International
IOR Rectifier

APPLICATION NOTE

Application Note AN-1059

DirectFET® Technology
Thermal Model and Rating Calculator

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DirectFET's thermal properties are fundamentally different from industry-standard, encapsulated power semiconductors. Its construction encourages heat to disperse from the die in opposite directions, cooling through both the substrate pad connections (source and gate) and the metal can on top of the device. The can-to-ambient thermal interface can be maximized by fitting a heat sink.

Introduction

Encapsulated power semiconductors in packages such as the TO-220 or D-Pak are fairly easy to model thermally, using only one thermal parameter. The assumption is that most of the power generated in the silicon chip travels in one direction. The assumption is reasonable because the silicon chip is soldered (or epoxy-attached) to a lead frame that provides the main cooling path to the environment. Heat flow in the opposite direction is limited because the die is insulated with a layer of encapsulation 'plastic'. The dissipation of heat from the lead-frame into the environment is often enhanced by fitting a heat sink.

DirectFET® is fundamentally different. Its construction encourages heat to disperse from the die in opposite directions, cooling through both the substrate pad connections (source and gate) and the metal can on top of the device. The can-to-ambient thermal interface can be maximized by fitting a heat sink. The design of the can also provides a parallel or shunt thermal path from the can to substrate.

Figure 1 shows the direction of heat flow from a DirectFET device and an approximate thermal equivalent circuit for such a device in use.

Measuring the thermal resistance of a DirectFET device inevitably produces a composite result based on the temperatures measured at the junction, can or substrate using the total power dissipated by the silicon. While this gives the effective thermal resistance under particular cooling conditions, it does not give a value that applies under other conditions.

When determining a value for dual-sided cooling conditions, the most significant factors are the thermal resistance of the heat sink and substrate. To assess these correctly, the power flow through each path must be known. This requires a method of predicting the proportion of power flow through the paths. The temperature of the can and the substrate will change with different levels of can and substrate cooling. Indeed, it is this feature of DirectFET construction – which enables cooling from both sides of the silicon die – that gives the devices their particular benefits.

This application note provides an easy method for assessing the proportion of power flow from each of a DirectFET device's surfaces, so that the appropriate thermal resistance figures are used and the true rating is accurately determined.

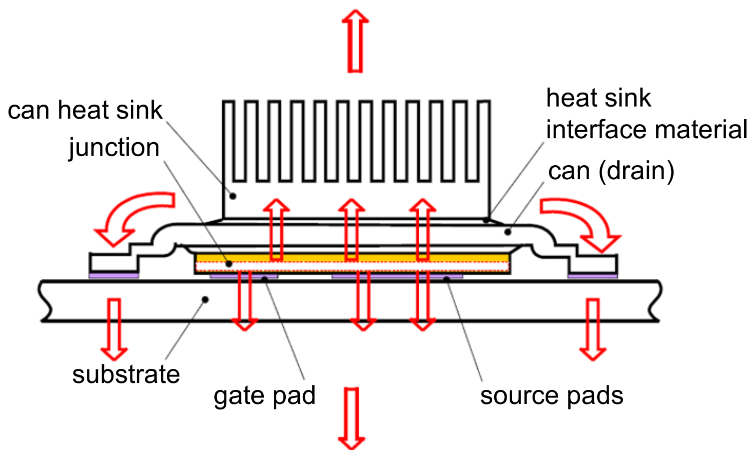


Figure 1a Directions of heat flow (indicated by the red arrows)

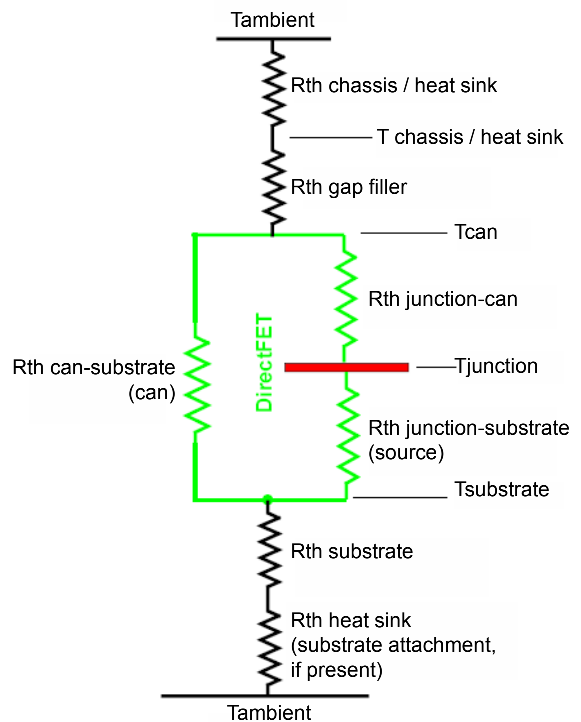


Figure 1b Approximate thermal equivalent circuit

Equivalent circuits

Thermal resistance values

With the thermal modeling software available today, it is possible to predict temperatures at any chosen point in an entire cooling system. However, many circuit designers do not have access to such software nor time to spend on numerous lengthy computations for each possible set of cooling arrangements.

With this in mind, International Rectifier provides equivalent thermal resistance values for DirectFET devices. These can be entered into an online Rating Calculator that rapidly returns the maximum permitted power generation by the device in any combination of substrate and can cooling conditions.

Figure 2 shows how the three parameters (R1, R2 and R3) relate to the physical construction of a DirectFET device. Their values are derived using a combination of the dimensions and conductivity of the materials used in constructing the device.

The table at the right shows these equivalent thermal resistance values for the current range of DirectFET devices (both lead and lead-free variants).

Analysis

The analysis is carried out on the equivalent thermal circuit of the DirectFET device (the green circuit in Figure 3). It also includes the additional cooling resistance paths to the can and to the substrate (the black circuits above and below it in Figure 3).

Thermal resistance R_C represents the total thermal resistance of the path from the surface of the can to the ambient cooling medium. This must include any interface resistances resulting from isolation or mounting materials fitted in this path.

Thermal resistance R_S represents the total thermal resistance of the path from the bottom of the DirectFET device through the substrate. This may include a substrate heat sink.

Using the information shown in Figure 3, International Rectifier has generated an equation that satisfies all the various power flow constraints. This is shown in Appendix A as Equation 1. In summary:

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

Outline	Can size	R1	R2	R3
Non-PbF devices				
SH	small	1.39	3.47	0.98
SQ	small	1.14	3.47	0.98
ST	small	1.08	2.58	0.98
MN	medium	0.43	0.97	0.80
MQ	medium	0.99	2.60	1.10
MT	medium	0.33	0.97	0.80
MX	medium	0.50	1.50	0.80
PbF devices				
SH	small	2.96	3.48	0.98
SJ	small	2.05	2.22	0.98
SQ	small	2.43	3.48	0.98
ST	small	2.36	2.58	0.98
MN	medium	0.91	0.97	0.80
MP	medium	2.26	2.58	1.54
MQ	medium	2.07	2.58	1.54
MT	medium	0.71	0.97	0.80
MU	medium	1.91	2.58	1.54
MX	medium	1.04	1.18	0.98
MZ	medium	1.62	0.97	0.80
S1	small	4.18	3.43	1.53
S2	small	2.35	4.55	1.60
SB	small	2.68	2.47	1.05
M2	medium	2.09	1.03	1.33
M4	medium	1.27	0.68	0.80
L4	large	1.06	0.56	1.06
L6	large	0.80	0.44	0.56
L8	large	0.65	0.25	0.49

Two options for ratings then become available:

- For applications where conduction and switching losses are both significant (such as DC/DC buck circuits and other high-frequency circuits), the expression may be arranged to give the maximum permitted power rating. This is shown in Appendix A as Equation 2a.
- For low-frequency applications (say lower than 30–50 kHz), only conduction losses need be considered and the expression may be arranged to give the maximum permitted current rating. This is shown in Appendix A as Equation 2b.

Note: Some International Rectifier data sheets provide more information about switching power losses. For example, PD-94574A for the IRF6607 DirectFET: www.irf.com/product-info/datasheets/data/irf6607.pdf

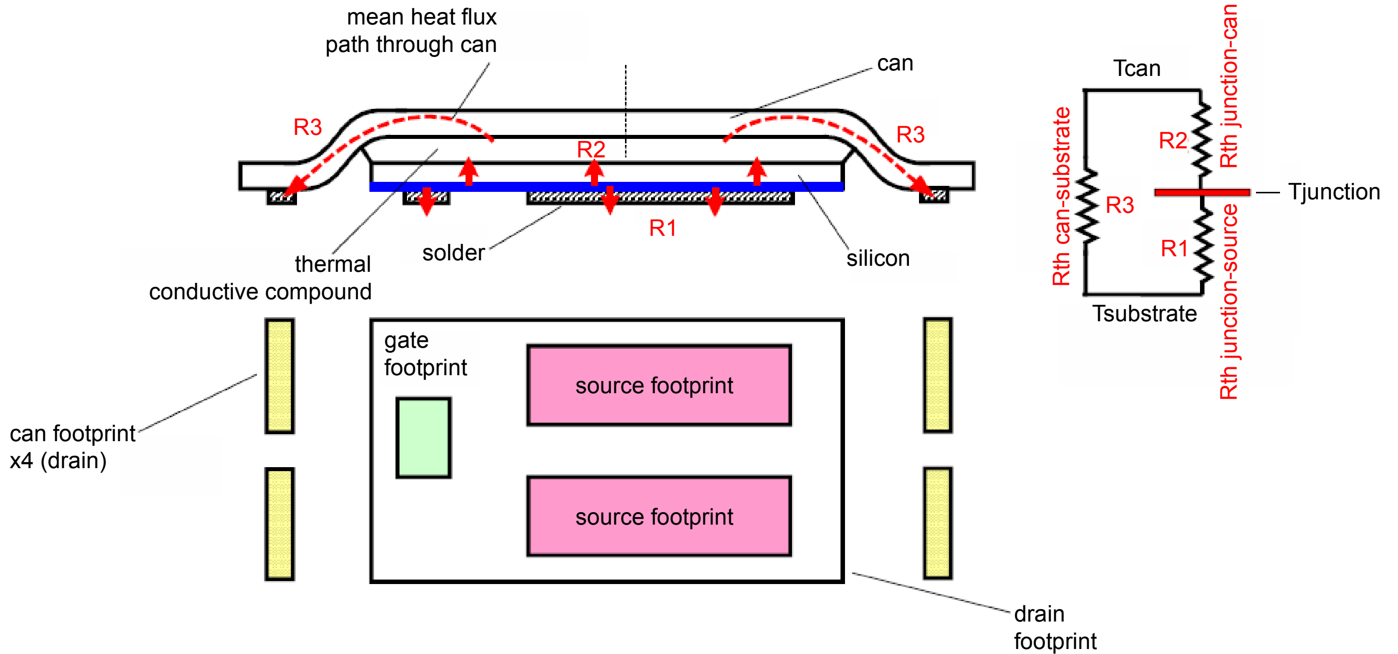
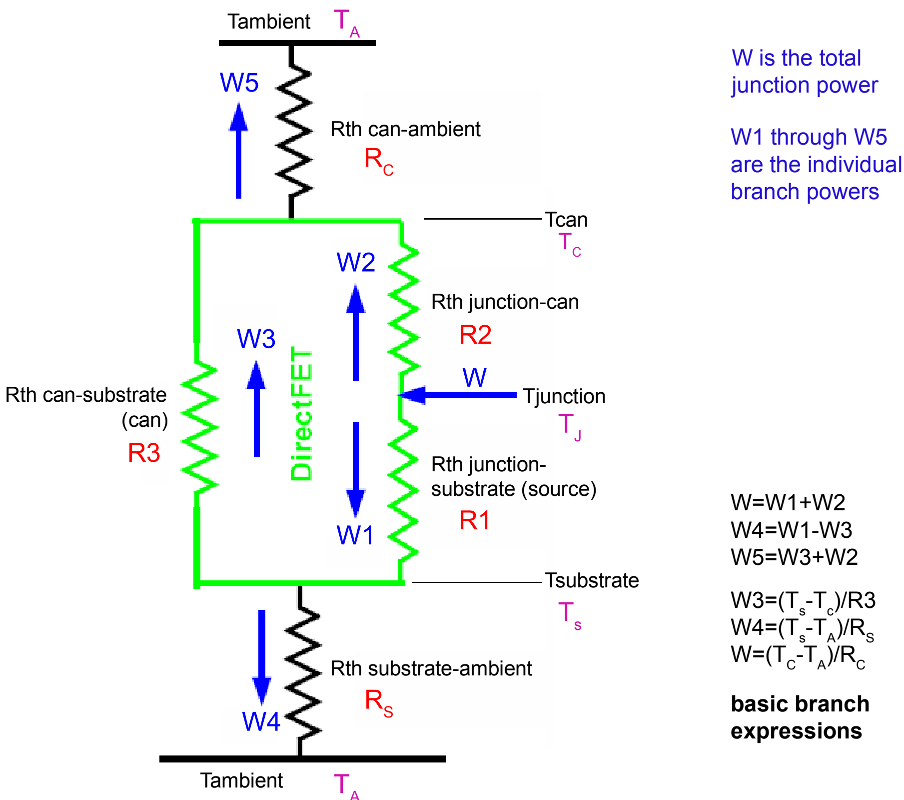


Figure 2 Physical realization of parameters R1, R2 and R3



W is the total junction power

W1 through W5 are the individual branch powers

W=W1+W2
W4=W1-W3
W5=W3+W2

$W3=(T_s-T_c)/R3$
$W4=(T_s-T_A)/R_S$
$W=(T_C-T_A)/R_C$

basic branch expressions

Figure 3 Thermal equivalent circuit with basic assumptions

Rating Calculator

The DirectFET Rating Calculator is available at:

www.irf.com/product-info/hexfet/thermalcalc.html

The Rating Calculator applies the equations from Appendix A. It uses a simple tabular entry format to facilitate fast and accurate calculations.

Notes on use

- For high-frequency applications, use the value returned for **maximum permitted power**.
- For low-frequency applications (where switching losses are not significant), enter a worst-case value for $R_{DS(on)}$ and use the value returned for **maximum permitted current**.
- Obtain values for the thermal resistance of the substrate from the manufacturer's material data but make sure it is correct for the device footprint, board thickness and power rating.
- Obtain values for the thermal resistance of the heat sink from the manufacturer's curves – include the mounting interface as appropriate.
- Appendix B gives guidance for applications where the can is cooled through the chassis or case.
- Appendix C gives guidance for small and medium can devices that have no additional heat sinking.
- Where fan or forced cooling is used, thermal resistance tends not to vary with power. This makes it easier to use the Rating Calculator.
- Where thermal resistance varies considerably with power, estimate the relative power flow through the can and substrate. Run the Rating Calculator and use the result to review the resulting power flow, checking if thermal resistance values are still correct for those power levels. If not, adjust the inputs, repeat the calculation and check the power flow again. Repeat until the power flows through the substrate and heat sink align with their thermal resistances for those flows. Appendix D demonstrates this procedure.

Rating Calculator inputs

Required Inputs

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.)	0.00459	Ohm

calculate

Enter:

- R1, R2 and R3 for the appropriate DirectFET device from the table on page 3
- Rth substrate-ambient for the appropriate cooling conditions and power (estimate the power flows through this path for the first iteration)
- Rth heat sink if one is used, taking into account the cooling conditions and power flow (estimate the power flows through this path for the first iteration) – if no heat sink is fitted to the can, enter the figures for Rth can-ambient from Appendix C.
- Ambient temperature of the environment
- Maximum permitted junction temperature
- The hot $R_{DS(on)}$ of the device – enter this only if a low-frequency current rating is required.

Rating Calculator outputs

Result

Maximum permitted power		W
Maximum permitted current (Low frequency only)		A
Power through substrate		W
Power through heatsink		W

The Rating Calculator returns maximum current or maximum power. If Rth substrate-ambient or Rth can-ambient varies significantly with power, adjust the values to reflect the actual power returned by the Rating Calculator. Refer to the last of the notes on using the Rating Calculator (left) and to Appendix D.

Types of cooling

As stated, one of the main difficulties in making this calculation is that the thermal resistance of a path varies with the power passing through it (Figure 4). This is most relevant for natural-air cooling systems (represented by the black curve) and least for forced-air cooling systems (represented by the blue curve).

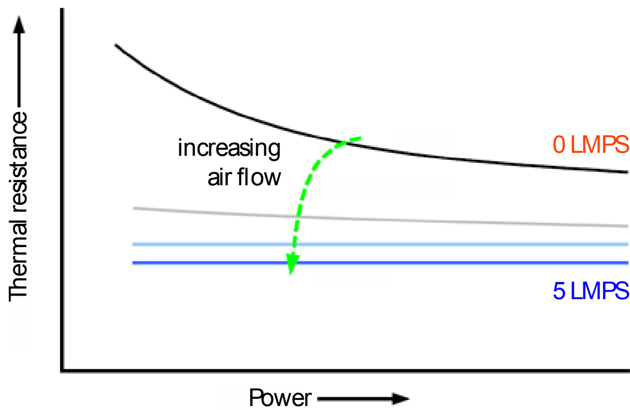


Figure 4 Typical thermal resistance characteristics

Validation of results

Model

The basic expressions in Equations 2a and 2b (Appendix A), used for the Rating Calculator, were verified for mathematical integrity using SIMetrix. Developed by SIMetrix Technologies (formerly known as Catena Software Ltd), this mixed-mode circuit simulation package includes a SPICE simulator.

Analogous electrical parameters were used to represent thermal parameters:

- Resistance for Rth
- Voltage for temperature
- Current for power

This simulation can be used to demonstrate identical power flow distributions in DirectFET devices. Figure 5 shows the analogous electrical circuit.

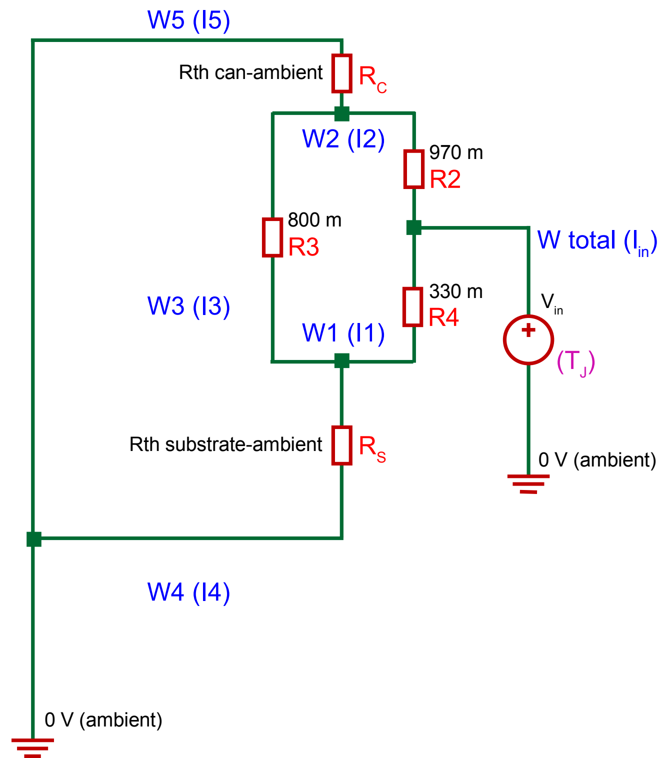
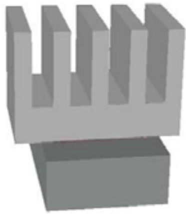


Figure 5 Analogous electrical circuit

Values

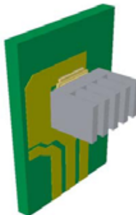
Using FloTHERM thermal analysis software from Mentor Graphics (formerly known as the Flomerics Group), detailed analyses were generated for individual elements in the thermal system:

- Heat sink (with interface compound)



- Substrate + device
  (with insulation on device side – not shown here)

- Substrate + device (with heat sink fitted).



For a flow of 2 linear metres per second (LMPS), the thermal resistance of these elements was:

- Heat sink: 40°C/W
- Device + substrate: 95°C/W
- Device + substrate + heat sink: 30°C/W

With DirectFET devices mounted on token boards and placed in a wind tunnel, supportive measurements were taken with (Figure 6) and without a heat sink.

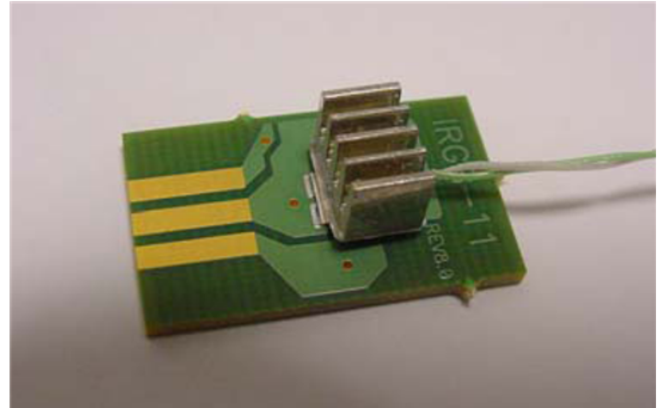


Figure 6 Device and heat sink on a token board

For a given amount of power generated by the device under prescribed cooling conditions, effective junction temperatures were measured using the body diode as the temperature-sensitive parameter.

It was possible to confirm the maximum permitted power rating for the chosen conditions, within limits of experimental accuracy, by transferring the following information to the Rating Calculator:

- Junction temperature
- Ambient temperature
- Expected thermal resistance of the heat sink
  (or Rth can-ambient if no heat sink is used).

For any thermal prediction of this sort, the accuracy of the result depends on the accuracy of the thermal resistances used for the cooling attachments. That is, it depends on the figures entered for the substrate to ambient and for the heat sink (or for the can to ambient if no heat sink is used).

Appendices B and C suggest thermal resistances for small and medium can DirectFET devices used with chassis cooling and no additional heat sink. The usual approach for obtaining figures for other external cooling attachments is to consult manufacturers' data.

Thermal resistance values

With equipment chassis or case cooling

For popular substrate materials such as FR-4, polyimide and IMS, suppliers provide thermal properties. Use these to estimate the thermal resistance of specific device footprints and board thicknesses.

Many proprietary gap fillers (pads and compounds), are now reinforced with substances such as boron nitride. These deliver significant improvements in thermal conductivity compared with materials of only a few years ago. There are many suppliers, including Dow Corning, Bergquist and Thermagon.

Where discrete heat sinks are fitted to DirectFET devices, the supplier will provide the thermal resistance. In many applications, however, it is beneficial and economically sensible to use the chassis or case to cool both sides of the devices.

With chassis or case cooling, it is more difficult to estimate the thermal resistance of the path from can to ambient. As a guide, Appendix B contains the results of a simulated thermal analysis of nine DirectFET devices (IRF6603) in a 3 x 3 matrix.

As the can on the device is also the drain contact, it usually needs to be electrically insulated from the cooling surface (Figure 6). The insulating pad or compound also acts as a gap filler, compensating for any dimensional inconsistencies between the mating surfaces. The thermal resistance of the material used, taking into account the area covered and thickness applied, must be added to the figures in Appendix B.

The simulation in Appendix B predicts that the can of the centrally located device will reach the highest temperature. This is to be expected because this device is subjected to the greatest mutual heating effects from other heat sources.

The simulation also shows that aluminum is more effective than steel for chassis or case cooling. This is a result of its higher thermal conductivity.

With no additional DirectFET can cooling

The flows assumed for the circuit analysis (Figure 3) show power flowing from the substrate to the can through the shunting thermal resistance of the can (R3). This implies that the substrate is hotter than the can, which is usually true where additional cooling is used (through heat sinks, chassis or case).

However, without additional cooling, the effective thermal resistance of the path from the can to ambient is usually much larger than that of the substrate. The can then becomes hotter than the substrate, reversing the power flow. The model automatically resolves this and heat is transferred from the can to the substrate.

Understanding the implications of this change in power flow direction is important when designing circuits for some applications. For example, where DirectFET devices are located on a substrate with other components that are dissipating large amounts of power, applying additional cooling to the cans provides another channel for power dissipation and avoids over-burdening the substrate.

Appendix C predicts the probable thermal resistance in these circumstances. Enter these values into the Rating Calculator. This is illustrated in the following example, in the scenario without a can heat sink.

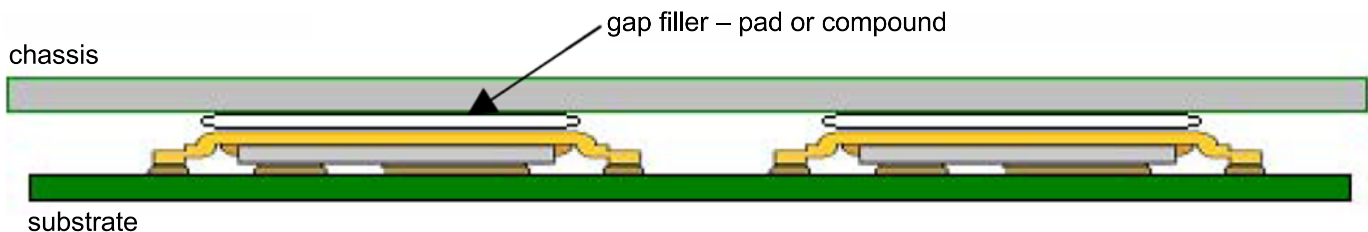


Figure 6 Case or chassis cooled DirectFET devices

Example of use of Rating Calculator

Using the Rating Calculator for IRF6603 DirectFET devices mounted on polyimide token boards gives the following results. Two scenarios are shown, one with and one without a heat sink fitted to the can.

		Can heat sink	
Set conditions	**Units**	**With**	**Without**
Max ambient temperature	°C	40	40
Max junction temperature	°C	125	125
Air flow rate	LMPS	2	2
Parameter R1	°C/W	0.33	0.33
Parameter R2	°C/W	0.97	0.97
Parameter R3	°C/W	0.8	0.8
Rth substrate-ambient @ 2 LMPS (previously determined)	°C/W	95	95
Rth heat sink (including 2°C/W for mounting/attachment compound)	°C/W	40	—
Rth can-ambient (Appendix C)	°C/W	—	175
$R_{DS(on)}$ for IRF6603 @ 125°C Vgs=10 V	Ω	$4.59e^{-3}$	$4.59e^{-3}$
Max permitted power	W	2.98	1.37
Max permitted current (for low-frequency operation)	A	25.49	17.31
Substrate power	W	0.89	0.89
Heat sink power	W	2.09	0.48

Summary

The thermal performance of DirectFET devices can be satisfactorily represented by three internal thermal resistances: R1, R2 and R3.

By entering these parameters into an online Rating Calculator, with the properties of the thermal paths through the substrate and can, the maximum permitted dissipated power can be calculated. For low-frequency applications, the Rating Calculator also gives the maximum operating current.

The Rating Calculator enables ratings to be rapidly assessed and provides an insight into the power flows within the DirectFET device. Using attachments with appropriate thermal resistances is essential to achieve the required cooling, whether through the substrate or the can. Understanding the proportion of power that flows through the different paths is essential to select the optimum combination of can or substrate cooling.

The Rating Calculator is, therefore, a useful aid in making thermal management decisions for DirectFET applications.

Appendix A

Equation 1

$$T_J = (\delta * W / (\alpha + \beta - (\delta (\gamma + \varsigma)) / \Phi)) + T_A$$

where:

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

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

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

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

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

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

T_J is the maximum junction temperature

W is the maximum permitted power

T_A is the ambient temperature

Equation 2a

$$W = ((T_J - T_A) * (\alpha + \beta - (\delta (\gamma + \varsigma)) / \Phi)) / (\delta)$$

Equation 2b

Where all losses are considered conduction losses:

$$I = \sqrt{[((T_J - T_A) * (\alpha + \beta - (\delta (\gamma + \varsigma)) / \Phi)) / (\delta * R_{DS(on)} (@ T_J \max)]}$$

where:

I is the low-frequency current rating

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

Appendix B

This simulation is based on a 3 x 3 matrix of IRF6603 medium can DirectFET devices fitted in an equipment case with an effective air flow of about 0.5 LMPS (as shown in Figure B.1).

Rth of each device (°C/W)	Can spacing		
Case composition	**5 mm**	**10 mm**	**20 mm**
Mild steel (1 mm)	47	38	30
Aluminum (1 mm)	20	17.5	14

Note: For small can DirectFET devices, multiply these results by 2 to reflect the reduced contact area.

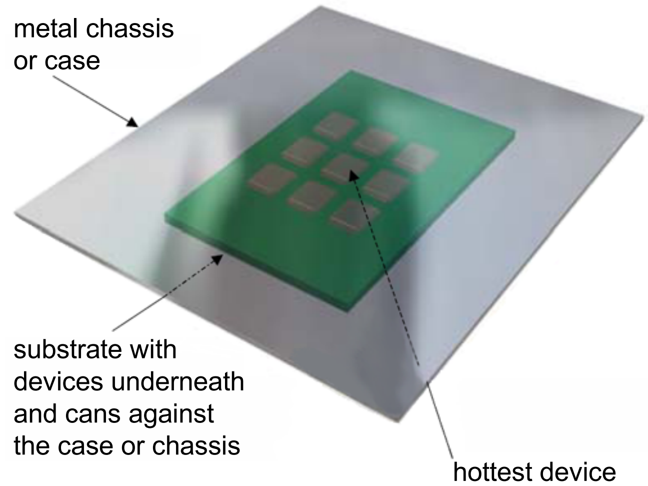


Figure B.1 Devices fitted against the equipment case

Appendix C

Figures C.1 and C.2 show can-to-ambient thermal resistance curves for medium and small can DirectFET devices with no additional heat sinks. These were simulated devices where the heat flow is channeled solely through the can surface. These figures, intended for use in the Rating Calculator, represent the effective Rth can-ambient only for the power flow through the surface of the can.

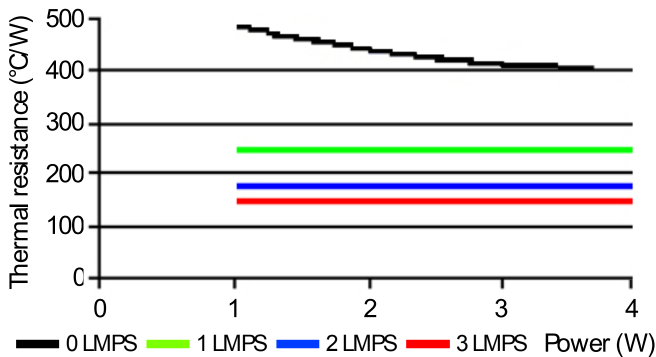


Figure C.1 Rth can-ambient (medium can)

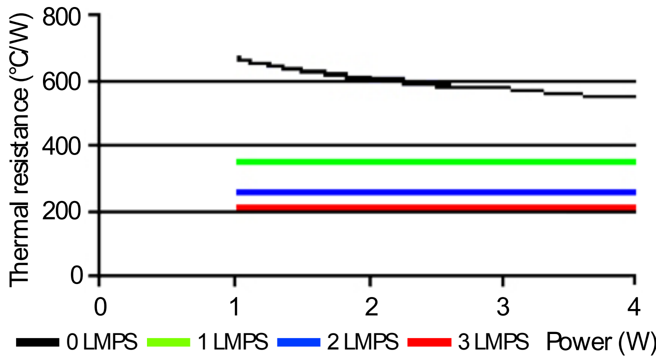


Figure C.2 Rth can-ambient (small can)

Appendix D

For applications using natural-air cooling, use this iterative procedure with the Rating Calculator.

Consider a device mounted on a substrate and fitted with a heat sink on its can (sample data in Figure D.1).

DirectFET device: IRF6603
Maximum ambient temperature: 40°C
Maximum junction temperature: 125°C
$R_{DS(on)}$ @ Tj maximum: 4.59 mΩ

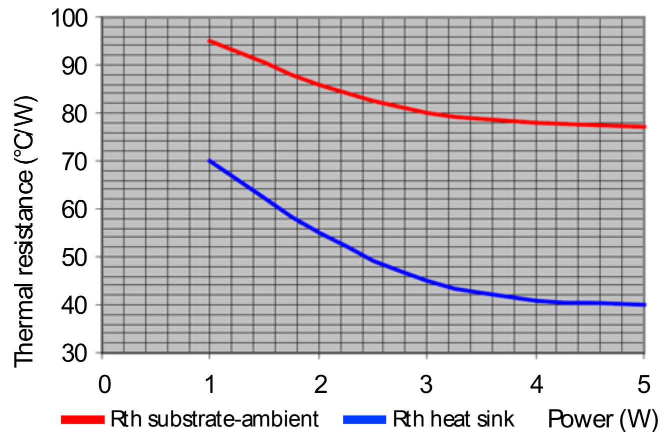


Figure D.1 Sample thermal resistance curves

First assume that power through the substrate is 1 W and through the heat sink is twice that at 2 W.

Reading from the curves:
Rth substrate-ambient at 1 W = 95°C/W
Rth heat sink at 2 W = 55°C/W

Running the calculation with these inputs returns:
Substrate power = 0.89 W (96°C/W from the curve)
Heat sink power = 1.53 W (62°C/W from the curve)

Adjust the inputs to match the curves more closely:
Leave Rth substrate at 95°C/W
Increase Rth heat sink to 57°C/W

Repeating the calculation with these inputs returns:
Substrate power = 0.89 W (96°C/W from the curve)
Heat sink power = 1.48 W (63°C/W from the curve)

Adjust the inputs again:
Leave Rth substrate at 96°C/W
Increase Rth heat sink to 65°C/W

Repeating the calculation with these inputs returns:
Substrate power = 0.88 W (96°C/W from the curve)
Heat sink power = 1.3 W (63°C/W from the curve)

The values entered for thermal resistance are now very close to those supplied by the the manufacturer.