Online Junction Temperature Monitoring of SiC MOSFET with Full-range and Gate oxide Defect Insensitivity

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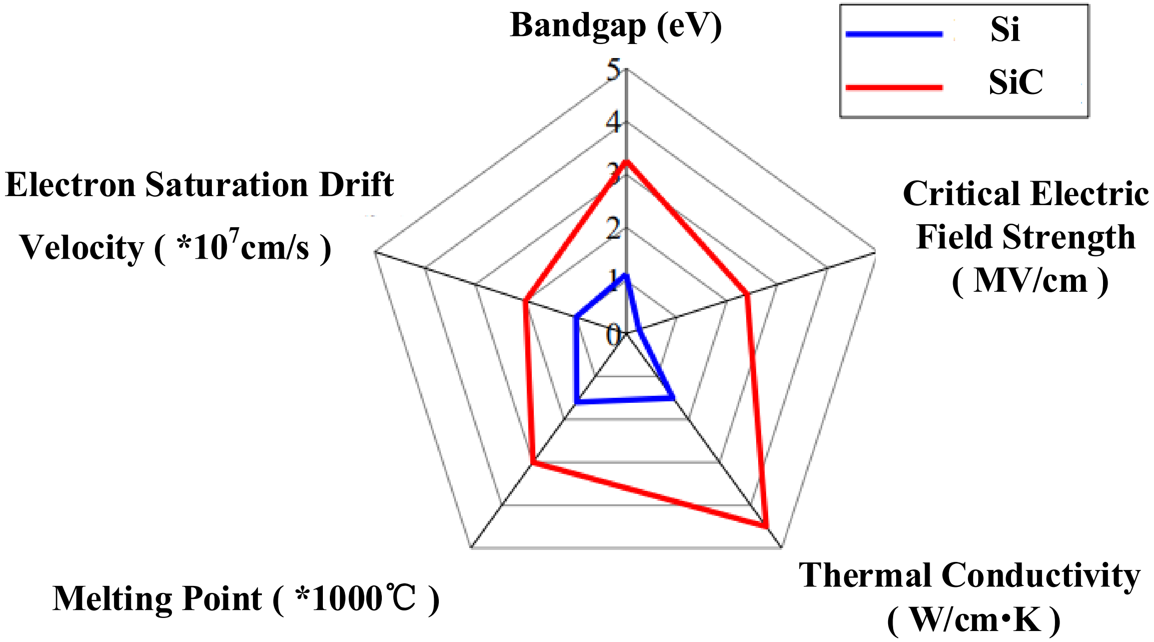
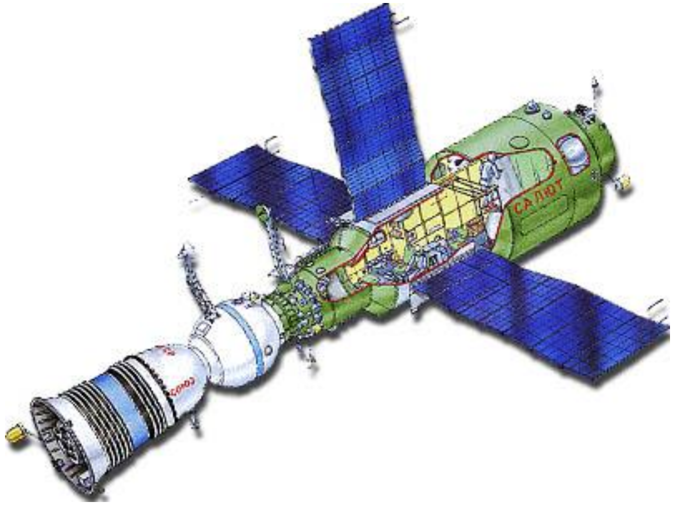
Significance of TJ monitoring

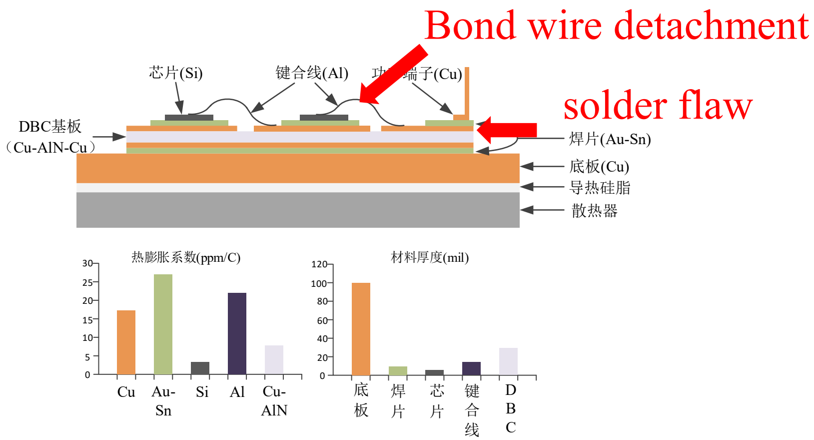
SiC MOSFETs, renowned for their excellent electrical and thermal properties, have been widely adopted in new energy vehicles, aerospace, and other high power density applications.





Significance of TJ monitoring

Junction temperature (TJ) is a significant parameter of SiC MOSFET

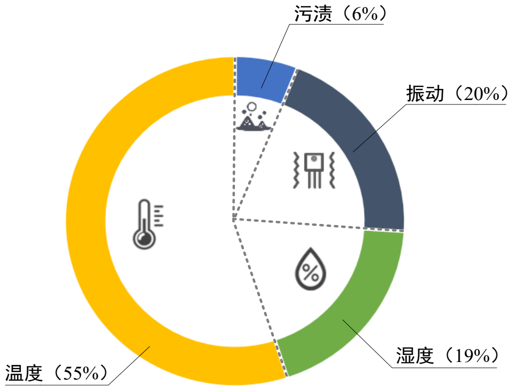


Improve the reliability of the power module

TJ is an important parameter

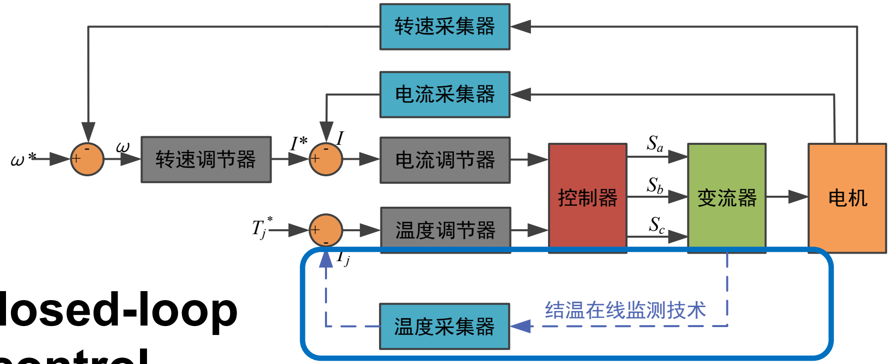
Coffin-Manson模型	$N_f = A(\Delta T_j)^{-n}$
Lesit模型	$N_f = A f^{-n} \left(\Delta T_j\right)^{-\alpha} e^{E_a/(kT_m)}$
Norris-Landzberg模型	$N_f = A\left(\Delta T_j\right)^{-\alpha} e^{E_a/(kT_m)}$

provide fundamental data for PHM



Inducement of failure

TJ closed-loop control



Increase the available capacity of the inverter

Problems of TJ monitoring online

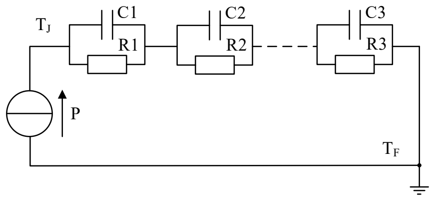
Research Status of online junction temperature monitoring methods for power module

Juction Temperature Sensing

- Optical Method

- Sensor based Method

- Thermal-mode based mothed



- Thermal sensitive electrical parameter method **(TSEP Method)**
  - Dynamic parameters
    - $\mathrm{d}i_D/\mathrm{d}t$ ΔV_{DS}
    - t_{d_off} V_{GP}
  - Static parameters
    - V_{TH} R_{DS}
    - V_{DS} …

How to select ?

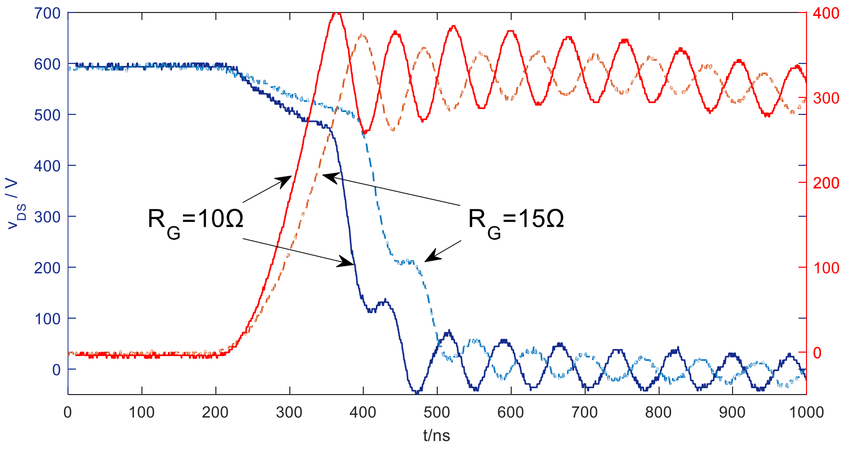
Non-invasiveness,

Easy to implement,

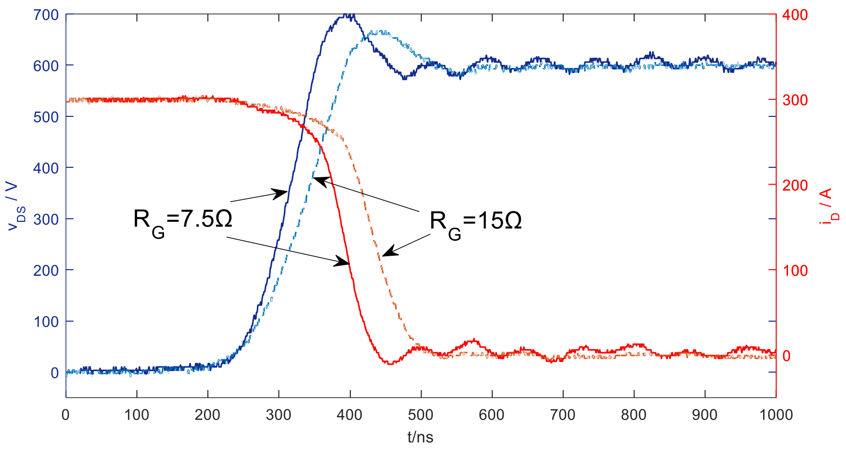
High accuracy

Problems of TJ monitoring online

Challenges in SiC MOSFET : **1. short switching transient (<100ns)**



(a) Turn-on



(b) Turn-off

Dynamic parameters

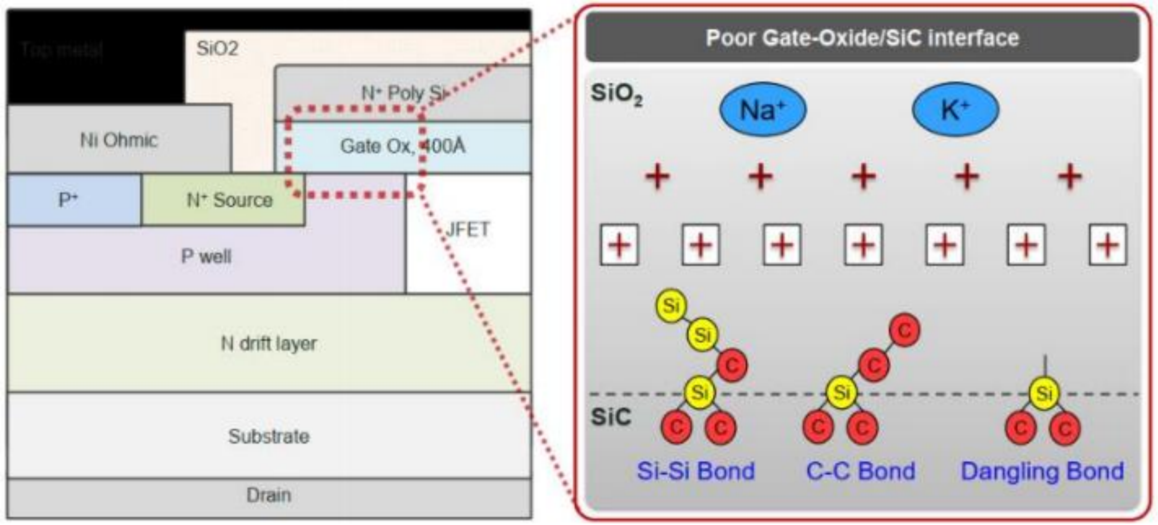
di_D/dt ΔV_{DS}

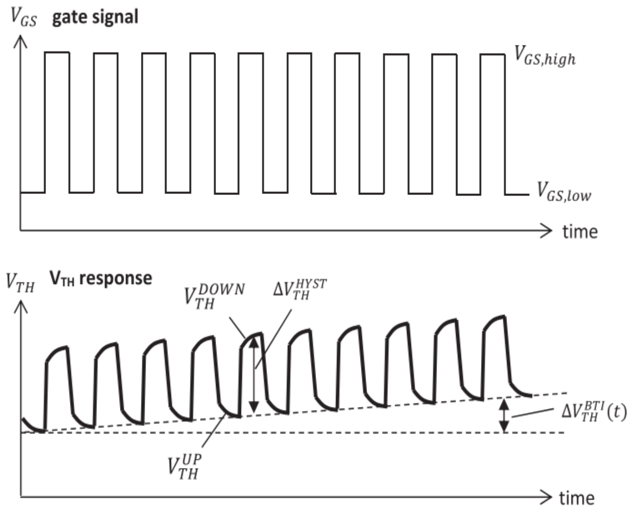
t_{d_off} V_{GP}

Most Dynamic Parameter measurement require excessively high bandwidth (>10MHz)

Problems of TJ monitoring online

Challenges in SiC MOSFET : 2. instability caused by gate oxide interface defects





TSEPs corelated with V_{TH}

di_D/dt ΔV_{DS}

V_{DS} R_{DS}

t_{d_off} V_{GP}

short-term Vth shift

short-term Vth drift

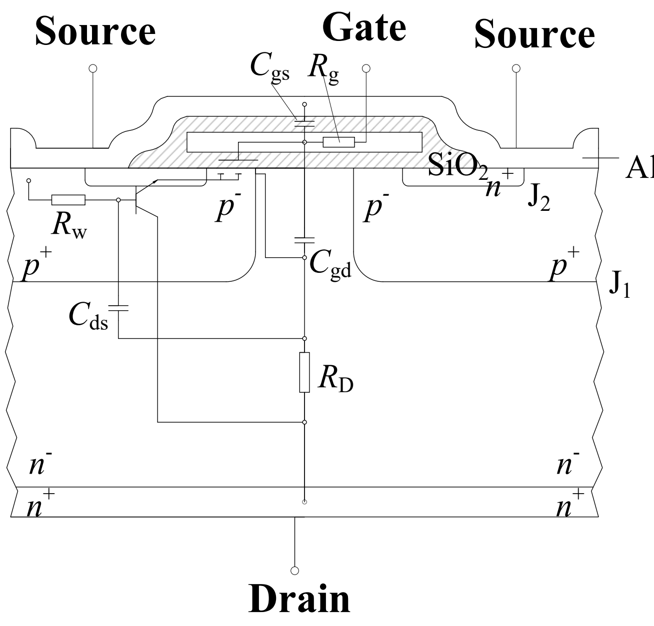
Gate oxide interface defects cause V_{TH} drift.

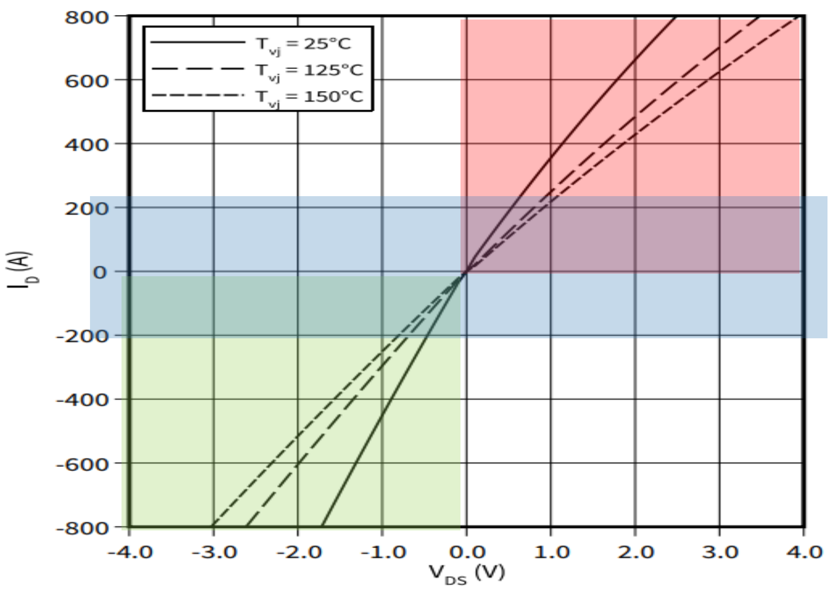
Most TSEPs related with V_{TH}

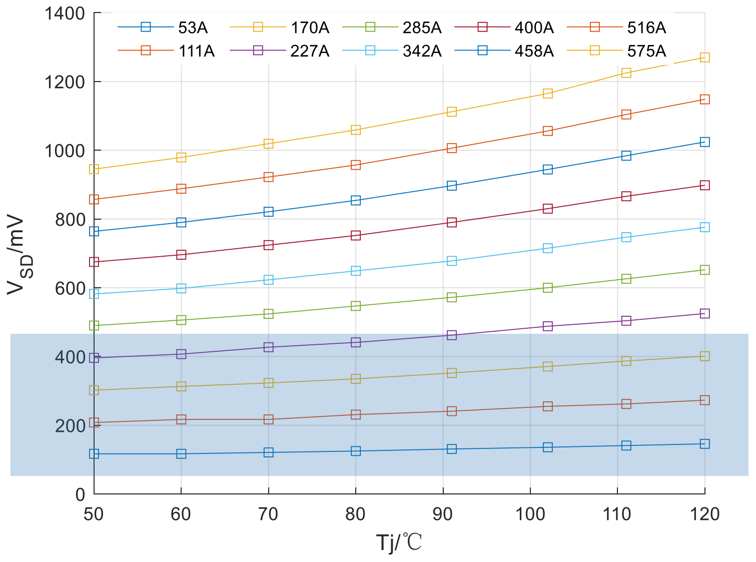
$$R_{CH} = \frac{L_{CH}}{W} \frac{1}{\mu_{nc} C_{OX} \left(v_{gs} - V_{TH} \right)}$$

Problems of TJ monitoring online

Challenges in SiC MOSFET : 3. Narrow measurement range







$$V_{DS\_C} = R_{DS0} * (1 + K_T * T_J) * I_D$$

Temperature Resolution ： $K_T * I_D$

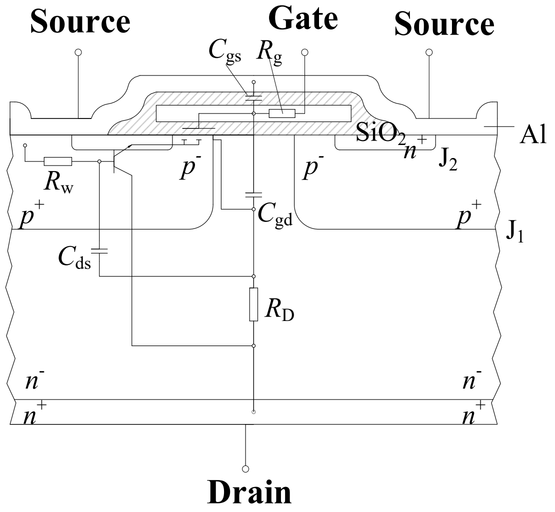
V_{DS_C} has no forward voltage.

When I_D is low, V_{DS_C} is too small to measure

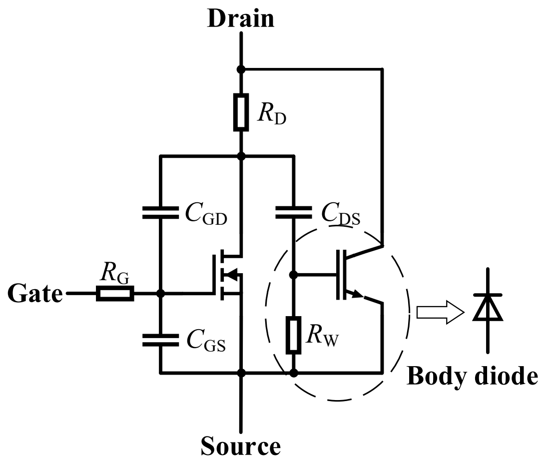
Problems of TJ monitoring online

TSEP in this paper: V_{SD_F}

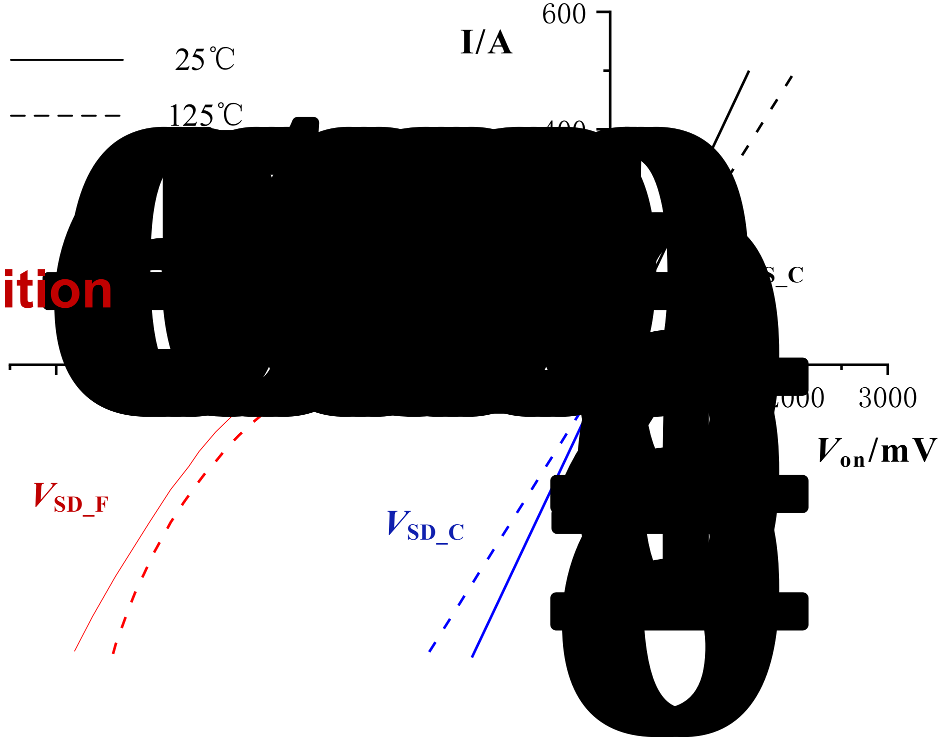
1. Easy to implement
2. Gate oxide Defect Insensitivity
3. High temperature Resolution even in low current condition



Chip Structure



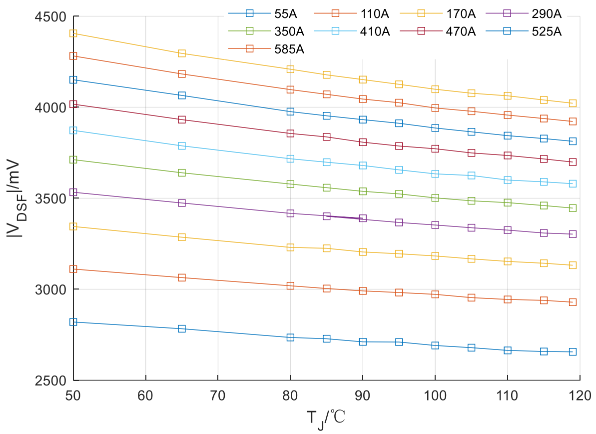
Equivalent Circuit

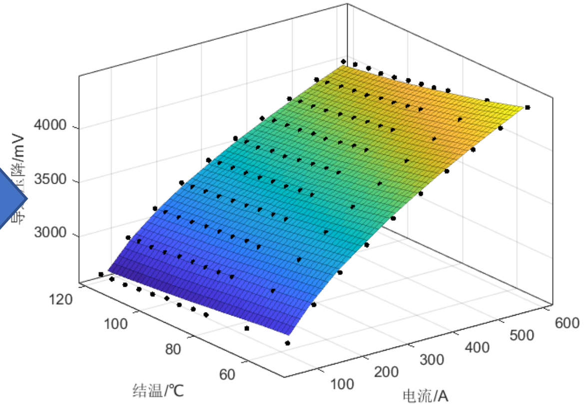


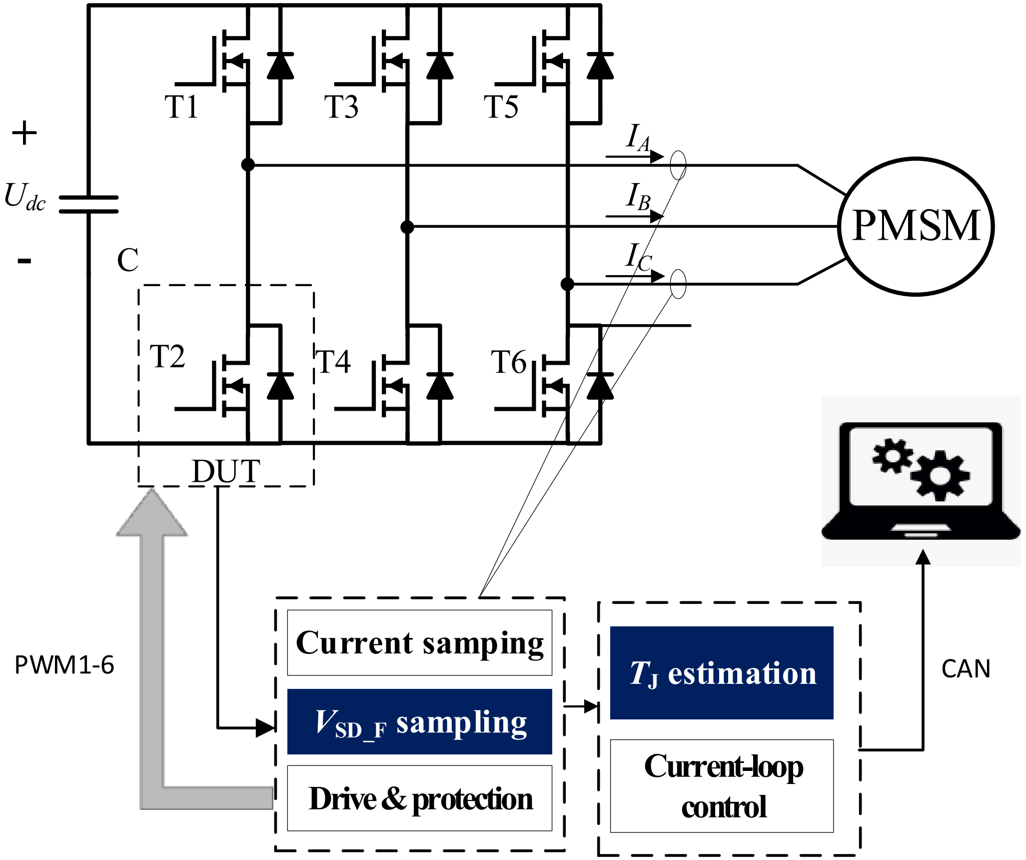
3 on-state voltages:

1. V_{GS}=15V, I_D>0, V_{DS_C}
2. V_{GS}=15V, I_D<0, V_{SD_C}
3. V_{GS}=-5V, I_D<0, V_{SD_F}

Topological structure of the TJ monitoring system





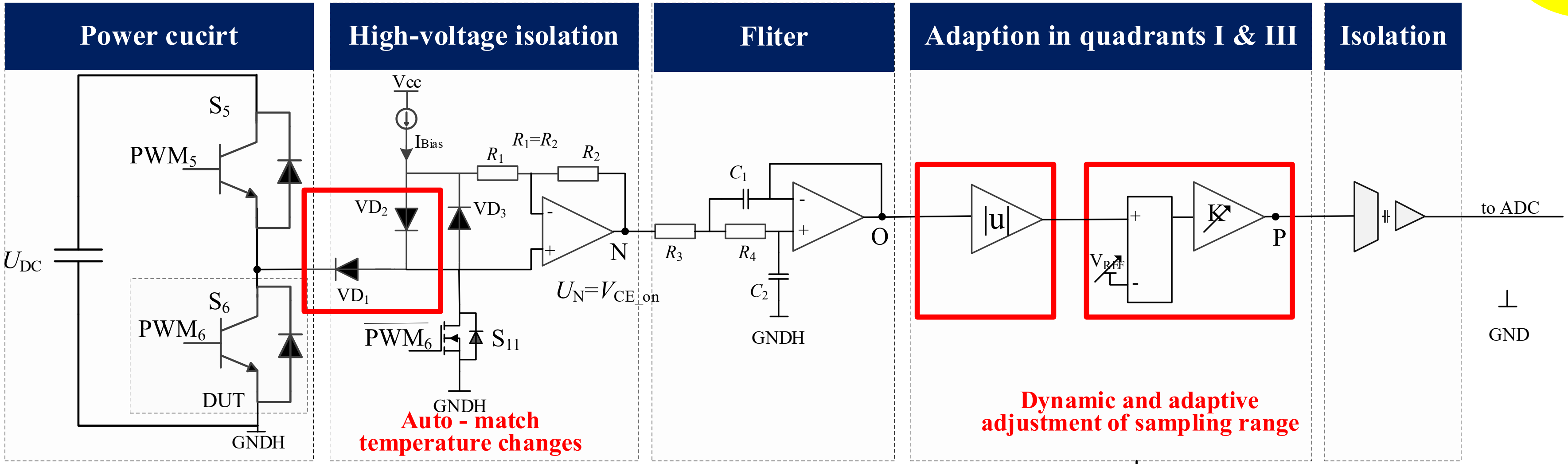


$$T_J = f(V_{SD\_F}, I_D)$$

Design of TJ monitoring system

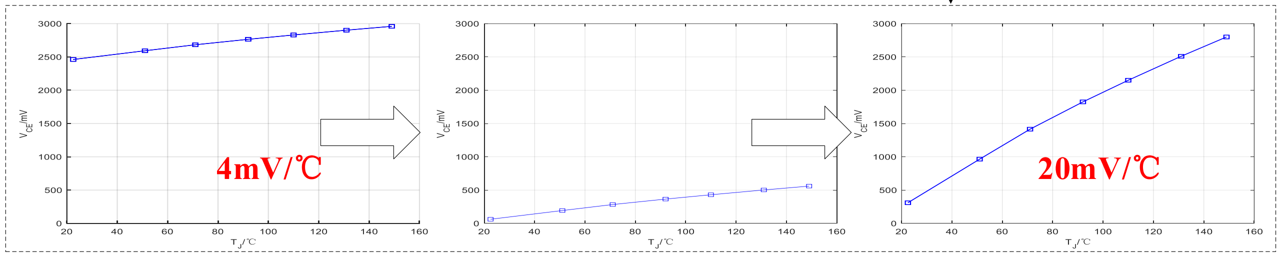
High-resolution sampling circuit 高精度采样电路

1. Dual-diode configuration **cancels out thermal drift voltage**
2. Dynamic Adaptive sampling circuit **enhances temperature resolution >4×**



range: ±5V

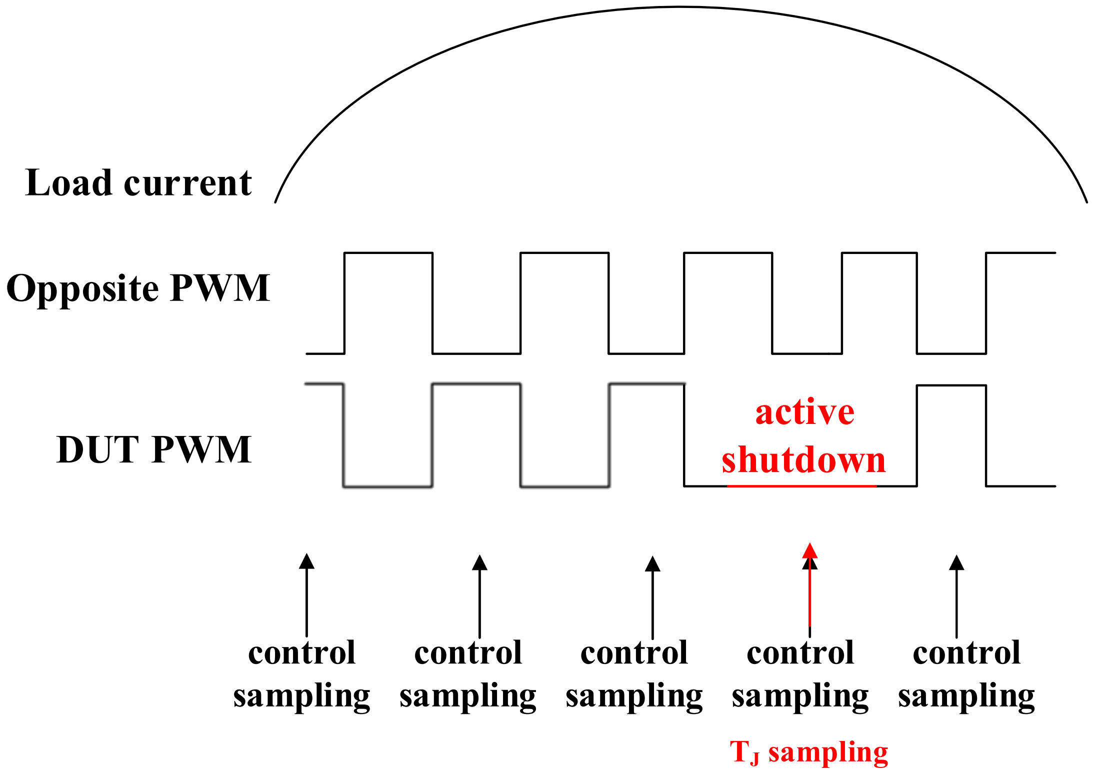
error: ±10mV



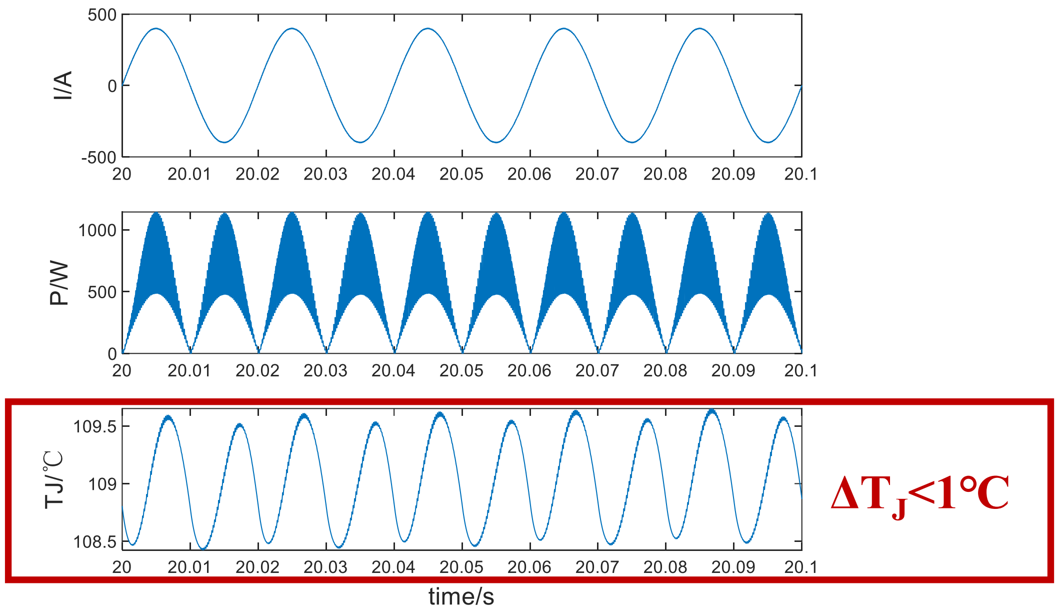
Design of TJ monitoring system

How to get V_{SD_F} ?

Active shut down method 主动关断技术



Sampling and PWM modulation strategy



Simulation waveforms of current, loss and TJ

Sampling once per sine wave cycle. This fs is sufficient and no impact on normal state.

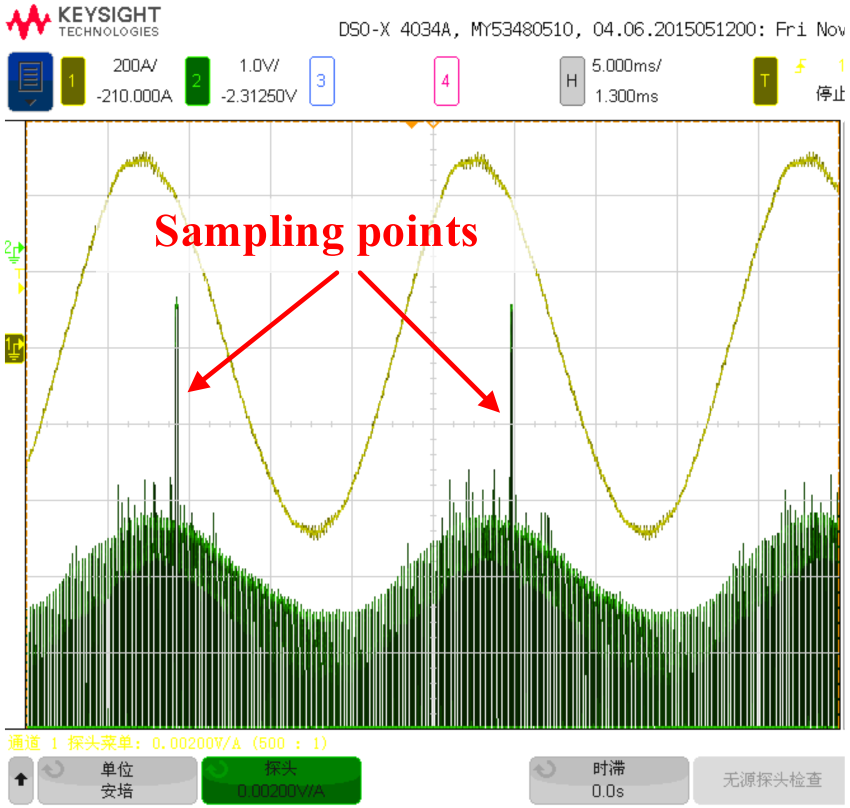
Design of TJ monitoring system

Sampling waveforms during the operation of the SiC controller

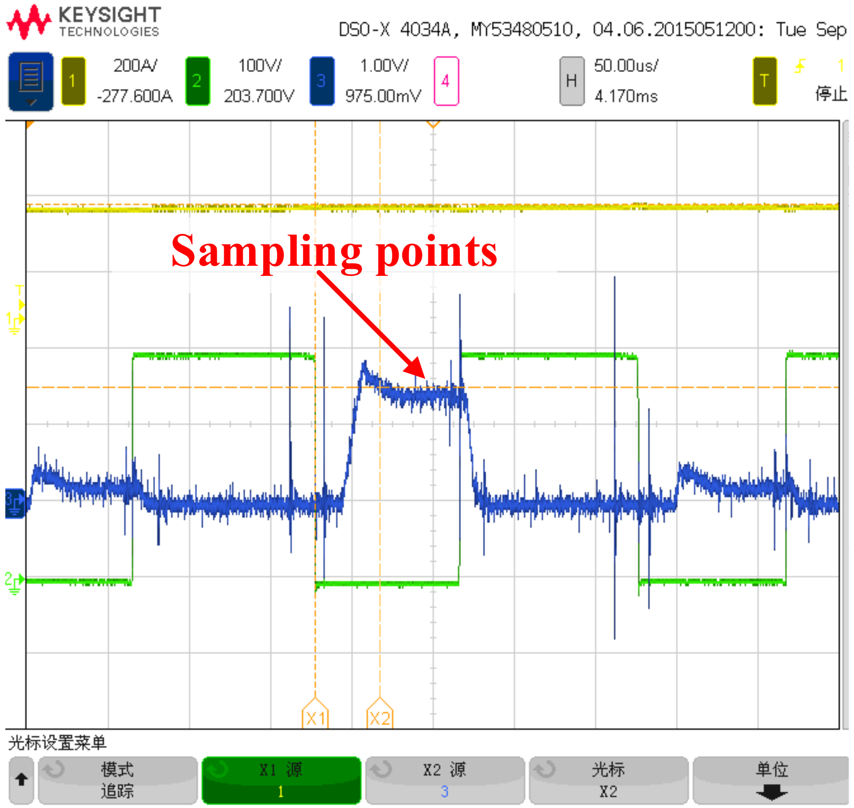
Ch1: IL

Ch2:VGS

Ch3: VSD_F



(a) 5ms/div

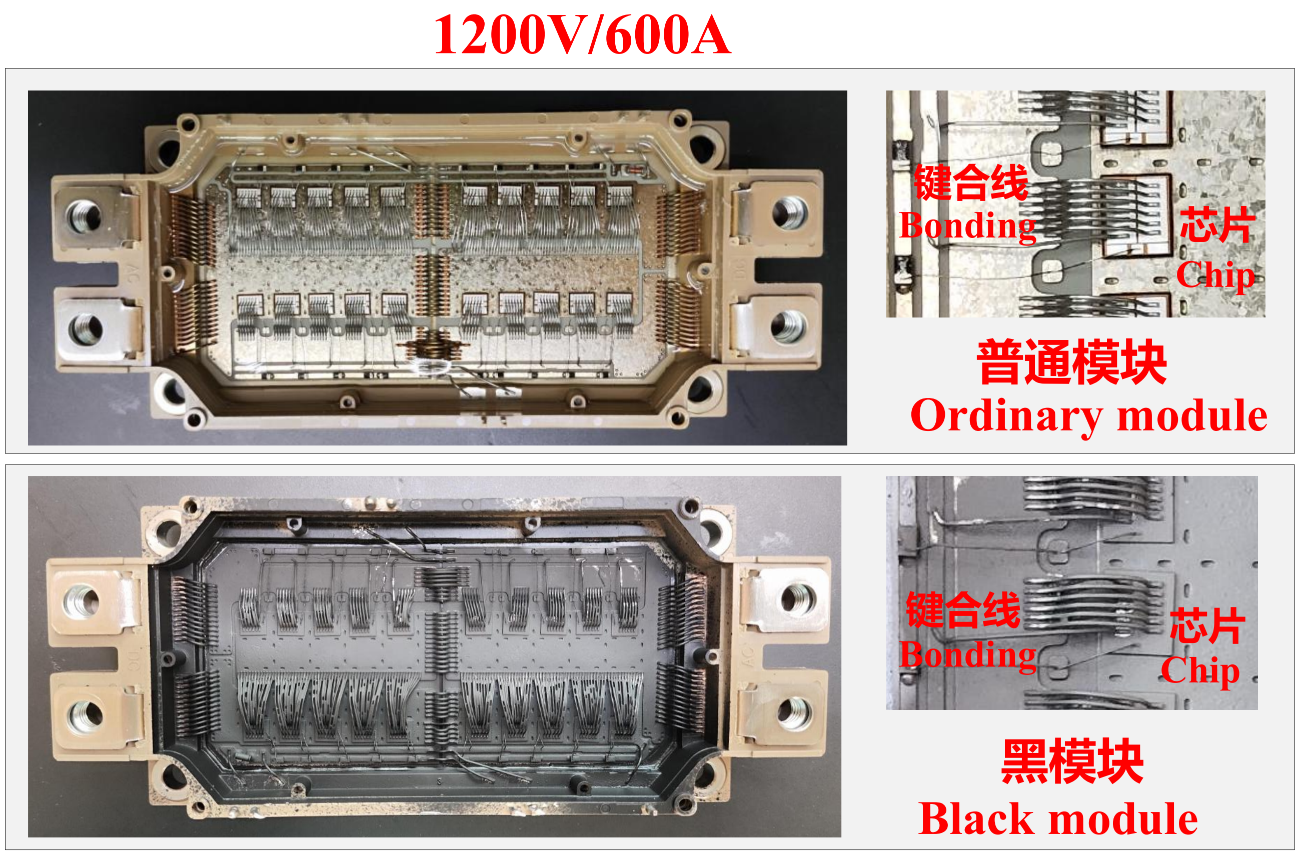


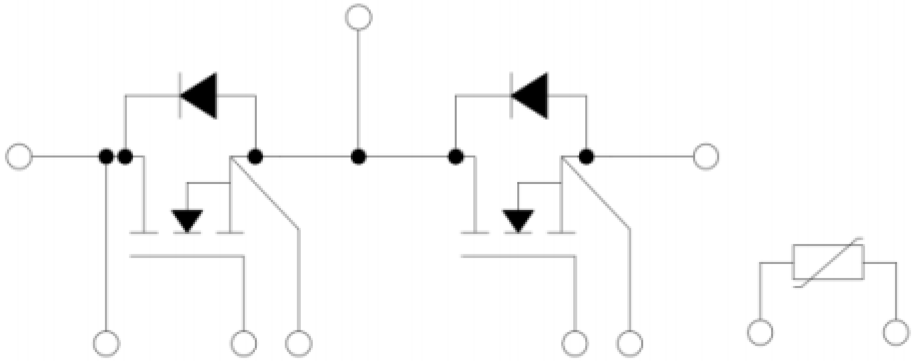
(b) 50μs/div

Different sampling positions have little impact on accuracy

Experimental verification

SiC MOSFET Module: 1200V/600A, 10 chips



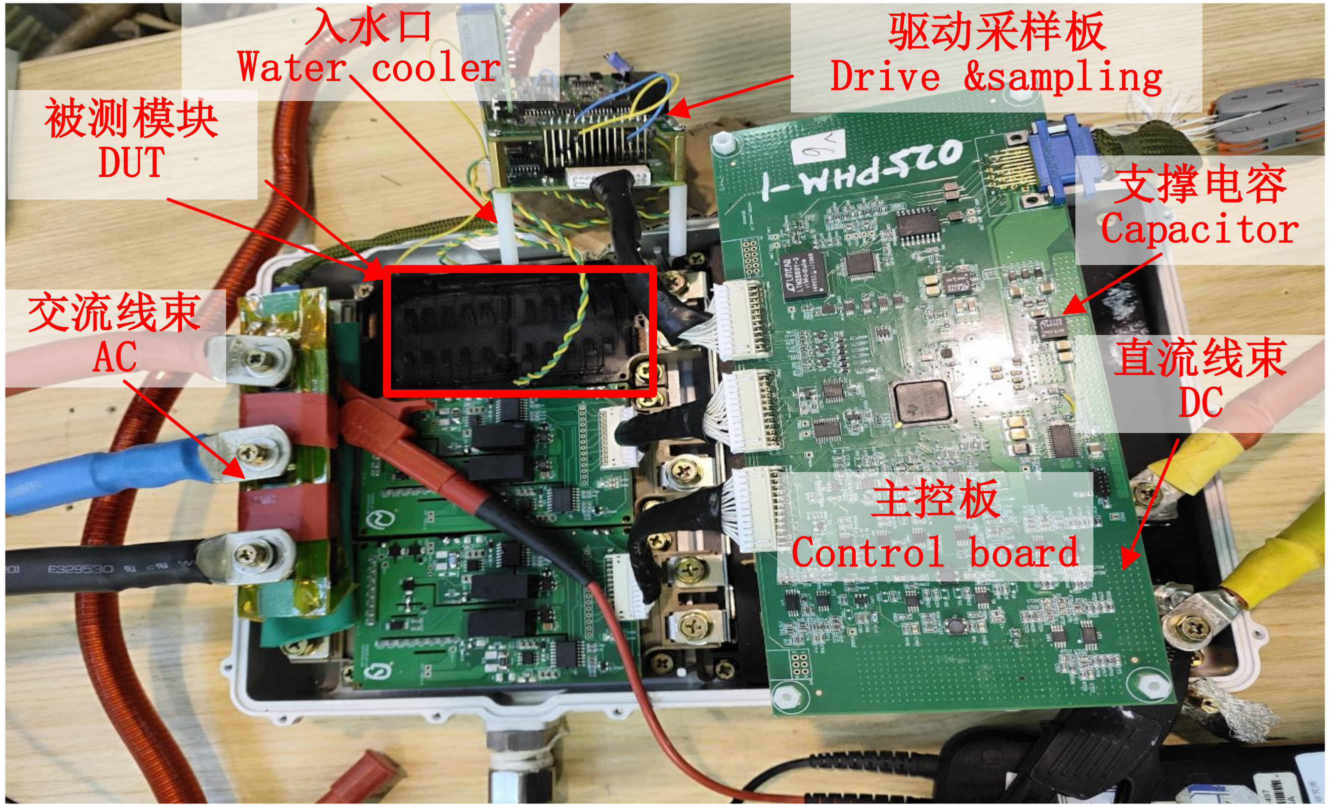


Equivalent Circuit

Chose a black module for comparison with thermal imager

Experimental verification

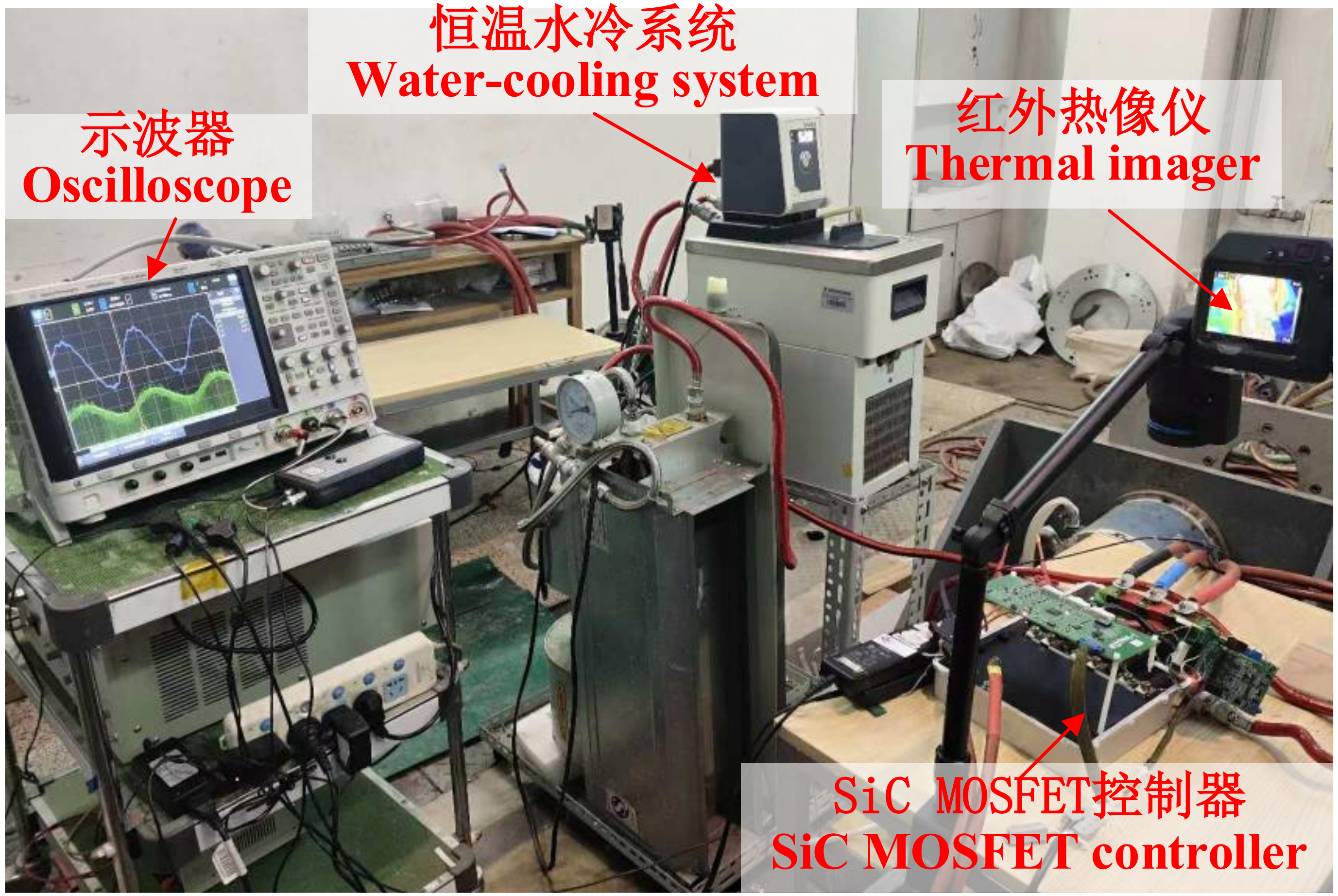
Inverter and module layout



Parameter	Value
Switching frequency	5 kHz
AC frequency	50 Hz
DC voltage	200 V
load inductance	3 mH
Dead time	1 μs
Gate voltage	+15 V / -3 V

Experimental verification

Experiment setup



Parameter	Value
Switching frequency	5 kHz
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DC voltage	200 V
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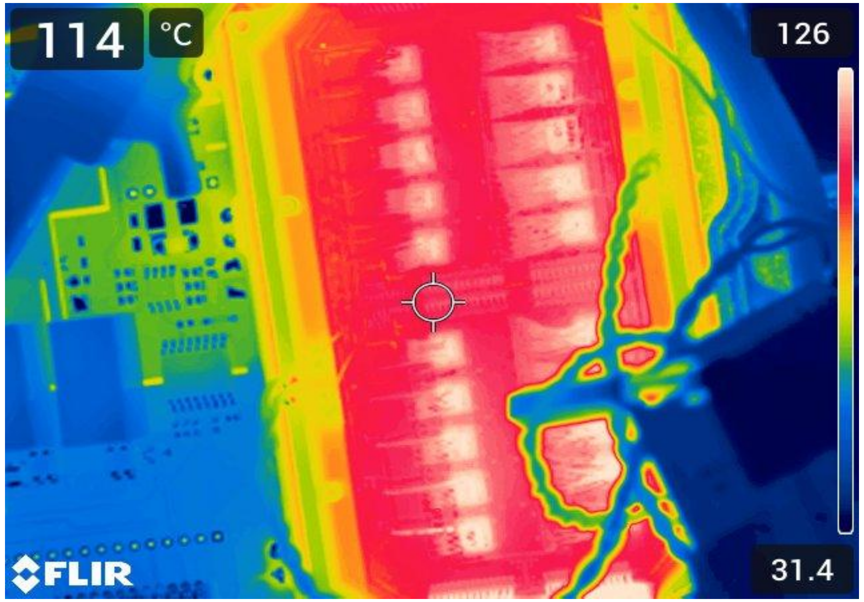
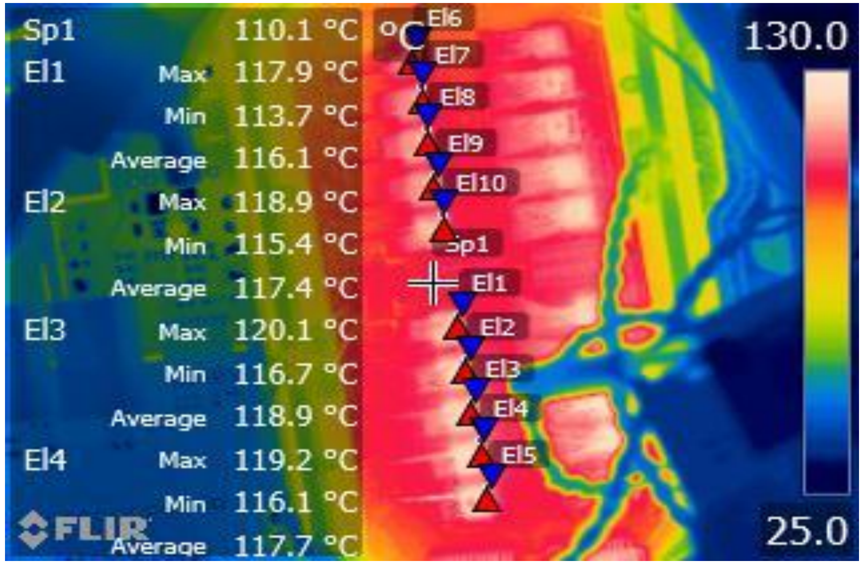
Gate voltage	+15V / -3V

Experimental verification

Comparison with Infrared Thermal Imager

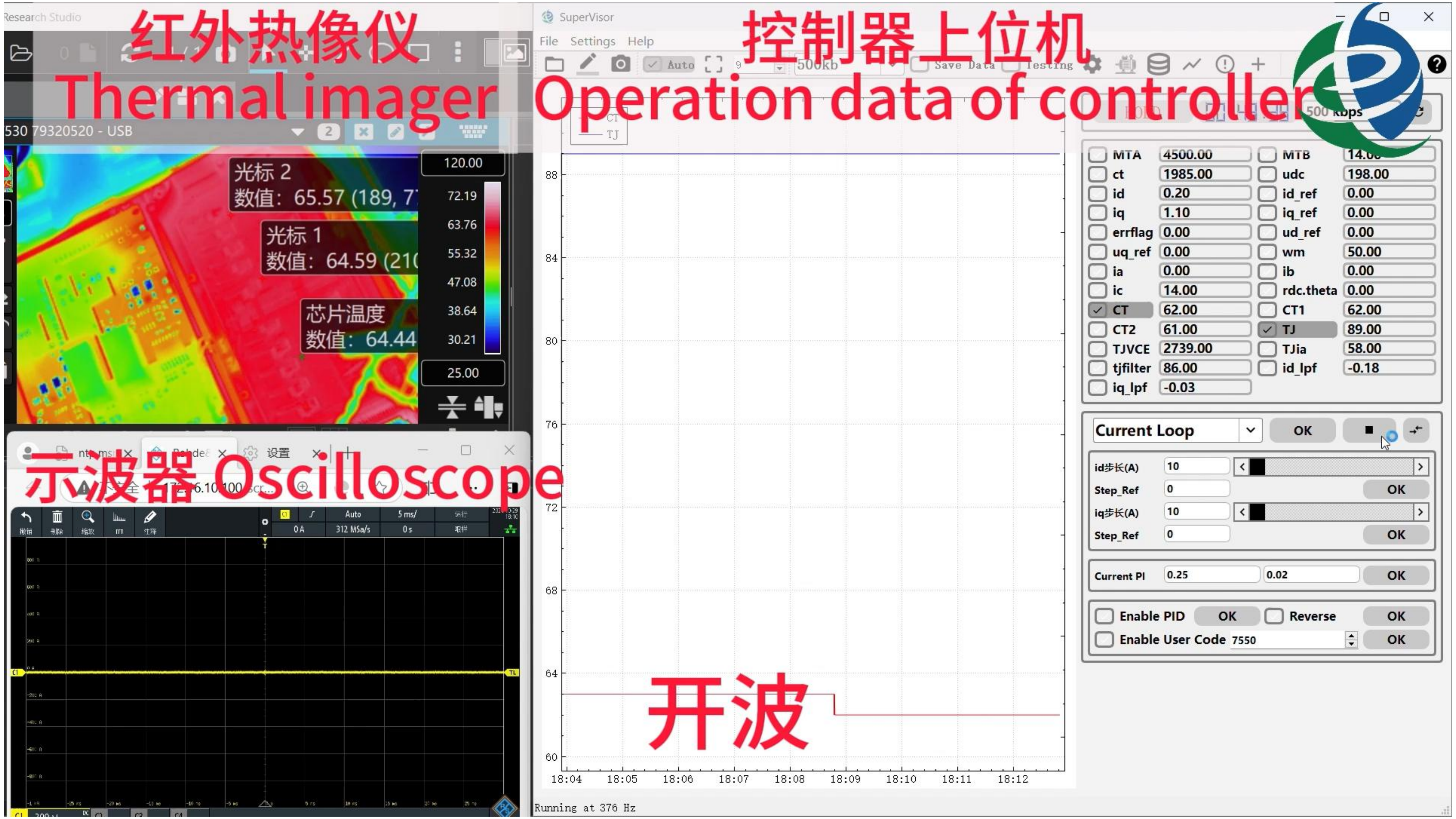
Thermal imager Layout





Experimental verification

Synchronized test video of oscilloscope, thermal imager, and online monitoring



Experimental verification

Comparison of online monitoring and Infrared Thermal Imager

Test data in different operating conditions

Current /A	Online T_J monitoring / °C	T_J on thermal camera /°C	Err /°C
50	64	64.8	-0.8
100	63	65.5	-2.5
150	68	68.3	-0.3
200	76	71.8	4.2
250	76	77	-1
300	82	83	-1
350	90	90.5	-0.5
400	97	97.2	-0.2

Err<5℃ in full range

Independent test report

中汽研汽车检验中心（天津）有限公司　　报告编号：QA24XX2XV0321

检　验　报　告

共 7 页　第 1 页

检验结论

样品名称	电机控制器	商　　标	——
型号规格	EVC025	检验类别	委托检验
委托单位	中国科学院电工研究所		
生产企业	中国科学院电工研究所		
送 样 者	张栋	送样日期	2024 年 10 月 28 日
样品数量	1 套	生产日期	——
检验依据	《SiC 模块结温监测误差测试方案》	检验项目	SiC 模块结温监测误差测试
检验结论	经检验，该样品的 SiC 模块结温监测误差测试 检验项目符合《SiC 模块结温监测误差测试方案》的要求。 签发日期：2024 年 11 月 12 日		
备　注	----		

批准：黄昕　　审核：赵凌霄　　主检：

summary

1. A novel real-time TJ monitoring method for MOSFET is proposed, which use the on-state voltage of the body-diode in the third quadrant as the sensing parameter. Compared with other solutions, this method features high temperature resolution, immunity to gate oxide degradation, and full-range applicability.

2. A high-resolution sampling circuit with dynamic and adaptive range adjustment is developed, which improve the sampling resolution by more than four times.

3. A sampling and PWM modulation strategy is proposed to solve the adaptability problem of voltage measurement in the third quadrant.

4. The system's accuracy was verified on a SiC-based inverter platform. Comparison with thermal imaging data shows a maximum error within 5°C over a wide current range from 50 to 400 amps.

谢谢!

Thanks for listening

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