



如何在元件操作(switching)狀態下執行
功率半導體/寬能隙半導體材料氮化鎵
(GaN)分析？

How to measure dynamic $R_{ds(on)}$, dynamic V_{th}
from trapping effect of GaN?

品勛科技股份有限公司
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氮化鎵的優點GaN(Gallium nitride) benefits

擁有較寬帶隙，可承受高溫、高壓、高頻以及高電流及高能源轉換效率

- ◆ Higher power transistor than any other solid state solution
- ◆ Highest power density, bringing the smallest convertor size
- ◆ Excellent temperature stability
- ◆ Superior efficiency

面對嚴苛測試要求，我們獨家代理販售「元件動態參數分析系統」，解決GaN元件在操作(switching)狀態下執行動態參數分析的困難

In the face of high-voltage and high-current dynamic testing requirements, we provided Device Dynamics Analyzer to solve the difficulty of dynamic analysis under programmable switching condition.

Difficult 1. 如何擷取/量測電荷補陷所造成的元件動態特性?
How to extract trapping induced dynamic characteristics.

Difficult 2. 如何在實際應用中評估GaN動態性能?
How to evaluate dynamic performance in real application.

Difficulty

1. 靜態特性不適用於實際應用
Static characteristics are not presentive to real applications.
2. 在GaN的高速瞬態下難以進行測量
Hard to do measurement under high speed transient of GaN.
3. 尚無商業解決方案來測量動態特性
No commercial solution to extract dynamic characteristics under system-like operation.
4. 尚無商業解決方案可執行動態可靠度測試
No commercial solution to extract dynamics reliability under independent factor acceleration.

Our Solution

1. 創新的結構可模擬DUT的切換條件
Innovated topology to simulate switching condition of application.
2. 創新的電路響應~100ns
Innovated clamping circuit response ~100ns.
3. 可設置精確的動態特性條件
Programmable conditions to exact dynamic characteristics under system-like operation.
4. Multi-DUT的5個獨立參數測試並可即時動態參數監控
5 independent accelerations for Multi-DUT with real-time monitoring of dynamic parameter.

◆◆ Our Products: Testing tools for GaN devices



- Device Statics Analyzer (DSA1010)
- Device Dynamics Analyzer (DDA8010)*
- Device Dynamic Reliability Analyzer (DDRA8010, 2022Q1)**

* Dynamics = Trapping induced Dynamic Characteristics under system-like operation

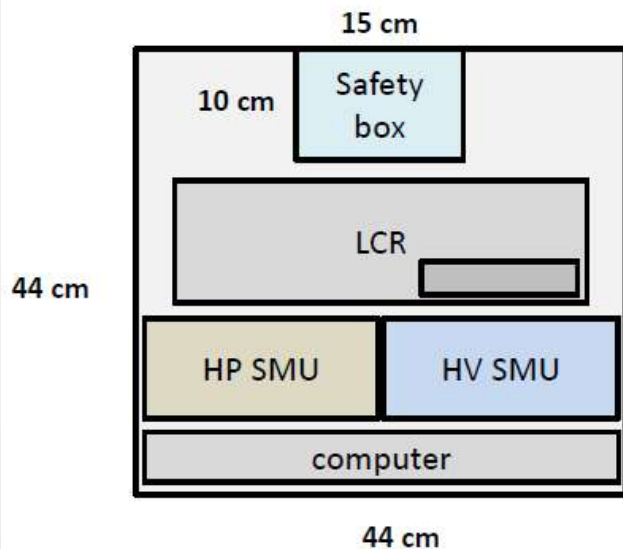
** Dynamic Reliability = Lifetimes prediction under system operation



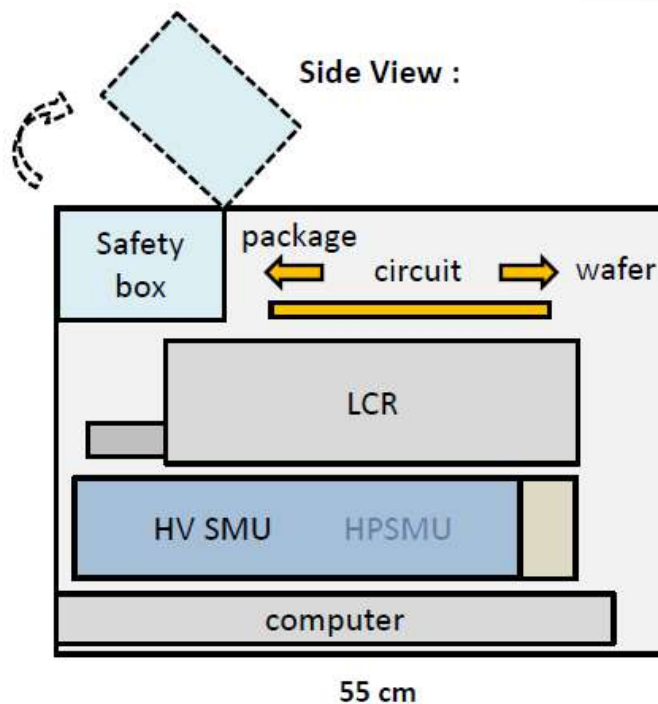
◆ Device Statics Analyzer (DSA1010) : Mechanics

- Package or Wafer
- Standard Rack fitted

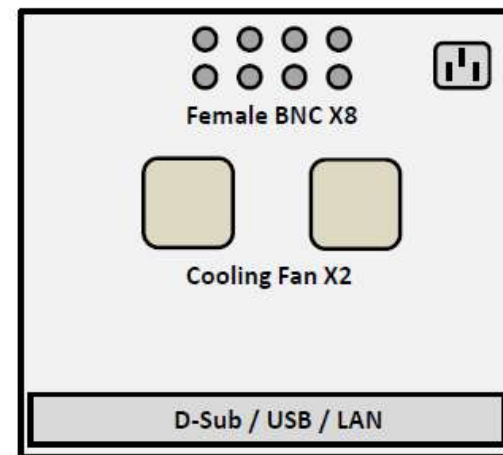
Front View :



Side View :



Rear View :



❖ Device Statics Analyzer (DSA1010)



◆ Device Statics Analyzer: DSA1010 Features



- **Friendly user interface**

- Transistor mode or Diode mode
- Testing Plan for series tests

- **Flexible DUT connection**

- Package-Level
- Wafer-Level

- **I-V & C-V automation**

- SMU + CMU auto switch
- HV Bias-Tee integrated

- **DC & Pulse automation**

- DC SMU + Pulse SMU auto switch

- **Specification**

- DC : 1000V/10mA, 40V/3A
- Pulse : 20V/10A, 35V/5A



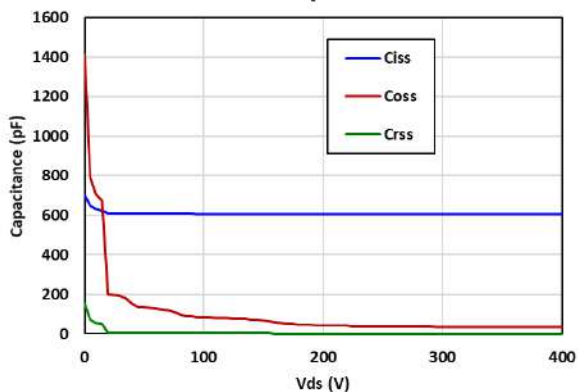
DS1010 : Device FOM Benchmark

FOM	Transphorm	GaN Systems	Infineon	Unit
Rdson	116	123	136	mΩ
Qoss	36	18.9	15.7	nC
Qgd	1.69	0.55	0.62	nC
Eoss	3.84	2.22	2.56	μJ
Ron*Qoss	4176	2325	2135	mΩ*nC
Ron*Qgd	196.0	67.7	84.3	mΩ*nC
Ron*Eoss	445.4	273.1	348.2	mΩ*μJ

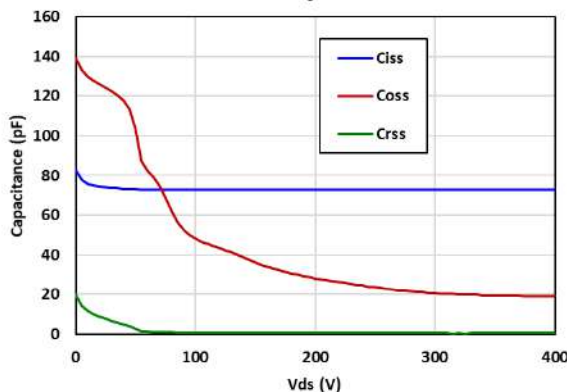
Figure of Merit (FOM) :

- Normalized to Rdson for size independent
- $R_{dson} \times \text{Die size} = R_{sp}$ for wafer cost
- $R_{dson} \times Q_{oss}$ for reverse (diode) switching loss
- $R_{dson} \times Q_{gd}$ for turn-on speed (switching loss)
- $R_{dson} \times E_{oss}$ for turn-off switching loss

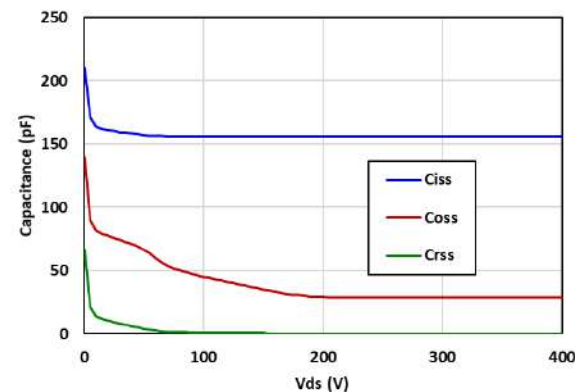
Transphorm



GaN Systems



Infineon



- Device Statics Analyzer (DSA1010)
- Device Dynamics Analyzer (DDA8010)*
- Device Dynamic Reliability Analyzer (DDRA8010, 2021Q3)**

* Dynamics = Trapping induced Dynamic Characteristics under system-like operation

** Dynamic Reliability = Lifetimes prediction under system operation



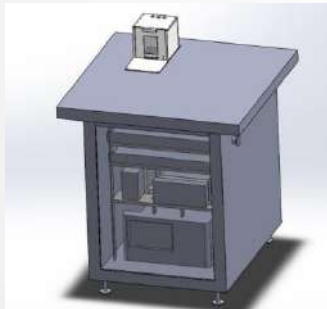
◆ Device Dynamics Analyzer (DDA8010) Photo



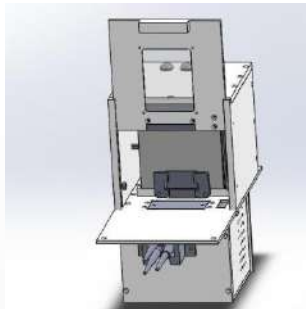
◆ Device Dynamics Analyzer: DDA8010 Prototype



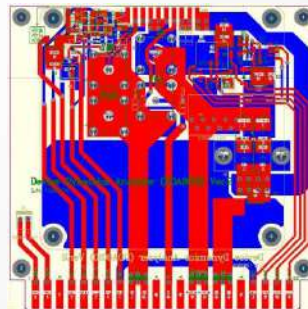
- ◆ Switching On-Vg : -12V~12V for device benchmark
- ◆ Switching Voltage : <800V
- ◆ Switching Current : <10A
- ◆ Switching Frequency : <500kHz
- ◆ Switching Duty : 10%~90%
- ◆ Temperature : 25C~175C
- ◆ Characterization Items : Dynamic Rdson(HSW, ZVS), Dynamic Rsdon(ZVS), Dynamic Vth, Dynamic Vsd, Dynamic HTOL (SALT), Pulse I-V...



Mechanical & thermal Control

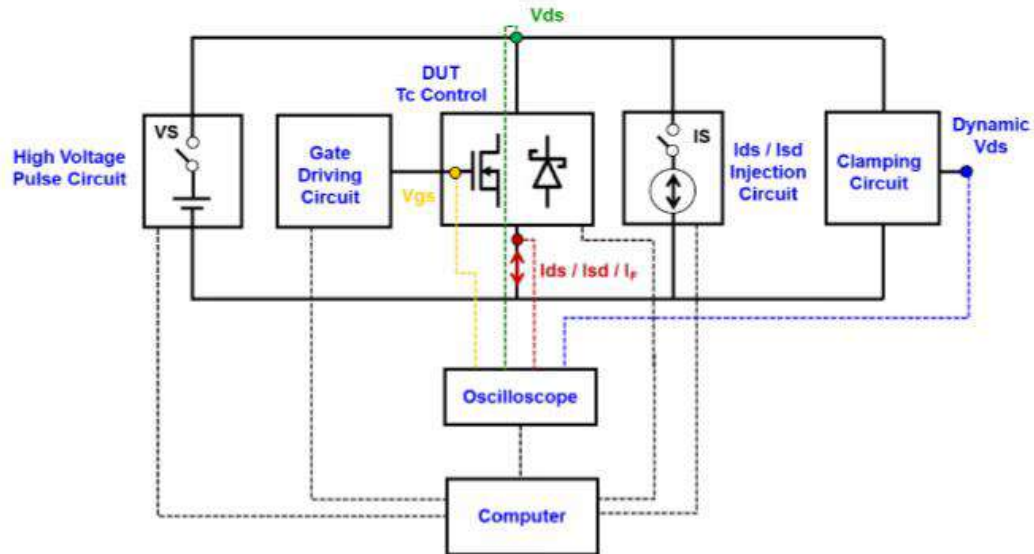


Safety Box of DUT

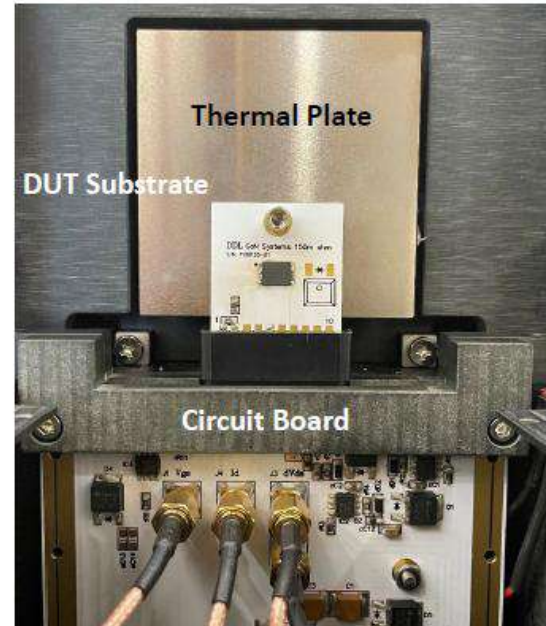
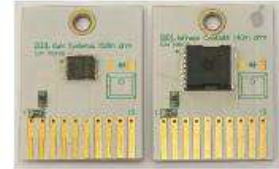


Circuit Board

◆ DDA8010 : Configuration



Different Packages
on DUT Substrates



DDA8010 : User Interface of Pulse IV



Device dynamics analyzer v2.3.0

File Edit Operate Tools Window Help

Device Dynamics Lab

Save folder: D:\DATA\DDL Device name: Device#1

Testing Plan

Temp	Test Item
125	Dynamic Rdson
25	END

Add View Replace Remove Clear Save Load

Switching On-Vg: 6 Switching Off-Vg: 0 Temperature: 25

Process Temperature: 48.9C Set Temperature: 25.0C

Standby Testing Tc>50C Pump status

Run ALL STOP

Start setting Pulse IV Dynamic Vsd Dynamic Rdson Dynamic Vth Dynamic HTOL Dynamic HTRB Baking END

ON Drain Current vs Gate Voltage

Id-Vg: Vd (V) Step Vd (V) Snapshot Scope Save Save interval STOP

Id-Vg: Vg range (V) Step Vg(V)

25C,Vd=0.5 25C,Vd=1.0

ON Drain Current vs Drain Voltage

Id-Vd: Vg (V) Step Vg (V) Snapshot Scope Save Save interval STOP

Id-Vd: Vd range (V) Step Vd (V)

25C,Vg=1.0 25C,Vg=2.0 25C,Vg=3.0 25C,Vg=4.0 25C,Vg=5.0 25C,Vg=6.0

DDA8010 : User Interface of Dynamic Rdson



Device dynamics analyzer v2.3.1

File Edit Operate Tools Window Help

Device Dynamics Lab

Save folder: D:\DATA\DDL Device name: Device#1

Testing Plan

Temp	Test Item
25	Dynamic Rdson
25	END

Add View Replace Remove Clear Save Load

Switching On-Vg: 6 Switching Off-Vg: 0 Temperature: 25

Process Temperature: 24.9C Set Temperature: 25.0C

Standby Testing Tc>50C Pump status

Run ALL STOP

Start setting Pulse IV Dynamic Vsd Dynamic Rdson Dynamic Vth Dynamic HTOL Dynamic HTRB Baking END

Dynamic Rdson: Frequency (Hz) 100k Step (Hz) 100k

Dynamic Rdson: Duty (%) 50% Step (%) 20%

Dynamic Rdson: Ids (A) 2 Step (A) 1

Dynamic Rdson: Drain voltage range (V) 0 600 Step (V) 50

Record time Interval (sec) 15

Snapshot Scope Save interval 1

STOP

Dynamic Rdson (mΩ) vs Vd (V) graph

25C, 100kHz, 50%, 2.0A ZVS
25C, 100kHz, 50%, 2.0A HSW

DDA8010 : User Interface of Dynamic Vth



Device dynamics analyzer v2.3.1

File Edit Operate Tools Window Help

Device Dynamics Lab

Save folder: D:\DATA\DDL Device name: Device#1

Testing Plan

Temp	Test Item
25	Dynamic Rds(on)
25	END

Buttons: Add, View, Replace, Remove, Clear, Save, Load

Switching On-Vg: 6 Switching Off-Vg: 0 Temperature: 25

Process Temperature: 25.1°C Set Temperature: 25.0°C

Run ALL STOP

Standby Testing Tc>50°C Pump status

Start setting | Pulse IV | Dynamic Vsd | Dynamic Rds(on) | **Dynamic Vth** | Dynamic HTOL | Dynamic HTRB | Baking | END

ZVS **HSW**

Dynamic Vth : Frequency (Hz) Step (Hz)
100k 100k 0

Dynamic Vth : Duty (%) Step (%)
50% 50% 0

Dynamic Vth : Drain voltage (V) Step (V)
0 400 <400>

Dynamic Vth : Vds Voltage (V) Step (V)
0.5 0.5 0

Dynamic Vth : Gate Voltage range(V)
0 6 Step (V) 0.2

STOP

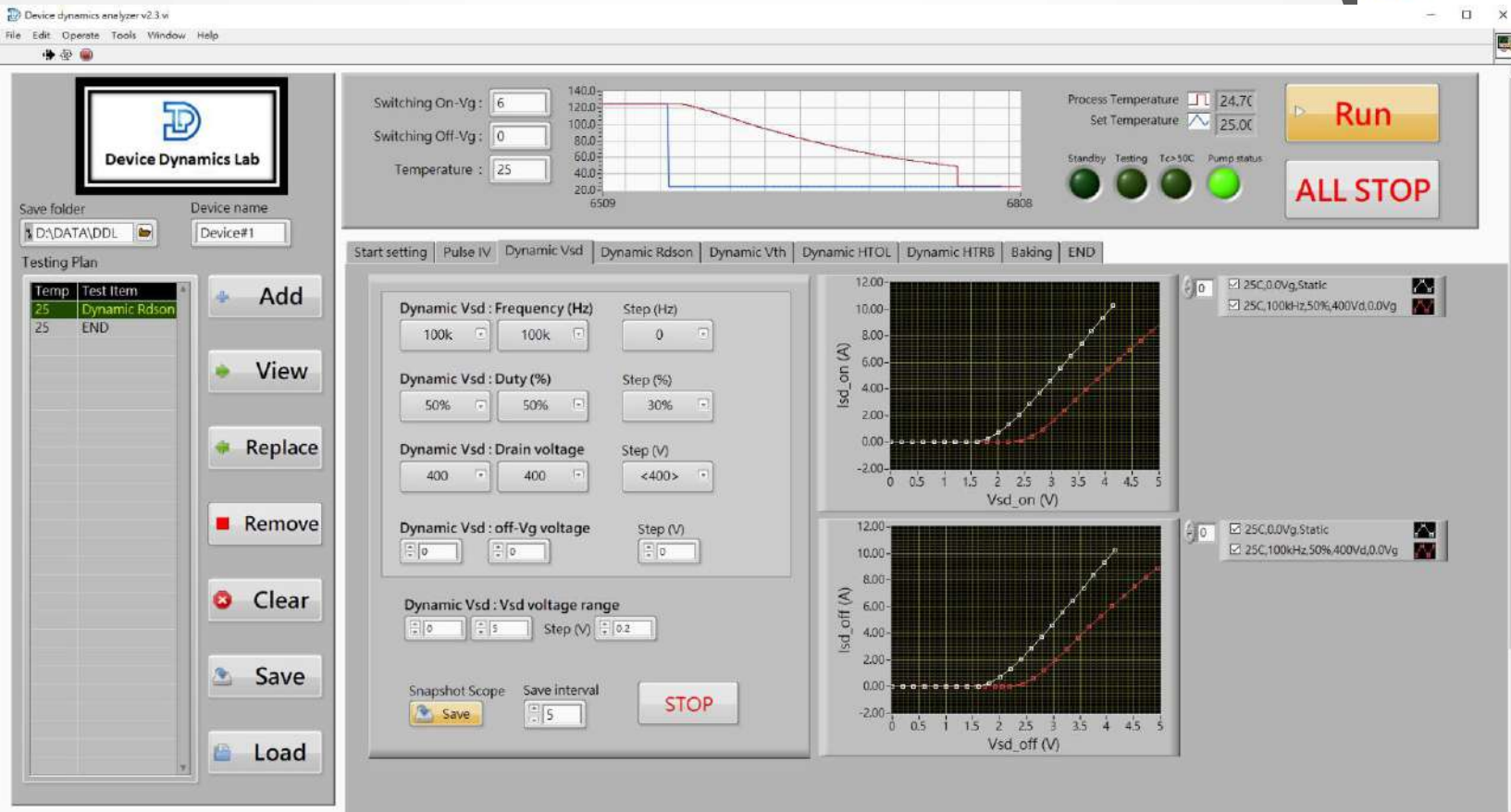
Snapshot scope Save interval
Save 5

Graph: Id (A) vs Vgs (V)

Legend:

- ☒ 25C,0.50Vds,static
- ☒ 25C,100kHz50%,0Vd,0.50Vds,ZVS
- ☒ 25C,100kHz50%,400Vd,0.50Vds,ZVS
- ☒ 25C,100kHz50%,0Vd,0.50Vds,HSW
- ☒ 25C,100kHz50%,400Vd,0.50Vds,HSW

DDA8010 : User Interface of Dynamic Vsd



❖ Device Dynamics Analyzer: DDA8010 specification

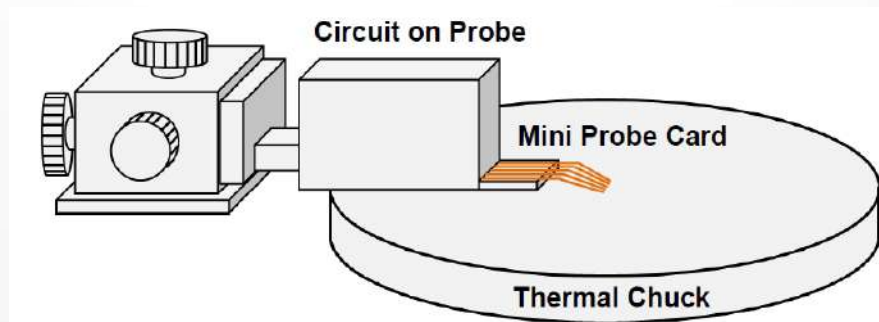
Specification of Device Dynamics Analyzer (DDA8010)

Parameter	Operation Condition						Unit
Vgs	-12 ~ +12						V
Temperature	25 ~ 175						°C
Voltage	< 800				< 650		V
Frequency	100	200	300	400	500	kHz	
Duty	10, 20, 30, 40, 50, 60, 70, 80, 90				20, 30, 40, 50, 60, 70, 80, 90		%
Current	10, 8, 8, 6, 6, 4, 4, 3, 3				8, 8, 6, 6, 4, 4, 3, 3		A
Pulse I-V	20V / 30A (>1us pulse width)						V / A

❖ Wafer Probing Device Dynamics Analyzer : WPDDA6505



- One positioner occupied only on Semi-Auto or Manual station
- Switching On-V_g : -12V~12V
- Switching Voltage : <650V
- Switching Current : <5A
- Switching Frequency : <300kHz
- Switching Duty : 10%~90%
- Temperature : Thermal chuck limited
- Characterization Items : Dynamic R_{dson}(HSW, ZVS), Dynamic R_{sdon}(ZVS), Dynamic V_{th}, Dynamic V_{sd}, Dynamic HTOL (SALT), Pulse I-V...



❖ Wafer Probing Device Dynamics Analyzer : WPDDA6505_RF

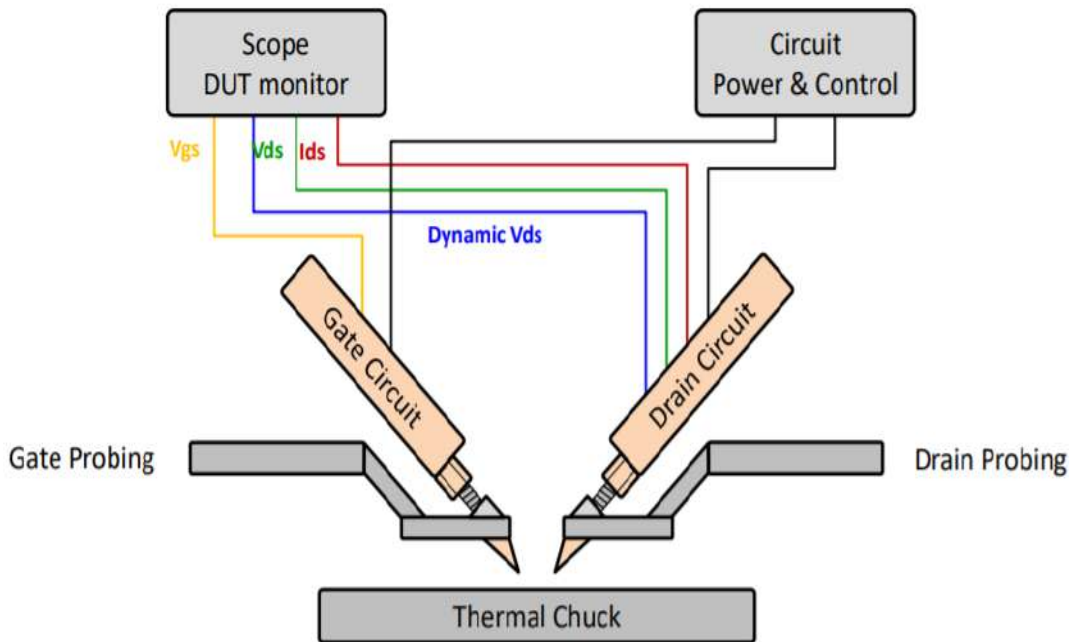


Characterization items :

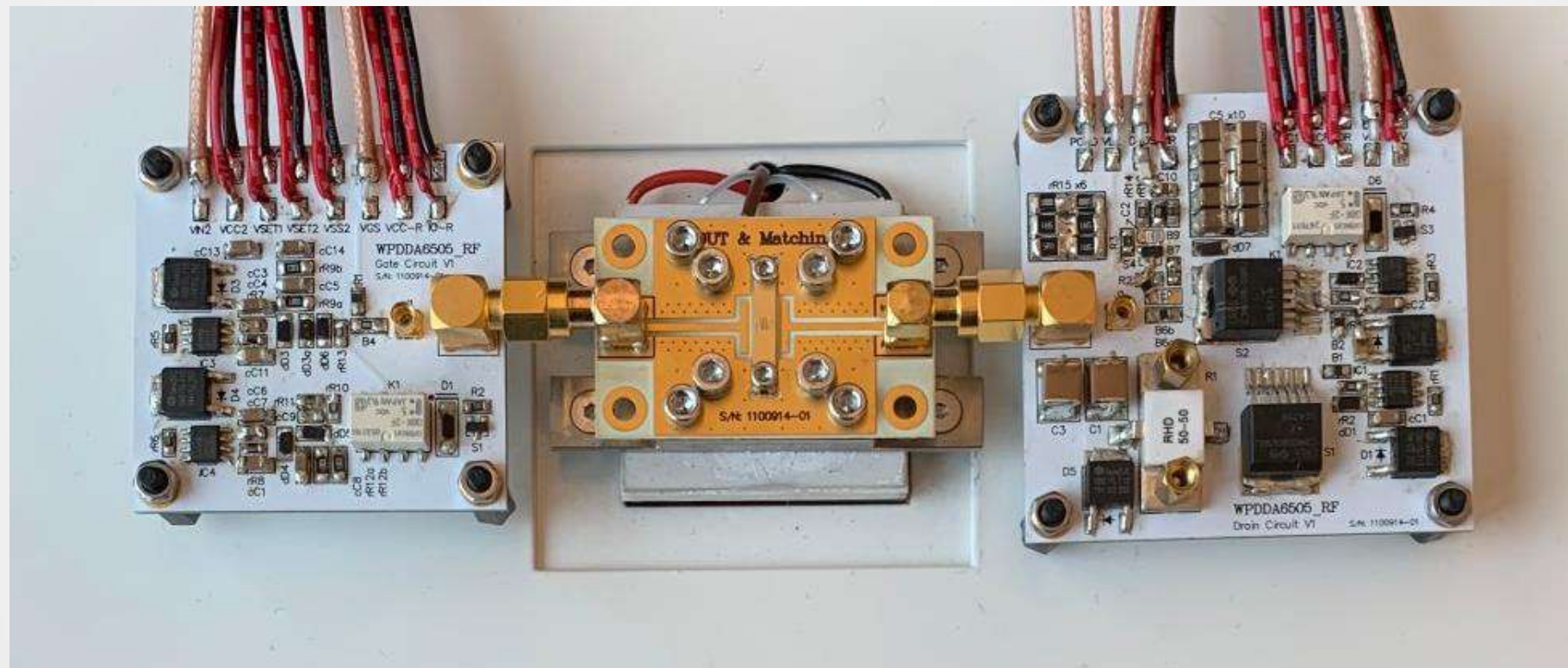
- Dynamic $R_{ds(on)}$ (HSW / ZVS)
- Dynamic V_{th} (HSW / ZVS)
- Dynamic V_{sd}
- Dynamic HTOL (HSW / ZVS)
- Pulse I-V

Customized items for RF

- Dynamic HTRB
- I_{dq} Drift
- DC HTOL (MTTF)
- Pulse I-V (Drain Lag)

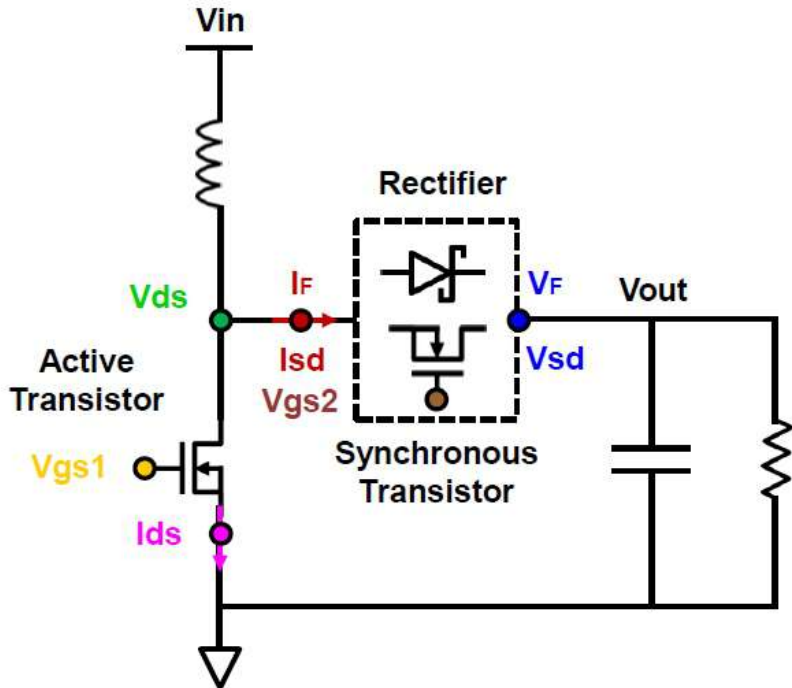


❖ WPDDA6505_RF Verified on Direct-Mount DUT



❖ Power Device Operation : Boost Application

Conventional Boost Convertor : Waveform : Continuous Current Mode (CCM)

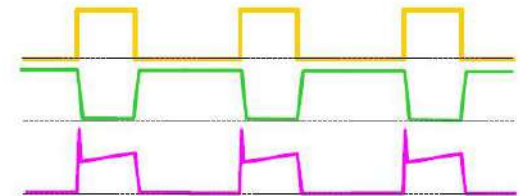


Active Transistor

V_{gs1}

V_{ds}

I_{ds}

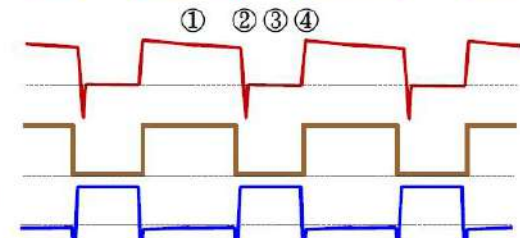


Rectifier
Sync. Transistor

I_F / I_{sd}

V_{gs2}

V_F / V_{sd}

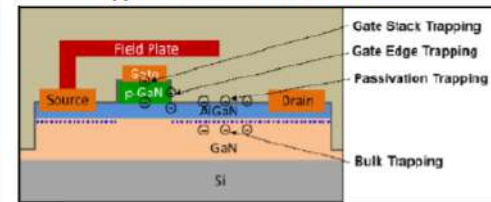


Period	①	②	③	④
Active Transistor	Off-state	HSW turn-on	Dyn. $R_{ds(on)}$ Dyn. V_{th}	Turn-off transient
Rectifier	Dyn. V_F	Dyn. T_{rr}/Q_{rr}	Reverse	Forward transient
Sync. Transistor	Dyn. $R_{sd(on)}$ Dyn. V_{th}	Dyn. V_{sd}	Off-state	ZVS turn-on

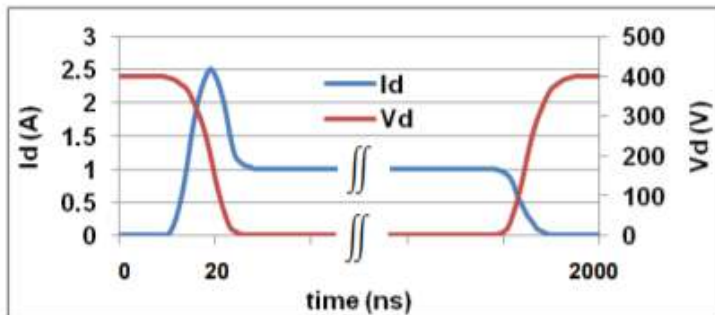
❖ Dynamic Characteristics : Dynamic R_{dson}

- Trapping induced R_{dson} increasing during switching
- Hard switching worse than Soft switching (ZVS)
- Switching Voltage dependent

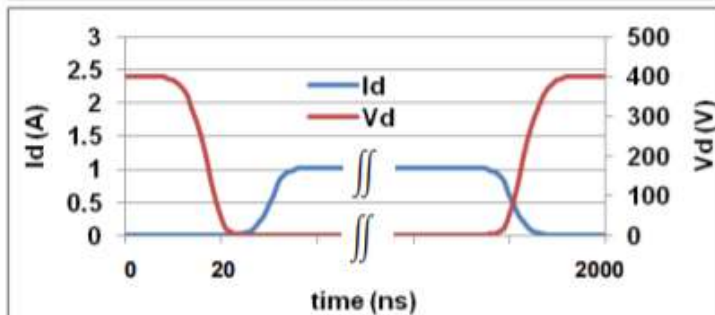
Typical GaN e-mode HEMT



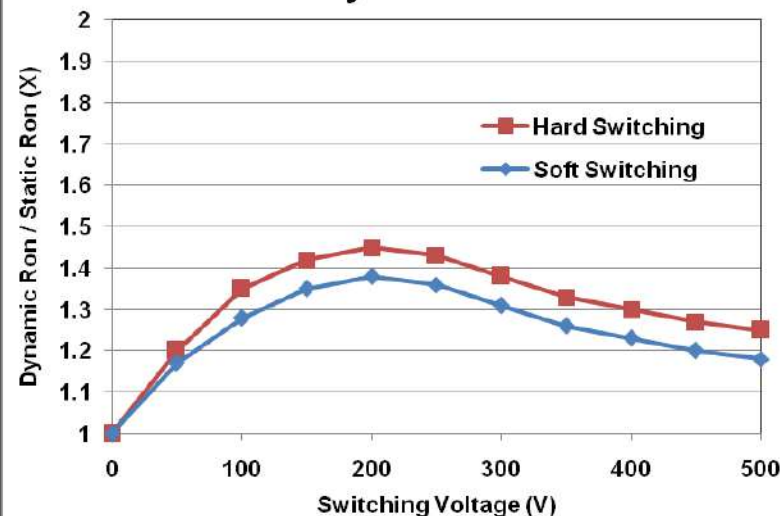
Hard Switching



Soft Switching



Dynamic R_{on}



Dynamic Rdson Demonstration

- DUT : GaN Systems
(650V, 150mOhm; GS-065-011-1-L)

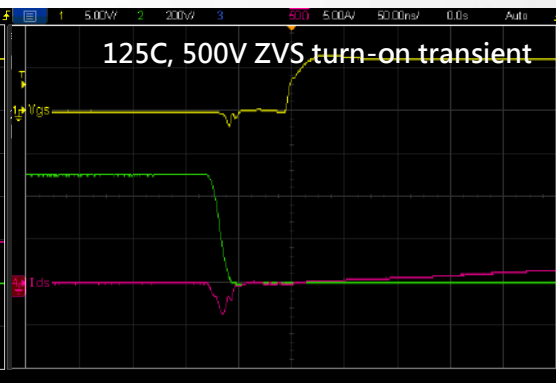
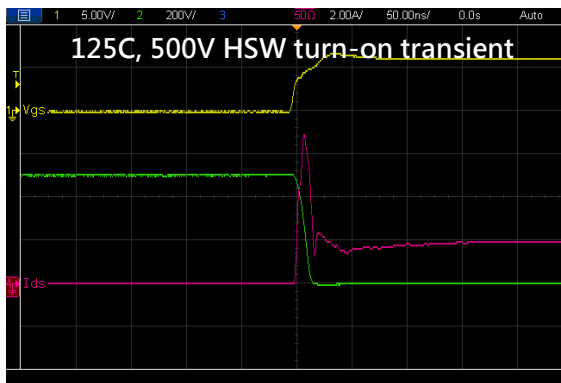
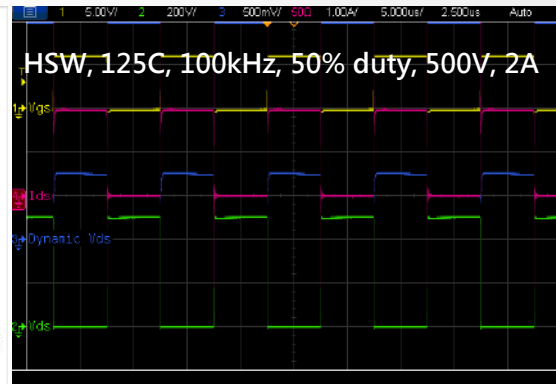
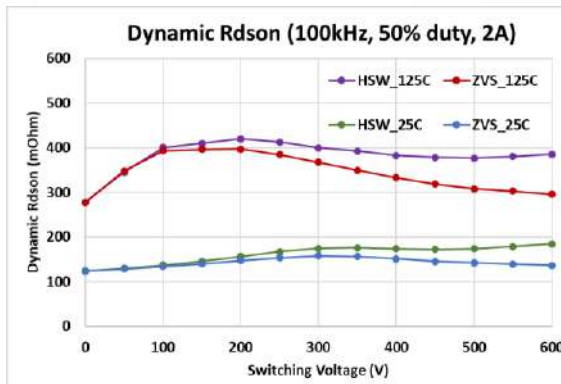


Methodology :

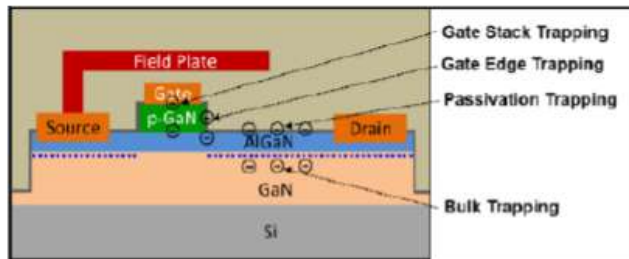
- Dynamic Rdson extraction
under system-like operation

Switching Condition :

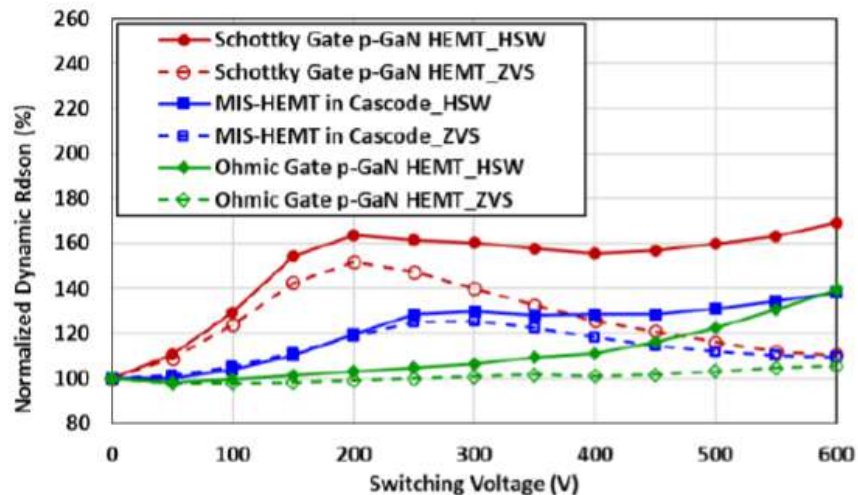
- HSW vs. ZVS
- 25C vs. 125C
- F=100kHz, Duty=50%
- Id=2A



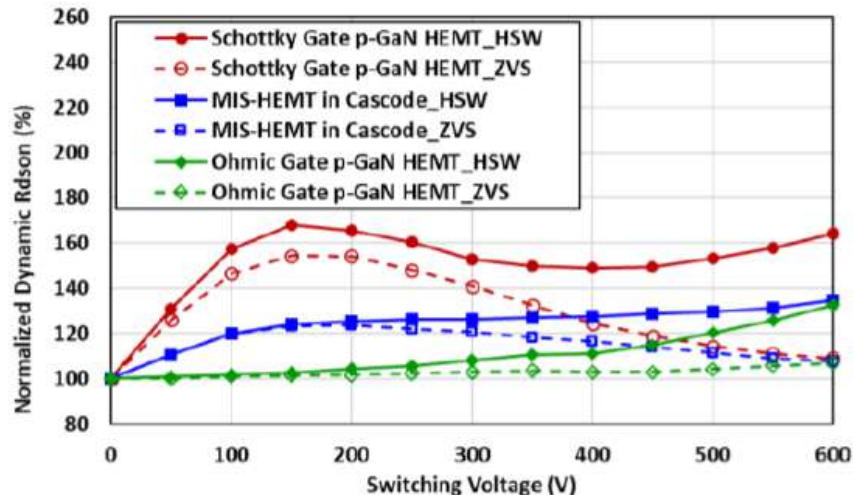
Dynamic Rdson Benchmark



Dynamic Rdson : 25C, 200kHz, 50% duty, 2A

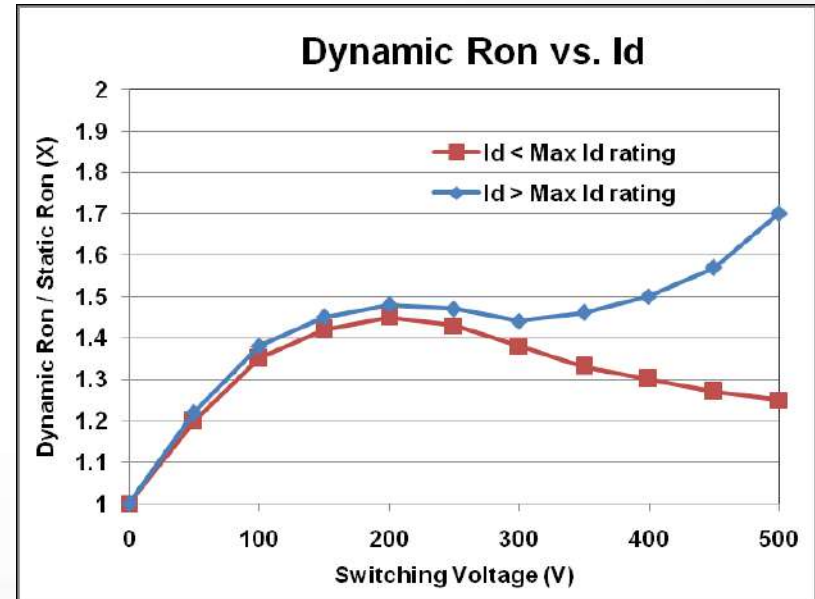
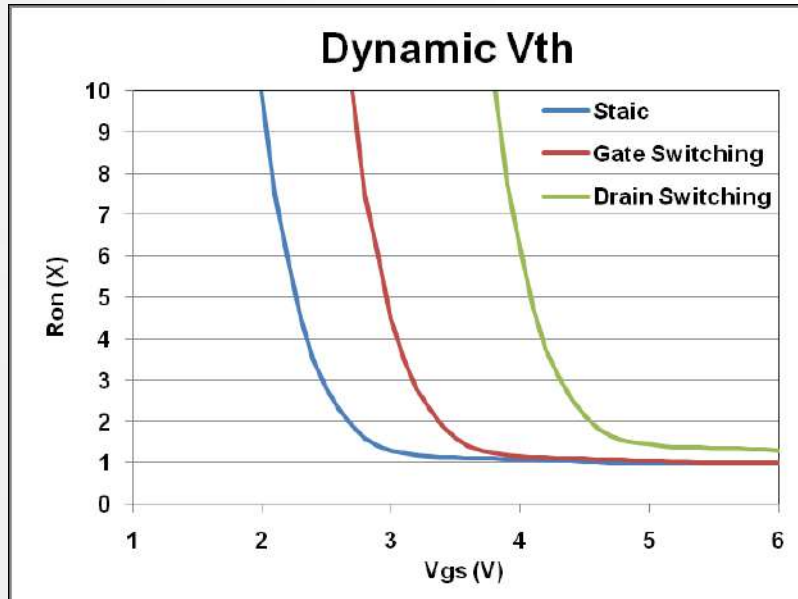
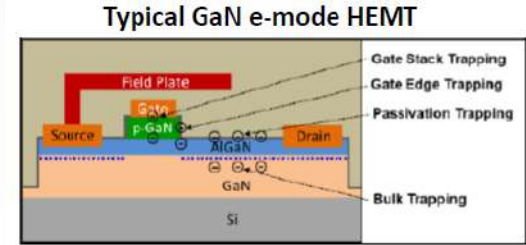


Dynamic Rdson : 125C, 200kHz, 50% duty, 2A



❖ Dynamic Characteristics : Dynamic V_{th} (R_{on} - V_g)

- Trapping induced V_{th} shift during switching
- Hard switching worse than Soft switching (ZVS)
- Voltage & Temperature dependent
- Impact to switching current capability



Dynamic Vth Demonstration : Ron-Vg

- DUT : GaN Systems
(650V, 150mOhm; GS-065-011-1-L)

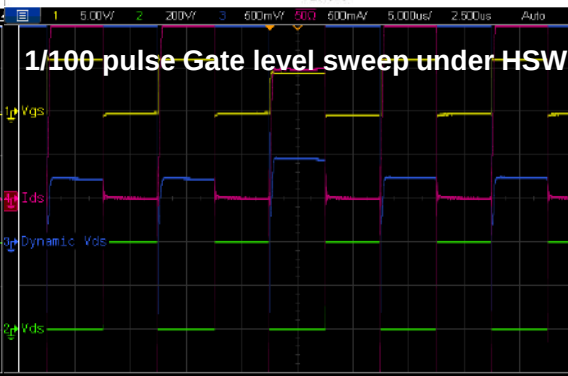
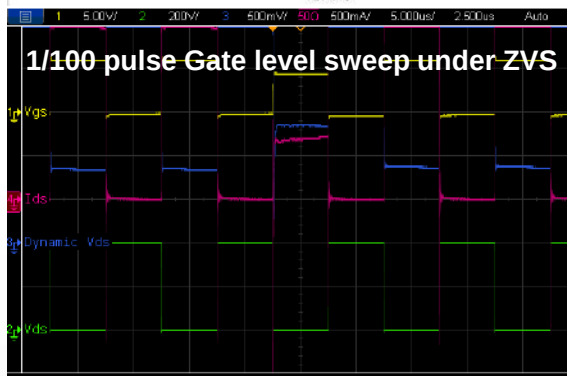
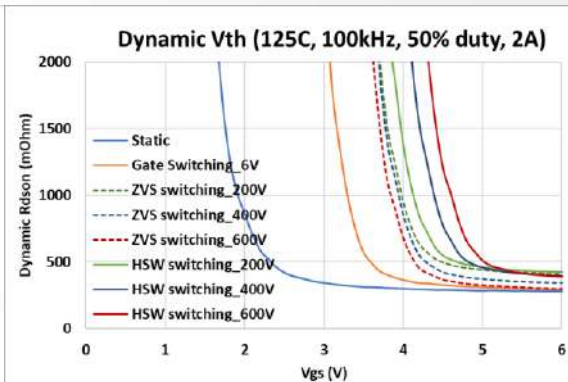
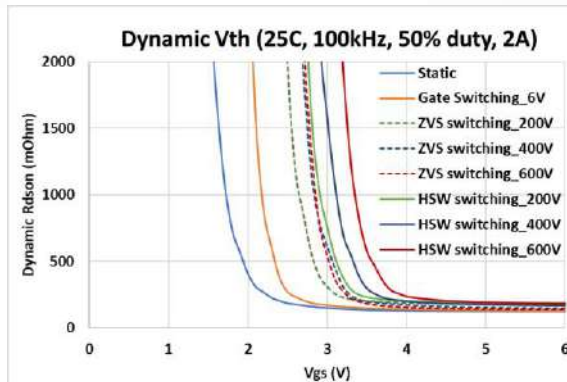


Methodology :

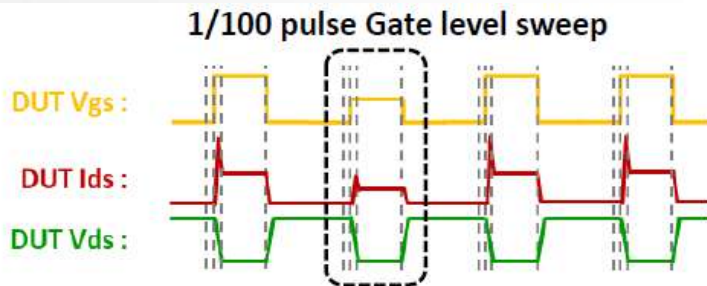
- 99/100 pulses under system-like operation
- 1/100 pulse sweeps Gate level to extract dynamic Ron(Vg)

Switching Condition :

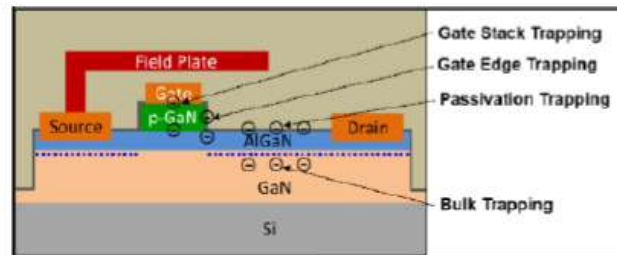
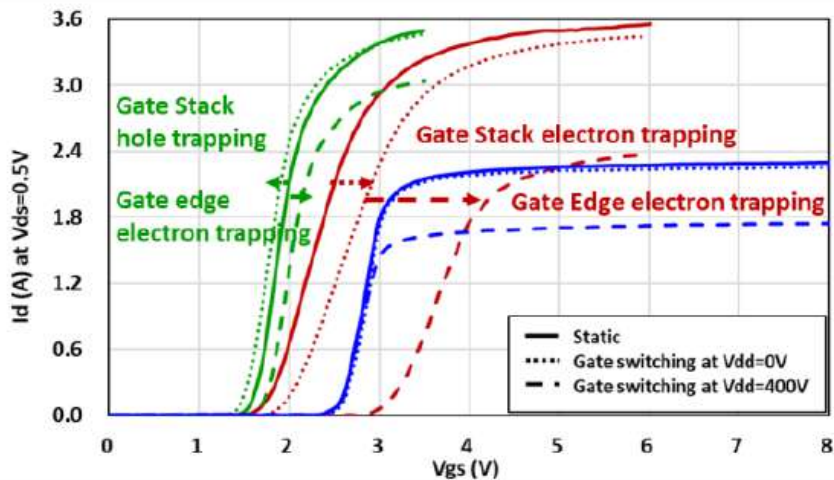
- HSW vs. ZVS
- 25C vs. 125C
- F=100kHz, Duty=50%
- Id=2A



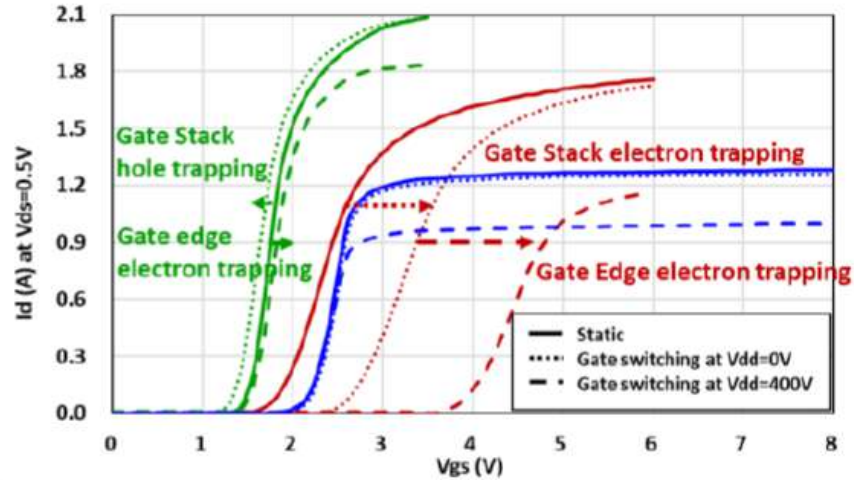
Benchmark of Dynamic V_{th} : I_d - V_g



Dynamic V_{th} : HSW, 25C, 200kHz, 50% duty

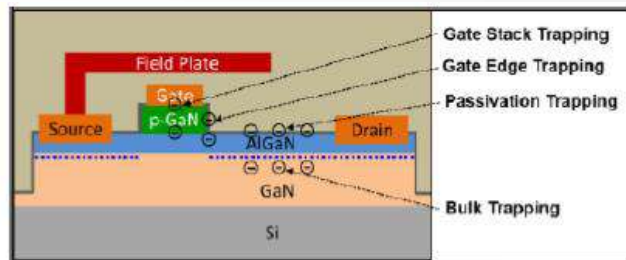
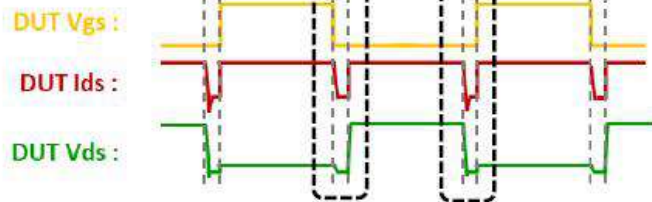


Dynamic V_{th} : HSW, 125C, 200kHz, 50% duty



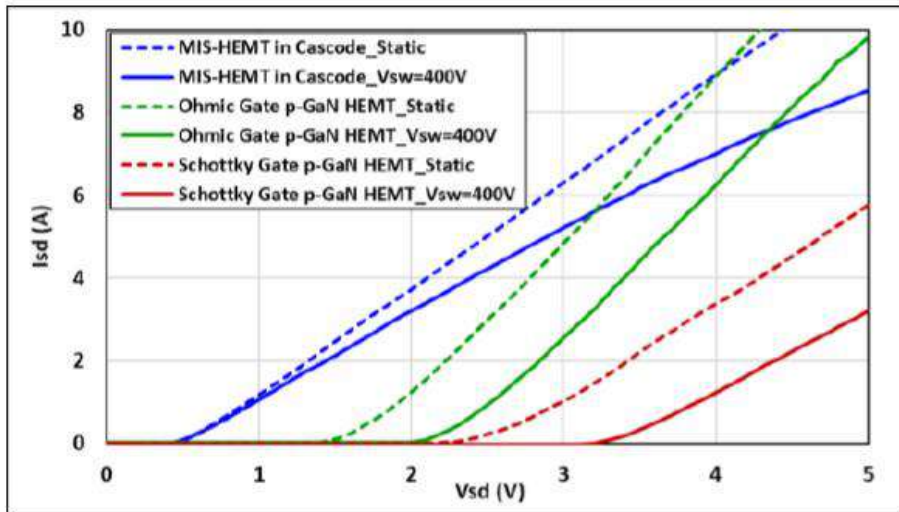
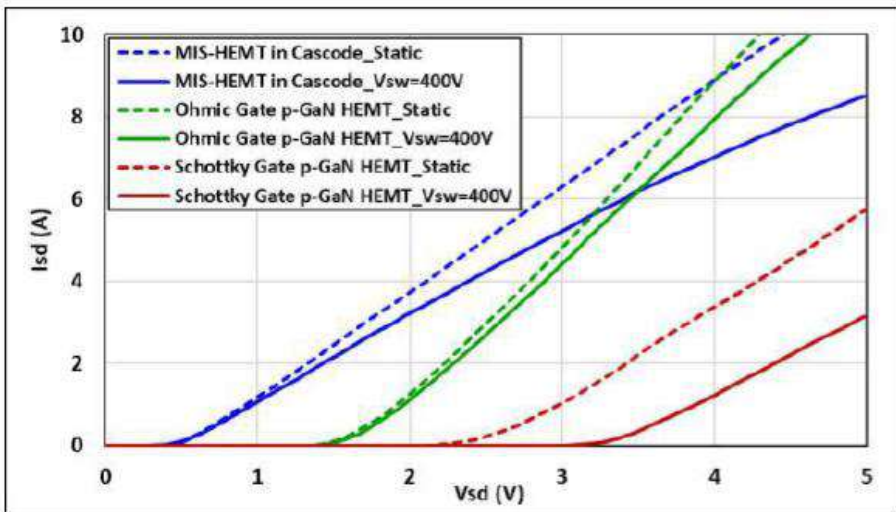
Dynamic Vsd Benchmark

Vsd at Gate turn-off edge Vsd at Gate turn-on edge



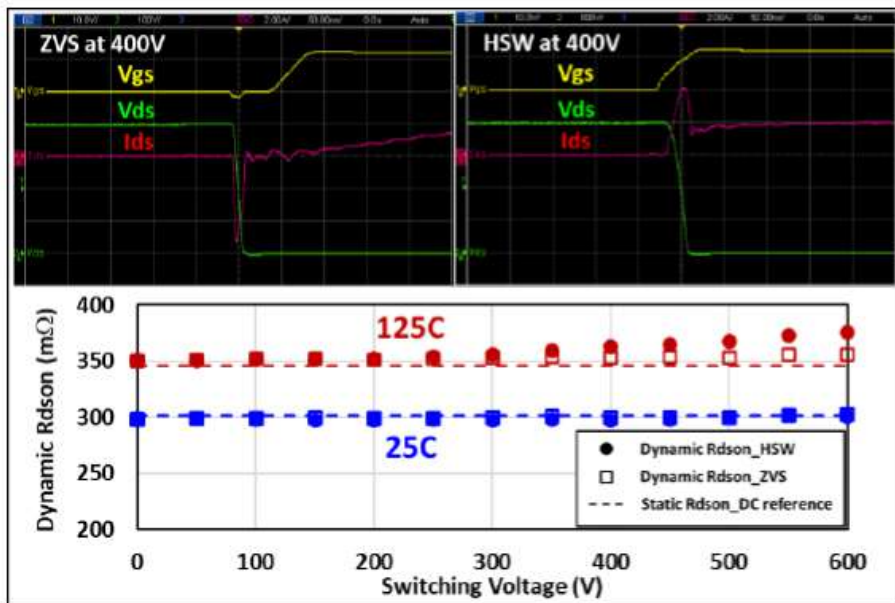
Dynamic Vsd : 125C, 200kHz, 50% duty at turn-off edge

Dynamic Vsd : 125C, 200kHz, 50% duty at turn-on edge

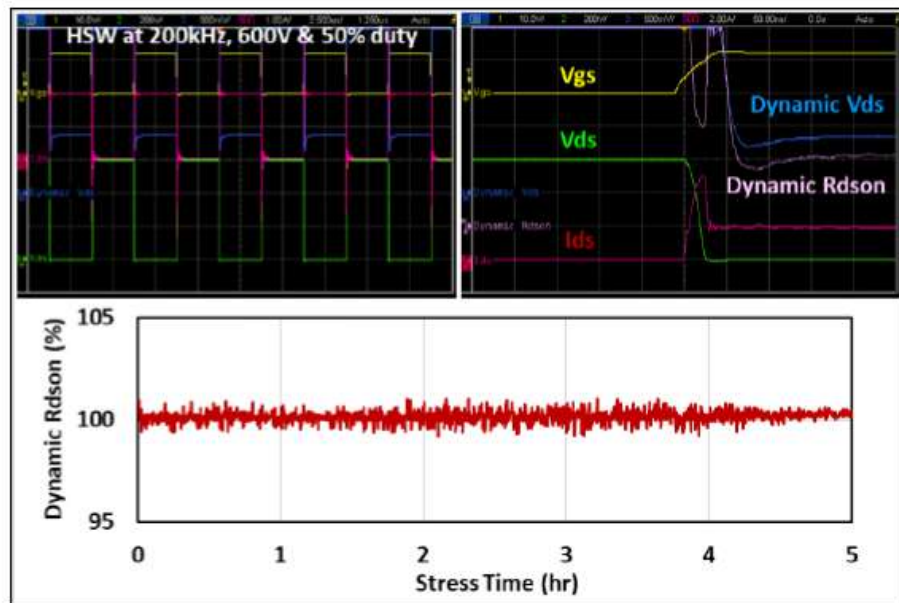


Accuracy & Resolution of Dynamic Rdson

Dynamic Rdson verification on SiC MOSFET



Accuracy : Ron offset < 1%



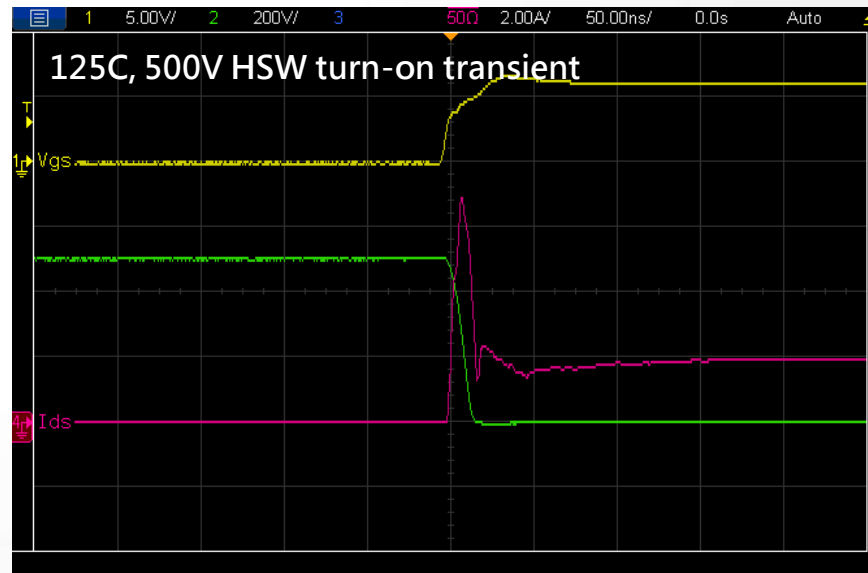
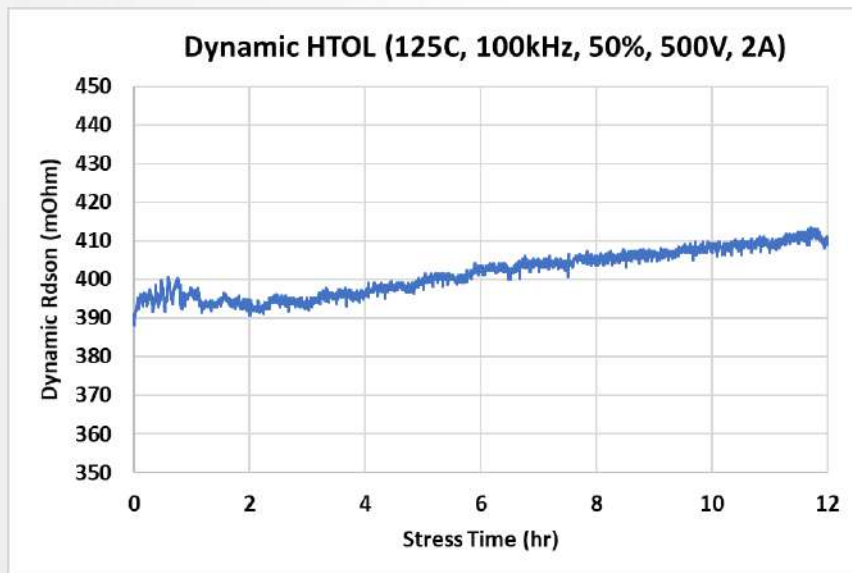
Resolution : $\Delta R_{on} < \pm 1\%$; 100ns response time

Dynamic HTOL Demonstration

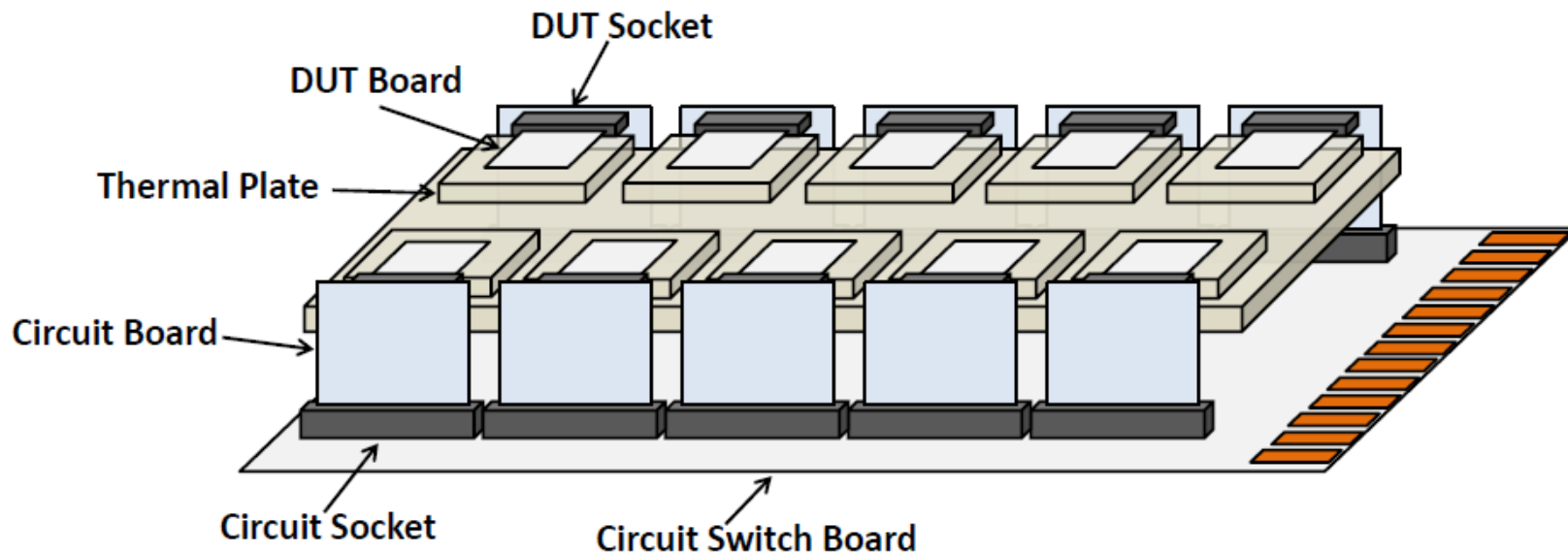
DUT : GaN Systems
(650V, 150mOhm; GS-065-011-1-L)

Methodology :

- Real-time Dynamic $R_{ds(on)}$ monitoring under system-like operation



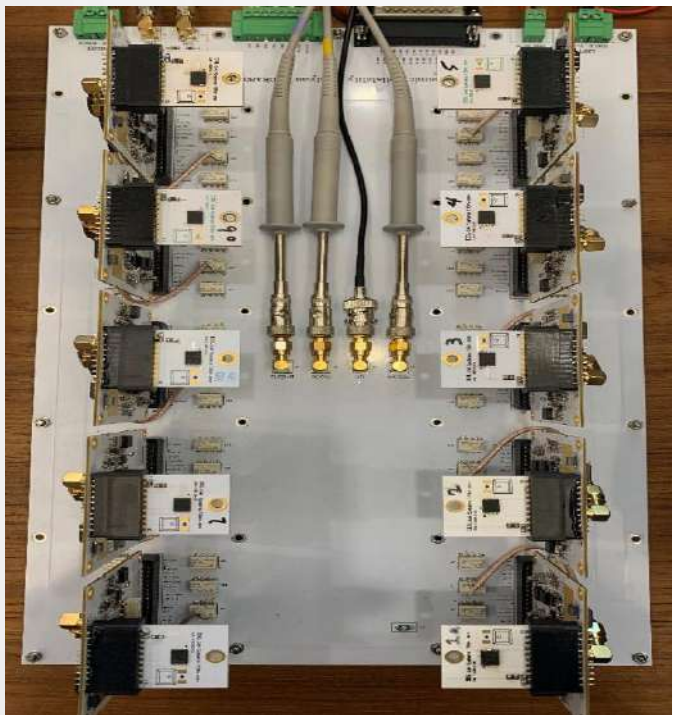
10 DUT Module



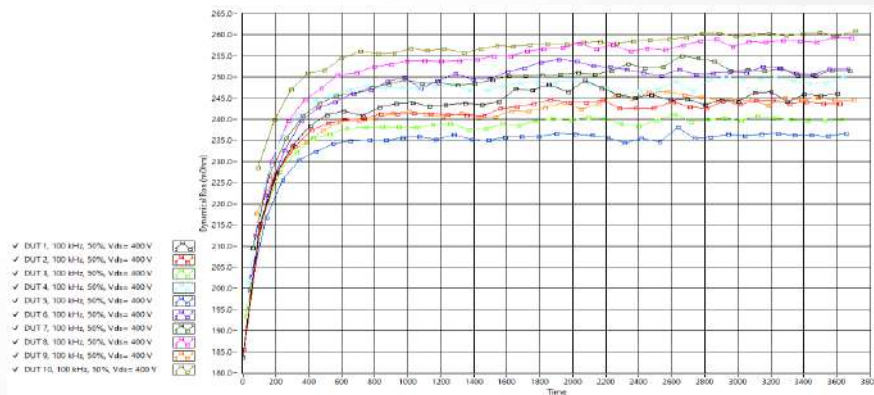
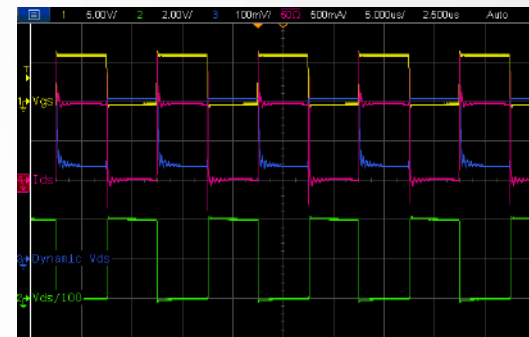
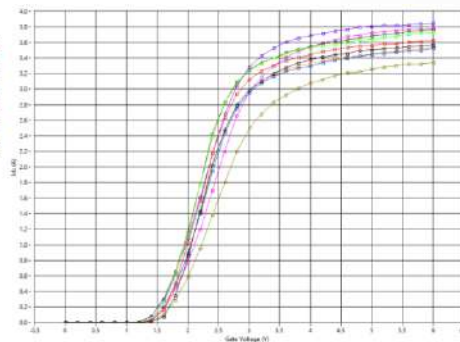
Device Dynamic Reliability Analyzer(DDRA8010)



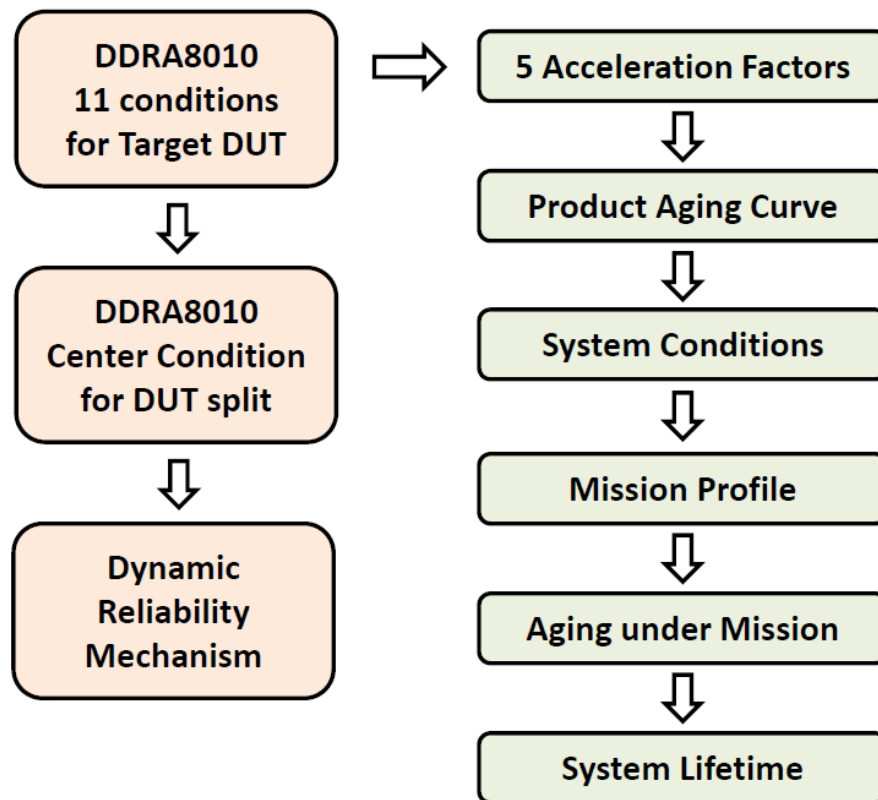
10 DUT Module : Function Verified



✓ DUT 1, 100 kHz, 50%, Vds= 400V
✓ DUT 2, 100 kHz, 50%, Vds= 400V
✓ DUT 3, 100 kHz, 50%, Vds= 400V
✓ DUT 4, 100 kHz, 50%, Vds= 400V
✓ DUT 5, 100 kHz, 50%, Vds= 400V
✓ DUT 6, 100 kHz, 50%, Vds= 400V
✓ DUT 7, 100 kHz, 50%, Vds= 400V
✓ DUT 8, 100 kHz, 50%, Vds= 400V
✓ DUT 9, 100 kHz, 50%, Vds= 400V
✓ DUT 10, 100 kHz, 50%, Vds= 400V

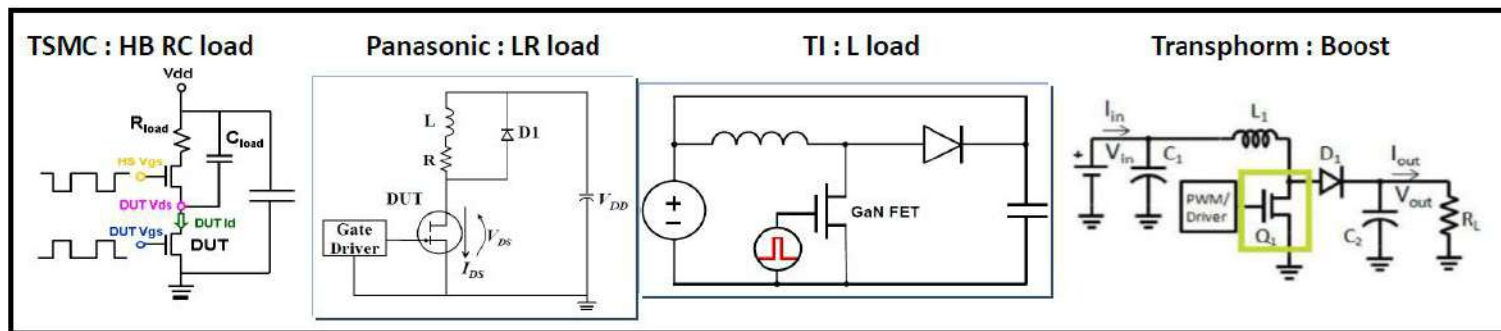


❖ Methodology to Evaluate System Lifetime



Refer to “New Circuit Topology for System-Level Reliability of GaN” (ISPSD2019)

Proposed HB RC load showed advantages as a hard switching test vehicle

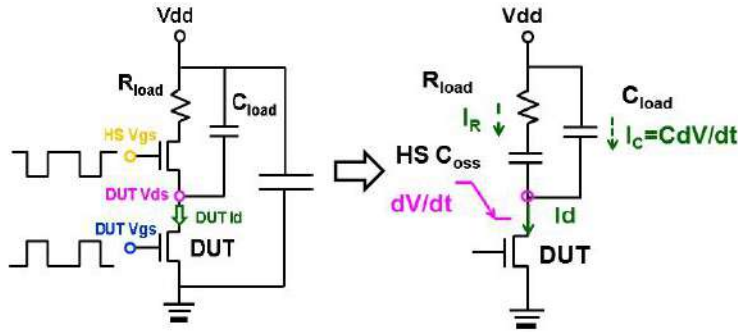


Hard Switching Test Vehicle		TSMC	Panasonic	TI	Transphorm
Setup		Half-Bridge RC load	LR load	L load	Boost Converter
Power consumption		Low (<10W)	High (>100W)	Medium (>10W)	High (400W)
Multi-DUT (sample size)		V	limited	V	limited
Acceleration Flexibility	Temperature	V	V	V	V
	Voltage	V	V	V	V
	Current	V	V	V	V
	Frequency	V	limited	limited	limited
	Duty	V	limited	limited	limited

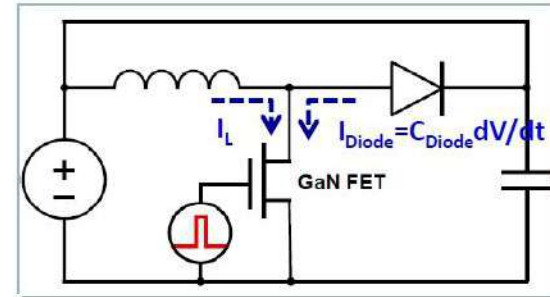
Dynamic Reliability (2021Q4)

- Harshness of hard switching is tuned by locus of turn-on transient
- HB RC load can create similar stressful locus like inductive load

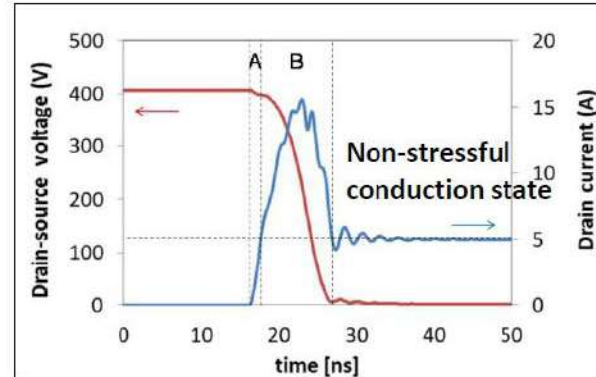
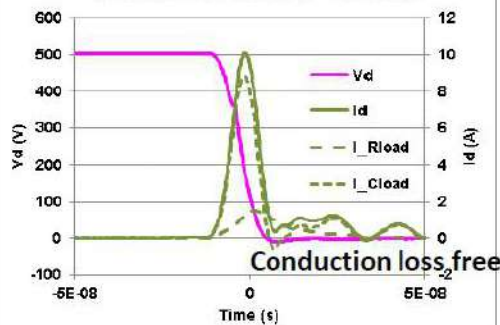
Half-Bridge RC Load:



Inductive Load:



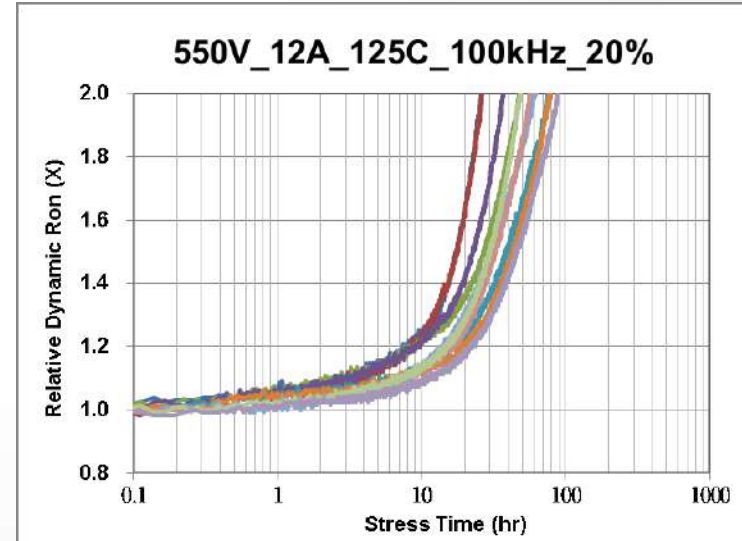
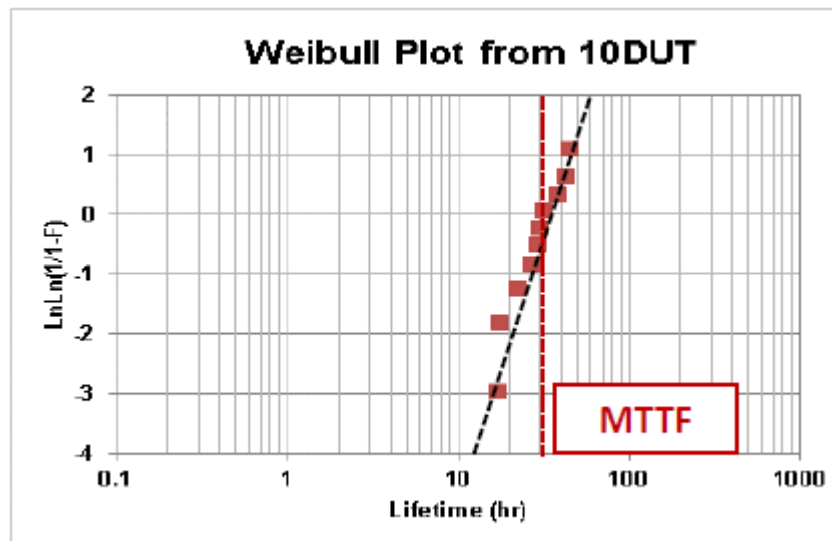
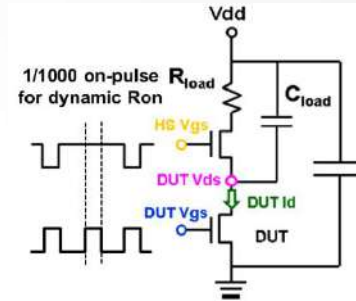
Turn-on Transient of RC Load



Dynamic Reliability (2021Q4)

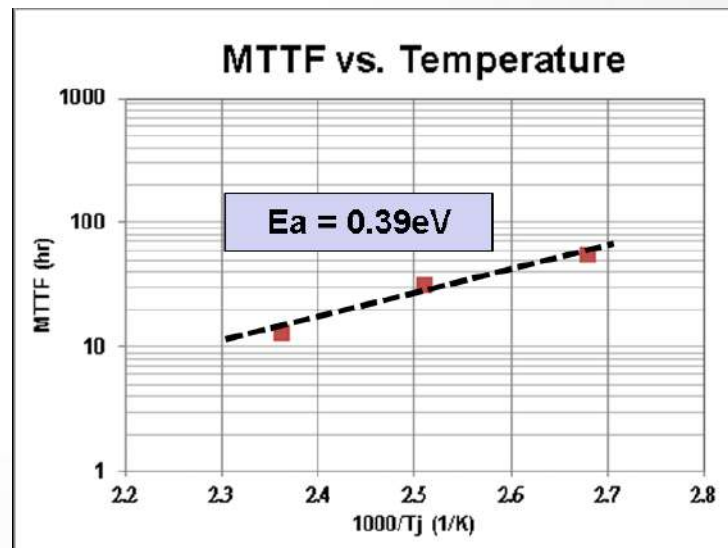
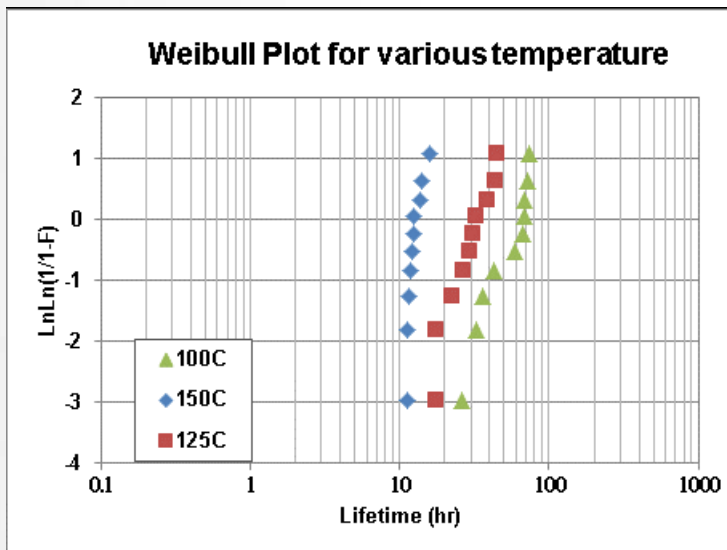
Mean time to failure (MTTF)

- In-situ dynamic Ron for 1/1000 on-pulse
- 10 DUT were stressed & monitored in parallel
- 50% dynamic Ron shift for failure criteria
- Weibull Plot for MTTF



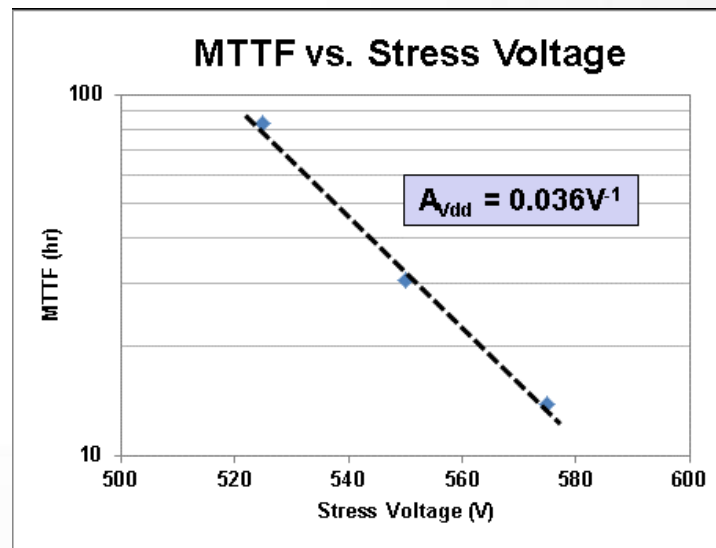
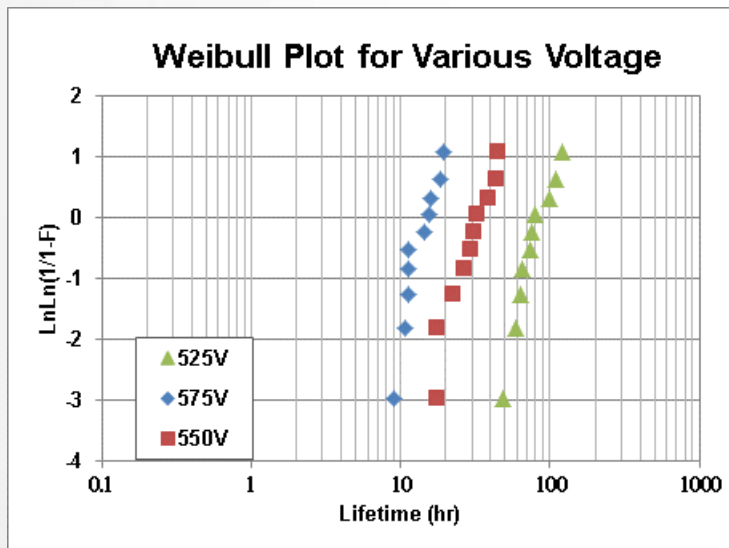
Temperature Acceleration :

- $E_a = 0.39\text{eV}$ extracted from temperature acceleration at 100C, 125C & 150C
- Stress condition : $V_{dd}=550\text{V}$, $I_{pk}=12\text{A}$, $f=100\text{kHz}$ & on-duty=20%



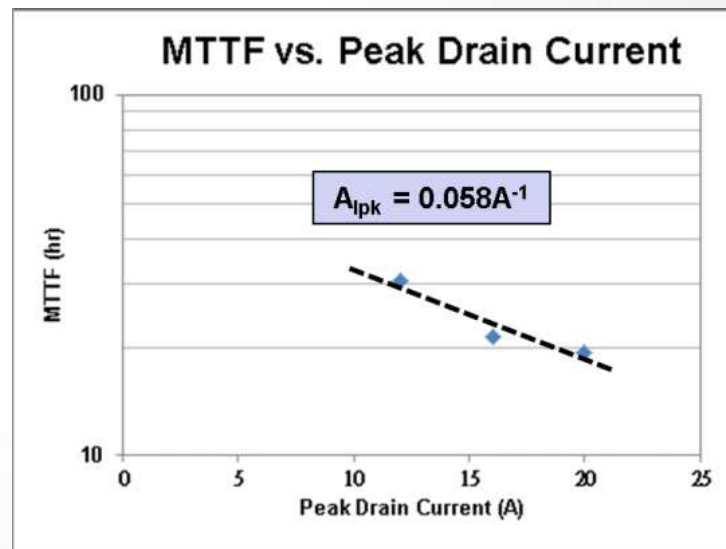
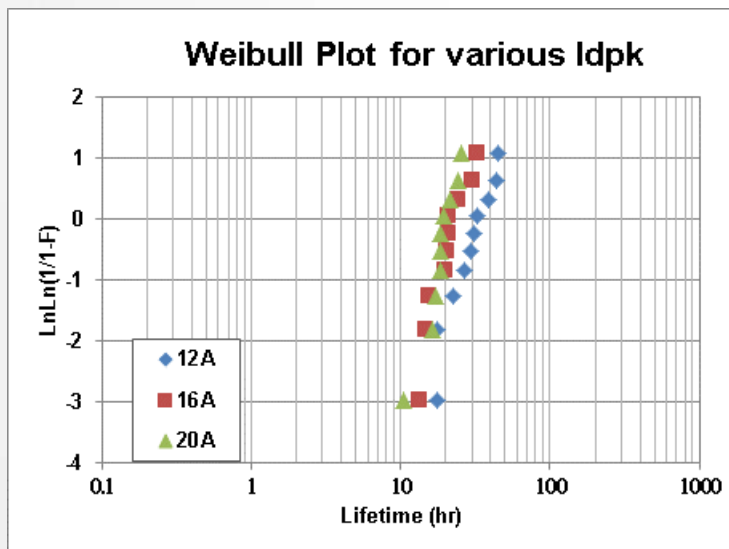
Voltage Acceleration :

- $A_{Vdd} = 0.036V^{-1}$ was extracted from voltage acceleration at 525V, 550V & 575V
- Stress condition : $T_j = 125^{\circ}C$, $I_{pk} = 12A$, $f = 100kHz$ & on-duty=20%



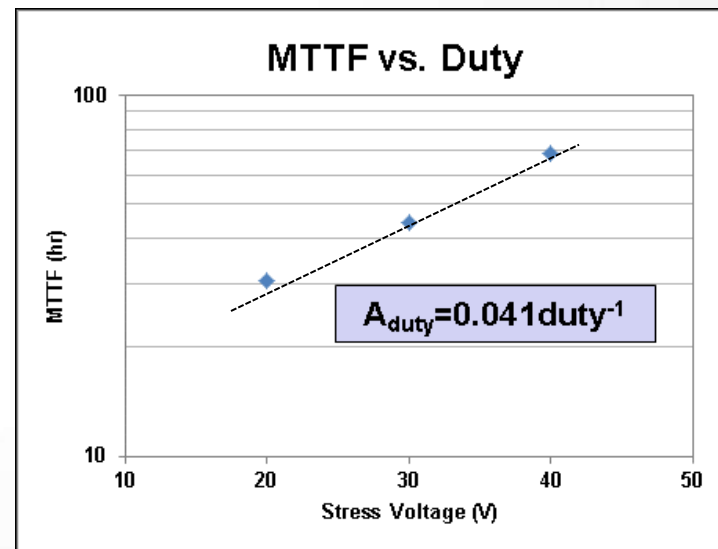
Current Acceleration :

- $A_{ipk} = 0.058A^{-1}$ was extracted from current acceleration at 12A, 16A & 20A
- Stress condition : $T_j = 125C$, $V_{dd} = 550V$, $f = 100kHz$ & on-duty=20%



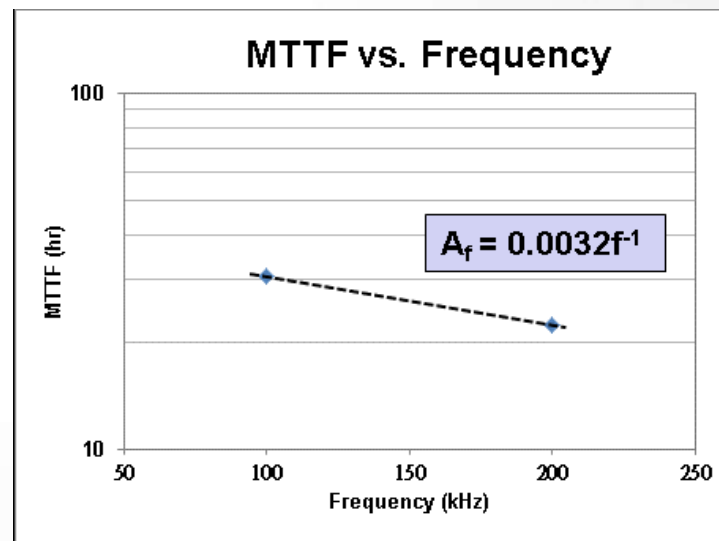
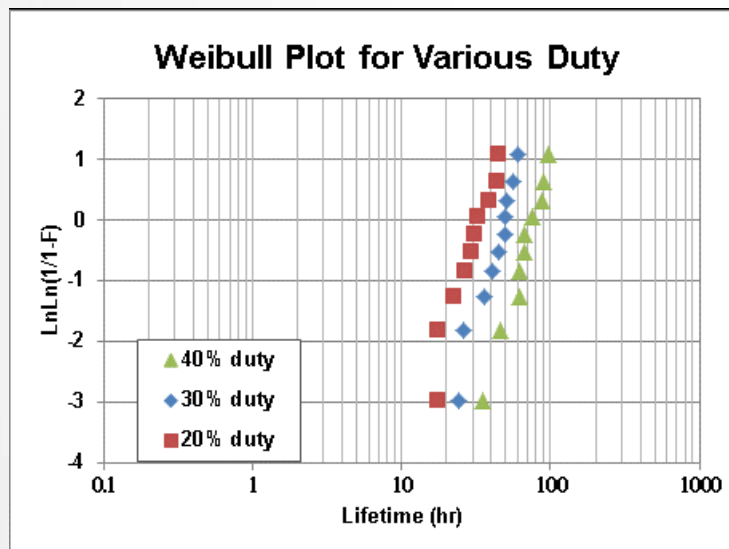
Duty Acceleration :

- $A_{\text{duty}} = 0.041 \text{duty}^{-1}$ was extracted from duty acceleration at 20%, 30% & 40%
- Stress condition : $T_j = 125^\circ\text{C}$, $V_{\text{dd}} = 550\text{V}$, $I_{\text{pk}} = 12\text{A}$ & $f = 100\text{kHz}$



Frequency Acceleration :

- $A_{\text{frequency}} = 0.0032f^{-1}$ was extracted from frequency acceleration at 100kHz & 200kHz
- Stress condition : $T_j=125^\circ\text{C}$, $V_{dd}=550\text{V}$, $I_{pk}=12\text{A}$ & duty=20%



Contact me

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