GN002 应用笔记

GaN*PX*®封装器件的热设计

GaN Systems公司

2021年7月20日

应用手册内容

1. 动力: 控制器件温度的重要性
2. 功耗以及散热基础的介绍
3. 顶部散热器件的热设计考量
4. 底部散热器件的热设计考量
5. 基于热的考虑来选择器件
6. 功耗以及热模型

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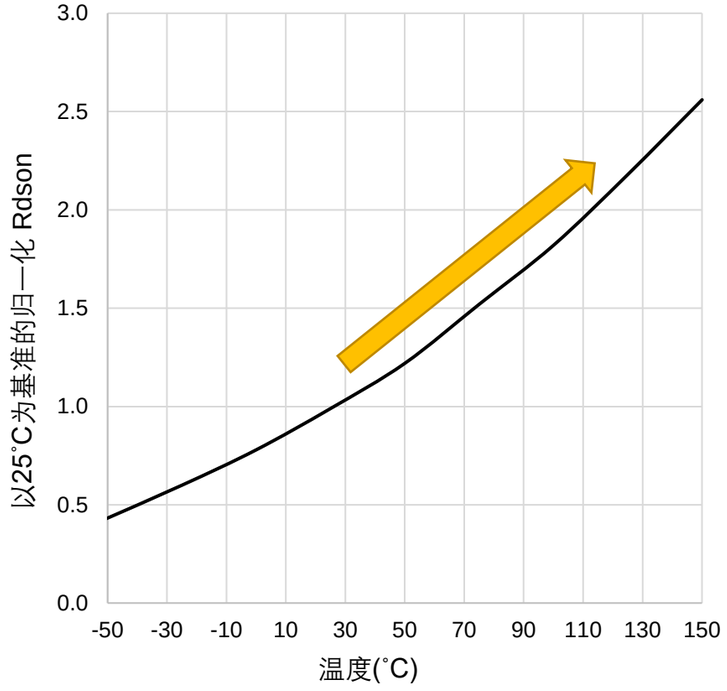
6. 功耗以及热模型

1. 动力: 控制器件温度的重要性

两项电气参数都取决于温度

1. $R_{DS(on)}$ 以及导通损耗

$R_{DS(on)}$ 与温度的关系

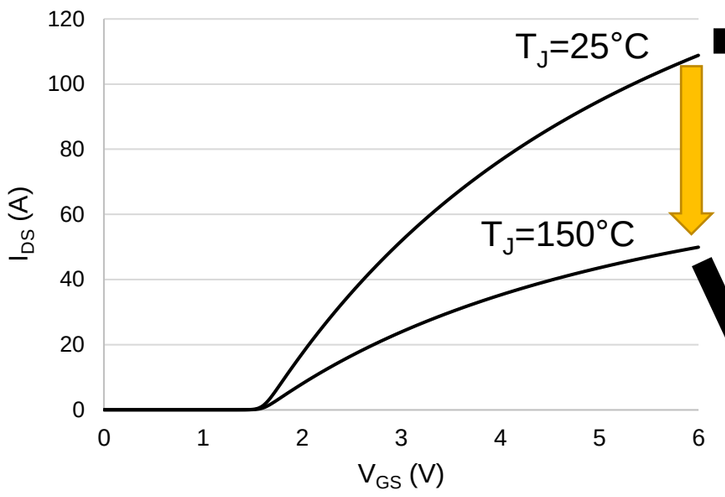


GS66508B的Rdson与T_J的关系

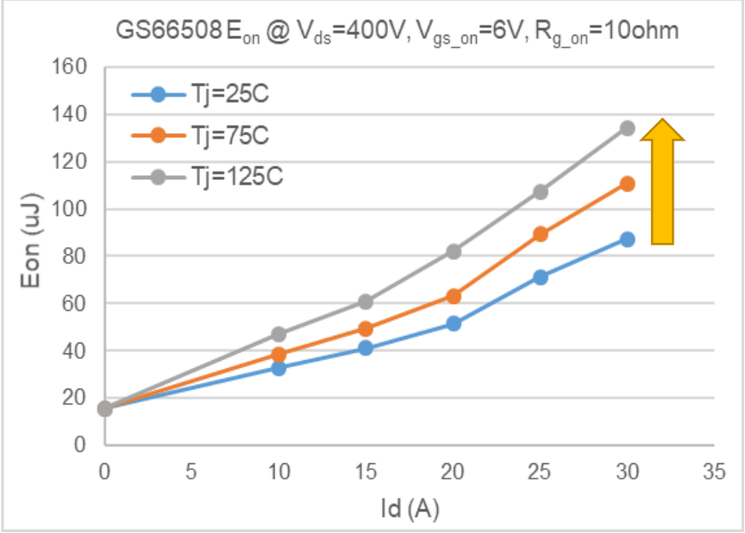
需要控制好T_J 来优化损耗

2. 跨导以及开关损耗

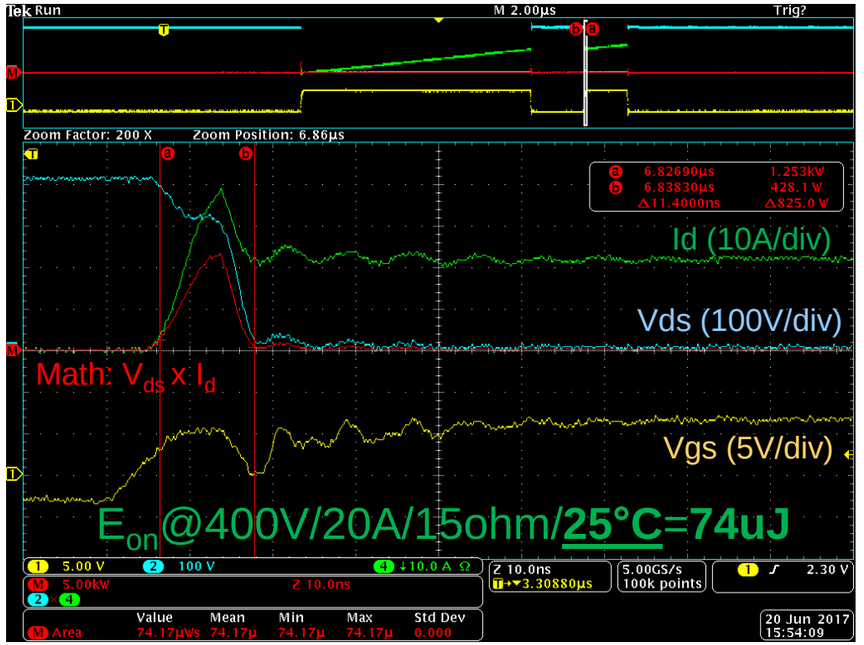
I_{ds}典型值与V_{gs} 的关系

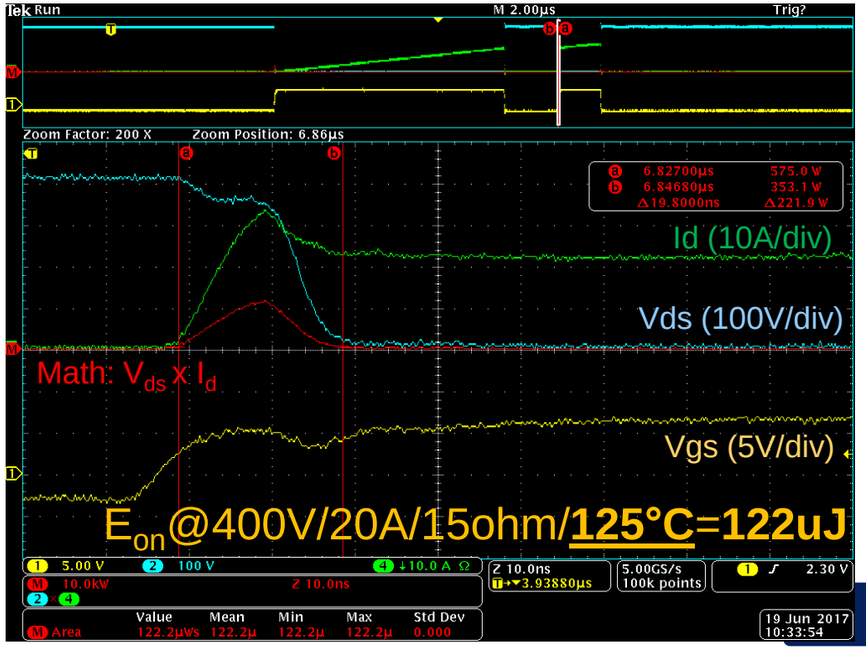


GS66508B 的跨导g_m与T_J的关系



GS66508 的E_{on} 随 T_J 变化曲线

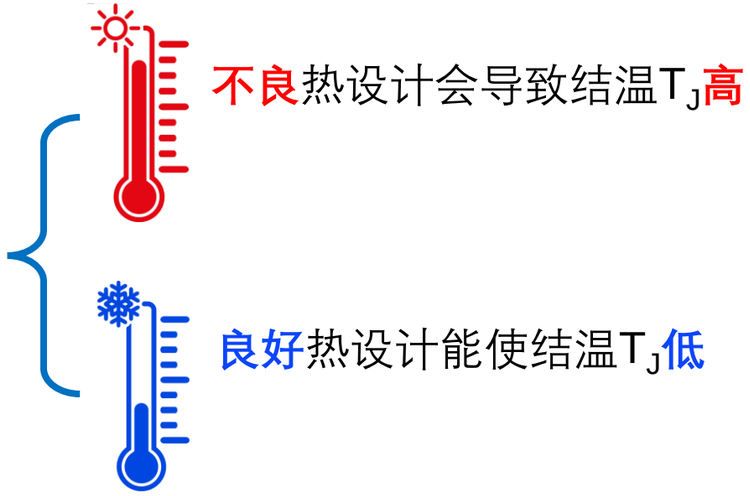




1. 动力: 控制器件温度的重要性

为什么要控制器件温度:

1. 防止在最恶劣条件下热失衡

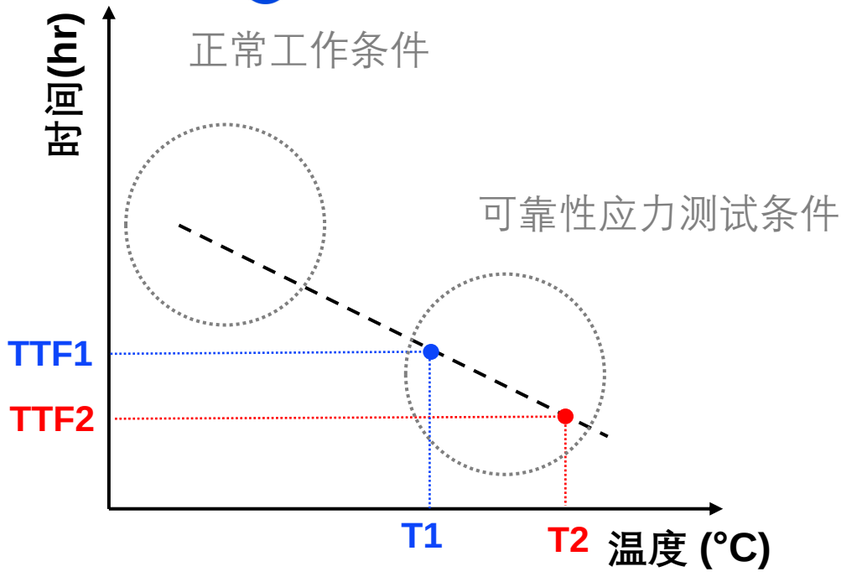


并且:

2. 降低总体损耗和提高系统效率

3. 提高系统可靠性

器件级和系统级的良好热设计至关重要。



失效时间随温度加速升高的关系

1. 动力: 控制器件温度的重要性

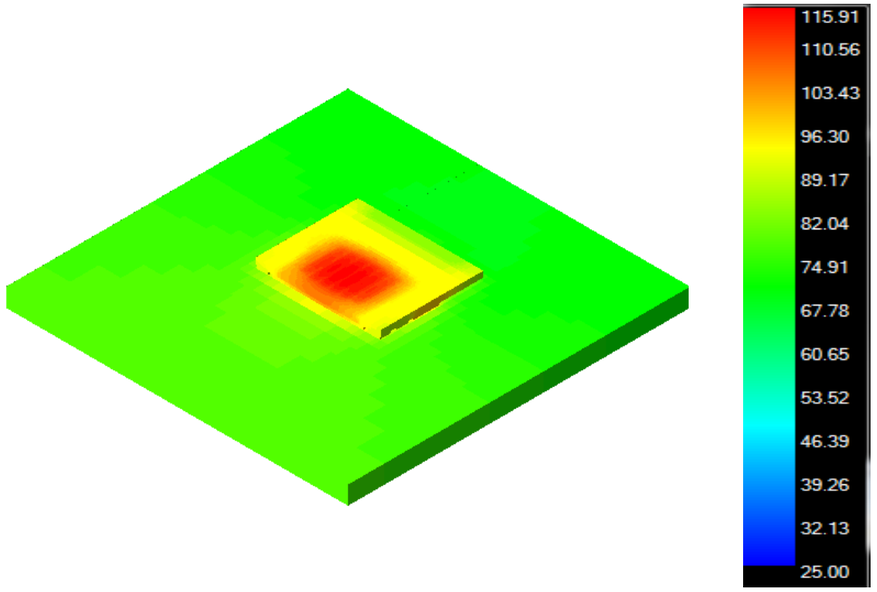
良好的热设计可以提高功率密度

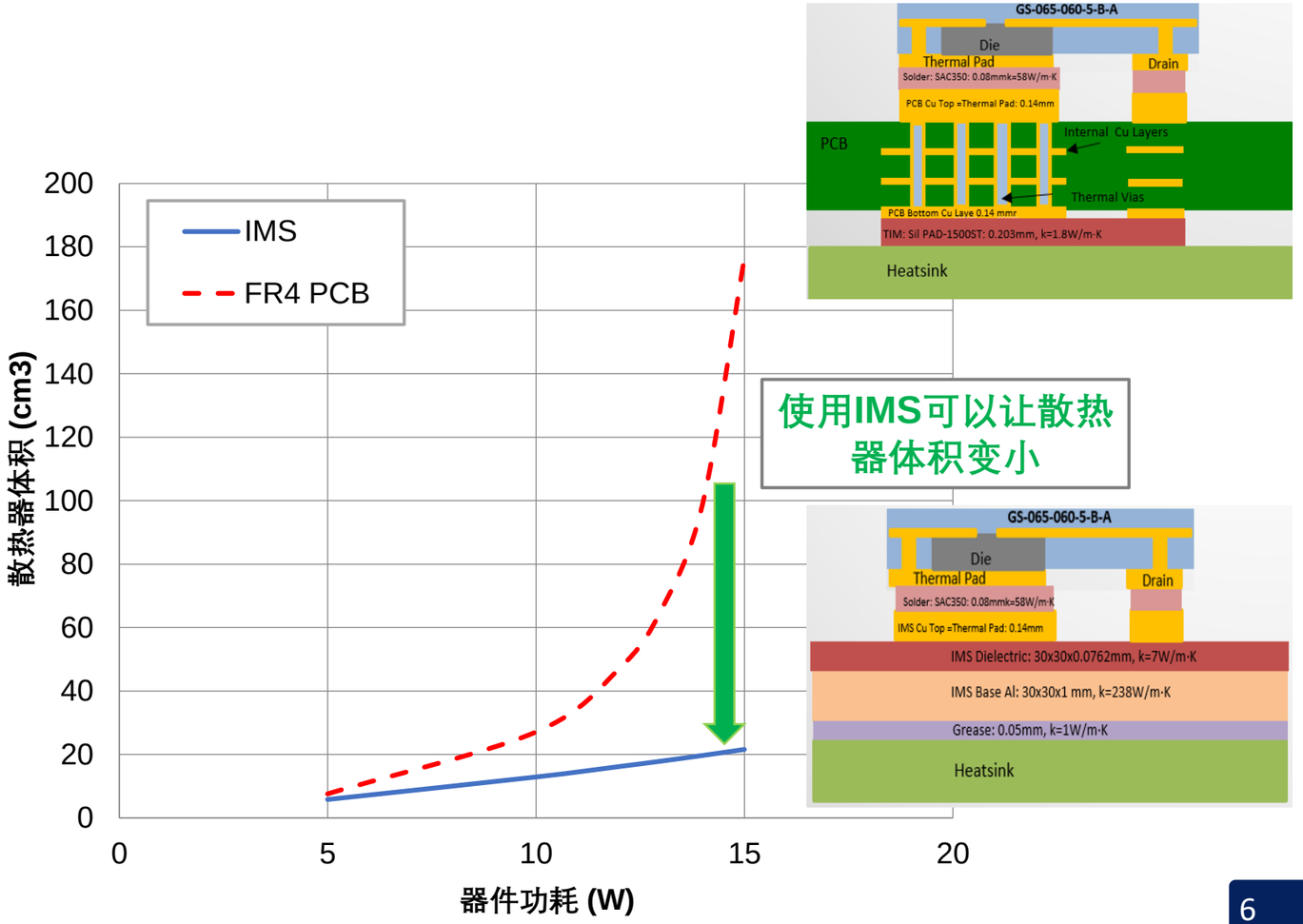
例子:

在大功率应用中, 对比FR4 PCB的散热方式, GaN Systems的绝缘金属基板(IMS)设计可以减少散热器的体积。

IMS与FR4 PCB对比的仿真比较:

- 强制风冷, T_A=25 °C, 相同PCB尺寸;
- 为了保持T_J=100 °C, 随着功耗增加，需要加大散热器尺寸来保持T_J 稳定。





应用手册内容

1. 动力: 控制器件温度的重要性

2. **功耗以及散热基础的介绍**

   2.1 功耗

   2.2 散热, 热阻以及结温

3. 顶部散热器件的热设计考量

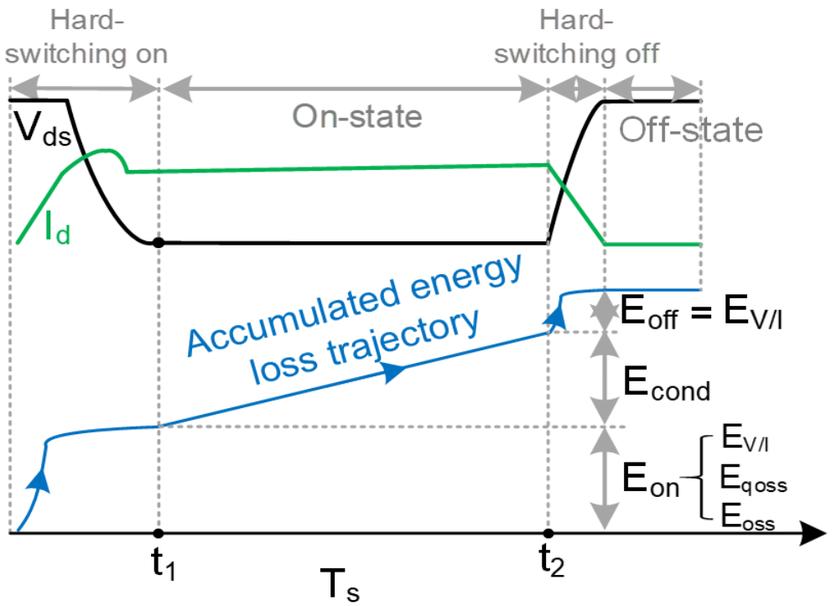
4. 底部散热器件的热设计考量

5. 基于热的考虑来选择器件

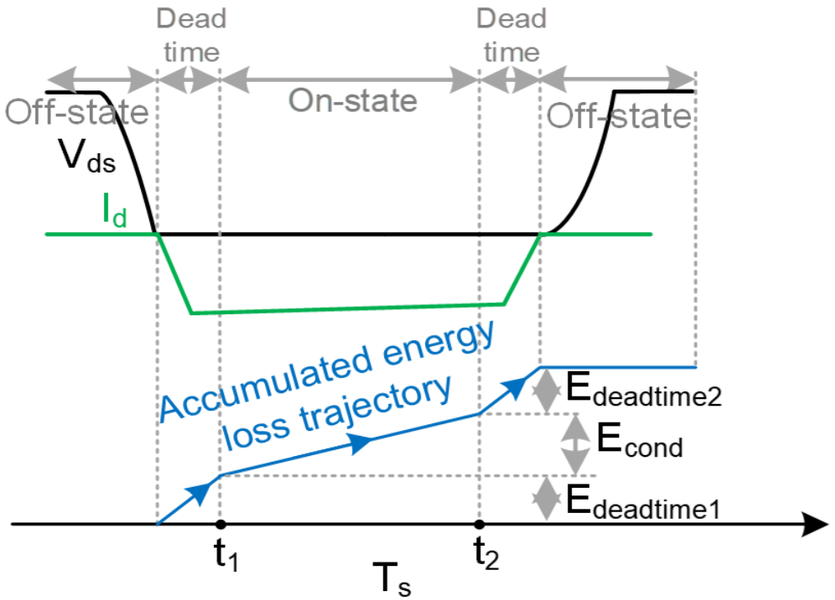
6. 功耗以及热模型

2.1 功耗机制的介绍

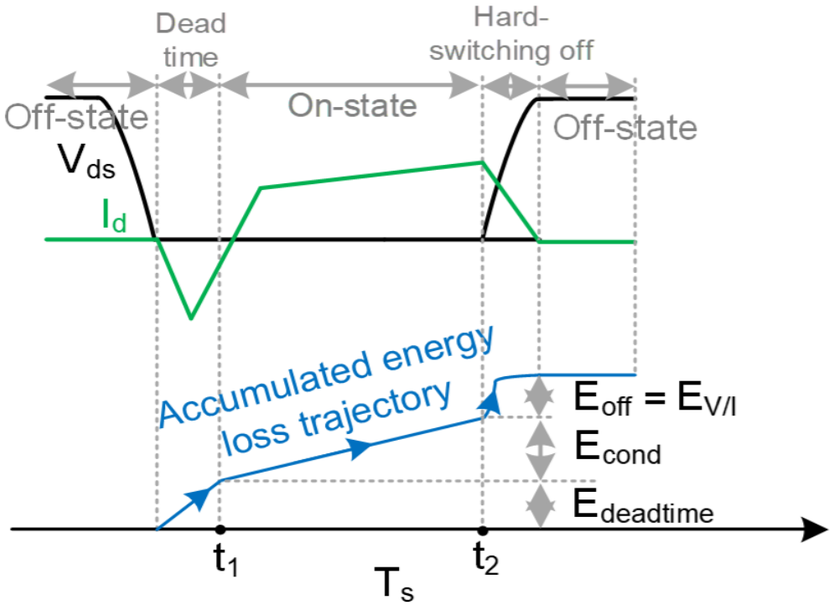
开关器件的能耗 E 主要有三种，而功耗 $P = E \times F_{sw}$



1. 硬开关器件能耗轨迹

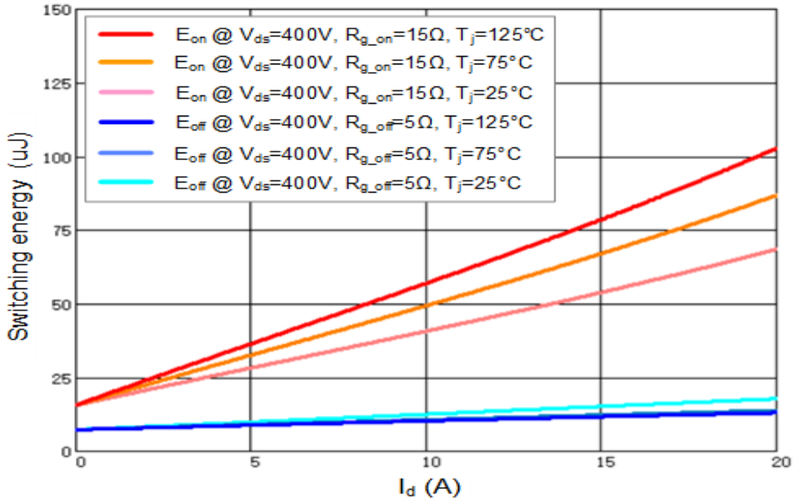


2. 同步整流器件能耗轨迹

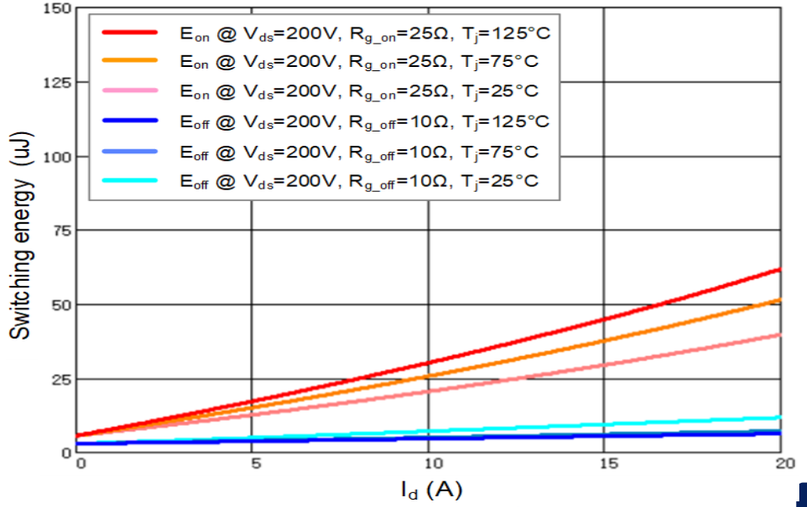


3. 零电压软开关器件能耗轨迹

在此对各种条件下的功耗机制都作详细探讨和归纳



GS66508T 开关损耗@ 400V

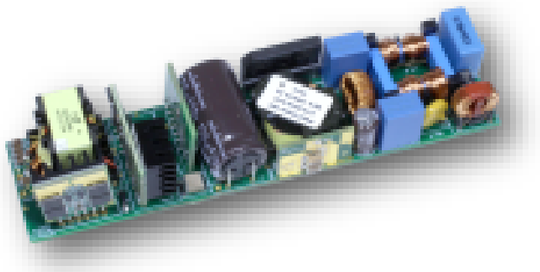


GS66508T 开关损耗@ 200V

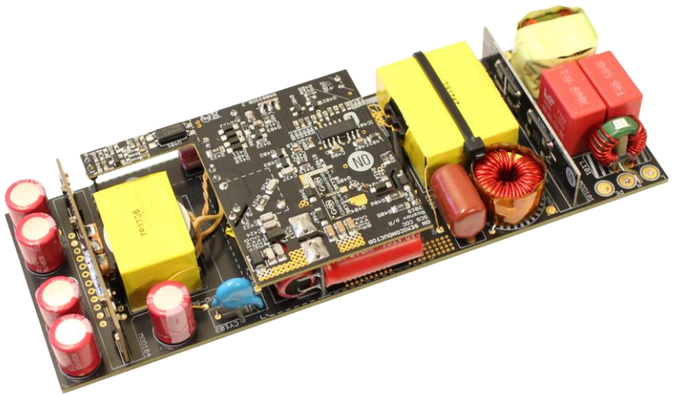
2.1 使用GaN降低功耗的介绍

开关方式	GaN 特点	对系统的影响
3. 零电压软开关模式	开关速度快	关断损耗 ↓
	能量相关结电容$C_{oss(ER)}$低	实现零电压所需的电感能量小, 更少的无功功耗 ↓
	时间相关结电容$C_{oss(TR)}$低	死区 ↓
	门极电量Q_g低	门级驱动损耗 ↓
1. 硬开关模式	反向恢复损耗为零 结电容能耗E_{oss}/E_{qoss} 低 极好的跨导	开通损耗 ↓

由于极好的电气性能, GaN HEMT 大大优化了软开关和硬开关的应用。



170 W PFC + LLC 适配器



300 W PFC + LLC 适配器

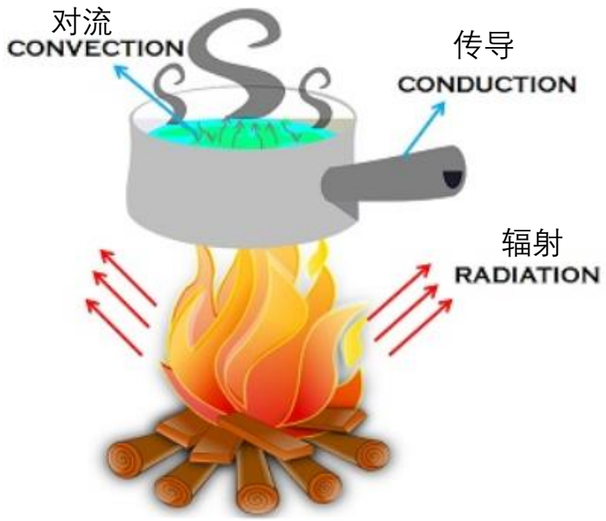
3 kW CCM 图腾柱 PFC

10 kW 三相牵引逆变器

2.2. 散热, 热阻以及结温

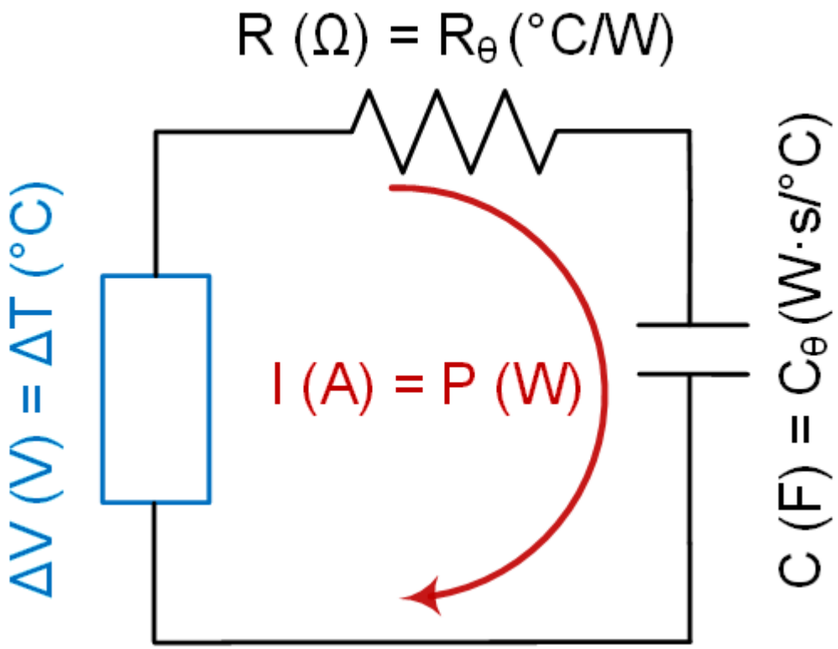
散热主要有三种方式:

- **传导** – 通过直接接触
- **对流** – 通过流体运动 (包括空气)
- **辐射** – 通过电磁波

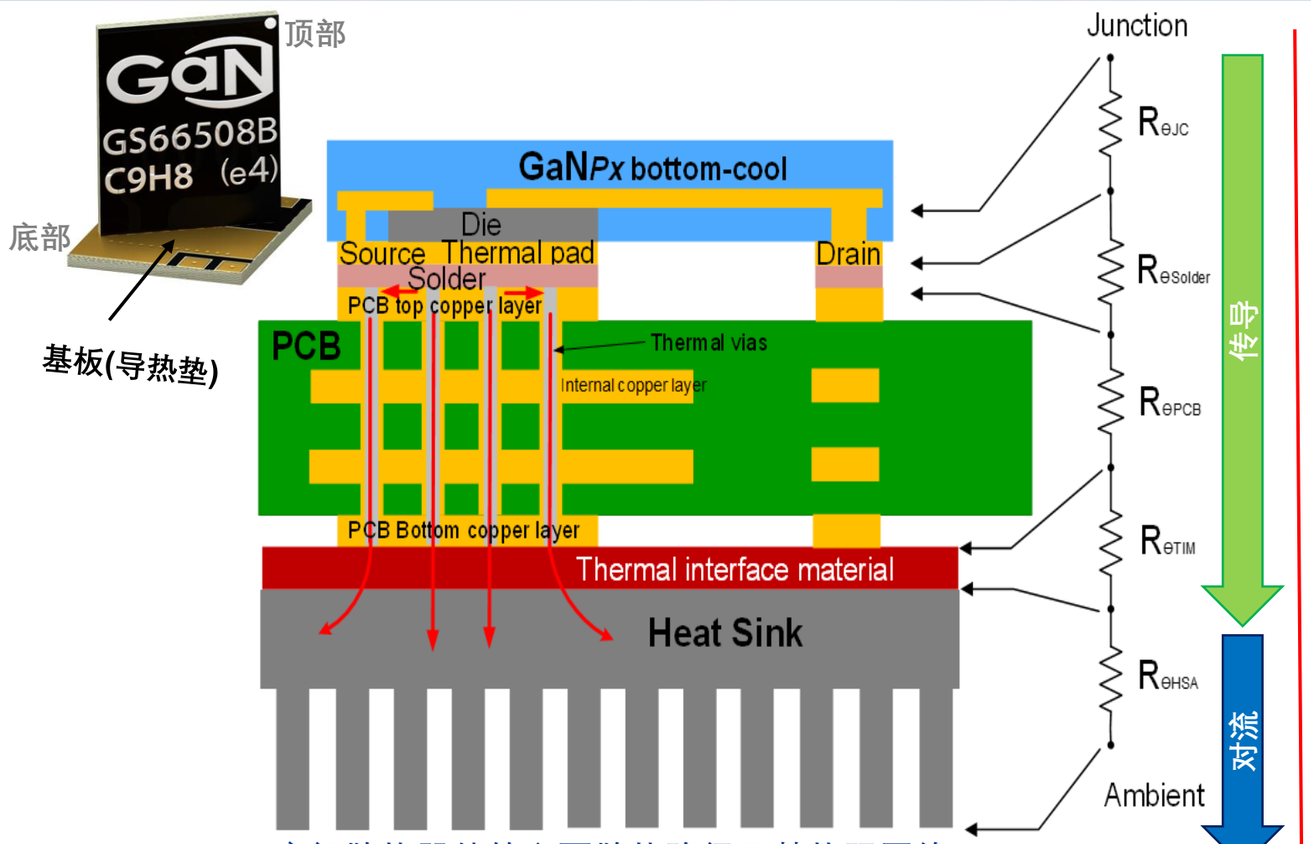


热和电气参数的类比

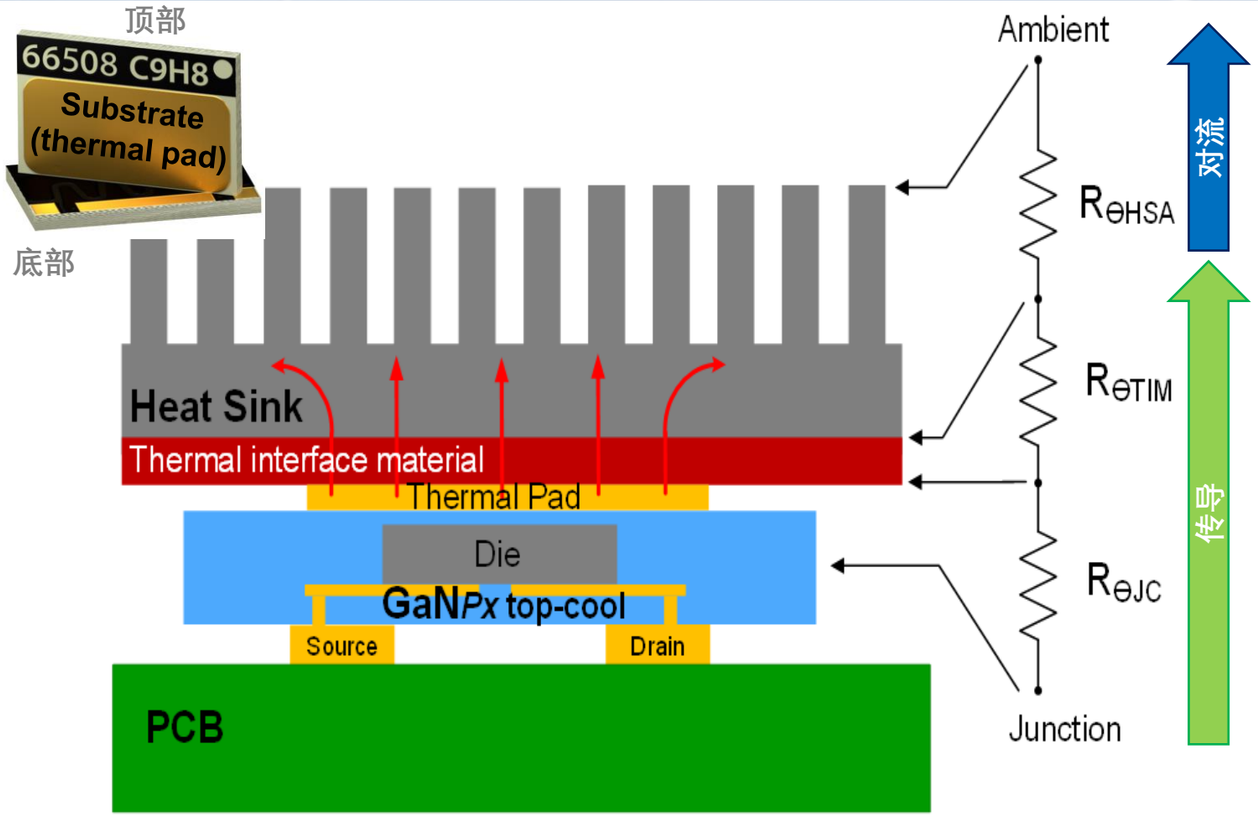
热参数	电气参数
温度 T (°C)	电压 V (V)
功率 P (W)	电流 I (A)
热阻: R_θ (°C/W)	电阻 R (Ω)
热容: C_θ (W·s/°C)	电容 C (F)



2.2. GaN的散热和热阻



底部散热器件的主要散热路径及其热阻网络



顶部散热器件的主要散热路径及其热阻网络

结温计算： $T_J = T_A + P \times R_{\theta JA}$

GaN HEMTs的极好电气性能 (品质因子FOM) 可优化总体功耗

除了提及传统的“品质因子”，该应用手册也会描述如何有效利用GaN特性进行热设计，以此优化GaN HEMTs的总体性能。

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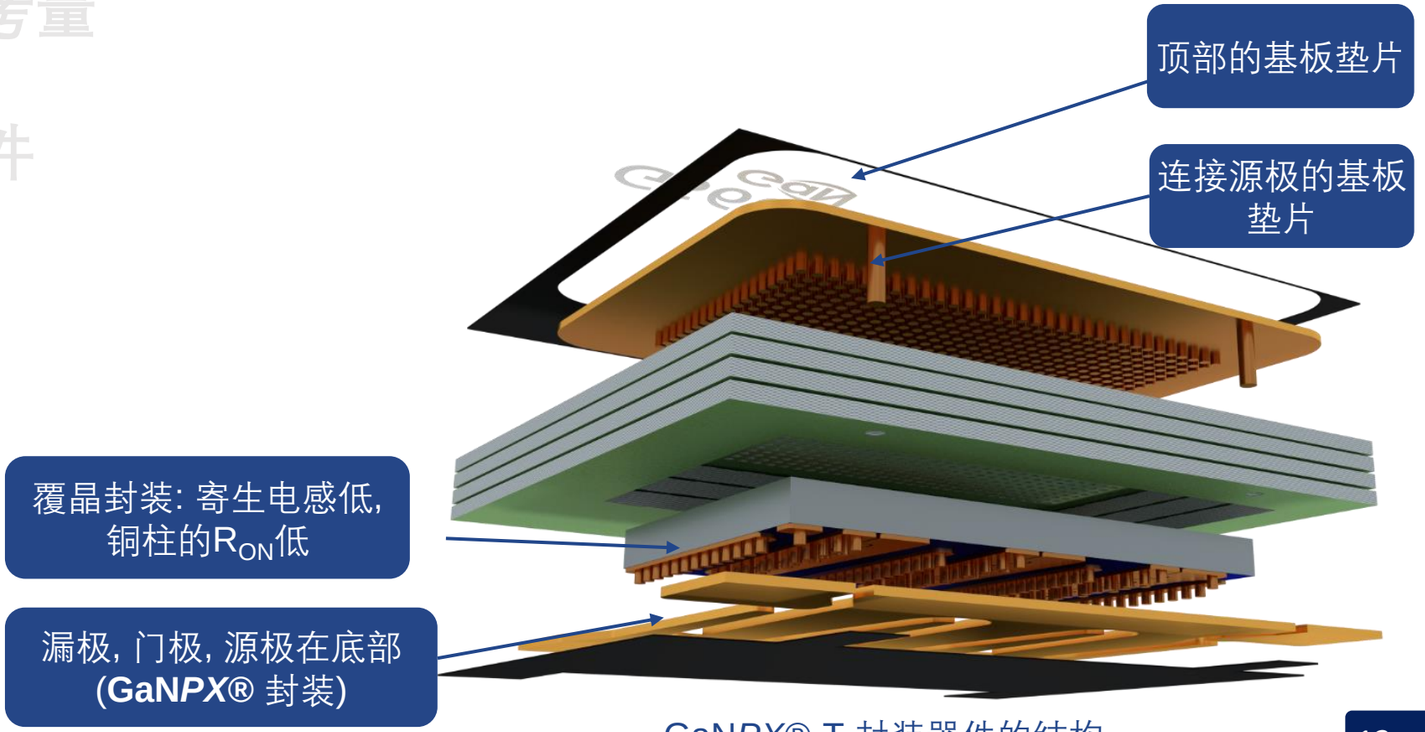
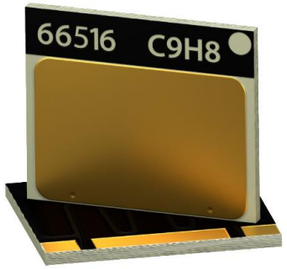


GaN*PX*®-T 封装器件的结构

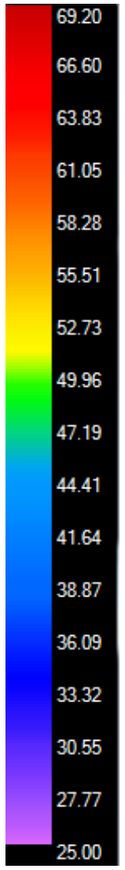
3. 顶部散热设计– 散热介质材料(TIM)的选择

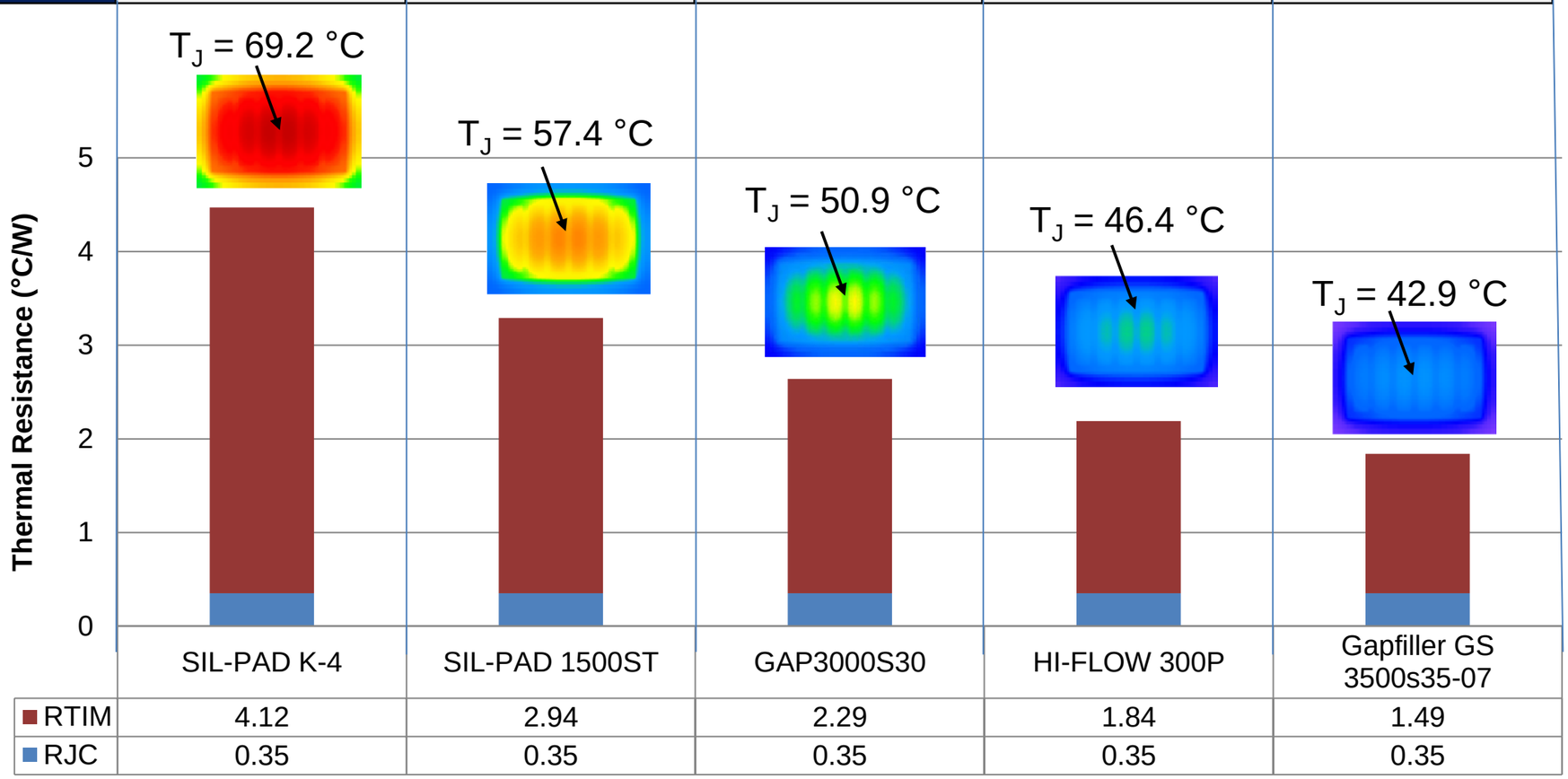
热仿真的工作条件:

- GS66516T 的功耗为10 W
- T_{HS} = 25 °C



	SIL-PAD K-4	SIL-PAD 1500ST	GAP3000S30	HI-FLOW 300P	GAPFILLER GS 3500S35-07
TIM厚度(mm)	0.152	0.203	0.25	0.102	0.178
热导率(W/m·K)	0.9	1.8	3.0	1.6	3.6





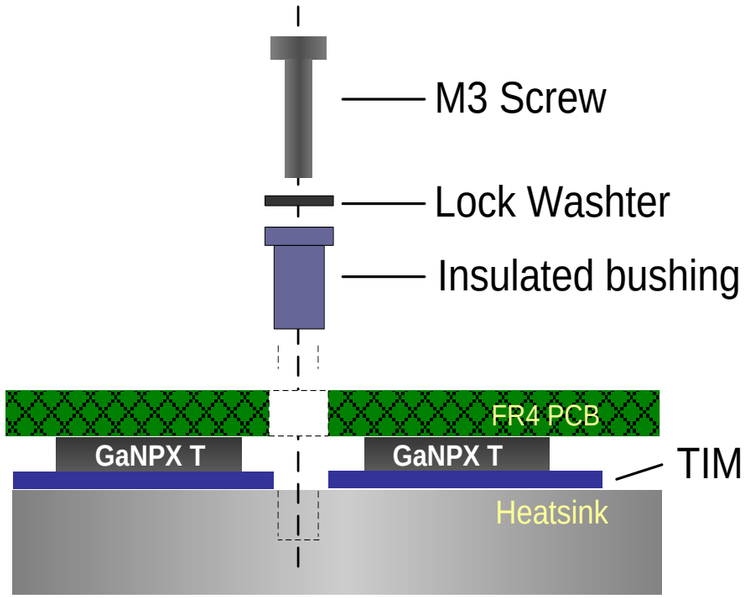
选择散热介质材料的关键因素: 绝缘强度, 机械强度以及成本。

所列TIM来自材料生产商Bergquist *http://www.bergquistcompany.com/thermal_materials/

3. 顶部散热设计 – 安装考量

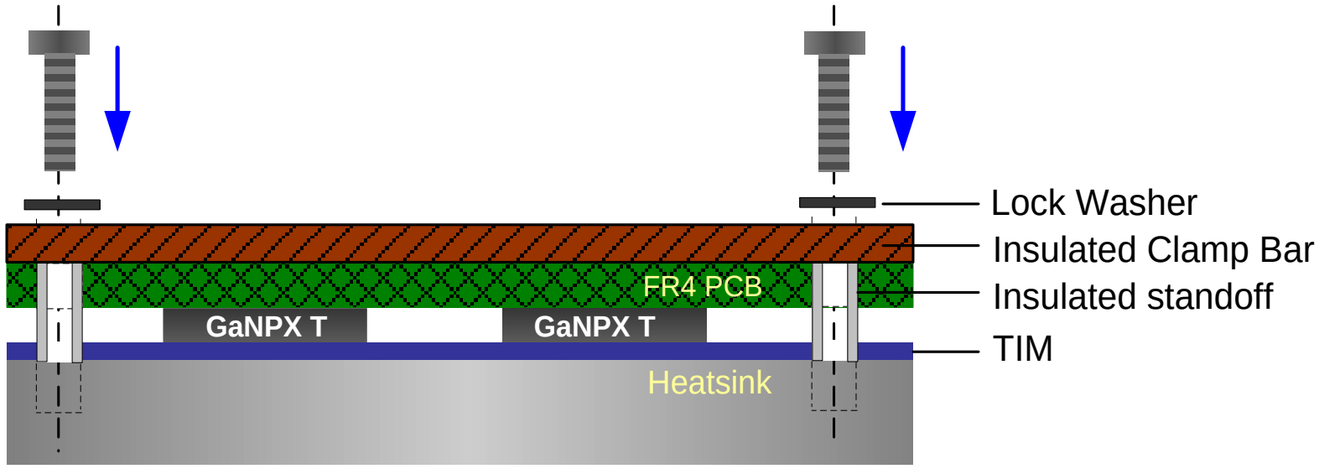
小型散热器可采用一个中部安装孔

- 可以平衡两个器件之间的压力
- 推荐的最大压力典型值约为50psi
- 在压力高达100psi的以往测试中，没有发现失效



大型散热器可采用两个或多个安装孔

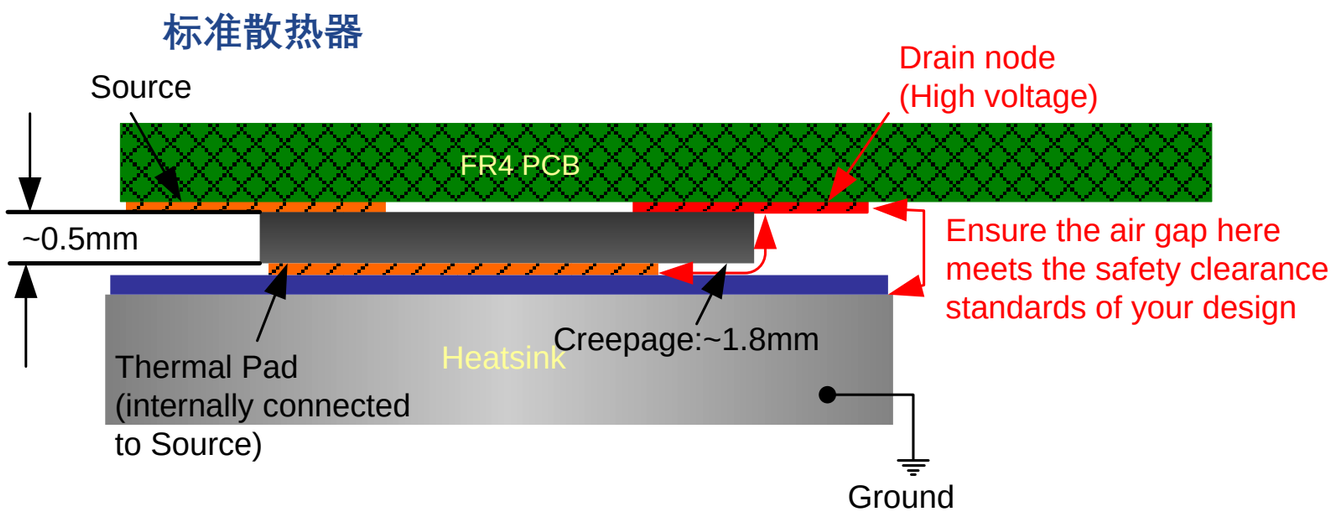
- 要避免过大的PCB弯曲造成应力施加在SMD器件上
- 安装孔可定位于GaN*PX*®-T封装器件附近
- 在某些情况下，PCB顶部可加支撑夹片作额外的机械支撑，但这不太常见

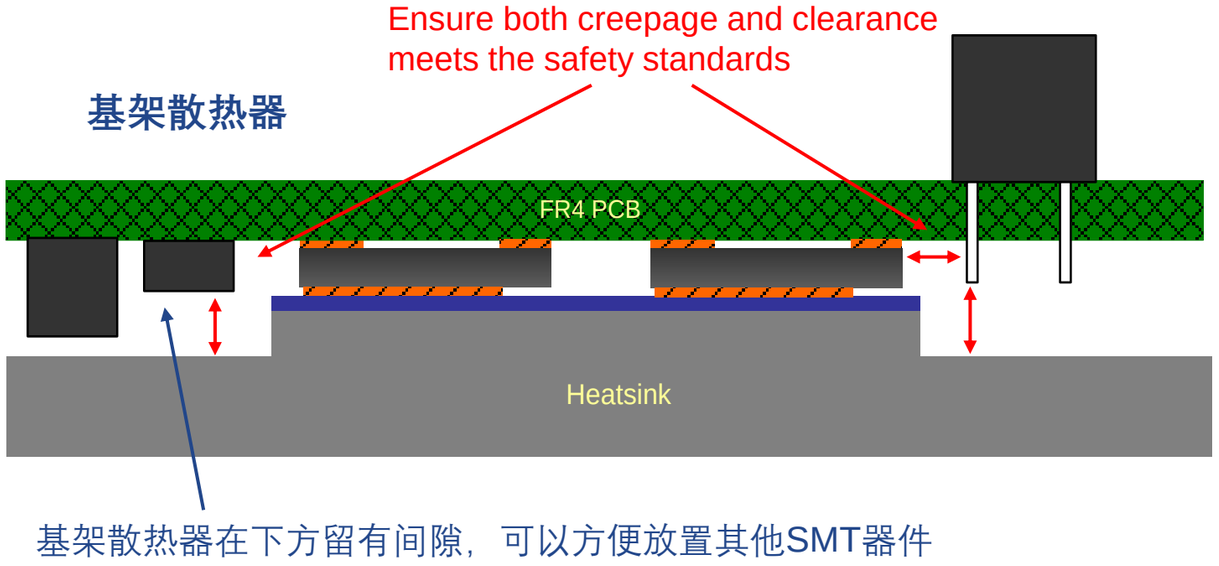


3. 顶部散热设计 – 电压绝缘距离

使用散热器时，设计要满足规定的爬电距离以及绝缘间隙

- TIM可用来填充散热器的边缘部分，以满足标准要求的间隙
- 避免直插器件放置在GaN*PX*® -T封装器件附近
- 可使用**基架散热器**来增加间隙，也便于在散热器下放置其他SMT器件

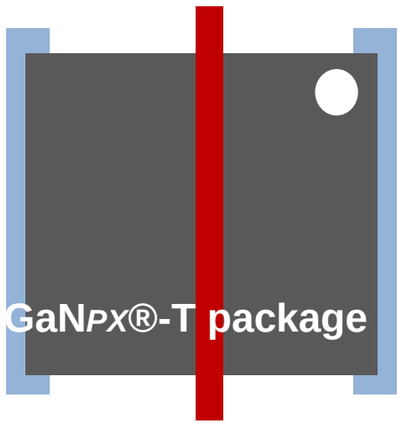




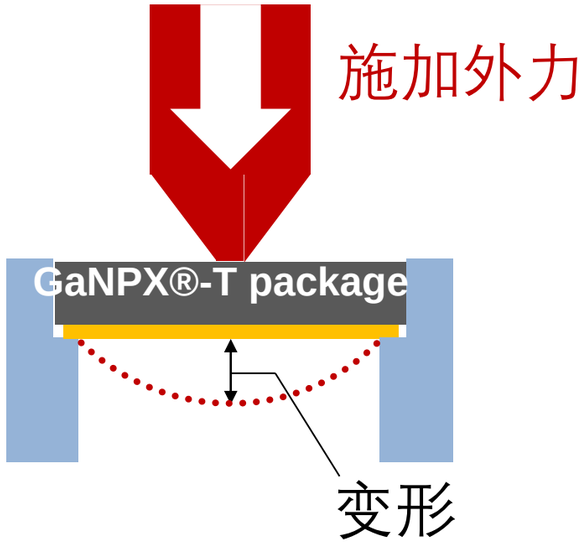
3. 顶部散热设计 – 封装弯曲应力和变形

产品型号	变形安全极限(μm)	压力安全极限(PSI)
GS66508T	50	100
GS66516T	120	100

变形测试

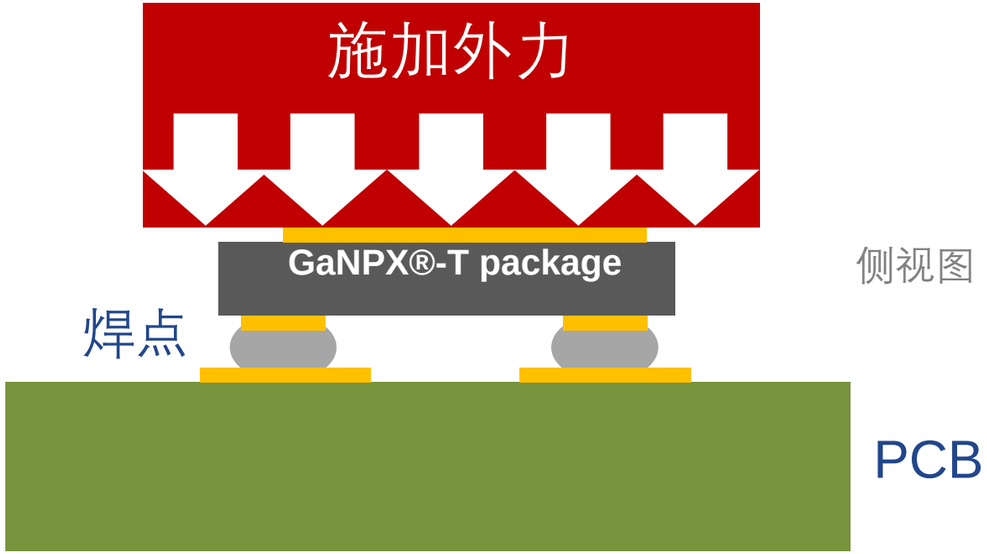


俯视图



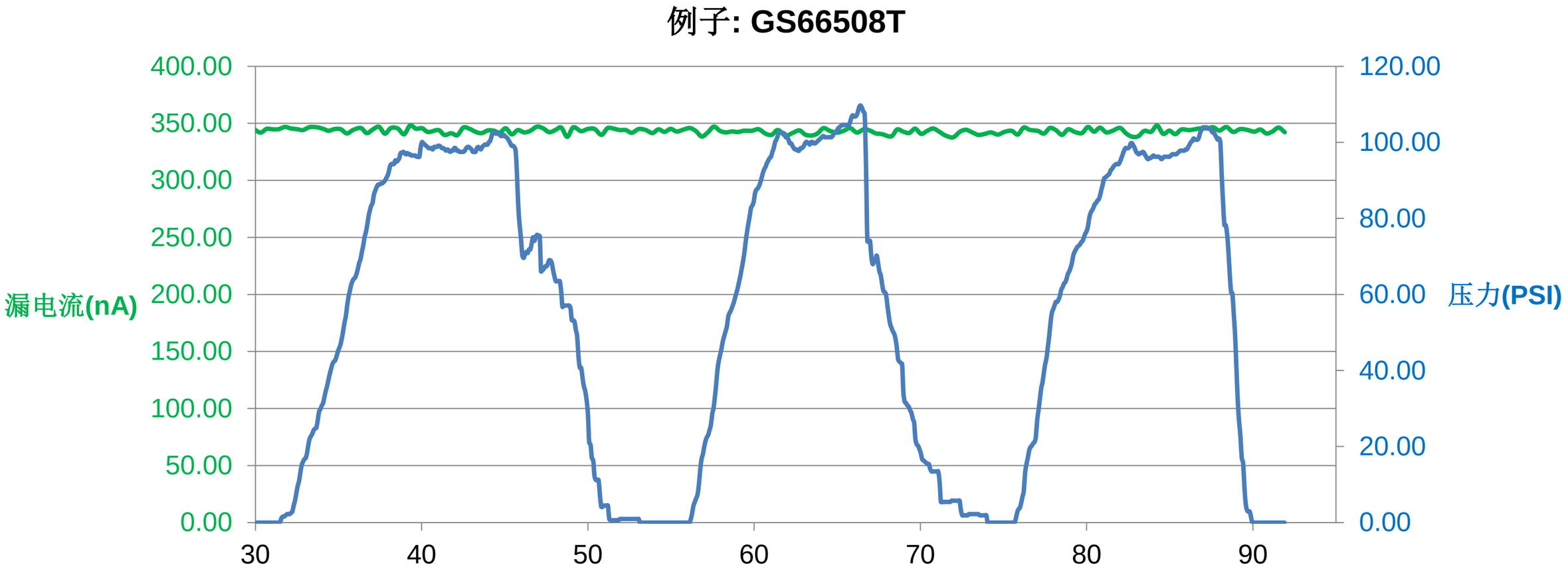
侧视图

压力测试



侧视图

3. 顶部散热设计 – 弯曲度压力测试方式



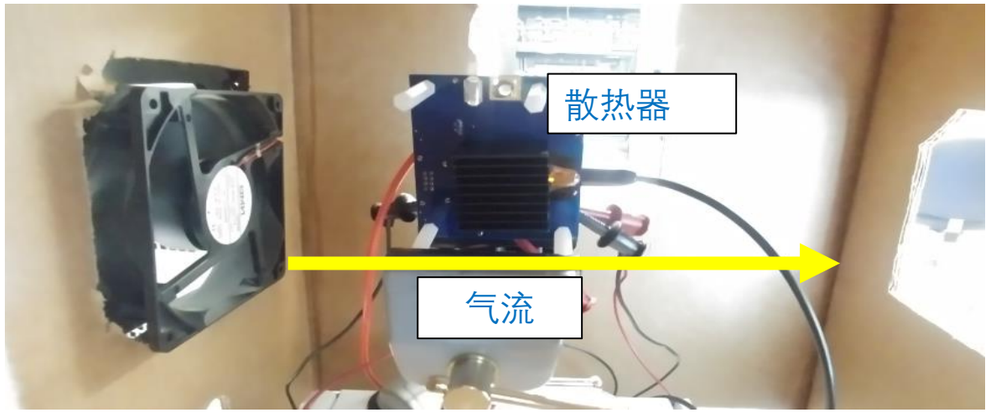
超过3个脉冲的100 PSI应力被施加于DUT, 漏电流没有漂移

每个DUT的V_{DS}为400V (@ 25˚C)

漏电流= I_{DSS} + I_{GS} + I_{BULK}* (*衬底)

3. 顶部散热设计 – 热阻测量

1. GS66516T测量出的$R_{\theta JHS}$和$R_{\theta JA}$ 分别为3 °C/W和4.2 °C/W。
2. GS66516T 每个器件可以散掉29W的损耗。

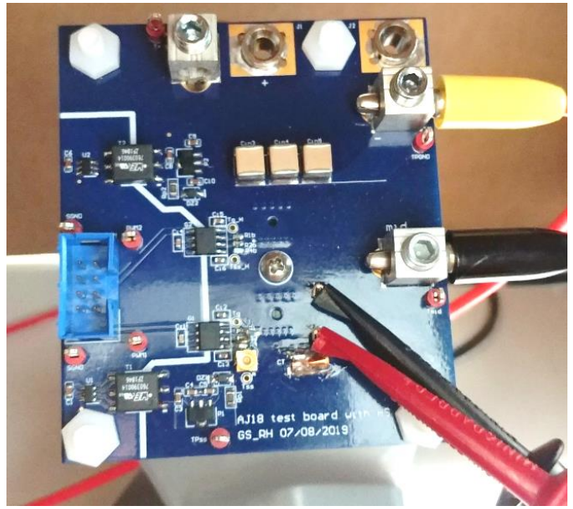


装置盒子的内部图

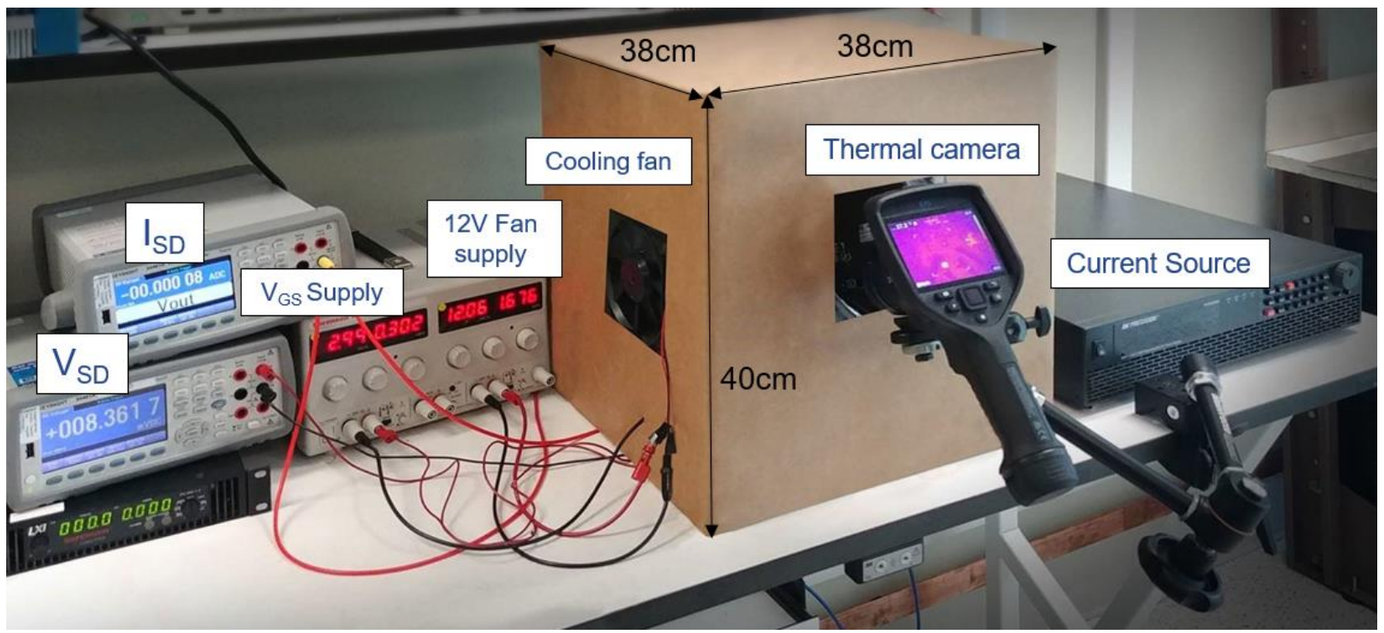
散热器尺寸:
3.4x3.4x2.5 cm³

风扇风速:
3.3 m³/min

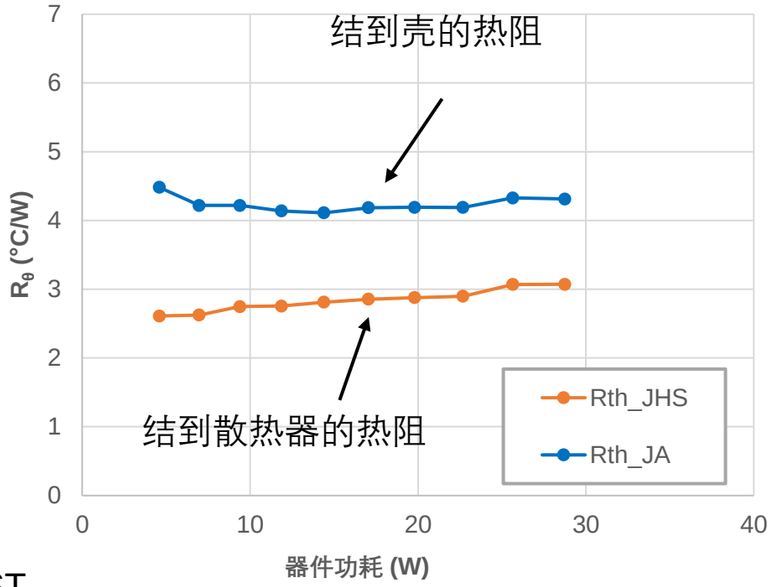
TIM: Sil-Pad 1500ST

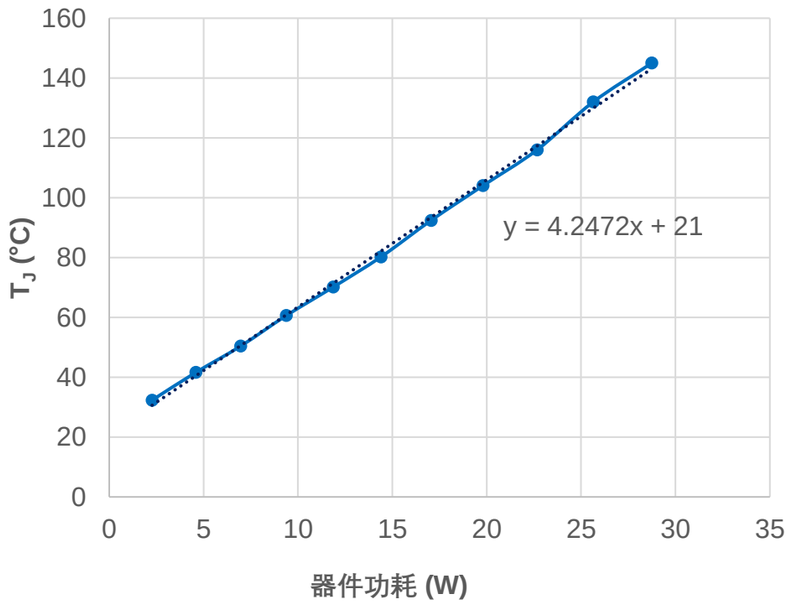


用于测试的GS66516T评估板



顶部散热，强制对流的热阻测试环境





应用手册内容

1. 动力: 控制器件温度的重要性

2. 功耗以及散热基础的介绍

3. 顶部散热器件的热设计考量

4. 底部散热器件的热设计考量

4.1 FR4 PCB 底部散热设计

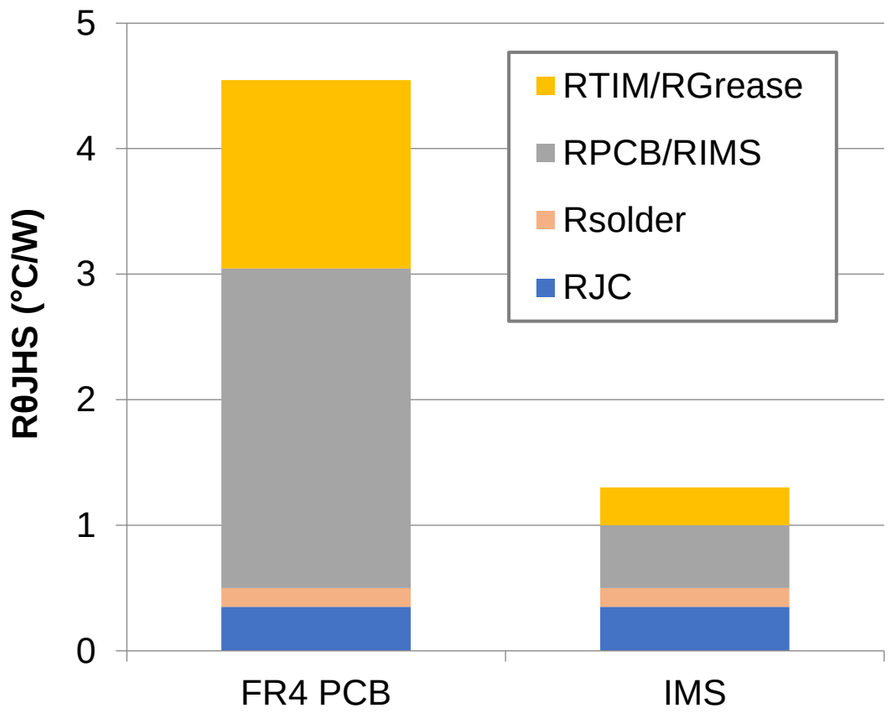
4.2 IMS 底部散热设计

5. 基于热的考虑来选择器件

6. 功耗以及热模型

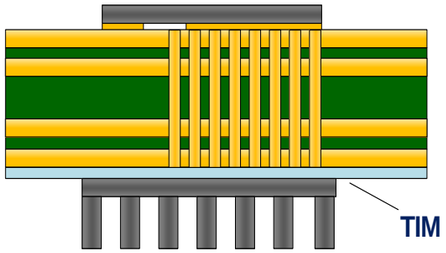
4. 底部散热器件的散热设计

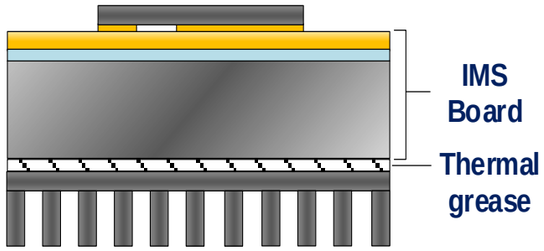
底部散热器件的散热方案概览



GS66516B的结到散热器热阻比较($R_{\theta JHS}$)

FR4 PCB以及IMS都是底部散热的合适方案。用户可以取舍选择。





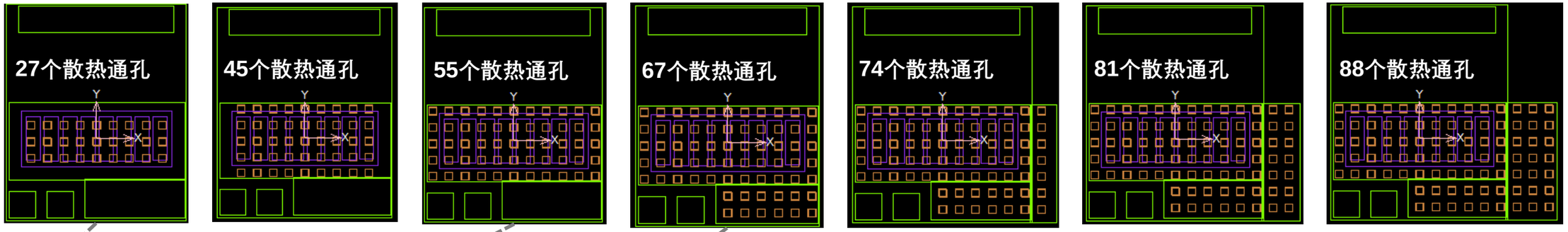
	FR4 PCB通过通孔散热	绝缘金属基板(IMS)
热阻	良好	最佳
电气绝缘	使用TIM	自身带有
成本	最低	低
优点	• 标准制程 • 布局灵活	• 电气隔离
设计难度	• PCB的热阻高	• 通常仅有一层布局 • 有寄生电感 • 金属基板有耦合电容

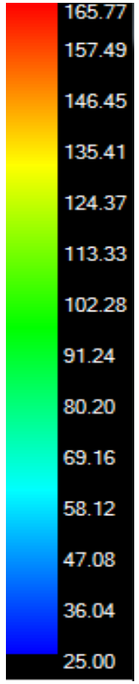
底部散热器件的两种热设计的性能比较

4.1. FR4 PCB底部散热设计 – PCB的散热设计

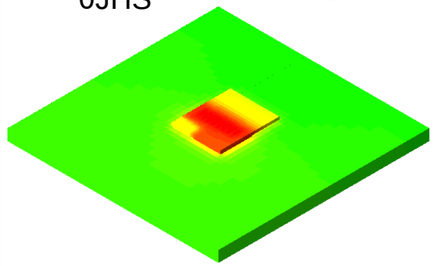
散热通孔设计例子

- GS66508B的器件功耗为10 W。4层板，铜厚为2 oz (70 µm)。T_{HS} = 25 °C
- 散热通孔设置: 直径为0.3 mm, 外圈为0.64 mm；标准的25 µm 铺铜厚度；不填充通孔。



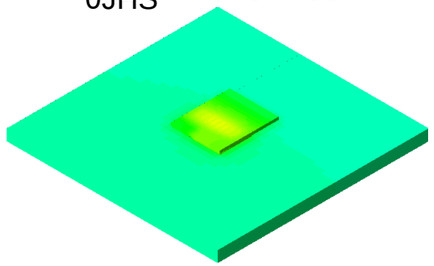


$R_{\theta JHS}$ = 14.1 °C/W



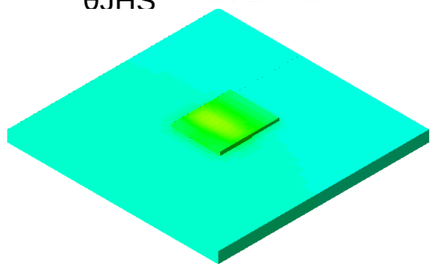
27个散热通孔

$R_{\theta JHS}$ = 8.8 °C/W



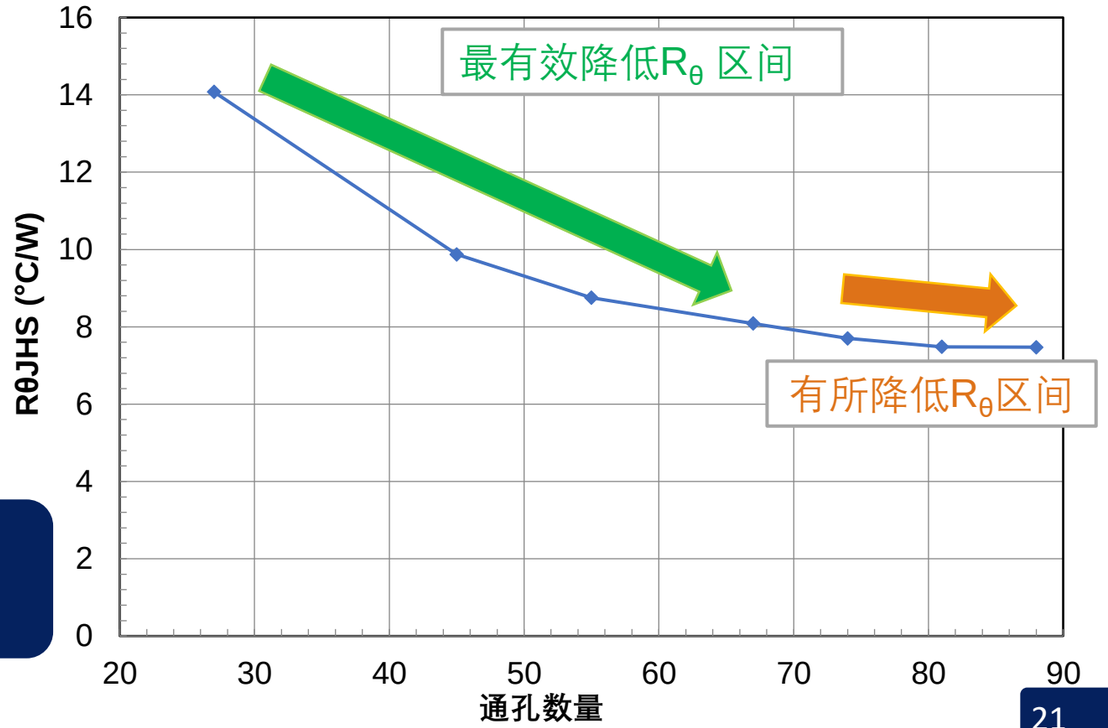
55个散热通孔

$R_{\theta JHS}$ = 8.1 °C/W



67个散热通孔

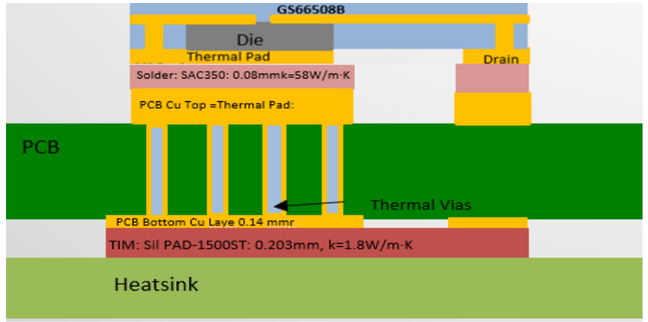
- 散热通孔完全放置于器件焊盘底下，以使来效果最优化
- 可根据PCB的设计面积展开散热通孔的区域



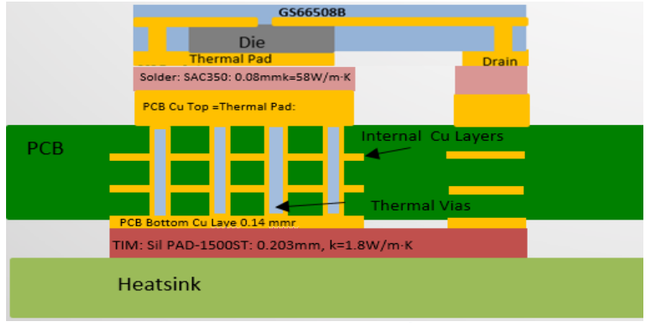
4.1. FR4 PCB底部散热设计 – PCB的散热设计

层数以及铜厚例子

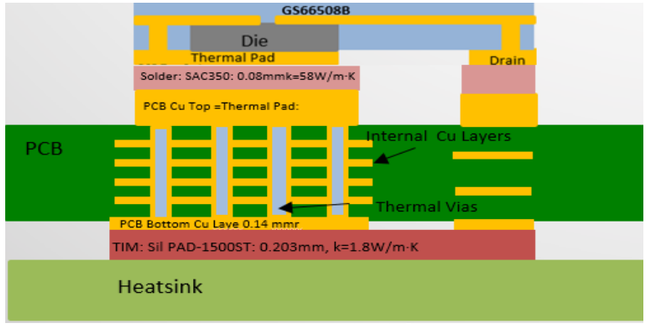
- GS66508B的器件功耗为10 W。T_{HS} = 25 °C。PCB总厚度保持一致 (1.6mm)。
- 这里以55个散热通孔为例。



2层PCB设计

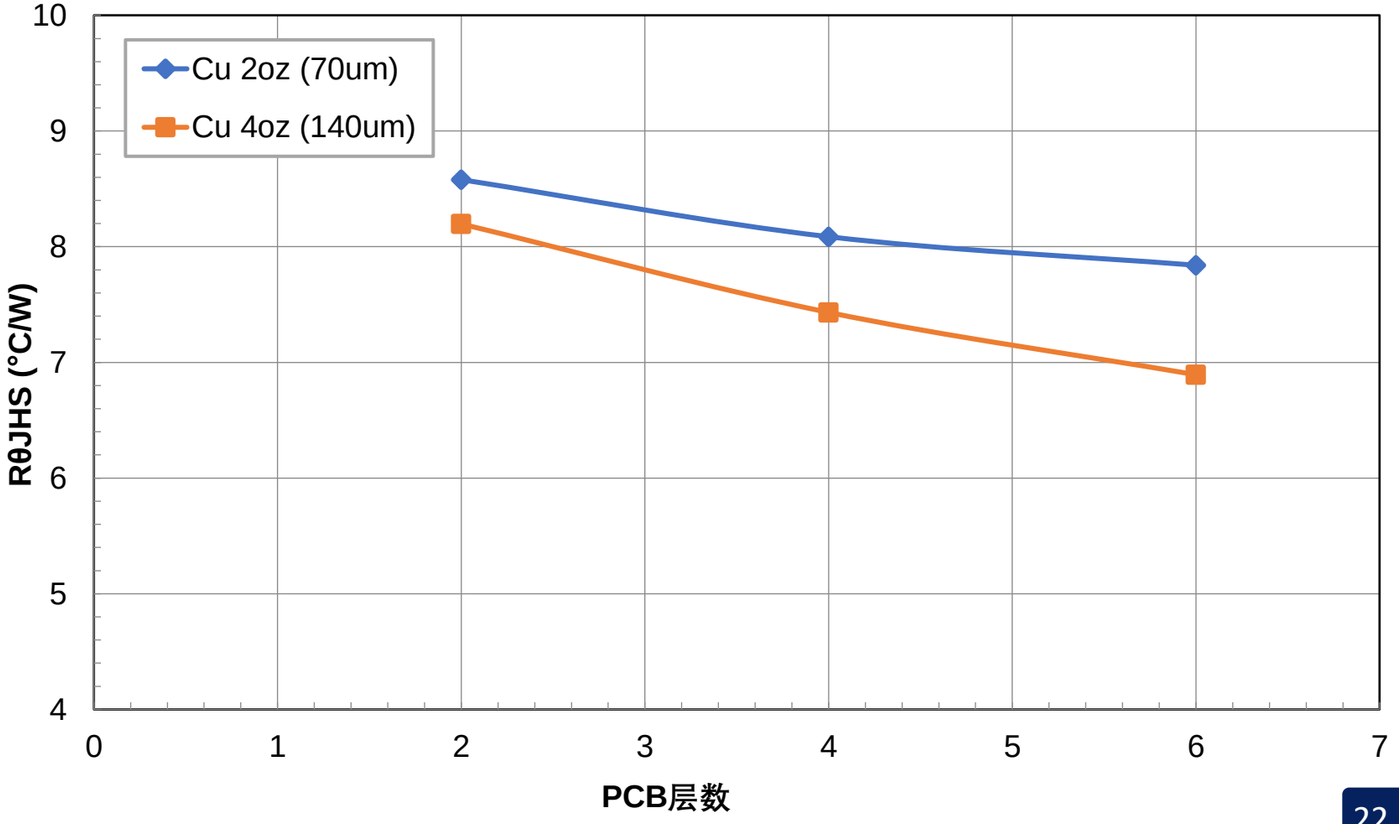


4层PCB设计



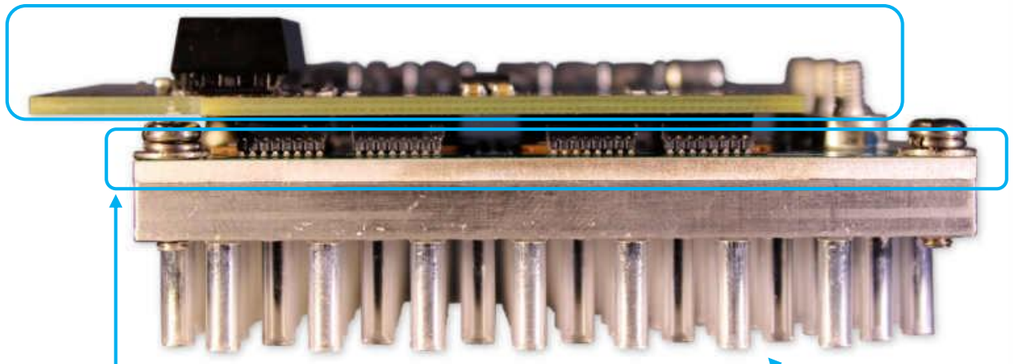
6层PCB设计

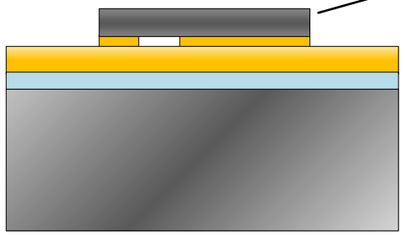
增加PCB层数和铜厚可以进一步降低R_θ, 但需考虑PCB成本。



4.2. IMS 底部散热设计

IMS设计的侧视图





SMT Power Package

Copper Foil:
- Typ. 1-4oz (35-140um) up to 10oz

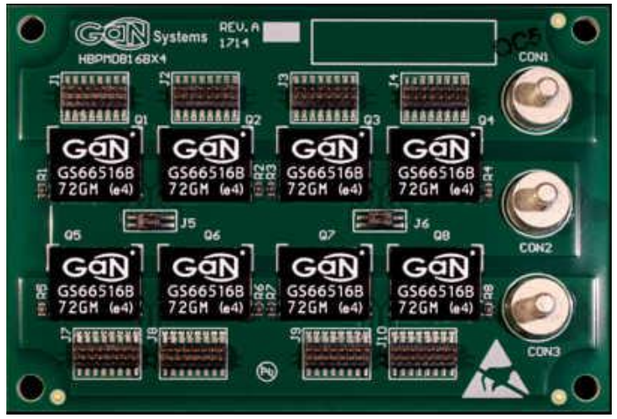
Dielectric Layer:
- Electrical insulation
- Typ. 30-200um thickness
- Thermal conductivity: 1-3W/mK

Metal Substrate/Base
- Electrically isolated
- Aluminum or copper

在大功率场合，IMS可以提高功率密度。

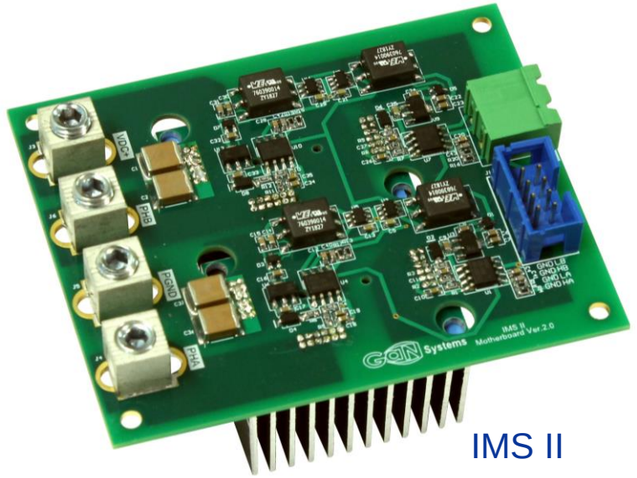
IMS I
- 用于大功率场合 (3~12kW).
- 所用GaN HEMT:单颗GS66516B, 或者2或4颗并联

IMS I



半桥(650V/240A, 6mΩ)

IMS II
- 紧凑设计，用于中等功率场合(1~3kW).
- 所用GaN HEMT: 单颗GS66508B or GS66516B



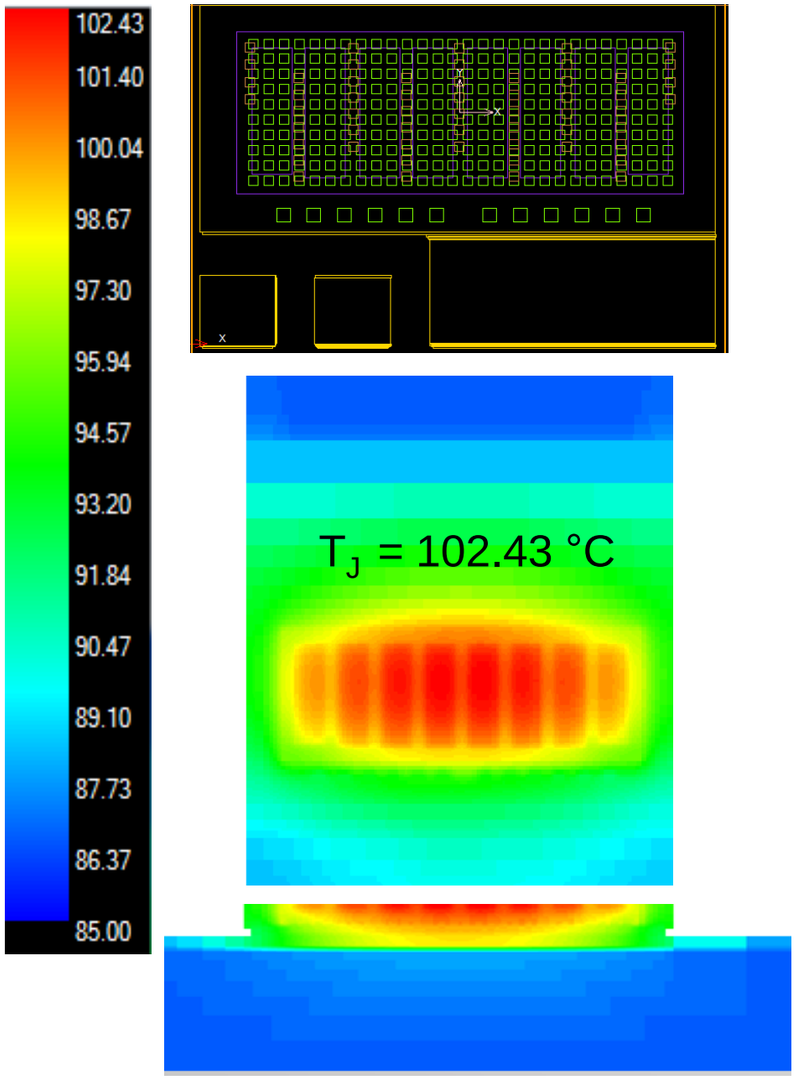
IMS II

半桥(650V/30A, 50mΩ)

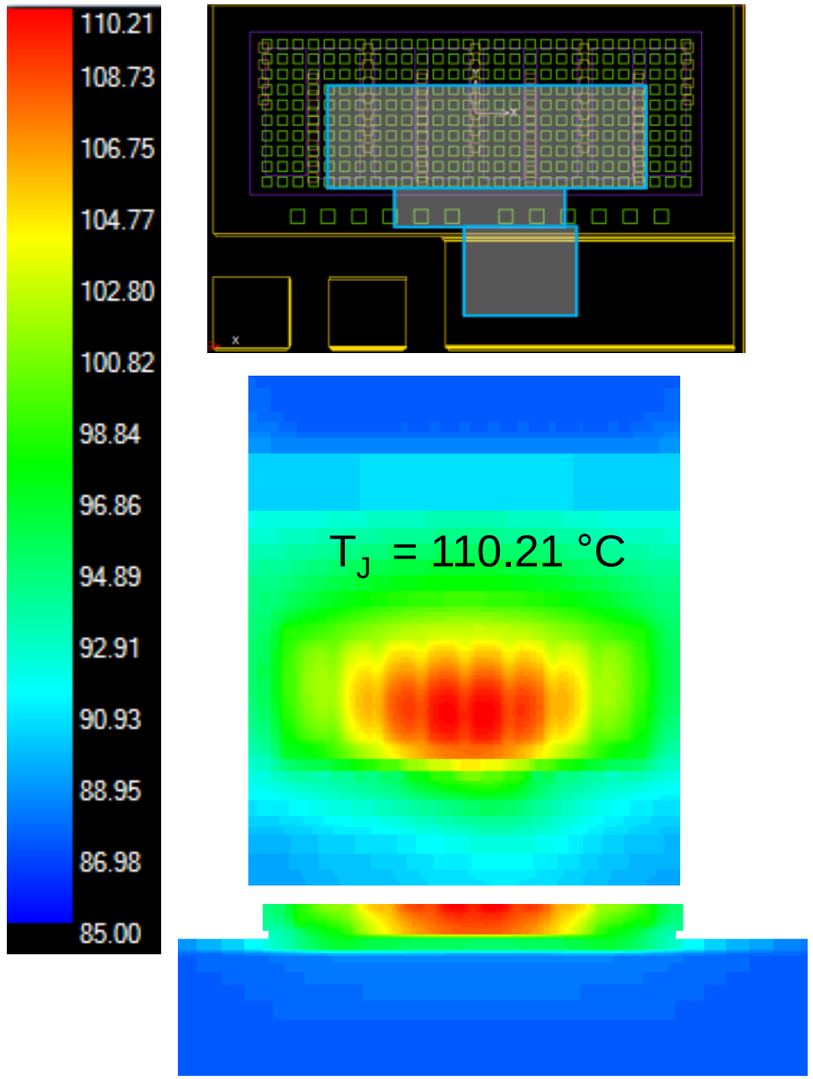
4.2. IMS 底部散热设计 – 焊接空洞考量

工作条件: P = 7.98 W, T_{IMS} = 85 °C, 使用GS66508B

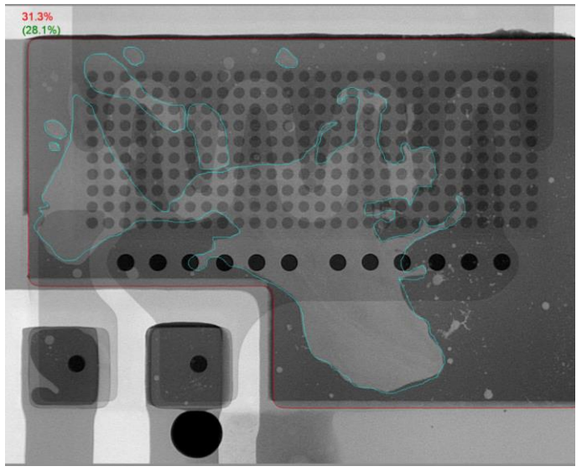
器件下无空洞: $R_{\theta JIMS}$= 2.18 °C/W



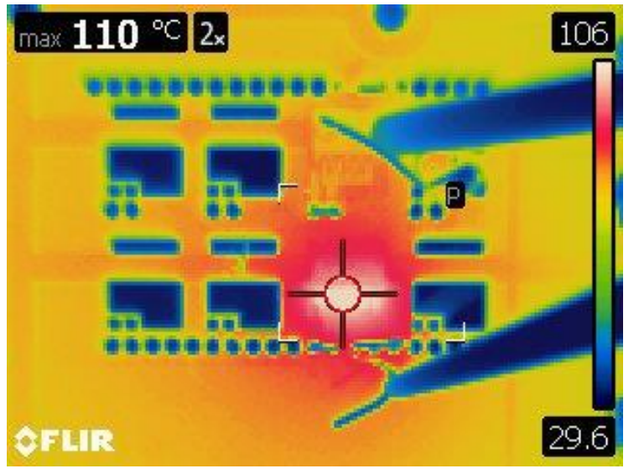
器件下有32 %空洞: $R_{\theta JIMS}$ = 3.16 °C/W



测量和镭射照片



有空洞器件的镭射照片

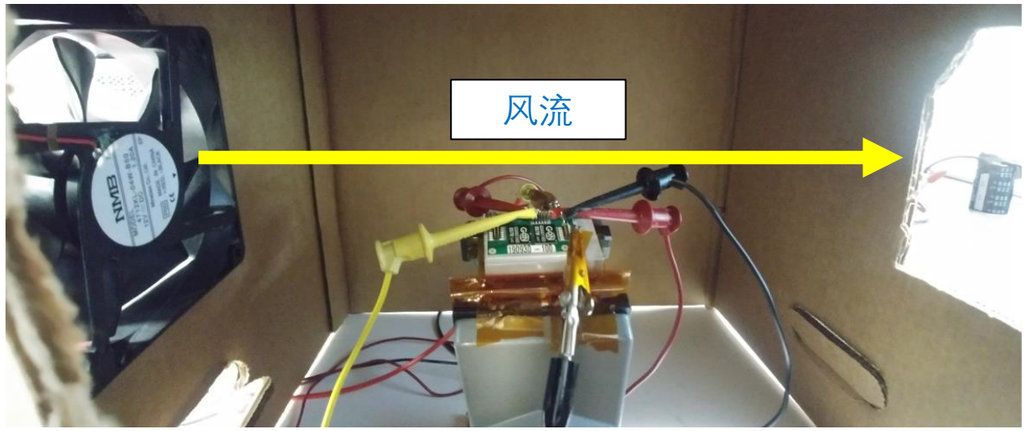


有空洞器件的实验结果

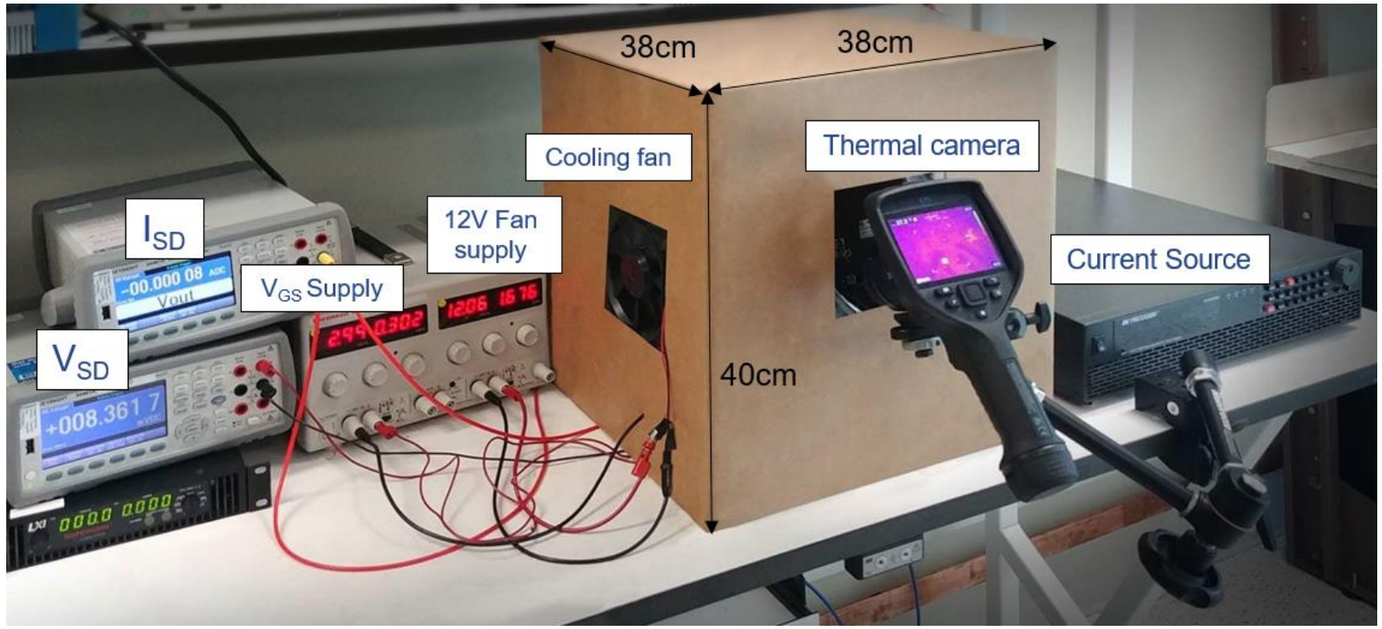
减少空洞来达到最佳的IMS散热性能

4.2. IMS底部散热设计 – 热阻测量

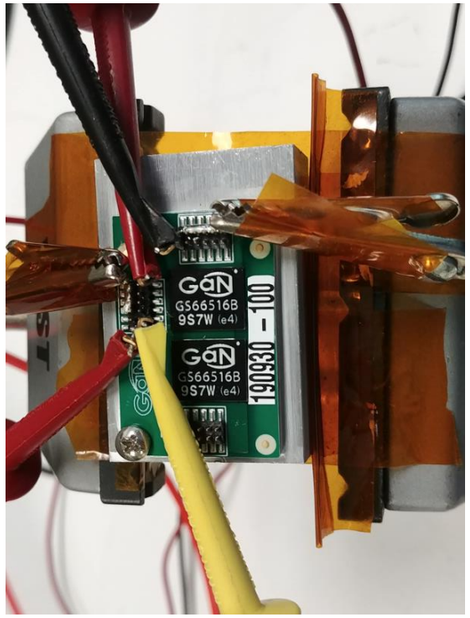
1. 基于GS66516B的IMS的热阻$R_{\theta JA}$为2.9 °C/W。
2. 每个GS66516B可以散掉43 W 功耗。



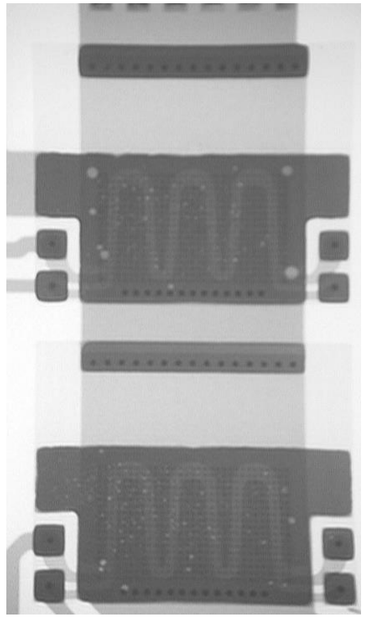
装置盒子内部图



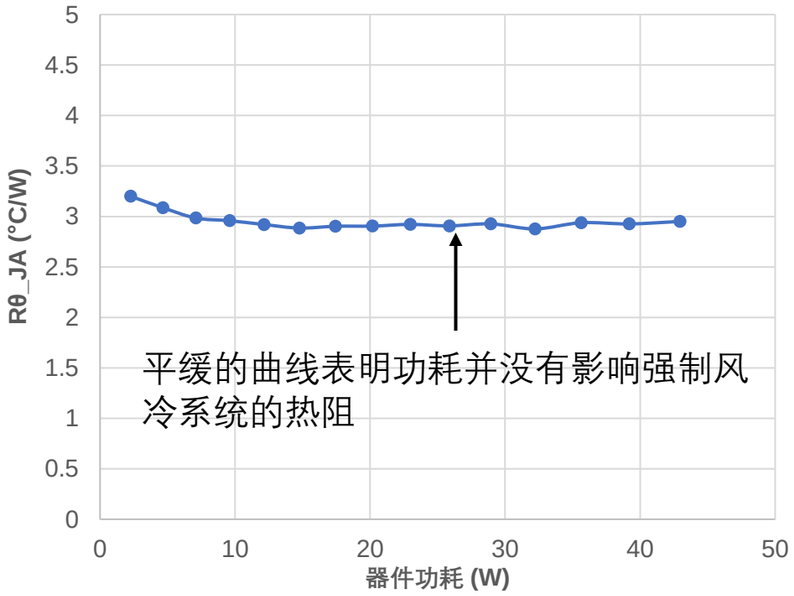
IMS强迫对流下热阻的测试环境

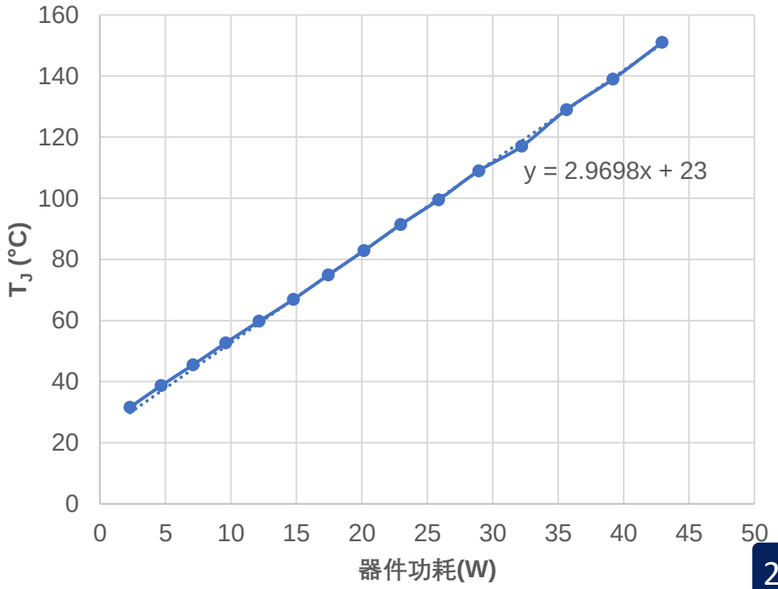


测试的GS66516B IMS



最少的焊接空洞





应用手册内容

1. 动力: 控制器件温度的重要性
2. 功耗以及散热基础的介绍
3. 顶部散热器件的热设计考量
4. 底部散热器件的热设计考量
5. **基于热的考虑来选择器件**
6. 功耗以及热模型

5. 基于热的考虑来选择器件 – 单颗器件

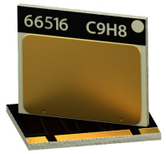
*$R_{\theta HSA}$ =1.25 °C/W
3.4x3.4x2.5 cm³

**$R_{\theta HSA}$ =1.5 °C/W
4.6x3.0x1.4 cm³

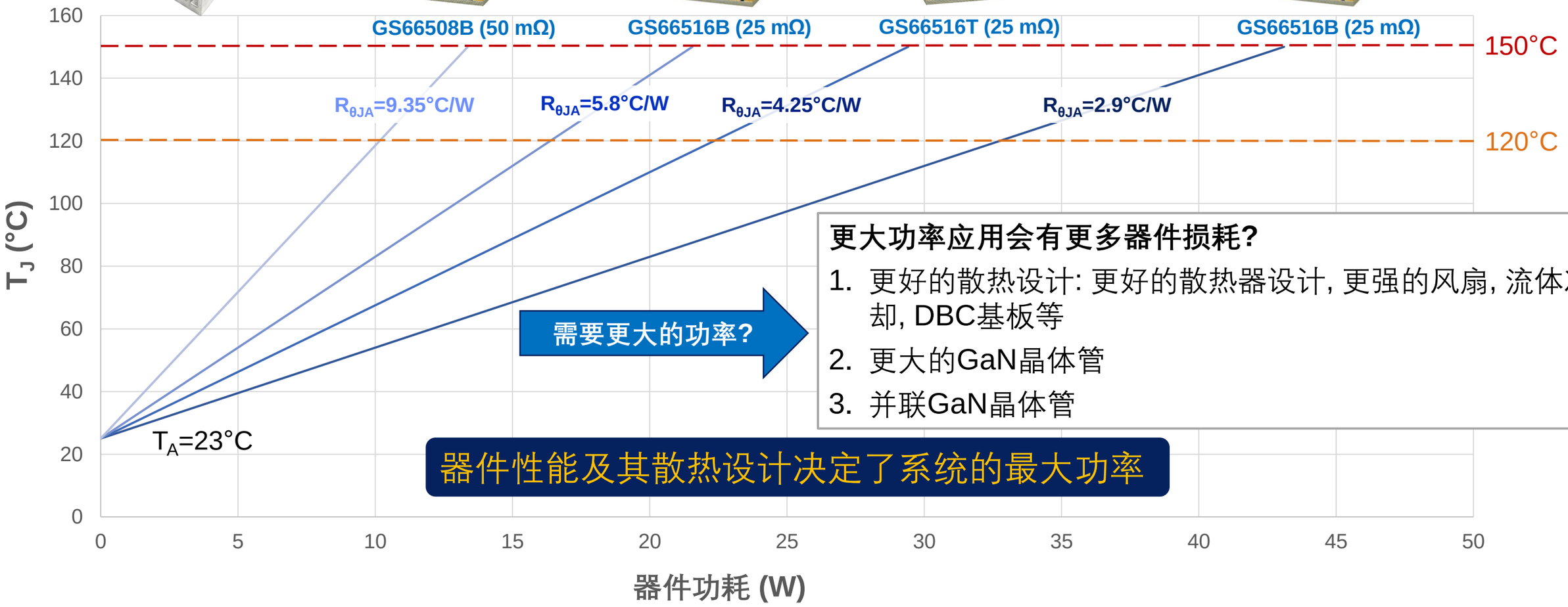
FR4 PCB ($R_{\theta HSA}$=1.25°C/W*)

FR4 PCB ($R_{\theta HSA}$ =1.25°C/W*)

Top-cool ($R_{\theta HSA}$ =1.25°C/W*)



IMS ($R_{\theta HSA}$ =1.5°C/W)**



需要更大的功率?

更大功率应用会有更多器件损耗?

1. 更好的散热设计: 更好的散热器设计, 更强的风扇, 流体冷却, DBC基板等
2. 更大的GaN晶体管
3. 并联GaN晶体管

器件性能及其散热设计决定了系统的最大功率

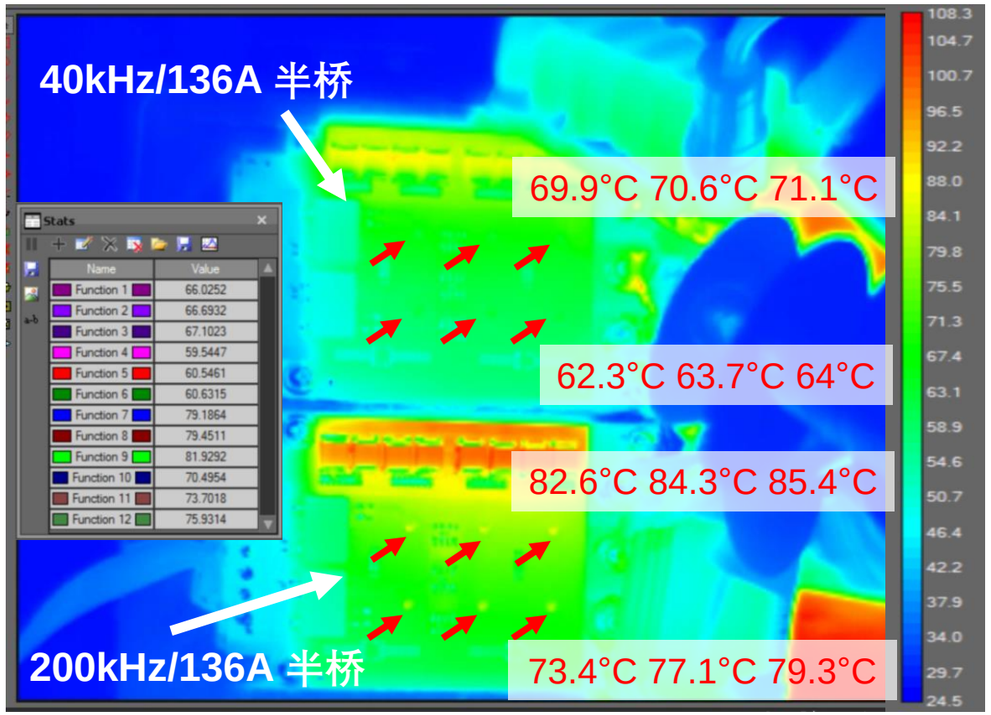
在不同冷却方式下，测量的器件功耗跟T_J 的关系 – 单颗器件方案

5.2 通过并联来提高散热性能

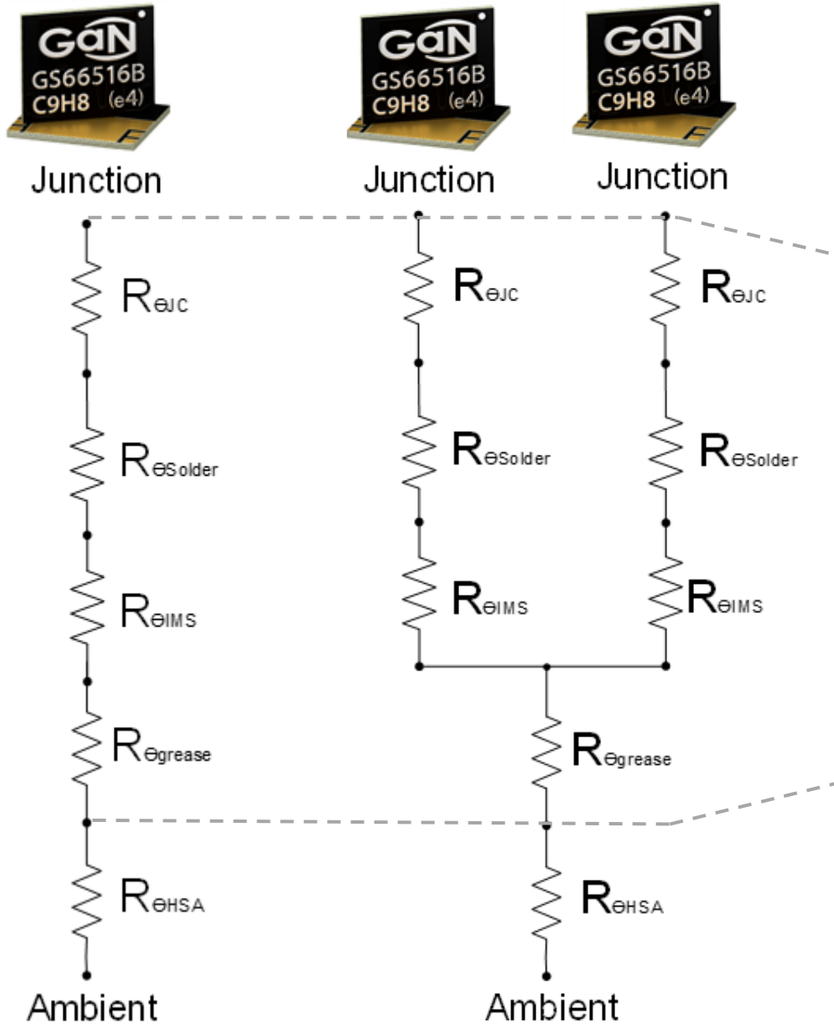
实验证明并联GaN可以提高系统功率

例子:

- 在硬开关情况下，4颗GS66516B并联可以均流136A 负载电流
- 器件都是随机选取的
- 最恶劣情况下，T_J 温差小于 < 6 °C

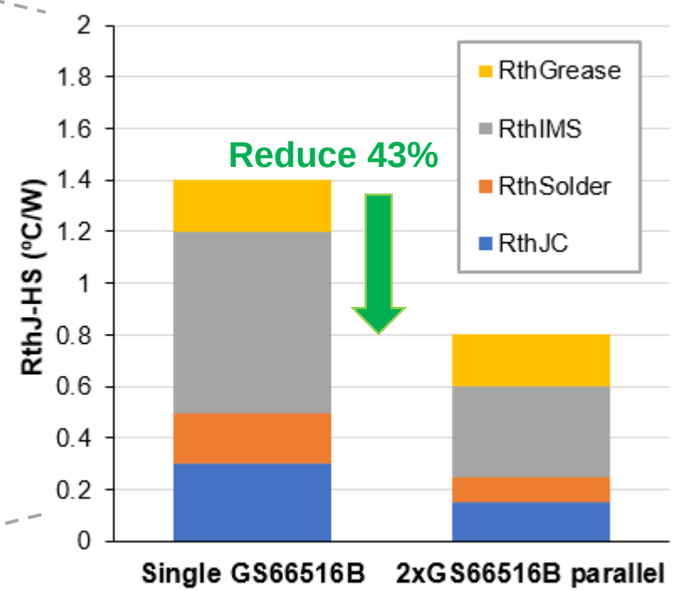


并联应用同时降低系统的$R_{DS(on)}$ (电气) 以及 R_θ (热)



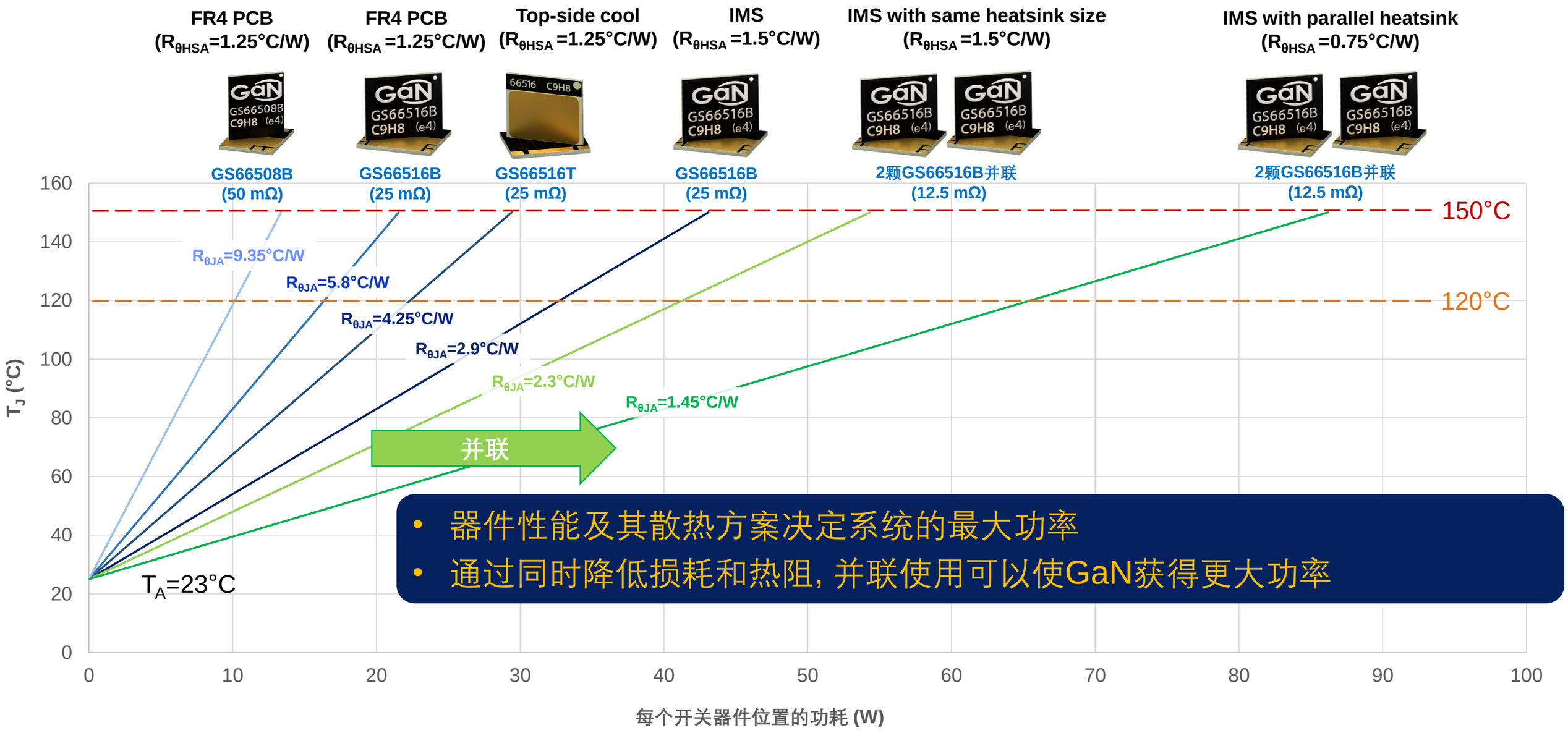
单颗GS66516B的热阻网络

两颗GS66516B并联的热阻网络



结到散热器的热阻网络对比

5. 基于散热考虑来选择器件 – 包括并联



- 器件性能及其散热方案决定系统的最大功率
- 通过同时降低损耗和热阻，并联使用可以使GaN获得更大功率

在不同冷却方式下（包括并联方案），器件损耗与T_J 的关系

应用手册内容

1. 动力: 控制器件温度的重要性
2. 功耗以及散热基础的介绍
3. 顶部散热器件的热设计考量
4. 底部散热器件的热设计考量
5. 基于热的考虑来选择器件
6. **功耗以及热模型**

   6.1 SPICE 模型

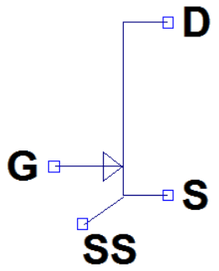
   6.2 PLECS 模型

6.1. SPICE 模型

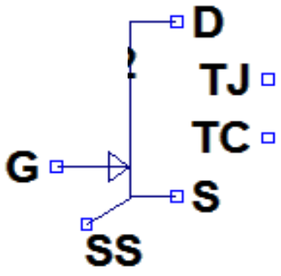
GaN Systems提供两级SPICE模型，热仿真可使用L3模型。

模型级别定义

后缀	级别	引脚	描述
_L1	1	G, D, S, SS (如果有的话)	系统/变换器级别电路的一般电气性能仿真，着重于仿真速度。
_L3	3	G, D, S, SS (如果有的话), Tc, Tj	在L1的基础上, L3同时包括热模型以及封装的寄生电感。



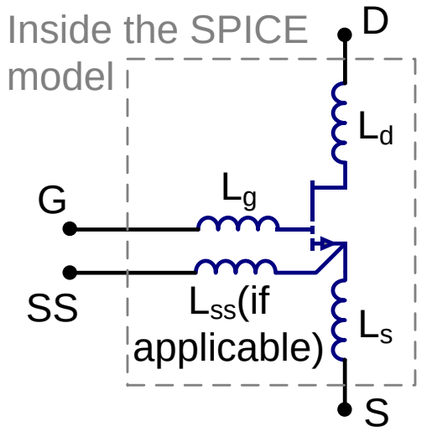
L1 器件符号



L3 器件符号

模型级别的功能

功能	Level 1	Level 3
随温度变化的IV性能	✓	✓
受电压影响的电容值	✓	✓
热模型	×	✓
封装的寄生电感	×	✓

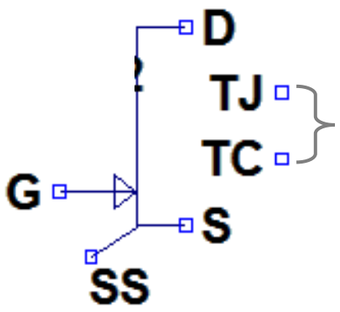


L3模型的内部寄生电感

6.1. SPICE 建模

结到壳的热阻建模

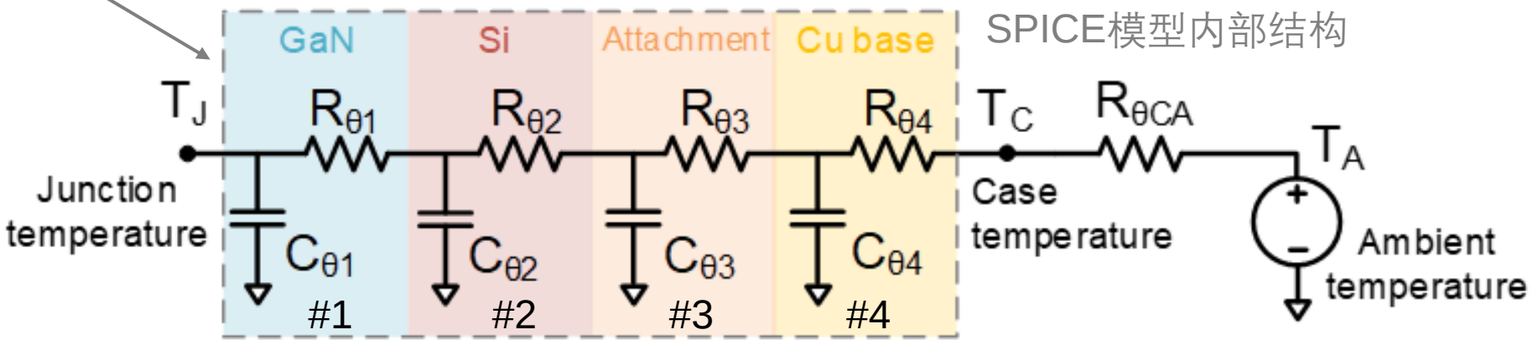
4级Cauer RC热模型，可以精确模拟器件性能



L3 器件符号

Cauer模型可用于结到壳热阻建模，原因如下:

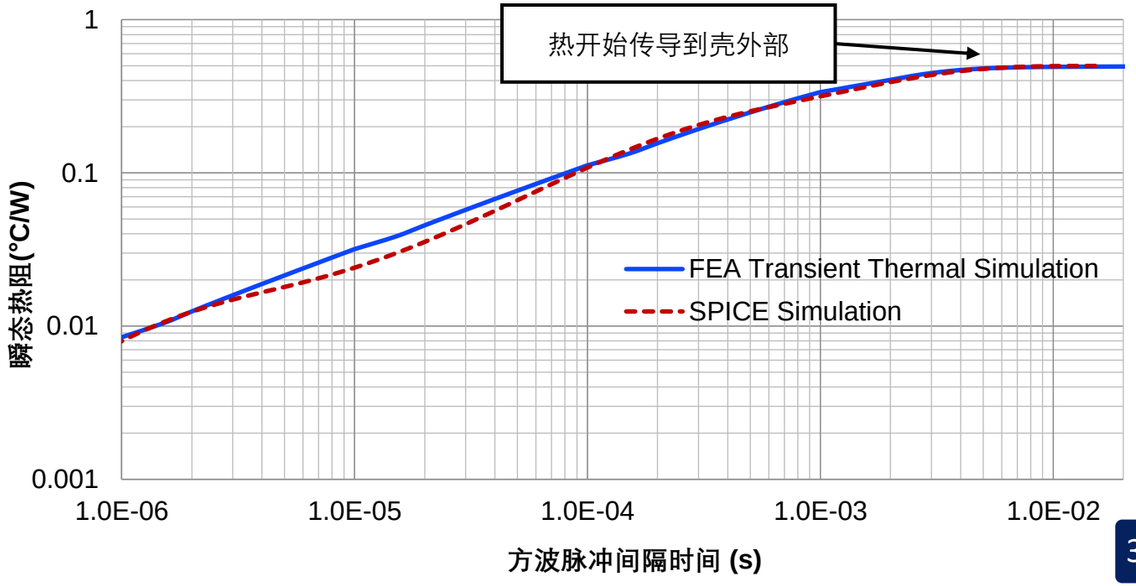
1. 不同于Foster模型 (曲线拟合模型), Cauer RC网络基于物理性能和封装结构
2. RC各要素分配于封装的各层



例子: GS66508B $R_{\theta JC}$ 建模

	R_θ (°C/W)	C_θ (W·s/°C)
#1	0.015	8.0E-05
#2	0.23	7.4E-04
#3	0.24	6.5E-03
#4	0.015	2.0E-03

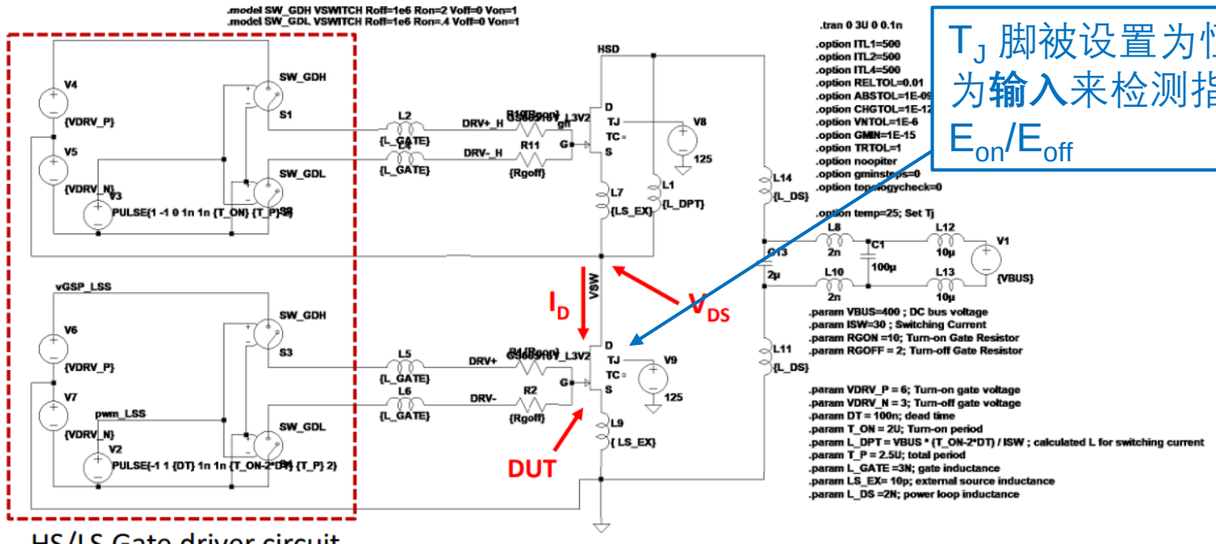
GS66508B Cauer RC模型参数



6.1. SPICE 建模

T_J 脚可作为输入或输出，取决于仿真目的

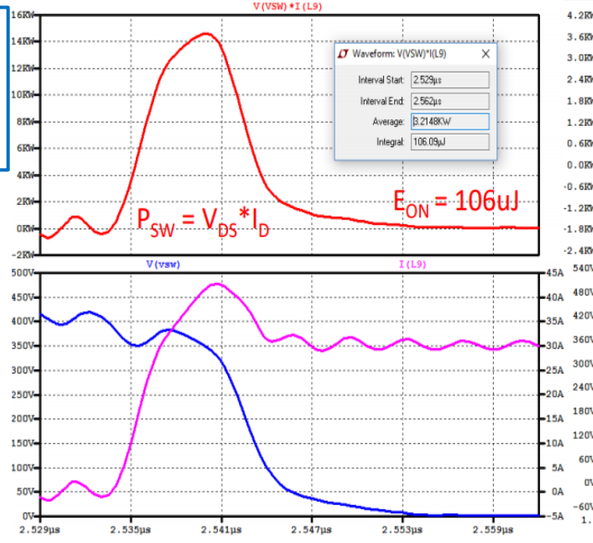
GAN SYSTEMS SWITCHING LOSS DOUBLE PULSE TEST BENCH



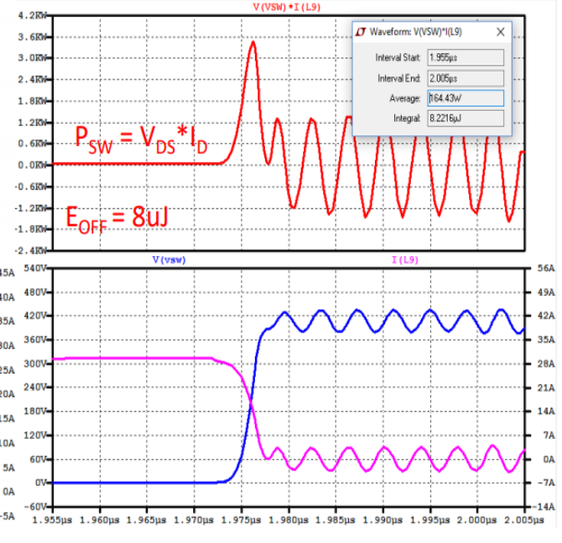
HS/LS Gate driver circuit

T_J 脚被设置为恒定值，作为**输入**来检测指定 T_J 下的 E_{on}/E_{off}

400V/30A Turn-on

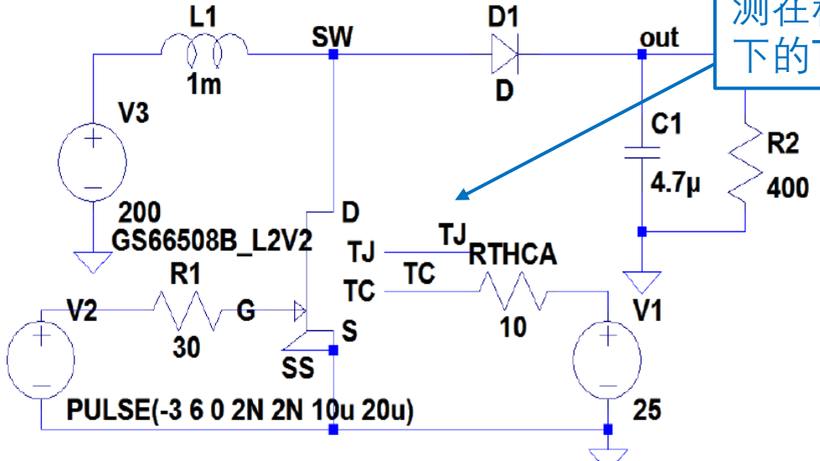


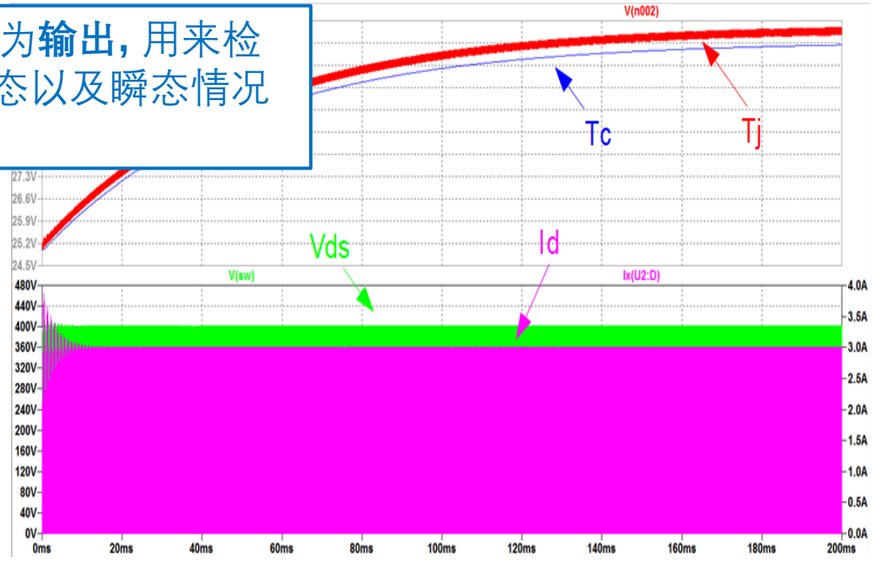
400V/30A Turn-off

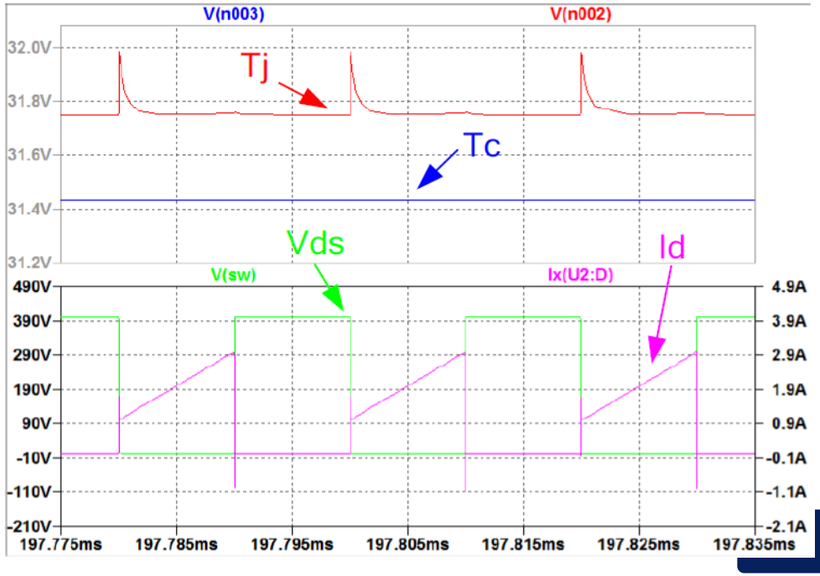


Continuous Converter Simulation

T_J 脚作为**输出**，用来检测在稳态以及瞬态情况下的T_J



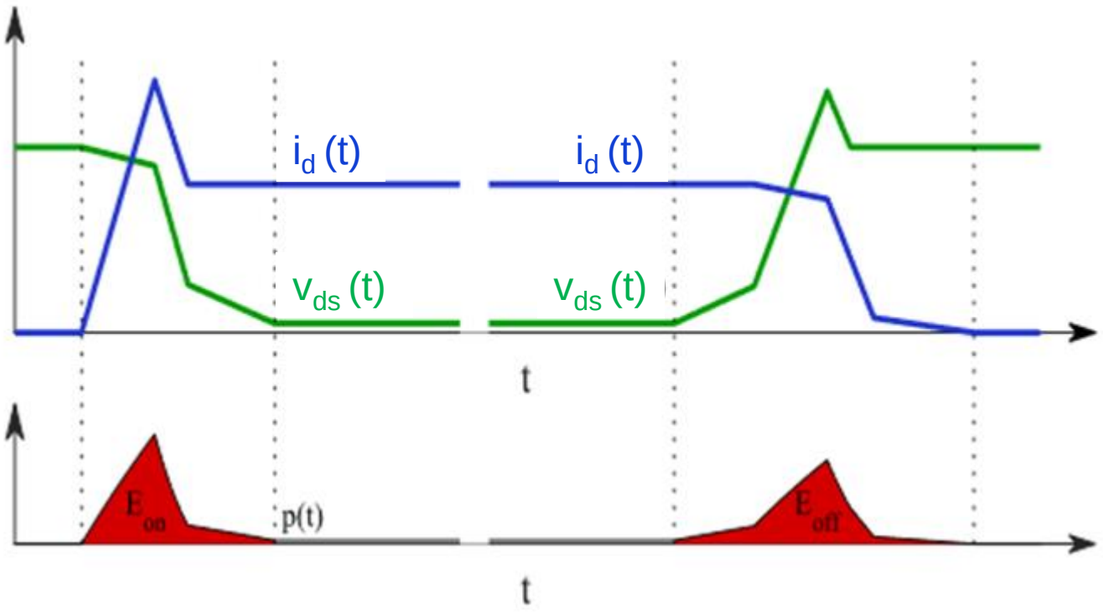




6.2. PLECS 建模

器件级仿真
(Ltspice 和 Pspice)

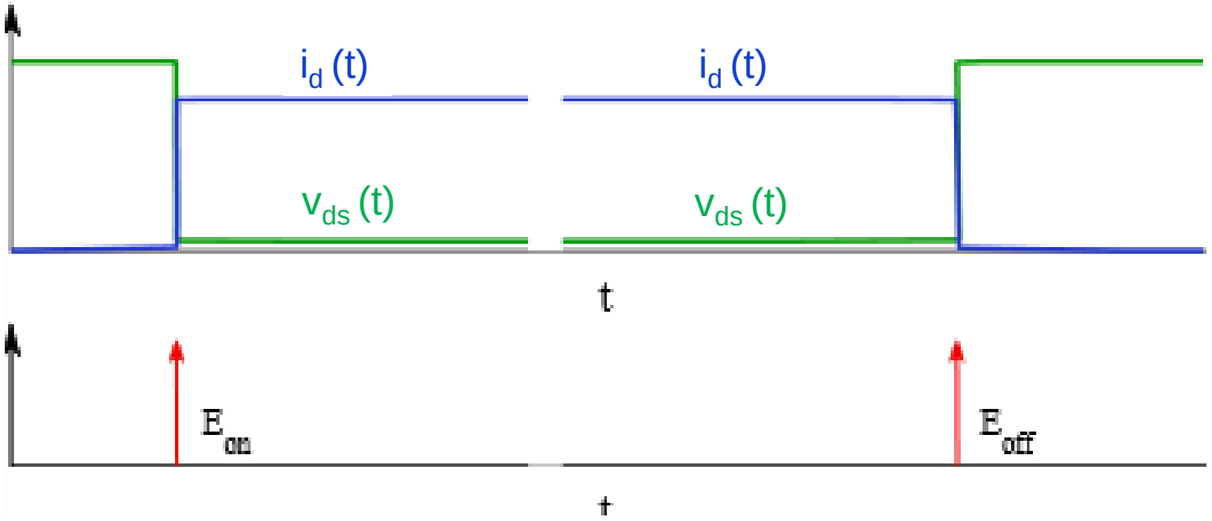
- 器件特性(Q_g, C_{oss}/C_{iss}, IV/CV curve, E_{on}/E_{off})
- 简单的系统仿真(双脉冲, Buck, Boost拓扑等)
- 可以得到寄生参数对开关性能的影响



SPICE硬开关时的开通瞬态波形以及损耗

变换器/系统级仿真
(PLECS)

- 简化开关瞬态工况
- 观察变换器工作波形
- 可以胜任复杂的由器件组建的系统级仿真/分析

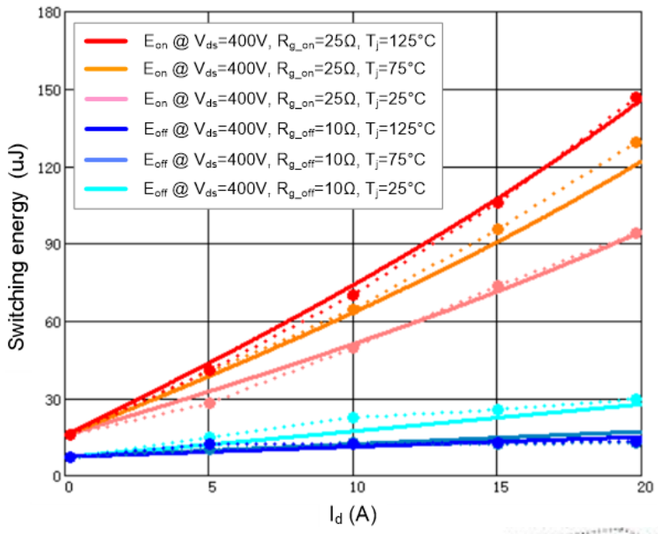


PLECS硬开关时的开通波形以及损耗

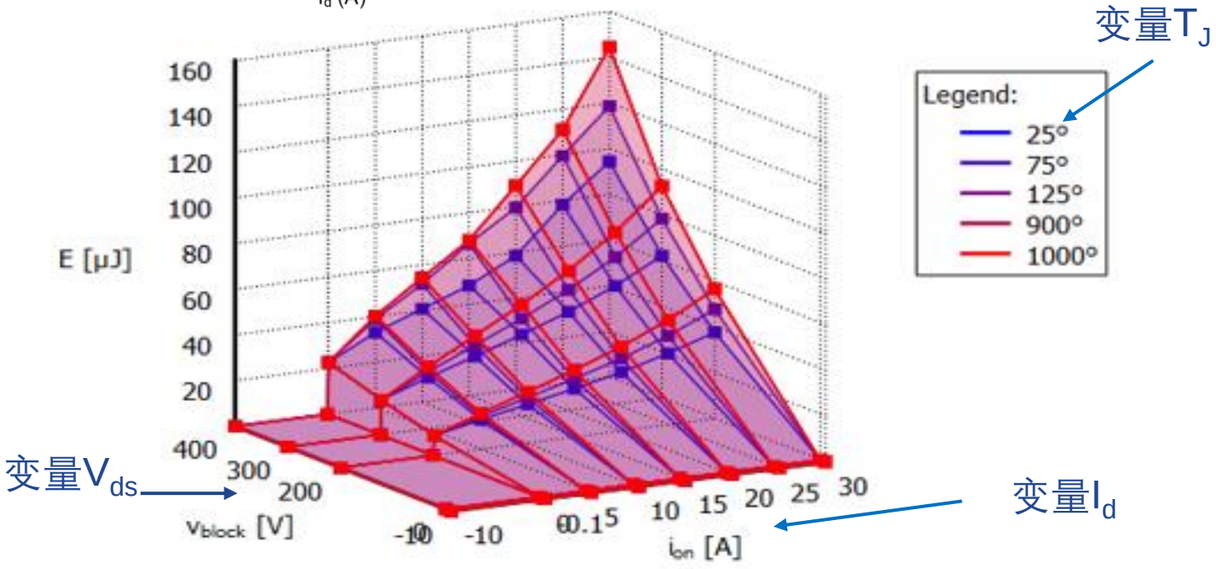
LTSPICE, PSPICE, 以及PLECS模型可以协助系统设计，优化系统性能

6.2. PLECS 建模

开关损耗建模



- GaN Systems开发了一种测量 E_{on}/E_{off} 的方法。
- 可以在不同T_J, V_{ds}, 和R_g的情况下测量E_{on}/E_{off} 数据。

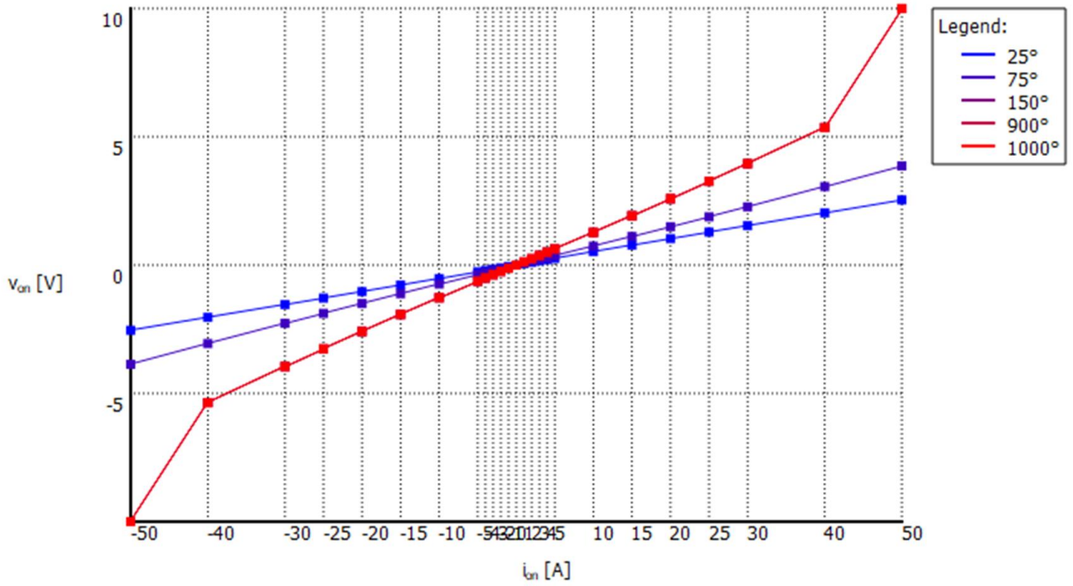


用PLECS建模的E_{on}

能耗随R_g变化公式:

E_{on}(v,i,T,E,Rgon,Rgoff,vgsoff,g) = ((Rgon-10)*(v*i)/2*(1.68e-9+2.2e-9*(i/24.4)/(1.3+i/24.4))/(6-1.3-i/24.4)+E)*g

导通损耗建模



死区损耗建模:

v_{on}(i,T,v,Rgon,Rgoff,vgsoff,g) = v-(i<0)*(1-g)*(1.3-vgsoff)

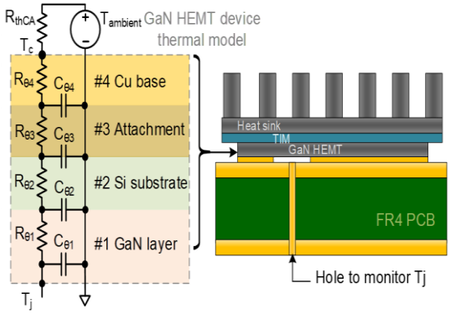
热建模(结到壳)

Manufacturer: GaN Systems

Part number: GS66508T

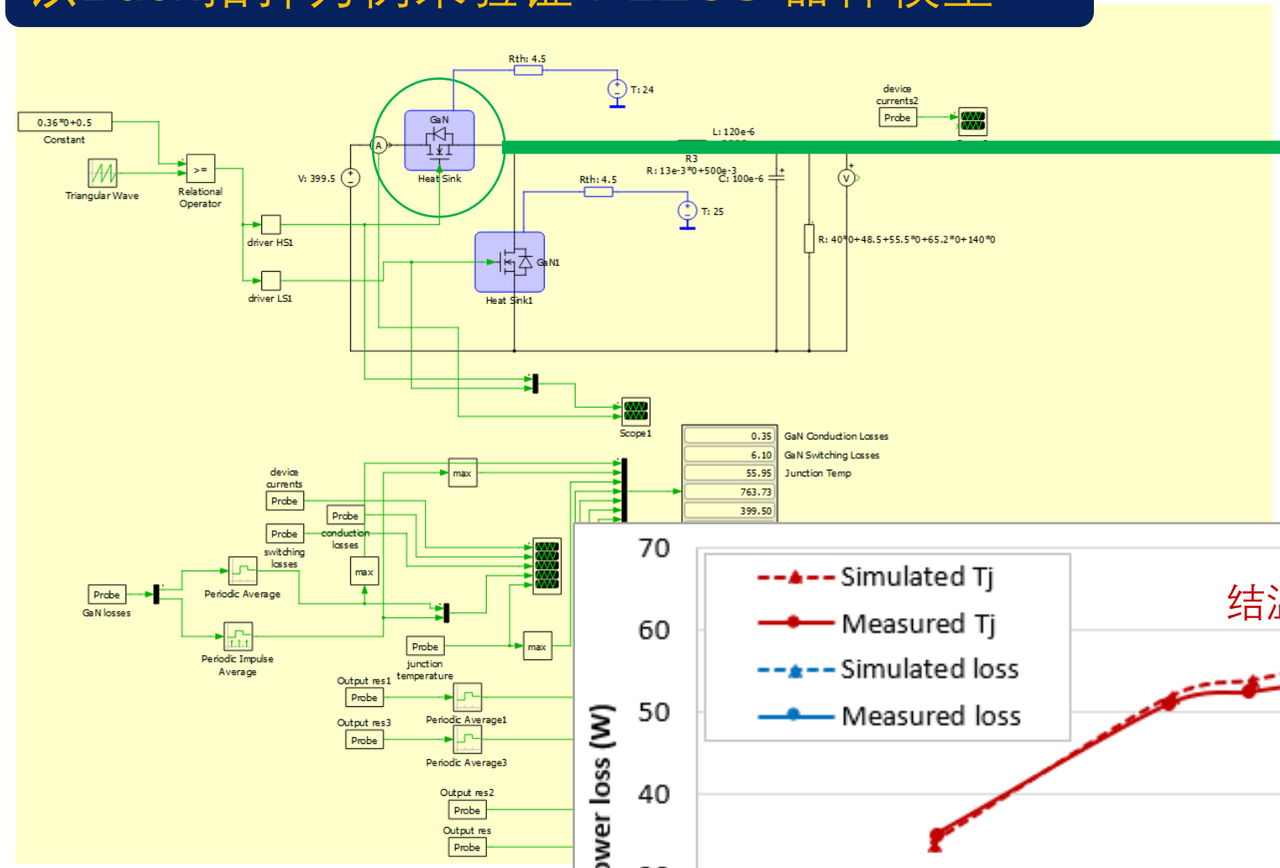
Turn-on loss | Turn-off loss | Conduction loss | Therm. impedance | Variables | Custom tables

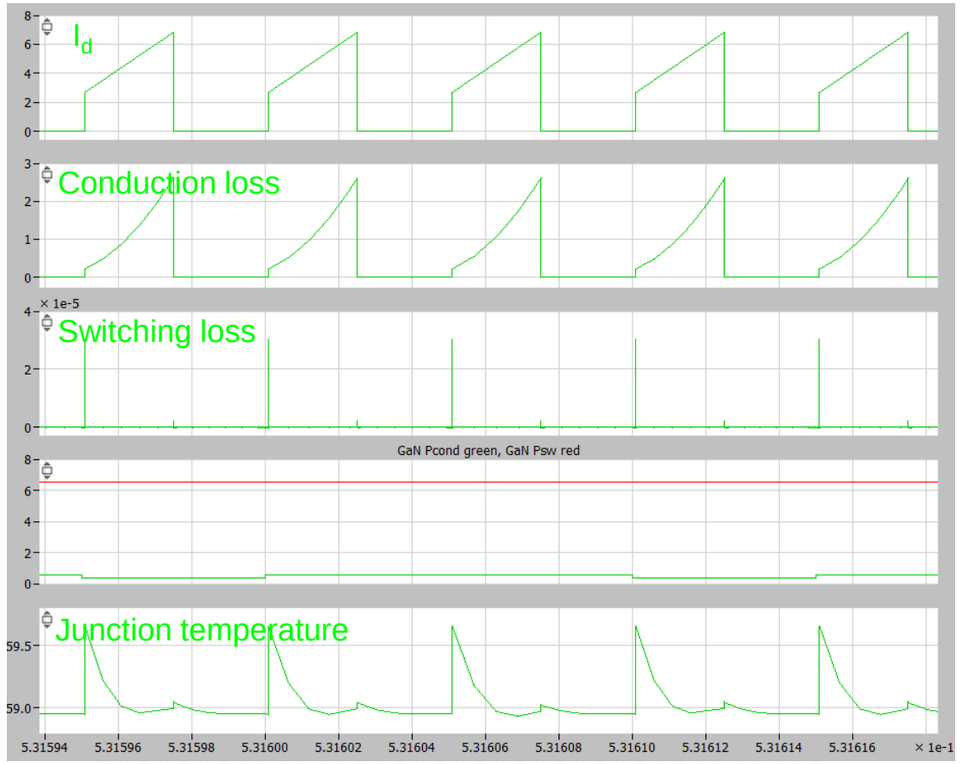
	1	2	3	4
R	0.011 K/W	0.231 K/W	0.237 K/W	0.021 K/W
C	4.25e-05 J/K	0.00296 J/K	0.000665 J/K	0.00101 J/K

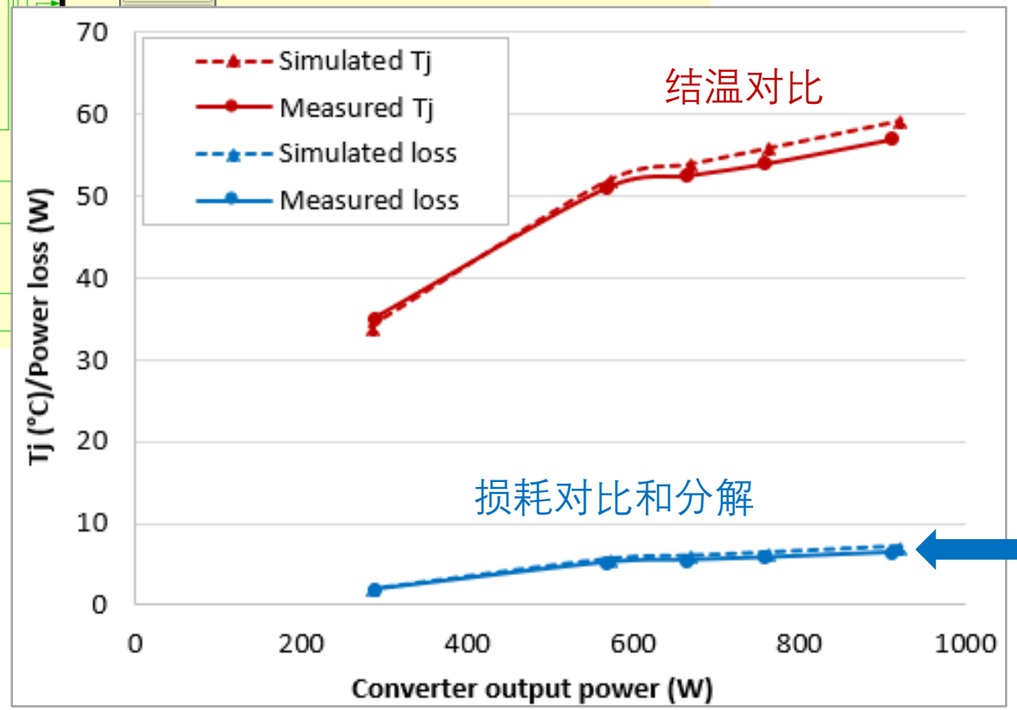


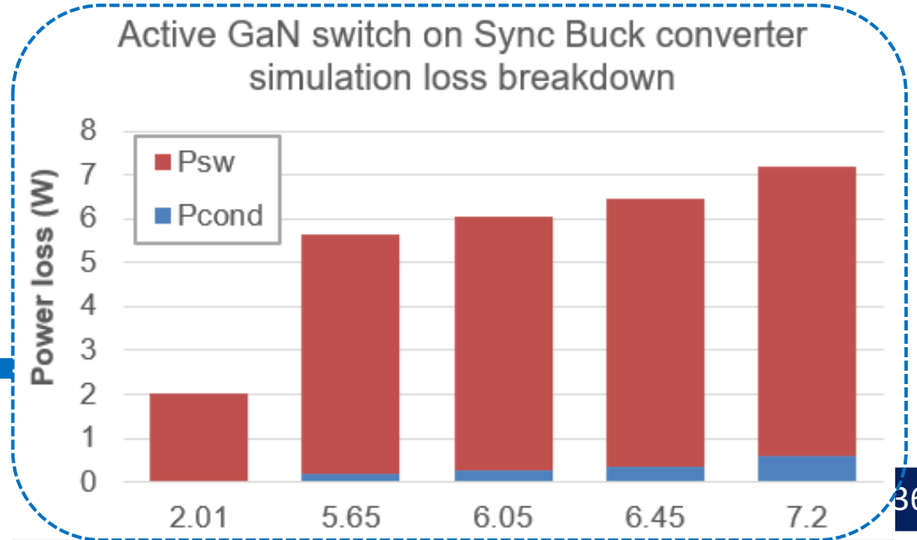
6.2. PLECS 建模验证

以Buck拓扑为例来验证 PLECS 器件模型









基于GS66508

F_{sw}=200 kHz,

V_{in}=400 V,

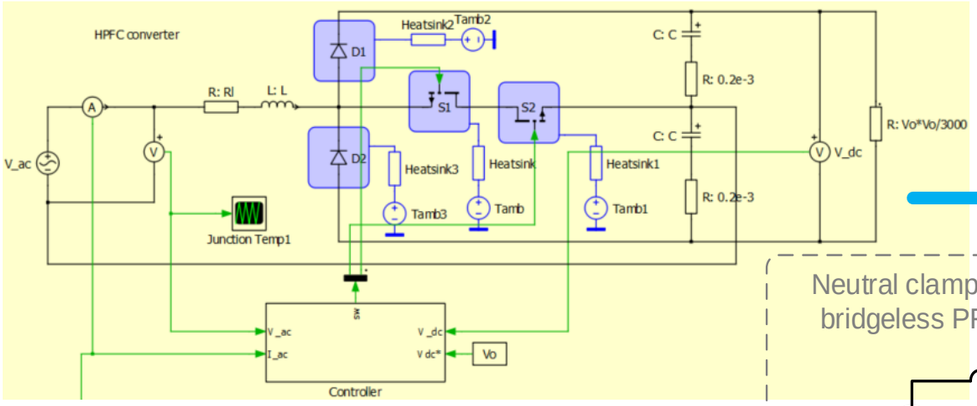
V_o=193 V

$R_{\theta CA}$=4.5 °C/W

6.2. PLECS 建模 – 系统损耗和热分析

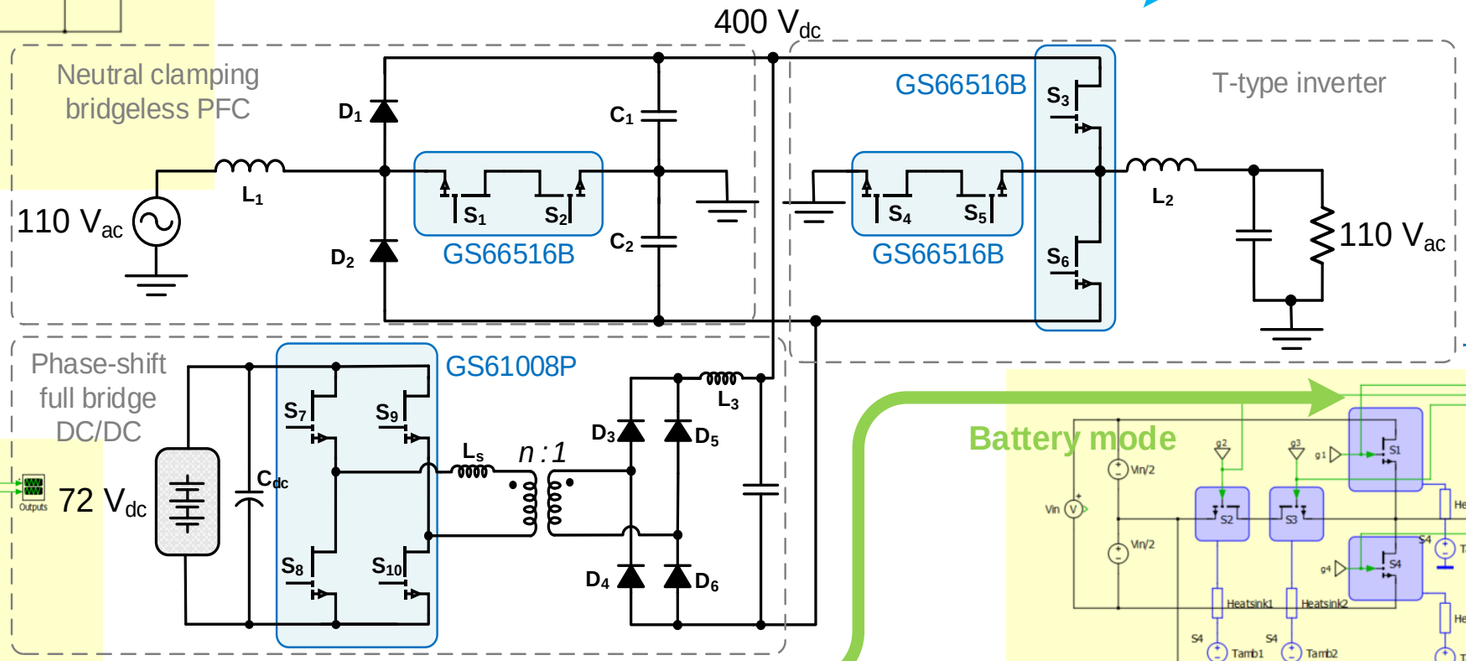
例子: UPS系统

PLECS 模型可用于系统级分析

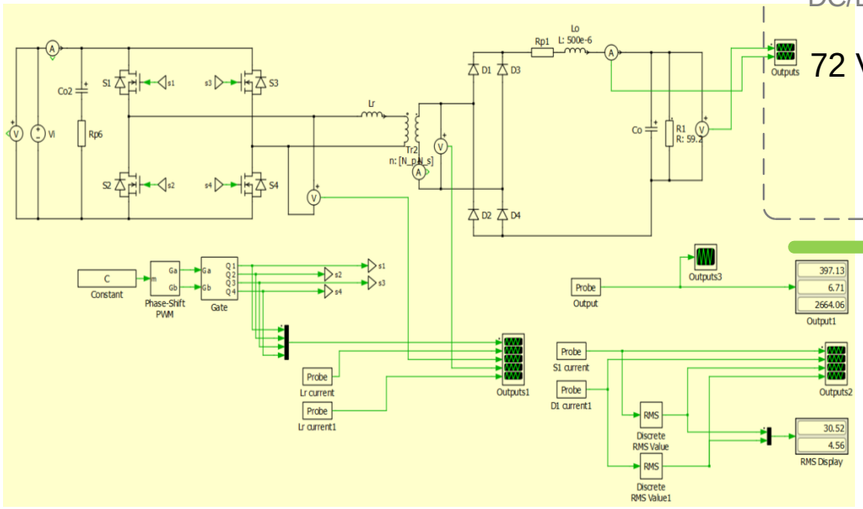


无桥PFC

Online mode

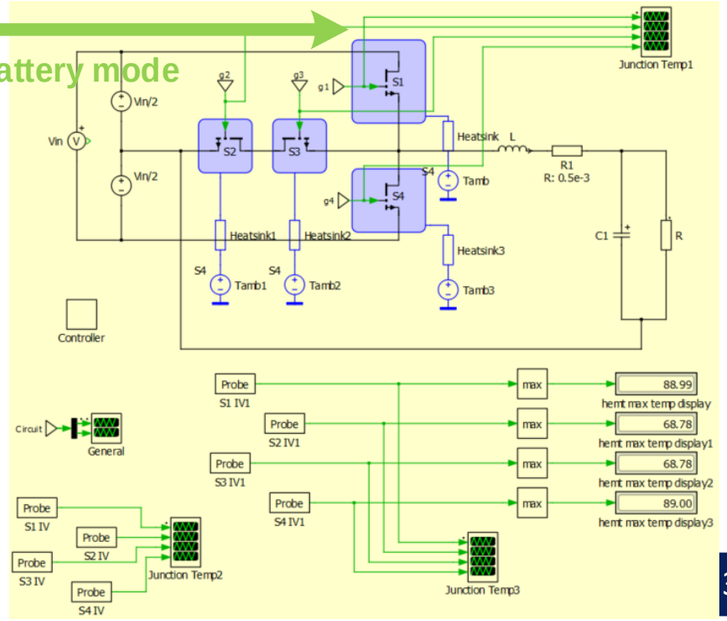


单相逆变器



隔离DC/DC

Battery mode



6.2. PLECS 建模 – 在线仿真工具

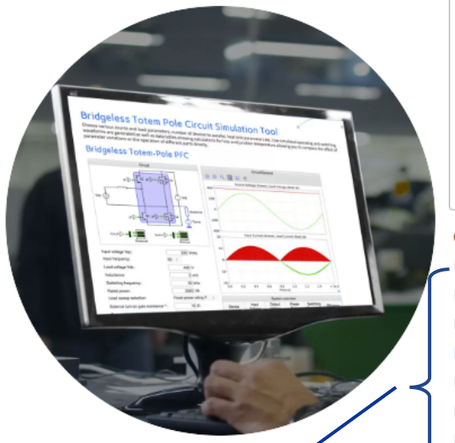
GaN Systems也提供基于PLECS模型的在线仿真工具

Welcome to the GaN Systems Circuit Simulation Tools

The Circuit Simulation Tool allows you to compare application conditions by implementing specific operating values. Choose various source and load parameters, number of devices to parallel, heat sink parameters etc. Live simulated operating and switching waveforms are generated as well as data tables showing calculations for loss and junction temperature allowing you to compare the effect of parameter variations or the operation of different parts directly.

You may also download the PLECS device model files for GaN Systems' transistors.

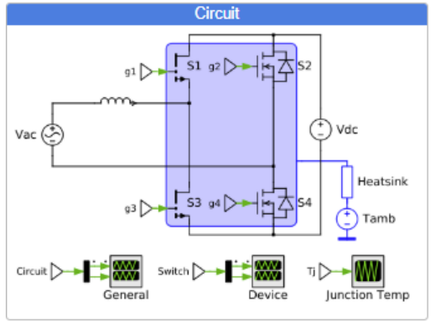
- BRIDGELESS TOTEM-POLE PFC
- SINGLE-PHASE, 2-LEVEL INVERTER
- SINGLE-PHASE, 3-LEVEL HALF-BRIDGE INVERTER
- SINGLE-PHASE T-TYPE 3-LEVEL INVERTER
- ISOLATED HALF-BRIDGE LLC CONVERTER
- ISOLATED PHASE-SHIFT FULL BRIDGE CONVERTER
- THREE-PHASE TRACTION INVERTER
- DUAL ACTIVE BRIDGE

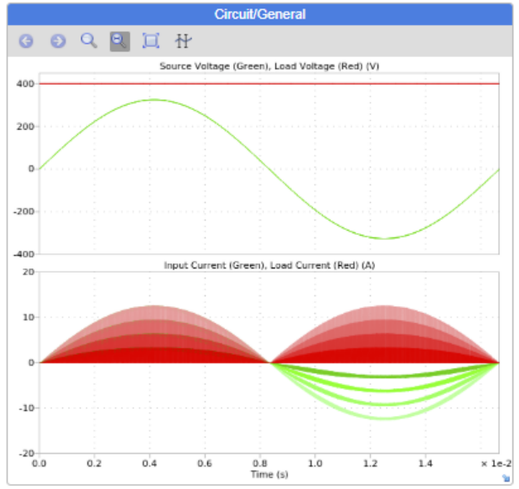


100V 和 650V GaN器件的 PLECS 模型

Bridgeless Totem Pole Circuit Simulation Tool

Choose various source and load parameters, number of devices to parallel, heat sink parameters etc. Live simulated operating and switching waveforms are generated as well as data tables showing calculations for loss and junction temperature allowing you to compare the effect of parameter variations or the operation of different parts directly. You may also download the PLECS device model files for GaN Systems' transistors.





GaN HEMT:

- ☐ GS66502B 650 V, 7.5 A, 200 mΩ
- ☐ GS66504B 650 V, 15 A, 100 mΩ
- ☐ GS66506T 650 V, 22.5 A, 67 mΩ
- ☑ GS66508B/T/P 650 V, 30 A, 50 mΩ
- ☐ GS66516B/T 650 V, 60 A, 25 mΩ
- ☐ GS-065-008-1 650 V, 8 A, 225 mΩ
- ☐ GS-065-011-1 650 V, 11 A, 150 mΩ
- ☐ GS61004B 100 V, 45 A, 15 mΩ
- ☐ GS61008P/T 100 V, 90 A, 7 mΩ

Input voltage Vac:	230	Vrms
Input frequency:	60	
Load voltage Vdc:	400	V
Inductance:	2	mH
Switching frequency:	50	kHz
Rated power:	2000	VA
Load sweep selection:	Sweep power rating P	

Scaling factor for power rating:

- ☑ 25%
- ☑ 50%
- ☑ 75%
- ☑ 100%

External turn-on gate resistance [1]:	10	Ω
External turn-off gate resistance [2]:	2	Ω
Turn-off gate-source voltage:	-2	V
Deadtime:	100	ns
Number of paralleled GaN transistors:	1	

System overview

GaN Device	MOSFET Rdson [3]	Input Voltage	Output Voltage	Power Rating	Switching Frequency	Efficiency
GS66508B/T/P	155 mΩ	230 V	400 V	488 W	50 kHz	99.48 %
GS66508B/T/P	128 mΩ	230 V	400 V	991 W	50 kHz	99.35 %
GS66508B/T/P	105 mΩ	230 V	400 V	1.492 kW	50 kHz	99.09 %
GS66508B/T/P	86 mΩ	230 V	400 V	1.992 kW	50 kHz	98.70 %

GaN transistor thermal overview

Device	Switching	Conduction	Combined Losses [4]	Junction Temperature
GS66508B/T/P	1.35 W	0.32 W	2.53 W	32 °C
GS66508B/T/P	1.62 W	1.22 W	6.46 W	40 °C
GS66508B/T/P	1.91 W	2.89 W	13.56 W	53 °C
GS66508B/T/P	2.33 W	5.81 W	25.89 W	76 °C

所有GaN Systems器件模型以及8种拓扑都可以在网上找到
https://gansystems.com/design-center/circuit-simulation-tools/

总结

结论

- 良好的散热设计可以提高GaN晶体管和系统的性能
- 优化GaN系统的电气**和**散热的设计可以提高软/硬开关的性能，无论是几瓦还是到上千瓦的应用。

该应用手册的几个关键设计技巧

- 顶部散热设计: TIM和散热器安装
- 底部散热设计: PCB设计和焊接空洞
- 器件选型（包括并联选择）
- 协助功耗计算和热设计的建模工具

参考文献

更多资料如下…

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8. J. L. Lu, R. Hou and D. Chen, "Opportunities and design considerations of GaN HEMTs in ZVS applications," in Proc. *2018 IEEE APEC*, San Antonio, TX, 2018.
9. R. Hou, J. Xu, and D. Chen, “Multivariable turn-on/turn-off switching loss scaling approach for high-voltage GaN HEMTs in a hard-switching half-bridge configuration,” in *Proc. 2017 IEEE WiPDA*, Albuquerque, NM, 2017.
10. R. Hou, Y. Shen, H. Zhao, H. Hu, J. Lu and T. Long, "Power Loss Characterization and Modeling for GaN-Based Hard-Switching Half-Bridges Considering Dynamic On-State Resistance," in *IEEE Transactions on Transportation Electrification,* Jun. 2020.

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丰富的产品线

650 V

GS66502B
7.5 A, 200 mΩ
6.6 x 5.0 mm

GS66504B
15 A, 100 mΩ
6.6 x 5.0 mm

GS66506T
22.5 A, 67 mΩ
5.6 x 4.5 mm

GS66508T
30 A, 50 mΩ
7.0 x 4.5 mm

GS66508B
30 A, 50 mΩ
8.4 x 7.0 mm

GS66516T
60 A, 25 mΩ
9.0 x 7.6 mm

GS66516B
60 A, 25 mΩ
11.0 x 9.0 mm

GS-065-060-5-T-A
60 A, 25 mΩ
9.0 x 7.6 mm

GS-065-060-5-B-A
60 A, 25 mΩ
11.0 x 9.0 mm

GS-065-150-1-D2
150 A, 10 mΩ
12.7 x 5.6 mm

5.0 x 6.0 mm
GS-065-004-1-L 4 A, 450 mΩ
GS-065-008-1-L 8 A, 225 mΩ
GS-065-011-1-L 11 A, 150 mΩ

8.0 x 8.0 mm
GS-065-011-2-L 11 A, 150 mΩ
GS-065-030-2-L 30 A, 50 mΩ

100 V

GS61004B
38 A, 16 mΩ
4.6 x 4.4 mm

GS61008P
90 A, 7 mΩ
7.6 x 4.6 mm

GS61008T
90 A, 7 mΩ
7.0 x 4.0 mm

多样的评估板和参考设计

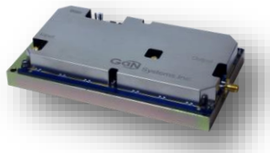
30W PD QR Charger

65W PD QR & ACF Chargers

100W PFC QR AC/DC Charger

250W PFC/LLC AC/DC Adapter

50W Wireless Power Amplifier

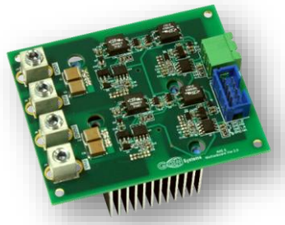

100W Wireless Power Amplifier

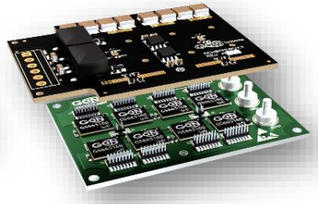
300W Wireless Power Amplifier

1kW Wireless Power Amplifier

3kW Bridgeless Totem Pole PFC

3kW LLC Resonant Converter


6kW Full Bridge, Dual Half Bridge


14kW IMS Half Bridge

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Product and application support at

gansystems.com