面向电路拓扑的GaN器件导通电阻测试方法与标准建议

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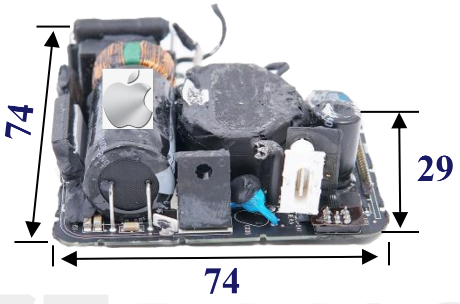
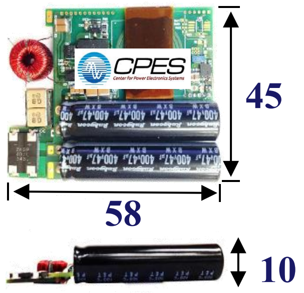
Advantages of GaN Power Converters: High Efficiency High Power Density

■ 65W power adapter

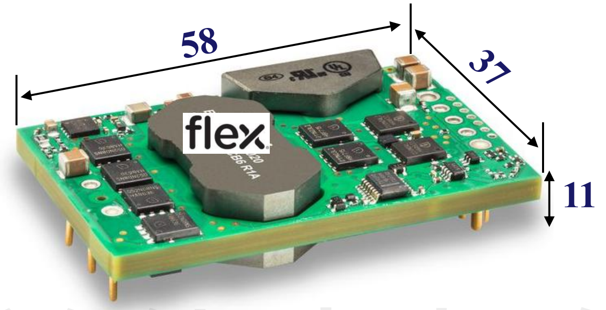


Si 120kHz, 7W/in^3 [1]

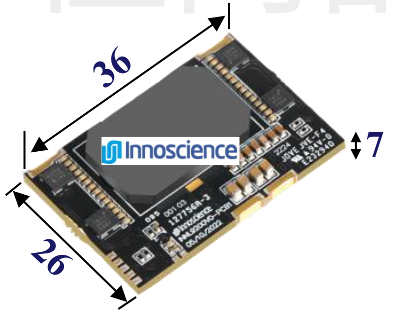


GaN 1MHz, 41W/in^3 [2]

■ On board DC/DC module

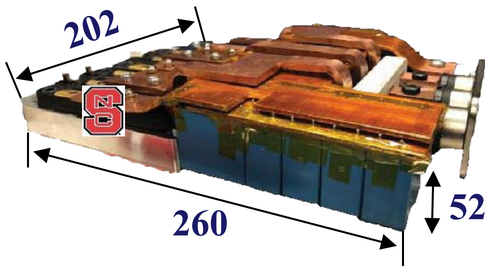


Si 180kHz, 412W/in^3 [3]

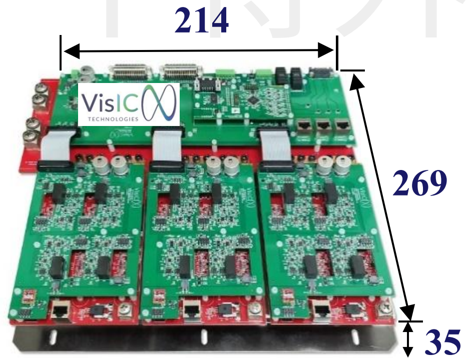


GaN 1MHz, 1500 W/in^3 [4]

■ Inverters



SiC 40kHz, 557 W/in^3 [5]

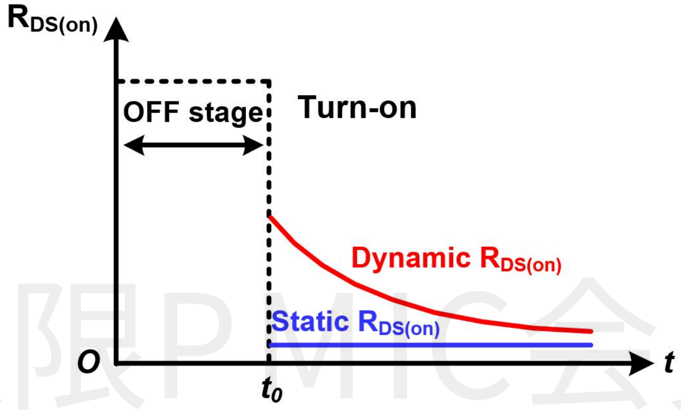


GaN 100kHz, 820 W/in^3 [6]

[1] https://post.smzdm.com/p/a25g6vz2/
[2] X. Huang "Design consideration of MHz active clamp flyback converter with GaN devices for low power adapter application,"
[3] Flex,BMR458 series
[4] https://laoyaoba.com/n/826044
[5] C. Zhang "A SiC-Based 100 kW High-Power-Density (34 kW/L) Electric Vehicle Traction Inverter,"
[6] VisIC, 800V 100kW 3-Phase GaN Inverter

GaN Device's Dynamic On-resistance Depends on Numerous Factors

■ Dynamic $R_{DS(on)}$ Degradation



- ☐ Conduction loss Increase
- ☐ Difficult to estimate real loss

■ Facts of Dynamic $R_{DS(on)}$

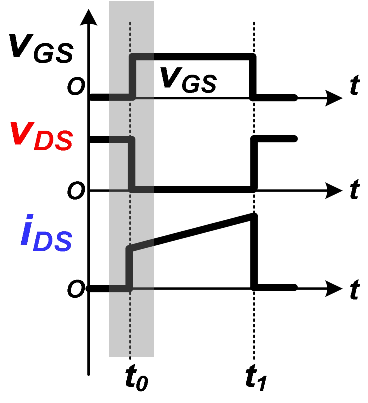
$dR_{DS(on)} \propto$

- ■ OFF-state drain bias voltage
- ■ Load current
- ■ Junction temperature

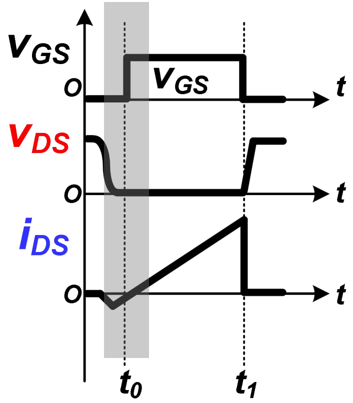
……

■ Relationship between Dynamic $R_{DS(on)}$ and switching conditions

☐ Hard Sw.

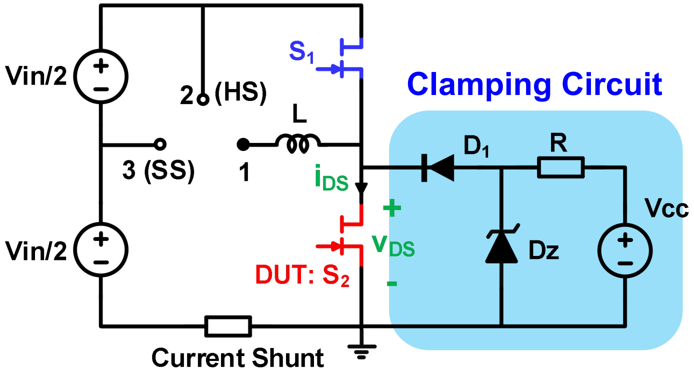


☐ Soft Sw.



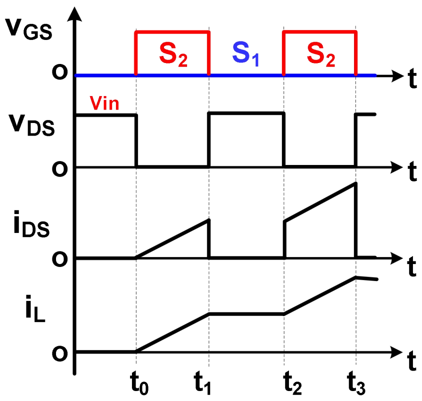
Dynamic $R_{DS(on)}$ can only be obtained by measurement

GaN Device's $R_{DS(ON)}$ Behaves Differently under Hard- and Soft- Switching Conditions [7]

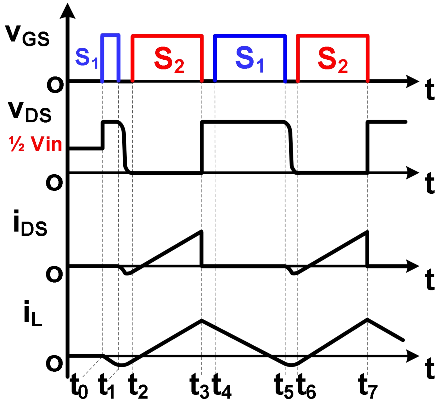


GS66508T	PGA26E19BA
650V	600V
50mΩ	150mΩ
p-GaN	HD-GIT
GaN System	Panasonic

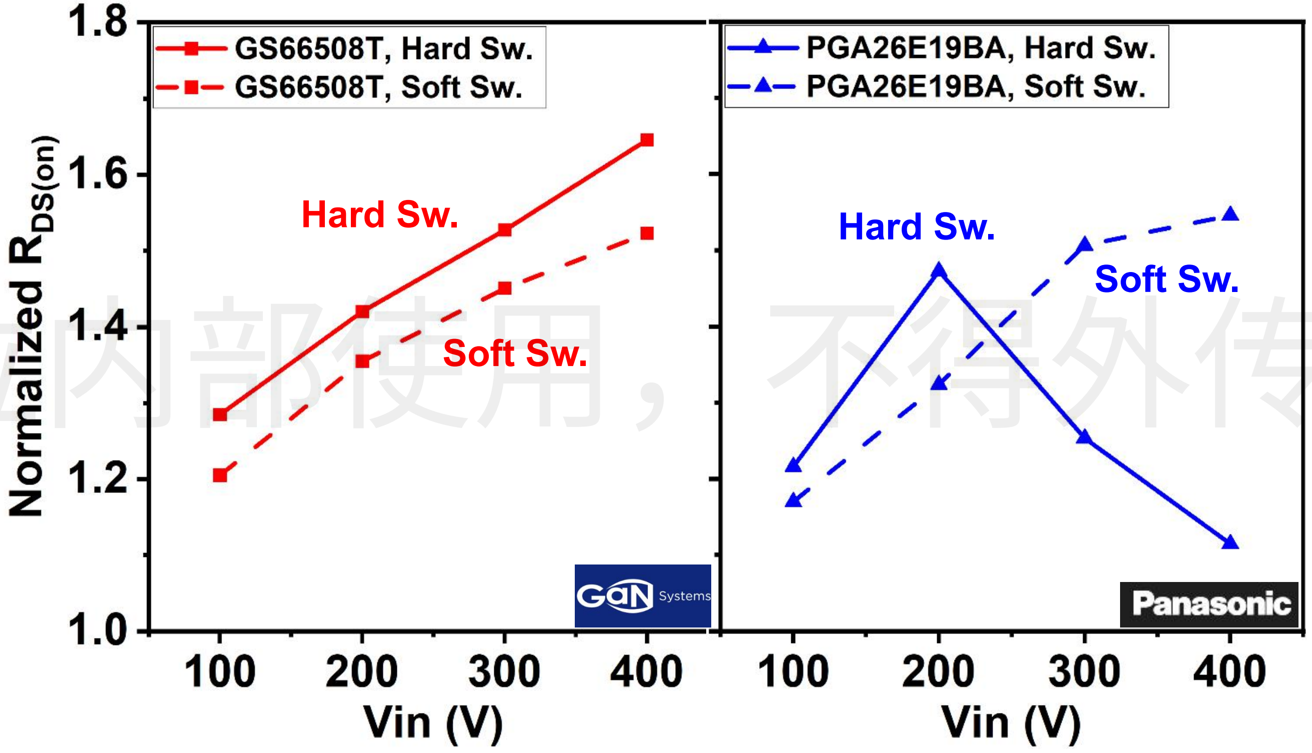
■ Hard Sw. Test



■ Soft Sw. Test



■ Double Pulse Test (DPT) @2μs on-time

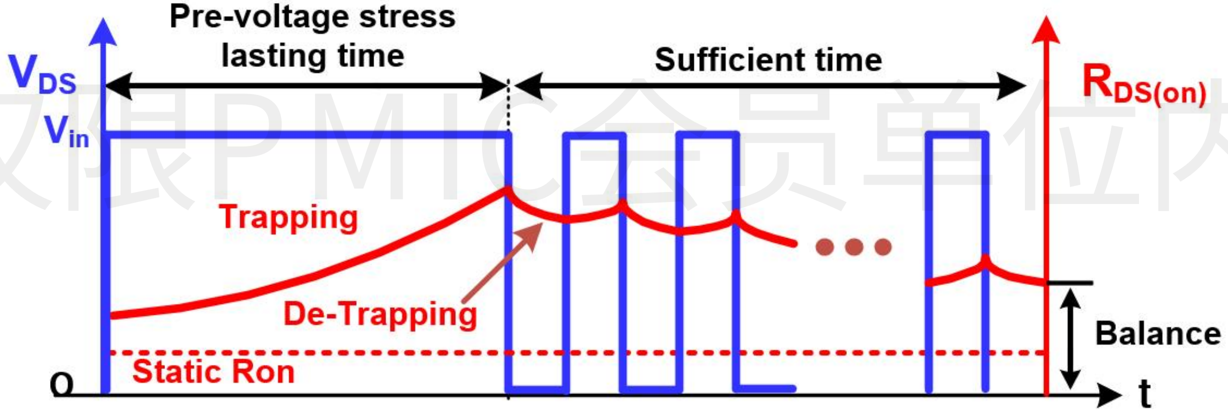


➤ $R_{DS(on)}$ change differs under HS and SS.

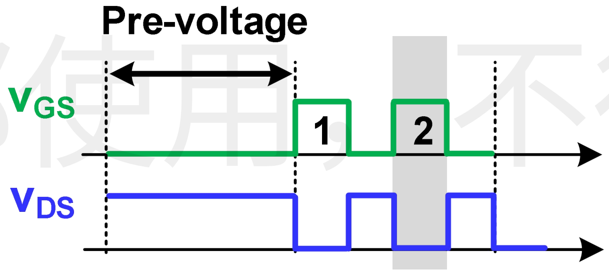
[7] R. Li, X. Wu, S. Yang, and K. Sheng, "Dynamic on-State Resistance Test and Evaluation of GaN Power Devices Under Hard- and Soft-Switching Conditions by Double and Multiple Pulses," IEEE Trans. Power Electron., vol. 34, no. 2, pp. 1044–1053, Feb. 2019

Pre-Voltage Stress's Interference can't be Eliminated in DPT

- V_{DS} bias effect in continuous pulse [10]



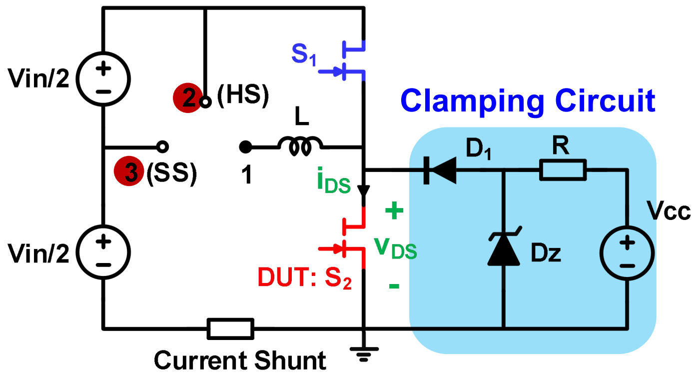
- DPT for dynamic $R_{DS(on)}$



- pre-voltage can't be ignored.

[10] K. Li, P. L. Evans, C. M. Johnson, A. Videt, and N. Idir, "A GaN-HEMT Compact Model Including Dynamic RDSon Effect for Power Electronics Converters,".

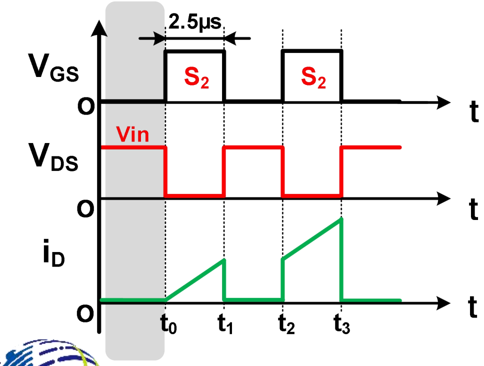
Different Influence of Pre-voltage Stress for Different GaN Devices under DPT



Same operation under Hard Sw.

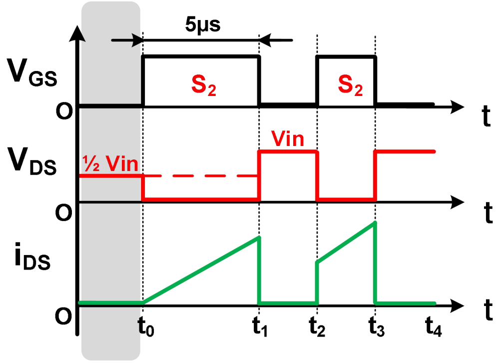
- 1 to 2

Pre-voltage stress = Vin

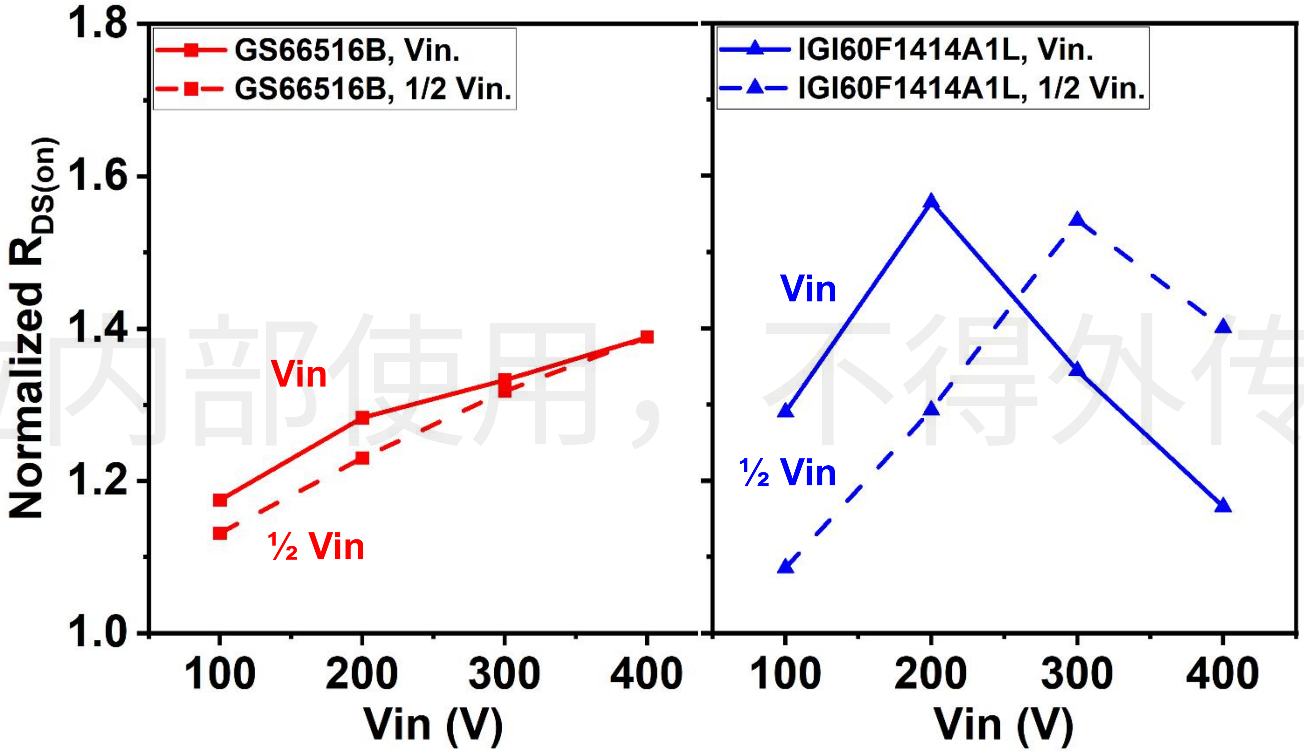


- 1 to 3

Pre-voltage stress = ½ Vin



➢ DPT Results @2.5μs on-time



☐ Different devices have different deterioration caused by pre-stress

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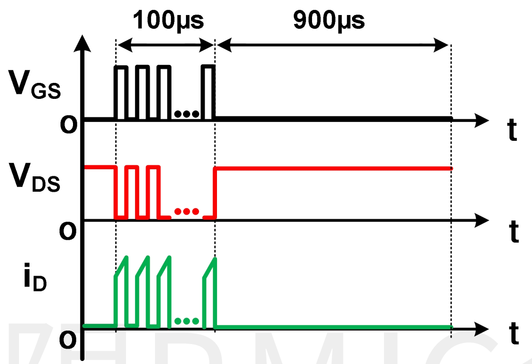
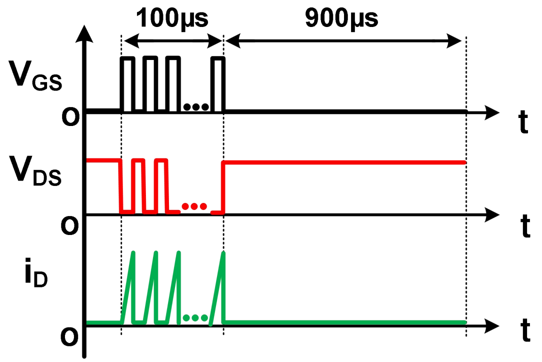
100μs Multi-Pulses Test (MPT) has Serious Self-heating

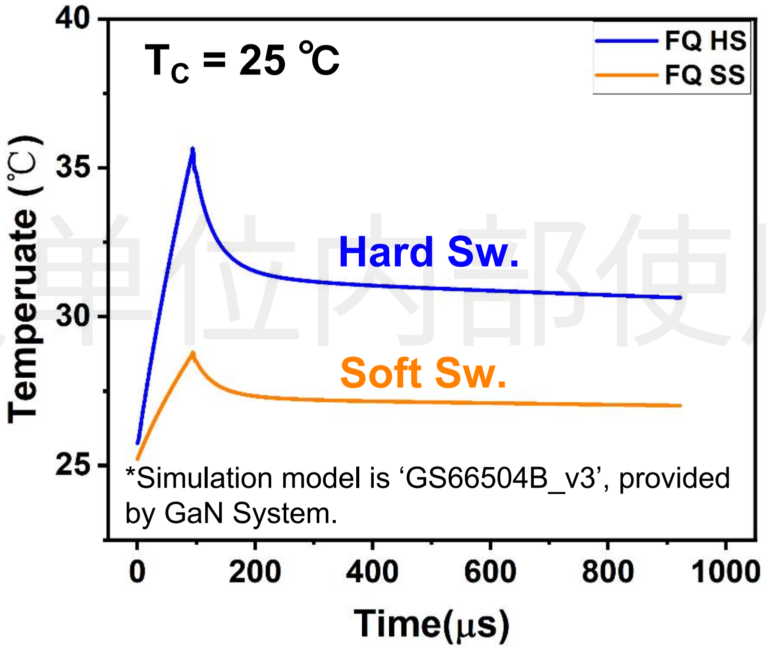
➢ 200kHz Hard Sw.



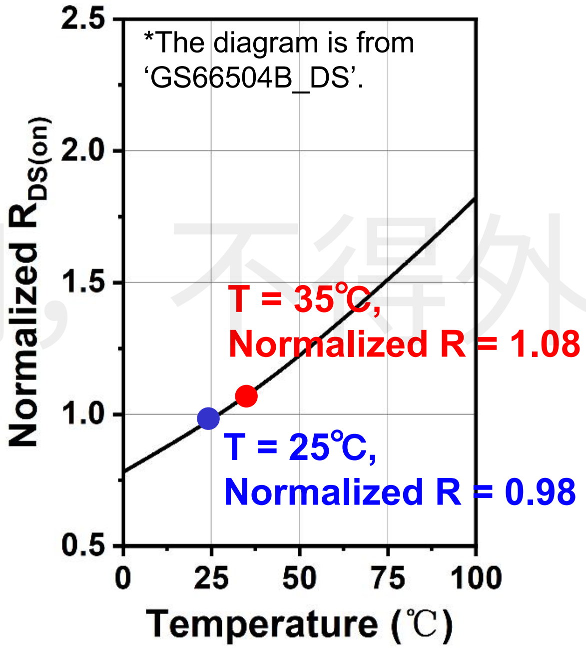
➢ 200kHz Soft Sw.



■ Thermal Simulation in PLECS



■ $R_{DS(on)}$ Temp. Dependence



➢ MPT is still unsuitable for dynamic $R_{DS(on)}$ measuring.

Multi-group Double Pulse Test (MGDPT) is Selected

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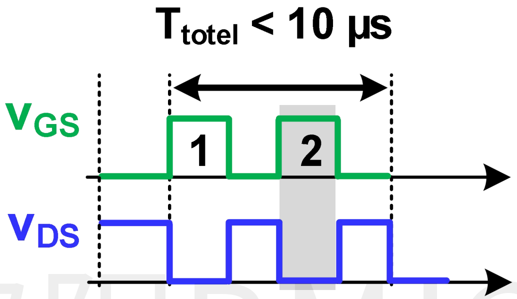
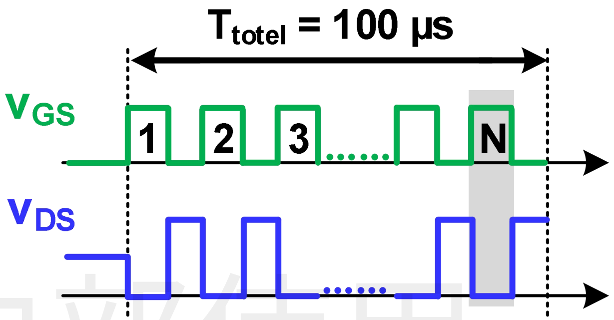
- Double Pulse Test (DPT)



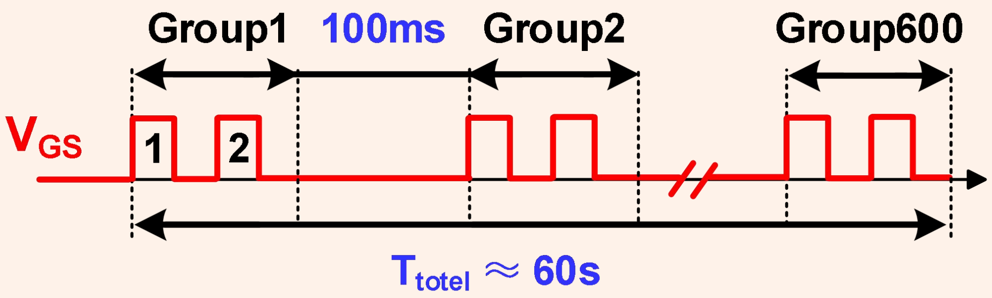
- ☐ No self-heating.
- ☐ Pre-voltage influence.

- Multi-pulse Test (MPT)



- ☐ Steady state.
- ☐ Self-heating.

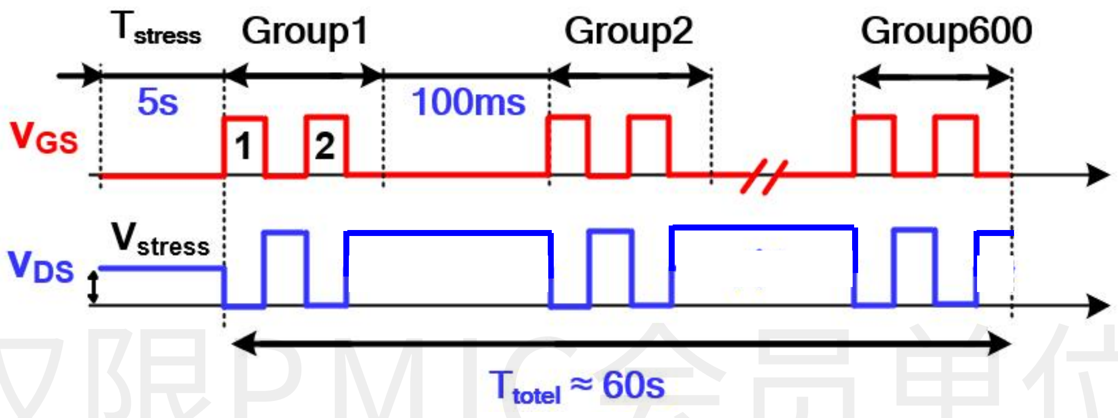
- Multi-group double pulse test (MGDPT) [11]



- ☐ Sufficient off-state pulse width for heat dissipation.
- ☐ Sufficient total time for reaching the steady state.

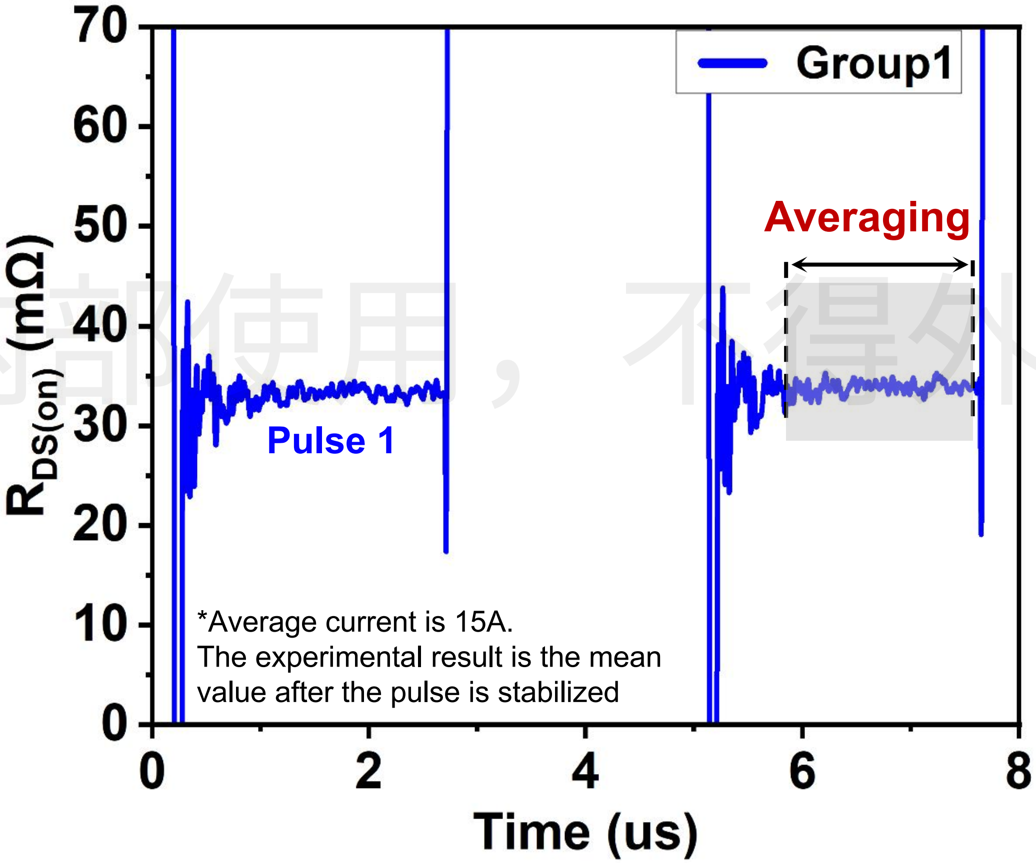
[11] CASA 005—2022 硬开关电路的GaN HEMT动态电阻测试方法.

Multi-group DPT's Experimental Conditions and Data Processing Methods



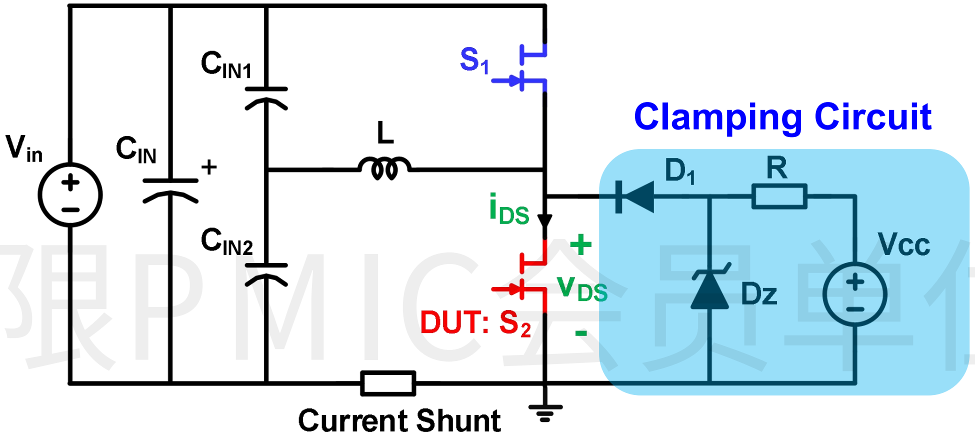
- ☐ Pre-T_{stress} = **5** s
- ☐ Pre-V_{stress} = **½ V_{BUS}**
- ☐ On-time = **2.5** μs

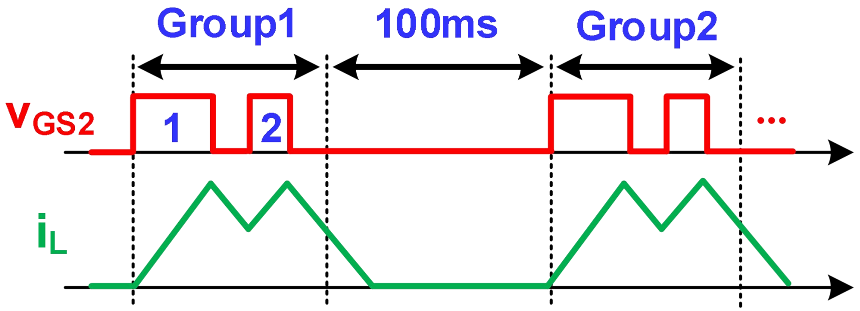
➢ **Multi-group DPT @400V, Hard Sw.**



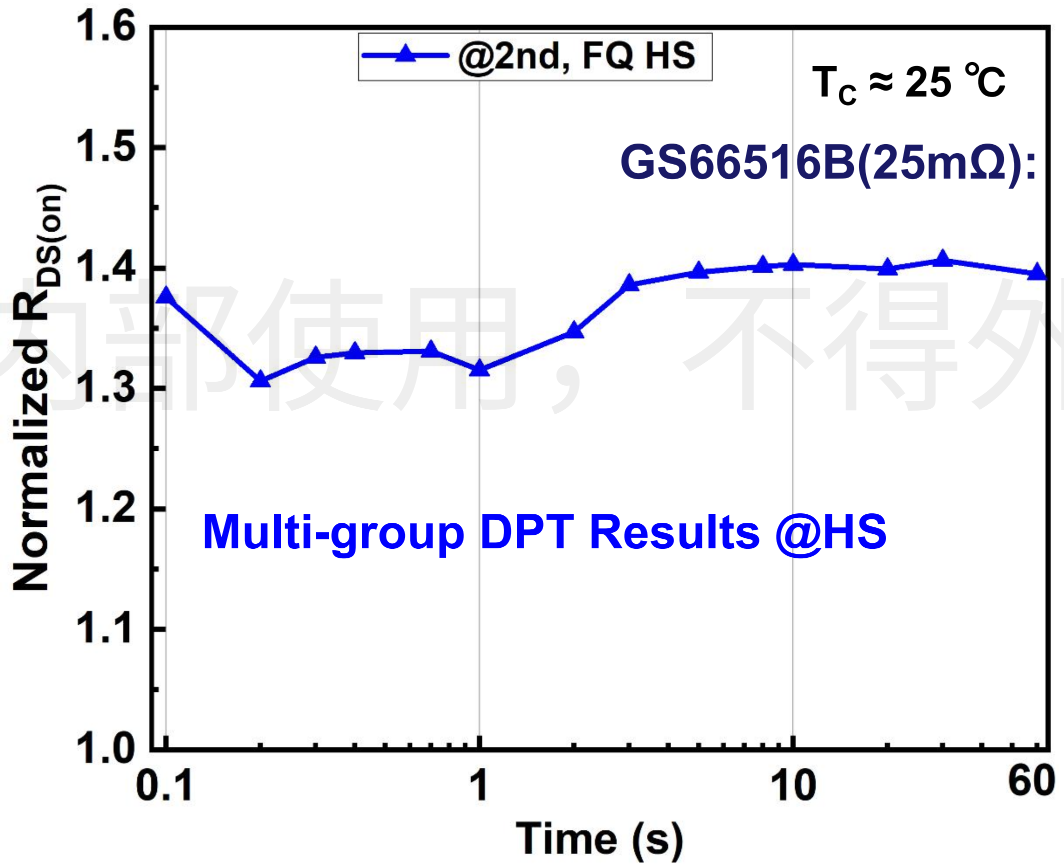
Hard Switching Multi-group DPT

■ Hard Switching Bench Circuit



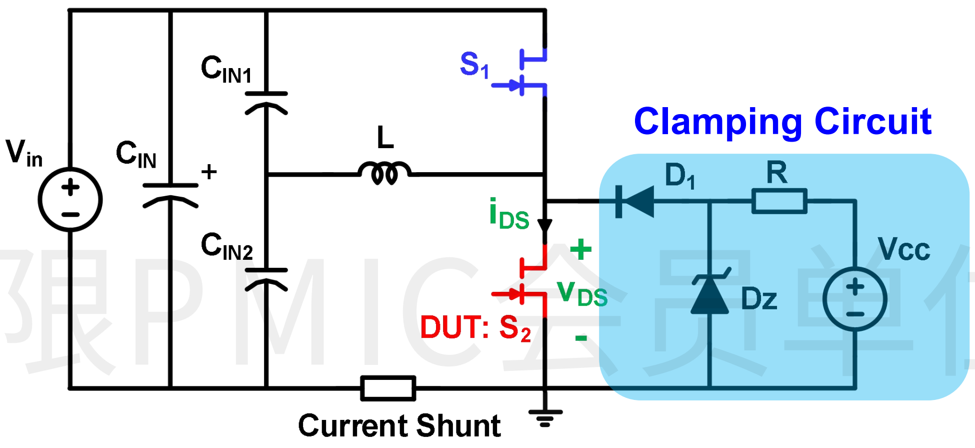


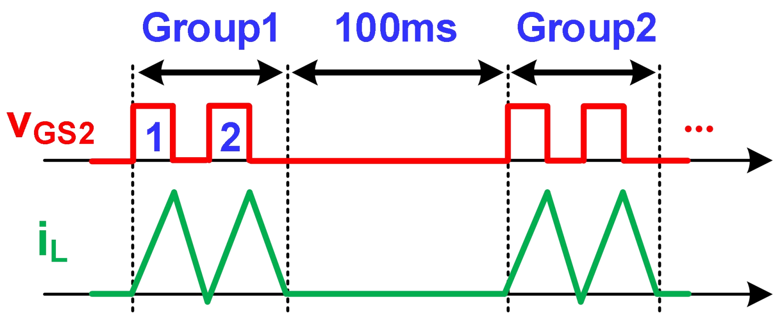
➢ @400V, 2.5μs on-time



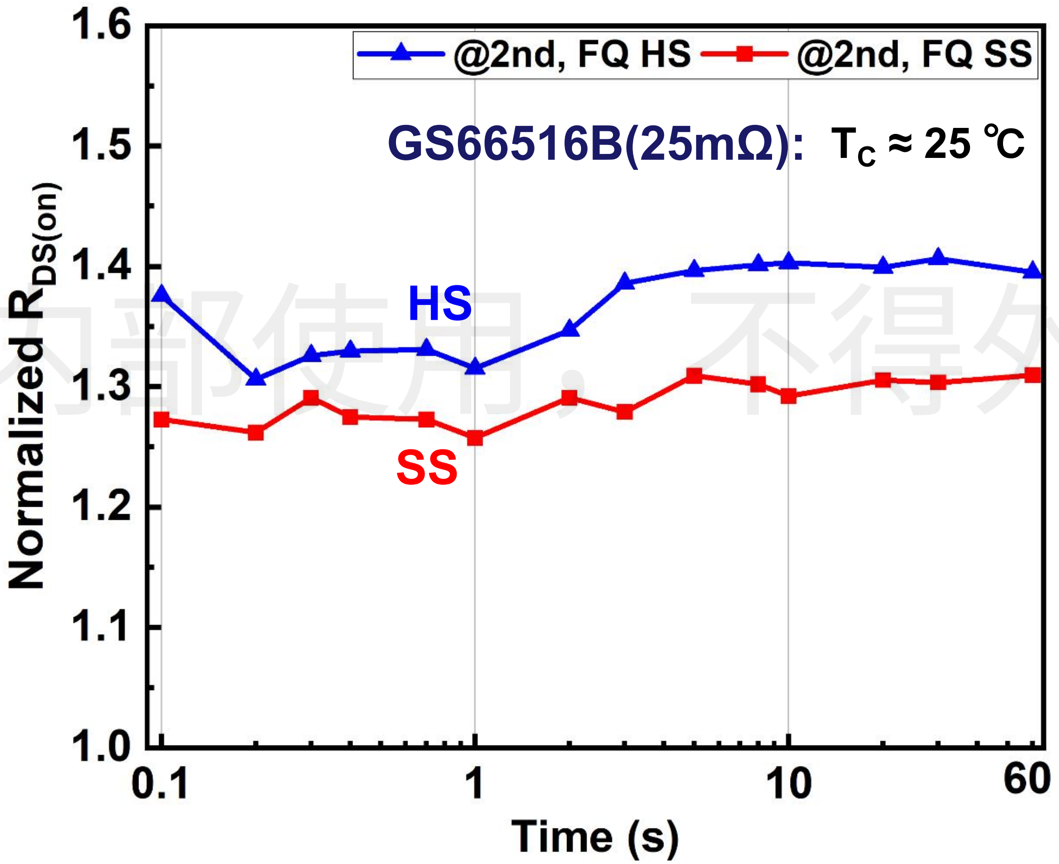
Soft Switching Multi-group DPT

■ **Soft Switching control method**

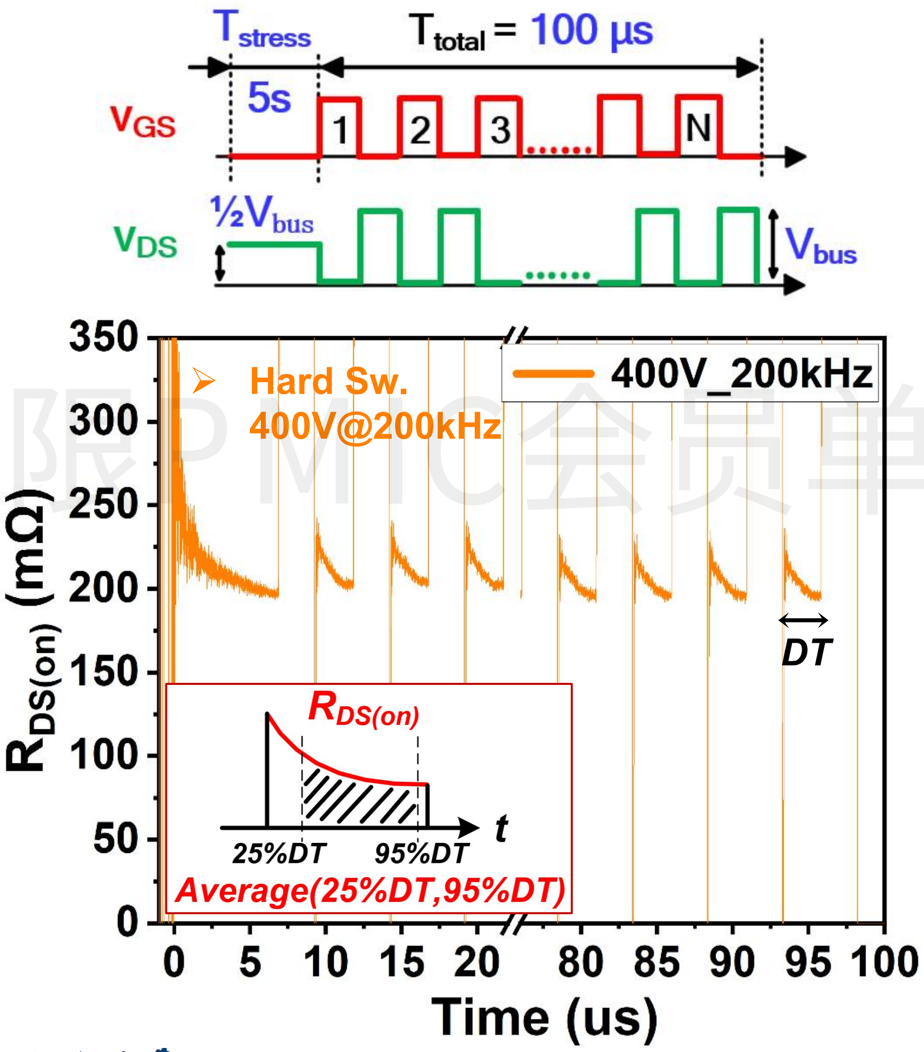


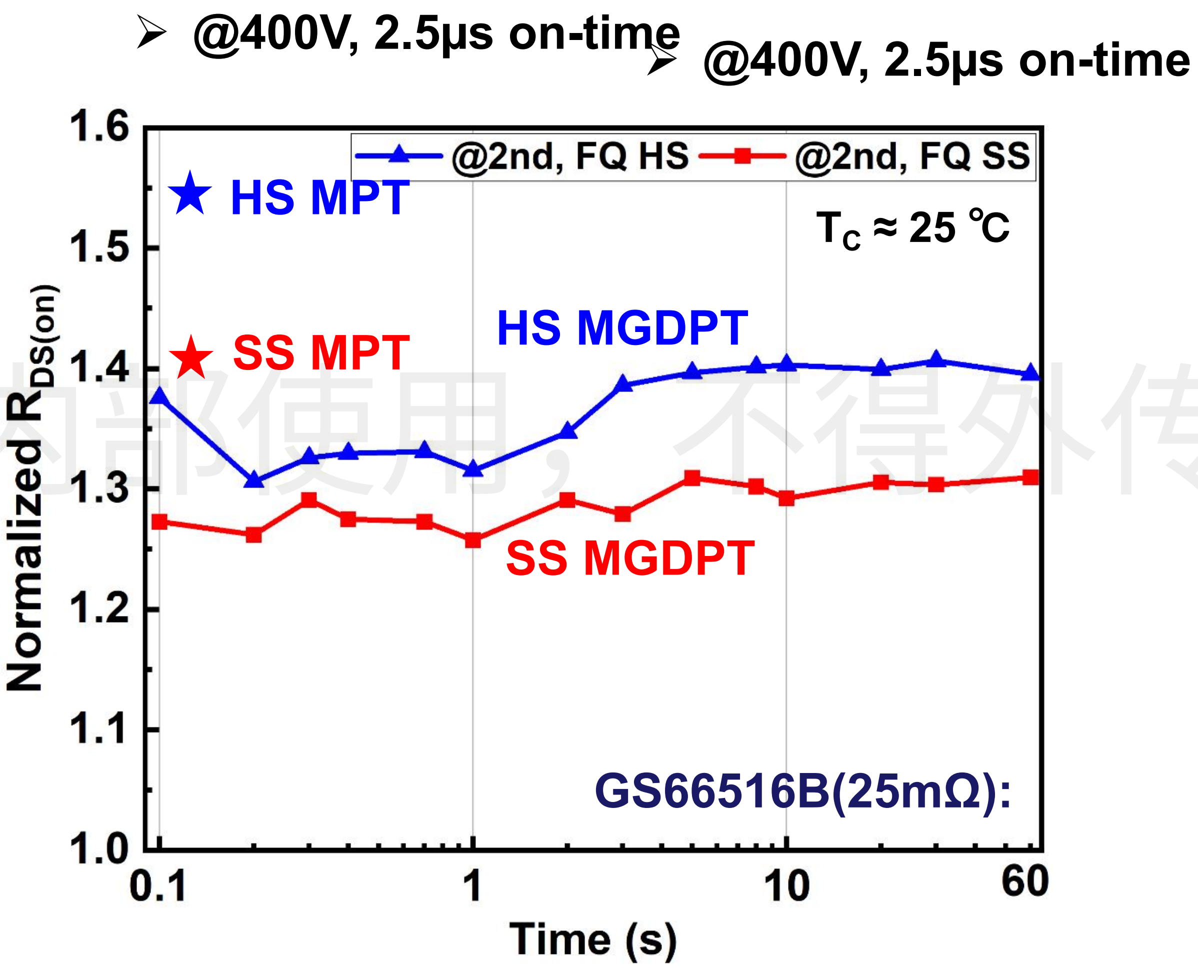


➢ **@400V, 2.5μs on-time**



Comparison between MPT and MGDPT





Test Results Comparison between Different GaN Devices under MGDPT and MPT（FQ@400V）

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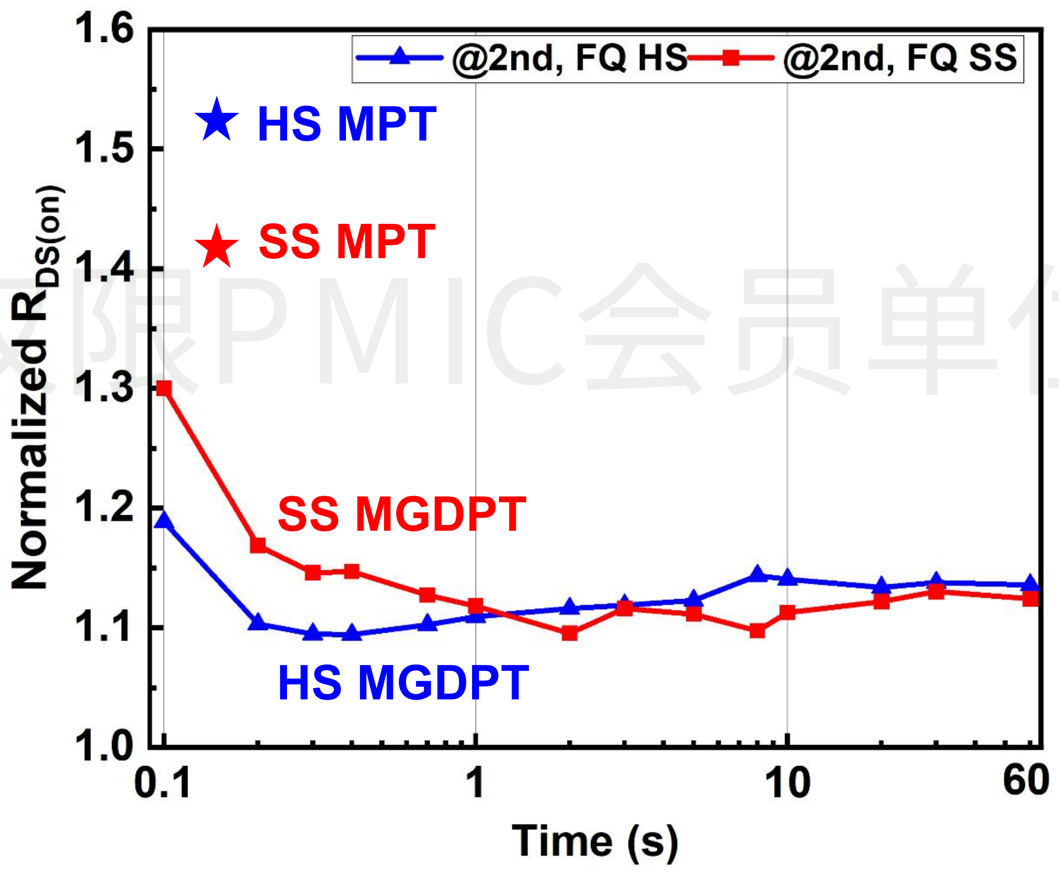
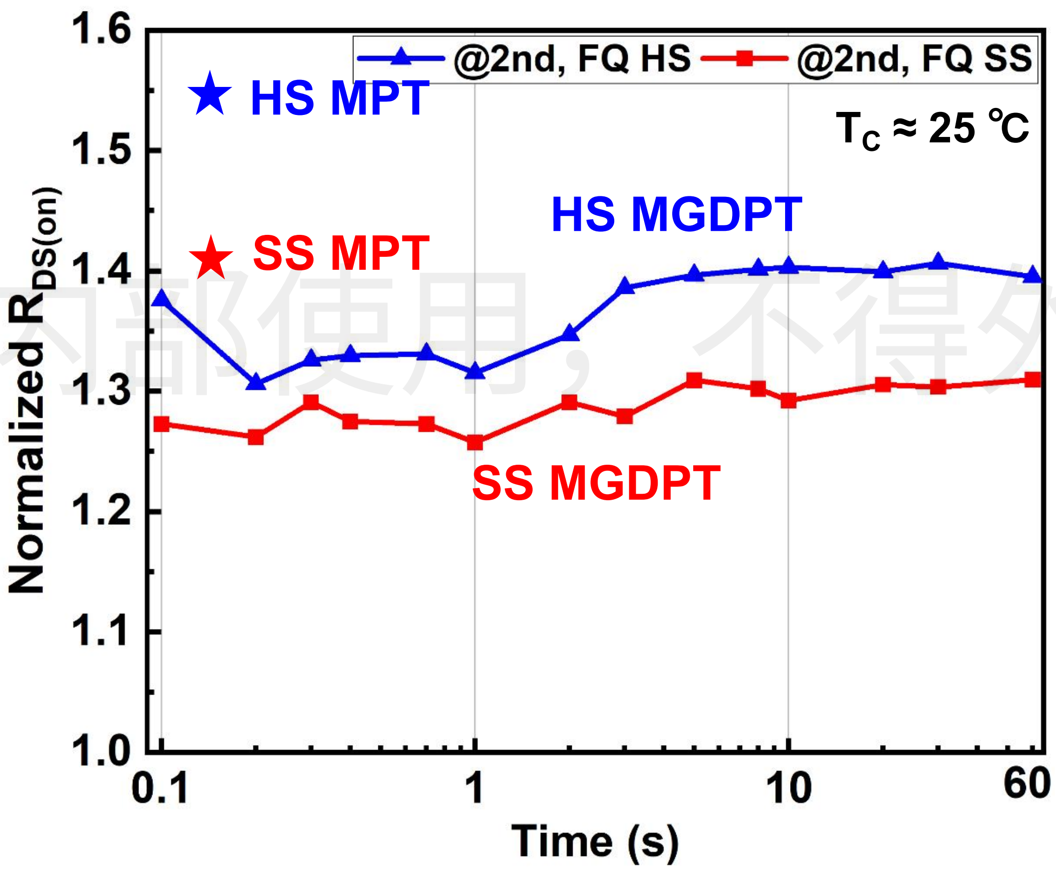
- IGI60F1414A1L (HD-GIT) 140mΩ

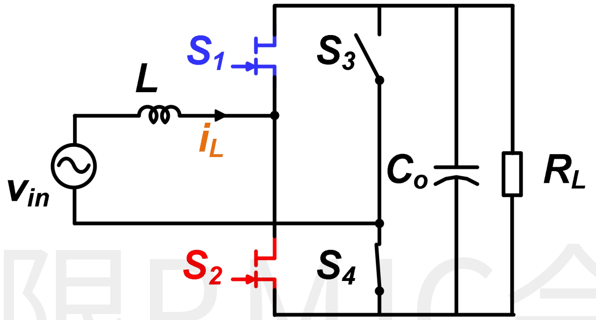


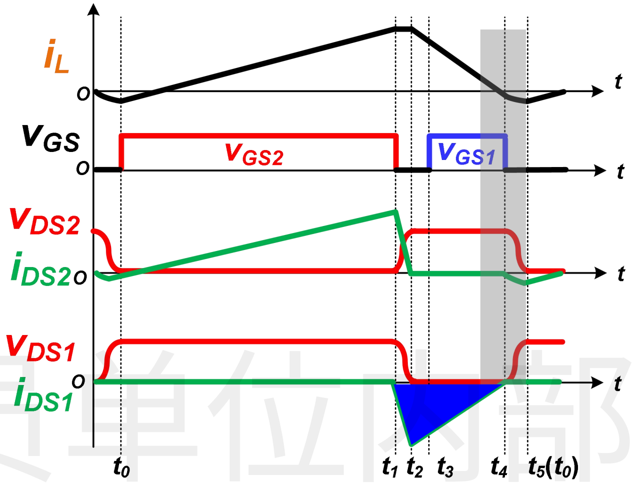
- GS66156B (p-GaN) 25mΩ



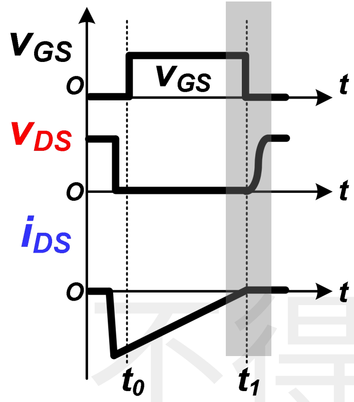
AC/DC Applications: GaN Devices Operate in the Third Quadrant

■ **Totem Pole PFC**

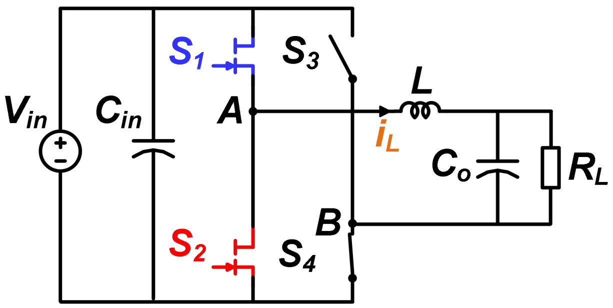


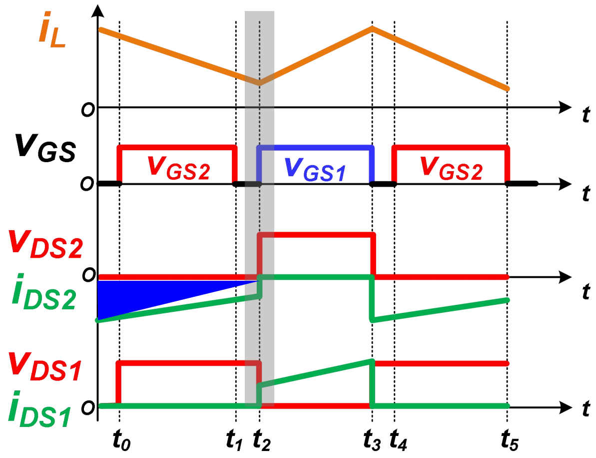


□ **Third Quadrant Soft Sw.**

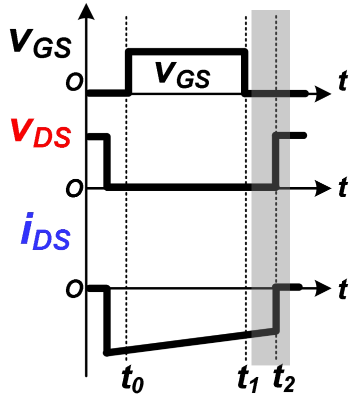


■ **Inverter**



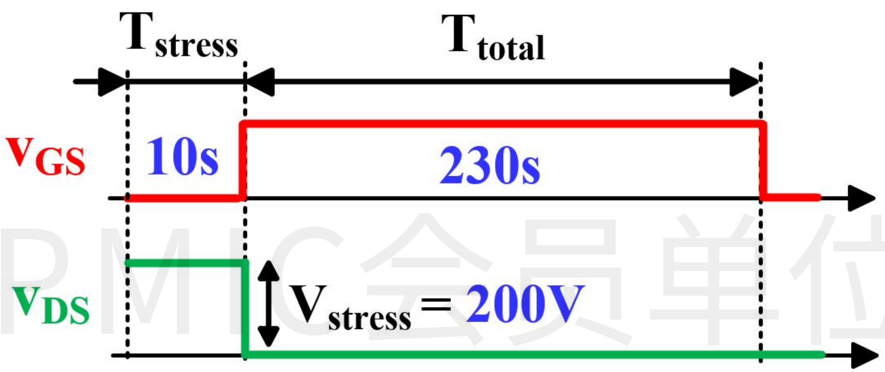


□ **Third Quadrant Hard Sw.**

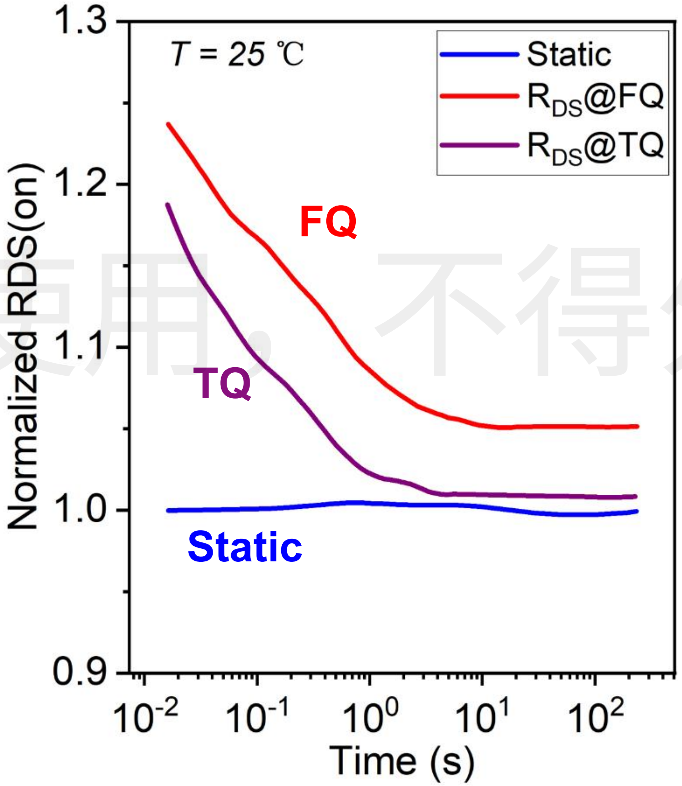


Third Quadrant $R_{DS(on)}$ Behavior of GaN Devices is Different with First Quadrant [12]

■ T_{stress} = 10 s ,V_{stress}= 200 V, T_{totel} = 230 s



Conventional p-GaN gate HEMT[12]



Conclusion:

- ☐ In third quadrant, dynamic $R_{DS(on)}$ degradation is slightly.

Areas for improvement:

- ☐ Considering higher voltage stress、Applying multi-group DPT

[12] D. Cingu et al., “Reliability of p-GaN Gate HEMTs in Reverse Conduction,” IEEE Trans. Electron Devices, vol. 68, no. 2, pp. 645–652, Feb. 2021

Third Quadrant HS & SS Multi-group DPT

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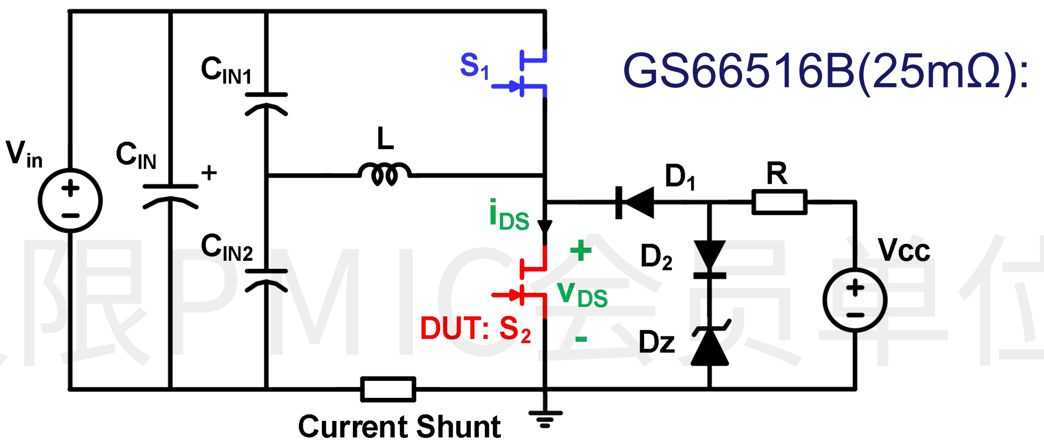
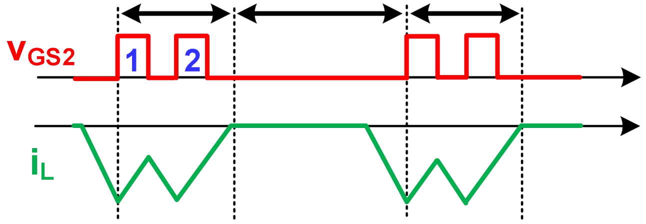
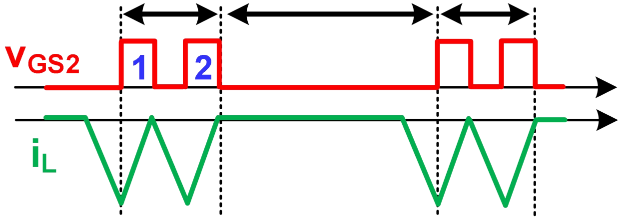
■ Third Quadrant Test Bench



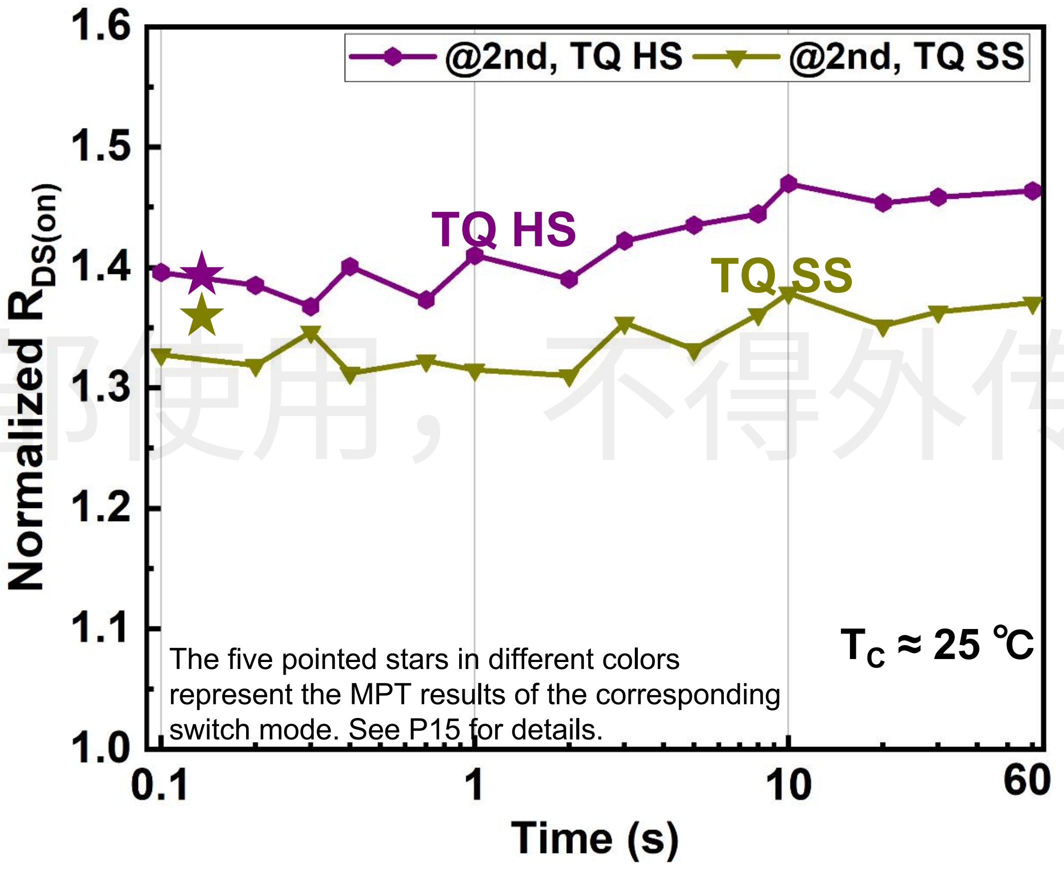


HS test waveforms



SS test waveforms

➢ @400V, 2.5μs on-time



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Test Results Comparison between Different GaN Devices under MGDPT and MPT（TQ@400V）

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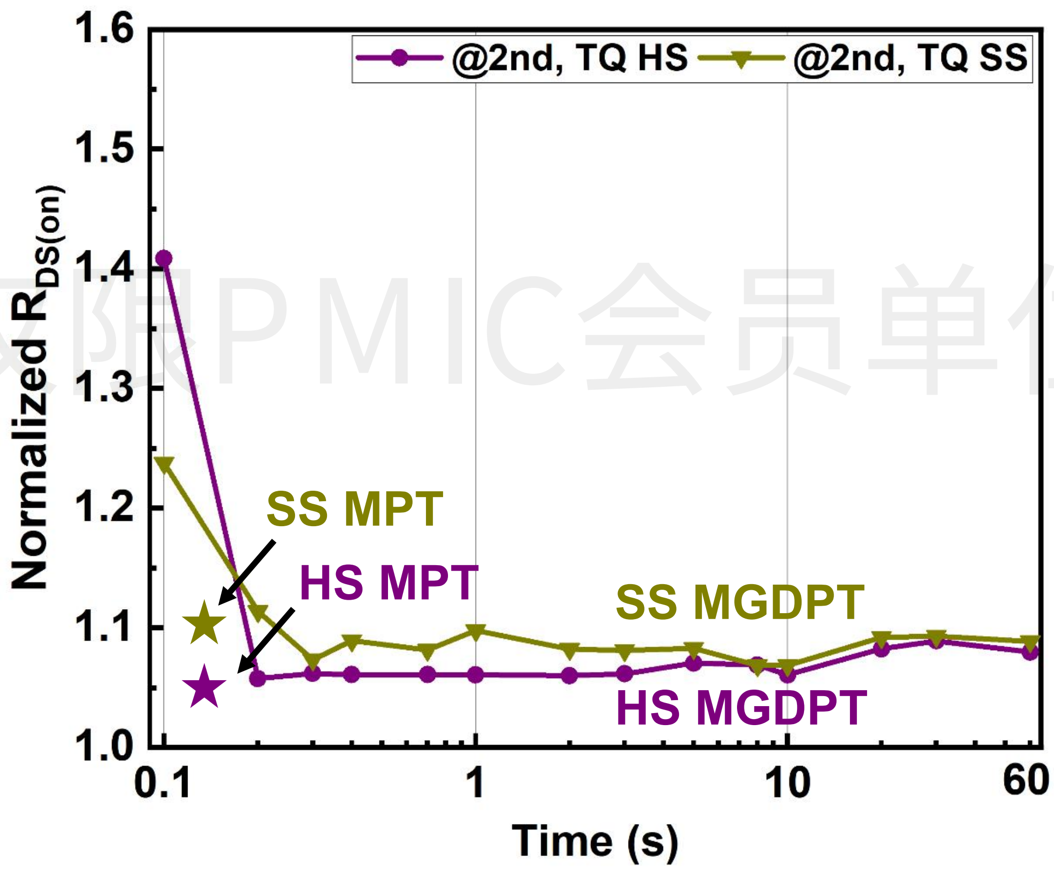
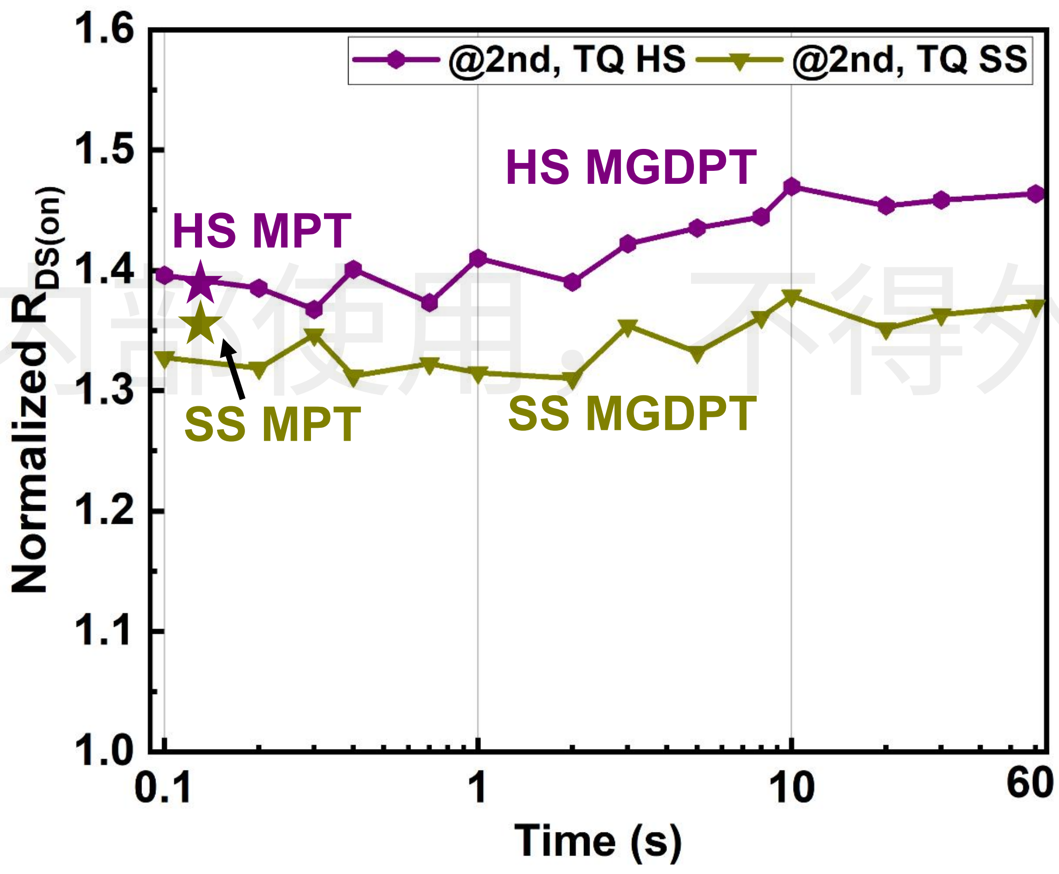
- IGI60F1414A1L (HD-GIT) 140mΩ



- GS66156B (p-GaN) 25mΩ



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Summary of Multi-group DPT Results under 1st & 3rd Quadrant @400V

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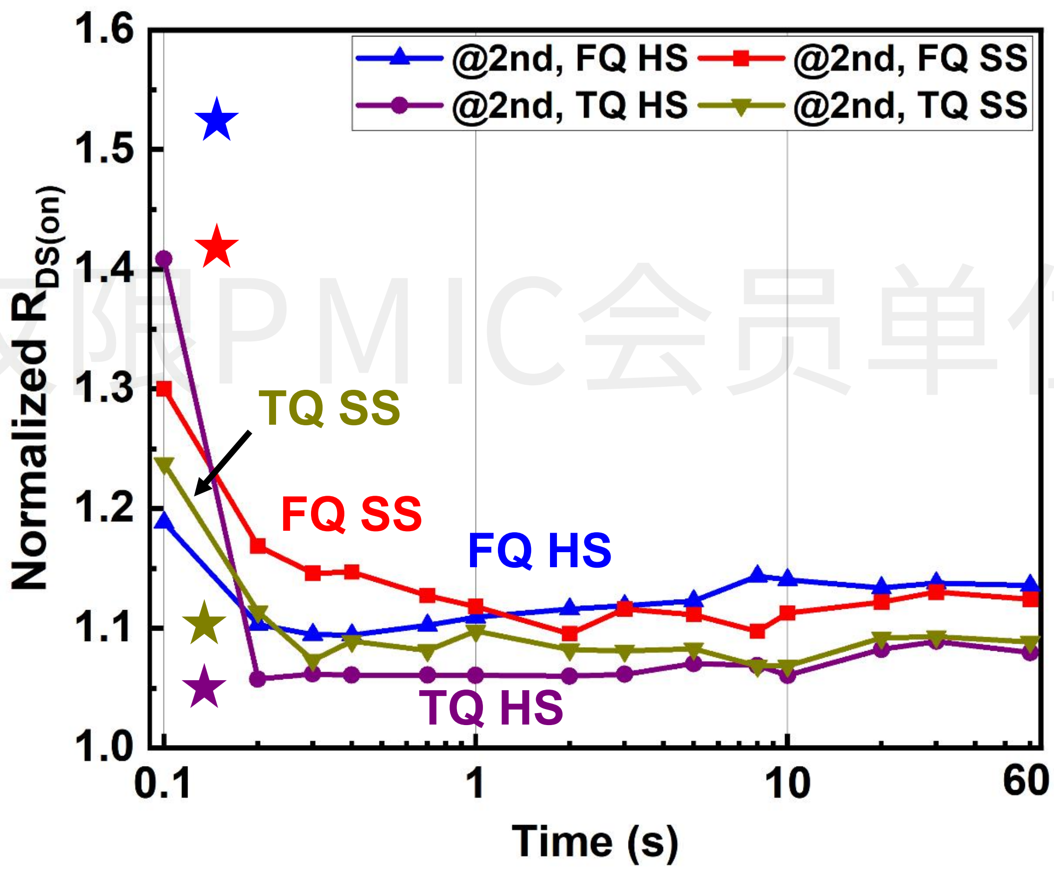
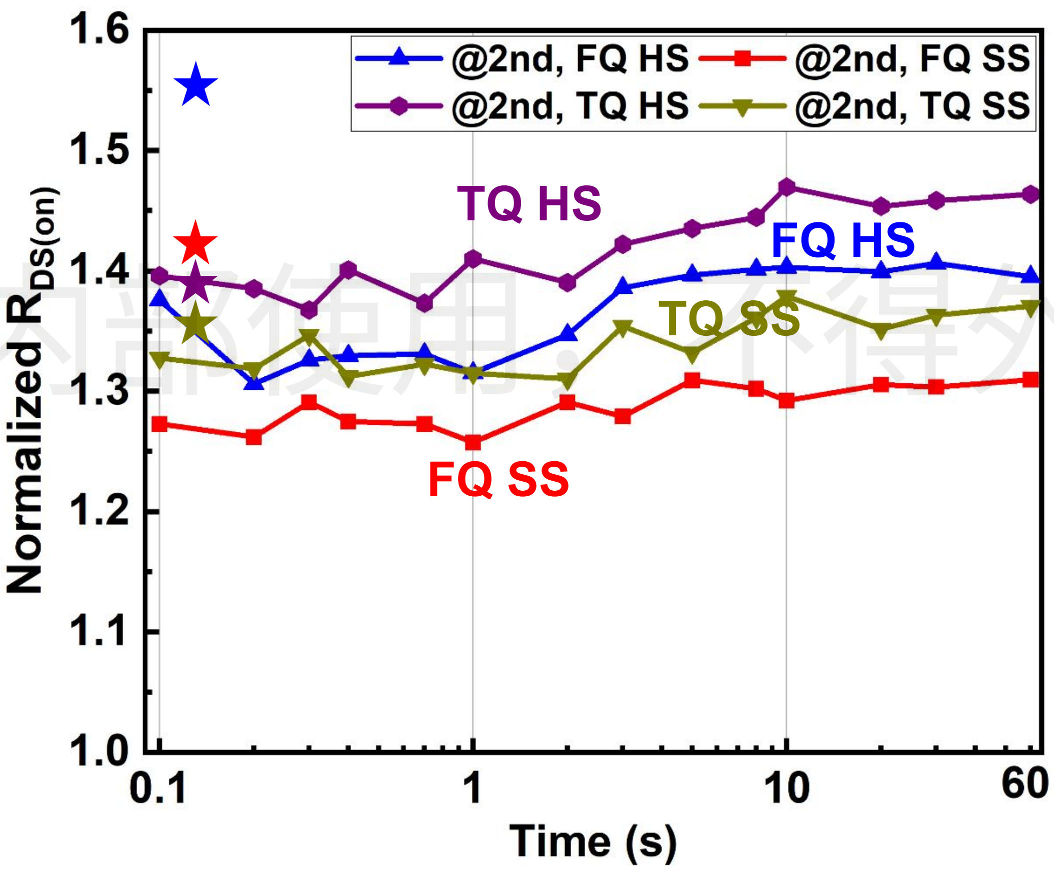
➢ IGI60F1414A1L (HD-GIT) 140mΩ



➢ GS66156B (p-GaN) 25mΩ



Conclusions

1. Test Bench for dynamic resistance of GaN device should consider the effect of numerous parameters, such as different detrap time of different devices structures, pre-stress, pulses, junction temp.,etc.

2. 3rd quadrant conducting of GaN is different to 1st quadrant , the dynamic resistance evaluation of GaN should consider it.

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- BPS 晶丰明源
- SINOMAGS 希磁科技

浙大科创中心电源管理技术创新联盟(PMIC)会员 2023

Power Management Innovation Consortium

PMIC 高校主导、行业共建的电源管理技术生态链

器件 → 装置 → 系统

矽力杰半导体
杰华特半导体
铭普光磁
芯朋微
纳微半导体
英诺赛科
横店东磁
希磁科技
晶丰明源
英飞凌

深圳英飞源技术	杭州英飞特新能源
杰瑞电子(716所)	奥海科技
长城电源	麦田能源
杭州富特科技	酷科电子（紫米）
铂科电子	茂硕电源
皓文电子	深圳雷能
麦格米特	欣锐科技
航芯源	爱科赛博

OPPO技术
台达电子
VIVO技术
中兴通讯
蔚斯博系统
小米科技

- 合作生态
- 模式探索
- 共性基础
- 未来技术

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Thank you
for your time

Test Bench with Clamping Circuit Applicable to the Third Quadrant

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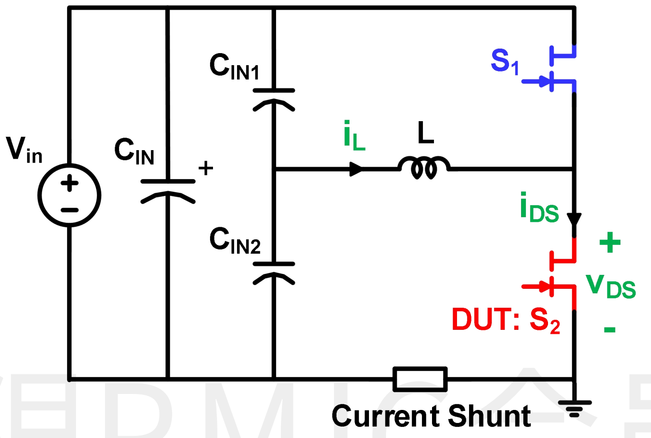
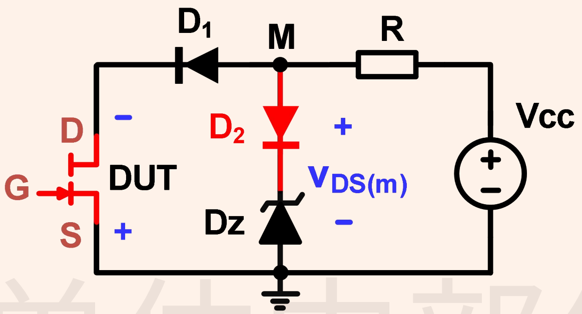
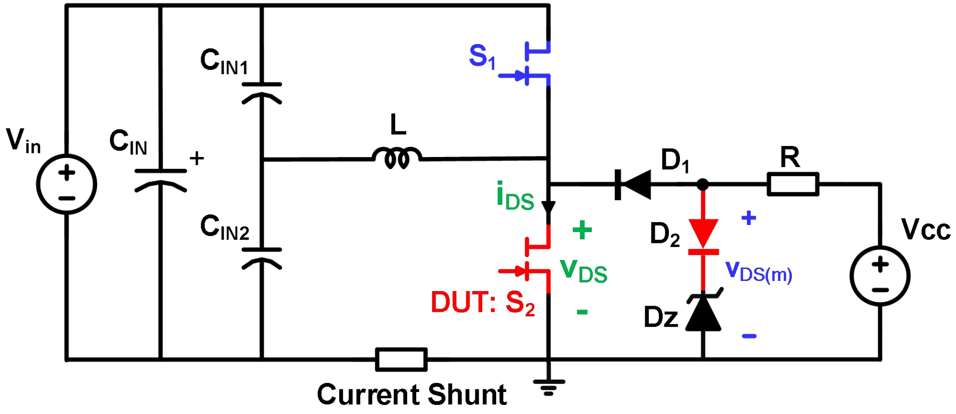


■ **Improved Clamping Circuit**

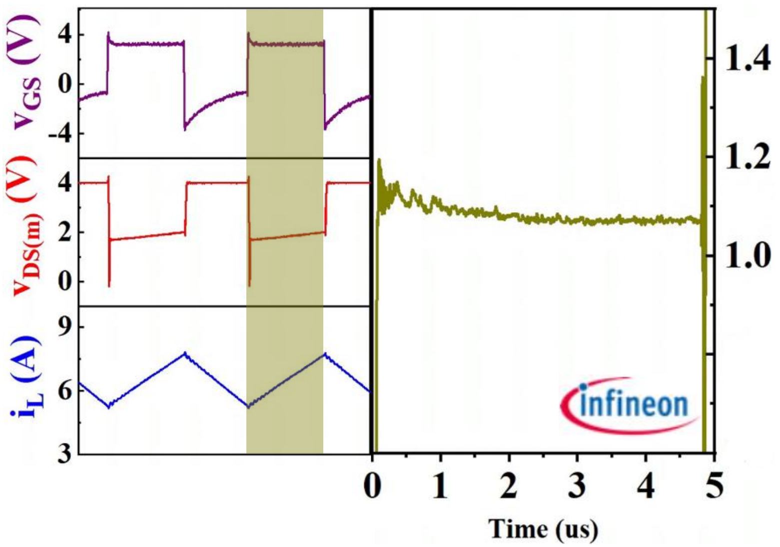


- ☐ Introduce D2 to block Dz's current
- ☐ Can be used in first and third quadrants.

Dynamic $R_{DSON} = (v_{DS(m)} - v_{D1})/i_{DS}$



➢ IGI60F1414A1L @100V



[7] R. Li, X. Wu, S. Yang, and K. Sheng, "Dynamic on-State Resistance Test and Evaluation of GaN Power Devices Under Hard- and Soft-Switching Conditions by Double and Multiple Pulses,"

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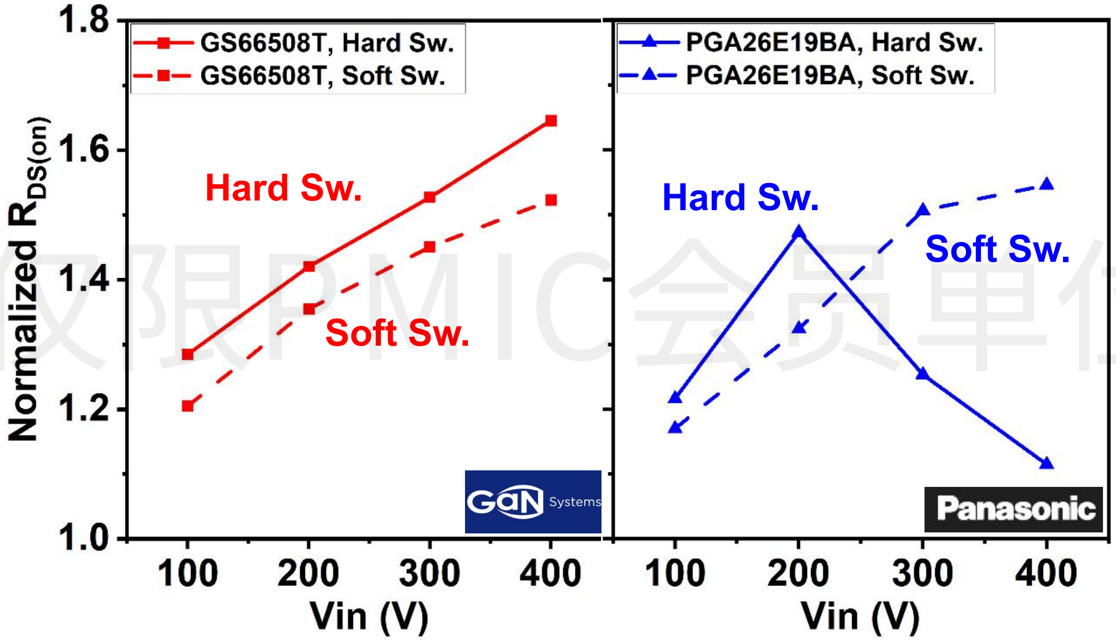
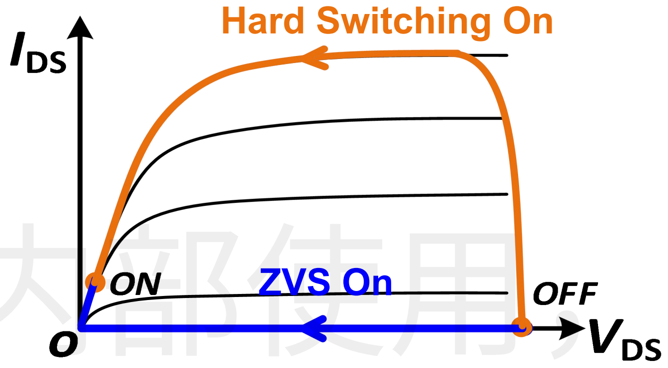
ZJU-Hangzhou Global Scientific and Technological Innovation Center

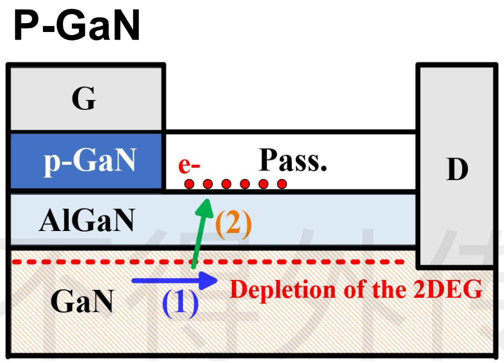
Hot Electrons Effect makes $R_{DS(on)}$ Higher under Hard Switching Conditions

■ Double Pulse Test (DPT) @2μs on-time



➢ Hot electrons effect（沟道热电子效应）



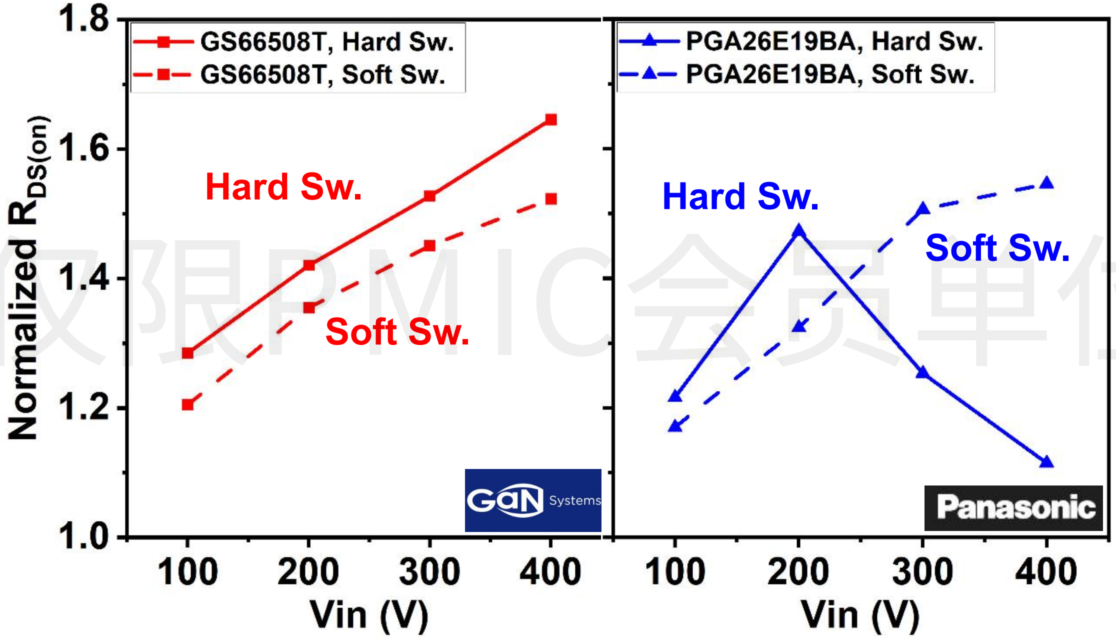


- ☐ Electric Field makes electrons "hot".
- ☐ Lead $R_{DS(on)}$ increase.
- ☐ $R_{DS(on)}$: Soft Sw. < Hard Sw.

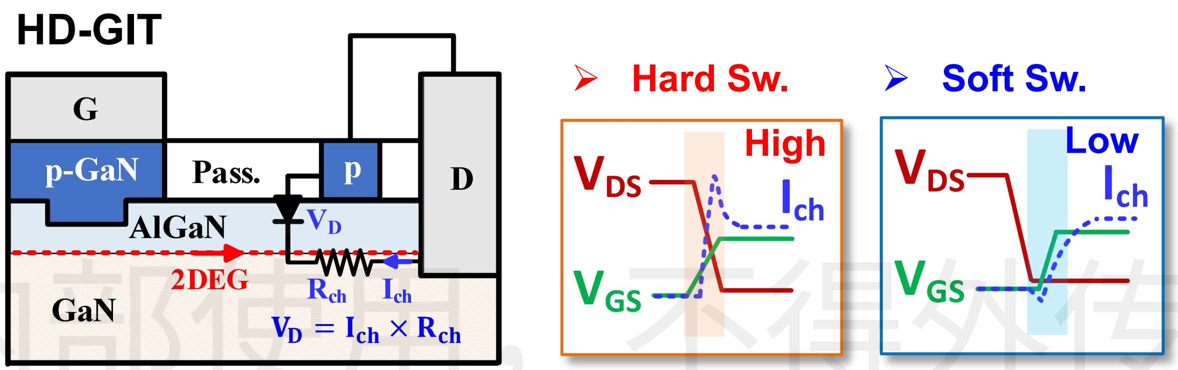
➢ Hot electrons effect dominates in p-GaN type device.

Hole Injection Effect Suppresses the $R_{DS(on)}$ Degradation under Hard Sw.

■ Double Pulse Test (DPT) @2μs on-time



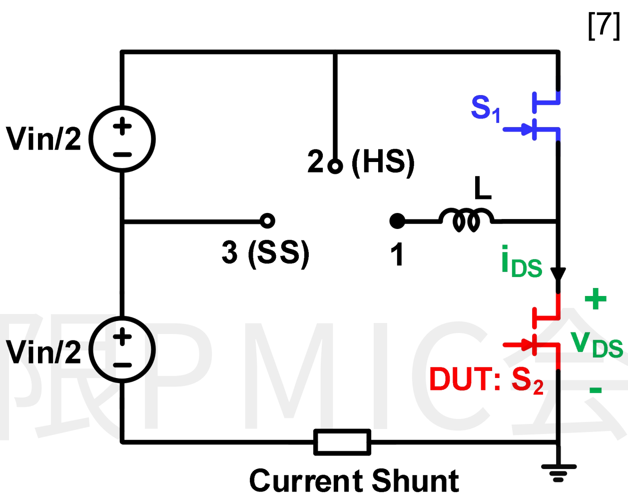
➢ Hole injection effect（空穴注入效应）



- ☐ High I_{ch} makes PN junction turn on.
- ☐ Dynamic Ron is suppressed
- ☐ $R_{DS(on)}$: Soft Sw. > Hard Sw.

➢ Hole Injection Effect plays a significant role in HD-GIT @V_{in} = 400V

Other Variables are Introduced in DPT: Different Pre-voltage Stress

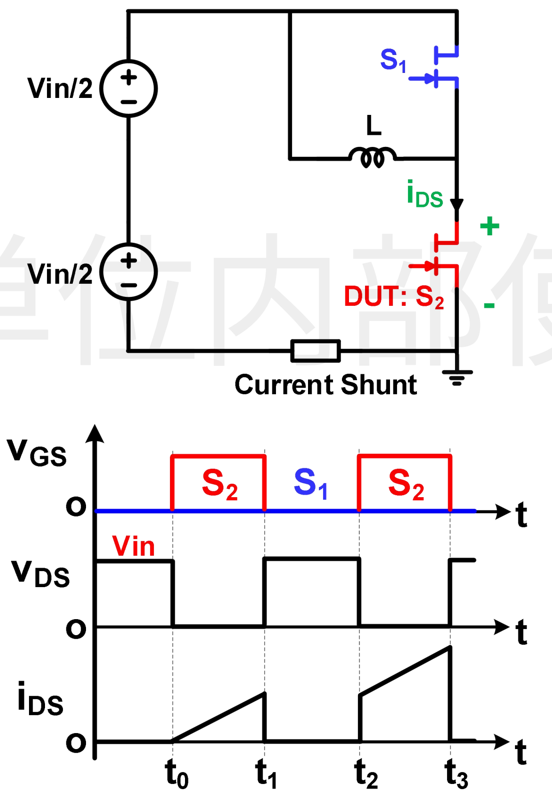


- Different switching mode
- Different pre-voltage stress

➢ **DPT results will be affected.**

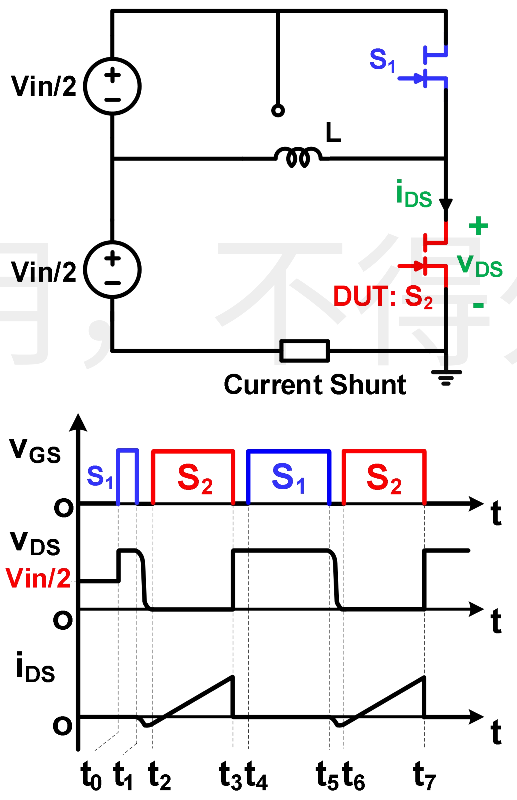
Connect 1 to 2 (HS).

Pre-voltage stress = Vin



Connect 1 to 3 (SS).

Pre-voltage stress = ½ Vin



[7] R. Li, X. Wu "Dynamic on-State Resistance Test and Evaluation of GaN Power Devices Under Hard- and Soft-Switching Conditions by Double and Multiple Pulses,"

Higher Pre-Voltage Stress Deepens the Electrons Trapping

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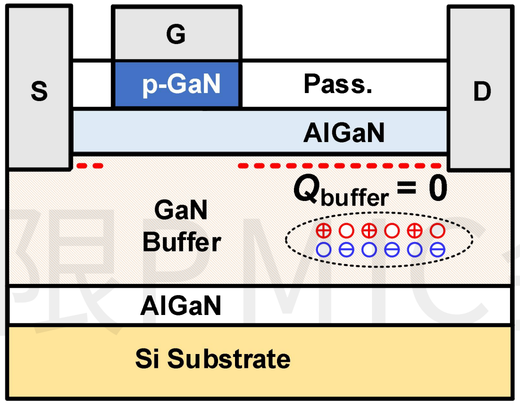
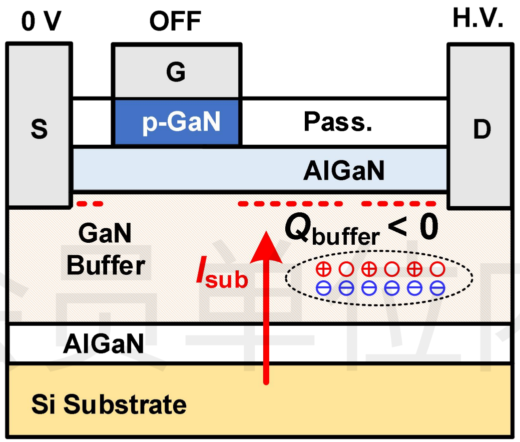
➢ OFF-state Trapping [8]

■ Fresh



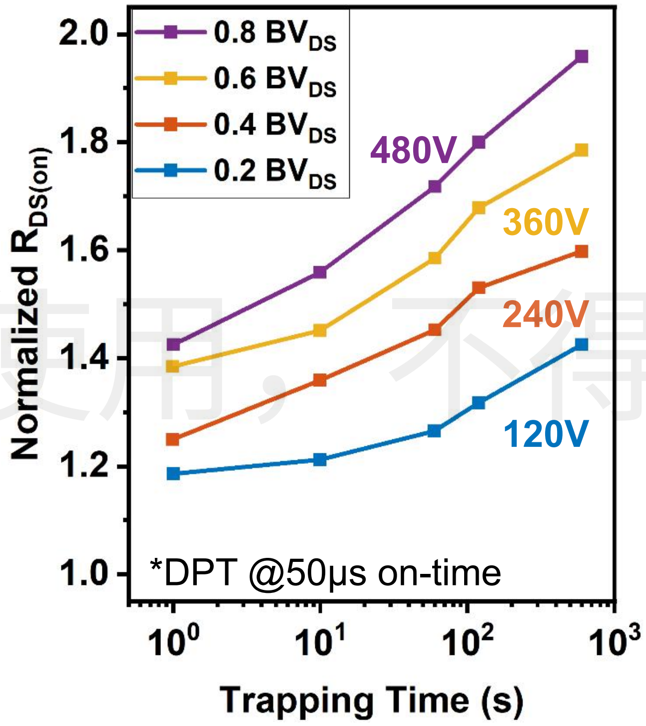
■ Large V_{DS} bias



☐ Lead to 2DEG depletion.

☐ Trapped electrons increase with V_{DS} bias.

➢ Dynamic $R_{DS(on)}$ vs. V_{DS} bias [9]



➢ V_{DS} bias seriously influence the dynamic $R_{DS(on)}$

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[8] S. Yang, C. Zhou, S. Han, K. Sheng, and K. J. Chen, “Buffer trapping-induced RON degradation in GaN-on-Si power transistors: Role of electron injection from Si substrate,”
[9] G. Zulauf, M. Guacci, and J. W. Kolar, “Dynamic on-Resistance in GaN-on-Si HEMTs: Origins, Dependencies, and Future Characterization Frameworks,”