The eGaN® FET Journey Continues

EFFICIENT POWER CONVERSION

GaN Reliability for Automotive: Testing Beyond AEC-Q

Dr. Robert Strittmatter- Vice President of Reliability

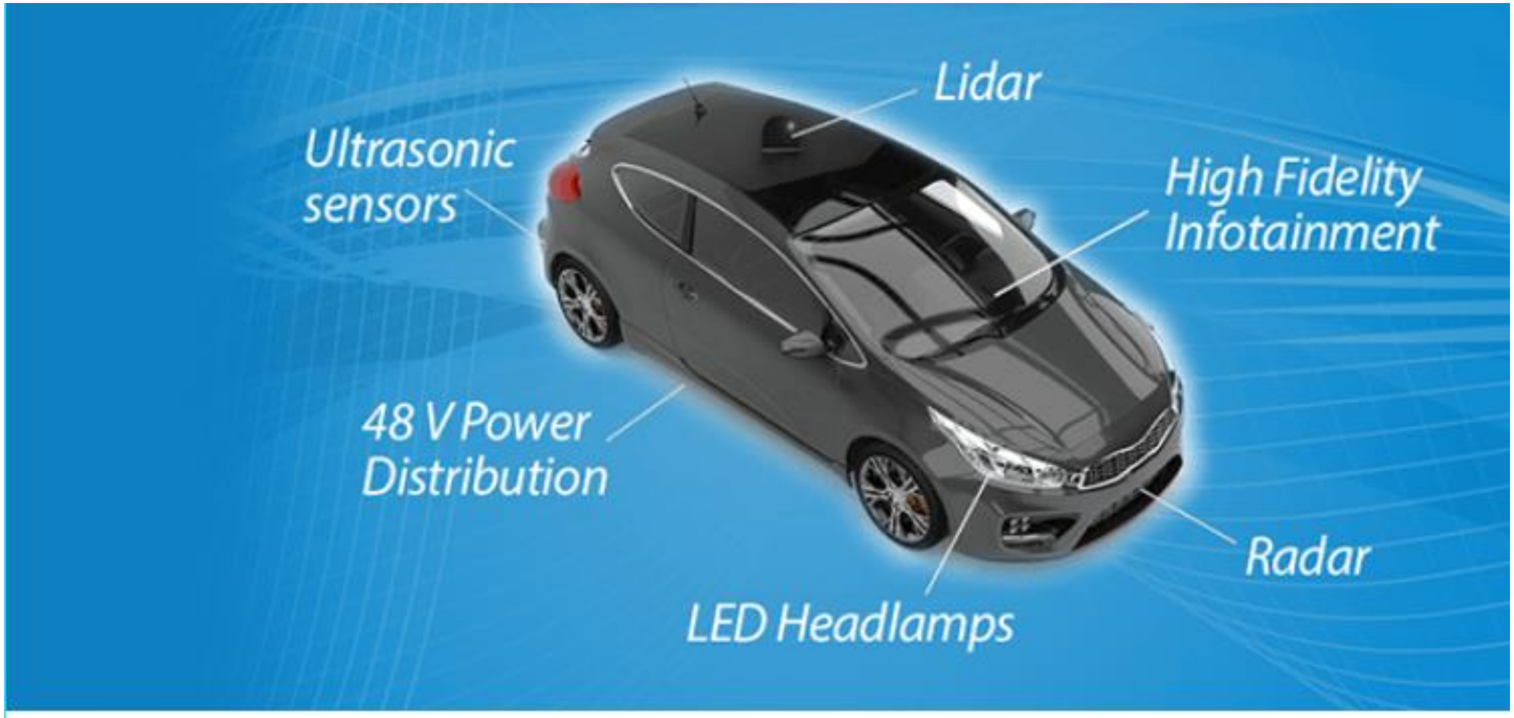
APEC 2019 PSMA Industry Session

Outline

- Automotive eGaN® FETs
- AEC-Q101 Qualification
- *Beyond AEC Testing*
  - *Gate reliability acceleration factors*
  - *Hard-switching reliability*
  - *Lidar Reliability*
- FIT Rates and Extrinsic Failure Rates
- Field Failure Rates

eGaN® FETs and ICs for Automotive

- GaN is expected to play a prominent role in 2 of the major automotive mega-trends in the years to come
  - Autonomous Vehicles (Lidar)
  - Electric Vehicles (dc-dc conversion)
- Reliability is a key factor affecting adoption of GaN technology



eGaN® AEC FETs

- 5 eGaN® FETs have completed AEC-Q101 qualification
- More discrete and IC products in the pipeline for release in 2019, ranging from 40V to 200V
- AEC-Q101 establishes a baseline reliability, but further testing is required to convince automotive customers

Part Number	Max V_{DS} (V)	Max V_{GS} (V)	Max $R_{DS(ON)}$ (mΩ)	Die Size (mm x mm)	Max Operating Temperature (°C)
EPC2214	80	6	20	S (1.35 x 1.35)	150
EPC2206	80	6	2.2	XL (6.05 x 2.30)	150
EPC2212	100	6	13.5	M (2.11 x 1.63)	150
EPC2202	80	5.75	17	M (2.11 x 1.63)	150
EPC2203	80	5.75	80	S (0.95 x 0.95)	150

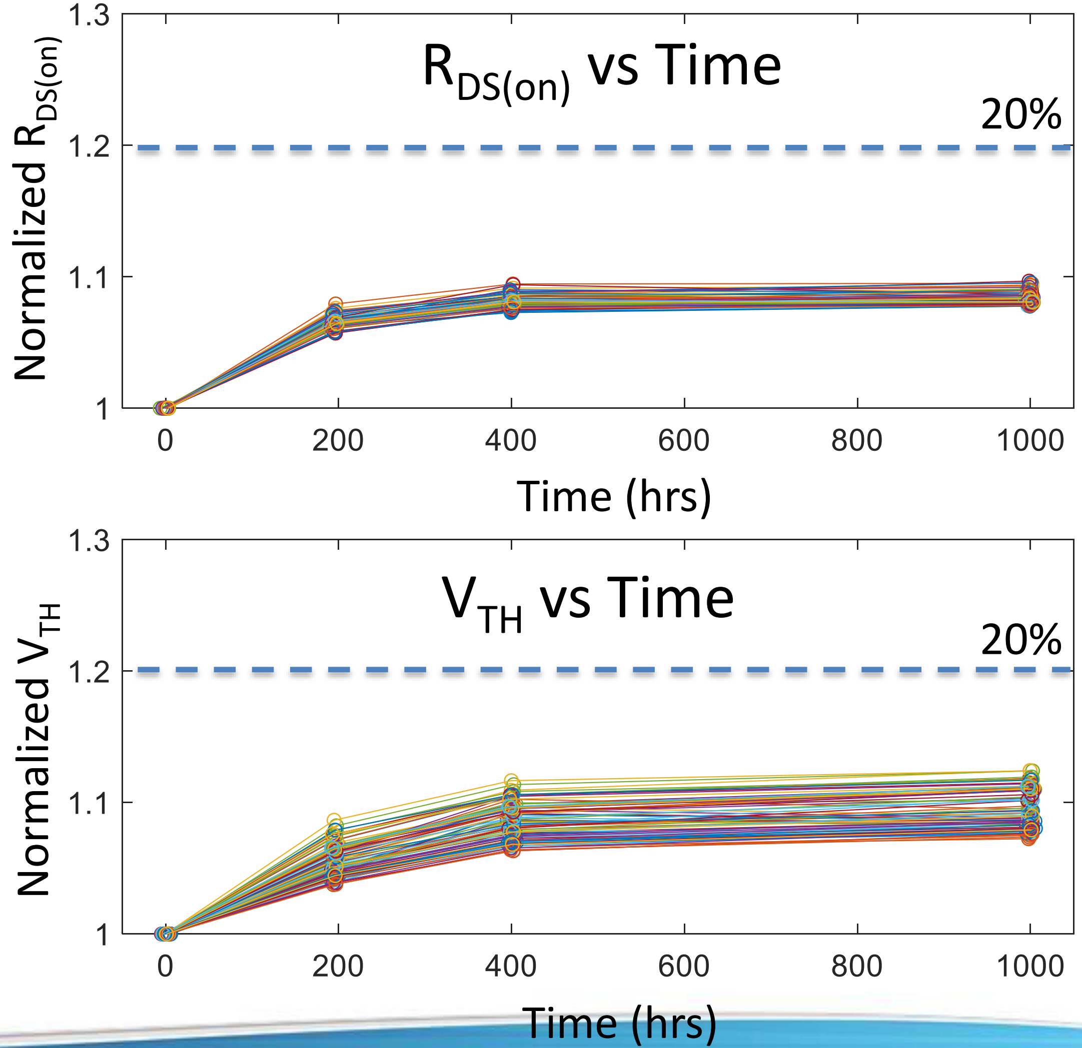
AEC-Q101 Testing

Test	Conditions	Duration	Sample Size (Parts x Lots)					Failures
			EPC2206	EPC2212	EPC2202	EPC2203	EPC2214	
HTRB	150 °C, V_{DS} = 100% V_{DSmax}	1000 hrs	77 x 3	77 x 3	77 x 3	77 x 3	77 x 1	0
HTGB	150 °C, V_{GS} = 100% V_{GSmax}	1000 hrs	77 x 3	77 x 3	77 x 3	77 x 3	77 x 1	0
uHAST	130 °C, RH = 85% VP = 33.3 psia	96 hrs	77 x 3	Matrix	77 x 3	77 x 3	77 x 1	0
TC	-55 to +150 °C, Air	1000 cyc	77 x 3	Matrix	77 x 5	77 x 3	77 x 1	0
H^3TRB	T=85°C, RH=85%, V_{DS} = 80% V_{DSmax}	1000 hrs	77 x 3	77 x 3	77 x 5	77 x 3	77 x 1	0
MSL1	T = 85 °C, RH= 8 5%, 3x reflow	168 hrs	77 x 4	77 x 3	77 x 3	77 x 3	77 x 1	0
DPA	Post uHAST	-	2 x 1	2 x 1	2 x 1	2 x 1	2 x 1	0
ESD	HBM + CDM	-	10 x 1	Matrix	10 x 1	10 x 3	10 x 1	0
PV	-40 °C, 25 °C, 150 °C	-	25 x 1	25 x 1	25 x 1	25 x 1	25 x 1	0
IOL	ΔTj =125°C; ton / toff = 1 min /5 min	5000 cyc	32 x 1	Matrix	77 x 2	77 x 1	Matrix	0

Parametric Shift: HTRB

- Parametric shift during 1000 hrs HTRB shown for 77 parts of EPC2212
- 150 °C at full rated voltage (100V)
- Data is normalized to value at time = 0
- $R_{DS(on)}$ and V_{TH} show small initial rise, and then saturate over time
- Shifts well within AEC 20% limits

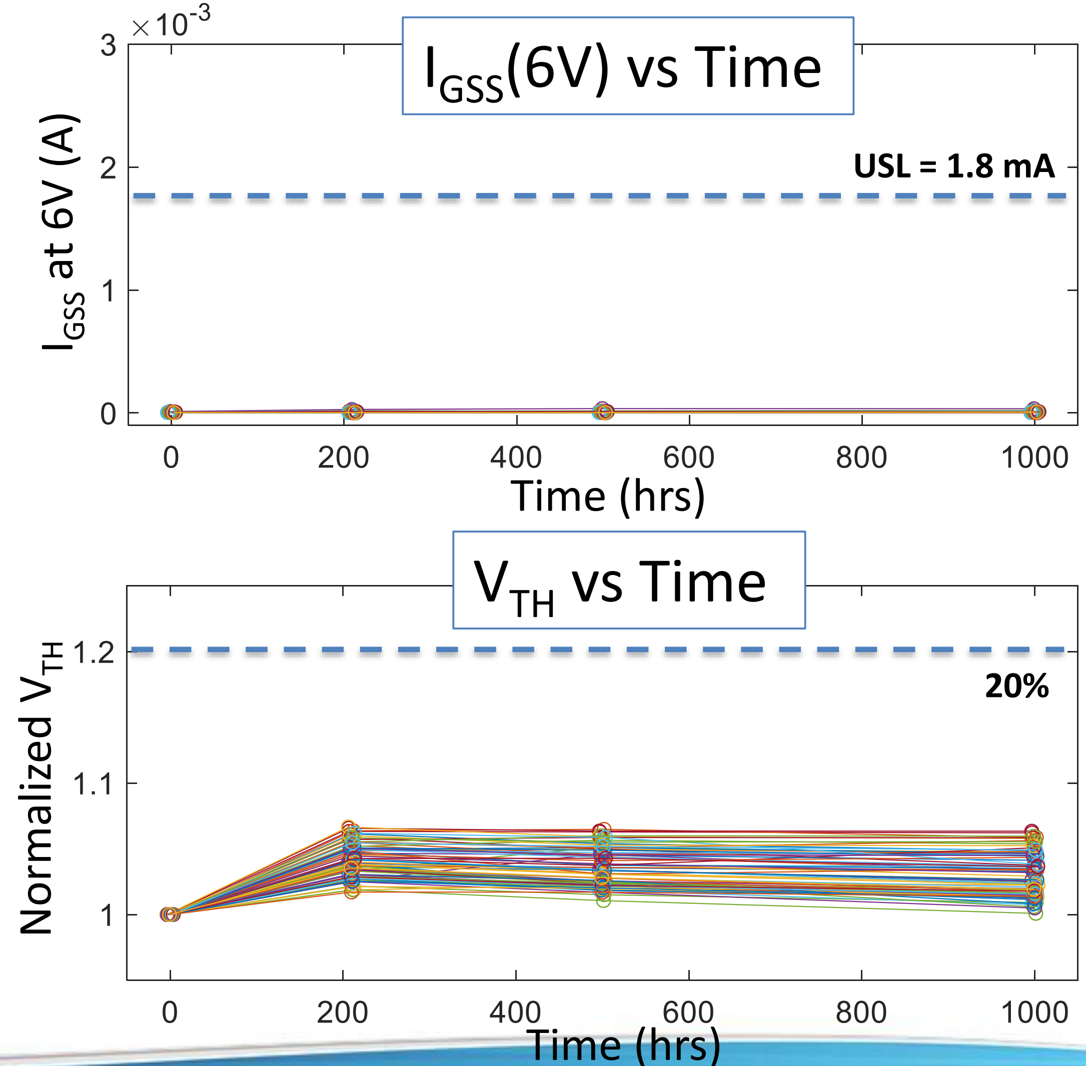
EPC2212 HTRB 1000 Hours 150 °C



Parametric Shift: HTGB

- Parametric shift during 1000 hrs HTGB shown for 77 parts of EPC2212
- 150 °C at full rated gate voltage (6V)
- Gate leakage remains flat (< 5x) and well below datasheet limits
- V_{TH} shows a small initial rise, staying well within 20% limits

EPC2212 HTGB 1000 Hours 150 °C



The Need for "Beyond AEC"

- Automotive customers care about lifetime
  - 8000 hrs, 15000 hrs, 20 years continuous
- They are skeptical that AEC-Q101 guarantees lifetime in their mission profile
- Traditional acceleration studies are one approach to demonstrate suitable lifetime
- The most convincing reliability data for automotive customers:
  - Parts are stressed in similar conditions to the end application circuit
  - *The outcome of the test provides a direct demonstration that lifetime requirements will be achieved, without need for activation energy or acceleration factor*

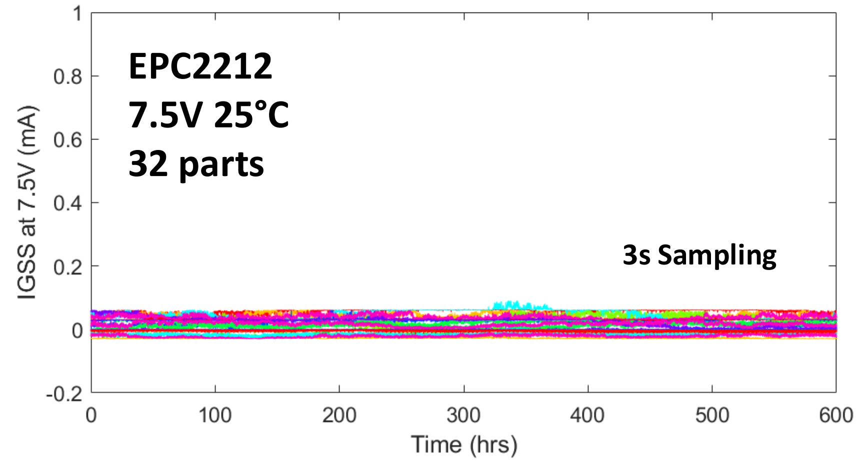
Beyond AEC-Q101 Testing

- On-going reliability monitoring program
- Conventional gate and drain acceleration factor studies over voltage and temperature
- Hard/soft-switching reliability tests
  - Measures dynamic $R_{DS(on)}$ changes (a.k.a. current collapse)
  - Parts are hard switched at 100 kHz, 80% rated voltage, and under switching conditions that accelerate hot carrier scattering
  - *$R_{DS(on)}$ vs time can be projected to 10 years of continuous operation.*
- In-circuit (buck converter) testing using EPC's dc-dc demo boards
  - Efficiency vs time
  - High and low side FETs are stressed simultaneously
- In-circuit LiDAR tests, monitoring peak pulse current vs time using EPC's EPC9126 demo board
- Long term LiDAR reliability tests
  - Short pulse switching circuit
  - *Accelerated repetition frequency to achieve 10 years of pulses in 1000 hrs*

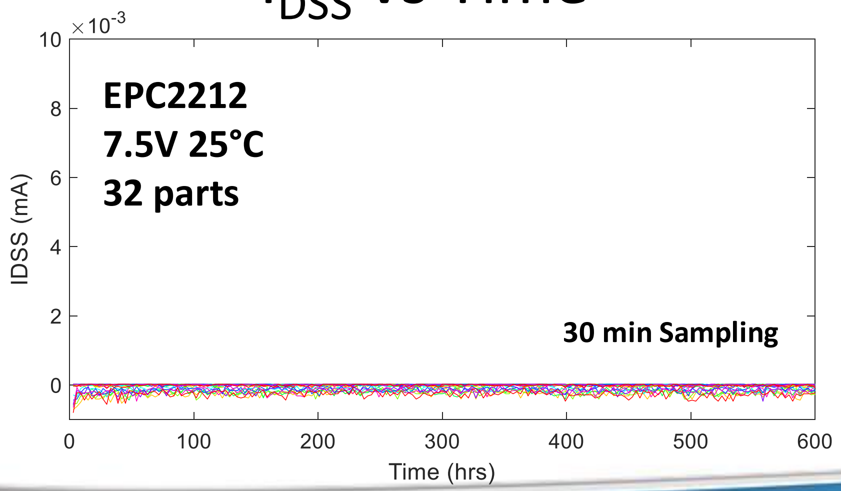
Gate Reliability Test System

- Custom test system developed to monitor multiple potential failure/degradation modes under accelerated gate stress
  - Gate leakage, threshold shift, drain leakage
- Time series data shown for EPC2212 (V_{GS} = 6V max) biased at 7.5V for 600 hours (32 parts)

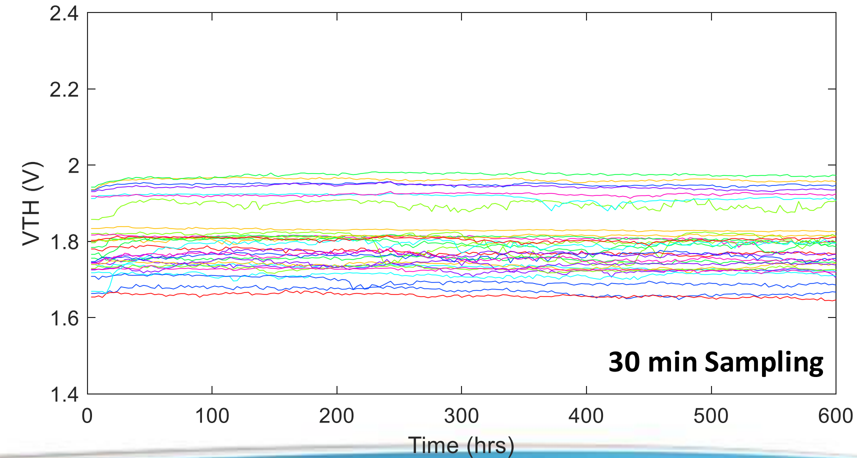
I_{GSS} vs Time



I_{DSS} vs Time



V_{TH} vs Time



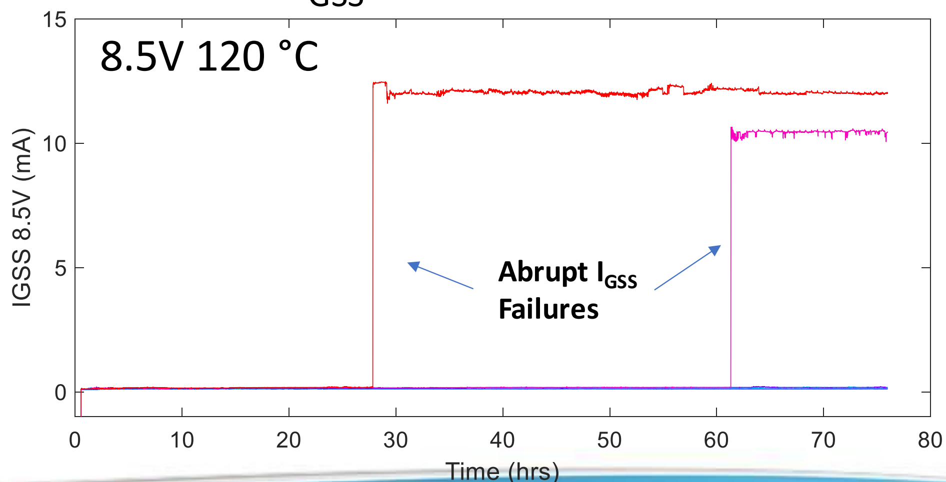
Gate Acceleration Study

- AEC EPC2212 tested at accelerated gate voltages beyond datasheet limit
- Dominant intrinsic failure mode above 8V is abrupt gate rupture
  - Phenomenologically similar to TDDB in MOSFET gates
  - Highly voltage accelerated
- No other failure/degradation mechanisms encountered

Test Matrix

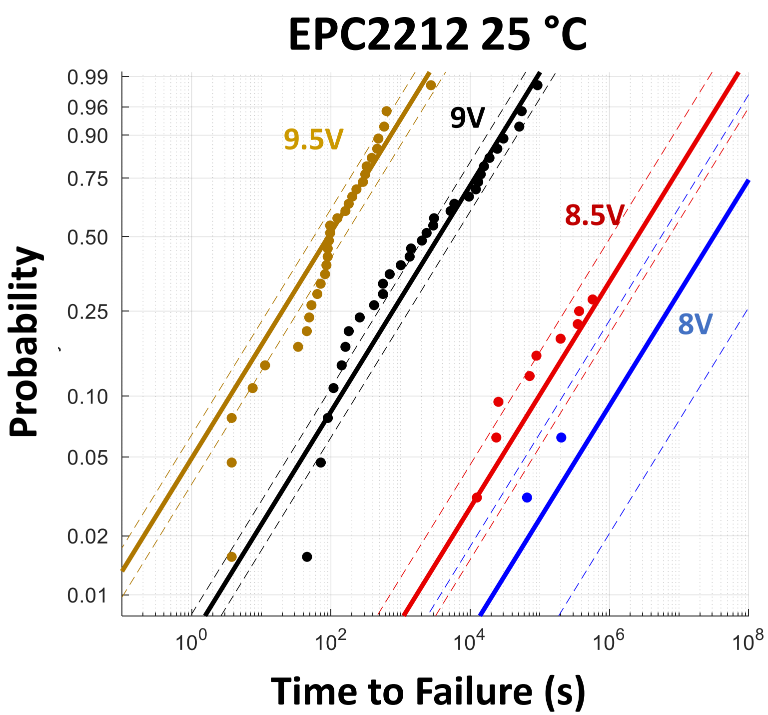
Temperature	Voltage (V)	Duration (hrs)	Failures
25 °C	7.5	600	0/32
	8	200	2/32
	8.5	200	9/32
	9	24	32/32
	9.5	24	32/32
120 °C	9	24	32/32
	9.5	24	32/32

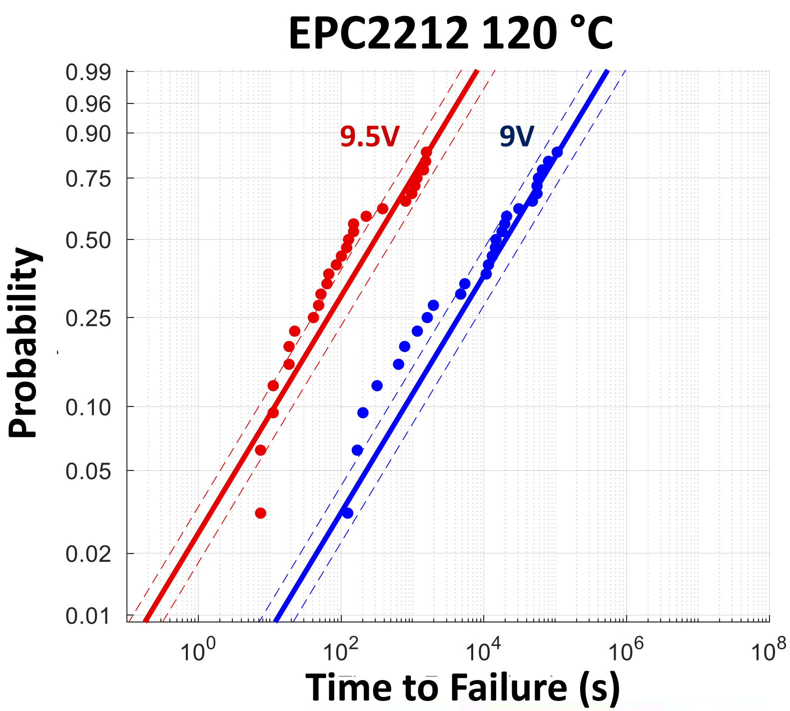
I_{GSS} vs Time at 8.5V



Gate Acceleration: Analysis

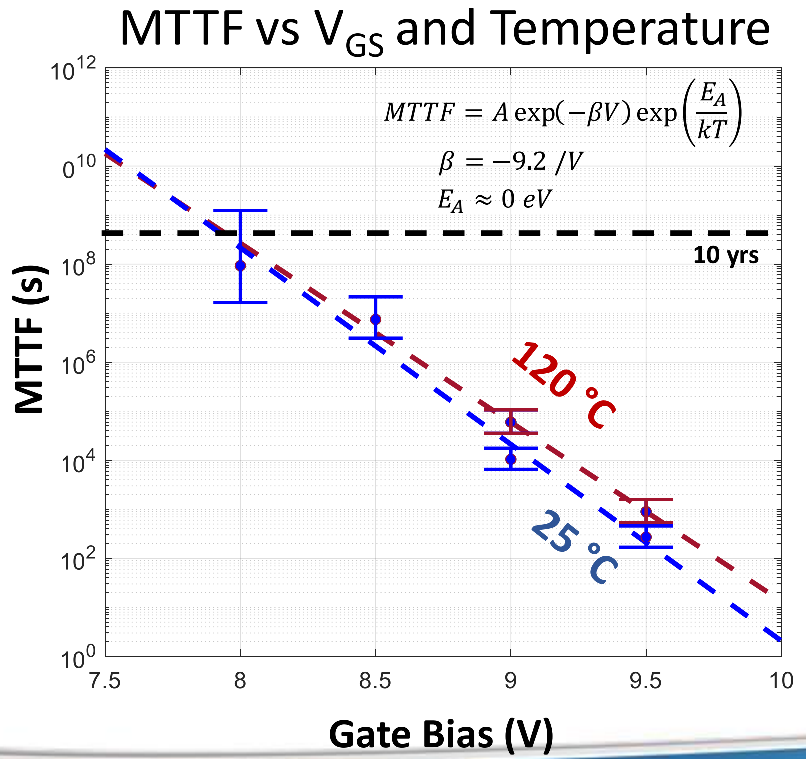
- Weibull plots for intrinsic gate rupture failures at 25 °C and 120 °C
- A common shape (slope) parameter was fit to all legs using maximum likelihood methods
- Scale (offset) parameter fit separately for each leg
- Dashed lines indicate 90% confidence intervals for the Weibull fit

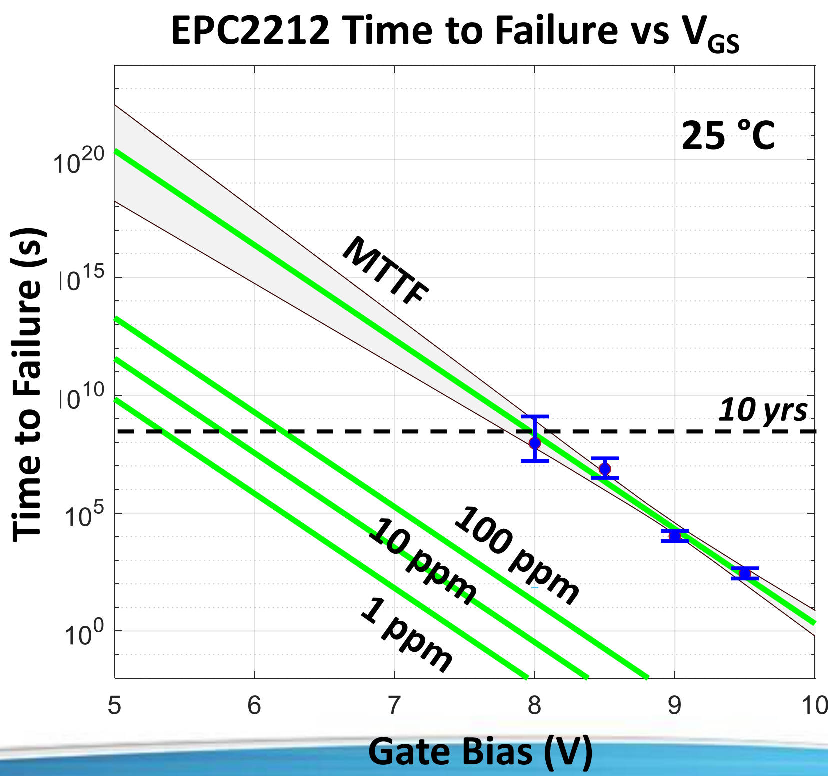




Gate Acceleration: Time to Failure

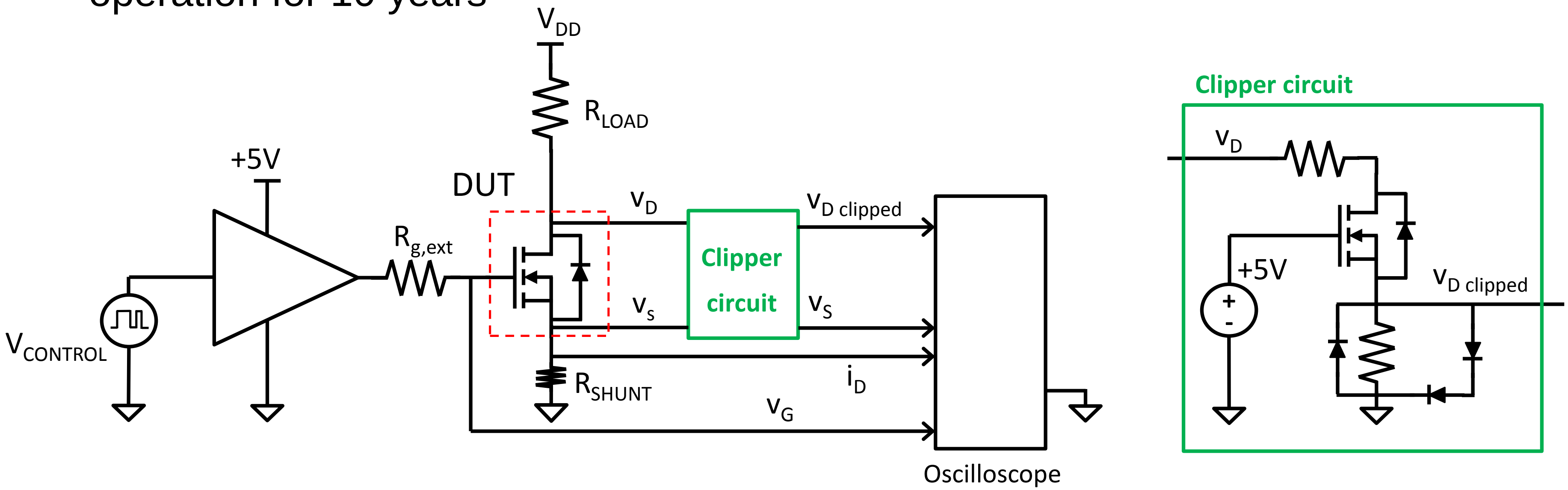
- MTTF well above 10 years at datasheet max 6V
- Strong voltage acceleration, weak (slightly negative) temperature acceleration
- Less than 100 ppm intrinsic failure rate in 10 years at datasheet max
- Less than 1 ppm intrinsic failure rate at 5V recommended operating voltage
- More stringent definition for V_{GSmax} than for Si MOSFETs





Hard Switching Reliability

- In addition to inductive double pulse testing (JEDEC JEP173), EPC uses a complementary resistive hard-switching test method to accelerate dynamic $R_{DS(on)}$ shifting at high V_{in}
- Designed to measure long term switching stability under continuous operation for 10 years
- $R_{DS(on)}$ monitored continuously in time for 1 to 100 hours while switching at 100-400 kHz
- Measurement with 100 ns of switching transition
- Transition deliberately slowed to accelerate hot carrier effects

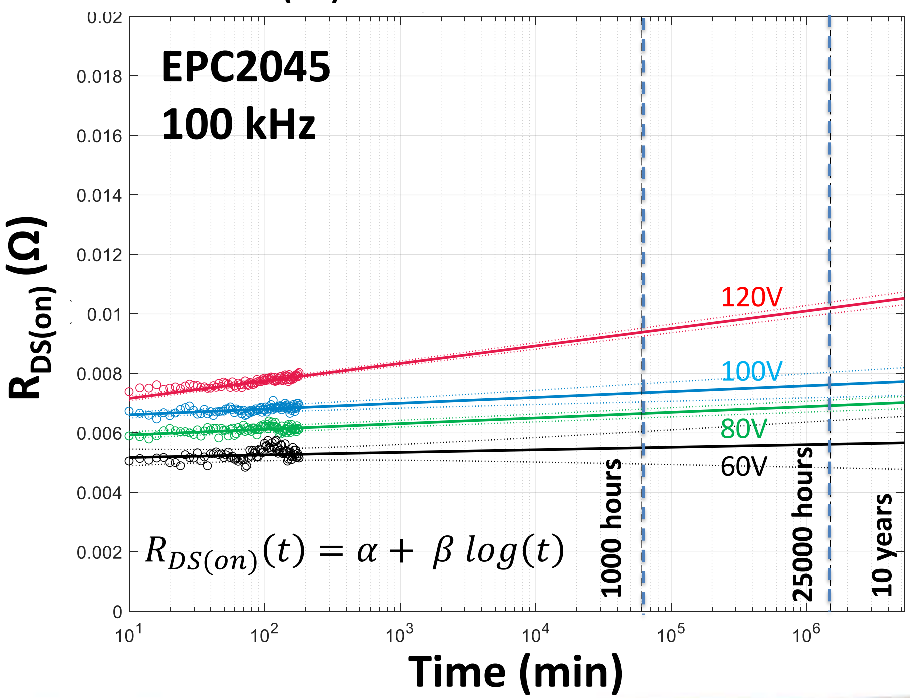


Hard-Switching: Effect of V_{in}

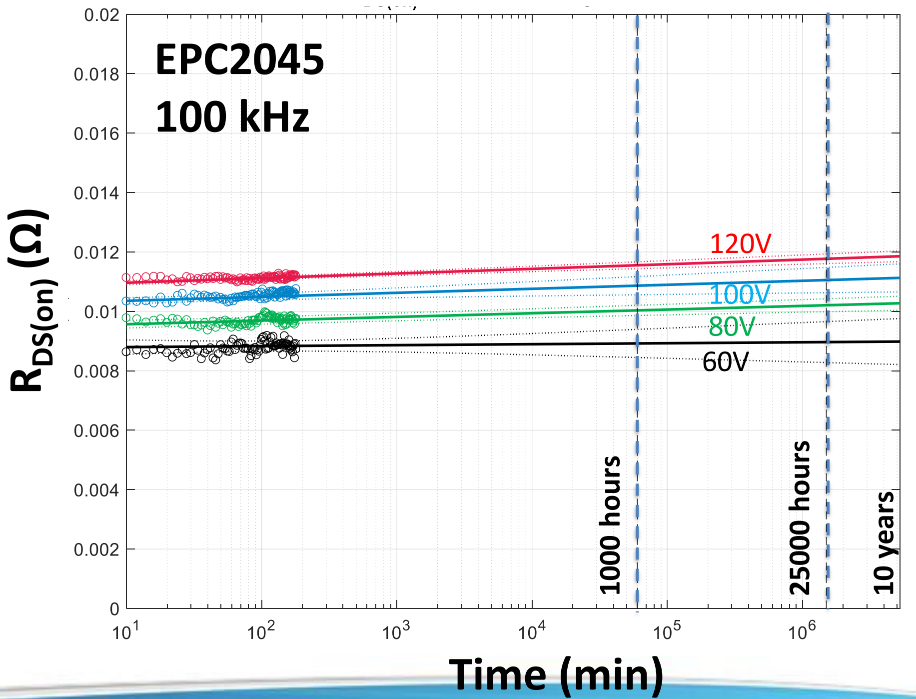
- $R_{DS(on)}$ grows with the log of time, allowing for long term extrapolations out to 10 years
- Time dependence has been verified on long term collects (> 200 hours) and is also observed under HTRB stress

- Data shown for EPC2045 (100V max) with V_{in} ranging from 60V to 120V
- $R_{DS(on)}$ shift < 20% at max V_{DS} for continuous hard-switching over 10 years

$R_{DS(on)}$ vs Time and V_{in} (25 °C)

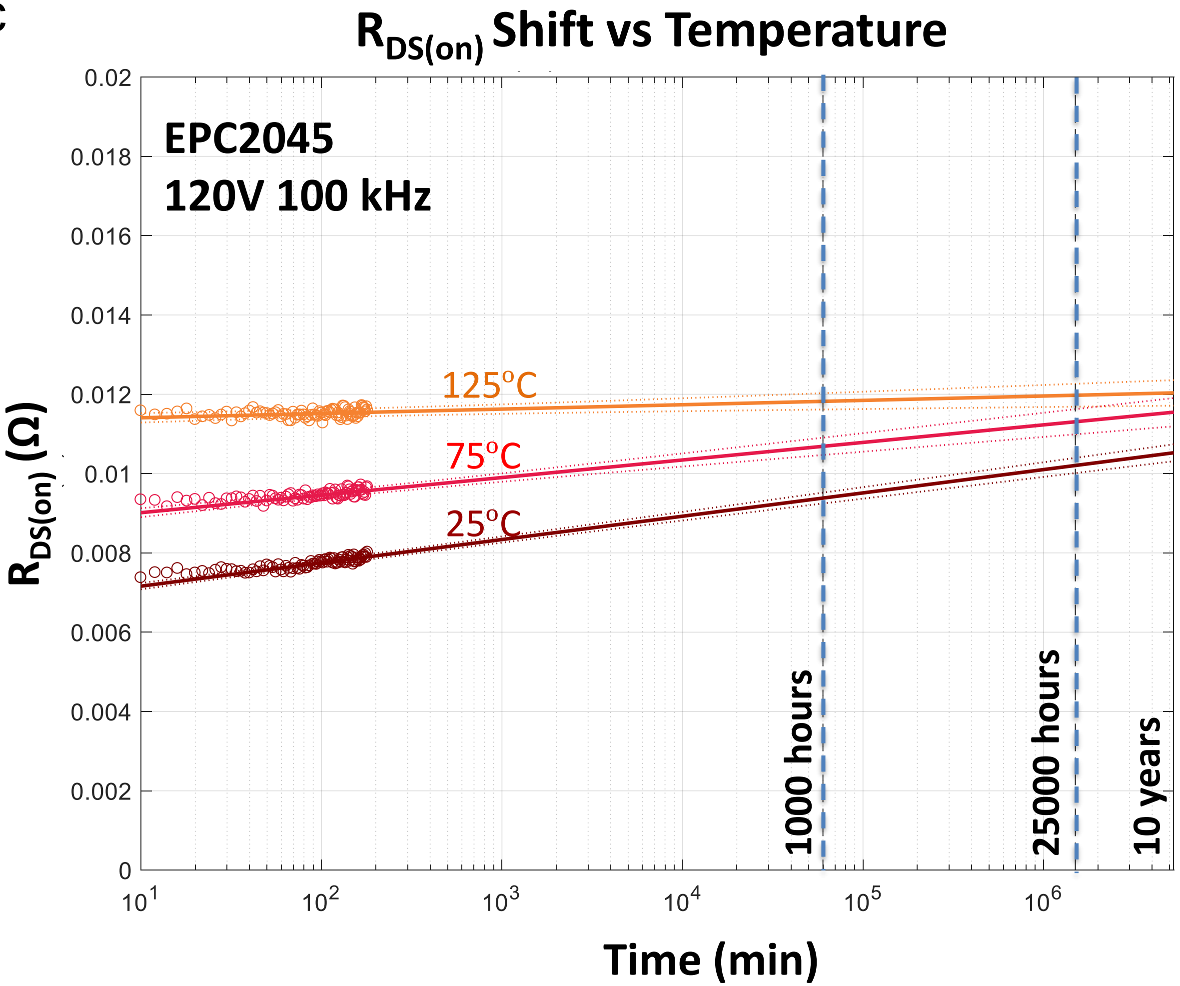


$R_{DS(on)}$ vs Time and V_{in} (125 °C)



Hard-Switching: Effect of Temperature

- Comparison of dynamic $R_{DS(on)}$ for EPC2045 operated above datasheet maximum at 3 different temperatures
- Shifting (slope) is lower at higher junction temperature
- This negative temperature activation is strong evidence of the hot-electron scattering theory

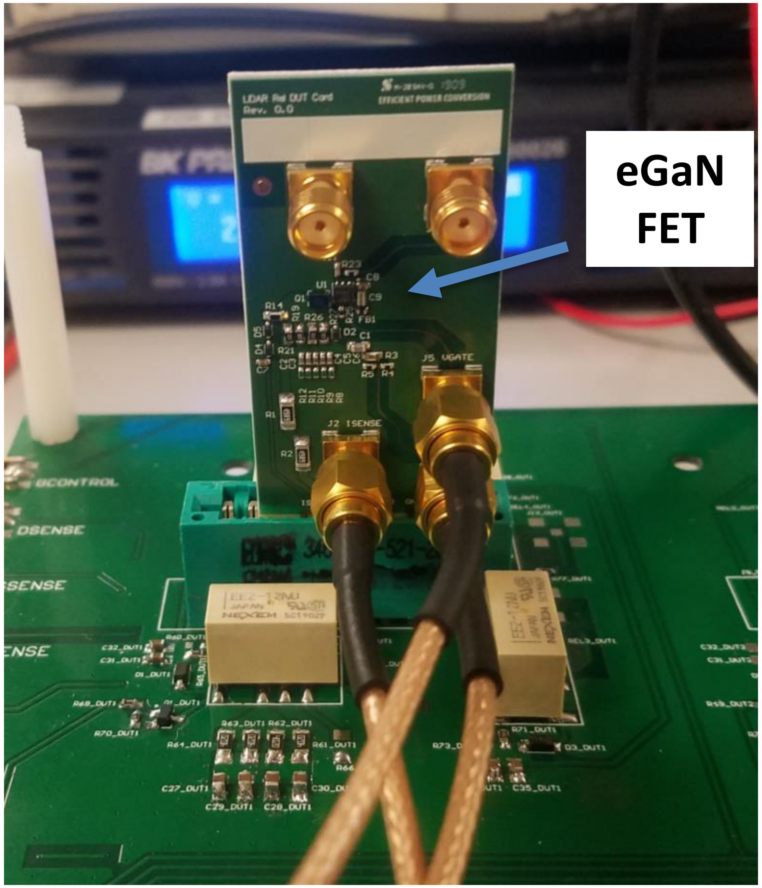


Lidar Reliability Test System

- Lidar applications subject FETs to very short (< 3 ns) high current pulses at low pulse frequency (1-10 kHz)
  - Unique stress conditions make it difficult to extrapolate lifetimes using conventional dc gate /drain stress tests
- EPC Lidar reliability test system subjects a population of eGaN FETs to accelerated stress conditions similar to Lidar applications
  - Repetitive short duration (< 3 ns) high current pulses
- By pulsing at a much higher frequency (1 MHz) than normal Lidar operation, parts can be tested to a total number of pulses commensurate with a typical automotive lifetime
  - ~10,000 hrs of pulses within < 1000 hrs
  - Avoids complicated acceleration factor extrapolations with dubious validity
- During Lidar stress testing, peak current, FWHM, $R_{DS(on)}$, V_{TH} , I_{DSS}, and I_{GSS} can be monitored in real time
  - V_{TH} shift is the highest risk degradation mechanism leading to reduction in peak pulse current

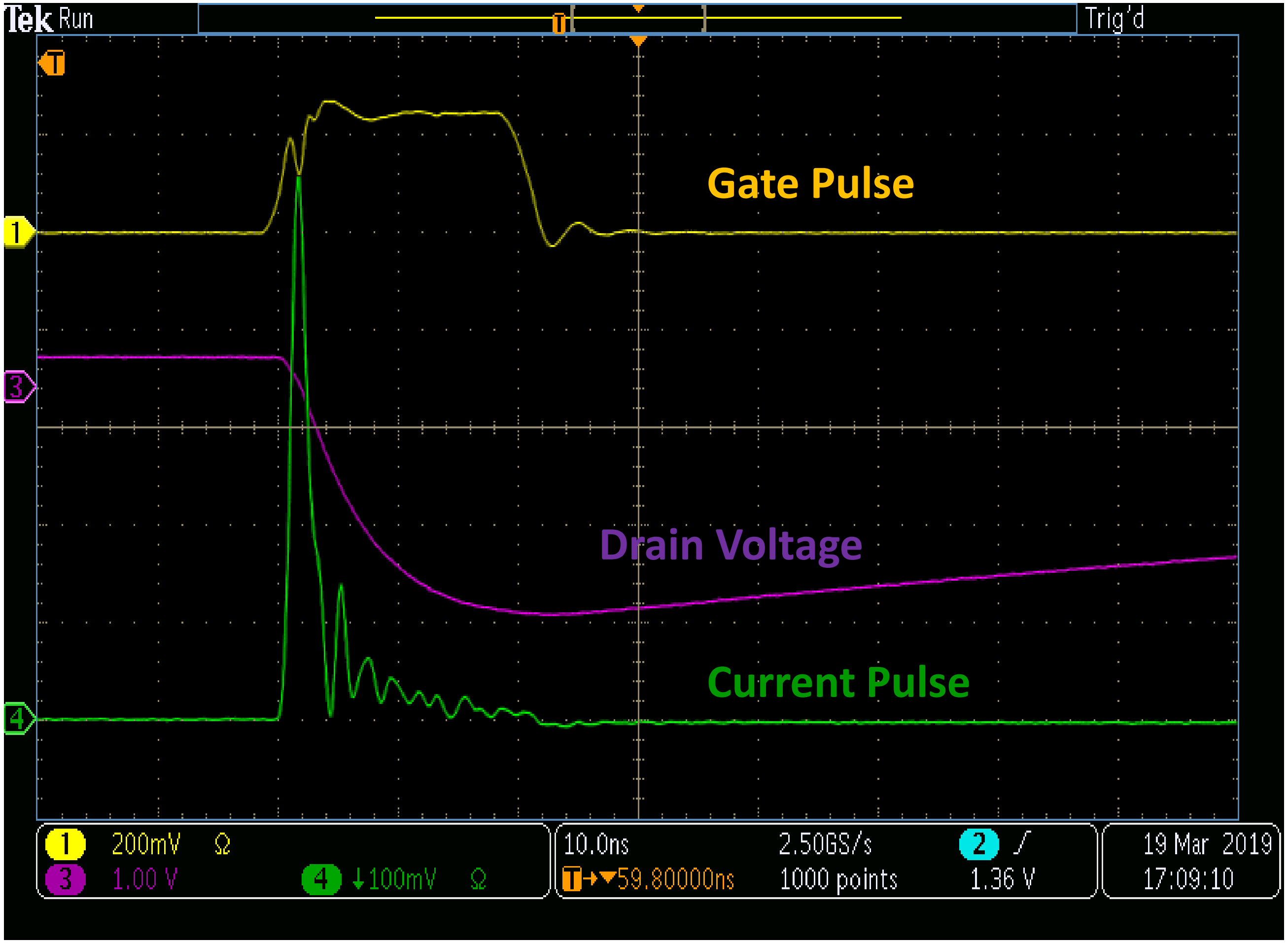
Hardware Description

- AEC eGaN FETs are mounted onto a custom daughter-board
  - Gate driver, capacitor, and diode in close proximity to device, allowing for ultra-short high current pulses
- Daughter-boards loaded onto an 8-DUT motherboard
  - Multiplexed I/O allows each part to be taken out of Lidar mode stress for parametric measurement
- Data-loggers record device parametrics over the entire test duration (1000 hrs)
- Multiple 8-DUT motherboards to be stacked
  - 24 parts x 3 device lots



Lidar Pulse Waveforms

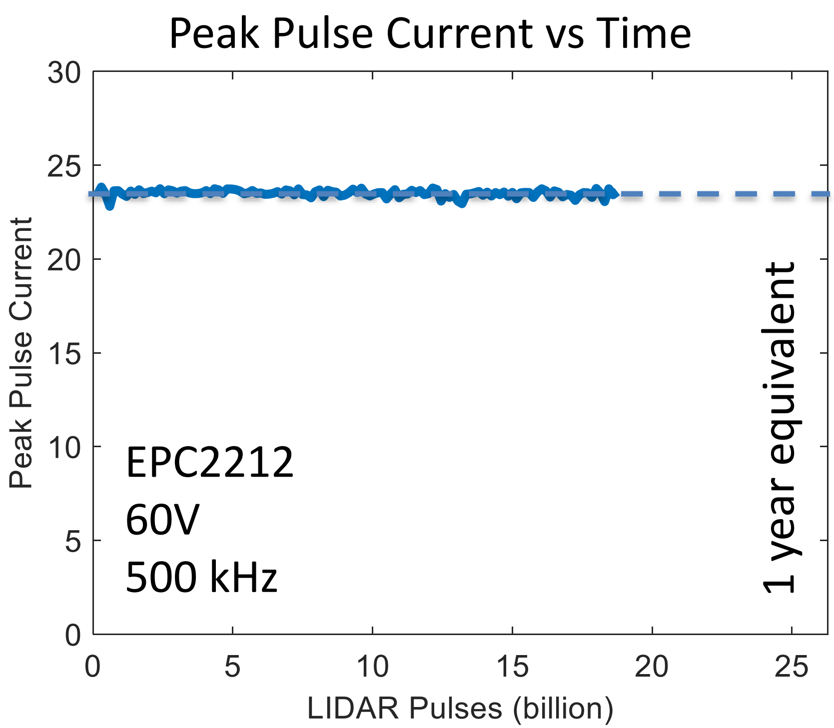
AEC EPC2212

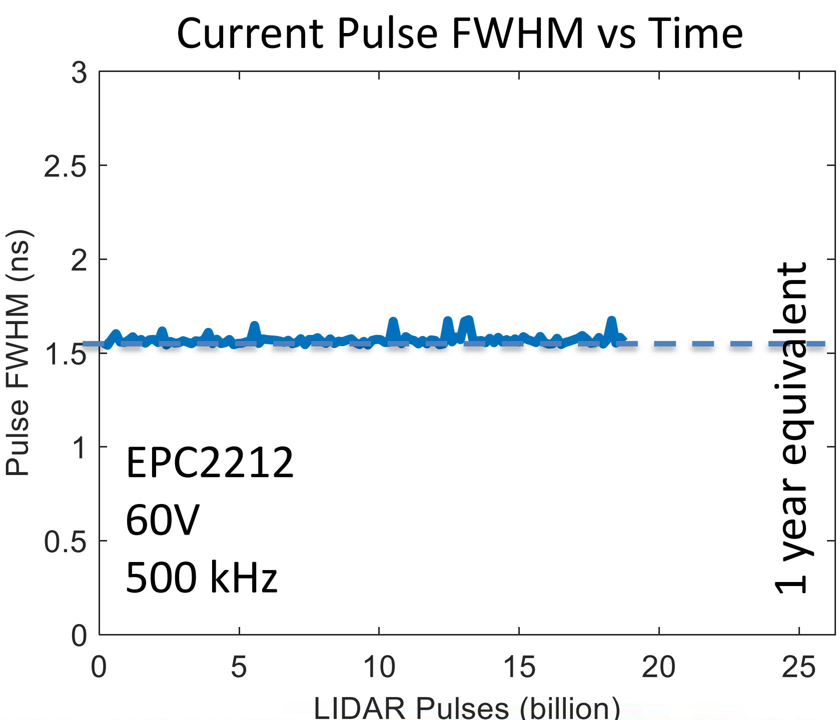


- 60 V Drain Discharge Voltage
- 24 A peak pulse current
- 2 ns pulse width
- 500 kHz rep rate

Long-Term Drift under Lidar Stress

- Initial test results show excellent stability in peak pulse current and FWHM
- Need ~300 billion pulses for typical 10 year automotive lifetime
  - Only 160 hours under accelerated test system





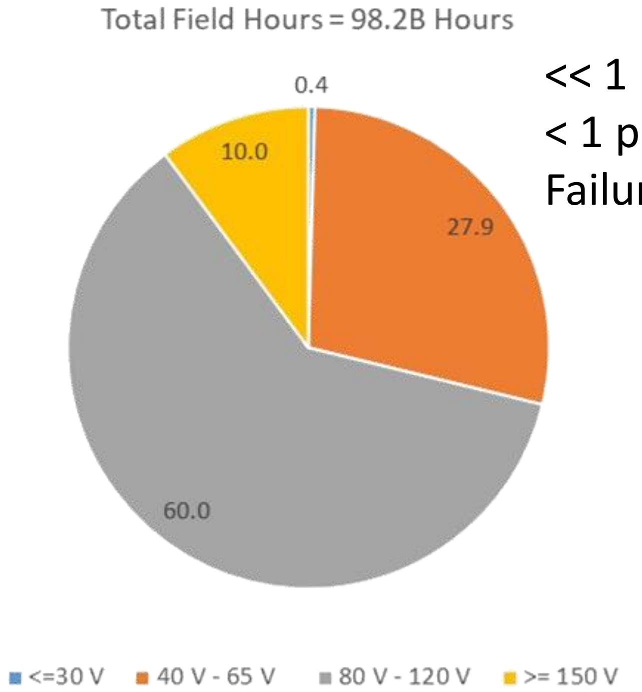
FIT Rates and Extrinsic Failure Rates

- FIT rate
  - Assumes constant failure rate in time
  - Based on cumulative device hours under reliability test at EPC
- Extrinsic failure rate
  - Based on large sample size ELFR studies (48 hours) and conventional HTRB/HTGB reliability tests
  - Upper bound on failure rate determined by finite sample size

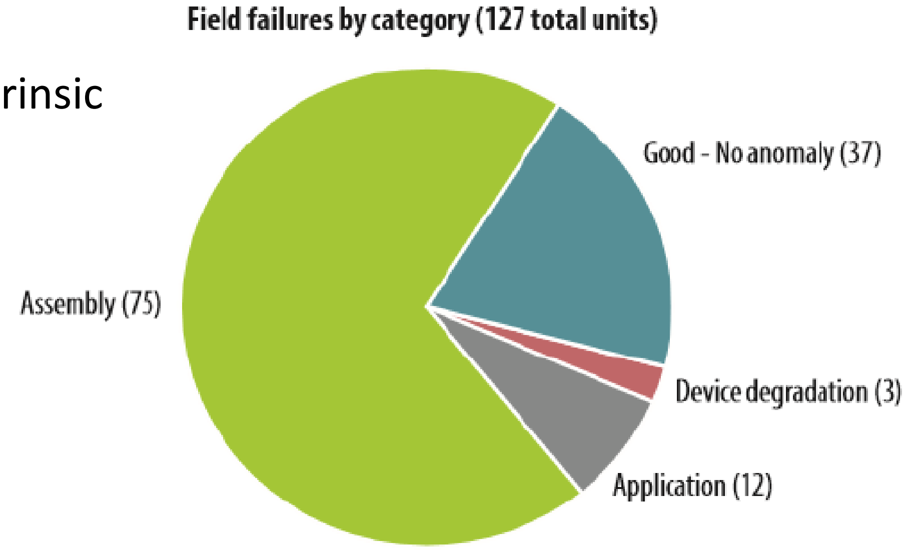
Stress Test	Sample Quantity	Equivalent Device (hrs)	Fail Quantity	Upper Bound Failure Statistics (60% Confidence)	Notes
HTRB	5102	5121960	0	179 FIT (637yrs)	$V_{DS} \geq 80\% \ V_{DS\ Max}$
HTGB	4639	5705360	0	160 FIT (713yrs)	$V_{GS} \geq 5.5V$
H3TRB	2388	2308960	0	397 FIT (287yrs)	$V_{DS} = 80\% \ V_{DS\ Max}$
ELFR_HTRB	11406	2460528	0	140 ppm	ELFR (48 hrs) and HTRB $V_{DS} \geq 80\% \ V_{DS\ Max}$
ELFR_HTGB	7393	2703344	0	218 ppm	ELFR (48 hrs) and HTGB $V_{GS} \geq 5.5V$
All Tests	30928	18300152			

Over 30,000 parts and 18 million device hours of reliability testing at EPC

Field Reliability



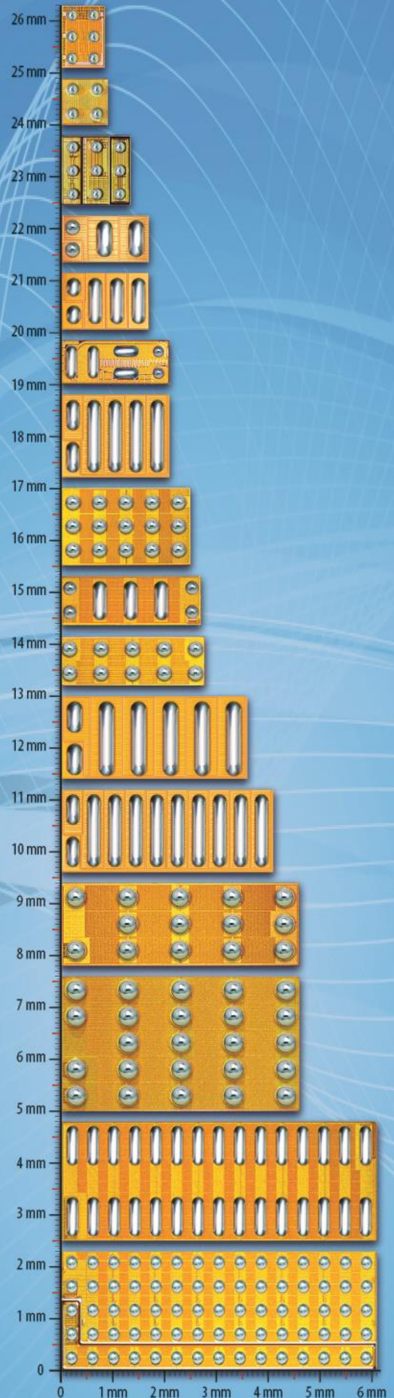
<< 1 FIT
< 1 ppm Extrinsic Failure Rate



- Mission Critical Applications
  - Automotive headlights
  - Automotive LiDAR
  - Spacecraft docking
  - Base station power
  - Surgical robotics
  - Military radios
  - Satellite Power
  - Tactical flashlights

Conclusions

- AEC-Q101 qualification represents a major milestone for GaN, but additional testing is required to address the concerns of automotive customers about this new technology
- Traditional acceleration factor studies are helpful, but often can not be directly applied to automotive applications (e.g. Lidar or dc-dc conversion)
- Tests which directly demonstrate reliability over the mission profile in the actual mission application are the most effective
  - Hard-switching reliability test -> extrapolation to 10 years
  - Lidar reliability tests -> commensurate total number of pulses



Please visit EPC website for Reliability Reports Phases 1-10

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