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AN-7515

单脉冲和重复UIS混合评估体系

总结

针对PowerMOS晶体管的非箝位感性开关(UIS)评估体系(已在飞兆半导体PowerMOS晶体管数据手册中广泛采用)可用于多种应用,并且还可通过叠加扩展至重复UIS脉冲。该体系允许PowerMOS晶体管用户确定他们的应用是否位于功率晶体管的额定能力之内。本文给出两个示例,分析代表性应用中的UIS应力程度。自1985年以来,PowerMOS晶体管耐受UIS的能力已得到认可。虽然Blackburn清楚表明^[1]UIS应力程度并不与电能大小直接相关,许多PowerMOS晶体管制造商依然为他们的产品指定电能耐受性额定值。由于电能耐受性随工作条件的变化而改变,该额定值仅在特定条件下才有效,且PowerMOS晶体管用户无法计算特定应用是否超过器件额定值。Ronan^[3]定义了一套评估体系^[3]——下文中称为UIS评估体系——

允许制造商指定PowerMOS晶体管耐受单脉冲UIS的能力,以使用户确定应用是否使器件暴露于比数据手册保证值更大的UIS应力下。

单脉冲UIS评估体系

该UIS评估体系仅要求用户确定流经PowerMOS晶体管的峰值电流(I_{AS})、UIS脉冲起始时刻的结温(T_J),以及晶体管处于雪崩状态的时间(t_{AV})。它允许确定任意应用是否符合特定UIS能力,并且可对最差情况进行仿真,同时还能非常灵活地计算尚未搭建的电路UIS应力,或计算不容易仿真的条件。

PowerMOS晶体管的UIS额定值(见 图1)

以图形表示,纵轴(I_{AS})表示最大雪崩电流,横轴(t_{AV})表示雪崩状态持续时间。显示两条线,一条表示25°C,另一条表示较高的结温。在大多数应用中,使用电流探针可方便地确定现有应用中的雪崩电流和雪崩持续时间。若绘制在UIS额定曲线上的雪崩持续时间和雪崩电流位于25°C线的上方和右方,则该应用超出器件的UIS额定值,用户器件存在故障风险。若绘制在额定曲线上的时间和电流位于最大结温线的下方和左方,则应用处于器件的UIS额定值内。这两种情况都无需进一步分析。若绘制在额定曲线上的时间和电流位于25°C线和最大结温线之间,则需进一步分析。

若要分析起始温度和雪崩时间位于25°C线和最大结温线之间的情况,需确定UIS脉冲起始时刻

PowerMOS晶体管的结温。若UIS应力发生在器件导通后的很长一段时间之后,则可通过测量器件壳温,并计算功耗和器件热阻引起的结至外壳之间温度上升值即可。其他任何方法都可使用。一旦确定了脉冲起始时刻的结温,通过在两条已公布的额定曲线间进行外推即可确定起始结温下的UIS能力。

Ronan^[3]、Stoltenburg^[2]和Blackburn^[1]都曾指出UIS能力 $I_{AS}^2 t_{AV}$ 与温度成线性函数关系。使用该函数关系可直线外推器件在计算所得结温处的UIS能力。然后,将计算得到的能力值与应力值相比较,确定器件是否位于额定值内。这种简单的方法可让用户决定应用是否对任意单UIS脉冲都是安全的。

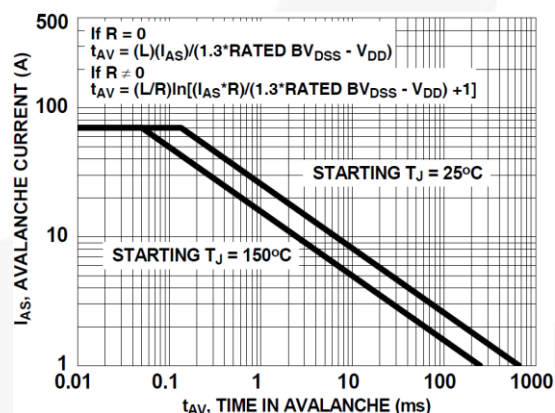


图1. FDB8444非箝位感性开关(单脉冲UIS)

多UIS或重复UIS

大部分PowerMOS晶体管制造商都忽略了重复UIS脉冲的处理，但有一家制造商例外，他们尝试指定25°C功率额定值0.01%的重复UIS，而无进一步的认证。Ronan^[3]提出的UIS评估系统采用叠加技术后，即可用于评估重复脉冲；叠加技术普遍用来评估重复SOA脉冲。每个UIS脉冲在评估时都视为独立事件，就像其他脉冲不存在一样。只需确定 I_{AV} （雪崩电流）、 t_{AV} （雪崩持续时间）和 T_J （脉冲起始时的结温），与单脉冲的情况相同。^[6]

通常一系列脉冲中的最后一个发出时，器件具有最高的结温，因此此时的应力最大。若PowerMOS晶体管位于该脉冲的UIS额定值内，那么可以肯定针对先前结温较低时的脉冲，器件必然位于UIS额定值之内。

PowerMOS晶体管在完全重复周期内的结温变化通常极小。器件具有热容量，不会立即改变温度，因此使用平均结温作为起始温度评估雪崩应力通常不会引起显著误差。若周期较长，则确定UIS脉冲起始时刻的结温时需要采取其他方法。

示例

下列两个示例仅用于演示计算PowerMOS晶体管是否位于UIS额定值内的技巧。由于UIS能力受其他环境应力影响，因此有必要将某些工作条件纳入计算中，作为分析的一部分。两个示例中的工作条件均为计算值而非测量值，而确定UIS能力时使用 I_{AV} 和 t_{AV} 的测量值虽然直观，但却是无关紧要的。第一个示例是“单”脉冲应力，且两次应力之间有足够的时间，使得后续脉冲之间不会互相影响。第二个示例的时间间隔很短，一次间隔的温度变化很小。

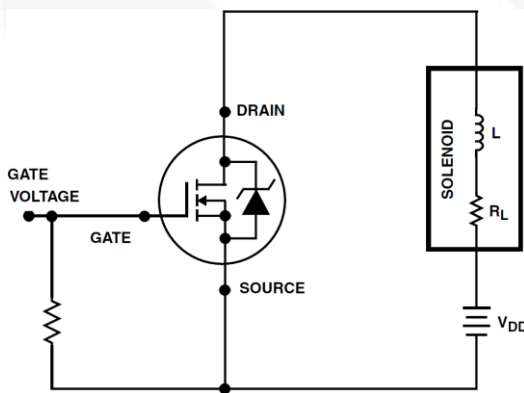


图2. 原理图

电磁阀驱动器：单脉冲

其中： $V_{DD}=13.4V$

$R_L=1.25\Omega$

脉冲宽度=稳态导通

晶体管=FDB8444, $R_{DS(ON)}=5.5m\Omega$

栅极“导通”驱动=10V

最大 $T_J=150^\circ C$

$T_A=110^\circ C$

计算： L （最大允许电感）

θ_{CA} （所需壳至环境热阻）

$R_{TOTAL}=R_L + R_{DS(ON)}=1.25 + (0.0055 \times 1.67)$

（参见图3150C $r_{DS(on)}$ 倍增系数）

$R_{TOTAL}=1.259\Omega$

$I_{AVALANCHE}=213.4/1.259=10.64A$ （峰值雪崩电流）

根据指南，雪崩电压等于额定击穿电压乘以1.3：

$V_{AVALANCHE}=40 \times 1.3=52V$

$t_{AVALANCHE}=(L/R_{TOTAL}) \times \ln[(I_{AV} \times R_{TOTAL})/(V_{AV} - V_{DD}) + 1]$

$t_{AVALANCHE}=(L/1.259) \times \ln[(10.64 \times 1.259)/(52 - 13.4) + 1]$

$L=t_{AVALANCHE} \times 0.237$

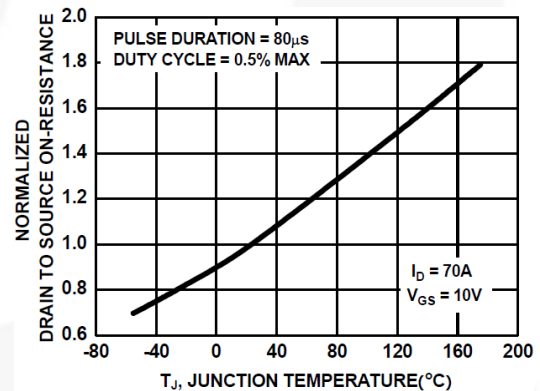


图3. FDB8444标准化 $I_{DS(ON)}$ 与结温的关系

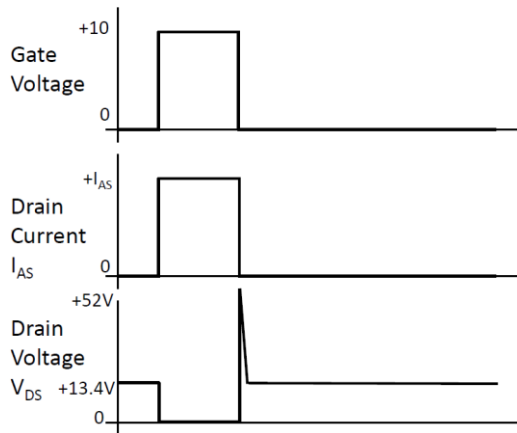


图4. 单UIS事件波形

参考FDB8444 UIS图（见 图1, 150°C），
而对于 $I_{AS}=10.64A$ ，选择允许的2ms
 $t_{AVALANCHE}$ 值。因此，允许的最大L为：

$$L = (0.002) / 0.237 = 8.45nH$$

其中，L= 最大允许电感

现在开始计算所需的散热片热阻：

$$P_D = (I^2 \times R_{DS(ON)}) = (10.06^2) \times (0.0055 \times 1.67) = 1.04W$$

$$\Theta_{CA} = [T_{JMAX} - P_D \times \Theta_{JC} - T_A] / P_D$$

$$\Theta_{CA} = [150 - (1.04 \times 0.9) - 110] / 1.04$$

其中，所需的壳至环境热阻为：

$$\Theta_{CA} = 37.6^\circ C/W$$

示例2

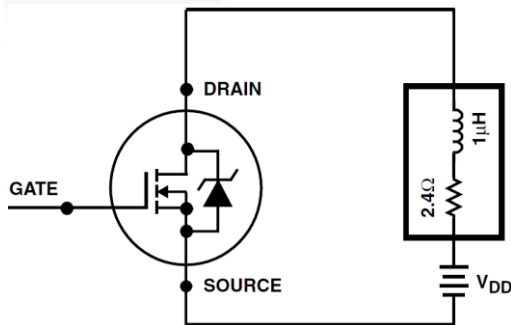


图5. 原理图

开关调节器 =100kHz

其中，

频率=100kHz

占空比=50%

$R_L=2.4\Omega$

$V_{DD}=13.4V$

$T_A=110^\circ C$

$T_{JUNCTION}=150^\circ C$ （最大结温目标值）

$L=1\mu H$ （泄露电感）

PowerMOS晶体管=FDB8444（ T_J 额定值为175°C）。

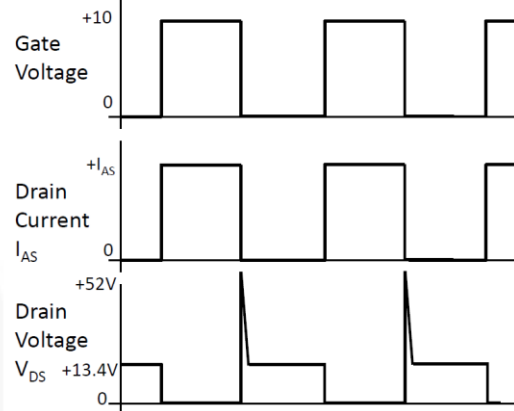


图6. 重复UIS波形

确定：

PowerMOS晶体管是否在UIS额定值内？

所需 Θ_{CA} 值为多少？

$$(1) \quad I_{AVALANCHE} = V_{DD} / (R_L + R_{DS(ON)})$$

$$I_{AVALANCHE} = 13.4 / (2.4 + (0.0055 \times 1.67)) \quad (\text{见图3中的} 150^\circ C \text{ } r_n \text{ 倍增系数})$$

$$I_{AVALANCHE} = 5.56A$$

$$(2) \quad t_{AVALANCHE} = (L / (R_L + r_{DS(ON)}) \times \ln[(I_{AV} \times (R_L + R_{DS(ON)}) / V_{AV} - V_{DD}) + 1]$$

$$(3) \quad t_{AVALANCHE} = (1E-6 / 2.409) \times \ln[5.34 \times 2.409 / (52 - 13.4) + 1]$$

$$(4) \quad t_{AVALANCHE} = 0.124\mu s$$

参考FDB8444 UIS图（见 图1, 5.56A）

器件 $t_{AVALANCHE}$ 能力为7.5ms（150°C时）。该应用未超出FDB8444的UIS能力范围。

(5)

计算所需的散热片热阻：

$$E_{AVALANCHE} = (V_{AVALANCHE} \times I_{AVALANCHE} \times t_{AVALANCHE}) / 2$$

$$E_{AV} = \{40 \times 1.3\} \times 5.34 \times (0.119\mu) / 2$$

每次雪崩的 $E_{AV}=17.9\mu J$

$$P_{AVALANCHE} = E_{AVALANCHE} \times \text{频率}$$

$$P_{AVALANCHE} = 17.9\mu J \times 100K$$

$$P_{AVALANCHE} = 1.78W$$

$$P_{CONDUCTION} = (I_{AV}^2 \times R_{DS(ON)}) / 2$$

$$P_C = \{5.56\}^2 \times 0.00919 / 2$$

$$P_C = 0.14W$$

$$P_{TOTAL} = P_{AV} + P_C$$

$$P_{TOTAL} = 1.78 + 0.14$$

$$P_{TOTAL} = 1.93W$$

$$\Theta_{CA} = [T_{JMAX} - (P_{TOTAL} \times \Theta_{JC}) - T_A] / P_{TOTAL}$$

$$\Theta_{CA} = [150 - (1.93 \times 0.9) - 110] / 1.93$$

$$\Theta_{CA} = 19.8^\circ C/W \quad (\text{可作为散热片的要求})。$$

其他电路的应用

通常，设计人员会仔细地确定器件在整个工作条件范围内的温度。仅使用UIS脉冲起始时的器件结温、脉冲持续时间和脉冲的电流水平，设计人员便可确定应用是否超出器件的UIS额定值。这些参数可方便地测量或计算。通过叠加，该评估体系还可用于多脉冲或重复脉冲应用，如前文两个示例所示。使用这种方法，可对任意电路进行UIS应力分析。无需进行额外的重复UIS评估。

热建模

工作波形中的雪崩波形通常具有幅度和重复率可变的雪崩电流。对这类波形进行热分析经常需要用到更为复杂的分析手段，以便适当地估算工作结温。使用电路仿真软件、器件热阻抗模型、散热片热阻抗模型（或PowerMOS晶体管壳体温度的合理估计值）以及工作波形，可得到合理的PowerMOS晶体管结温估计值。

对半导体器件的热响应进行测量涉及到校准功率脉冲的使用。由于芯片和封装之间存在热阻抗，器件内的功耗会导致结温上升。表达式 $Z_{\theta JC}(t)$ 描述结温除以功耗后的数值变化。

$$Z_{\theta JC}(t) = \frac{\Delta T_J(t)}{P_D} = \frac{T_J(t) - T_J(0)}{P_D}$$

(6)

基本半导体热模型和其电气模拟规格见
图7。器件结点处产生热量，热量通过硅片传导到壳体，最终到达散热片。

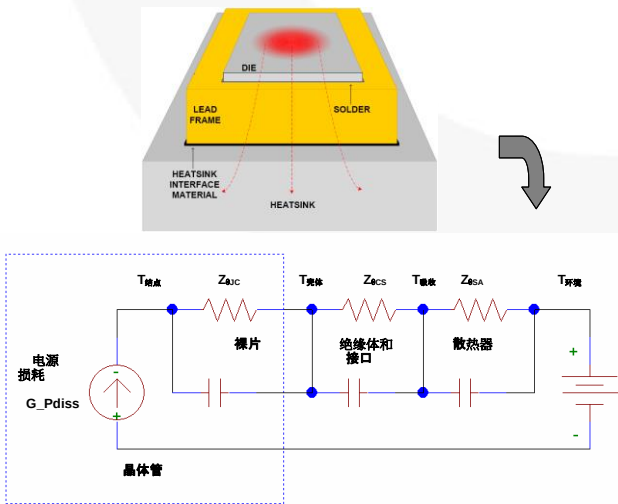


图7. 半导体热阻抗模型

结温信息由器件的热网络 $Z_{\theta JC}$ 和电流源 G_Pdiss 确定。 G_Pdiss 表示半导体的瞬时工作损耗，以电流形式表达。这是以电路形式表示的结温，表示为：

$$T_J = T_{\text{ambient}} + G_Pdiss \cdot (Z_{\theta JC} + Z_{\theta CS} + Z_{\theta SA})$$

(7)

- 其中：
- T_J = 结温
 - G_Pdiss = 瞬时功耗
 - $Z_{\theta JC}$ = 结至外壳热阻抗
 - $Z_{\theta CS}$ = 壳体至散热片热阻抗
 - $Z_{\theta SA}$ = 散热片至环境热阻抗

热系统电气模拟的单位转换见
表1。制造商数据手册中提供 $Z_{\theta JC}$ ，使用单脉冲标准化热阻抗曲线，如 图8所示
 $Z_{\theta JC}$ 可使用等效电气模拟模型代替，如 图9所示。

表1. 电气/热模拟

电气	热
Ω 电阻	$^{\circ}\text{C/W}$ (热阻)
F (电容)	$\text{J}/^{\circ}\text{C}$ (热容量)
A (电流)	W (功率)
V (电压)	$^{\circ}\text{C}$ (温度)

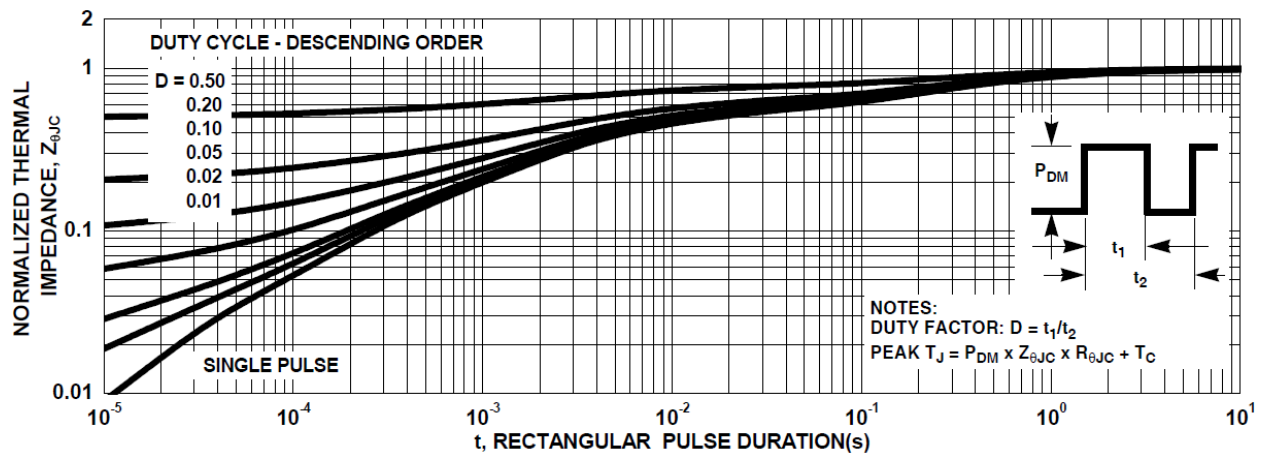
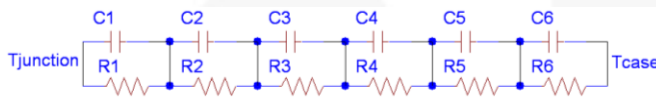


图8. FSB8444标准化瞬态热阻抗曲线

图9. $Z_{\theta JC}$ 热阻抗模型结构

当热模型参数不可用时，可参考数据手册中的 θ_{JC} ，并抽取单脉冲标准化瞬态热阻抗曲线的数据点。电气模拟模型可表述如下：

$$Z(t) = R_1 \cdot (1 - e^{-\frac{t}{R_1 C_1}}) + \dots + R_6 \cdot (1 - e^{-\frac{t}{R_6 C_6}}) \quad (8)$$

R-C参数可通过曲线拟合软件找到，如表Curve 2D^[5]。

知道工作波形和系统级热阻抗信息后，便可分析复杂波形的热响应。FDB8444

MOSFET在壳体温度为125°C并驱动1mH/0.6Ω电磁阀时的示例电路和仿真结果见图10（工作条件为PowerMOS关断时发生重复雪崩情况）。虽然平均功耗位于175°C器件工作温度额定值内(图11)，峰值温度在雪崩超出最大额定值时发生漂移，可能降低晶体管的工作寿命。

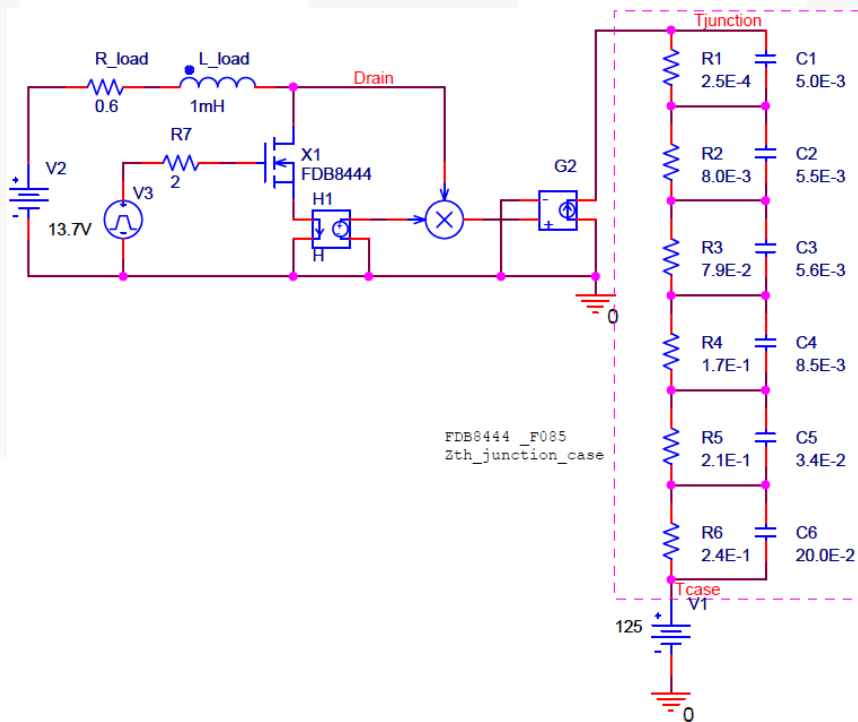


图10. 系统损耗的电气模拟

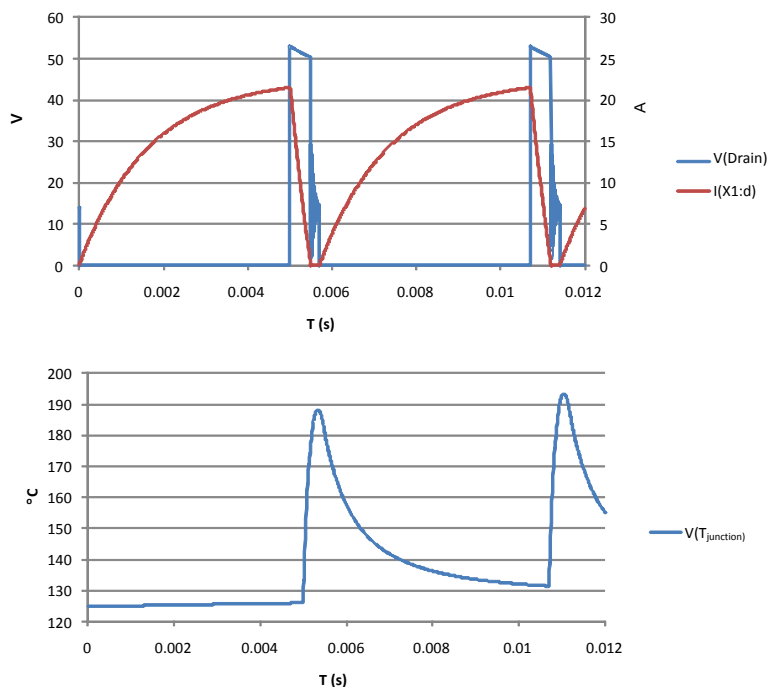


图11. 仿真结果

FDB8444 MOSFET热阻抗模型以RC梯形网络方式提供 (R1-R6、C1-C6)。

将MOSFET电流 I (H1) 乘以漏极电压, 即可评估瞬时功耗信息。结果中的功率脉冲以电压波形表示, 该波形随后由电流源G2转换为功率热脉冲的电气

模拟。以电压源V1设置壳体温度。可采用更详细的系统级热阻抗网络代替V1。瞬时结温信息在节点 T_j 处表示。

总结

本文描述简单和复杂重复UIS事件的热分析方法。可通过单脉冲UIS数据手册额定值曲线、PowerMOS热阻抗模型和晶体管环境工作条件的分析, 估算出合理的结温。

参考文献

若要获得飞兆半导体在互联网上发布的文档，请访问：<http://www.fairchildsemi.com>

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- [5] <http://www.systat.com/products/表Curve2D/>
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