1. 碳化硅(SiC) MOSFET 动态性能测试板

瑞能 SiC MOSFET 动态性能测试板是用来评估瑞能第一代 SiC MOSFET 高速开关性能的平台。该平台可用来评估 TO-247-3 和 TO-247-4 两种封装的 SiC MOSFET 产品。平台的电路拓扑结构为两个 MOSFET 开关器件构成的半桥结构， 也可以通过外接电感和负载构成 buck, boost 等连续运行的变换器拓扑。除此之外，该平台还具有的特点包括：

- 为高压母线设计，最高母线电压可达 800V
- 驱动信号侧与高压侧实现 3000V 电气隔离
- 10nH 一下的主回路杂散电感
- 同轴分流器高带宽电路测量
- 门极驱动电压可调，调整范围为-10V - +25V

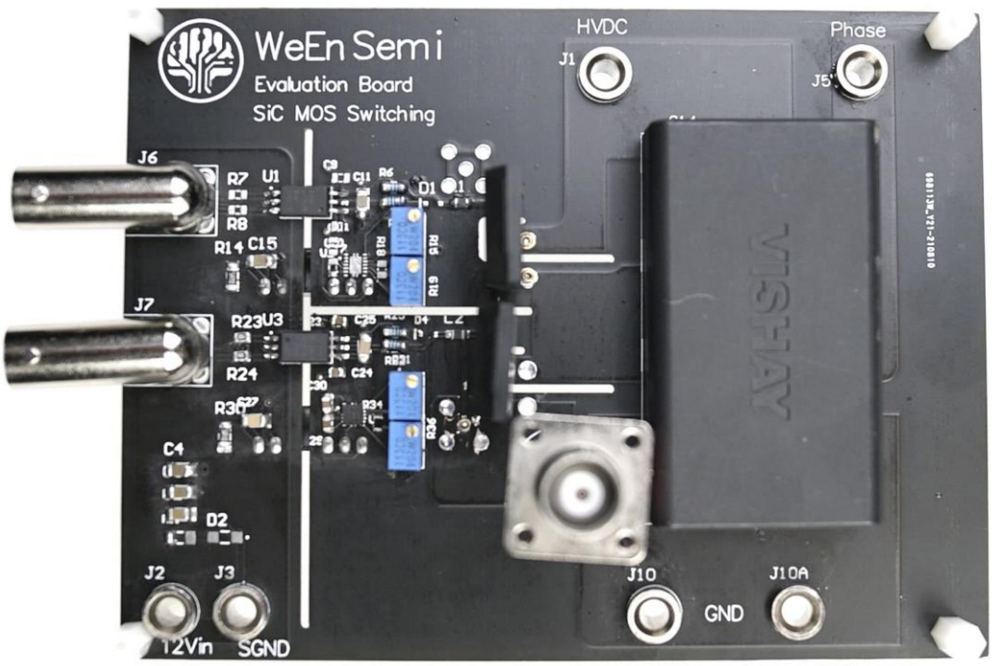


Fig. 1. SiC MOS 动态性能 测试板

2. 待测器件及其他主要元件

测试板上的待测器件(DUT)为：

器件类型	器件型号	额定导通电阻或电流	电压等级
SiC MOS	WNSCM80120W WNSCM160120W	80mΩ@20A, 25℃ 160mΩ@20A, 25℃	1200V
SiC Diode	WNSC2D101200W	10A	1200V

测试板上的其他主要元件为：

器件类型	器件型号	器件功能
门极驱动	UCC23513 or Si826x	4A-6A 门极驱动 IC
正负双向稳压器 LDO	TPS7A39	将 ±24V 电压源转换为所需的门极驱动电压
隔离驱动电源	E2424S-2WR3	±24V 电压源
同轴分流器	SDN-414-010	测量半桥下管电流波形
高压薄膜电容	MKP1848S	20uF 1000V 母线电容

3. 测试板原理图及所需设备

Function	Part #
Free Wheel Diode	WNSC2D101200W
Device Under Test	WNSCM80120W

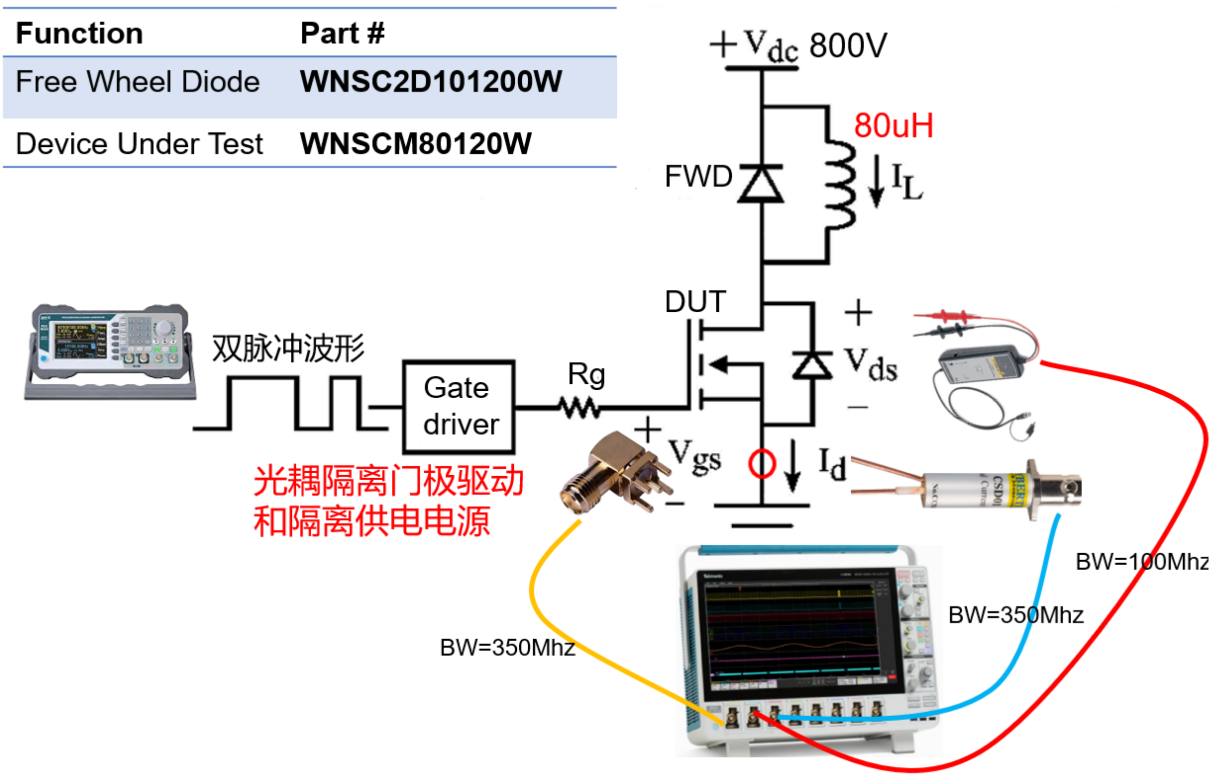


Fig. 2. SiC MOS 动态性能原理图

测试设备	设备功能
高压直流电源	提供高达 800V 的母线电压
低压直流电源	提供驱动信号电源， 一般为 12-15V
多通道高带宽示波器	记录 Vgs, Vds 及 Id 等波形
信号发生器	可调门极脉冲或连续高频信号

4. 测试步骤

- 在 HVDC 和 GND 端口之间接入 800V 电源, 在 12Vin 和 SGND 端口之间接入 12V 电源, 在 HVDC 和 Phase 端口之间接入电，J7 端口处接入下管驱动信号。示波器通道接好所要测试的信号。
- 打开 12V 电源， 通过 R34 和 R36 可调电阻调节所需要的门极驱动电压值，可在负压 -10V-0V， 正压+15-+24V 之间调节至任意所需电压。建议调节至负压-5V, 正压 20V。最大电压不超过为-10V-+25V。
- 在待测器件位置，插入 SiC MOS WNSCM80120W 和 SiC 二极管 WNSC2D101200W。
- 打开 800V 电源，将示波器调至触发模式， 手动触发信号发生器双脉冲信号。这样就可以得到一组双脉冲波形了。

5. 动态双脉冲测试波形

双脉冲波形为衡量 SiC MOSFET 及其他功率开关器件的重要方法。从双脉冲波形中我们可以得到的信息有：

- 给定电流下的开关过程中， 门极电压 Vgs 和漏极电压 Vds 的震荡情况
- 开通和关断过程中，因漏极电压与电流交叉产生的开关损耗
- 续流二极管（可为肖特基二极管或 MOSFET 体二极管）的反向恢复电流大小

在母线电压 Vbus=800V, 漏极电流 Id=20A 情况下，根据不同的门极电阻 Rg， 得出的开关损耗情况及门极震荡电压的最大最小值如图 Fig.3 所示。门极驱动电压 Vgs 的震荡情况很大程度上影响 SiC MOSFET 使用上的可靠性，如果瞬时震荡超过额定值可能会导致门极氧化层的击穿。瑞能 SiC MOSFET 从设计上降低了门极电压 Vgs 的震荡情况，Fig.6 所示为与某主要 SiC MOSFET 厂家在相同测试条件下的震荡情况对比（测试条件为 Rg=5Ω, Id=20A, Vds=800V，Vgs=-5-+20V）。

External gate resistor(-5-+20V, 25℃)	Eon(μJ)	Eoff(μJ)	Max Vgs during turn-on transient	Min Vgs during turn-off transient
0Ω	220	39	24.4V	-8.8V
2.5Ω	282	46	23.0V	-7.0V
推荐门极电阻值 5Ω	380	53	20.4	-5.6V
10Ω	467	60	20.0	-5.2V
15Ω	549	79	20.0	-5.2V

Fig.3. 开关损耗及门极电压震荡值

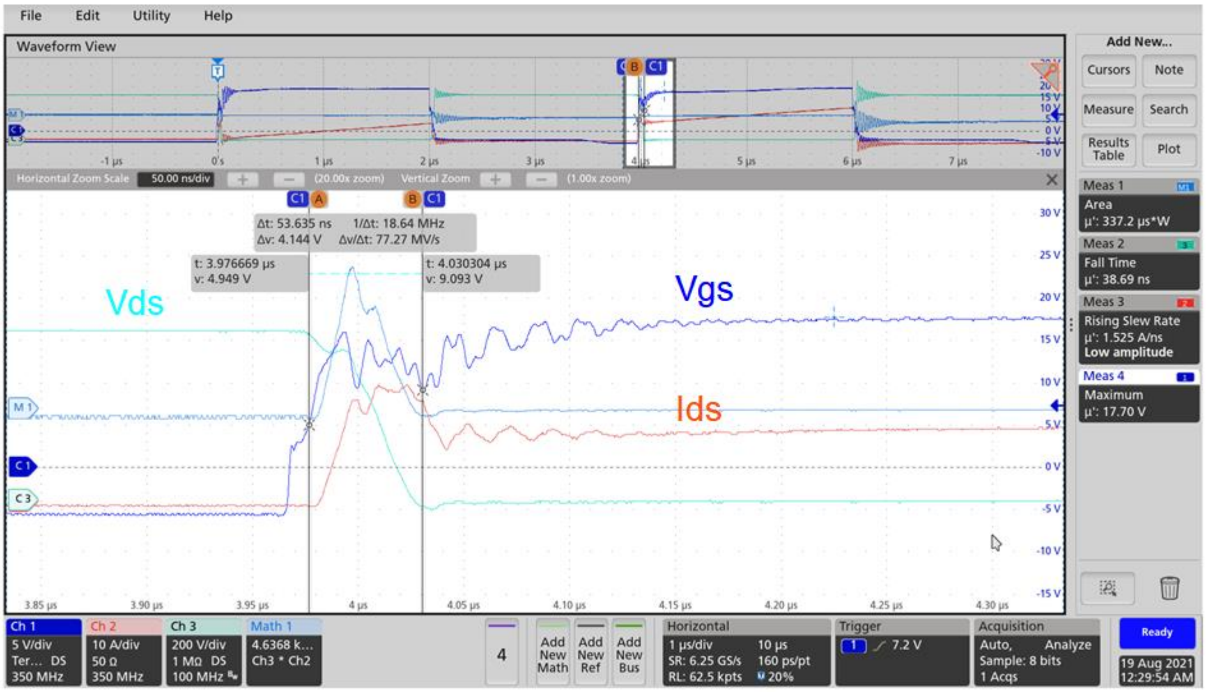


Fig.4. WNSCM080120W 开通过程波形（Rg=5Ω）

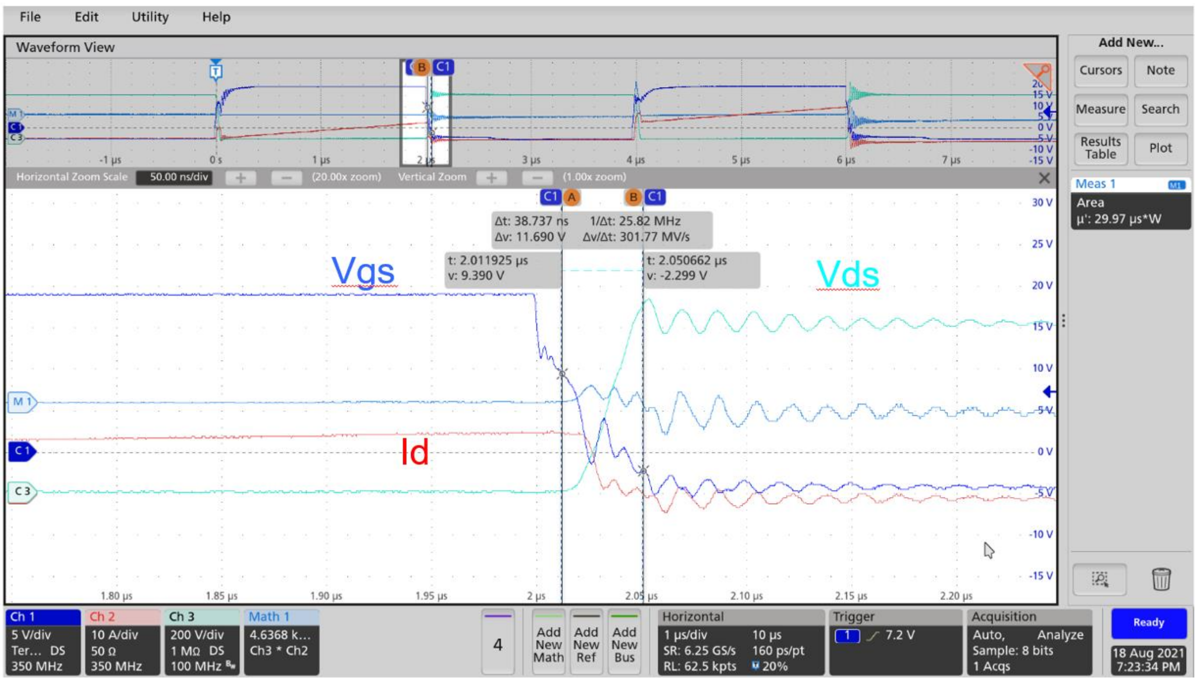


Fig.5. WNSCM080120W 开通过程波形（Rg=5Ω）

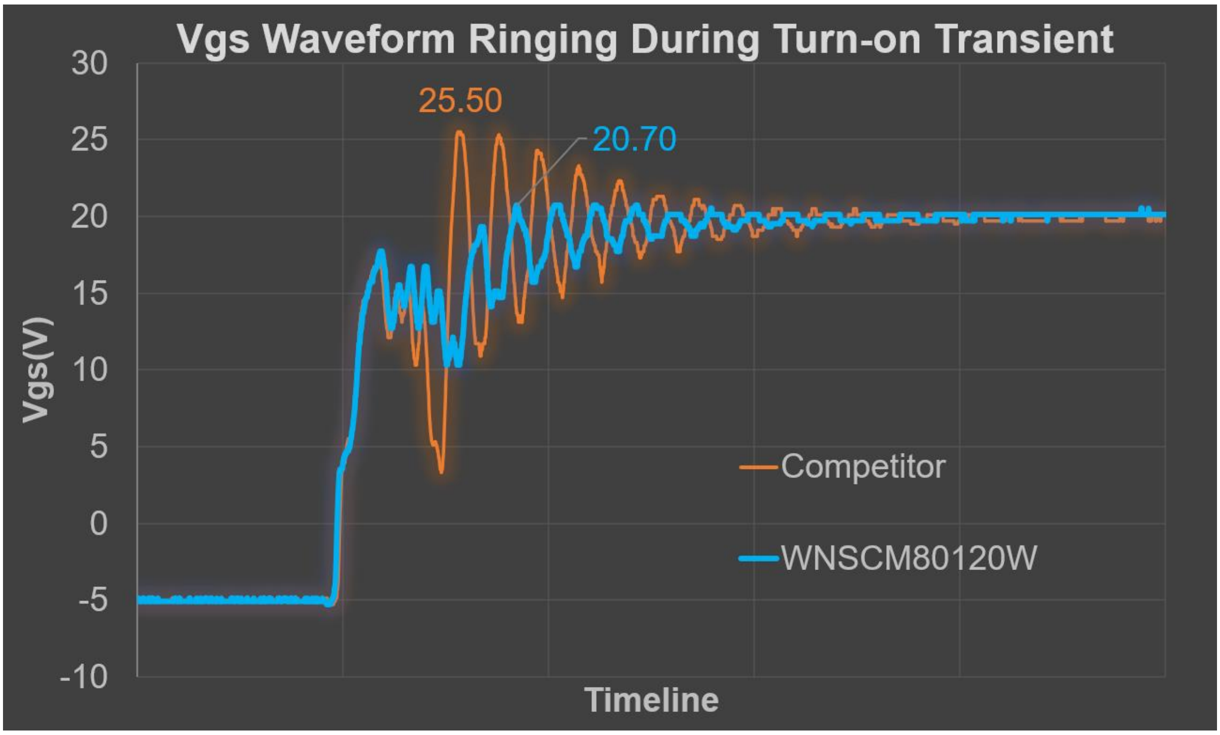


Fig.6. WNSCM80120W SiC MOS 和竞品开通过程中的 Vgs 震荡对比

6. 影响 SiC MOS 开关性能的其他因素

1) TO-247-3 和 TO-247-4 封装

与 TO-247-3 相比，TO-247-4 的封装会大幅提升高压高功率 SiC MOSFET 器件的开关性能。如图 Fig.7 中所示， TO-247-4 中由于 Kelvin Source 脚的加入，门极信号回路大大缩小且与主回路电流解耦。带来的好处包括门极电压震荡的减小，开关速度加快以及开关损耗大幅降低， 所以对于新设计来说，推荐使用带有 kelvin source 的 TO-247-4 封装。两种封装具体开关参数对比如下所示：

Part Number	Package(-5-+20V, 25℃, Rg=0Ω)	Eon(μJ)	Max Vgs during turn-on transient
WNSCM80120W	TO-247-3	220	29V
WNSCM80120R	TO-247-4	90	21V

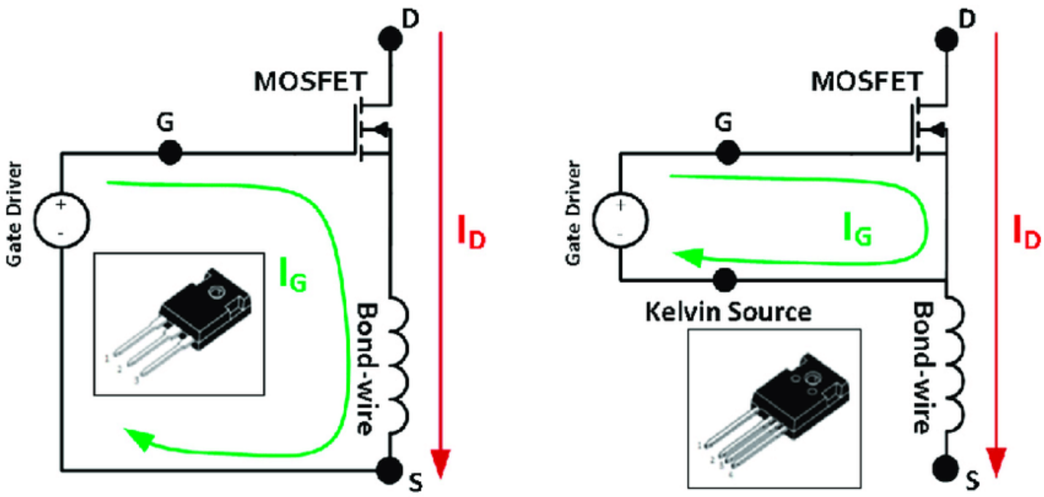
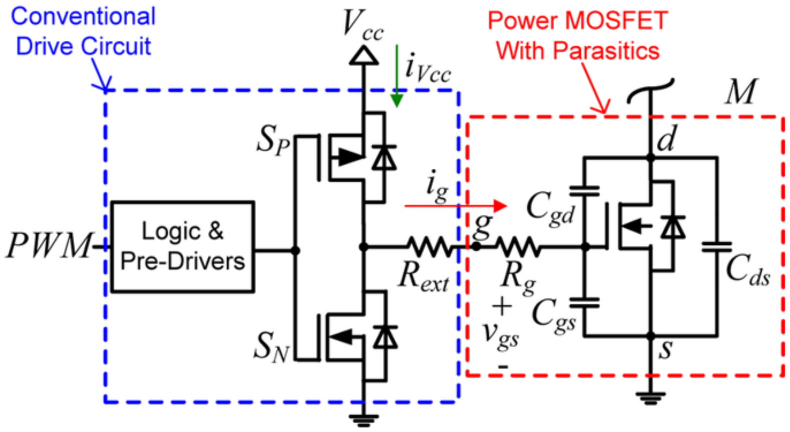


Fig.7. WNSCM80120W 3pin 与 WNSCM80120R 4pin 封装对比

2) 驱动电压 Vgs

瑞能 SiC MOSFET 的门极电压最大值为-10-+25V，推荐使用正压为 18-20V， 负压为-5-0V。由于碳化硅器件沟道载流子迁移率较低，推荐尽量使用正压 20V 驱动，来获得最佳的导通电阻 Rds(on)。除此之外，驱动电压的大小也会影响到开关过程中的损耗。其原理可见 Fig.8，驱动电压除以驱动回路的总电阻即为开关过程中的门极充放电电流 Ig，想要获得较大的充放电电流 Ig， 就要尽量增大电平 Vcc 的大小。这样可以加快开关速度，以获得相对小的开关损耗。Fig.9 是不同驱动电压开关损耗的比较。



门极驱动电流

$$i_g=\frac{V_{cc}-V_{ss}}{R_{driver}+R_{ext}+R_g}$$

Fig.8. SiC MOSFET 开关过程充放电电流 Ig

Gate-Source Voltage (Rg=5Ω, 25℃)	Eon(μJ)	Eoff(μJ)	RDSON(mΩ), ID=20A
-5V – +20V	377	25	75
0V – +20V	414	38	75
-5V – +18V	467	25	85
0V – +18V	505	38	85

Fig.9. 驱动电压对开关损耗的影响

3）器件结温

相比以上两点，器件结温对于 SiC MOSFET 开关损耗影响较小。结温影响开关损耗的主要原因是 SiC MOSFET 阈值电压会随结温而变化。当结温升高时，阈值电压略微减小，而阈值电压的降低会使 MOSFET 开通过程略微加快，关断过程略微减慢。Fig.10 为同一个 SiC MOSFET 器件在不同结温条件下的开关损耗表现。

Junction Temperature （Rg=5Ω，Vgs=-5-20V)	**Eon(μJ)**	**Eoff(μJ)**	**Max Vgs during turn-on transient**	**RDSON(mΩ) ID=20A**
25℃	380	53	20.5V	80
50℃	380	55	-	-
75℃	369	59	-	-
100℃	351	60	-	-
125℃	339	66	-	-
150℃	328	74	22V	115

Fig.10. 器件结温对开关损耗的影响

Revision history

Rev	Date	Description
v.01	20211223	New Application Note

Contact information

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