Recent Advancements in the Understanding of Dynamic On-Resistance and Electromigration in Enhancement Mode GaN Devices

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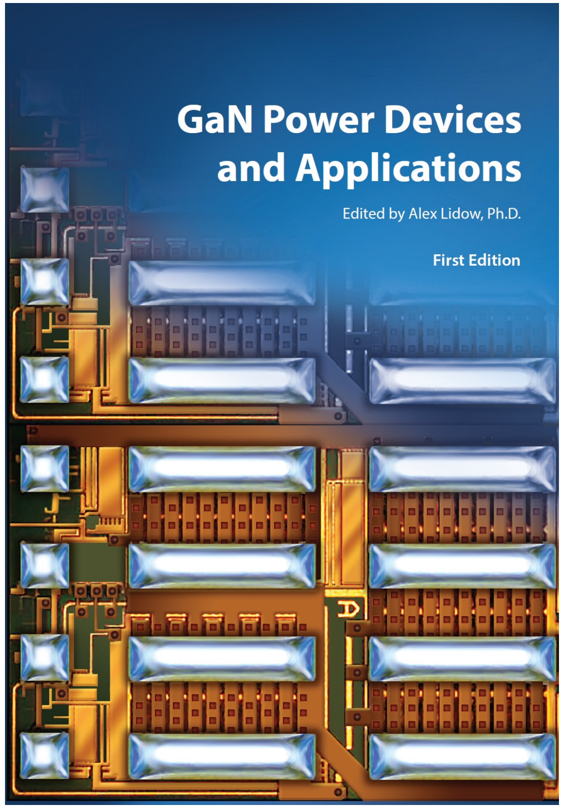
Speaker Biography

Robert Strittmatter is the vice-president of R&D Strategic Projects at Efficient Power Conversion. He received his PhD in Physics from the California Institute of Technology in 2003, specializing in GaN epitaxy, processing and micro-electromechanical devices. Since joining EPC in 2010, Robert has been heavily involved in the reliability characterization and qualification of GaN FET's and IC's. This includes: (i) understanding the fundamental physics of failure in GaN HEMTs; (ii) device simulation and optimization for enhanced reliability; and (iii) developing novel test methodologies and standards for GaN devices. Prior to EPC, he worked for 10 years in opto-electronics for the Aerospace industry, focusing on advanced semiconductor imaging technologies.

Reliability Reports and Methodology

Stressor	Device/ Package	Test Method	Instrinsic Failure Mechanism
Voltage	Device	HTGB	Dielectric failure (TDDB)
			Threshold Shift
		HTRB	Threshold Shift
			$R_{DS(on)}$ Shift
		ESD	Dielectric rupture
Current	Device	DC Current (EM)	Electromigration
			Thermomigration
Current + Voltage (Power)	Device	SOA	Thermal Runaway
		Short Circuit	Thermal Runaway
Voltage Rising/Falling	Device	Hard-switching reliability	$R_{DS(on)}$ Shift
Current Rising/Falling	Device	Pulsed Current (Lidar reliability)	None found
Temperature	Package	HTS	None found
Humidity	Package	MSL1	None found
		H3TRB	None found
		AC	None found
		Solderability	Solder corrosion
		uHAST	Dentrite Formation/Corrosion
Mechanical/ Thermo-mechanical	Package	TC	Solder Fatigue
		IOL	Solder Fatigue
		Bending force test	Delamination
		Bending Force Test	Solder Strength
		Bending Force Test	Piezoelectric Effects
		Die shear	Solder Strength
		Package force	Film Cracking

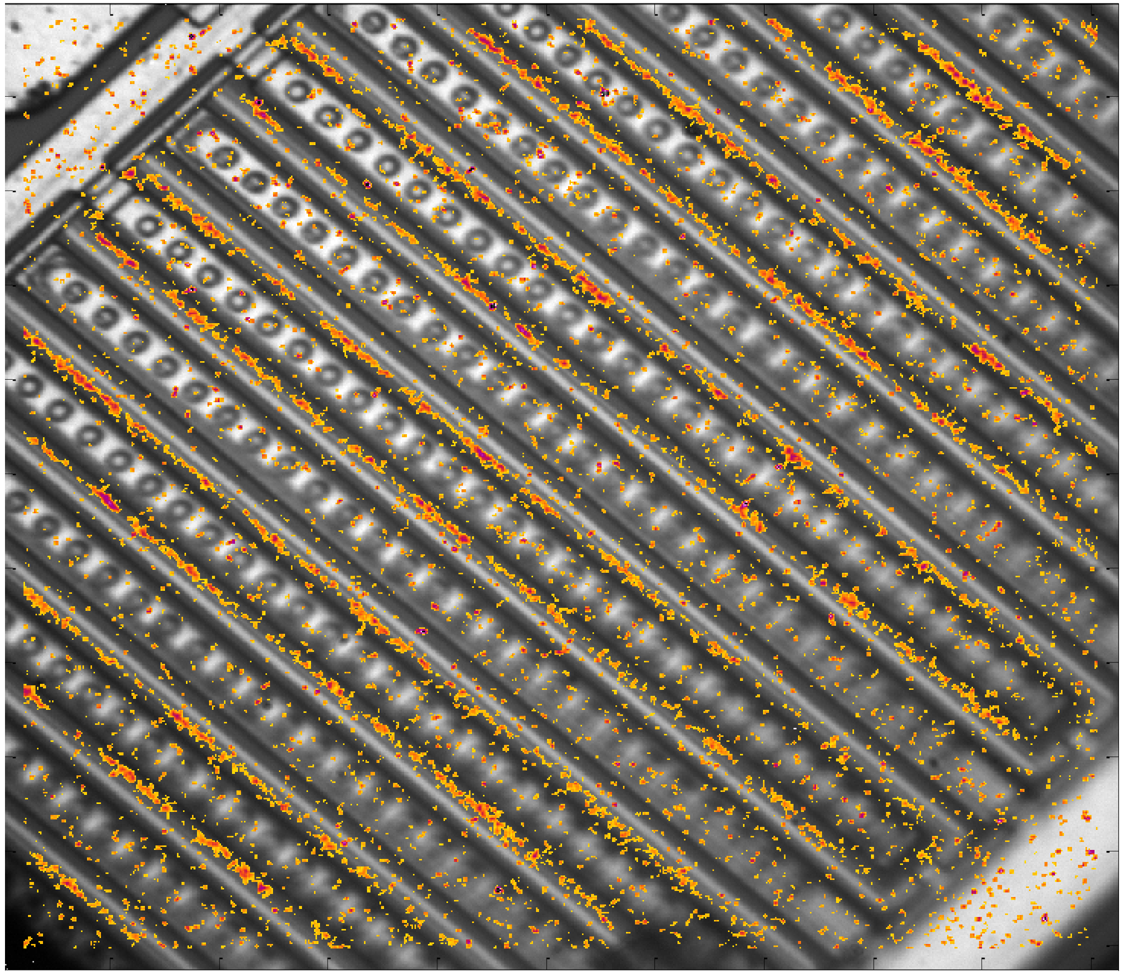


Switching Stress: High Voltage/High Current and Dynamic $R_{DS(on)}$

Phenomenology of Dynamic $R_{DS(on)}$ Degradation

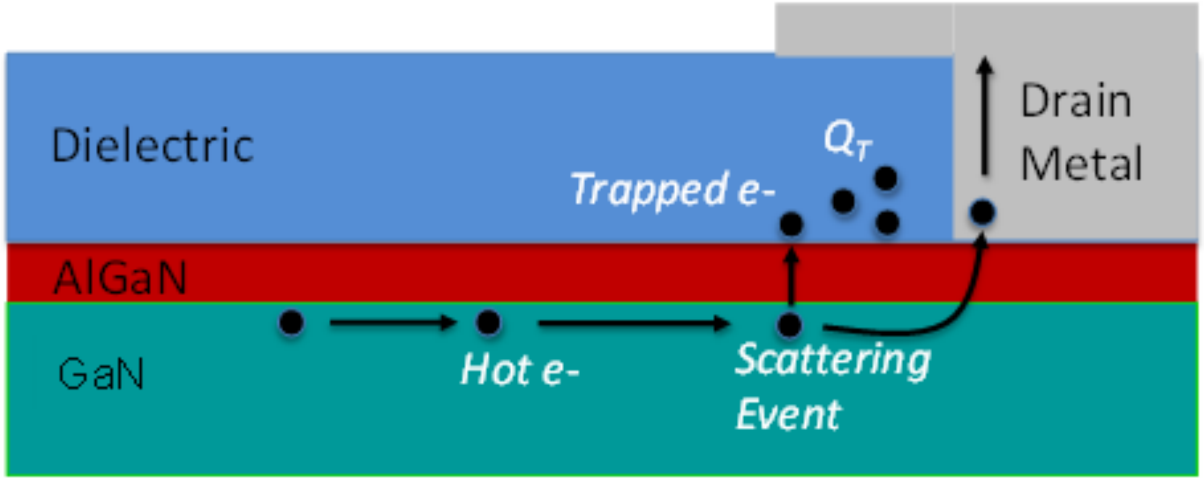
- Hot electron scattering and trapping is the primary cause of $R_{DS(on)}$ degradation in eGaN FETs
  - Simultaneous high voltage/high current
- Stress Factors
  - Drain Voltage: Strong influence
  - Temperature: Medium influence
    - Negative activation energy (i.e. degradation is less at higher temperature)
  - Switching frequency: Mild influence
  - Switch current: Mild influence
  - Inductive vs Resistive Hard-Switching: Mild influence
  - Soft vs Hard Switching: Strong influence
    - No degradation for soft switching (ZVS)
- Charge trapping is self-quenching, rising linearly with log(time)

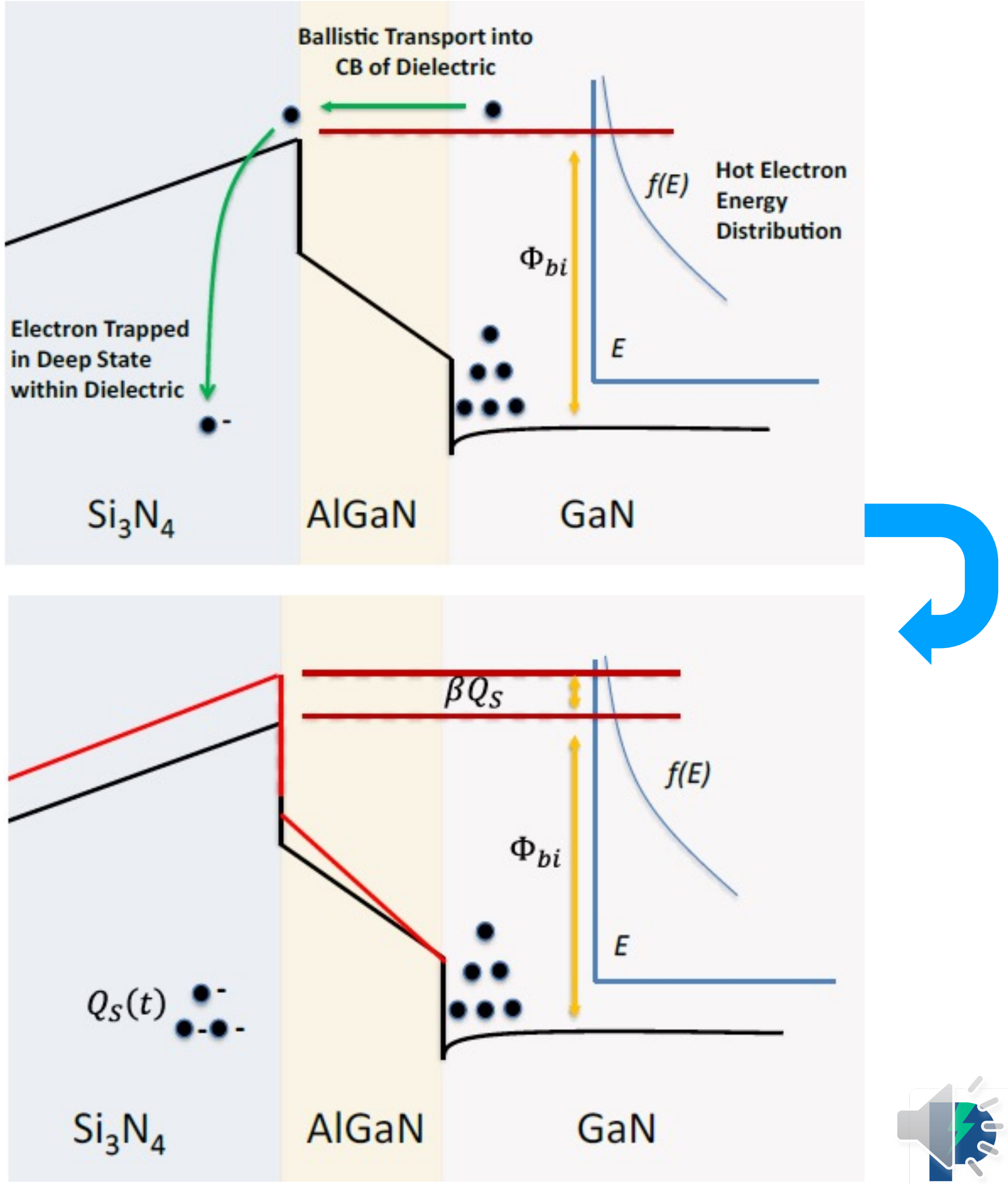
NIR Light Emission from Hot Electrons in an eGaN FET



0.7 um < λ < 1.1 um

Hot Carrier Trapping Mechanism





Mathematical Model

Basic Differential Equation for Trap Charge Injection Rate

$$\frac{dQ_S}{dt} = A \exp\left(-\frac{\Phi_{bi}+\beta Q_S}{qF\lambda}\right) \equiv B \exp\left(-\frac{\beta Q_S}{qF\lambda}\right) = \acute{B} I \exp\left(-\frac{\beta Q_S}{qF\lambda}\right)$$

Channel Electric Field vs Drain Bias: $F(t) = \log\left(1 + \exp\left(\frac{V_{DS}(t) - V_{FD}}{\alpha}\right)\right)$

Electron Mean Free Path: $\lambda = \sqrt{T} \exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$

Steady State Conditions:

If I and F (voltage) are not changing in time (or are in steady state)

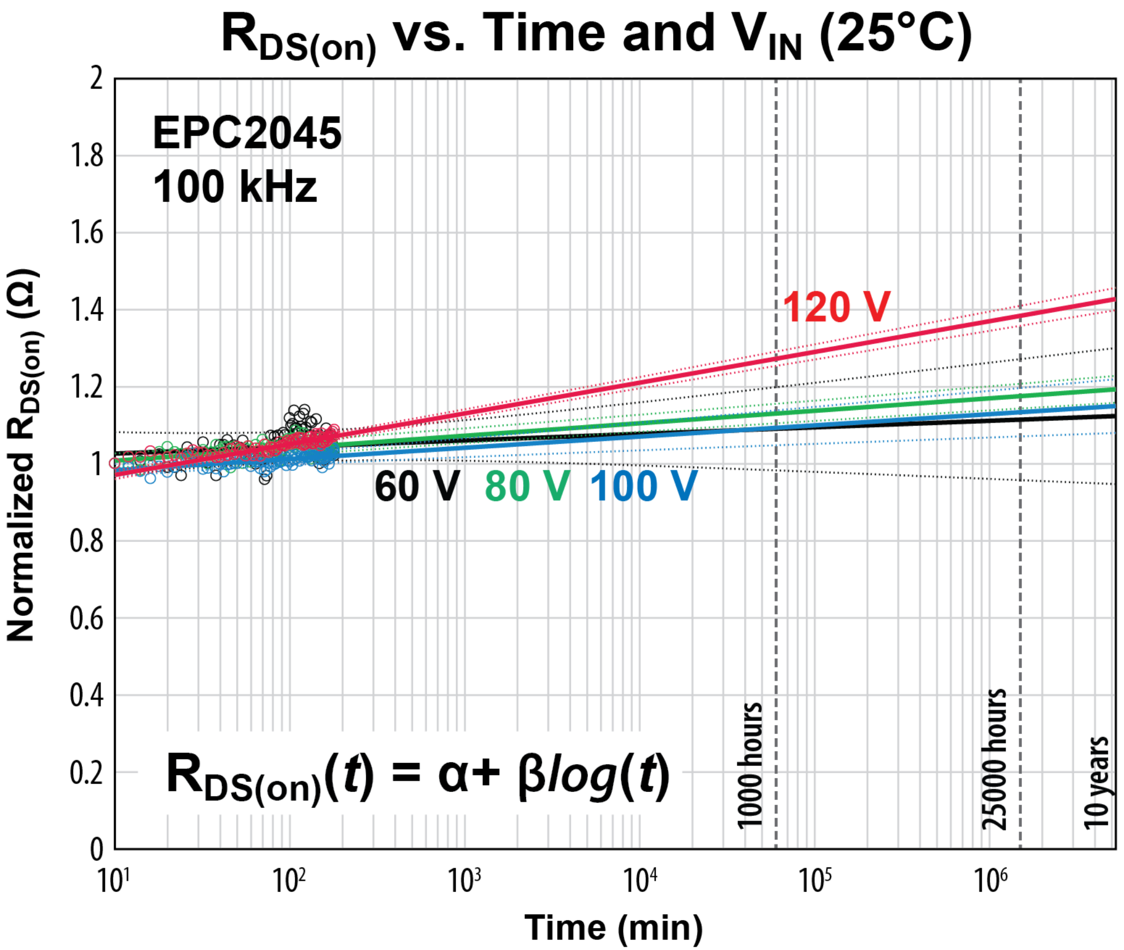
$$Q_S(t) = \frac{qF\lambda}{\beta} \log\left(1 + \frac{B\beta}{qF\lambda} t\right)$$

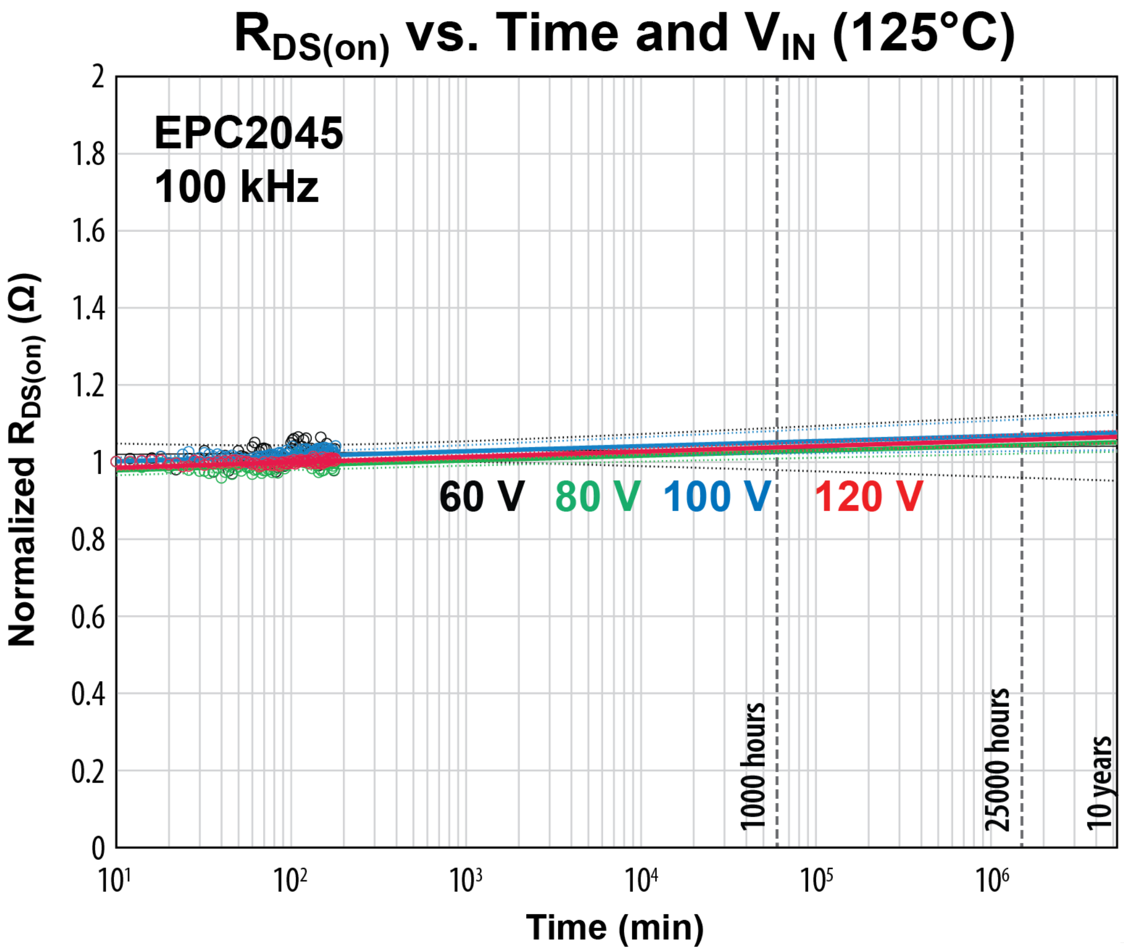
Time Dependent Conditions:

If I and F (voltage) are changing in time

$$Q_S(t) = \acute{B} \int_0^t I(t) \exp\left(-\frac{\beta Q_S}{qF(t)\lambda}\right) dt$$

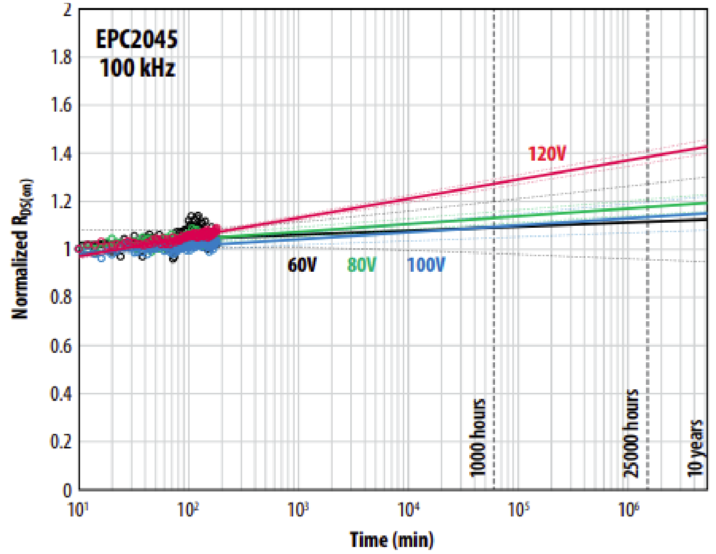
Hard-Switching: Effect of V_{IN} and Temperature

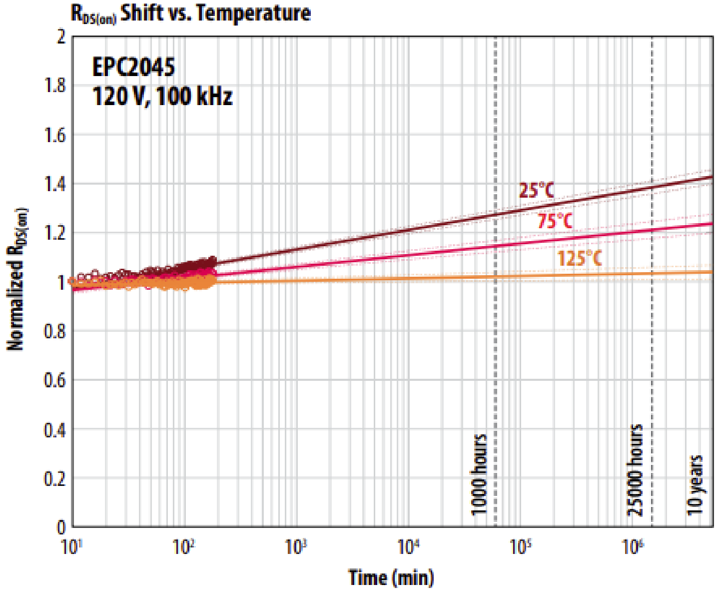




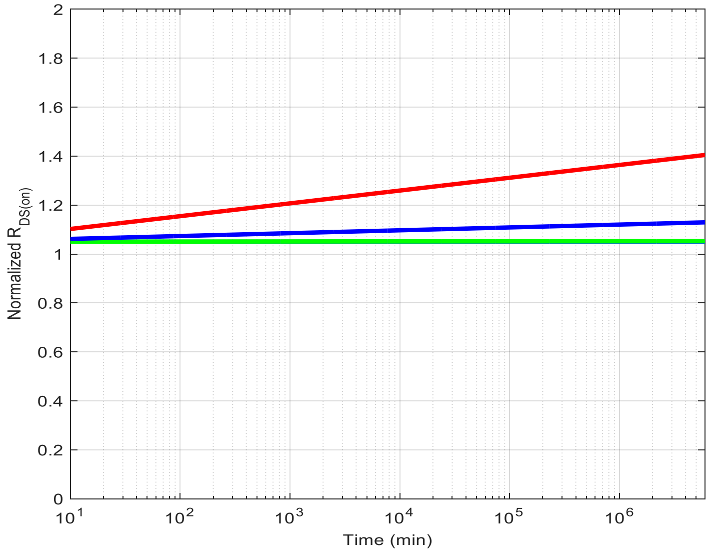
Model vs Measurement

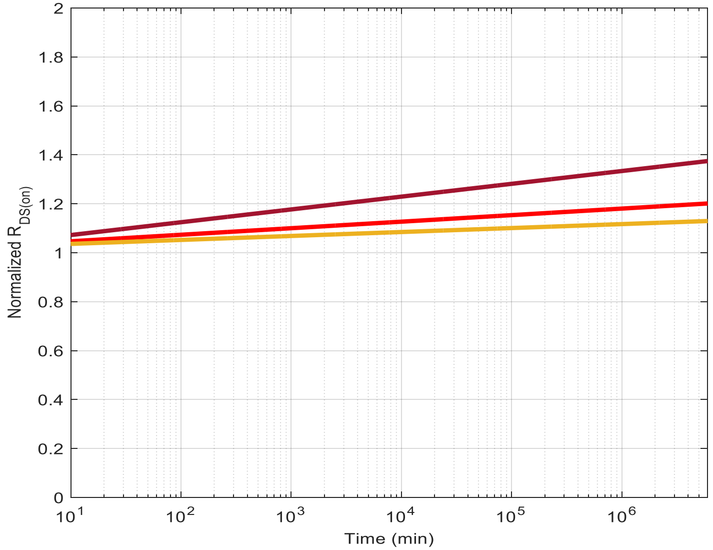
Measurement



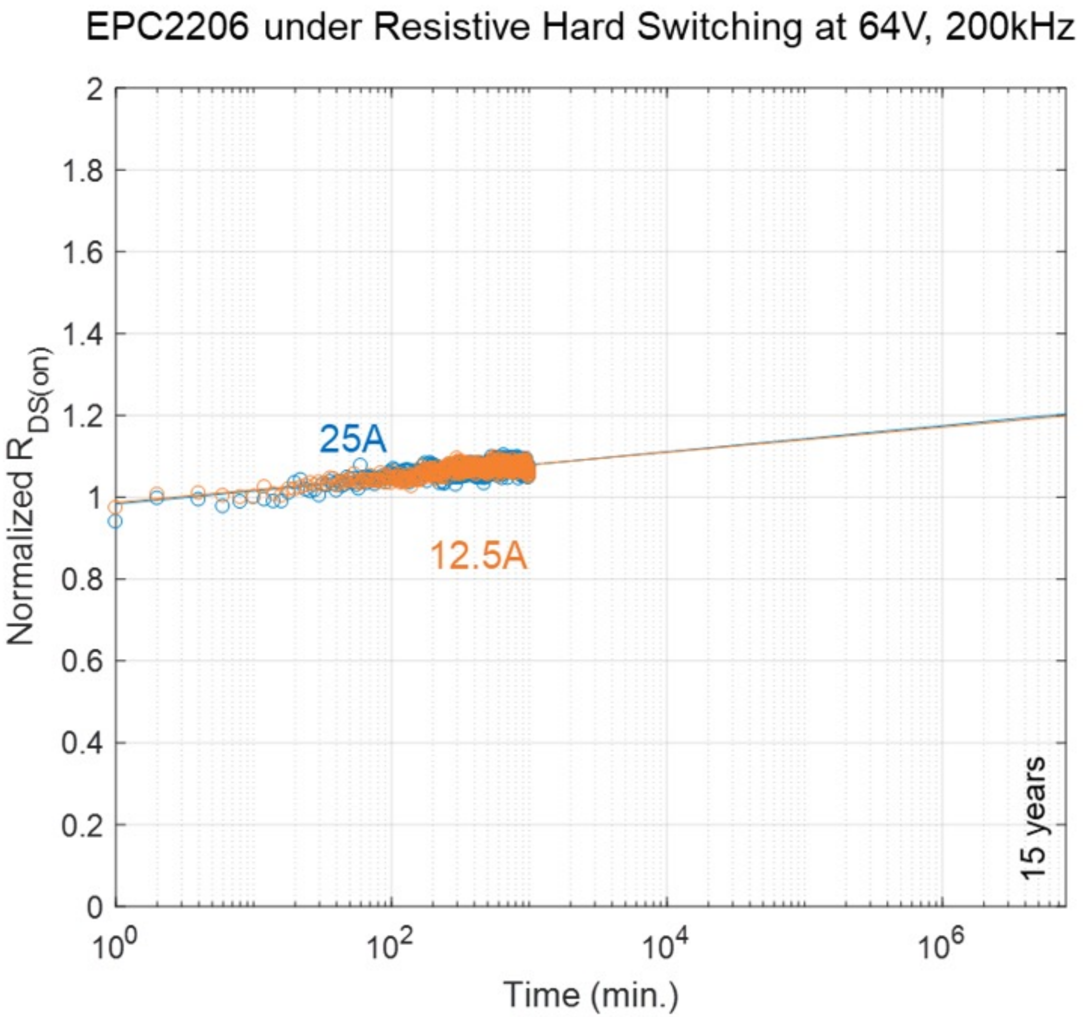


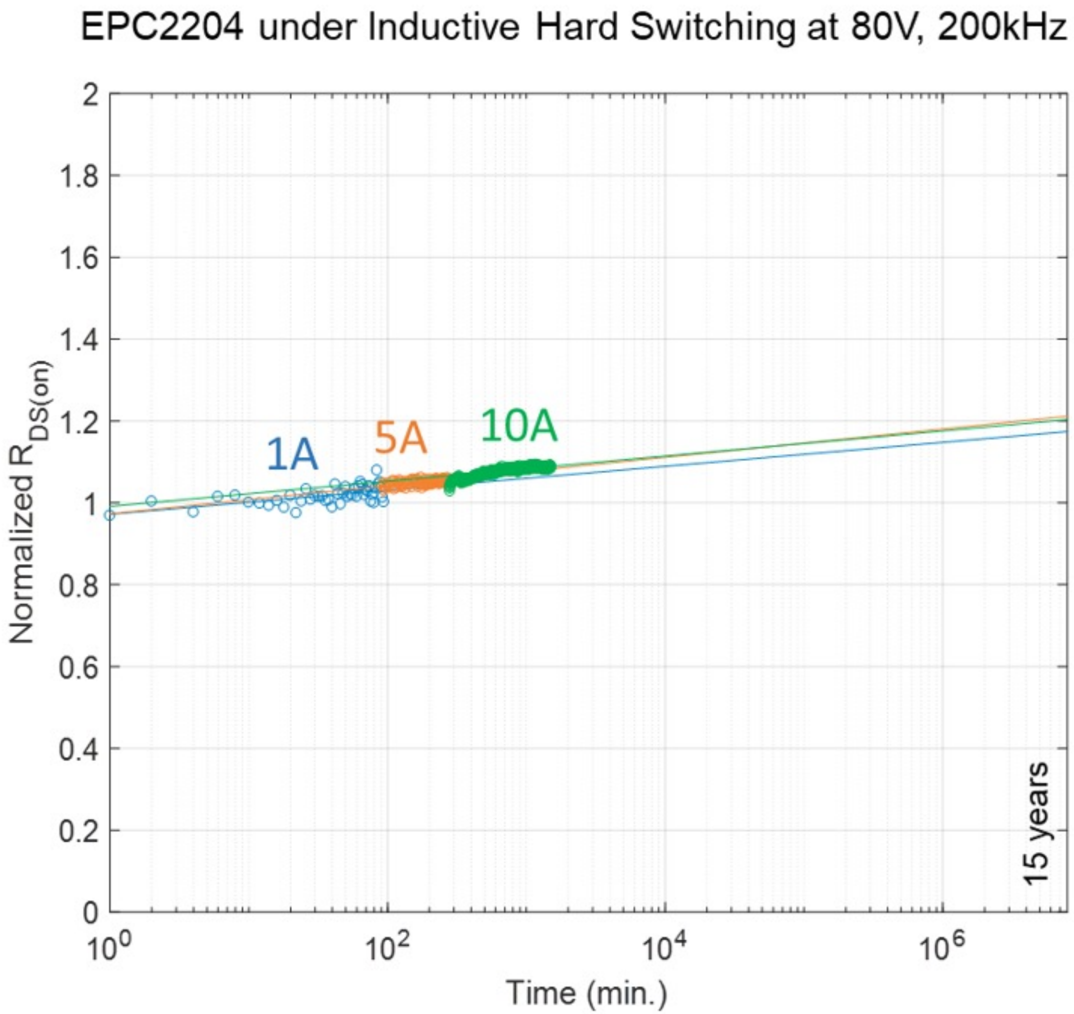
Model





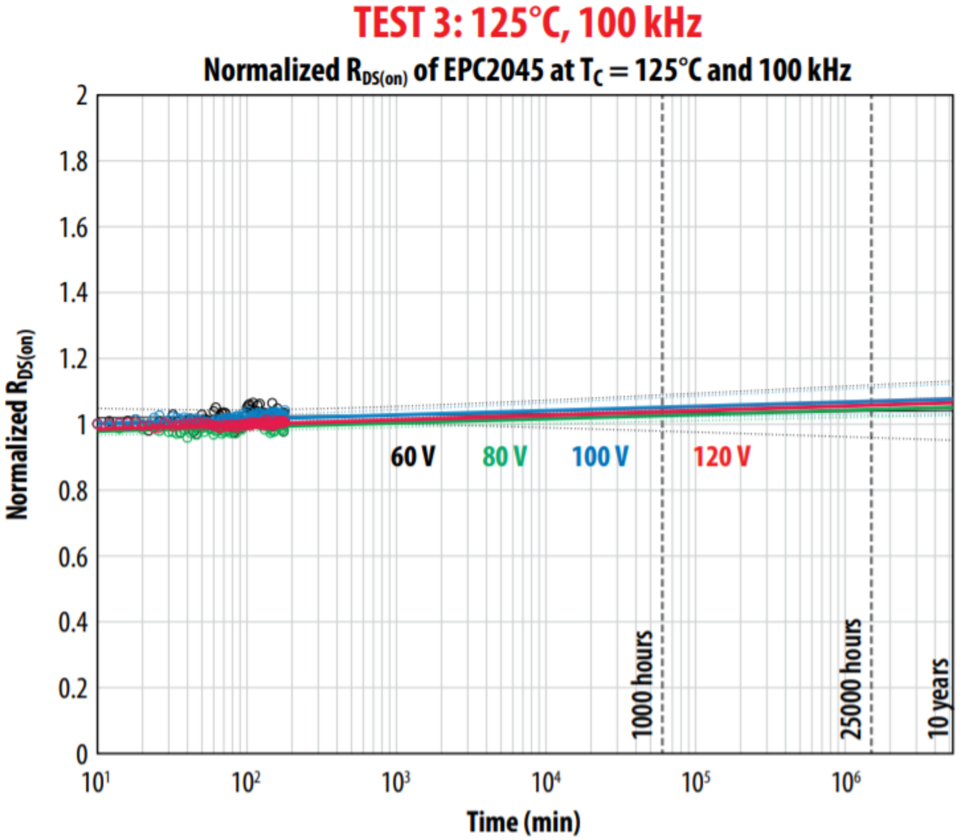
Effect of Switch Current on Dynamic $R_{DS(on)}$

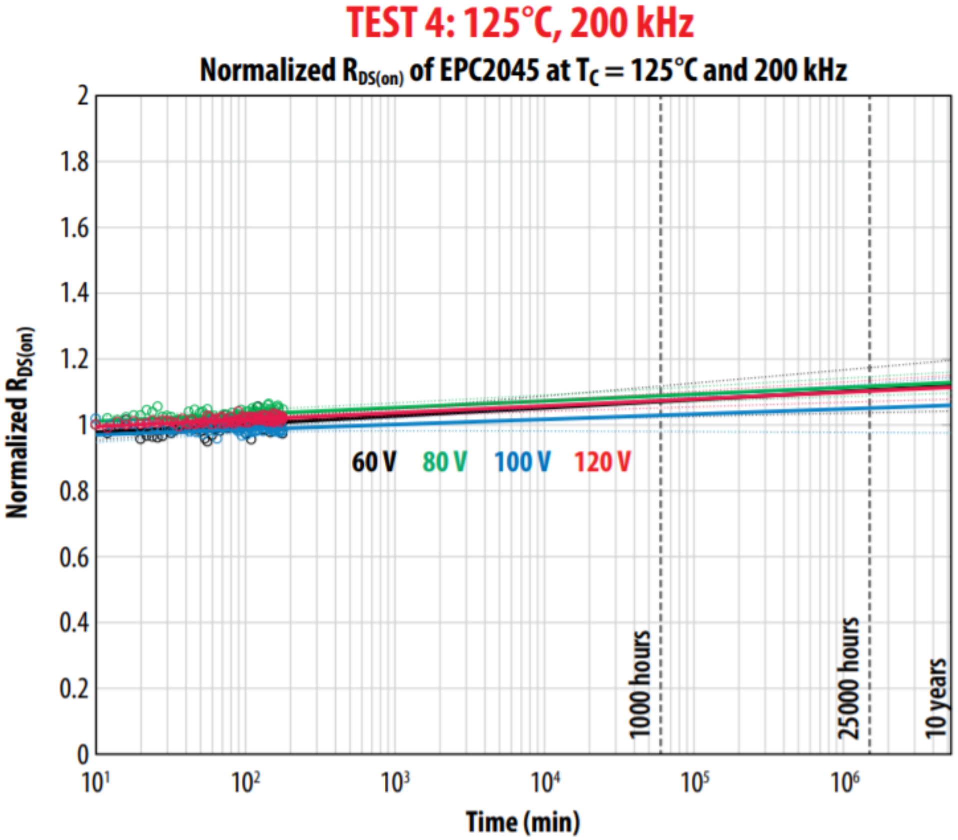




Switching current has a small impact in $R_{DS(on)}$ degradation

Dynamic $R_{DS(on)}$ vs Switching Frequency

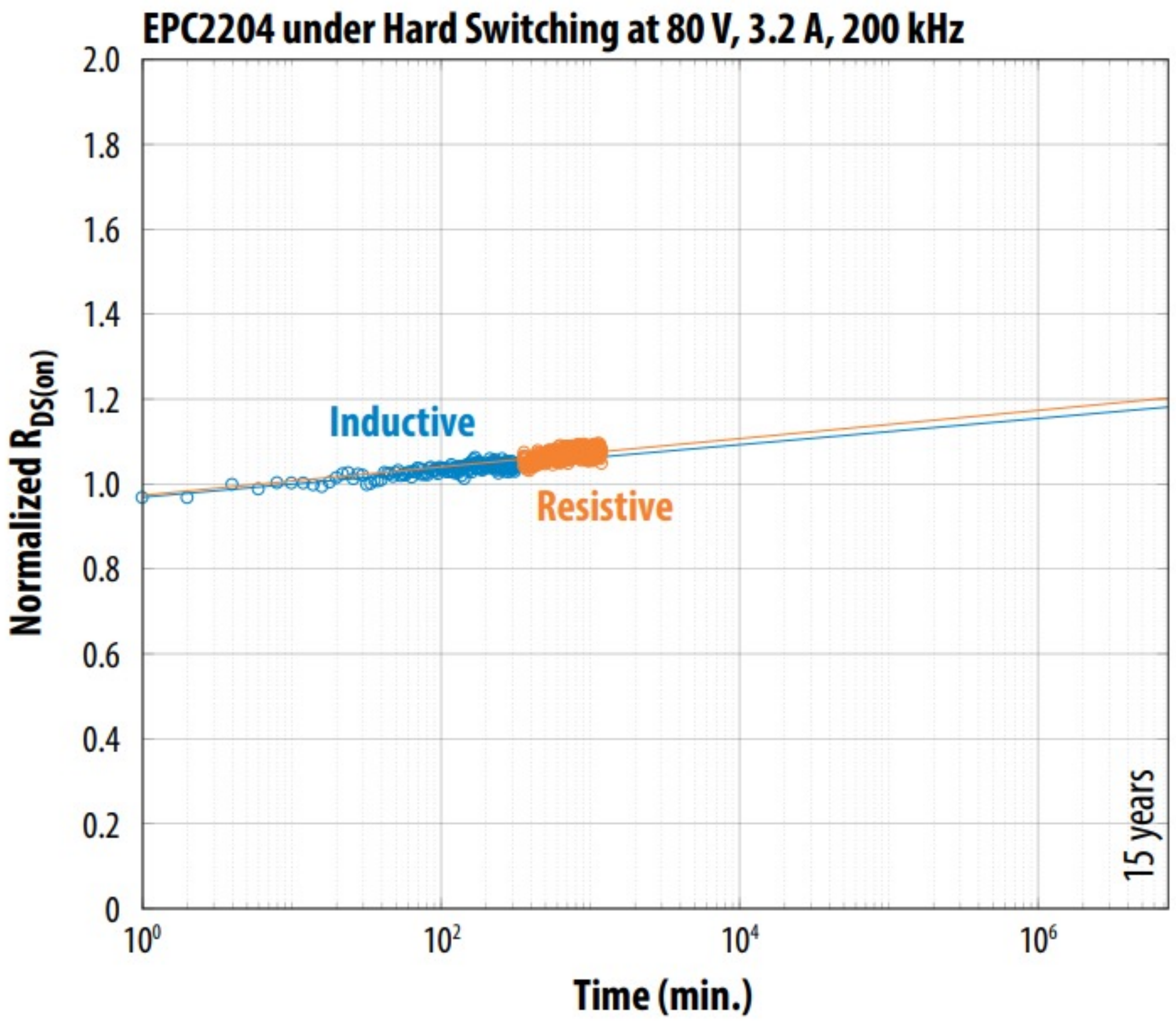




Switching frequency has a small impact in $R_{DS(on)}$ degradation

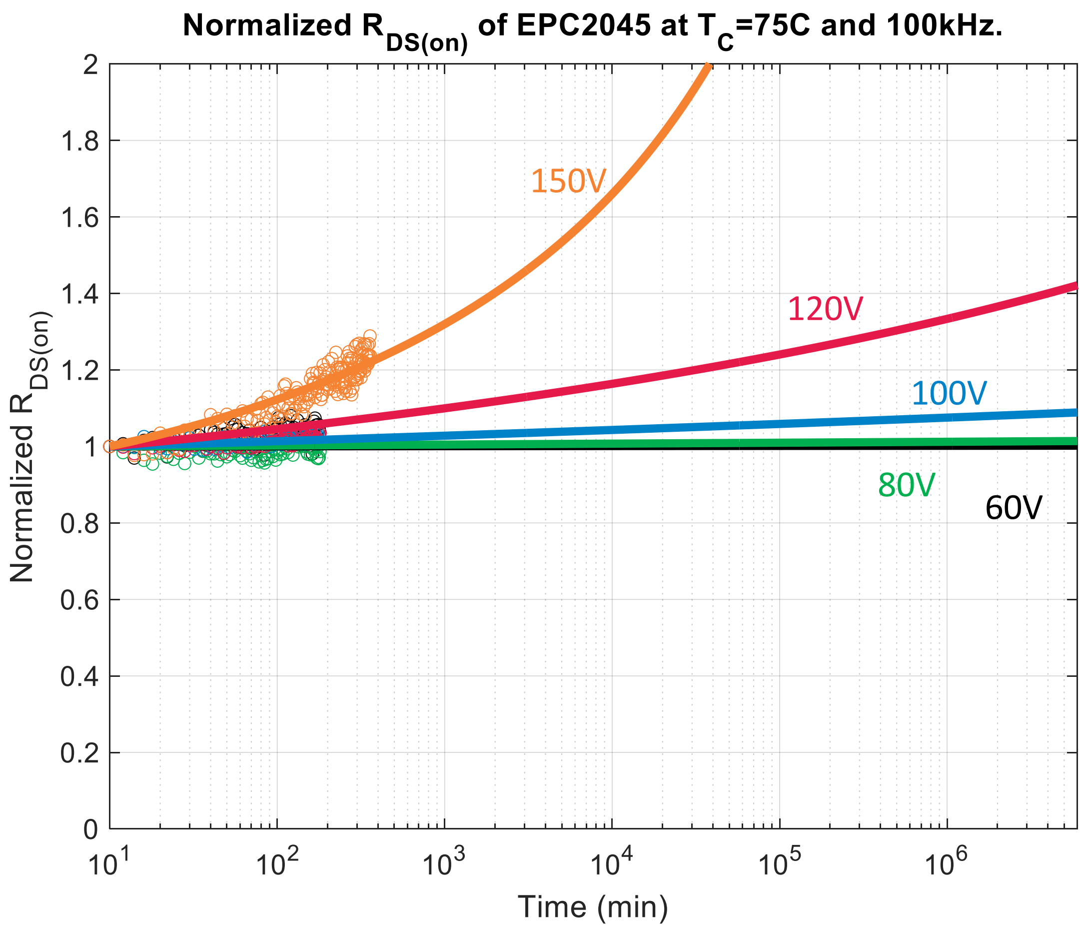
Inductive vs Resistive Hard Switching

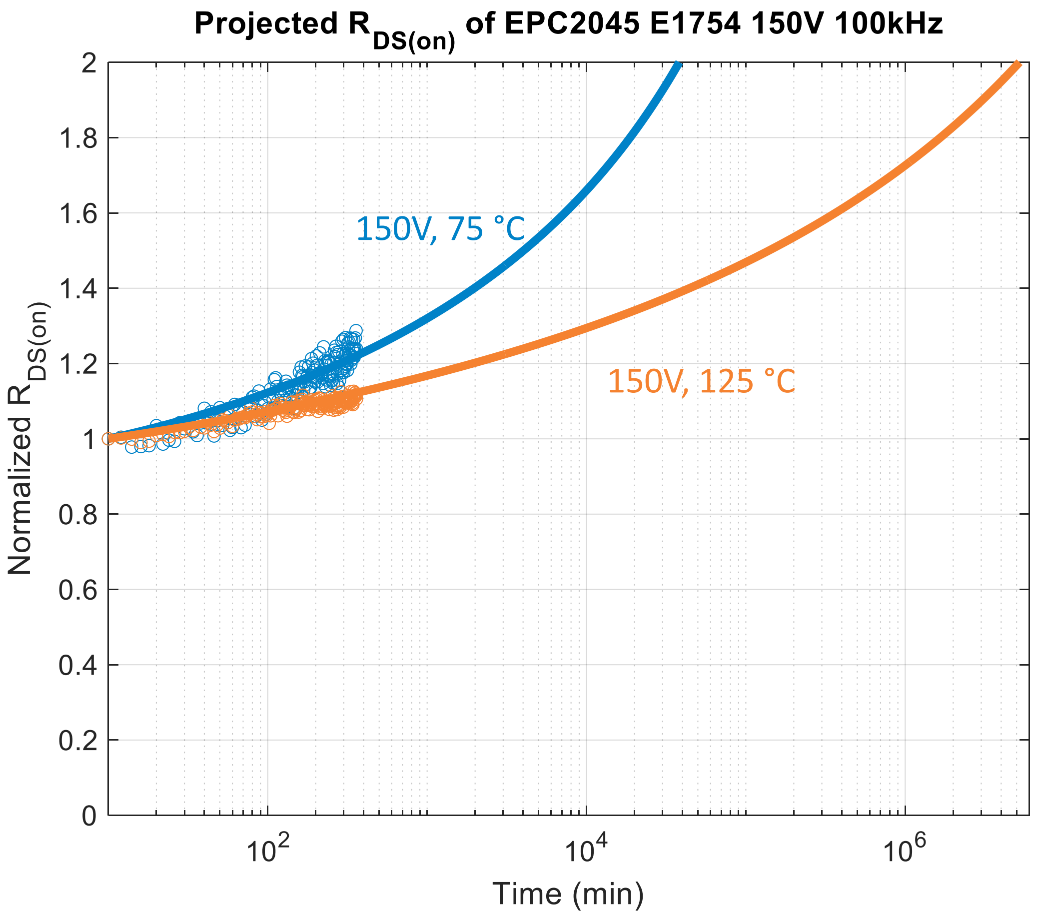
- Same part tested under inductive and then resistive hard-switching



Modeling at Extremes

As the number of trapped electrons Q_S approaches the number of electrons in the 2DEG, the $R_{DS(on)}$ growth characteristic deviates from a straight line along the log(t) axis





Dynamic $R_{DS(on)}$ Models for eGaN Products

$$\frac{\Delta R}{R} = a_1 \left[\frac{a_2 \Psi \log(1 + a_3 t/\Psi)}{1 - a_2 \Psi \log(1 + a_3 t/\Psi)} \right]$$

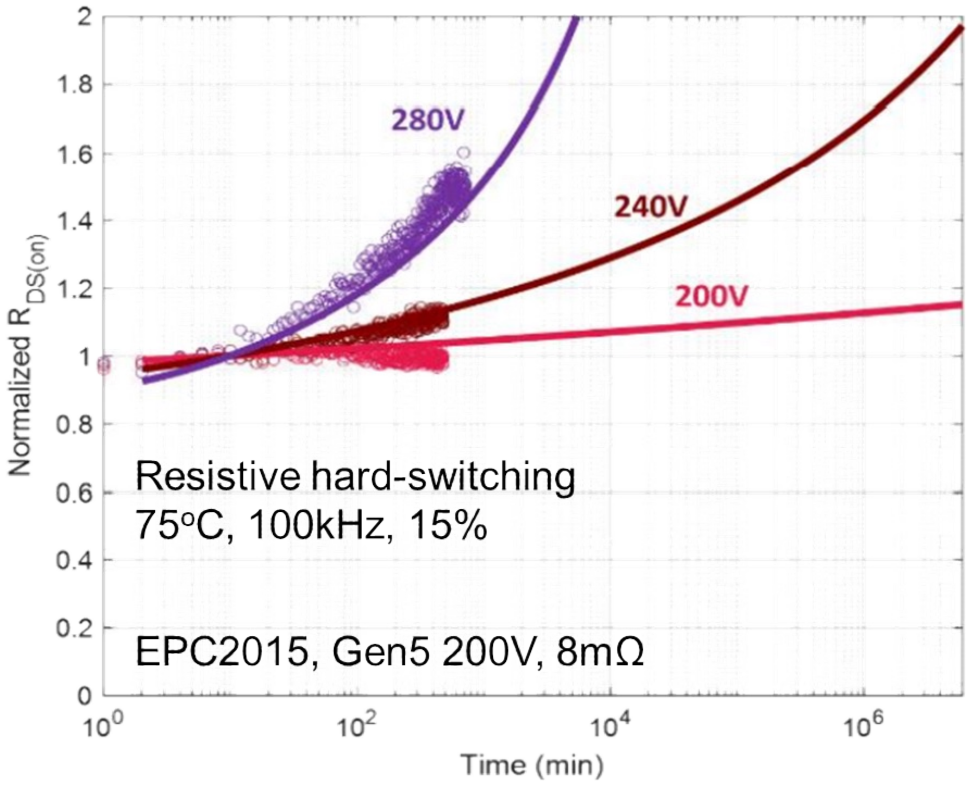
where

$$\Psi = \log\left(1 + \exp\left(\frac{V_{DS} - V_{FD}}{\alpha}\right)\right)\sqrt{T}\exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$$

a_1 = 0.6 (unitless)
a_2 = 9.33E-5 ($K^{-1/2}$)
a_3 = 1000 ($K^{1/2}$ min^{-1})
$\hbar\omega_{LO}$ = 92 meV
V_{FD} = 210 V (*Gen5 200V*)
α = 25 (V) (*Gen5 200V*)
T = Device temperature (K)
t = Time (min)

- ***Specific to each device families of eGaN FETs***
- ***Available upon request***

Normalized $R_{DS(on)}$ vs Time



Stress:
High Current and Electromigration

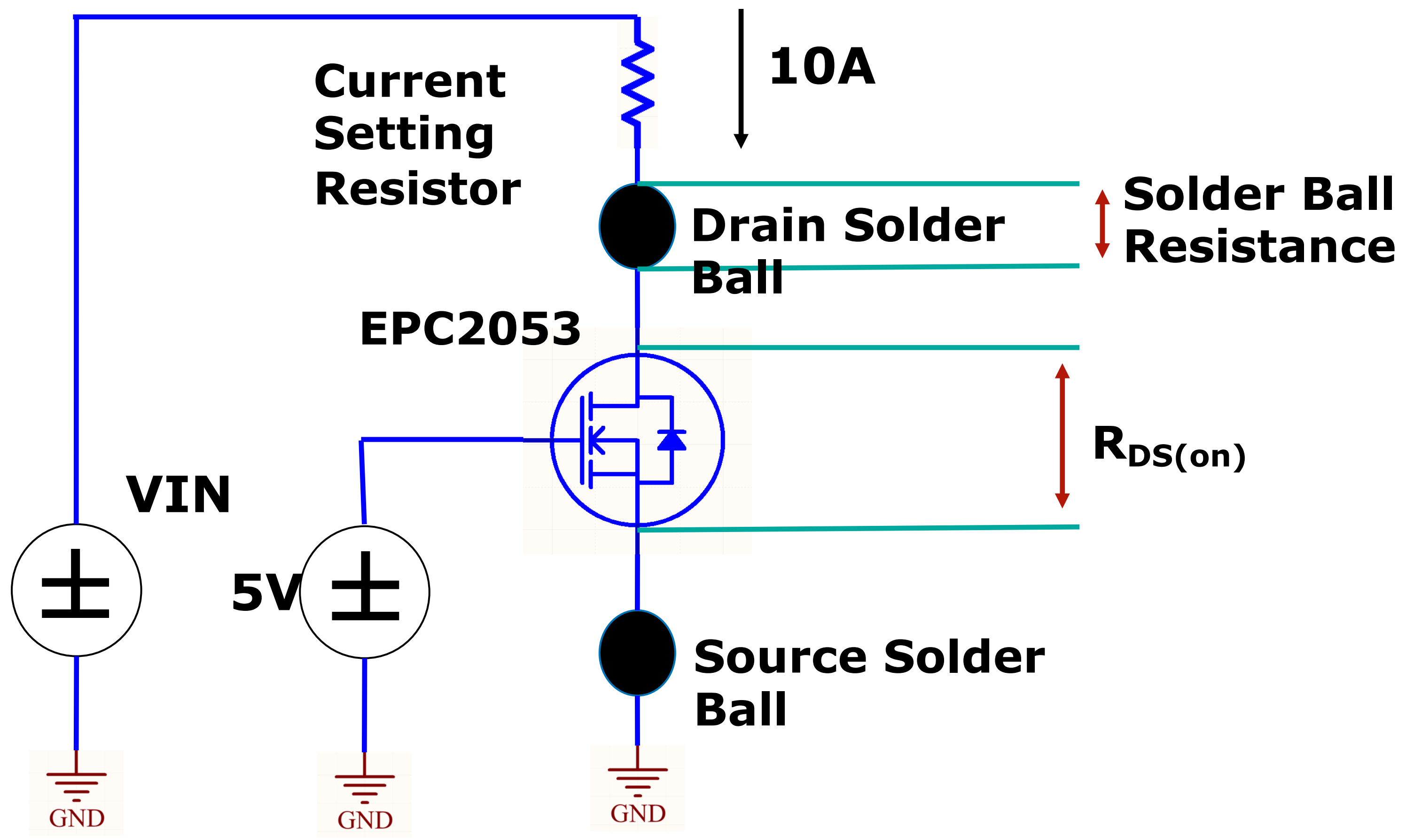
Modeling Time to Failure from Electromigration

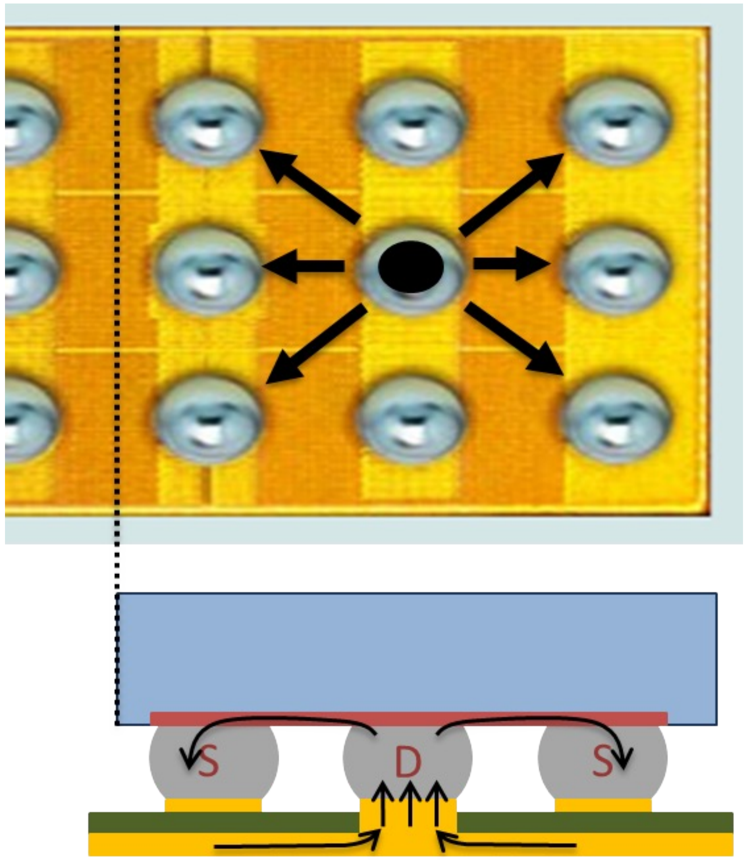
- Continuous current density in eGaN FETs is based on electromigration limits for solder joints and thermal limits, whichever is lower
  - Continuous current rating of eGaN FETs is based on a (conservative) maximum current density of 5 kA/cm^2 through the solder bumps
- Electromigration in solder material is not unique or special for GaN-based transistors. The same mechanism occurs in Si-based power MOSFETs, and manufacturers of those products must take it into account
- The mechanism of electromigration in solder materials is similar that in other metals (Cu, Al). Mean time to failure is modeled using Black's equation (see below), and is driven by 2 stressors: current density and temperature

$$MTTF = \frac{A}{J^n} e^{\frac{Q}{kT}}$$

MTTF: Mean Time To Failure
A: Constant
J: Current density
n: Model parameter
Q: Activation Energy
k: Boltzmann's constant
T: Absolute Temperature

Test Methodology





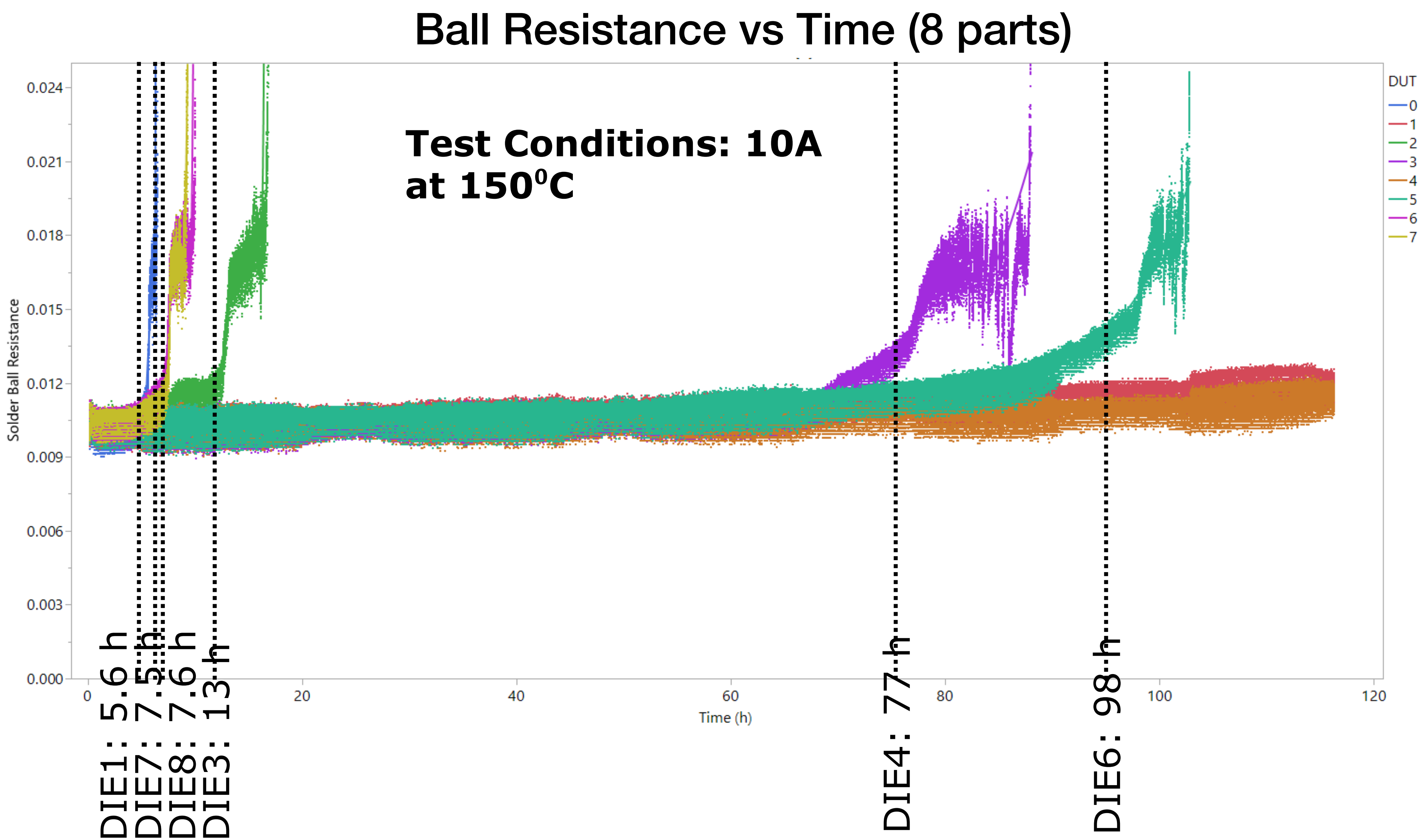
Test Matrix

Current thru Solder Ball

Temperature	5 A	10 A	15A
100 ^{0}C			
130 ^{0}C		X	
150 ^{0}C		X	X

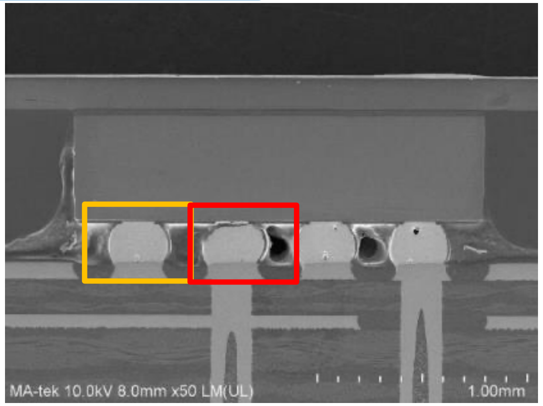
- 10A through a single solder ball is a current density of ~24kA/cm^2
- An industry accepted limit for solder joints is 10kA/cm^2
- EPC's employs a conservative design criterion of 5kA/cm^2

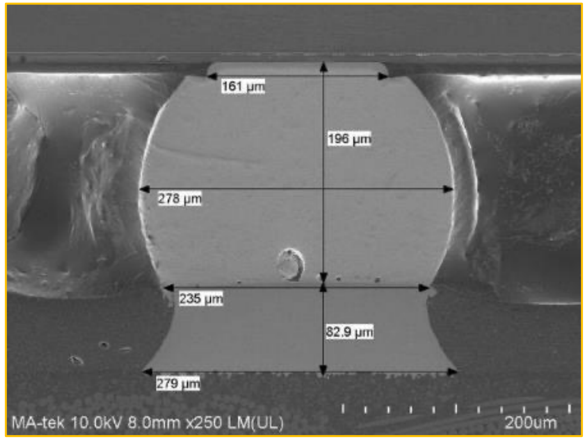
Solder Ball Resistance vs Time at 10A 150° C

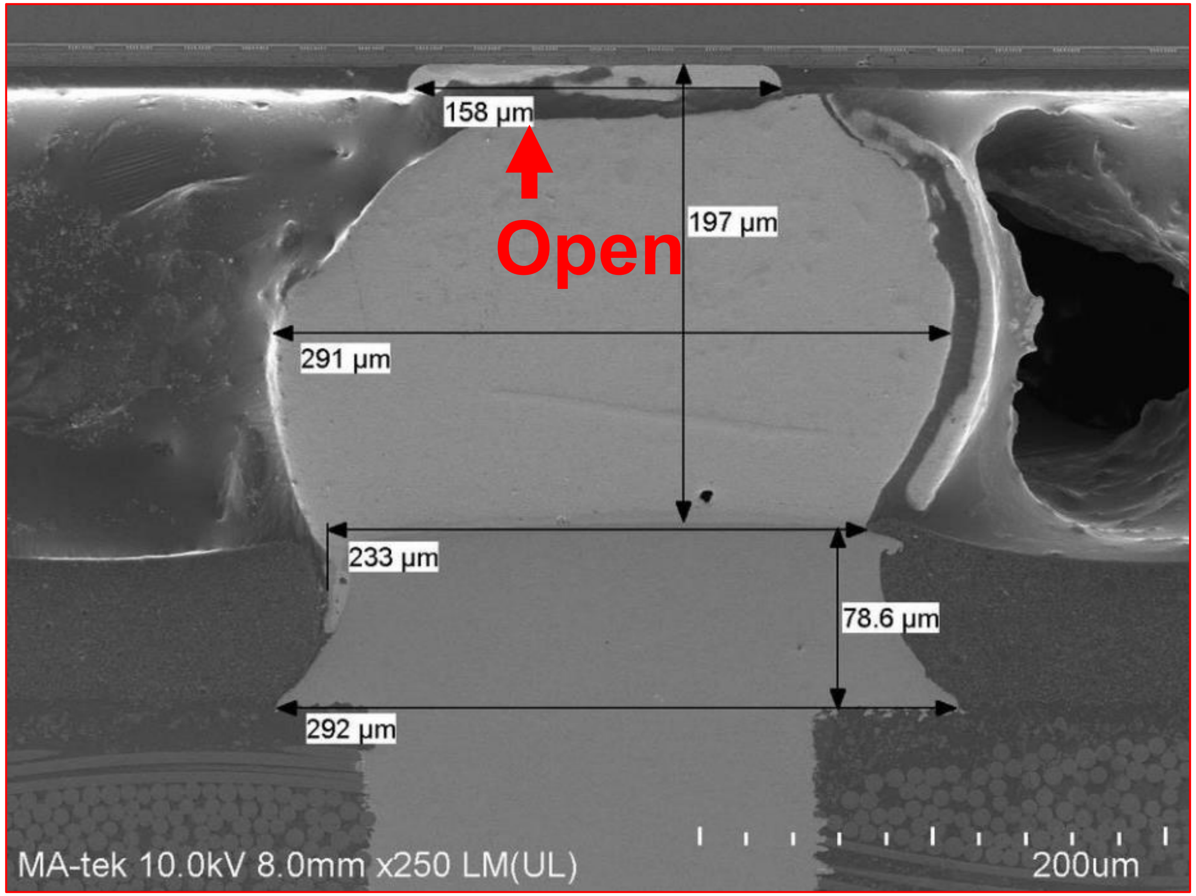


SEM Cross-Section of a Failed Solder Ball

failure

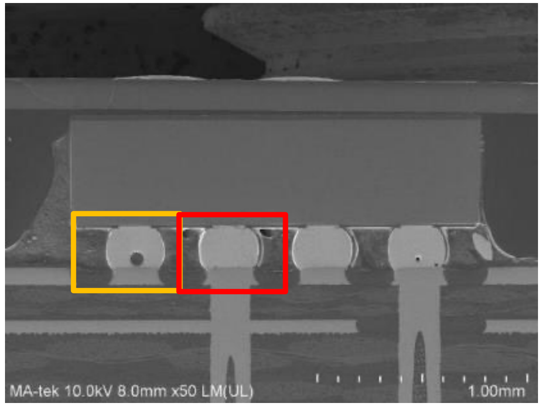


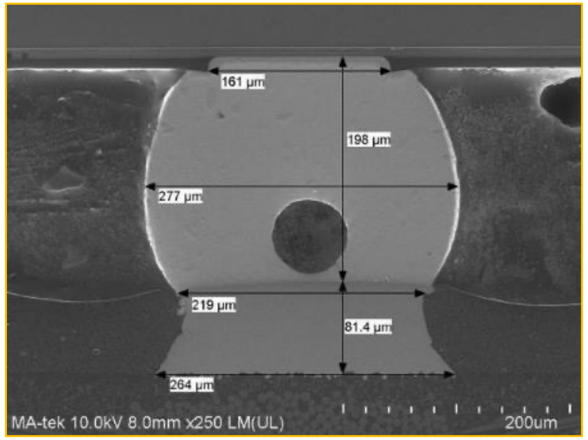




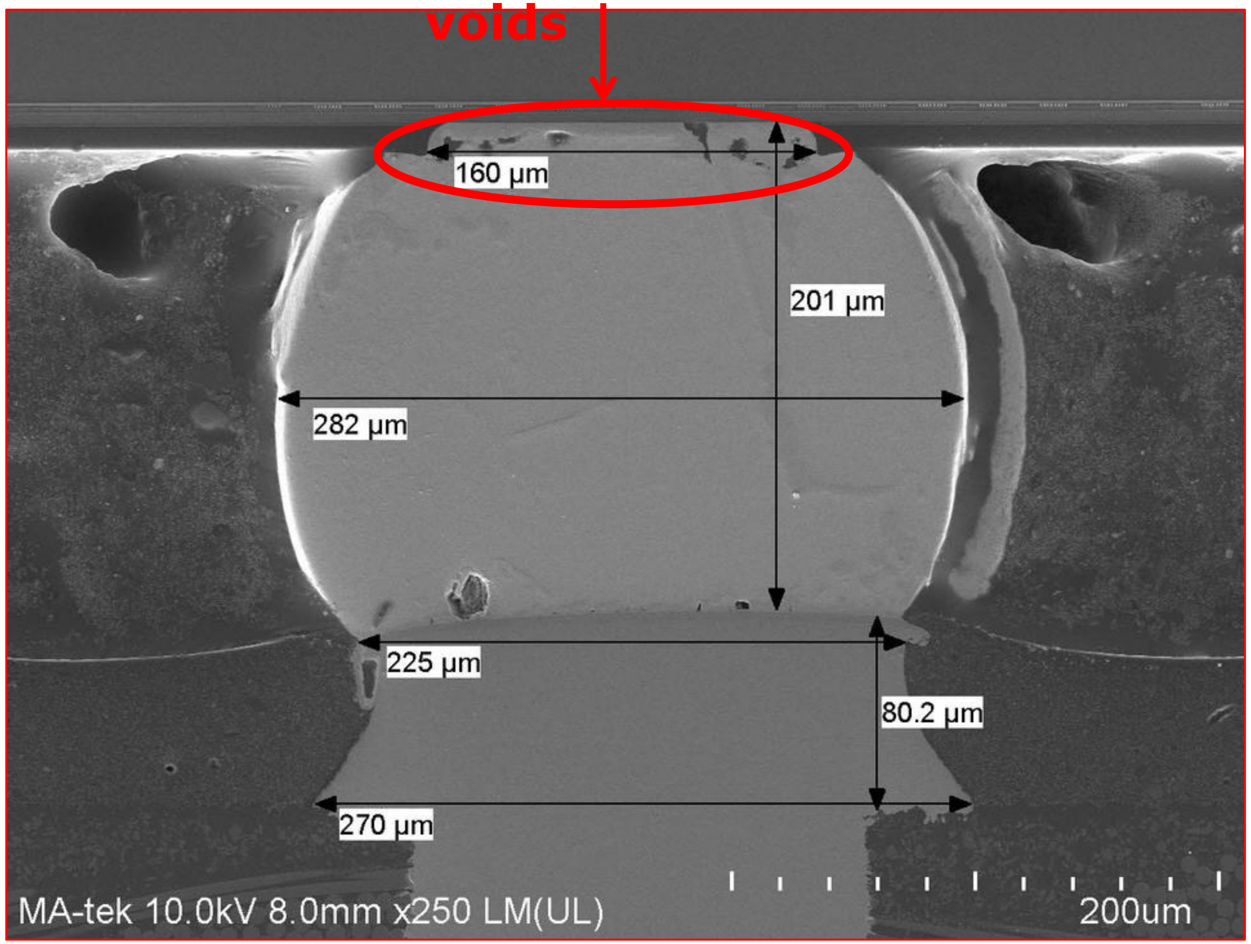
SEM Cross-Section of a Surviving Solder Ball

survivor

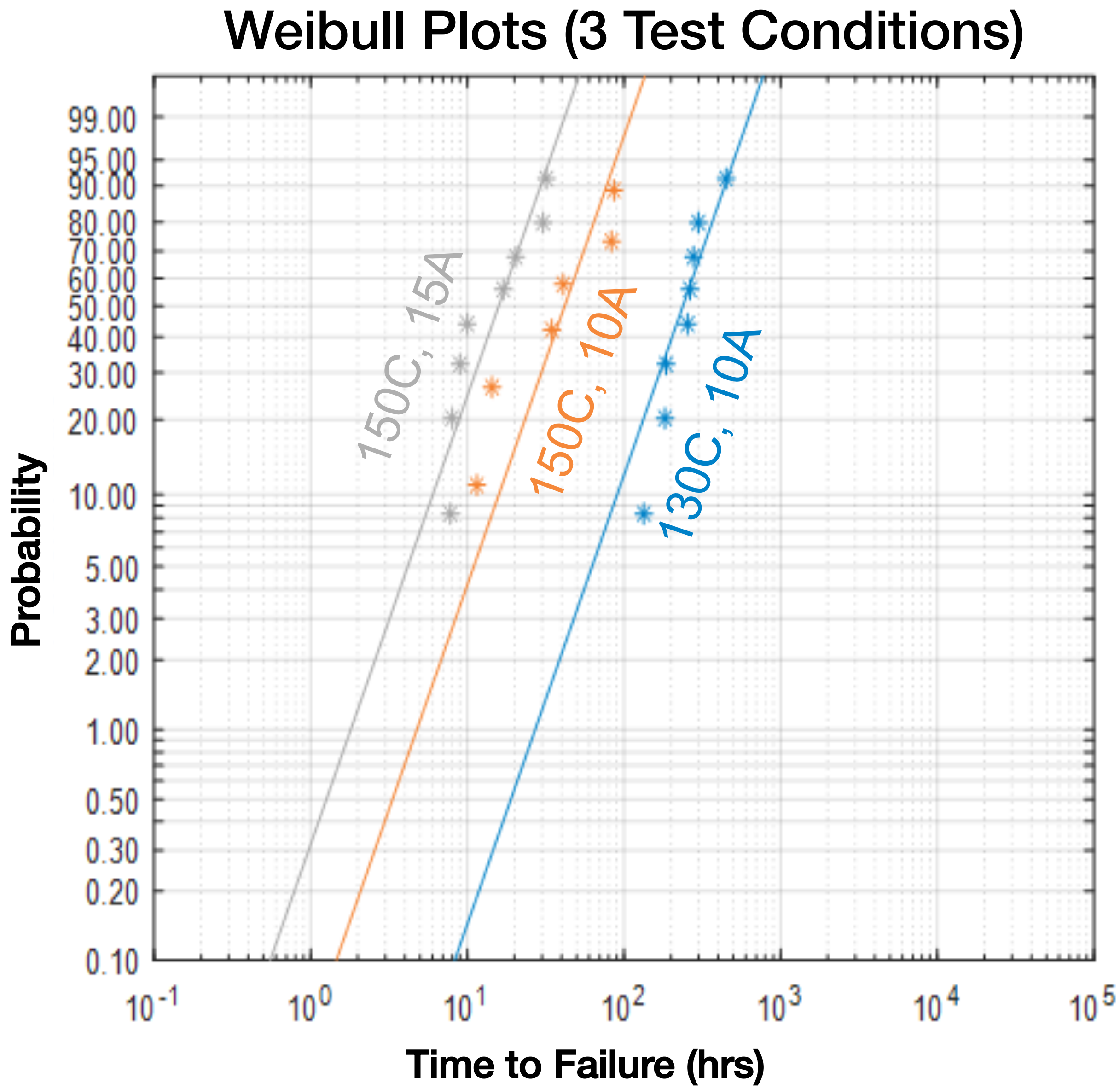




Formation of voids



Weibull Analysis and Fit to Black's Equation



eGaN Parameters for Black's Model

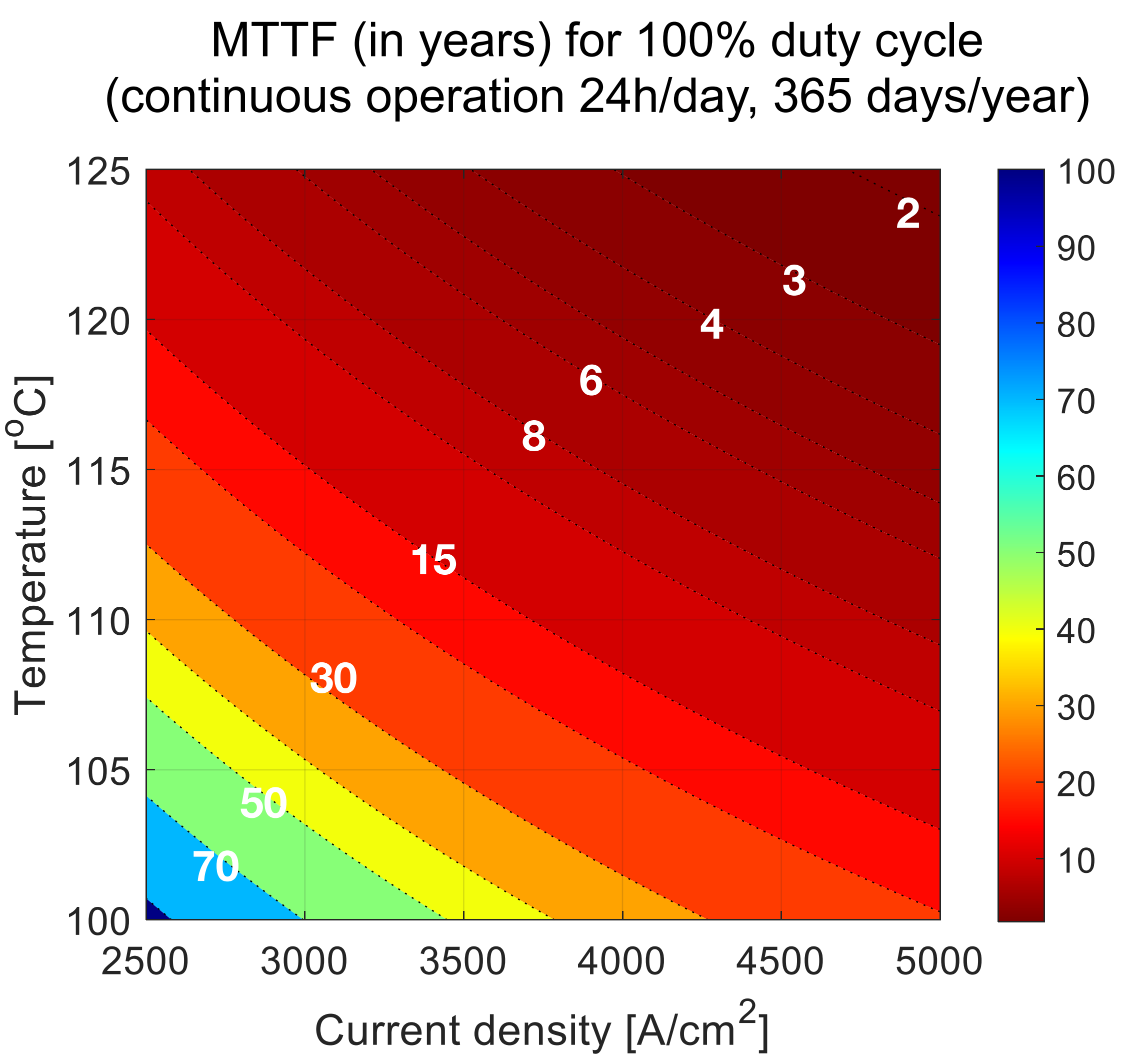
$$MTTF = \frac{A}{J^n} e^{\frac{Q}{kT}}$$

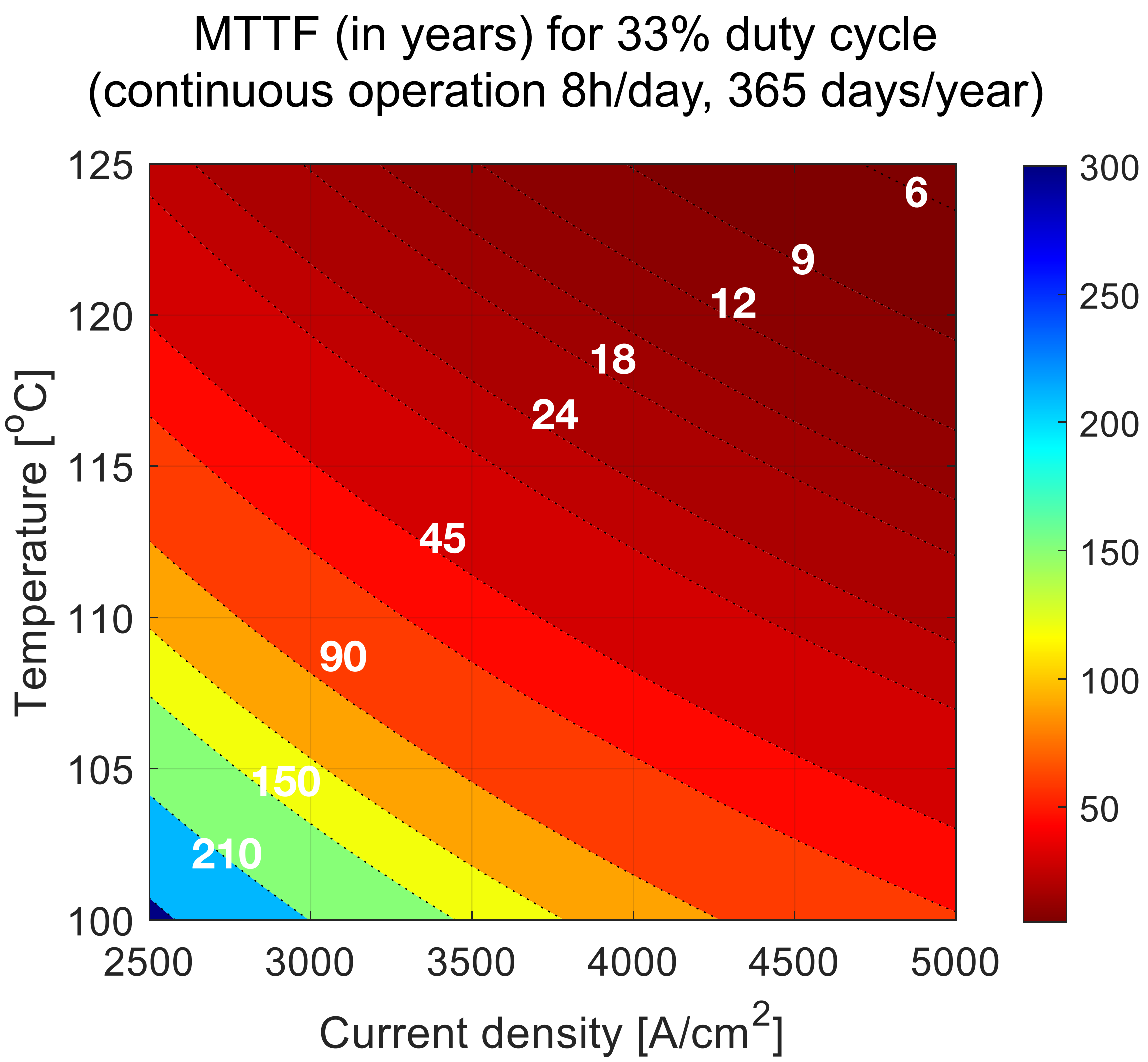
A = 9.65e-04 hrs $(A/cm^2)^{2.39}$
n = 2.39
Q = 1.2 eV
k = 8.617e-5 eV/K

Example 1: 125C, 1A (2.5 kA/cm2)
MTTF = 9 yrs

Example 2: 90C, 2.08A (5kA/cm2)
MTTF = 61 years

Estimated MTTF of eGaN FETs from Electromigration





Conclusions

- Physics based models were used to predict long-term reliability performance of eGaN devices
  - Under drain voltage stress (dc or switching), a first principles model of hot carrier scattering was developed to predict the evolution of on-resistance in GaN devices
  - Under high current stress, Black's equation was used to model solder joint failure from electromigration
- Both models can be used to predict behavior well outside of data sheet limits
- Both models predict excellent reliability when devices are operated within the conservative datasheet limits for $V_{DS;max}$ and $I_{D;max}$