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功率 MOSFET 雪崩应用指南

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引言

功率MOSFET是一种广泛用于开关电源和DC-DC转换器的开关器件。这些器件的工作频率不断提升,同时尺寸不断地缩小,功率密度不断地增加。其结果是器件具有高 di/dt ,增加了寄生电感的负面效应,导致关闭功率MOSFET时器件漏极和源极之间存在高电压尖峰。由于上电时大电容的电荷容量为空,并且电感较小(因为此时变压器初级端电感几乎达到漏电感水平),尖峰在上电时最为明显。幸运的是,功率MOSFET设计为可耐受一定程度的应力,无需使用昂贵的保护电路。本指南提供了一种确定功率MOSFET是否适用于某个应用的有效方法。设计人员可据此权衡成本和可靠性。

1. 一套评估体系: 单脉冲UIS SOA

飞兆半导体分立电源产品部门建立了一套评估体系,可指定功率MOSFET用于单脉冲非箝位感性开关(UIS)的能力。^[1]这套体系可方便地采用简单的参数确定和/或估计器件在任意应用中

的可行性: 雪崩时通过功率MOSFET的峰值电流(I_{AS})、UIS脉冲起始阶段的结温(T_j)和功率MOSFET保持雪崩状态的时间(t_{AV})。通过描绘 I_{AS} 和 t_{AV} 曲线,用户便可检查器件的UIS能力。飞兆半导体的专用UltraFET®和PowerTrench®提供这类评估图,并将于近期更新QFET™数据手册。

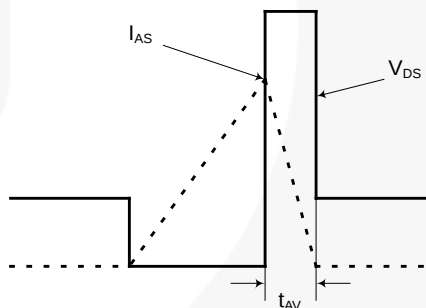


图1. UIS波形

2. 过压条件

实际应用中的过压条件可归类为两种情况。一种是功率MOSFET的漏源极电压超出指定的绝对最大额定值,但依然低于器件的击穿电压。这种情况不属于雪崩,器件的可行性可通过分析结温而确定。另一种情况是器件击穿,进入雪崩模式。该评估体系非常适合用于雪崩

模式分析。

3. 雪崩模式分析

当功率MOSFET发生雪崩时，漏源极电压箝位至有效击穿电压，电流换向流过寄生反并联二极管。图2显示开关电源中的典型雪崩波形。漏源极电压超过1kV，MOSFET中存在换向电流。

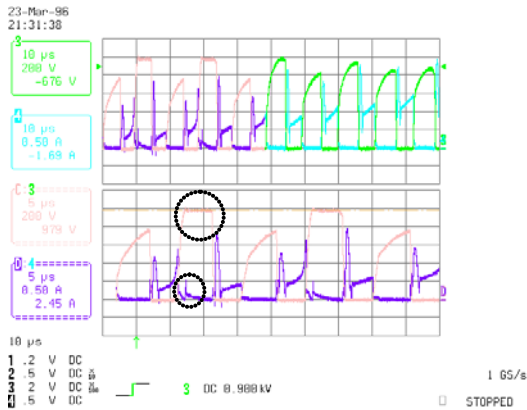


图2. 器件击穿，800V额定值MOSFET

UIS评估体系处理雪崩情况时非常有用。如图3所示，UIS SOA图形中存在三个区域：①25°C线的上方和右方、②最大结温线的下方和左方、③以及两条线的中间部分。①和②很容易确定：器件位于UIS额定值内(②)，或者超出额定值(①)。但是，若要确定③，则需UIS脉冲起始时刻的功率MOSFET结温数据。后文将详细讨论结温的分析方法。

采用叠加技术，该UIS评估体系还可用于重复脉冲。每个UIS脉冲单独进行评估，与单脉冲情况相同。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，从而此时的应力最大。若功率MOSFET位于最终脉冲的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。^[2]

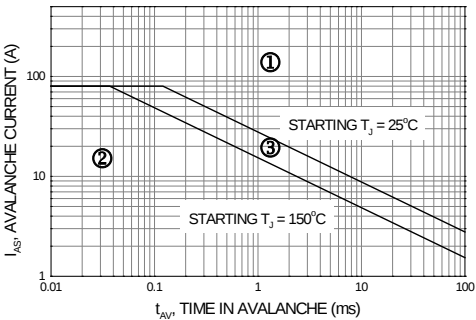


图3. UIS能力 (FDP050AN06A0)

4. 结温分析

通常很少发生功率MOSFET击穿的情况，哪怕漏源极电压超过绝对最大额定值。功率MOSFET的BV_{DSS}具有正温度系数，如图4所示。本例中，它在120°C时达到约990V。因此，在较高的温度下，需要更高的电压才能导致器件击穿。在很多情况下，功率MOSFET工作时的环境温度超过25°C，并且功率损耗导致功率MOSFET的结温上升至环境温度以上。

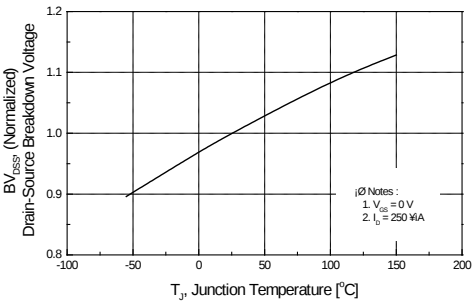


图4. 标准化BV_{DSS}与T_J的关系 (FQA11N90C)

此外，还需注意图4中的BV_{DSS}在250µA的漏电流下进行测量。在真实的击穿情况下，漏电流水平远高于此，且击穿电压甚至比上述值还要高。

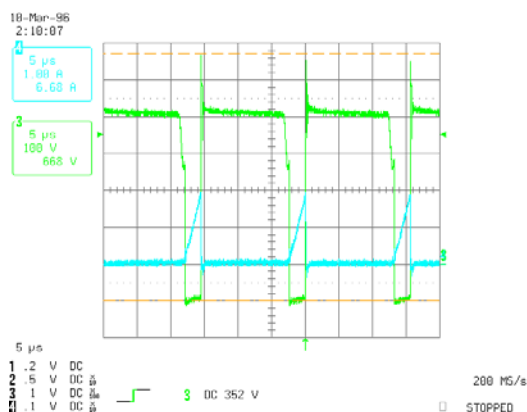


图5. 开关电源的波形，
600V额定值MOSFET

出于实际考虑，应用中真实击穿电压选为额定低电流击穿电压的1.3倍^[1]。图5显示了一个非击穿示例，数值超出绝对最大额定值。峰值漏源极电压为668V，但未发生击穿。

虽然异常电压峰值未导致器件击穿，但应保持功率MOSFET的结温低于指定的最大结温，确保器件的可靠性。稳态结温可表述如下

$$T_J = P_D R_{\Theta JC} + T_C \quad (1)$$

其中，

T_J : 结温

T_C : 壳温

P_D : 结点功耗

$R_{\Theta JC}$: 稳态热阻从

结至外壳的

然而，在许多应用中，功率MOSFET的功耗为脉冲形式，而非直流形式。当功率脉冲施加于器件时，峰值结温随峰值功率和脉冲宽度的变化而改变。特定时间的热阻称为瞬态热阻，表述如下

$$Z_{\Theta JC}(t) = r(t) \cdot R_{\Theta JC} \quad (2)$$

其中， $r(t)$ 是和与时间有关的系数，表示热容量。对于时间极短的脉冲， $r(t)$ 值非常小，但对于时间长的脉冲，该值接近1，且瞬态热阻接近稳态热阻。大部分飞兆半导体的功率MOSFET数据手册具有与图6相似的图形。

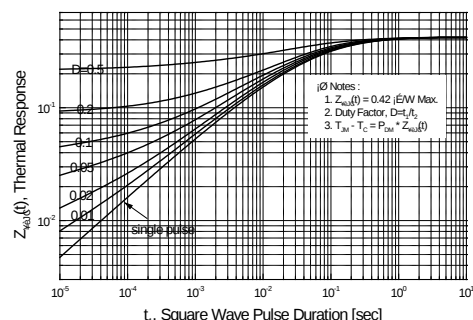


图6. 瞬态热响应 (FQA11N90C)

根据这条曲线，结温可通过下列方式获得：

$$T_J = P_D Z_{\Theta JC}(t) + T_C \quad (3)$$

例如，由1μs期间施加于FQA11N90C的单个2kW功率脉冲导致的温度上升值，可如下计算：

$$\begin{aligned} T &= P_D Z_{\Theta JC}(1\mu s) \\ &= 2000 \times 1.49 \times 10^{-3} \approx 3^\circ C \end{aligned}$$

施加的功率值非常高，但温度仅上升3度。请注意，数据手册中给出的功耗额定值为稳态时的数值，且在相对较短的时间内功率MOSFET甚至能耐受更大的功率脉冲。

然而，在上例中，1μs瞬态热阻未在图6中提供。万一给定的时间太短且超出该图范围，则单脉冲瞬态热阻与时间的平方根成比例。从而 $Z_{\Theta JC}(1\mu s)$ 变为

$$Z_{\Theta JC}(1\mu s) = Z_{\Theta JC}(10\mu s) \times \sqrt{\frac{1\mu s}{10\mu s}}$$

$$= 4.72 \times 10^{-3} \times \sqrt{0.1} = 1.49 \times 10^{-3}$$

其中，

$Z_{\Theta JC}(10\mu s)$ ：来源于图6

上述热响应基于矩形功率脉冲。任意波形都有可能获得响应。然而，由于数学解决方案太过复杂，将其转换为等效矩形脉冲则最为简便。图7显示三角波和正弦波功率脉冲的一些示例。

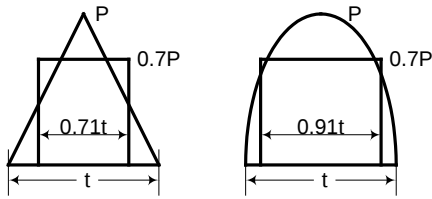


图7. 功率脉冲的转换

公式(3)还可用于重复脉冲应用。重复脉冲的瞬态热阻近似值可计算如下^[3]

$$Z_{\Theta JC}(t) = \left[\frac{t_1}{t_2} + \left(1 - \frac{t_1}{t_2} \right) r(t_1 + t_2) + r(t_1) - r(t_2) \right] R_{\Theta JC} \quad (4)$$

$$= \frac{t_1}{t_2} R_{\Theta JC} + \left(1 - \frac{t_1}{t_2} \right) Z_{\Theta JC}(t_1 + t_2) + Z_{\Theta JC}(t_1) - Z_{\Theta JC}(t_2)$$

其中，

t_1 ：功率脉冲的脉冲宽度

t_2 ：功率脉冲的周期

公式(4)适用于无限脉冲序列。若功率脉冲仅

持续一段有限的时间，则第一项中的 $R_{\Theta JC}$ 应替换为 $Z_{\Theta JC}(t)$ 。

假设如下场景：进行短路测试时，功率MOSFET施加于开关电源的漏源极电压在保护功能激活的延迟时间内超出数据手册中指定的最大额定值。特定条件如下：FQA9N90C开关器件，100ns t_{AV} ，9.2μs周期，20ms延迟时间。在这种情况下，瞬态热阻变为

$$Z_{\Theta JC}(t) = 0.01 * Z_{\Theta JC}(20ms) + (1 - 0.01) *$$

$$Z_{\Theta JC}(9.3\mu s) + Z_{\Theta JC}(100ns) - Z_{\Theta JC}(9.2\mu s)$$

$$= 0.00274$$

假设雪崩期间功耗为5kW，由此导致的结温上升值为

$$\Delta T = 5kW * 0.00274^{\circ}C/W = 13.7^{\circ}C$$

这是由于雪崩而引起的额外结温上升。因此，系统设计人员应首先计算正常工作时的结温，然后加入上述数值以获得雪崩时的瞬态结温。应当保持该温度低于最大允许的结温值，并根据设计人员的选择，留有一定安全裕量。

5. 结论

系统设计人员经常不得不确定功率MOSFET在应用中的适用性。可以通过极为实用的雪崩模型分析和/或结温分析解决这个问题。

参考文献

- [1] “单脉冲非箝位感性开关：一套评估体系”，飞兆半导体应用笔记AN-7514
- [2] “单脉冲和重复UIS混合评估体系”，飞兆半导体应用笔记AN-7515
- [3] Rudy Severns, 1984, “MOSPOWER晶体管的安全工作区和散热设计”，MOSPOWER应用手册，Siliconix

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