System-level reliability validation of GaN devices for power management

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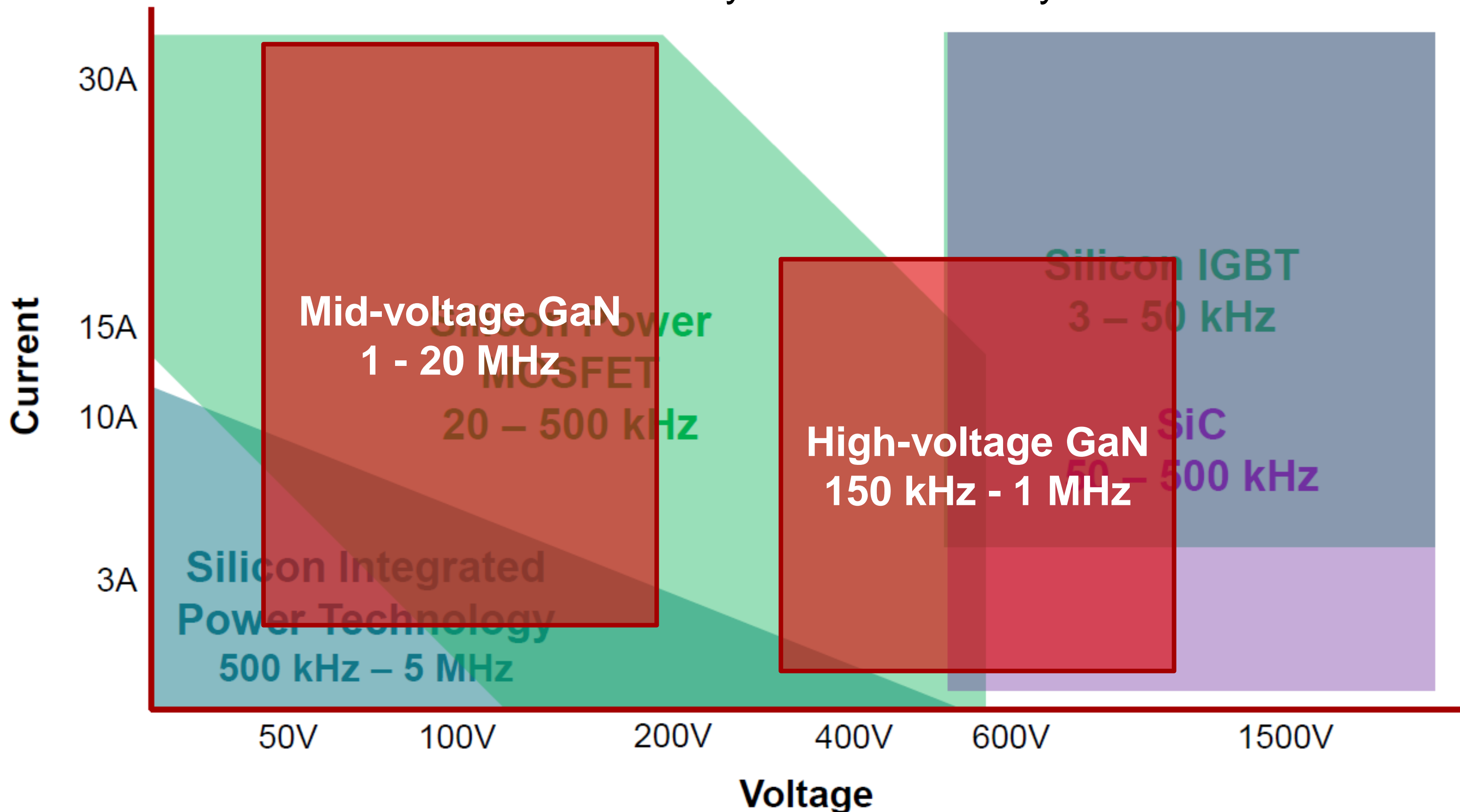
TEXAS INSTRUMENTS

GaN is a key enabler for power electronics

- GaN allows smaller form-factors and higher efficiency
- It also allows higher temperature operation, better radiation-hardness
- The lack of reverse recovery allows new topologies
- GaN is manufacturable as shown by the LED industry



What makes GaN superior for power

Benefit	Property	GaN	Si
High-voltage operation	Breakdown field (MV/cm)	3.5	0.3
High-temperature capability Radiation-hard	Bandgap Energy (eV)	3.4	1.1
Low on-resistance	Electron Mobility (cm^2/Vs)	2000	1400
Fast switching	Saturated Electron Velocity (10^7 cm/s)	1.3	1
	Peak Electron Velocity (10^7 cm/s)	2.8	1

However, the power industry is conservative and for widespread adoption (of any new technology), customers need to be assured of high reliability with a low probability of field returns

Are the traditional silicon qualification methods up to the task?

Does traditional qualification assure reliability?

1. **How long is the device qualified for?**
   - 1000h at Tj=125C → 9 yrs. at Tj=55C (Si E_A=0.7 eV), typically at 80%* of max. Vds.
   - 1000h at Tj=150C → 1.1y at Tj=105C (E_A=0.7 eV). E_A is uncertain for GaN (values of 0.1 to 1.84 eV)
2. **Is the testing representative of actual-usage?**
   - Traditional testing does not consider the switching conditions of power management.
3. **Will there be many field returns?**
   - Zero fails/231 parts (3x77) gives LTPD† =1, which represents an upper limit of 1% fail (90% confidence level) for the non-accelerated runtime.
   - 0/231 also gives a maximum FIT rate of about 50 (60% confidence) using the silicon assumptions.
   - In order to get accurate statistics, the acceleration factor needs to be determined for GaN, and the testing needs to be predictive of actual-use conditions

Traditional qualification is a good manufacturing, quality and reliability milestone.

* The 80% is common practice and not specified in the present standard
†LTPD=Lot Tolerant Percent Defective

Does traditional qualification assure reliability?

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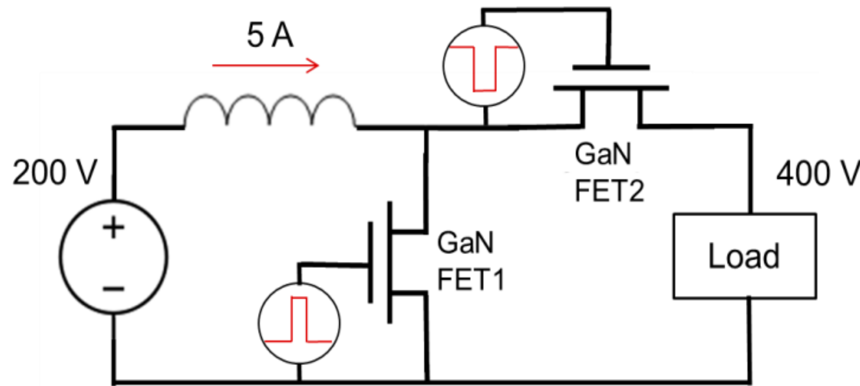
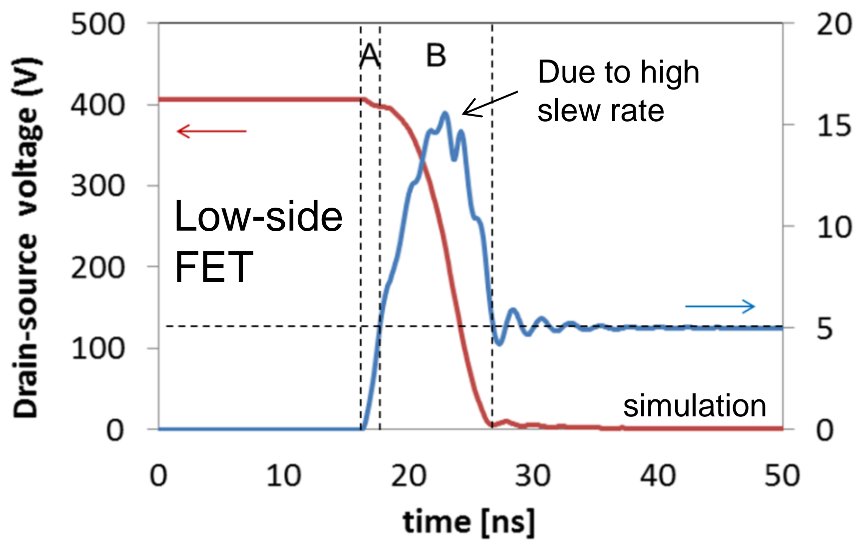
Hard-switching, a key use-profile for power management applications, is not covered by traditional qualification testing

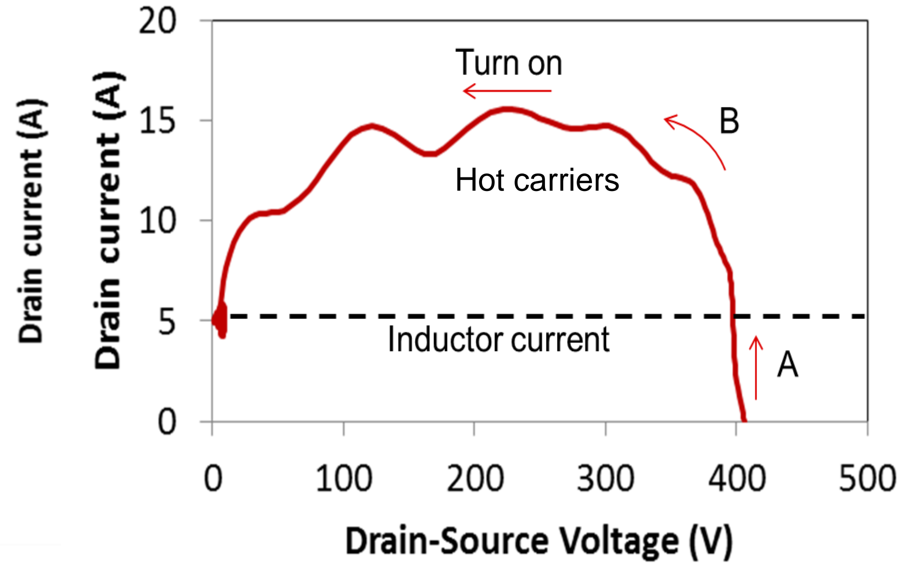
In fact, there is no generally prescribed testing to assure product-level reliability due to the ever-evolving applications and materials used in the industry (JESD94B)

Hard-switching is stressful for the device

e.g. boost converter







The FET is subject to repetitive hot-carrier stress, SOA boundaries, and high slew-rates.

Literature search for GaN application-reliability testing

- Rhea *et. al.,* Two-year reliability validation of 40V GaN (10 parts) in a 8V to 1V buck converter at 26.5C (WiPDA, 2015)
- Wu *et. al.,* Three-thousand hour operation of 600V GaN (7 parts) in a 200V:400V boost converter at 175C (WiPDA 2014)
- Sheridan *et. al.,* Three-thousand hour operation of 650V GaN (1 part) in a SEPIC (Single-Ended Primary-Inductor) Converter with 200V input and peak switch voltage of 400V at 150C. (PCIM 2014)

In general, JEDEC does not prescribe product stress tests due to evolving applications and materials (JESD94B)

How do we validate application reliability?

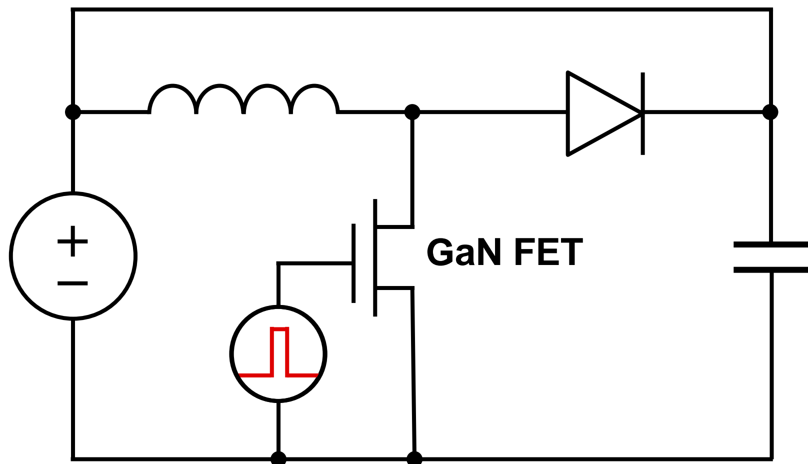
How do we validate application reliability

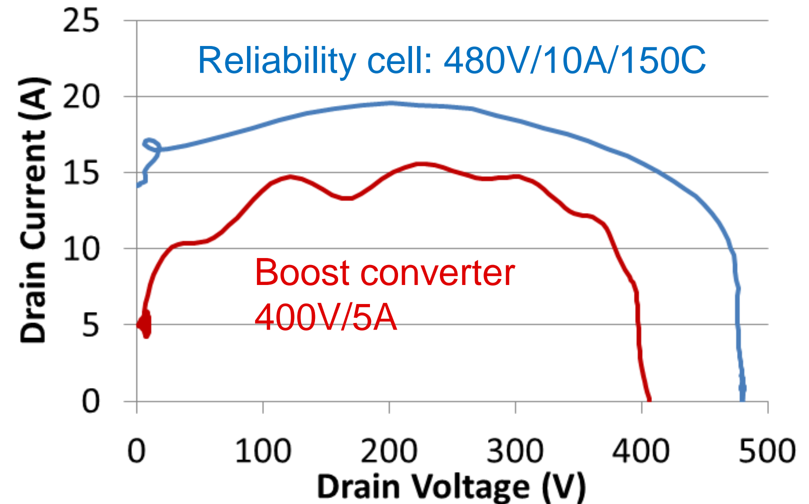
- We identify a fundamental application stress condition (Hard-switching) for power management applications.
- We choose a test vehicle to avoid product complexities which could mask intrinsic failure mechanisms
- This approach is in accordance with JEDEC guidelines (JESD226 and JESD94B)
- An ideal test vehicle will be well known, non-proprietary, and energy-efficient.

Fundamental stress condition + good test vehicle = device + tester.

JEDEC-compliant* hard-switching test-vehicle

Boost converter with output tied to input





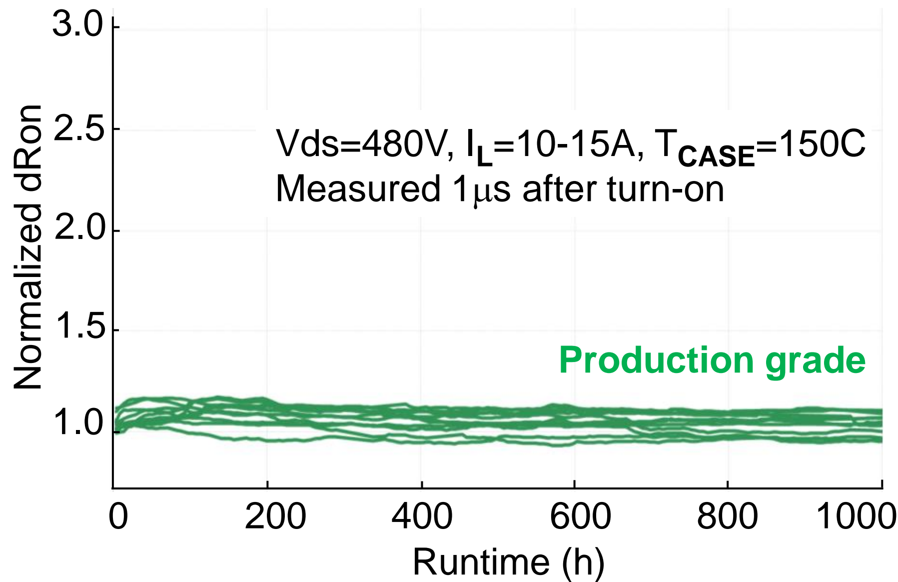
- Low-side only → no high-side drive complexity and failures
- Accelerated testing
- High-reliability SiC Schottky diode
- Short turn-on pulses save power

*From JESD94B– *"A test vehicle may be preferable since the actual product complexity may mask intrinsic failure mechanisms"*

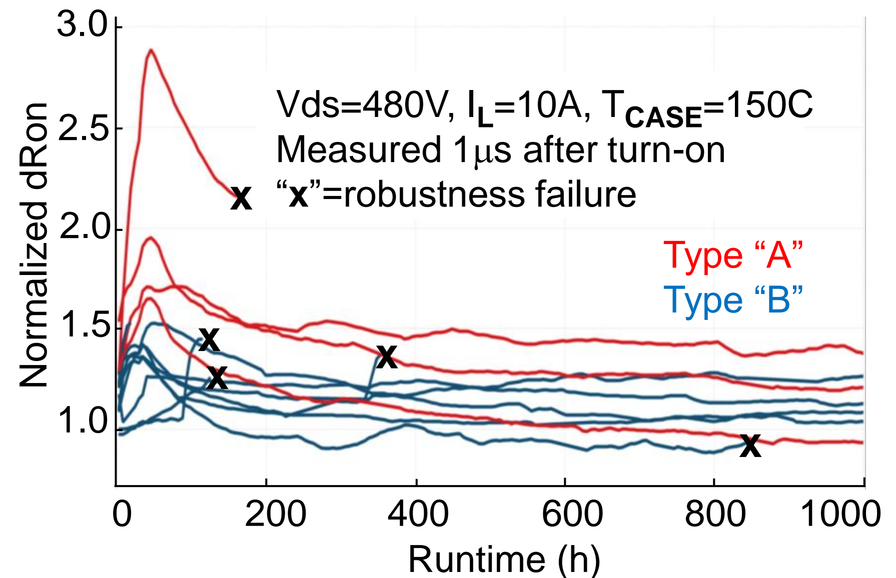
Hard-switching testing.

In JEDEC-compliant test-vehicle

Production-grade devices



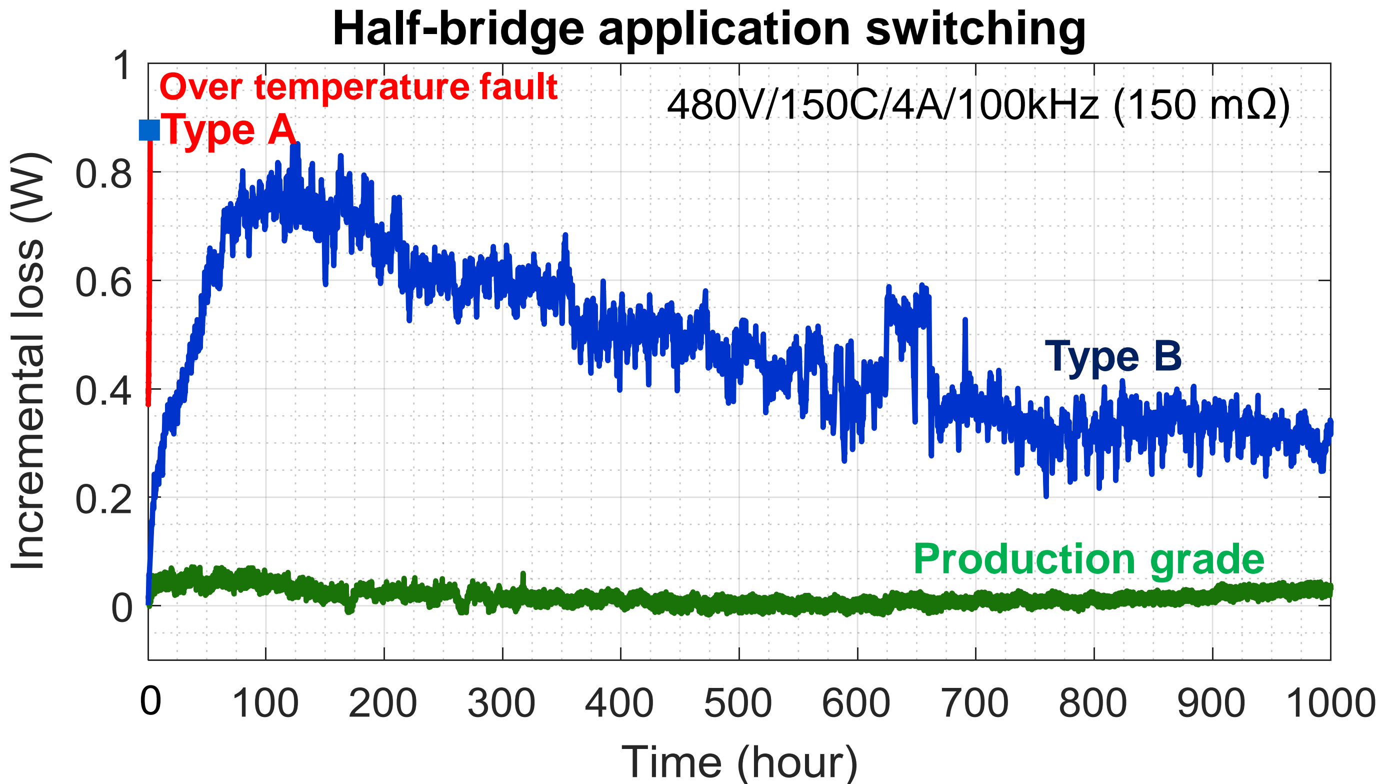
Non-production devices



- Hard-switching testing is able to detect the two key GaN failure modes: dynamic Rds-on degradation and robustness (device hard-fail).
- Several types of devices pass silicon qualification testing, but not all pass hard-switching testing

Poor application performance for hard-switching fails

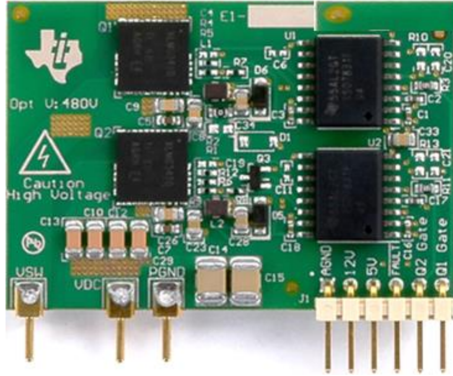
Devices that pass hard-switch testing run well in application without overheating, efficiency loss or over-temperature faulting

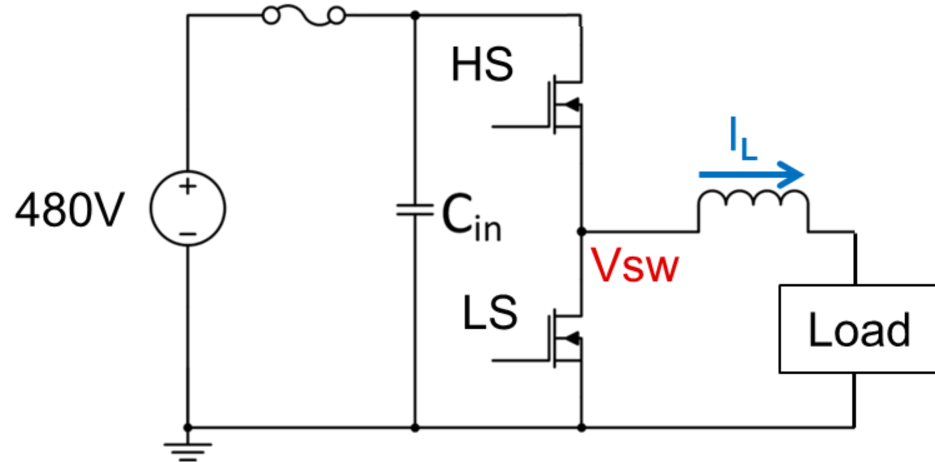


Passing silicon qual does not mean that devices will run well in application as shown for Type "A" and "B" devices

What are the system-level stresses?

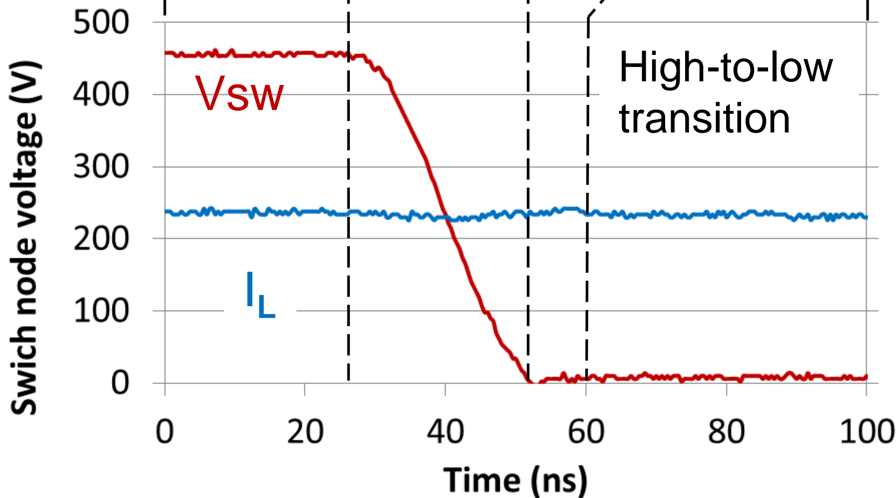
Half-bridge EVM card

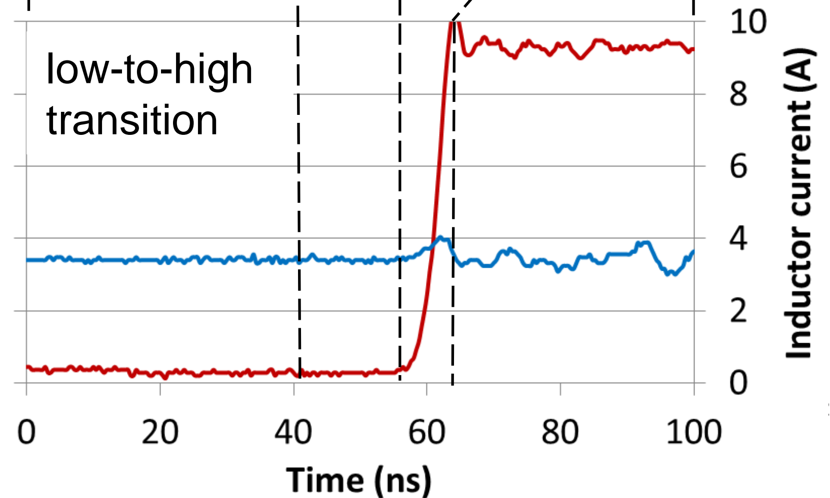




	static	switching	dead time	static
HS	on	~soft	off	off
LS	off	off	3Q	on

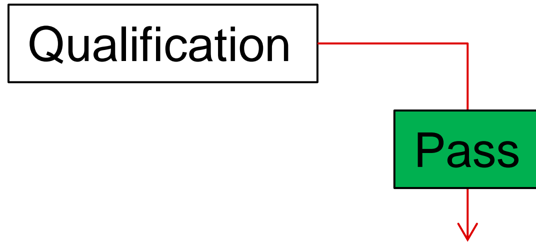
	static	dead time	sw	static
HS	off	off	hard	on
LS	on	3Q	off	off





Coverage of system-level stresses

Goal: full coverage without duplicating tests



Coverage:
Green: good
Red: poor

Hard Switching operation	Coverage
Device off with high drain bias	HTRB
Device on with high gate bias	HTGB
Third quadrant operation	
Switching transitions	

Static operating modes

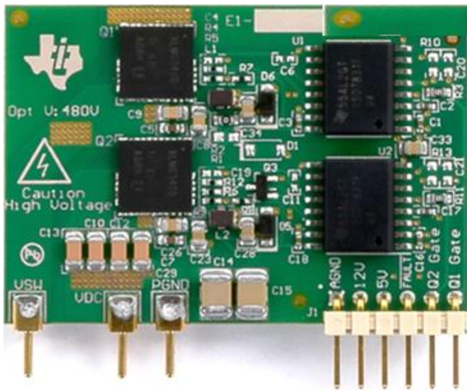
Dead time

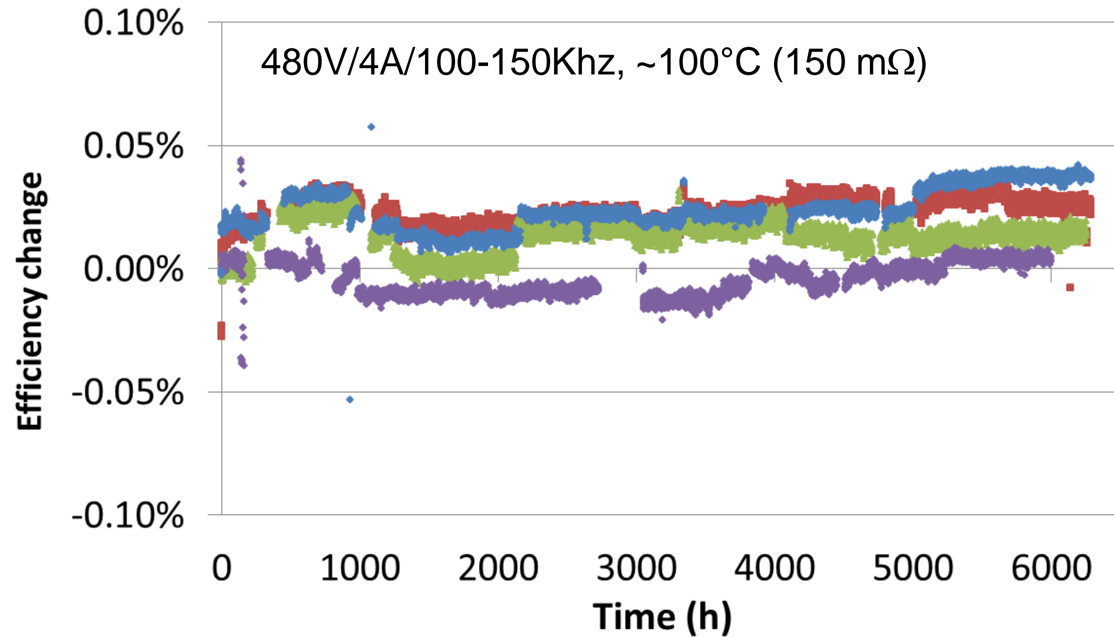
HTRB=High Temperature Reverse Bias
HTGB=High Temperature Gate Bias

Stable devices run well in system

Test vehicle: half-bridge EVM card

Production-grade devices (validated by hard-switching)





Production-grade devices show long-term stability

It shows that there are no other highly stressful failure modes

Reliability coverage assessment

Goal: full coverage without duplicating tests

Coverage:
Green: good
Red: poor

Qualification → Pass →

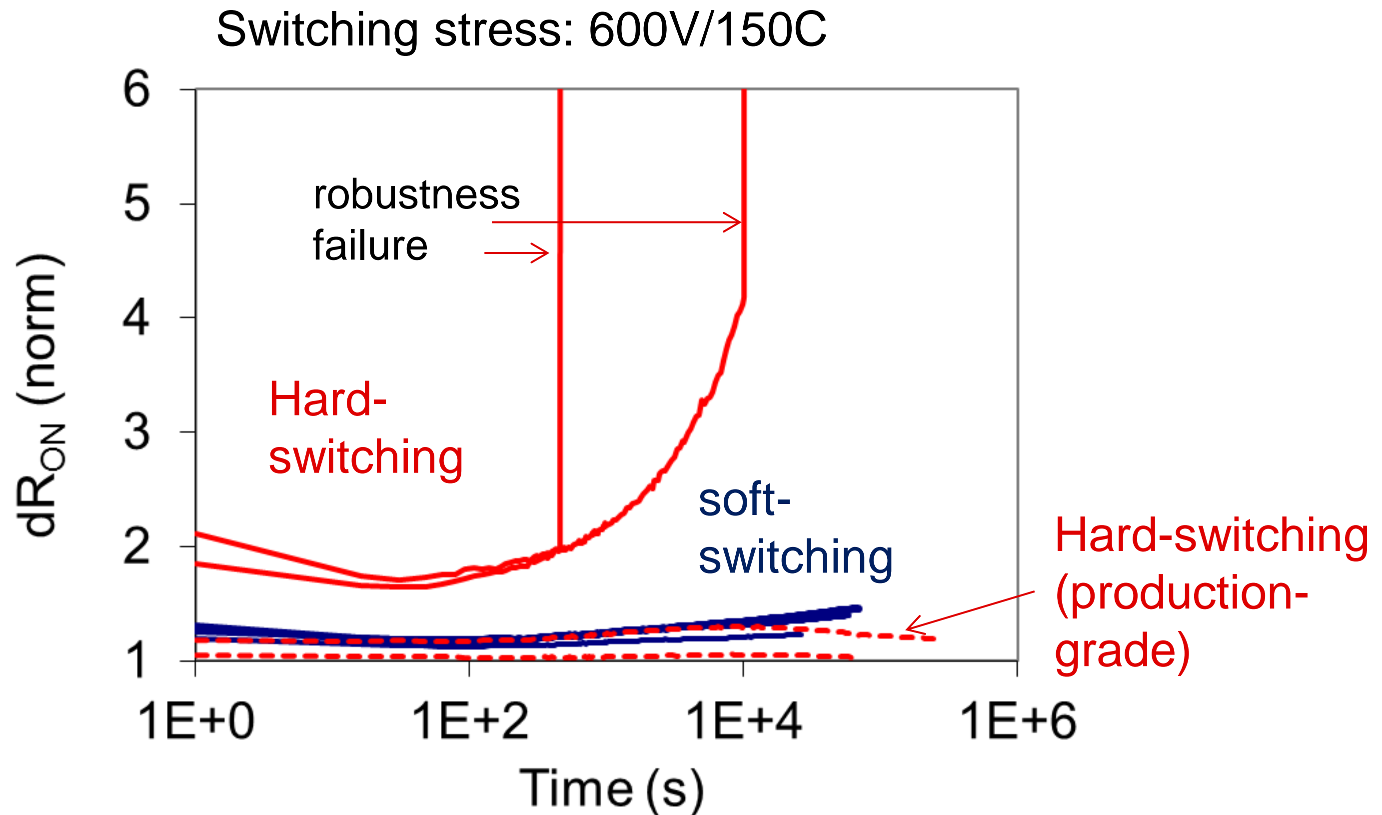
Hard Switching operation	Coverage
Device off with high drain bias	
Device on with high gate bias	
Third quadrant operation	
Switching transitions	

→ Pass →

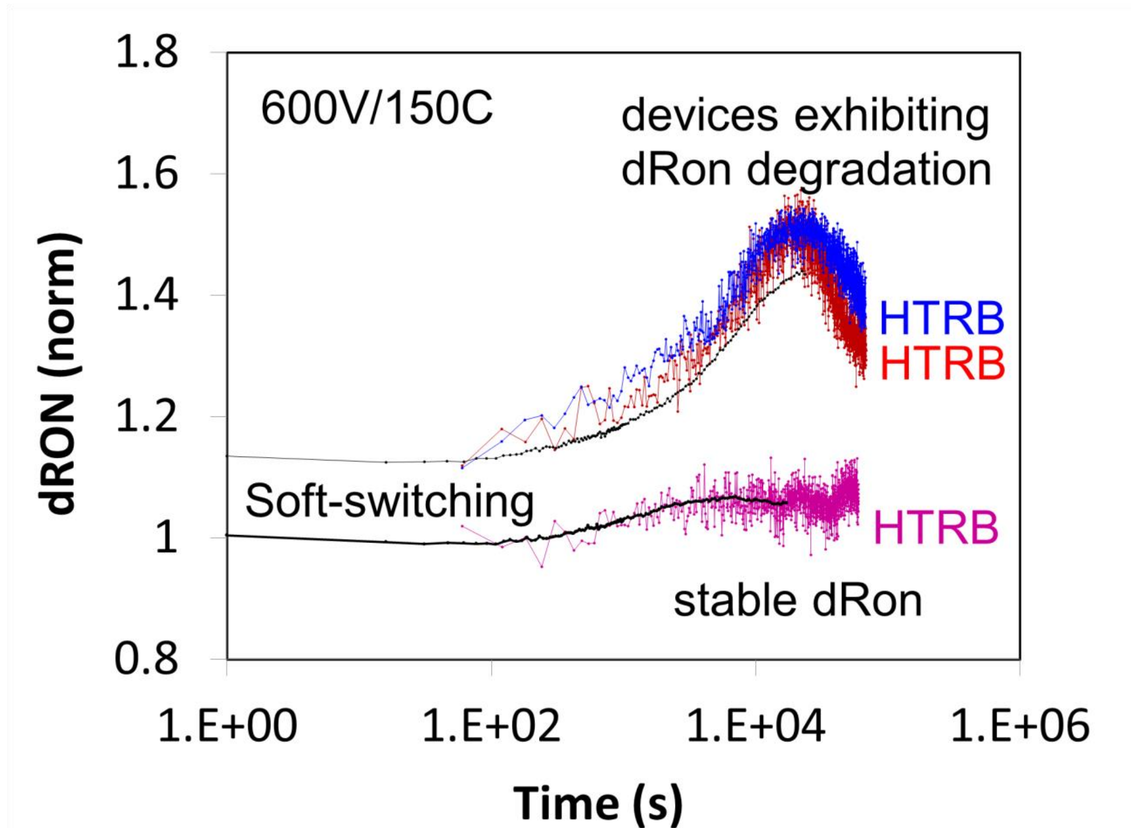
Soft-switching operation	?

Hard-vs soft-switching

Hard-switching is more stressful than soft-switching (shown on non-production devices)



Soft-switching and HTRB result in similar type of stress



- Off-state stress can cover dRon degradation during soft-switching
- It will not, however, stress the failure modes due to hard-switching: hot-carrier effects, SOA boundaries, and high slew-rate effects.
- HTRB plus hard-switching provides good reliability coverage

Coverage scorecard for a device passing qual and hard-switching testing

Coverage:
Green: good
Red: poor

Qualification → Pass ↓

Hard Switching operation	Coverage
Device off with high drain bias	
Device on with high gate bias	
Third quadrant operation	
Switching transitions	

→ Pass ↓

Soft-switching operation

Conclusions

- GaN is a key enabler for power electronics. To gain widespread acceptance in a conservative market, reliability needs to be assured.
- Traditional qualification testing does not cover power management device stresses, nor prescribe product-level qualification.
- We address this issue by identifying hard-switching as a fundamental switching profile for power management, and by using a test vehicle to apply the stress. This reduces the problem to one of a device and tester
- Hard-switching is necessary to assure product-level reliability for power management applications. We show that passing silicon qualification does not guarantee good application-level performance.
- Devices that pass silicon qualification and hard-switching reliability testing perform well in application

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