However many designers do not have access to expensive thermal modelling software, nor even would want to spend the time on a large number of lengthy computations for each set of possible cooling arrangements. So with this in mind, DirectFET™ equivalent thermal resistance parameters are proposed for use in a "Rating Calculator" which will rapidly provide the maximum permissible power generation by the semiconductor for any combination of substrate and "Can" cooling situations. The thermal resistance parameters in question are seen below in figure 2 as R1,R2 and R3.

The values of these parameters are assessed from the physical definition of the DirectFET™ using a combination of the dimensions and the conductivity of materials that make up the construction.

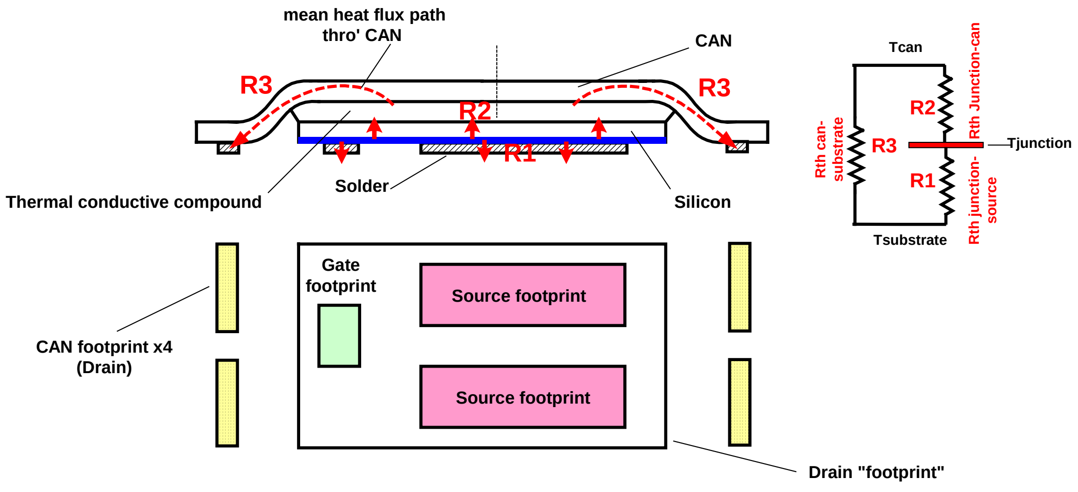

Figure 2. Physical realisation of parameters R1, R2 and R3

Table 1 shows a set of these parameters for the current range of parts.

Table 1 - DirectFET™ equivalent thermal resistance values

DirectFET™	R1	R2	R3	"Can" size
IRF6601	0.33	0.97	0.8	medium
IRF6602	0.98	2.57	1.09	medium
IRF6603	0.33	0.97	0.8	medium
IRF6604	0.98	2.57	1.09	medium
IRF6607	0.33	0.97	0.8	medium
IRF6608	1.07	2.57	0.97	small
IRF6618	0.33	0.97	0.8	medium

Equivalent circuit analysis

The analysis is carried out on the equivalent thermal circuit of the DirectFET™ shown in Figure 3 (the green circuit) but includes also the "additional" cooling resistance paths to "Can" and to substrate.

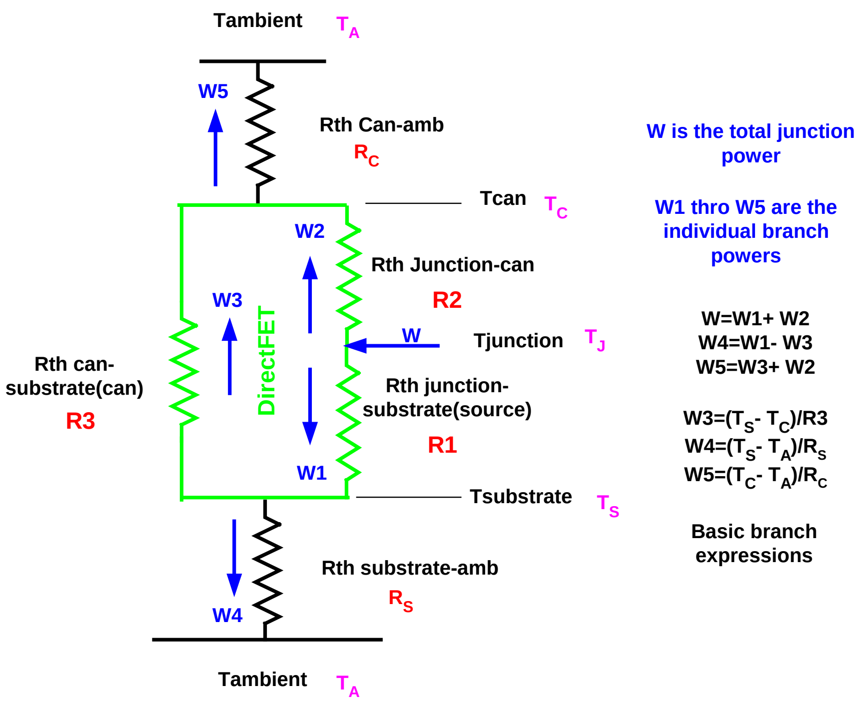

Figure 3. Thermal equivalent circuit with basic assumptions

Thermal resistance “R_C” represents the total thermal resistance in circuit from the “Can” surface to the ambient cooling medium. This must include any interface resistances occurring as a result of isolation or mounting materials in this path.
For the external thermal path through the substrate, the total thermal resistances (perhaps including a substrate heat sink) are similarly lumped together under the value “R_S”.

Using Figure 3, the basic branch power expressions and power flow directions as nominated, an equation has been generated satisfying all of the various power flow constraints.
Appendix “A”, provides a summary of this solution which is of the form:

$$T_J = fn\ (W, T_A\ \alpha, \beta, \delta, \gamma, \varsigma, \Phi, \delta)$$

The full expression is given in Appendix “A” as equation 1

Two options for ratings then become available: -

For applications where both conduction and switching losses are significant e.g. in DC/DC buck circuits and other high frequency circuits, the expression may be expressed generally in terms of power dissipation (W). Refer to equation 2a in the Appendix.

(For Sync buck circuits for example, IR provides guidance for switching power losses on some data sheets, an example being the IRF6607 [3])

For low frequency applications (at frequencies say lower than 30-50kHz), only the conduction losses need be considered and the expression may be specifically re-arranged to give the maximum permissible current rating. Refer to Appendix “A”, equation 2b for this version.

DirectFET™ Rating Calculator

The DirectFET™ Rating Calculator, shown next, uses the equations generated in the thermal circuit analysis and is designed to allow for fast and accurate rating calculations with a simple tabular parameter entry format.

DIRECTFET™ RATING CALCULATOR

REQUIRED INPUTS

DirectFET type	IRF6603	
Thermal parameter "R1"	0.33	°C/W
Thermal parameter "R2"	0.97	°C/W
Thermal parameter "R3"	0.8	°C/W
Rth substrate-ambient	95	°C/W
Rth CAN-ambient (or heat sink)	175	°C/W
Ambient temperature	40	°C
Maximum Junction temperature	125	°C
Hot Rdson (at Tj max.)	4.59E-03	Ω

RESULTS

Maximum permitted power	1.37	W
Maximum permitted current (Low frequency only)	17.31	A
Power through substrate	0.89	W
Power through heatsink	0.48	W

Try the DirectFET™ Rating Calculator

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DirectFET™ Rating Calculator – notes on its use

1. For high frequency applications use the "maximum permitted power" box.

2. For low frequency applications, where the switching losses are not significant, enter the worst-case Rdson and use the "maximum permitted current" box.

3. Substrate thermal resistance values may be obtained from manufacturer's material data but must be assessed for the correct device footprint size, board thickness and power rating.

4. Heat sink thermal resistance may be taken from manufacturer's curves -include mounting interface Rth as appropriate.

5. Where chassis or case cooling to the "Can" is used, figures in Appendix "B" may provide some guidance. For cases where there is no additional heat sinking applied to the "Can", Appendix "C" provides guidance for the two "Can" sizes currently available.

6. With fan or forced cooling, Rth values tend to be constant irrespective of power. This makes easier use of the DirectFET™ Rating Calculator. Where however Rth varies considerably with power, estimate the relative power flow through "Can" and substrate and run the calculator. With that result, review the resulting power flow, check if thermal resistance values are still correct for those power levels- if not, adjust, re-run calculation and re-check. Eventually, the power flows through substrate and heat sink will align with their thermal resistances for those particular power flows.

An example of this procedure is given in Appendix "D".

Calculator inputs

INPUT.. R1,R2,R3 for chosen DirectFET™- from Table1

INPUT.. Rth substrate for appropriate cooling conditions and power, estimating for a first iteration, how much power flows through this path.

INPUT.. Rth heatsink for appropriate cooling conditions and power, estimating for a first iteration, how much power flows through this path. *If no additional "Can" heat sinking is used, use this input box, but enter the figures suggested in Appendix "C".*

INPUT.. Ambient temperature.

INPUT.. Maximum permissible junction temperature.

INPUT.. The hot Rdson of the DirectFET™ –only if a low frequency current rating is required.

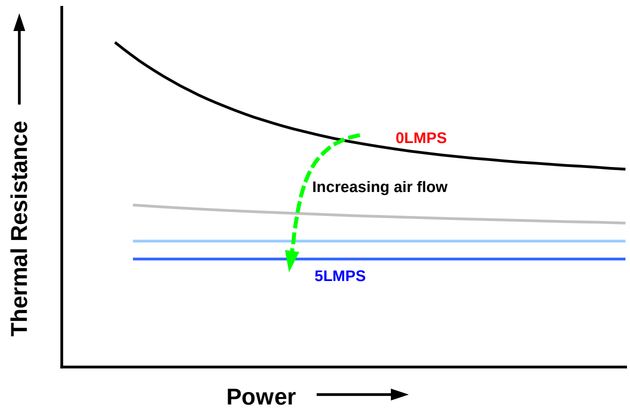
Calculator outputs

Maximum current or maximum power will be returned.
If the Rth sub-ambient or Rth "Can"-ambient varies significantly with power, then adjust the values of Rth to be more in line with actual power returned in the calculator. Refer to note 6 above and Appendix "D".

Thermal resistances of heat sinks and substrates

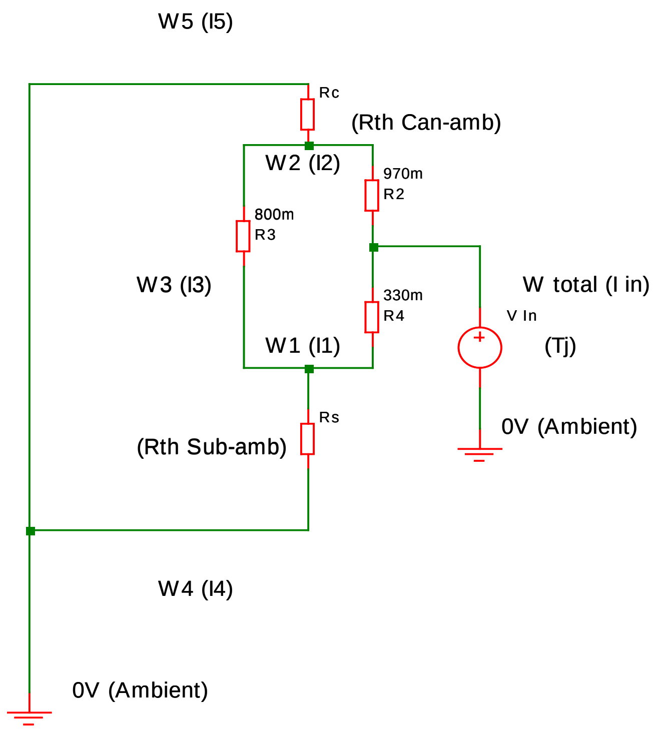
As indicated before, one of the main difficulties of this particular calculation is that the thermal resistance of both cooling "attachments" to the DirectFET™ will vary with the power it is passing. This is chiefly a characteristic of naturally-air cooled systems - only marginally relevant to most forced-air cooled arrangements. Refer to figure 4.

Figure 4 shows typical characteristics.



values.

Figure 4. Typical thermal resistance characteristics



Analogous parameters

Resistance : R thermal

Voltage : Temperature

Current : Power

Figure 5. P-spice based electrical analogy

Validation of results

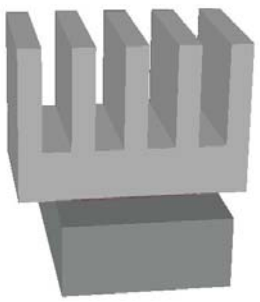
a. Model validation by simulation

The basic expressions in Equations 2a and 2b (Appendix A), used for the Rating Calculator, have been verified for their mathematical integrity using p-spice based simulation software (SiMetrix [1]) with analogous electrical parameters representing thermal parameters.
Identical distributions of DirectFET™ power flow can be demonstrated with this simulation. Figure 5 below shows this circuit.

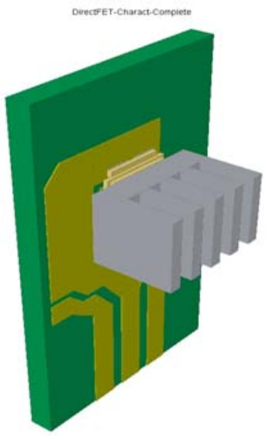
b .Value validation

Detailed thermal analyses using Flotherm [2] models have been generated for the individual "components" combination of the thermal system, i.e. -

- The heat sink,
- The substrate with DirectFET™, **(DirectFET™ side insulated).**
- The substrate and the DirectFET™ with heat sink in position.



Heat sink



Sub. + DirectFET™ + Heat sink

Sub. (token) + DirectFET™ (without DirectFET™ side insulated)

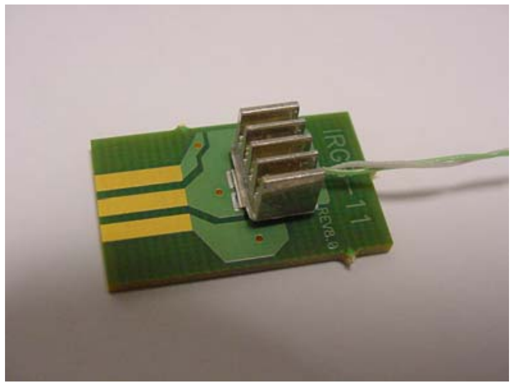
For 2LMPS,

Heat sink Rth = 40°C/W (allowing for interface compound)

DirectFET™ on substrate Rth = 95°C/W

DirectFET™ + substrate + heat sink Rth = 30°C/

With DirectFETs mounted on token boards and located in a wind tunnel, supportive measurements have been carried out for both the situation shown below and the case where no additional heat sinking is present.



Example of DirectFET™ with "Can" heat sink on a token board

For a given power generated by the DirectFET™ under prescribed cooling conditions, effective junction temperatures have been measured using the body diode as the temperature sensitive parameter.

With this information transferred to the Rating Calculator; that is the junction temperature, the ambient temperature, the anticipated heat sink Rth value (or the "Can" to ambient value where no heat sink is used), it has been possible to confirm the maximum permissible power rating for the chosen conditions, within limits of experimental accuracy.

Please note that for any thermal prediction of this sort, the final accuracy of the result will depend upon how well the assessment is made for the individual cooling "attachment" Rth values- that is for the substrate to ambient, the heat sink or the "Can" to ambient Rth. (where no heat sink is used)

Appendices "B" and "C" attached to this note, are intended to help with "Can" to

ambient Rth figures for the two existing "Can" sizes where "Cans" are chassis cooled where no additional heat sink is used.
Other external cooling "attachments" –heat sink and substrate values, are best determined from supplier's data, which would be the usual approach.

Rth guide with equipment chassis or case cooling

For popular substrate materials such as FR4, polyimide and IMS, suppliers can readily provide thermal material properties to enable thermal resistance estimations to be made for specific device footprint areas and board thicknesses.

Similarly, where discrete heat sinks are on DirectFET™ "Cans", the thermal resistances can be provided by the supplier. In many circumstances however, it will be beneficial and economically sensible to double-side cool DirectFET's utilising existing chassis or equipment case surfaces.
As "Can" surfaces are at electrical Drain potential and with most connections requiring electrical separation of these points, insulating pads or compound are needed between "Can" and cooling surface. These materials also serve to compensate for any dimensional inconsistencies that might exist between the mating surfaces. Refer to Figure 6 below.

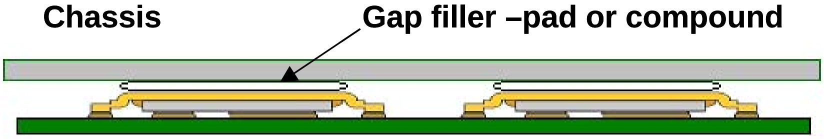


Figure 6 DirectFET's using case or chassis surface cooling.

Many proprietary gap fillers (pads and compounds), are now reinforced with substances such as Boron Nitride bringing significant improvements in thermal conductivities compared with those materials of a few years ago.
These companies include Dow Corning, Bergquist and Thermagon to name just a few.

For chassis or equipment case cooling, it is less easy to arrive at a thermal resistance value for the composite "Can"-ambient Rth value, but as a guide, the results of a simulated thermal analysis of nine DirectFet™ "Cans" (IRF6603) in a 3 x 3 matrix cluster are given in Appendix "B". To these values must be added the gap filler Rth value, for the appropriate "Can" area and gap filler thickness.

As might be expected, the simulation shows the highest temperature is predicted for the centrally located "Can". This is to be expected since it is this one that is subjected to most of the mutual heating effects from other heat sources.

It is clear also from the analysis, that for chassis cooling, the significant improvement for aluminium over steel, may be accounted for by its superior thermal conductivity.

Rth guide with no additional DirectFET™ "Can" cooling

The power flow directions assumed for the circuit analysis (figure 3), shows power flowing through the shunting "Can" thermal resistance R3, from substrate to "Can". This

implies that the substrate is hotter than the "Can".
This is usually the situation when additional "Can" cooling is present.
However, with no such cooling, the value of the effective thermal resistance of the "Can" surface to the ambient will probably be much larger than that for the substrate.
Consequently, the "Can" becomes hotter than the substrate and the power- flow through the "Can" shunt or parallel thermal path R3, reverses.
The model automatically resolves this and heat is transferred back to the substrate from the "Can" surface.
The implications of a better understanding of this power flow direction may well be of great importance to a design, where for example, DirectFETs located on a substrate with other components like a processor already dissipating considerable power, may be "Can" cooled to take some of the dissipated power via the "Can" rather than via an already over-burdened substrate.
Appendix "C" provides guidance for the Rth value that might be anticipated for these circumstances. These values should be entered in the Rating calculator for this situation.
An example of this case is shown in the "Without-Can-heat sink" example following next.

Example of use of Rating Calculator

Examples given below are for a IRF6603 DirectFET™ on polyimide token boards (as in "Validation of results"). Two examples are given, - one with and one without a "Can" heat sink.

Set conditions	Units	With "Can" heat sink	Without "Can" Heat sink
Maximum ambient temp.	°C	40	40
Maximum junction temp.	°C	125	125
Air flow rate	LMPS	2	2
Parameters R1, R2, R3 (Table 1)	°C/W	0.33,0.97,0.8	0.33,0.97,0.8
Rth sub.-amb. @ 2LMPS (previously determined).	°C/W	95	95
Rth heat sink (inc. 2°C/W for mounting /attachment compound)	°C/W	40	-
Rth "Can"– amb. (Appendix "C")	°C/W	-	175
Rdson for IRF6603 @ 125°C Vgs=10V	Ω	4.59e-3	4.59e-3
Maximum permitted power	W	2.98	1.37
Maximum permitted current (for low frequency operation)	A	25.49	17.31
Substrate / heat sink power	W	0.89 / 2.09	0.89 / 0.48

Try the DirectFET™ Rating Calculator

Click Here

Summary

The DirectFET™ can be satisfactorily represented thermally by three internal thermal resistance quantities R1,R2 and R3. Using these values and the thermal properties of the DirectFET's substrate, and "Can" thermal paths, the maximum allowable dissipated power, may be calculated with the Calculator shown in this Note.
For the "special" case of low frequency operation, the maximum operating current is available from the calculator.
The Rating Calculator enables rapid assessments of these ratings to be made, while at the same time providing an insight into the distribution of the power flow within the DirectFET™ package. This is often very important in the calculation process for ensuring that the correct thermal resistance values are applied to the external "attachments" whether it is the substrate or the "Can" heat sink. Moreover, a good understanding of the power flow proportions is essential for optimising the selection of additional "Can" or substrate cooling.
It is hoped therefore, that the Calculator tool will prove a useful aid in DirectFET™ thermal management decisions.

1. SIMetrix is SPICE and Mixed Mode circuit simulation software from Catena Software Ltd.

2. Flotherm is thermal analysis software from Flomerics Inc.

3. Data sheet PD-94574A for the IRF6607 DirectFET™ may be located on the International Rectifier Web site at http://www.irf.com

Appendix A

$$T_J = (\delta * W / (\alpha + \beta - (\delta(\gamma + \varsigma))/ \Phi)) + T_A \quad \text{..........eqn.1}$$

Where:

$\alpha = R3/(R_S*R2)$

$\beta = R3 /(R2*R3+R_C*R3+R_C*R2)$

$\gamma = R3 /(R_S*R3+R_S*R1+R1*R3)$

$\varsigma = R3 /(R_C*R1)$

$\delta = (\alpha / \gamma) - (\beta* R_C*R1)/R3$

$\Phi = (\gamma*R_S*R2)/R3 - (\varsigma/ \beta)$

Tj is the maximum junction temperature

W is the maximum permissible power

TA is the ambient temperature

From which:

$$W = ((T_J - T_A)* (\alpha + \beta - (\delta(\gamma + \varsigma))/ \Phi)) / (\delta) \quad \text{.....eqn. 2a}$$

Or, for the case where all losses may be considered conduction losses,

I = √ [((T$_J$ –T$_A$)* (α + β - (δ(γ + ς))/ Φ)) / (δ * Rdson (@ Tj max)]

$$I = \sqrt{\left[\left((T_J - T_A)^* \left(\alpha + \beta - \left(\delta(\gamma + \varsigma)\right)/ \Phi\right)\right) / \left(\delta * R_{dson} (@ T_{j\,max})\right) \right]}$$

…. eqn. 2b

Where:

I is the low frequency current rating

$R_{DS(on)}$ is the value at TJ max

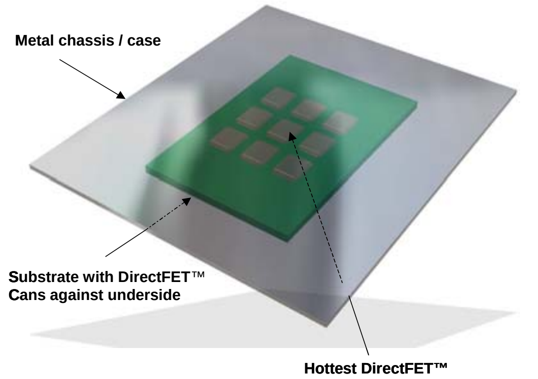
Appendix B

Simulation for the centre "Can" in a matrix of IRF6603 "Cans" (medium "Can" size) against a "small Desktop" case:-

Rth per DirectFET™ -°C/W

	Can spacing		
	5mm	10mm	20mm
Mild steel case: (1mm)	47	38	30
Aluminium case: (1mm)	20	17.5	14

For the "small" "Can" size, use as an approximation, a multiplier of 2 to reflect the reduced contact area.

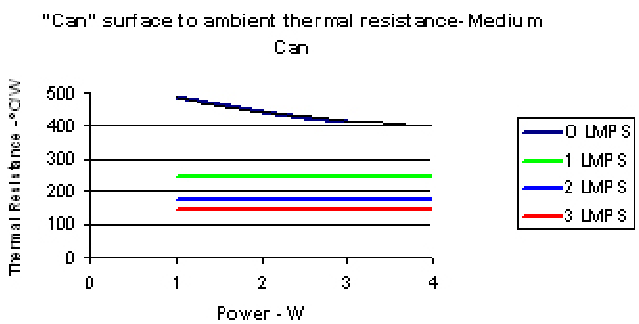


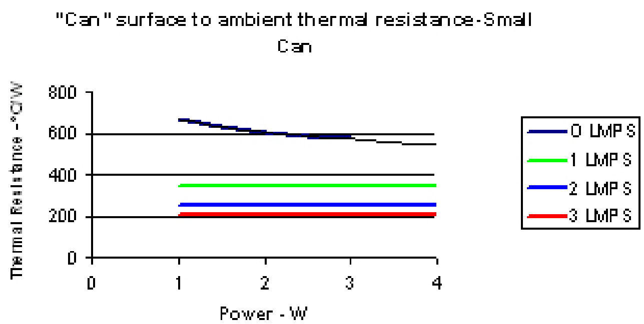
(Devices set in a typical equipment case with an effective airflow of about 0.5LMPS)

DirectFETs with "Can" surfaces cooled against case or chassis

Appendix C

The following graphs provide thermal resistance values for the Rth "Can" to ambient of a "medium" and a "small" "Can" for the case where no additional "Can" heat sinking has been applied. These have been simulated for the DirectFET™ "token" with the heat flow channelled through the "Can" surface only. Note that these figures are for use in the Calculator and represent the effective Rth of the "Can" to ambient **only** for the power flow from that surface.



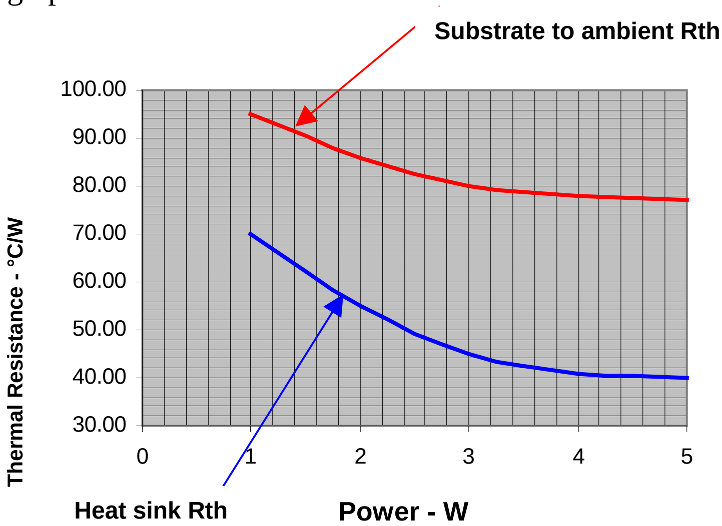


DirectFET™ "Can" surface to ambient thermal resistance (no additional heat sink)

Appendix D – Example of DirectFET™ Calculator iterative procedure for naturally air- cooled applications

DirectFET™ type: IRF6603
Maximum ambient temperature: 40°C
Maximum junction temperature: 125°C
Rdson of IRF6603 @ Tj maximum: 4.59mΩ (low frequency current rating)
Cooling: Air natural, on substrate, with additional "Can" heat sink

Using fictitious curves for the substrate and the heat sink combined on the following graph:



Assume at first that power through the heat sink is 2W and through the substrate is 1W (first guess). This might be a reasonable start with the heat sink Rth being about half that of the substrate.
In which case, Rth heat sink = 55°C/W & Rth substrate = 95°C/W

Run DirectFET™ Calculator with all inputs:
This returns heat sink power = 1.53W corresponding to 62°C/W with a substrate power = 0.89W corresponding to 96°C/W

Now, making some adjustments to the Rth values used in the Calculator to make the Rth align better with power on the graph... try setting Rth heat sink
= 57°C/W but leave Rth substrate = 95°C/W

Re-run calculator with these values:
This returns heat sink power = 1.48W corresponding to 63°C/W with a substrate power = 0.89W corresponding to 96°C/W

To make a final adjustment..
suggest Rth heat sink is set to 65°C/W and substrate Rth to 96°C/W
This returns Rth heat sink power = 1.3W with a substrate power of 0.88W

These values now align Rth values with graph power levels