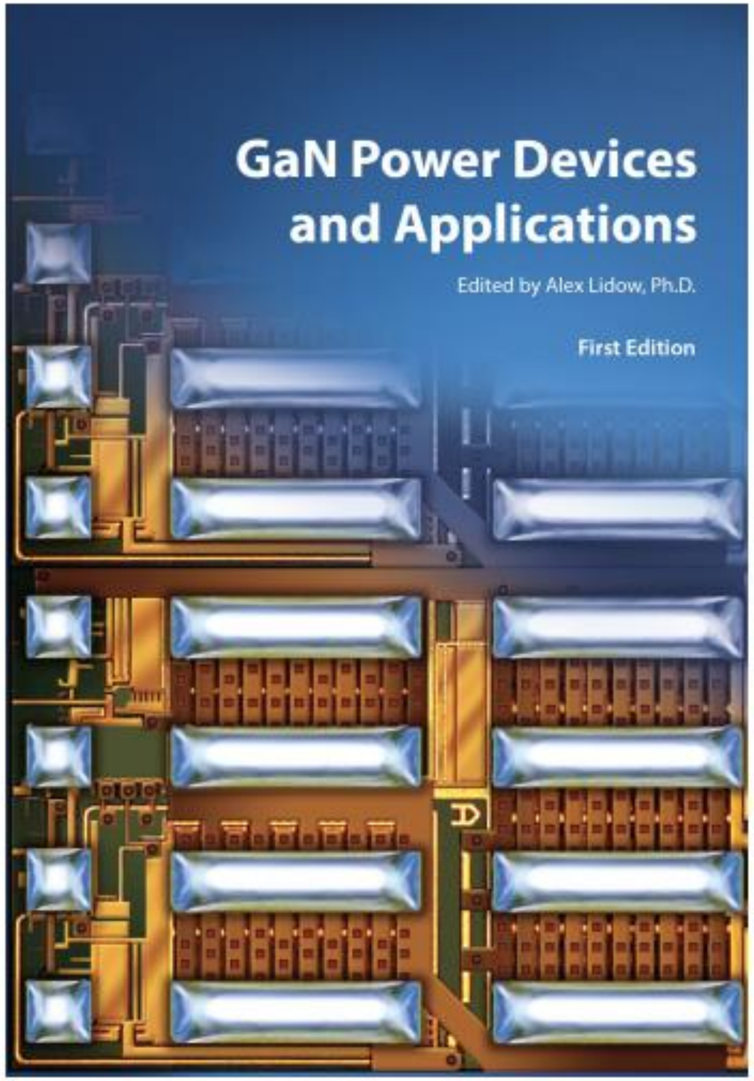
Using Test-to-Fail Methodology to Predict How GaN Devices Can Last More than 25 Years in Solar Applications

Why Test-to-fail?

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

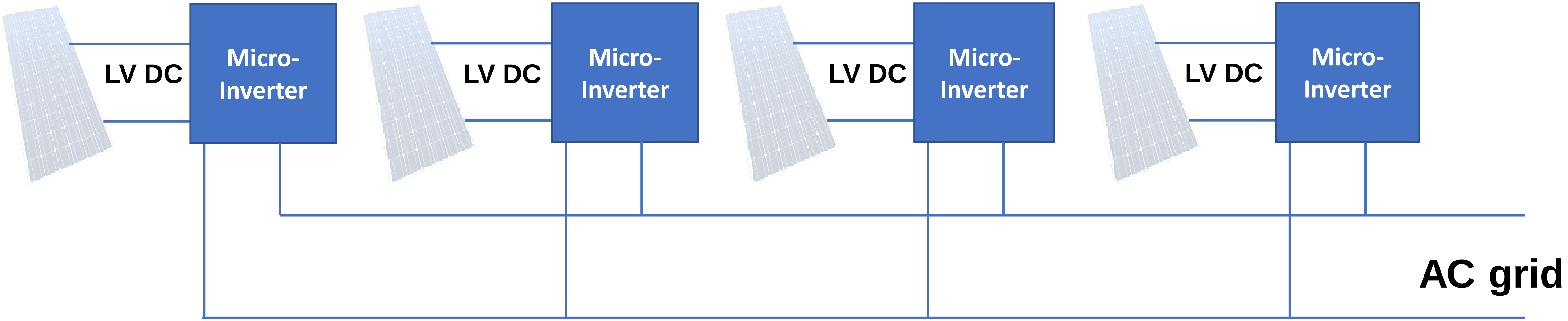


GaN Power Devices and Applications

Edited by Alex Lidow, Ph.D.

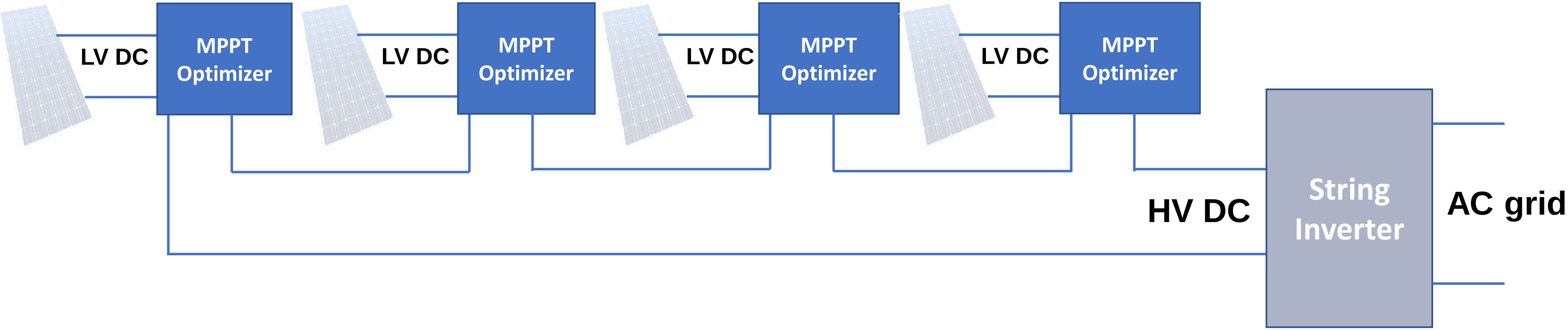
First Edition

Popular Topology in Solar: **Micro-Inverter**



EPC's Low voltage eGaN solution (V_{DSMax} < 200V) is a good fit for this solar application

Popular Topology in Solar: **Power Optimizer**



EPC's Low voltage eGaN solution (V_{DSMax} < 200V) is a good fit for this solar application

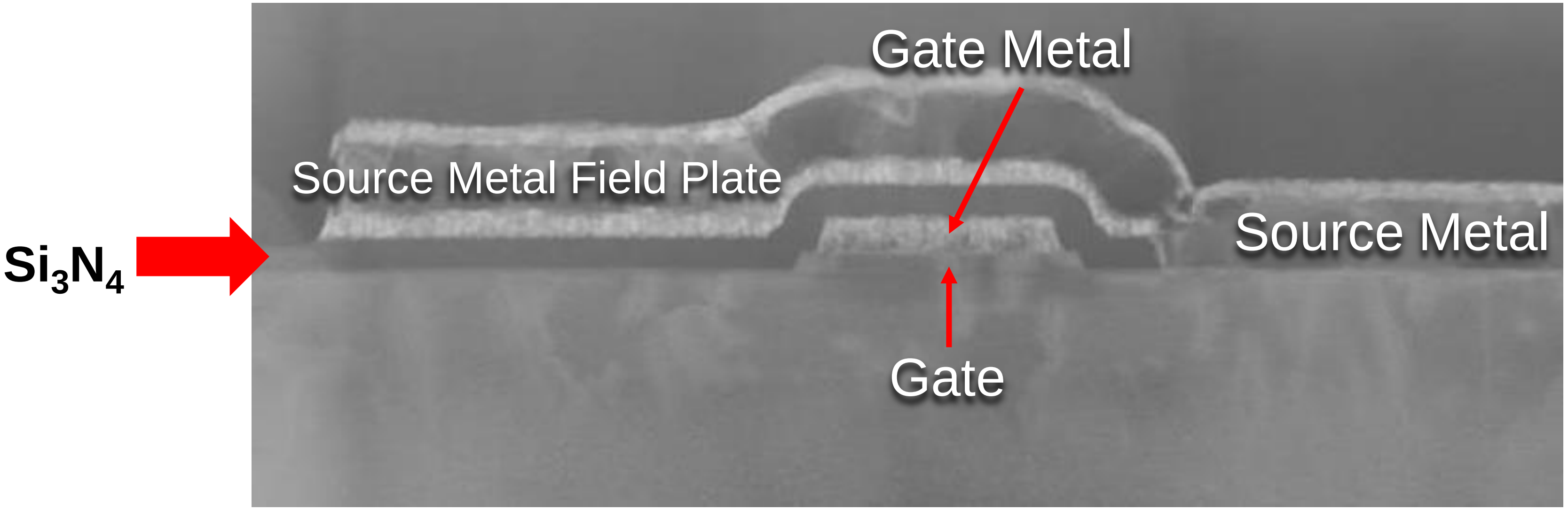
Main Stressors in Solar

- Gate Bias
- Drain Bias
- Temperature Cycling (TC)

$$\frac{1}{\mathrm{MTTF}_{\mathrm{Total}}} = \frac{1}{\mathrm{MTTF}_{\mathrm{Gate}}} + \frac{1}{\mathrm{MTTF}_{\mathrm{Drain}}} + \frac{1}{\mathrm{MTTF}_{\mathrm{TC}}}$$

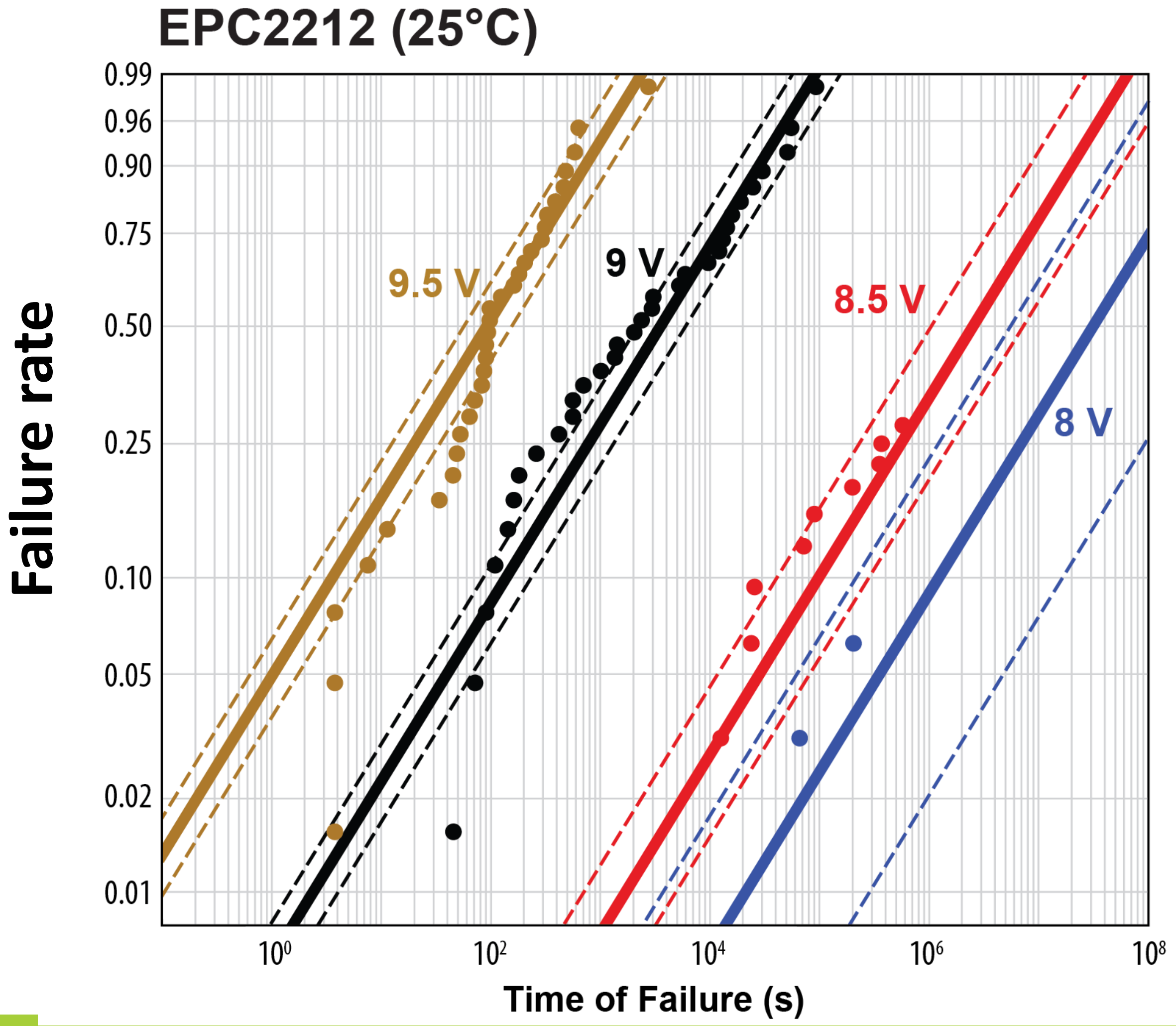
Gate Bias

Gate-Source Voltage Stress

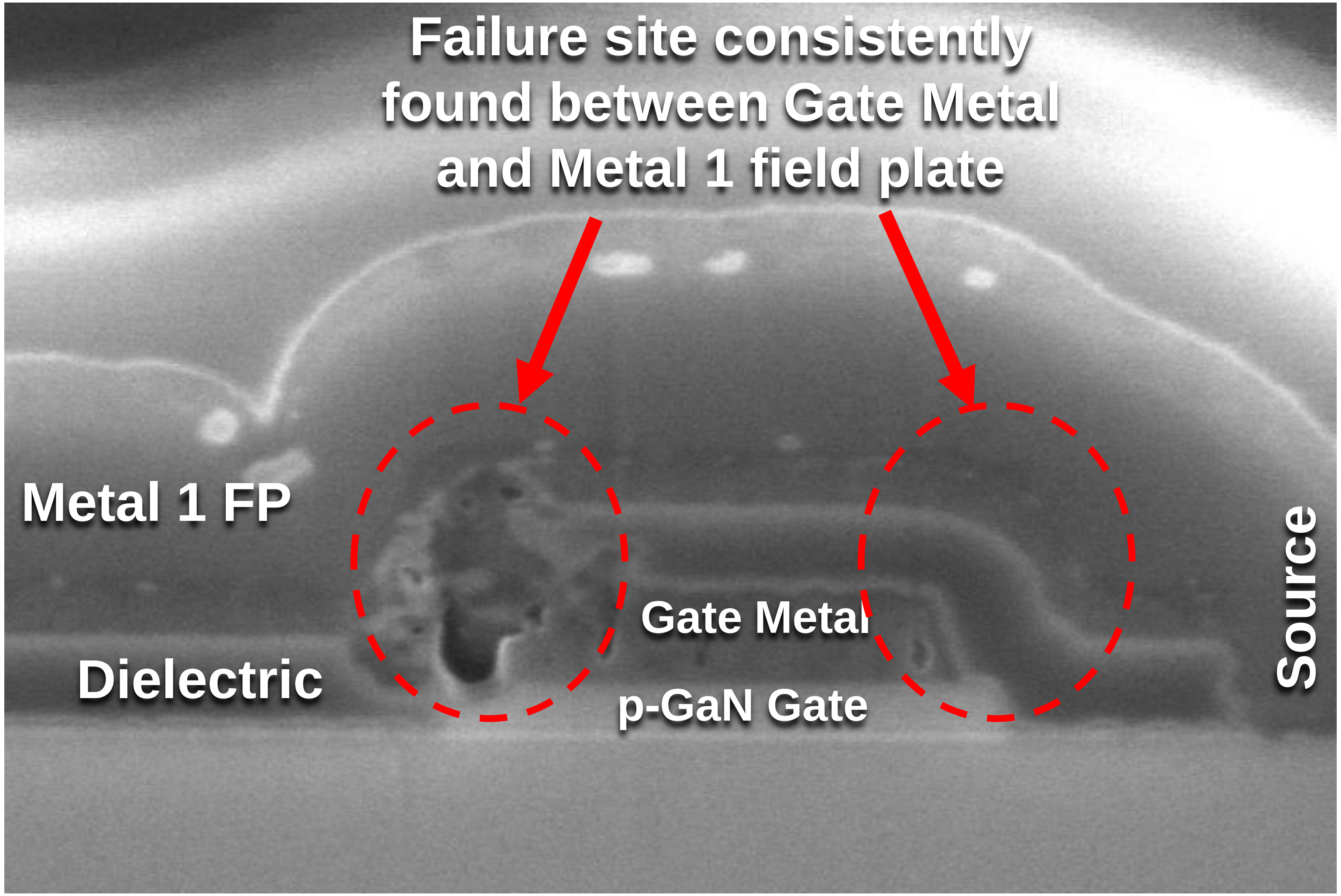


Weibull Analysis of Accelerated Gate Test

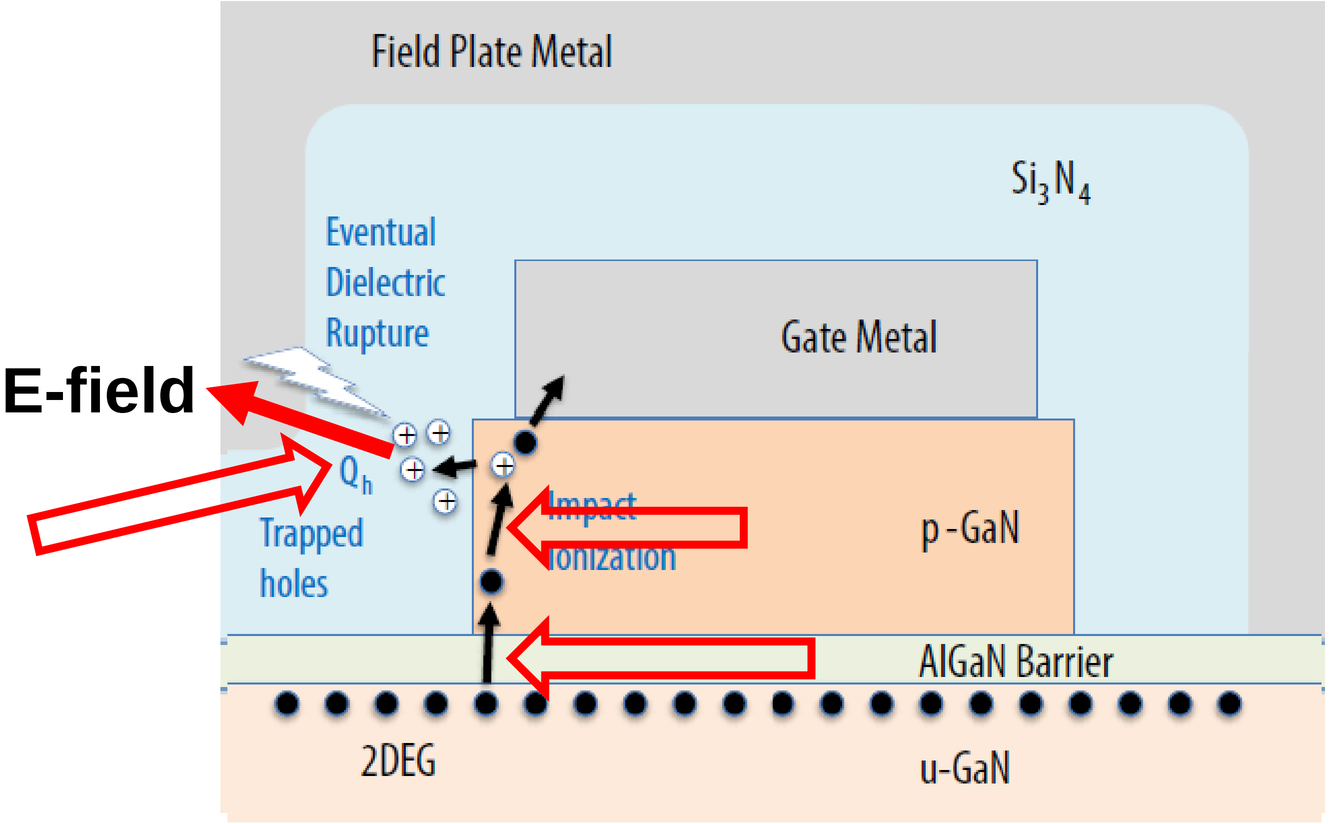
Data Sheet Maximum = 6V V_{GS}



Gate Failures Not in GaN



Gate Wear-out Mechanism: Impact Ionization



Impact Ionization Model Development

Electron-hole pair generation rate from impact ionization

$$G = \alpha_n \frac{|J_n|}{q} + \alpha_p \frac{|J_p|}{q}$$

$$G \approx \alpha_n \frac{|J_n|}{q} \qquad J_n >> J_p$$

Ionization coefficient

$$\alpha_n = a_n e^{-(b_n/F)^m}$$ [15]

Temperature dependence (Ozbek)

$$a_n(T) = a_{n;0}(1 - c\Delta T)$$ [13]

$c = 6.5x10^{-3}\ K^{-1}$

Ref	a_n(1/cm)	b_n(V/cm)	m
Ji et al.[12]	2.10E+09	3.70E+07	1
Ozbek [13]	9.20E+05	1.70E+07	1
Cao et al. [8]	4.48E+08	3.40E+07	1
Ooi et al. [15]	7.32E+07	7.16E+06	1.9

$$MTTF = \frac{Q_C}{G} = \frac{qQ_C}{\alpha_n J_n} = \frac{A}{(1-c\Delta T)} exp\left[\left(\frac{B}{V+V_0}\right)^m\right]$$

$m = 1.9$

$V_0 = 1.0\ V$

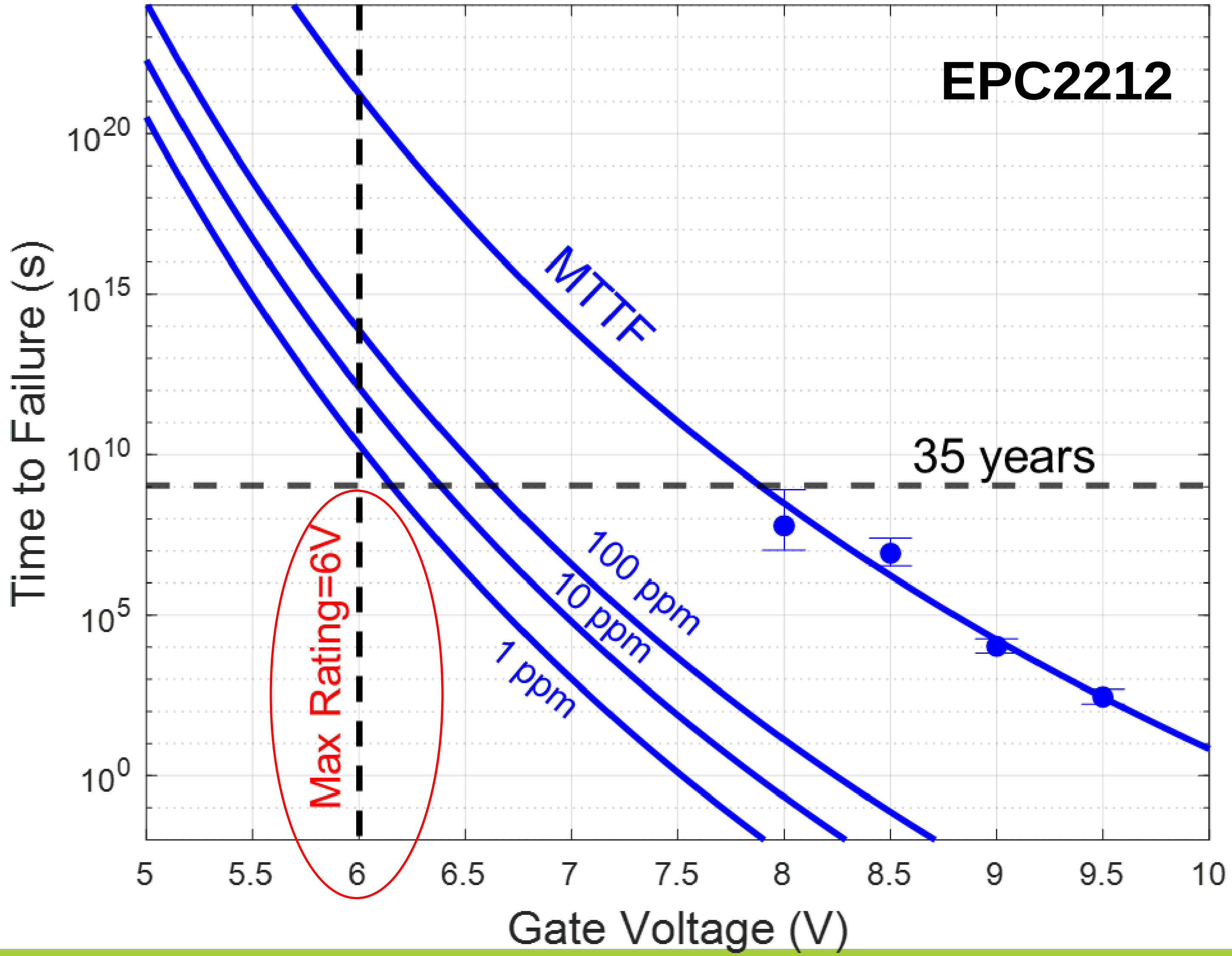
$B = 57.0\ V$

$A = 1.7x10^{-6}\ s$

$c = 6.5x10^{-3}\ K^{-1}$

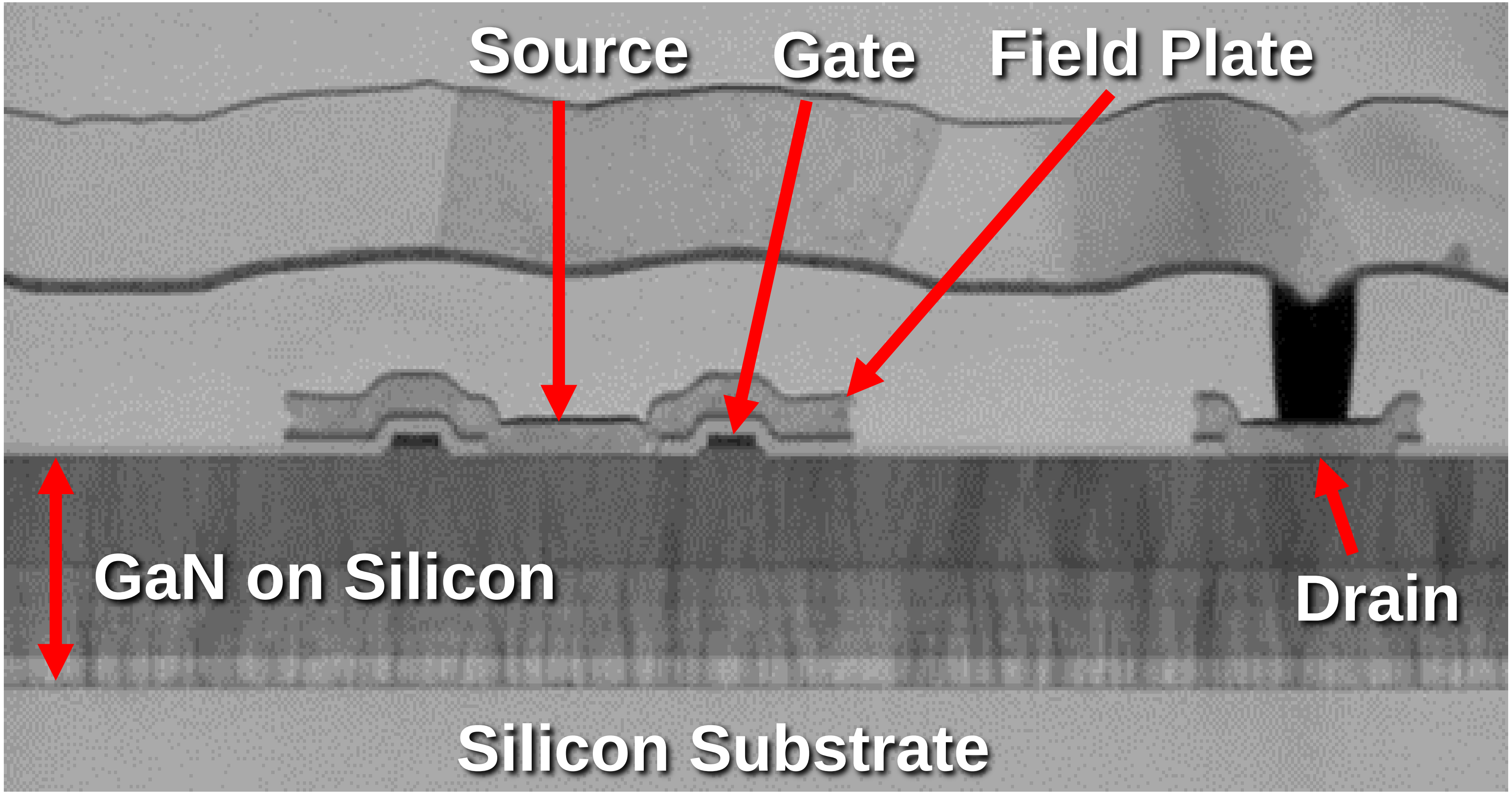
Gate Reliability and Lifetime Projection

<1ppm failure rate projected over more than 35 years of lifetime under continuous V_{GS}=6V DC gate bias (maximum rated V_{GS})

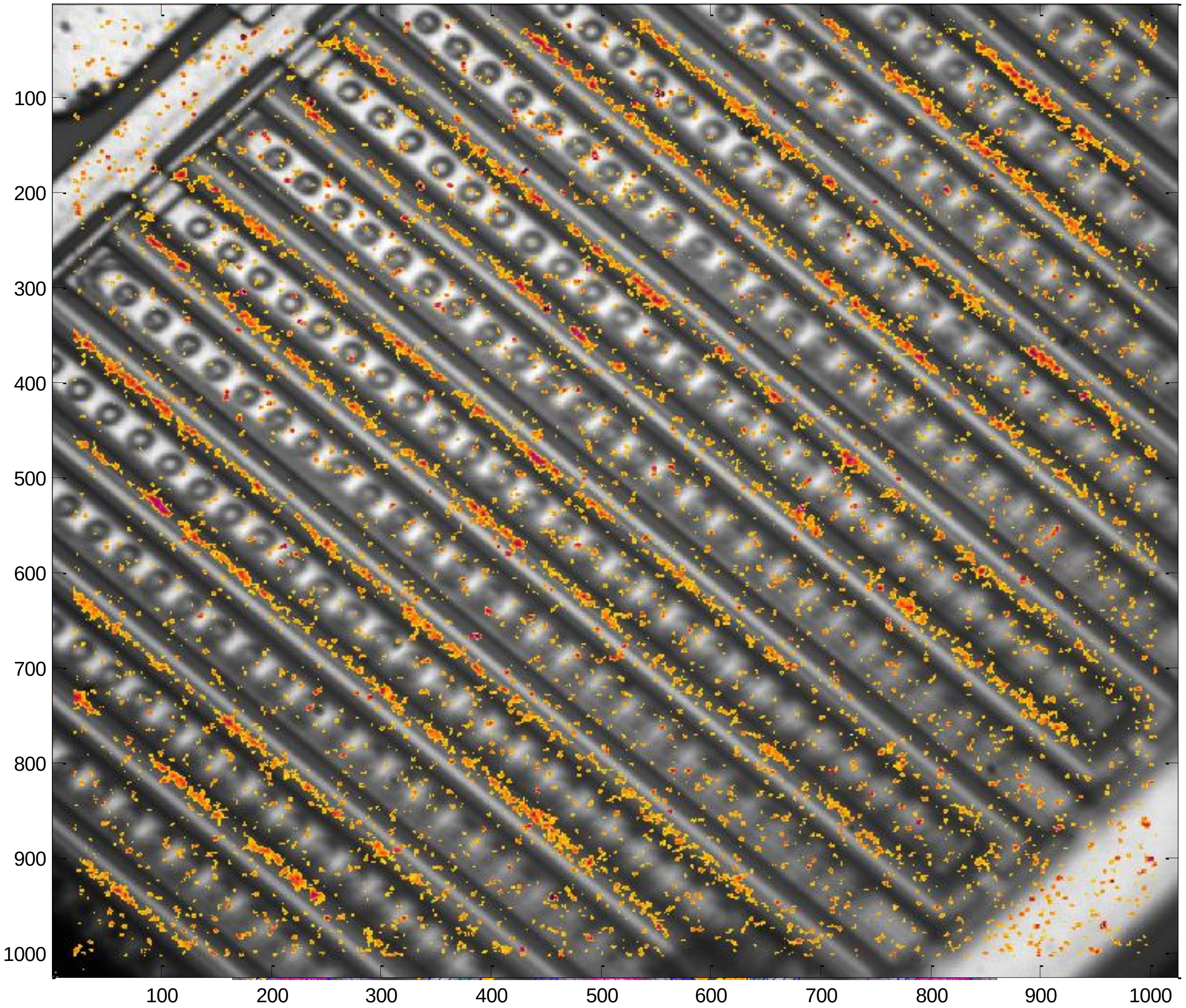


Drain Bias

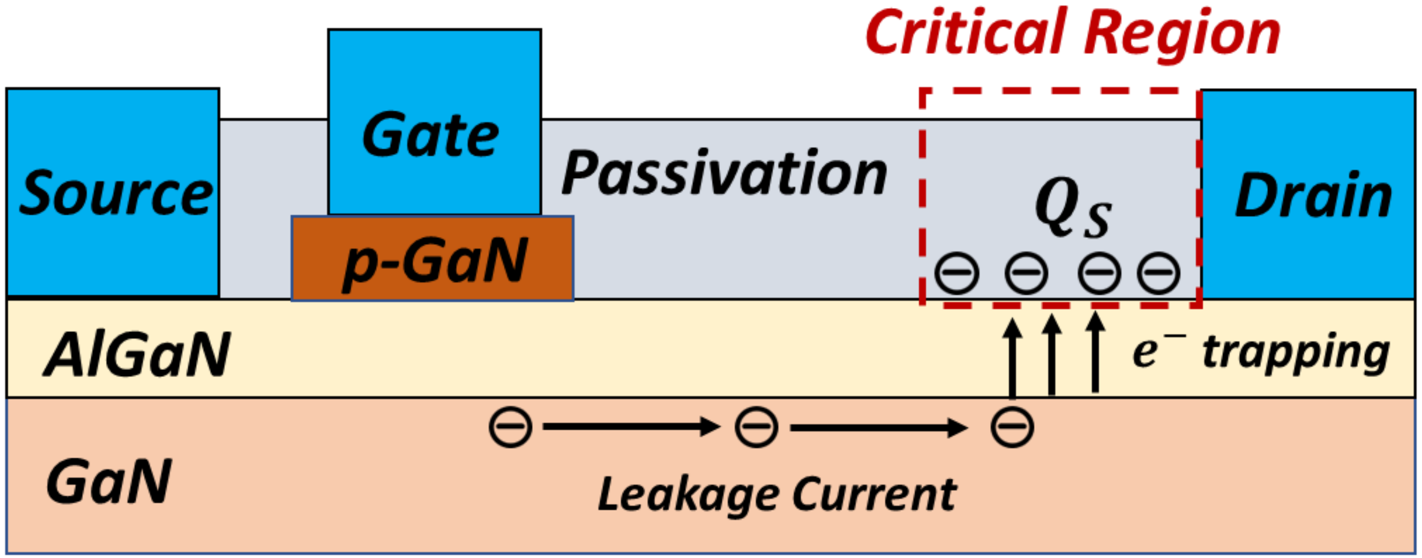
Drain-Source Voltage Stress

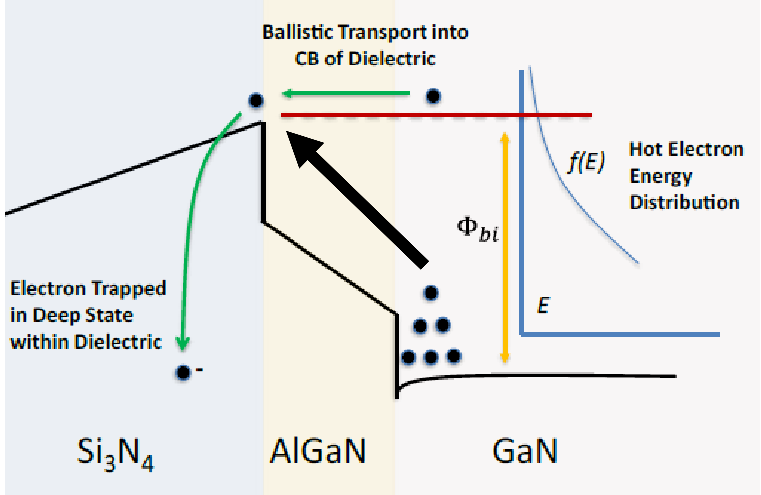


Physics of $R_{DS(on)}$ Shift – Hot Carrier Emission



Hot Carrier Trapping Mechanism





Hot Carrier Trapping Model

$$f(E)dE \propto E e^{-E/qF\lambda} dE$$

$$\frac{dQ_S}{dt} = A\int_{\Phi_{bi}+\beta Q_S}^{\infty} f(E)dE = A\int_{\Phi_{bi}+\beta Q_S}^{\infty} E e^{-E/qF\lambda} dE$$

$$\frac{dQ_S}{dt} = B\exp\left(-\frac{\beta Q_S}{qF\lambda}\right)$$

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

$$R(t) = R_0 + \frac{C}{Q_P - Q_S} = R_0 + \frac{C}{Q_P - \frac{qF\lambda}{\beta}\log\left(1+\frac{B\beta}{qF\lambda}t\right)}$$

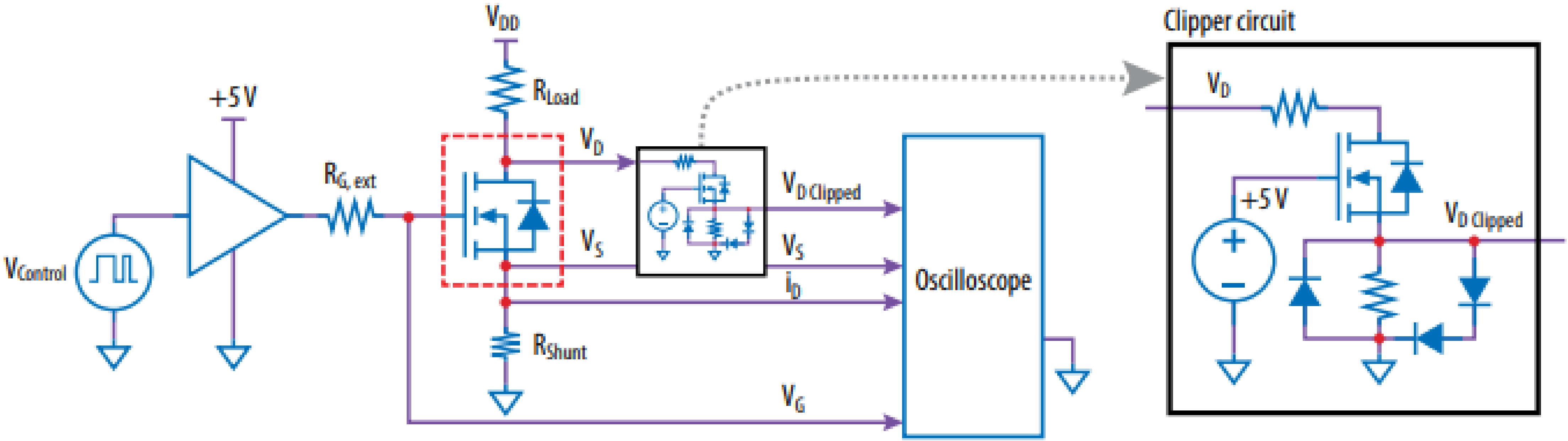
$$R(t) \approx R_0 + \frac{C}{Q_P}\left[1+\frac{qF\lambda}{Q_P\beta}\log\left(1+\frac{B\beta}{qF\lambda}t\right)\right]$$

$$\tau_{LO} \propto exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$$

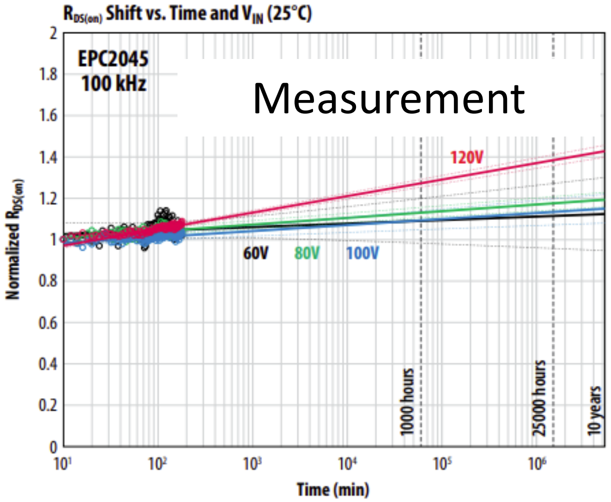
$$\lambda = v_{th}\tau_{LO} \propto A\sqrt{kT}exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$$

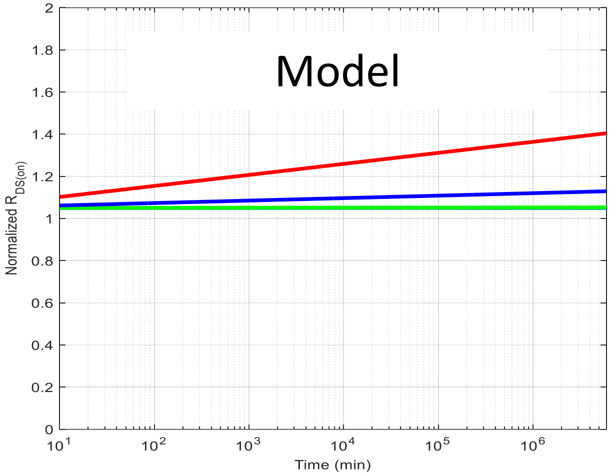
$$\frac{\Delta R}{R} = \frac{R(t)-R(0)}{R(0)} \approx a + bF\exp\left(\frac{\hbar\omega_{LO}}{kT}\right)\sqrt{T}\log(t)$$

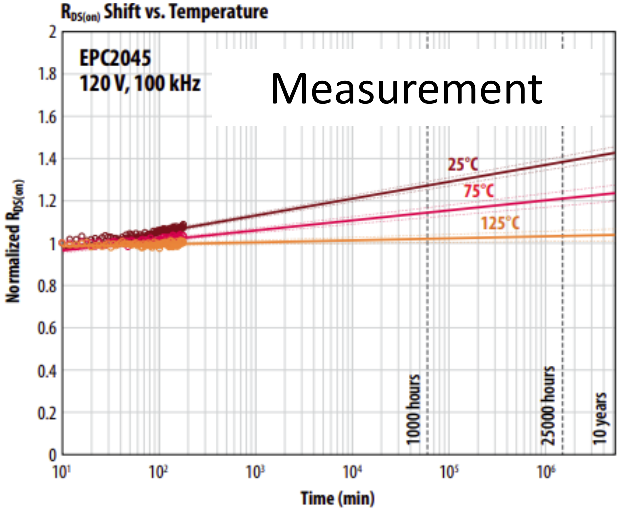
Resistive Hard Switching Circuit

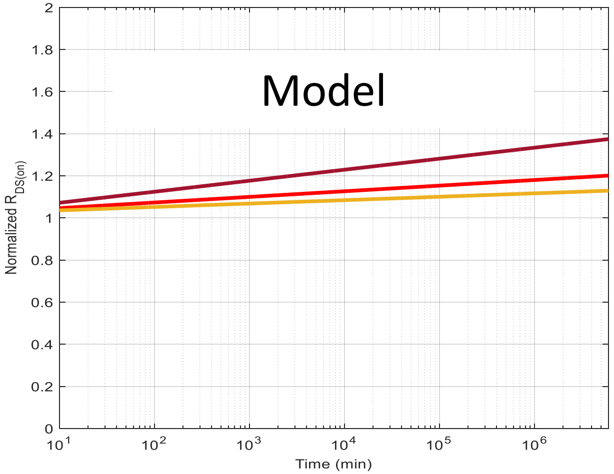


Model vs Measurement



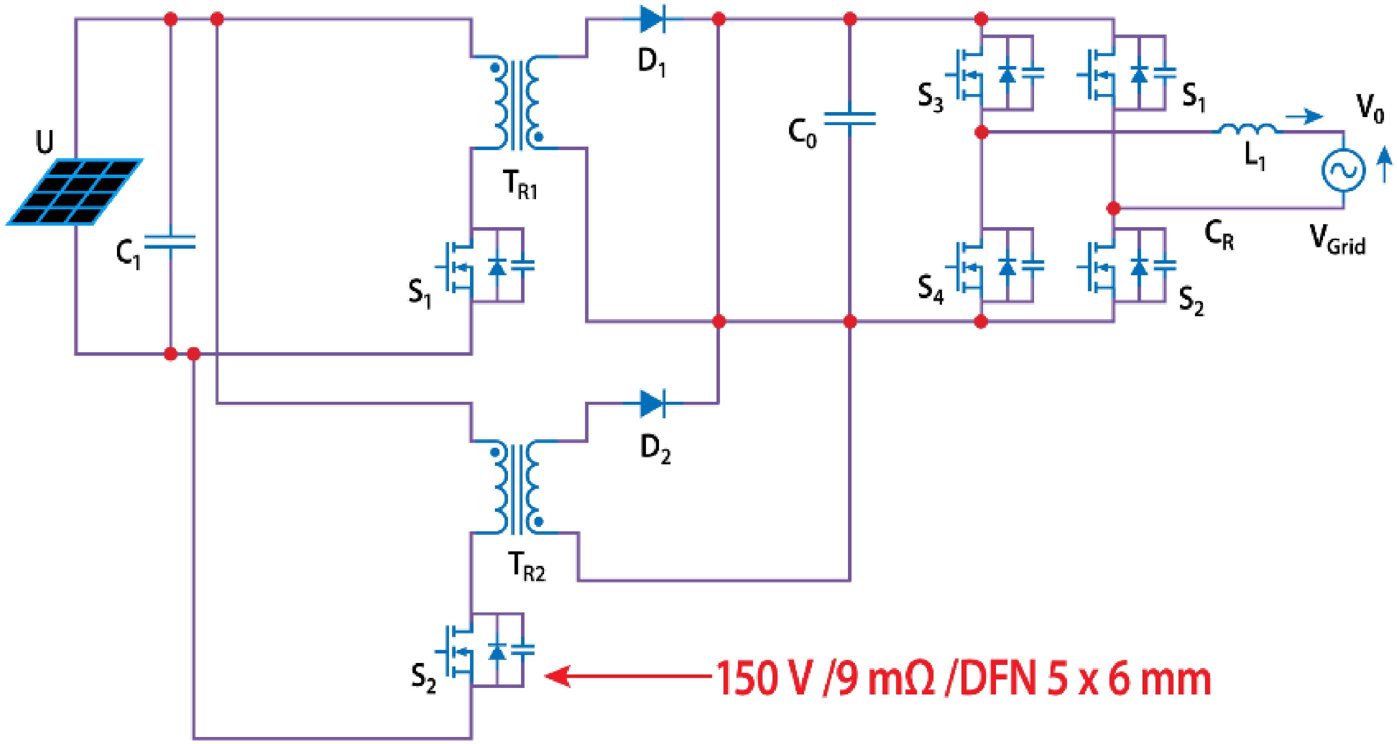






Apply the Model to Project Lifetime for Solar Mission Profile

Microinverter Flyback Topology



150 V /9 mΩ /DFN 5 x 6 mm

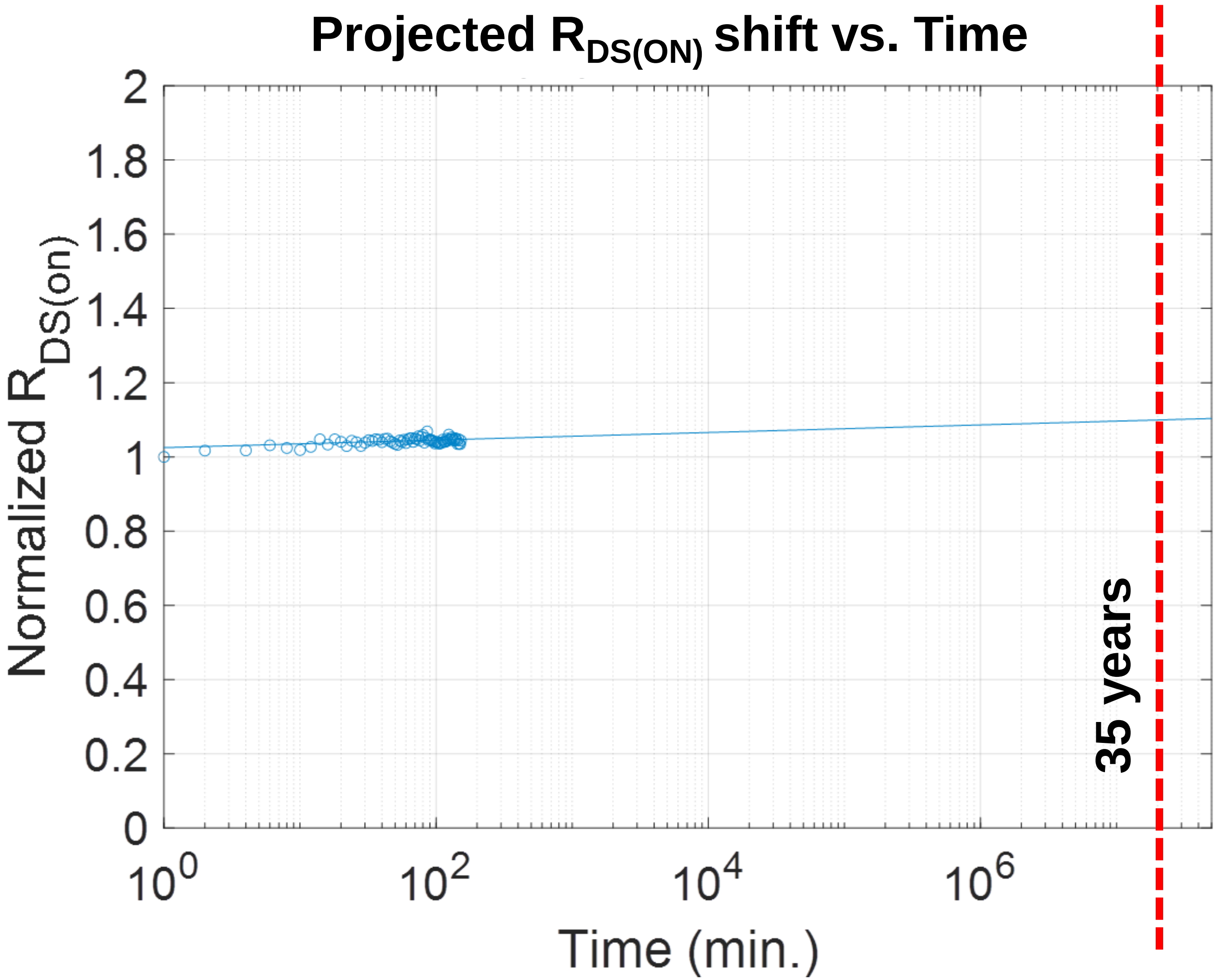
Part Number	**Size** (mm x mm)	**V_{DS} (V)**	**$R_{DS(on)}$ max (mΩ)**	**Q_G Typ (nC)**	**Q_{RR} Typ (nC)**
EPC2059	2.8 x 1.4	170	9	5.7	0
EPC2305*	3 x 5 QFN	150	3	21	0
EPC2308*	3 x 5 QFN	150	6	10	0

** Sampling*

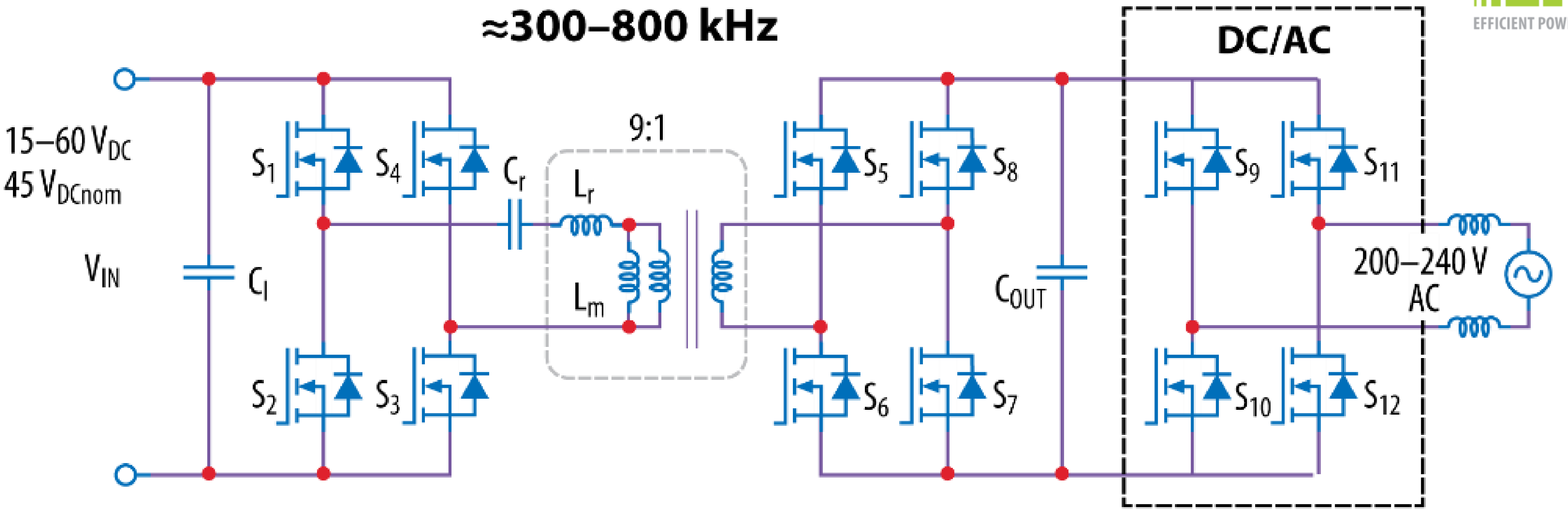
Drain Bias: Flyback Topology for Solar

- EPC2059 (170V V_{DSMax}) eGaN FET is a good fit for Flyback
- A representative EPC2059 device was tested under continuous hard switching at 100 kHz and 137V (80% V_{DSMax}) with case temperature of 80ºC

Projected $R_{DS(ON)}$ shift vs. Time



Microinverter Full Bridge Topology (Power Optimizer)



S_1–S_4 = 100 V, 3.2 mΩ (EPC2218)

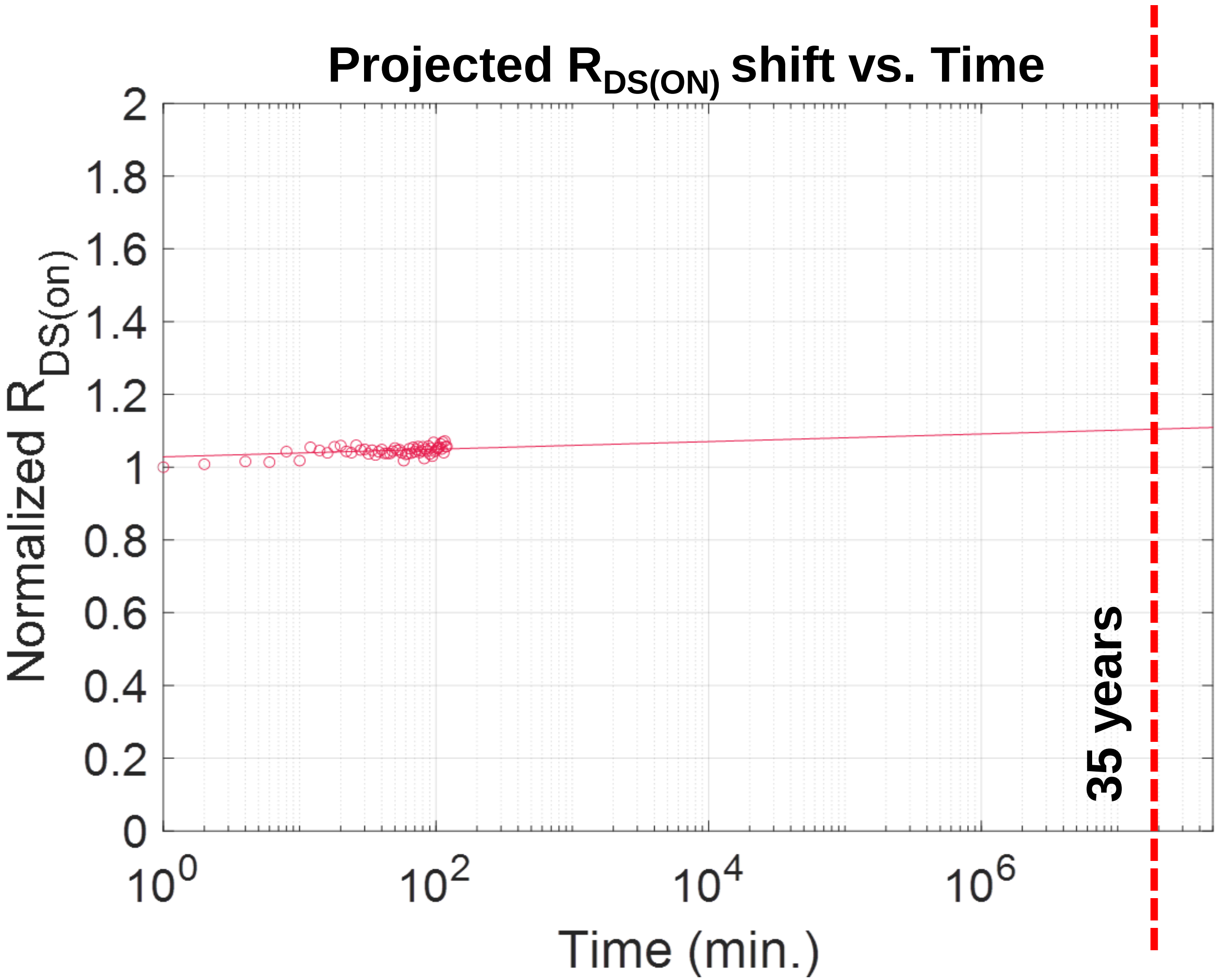
S_5–S_{12} = 650 V, 125 mΩ (NV6127, GS66504B)

Function	Part Number	Size (mm x mm)	V_{DS} (V)	$R_{DS(on)}$ max (mΩ)	Q_G typ (nC)	Q_{RR} typ (nC)
Primary	EPC2218	3.5 x 1.95	100	3.2	11.8	0
Primary	EPC2302	3 x 5 QFN	100	1.8	18	0
Primary	EPC2306*	3 x 5 QFN	100	3.8	11	0

** Sampling*

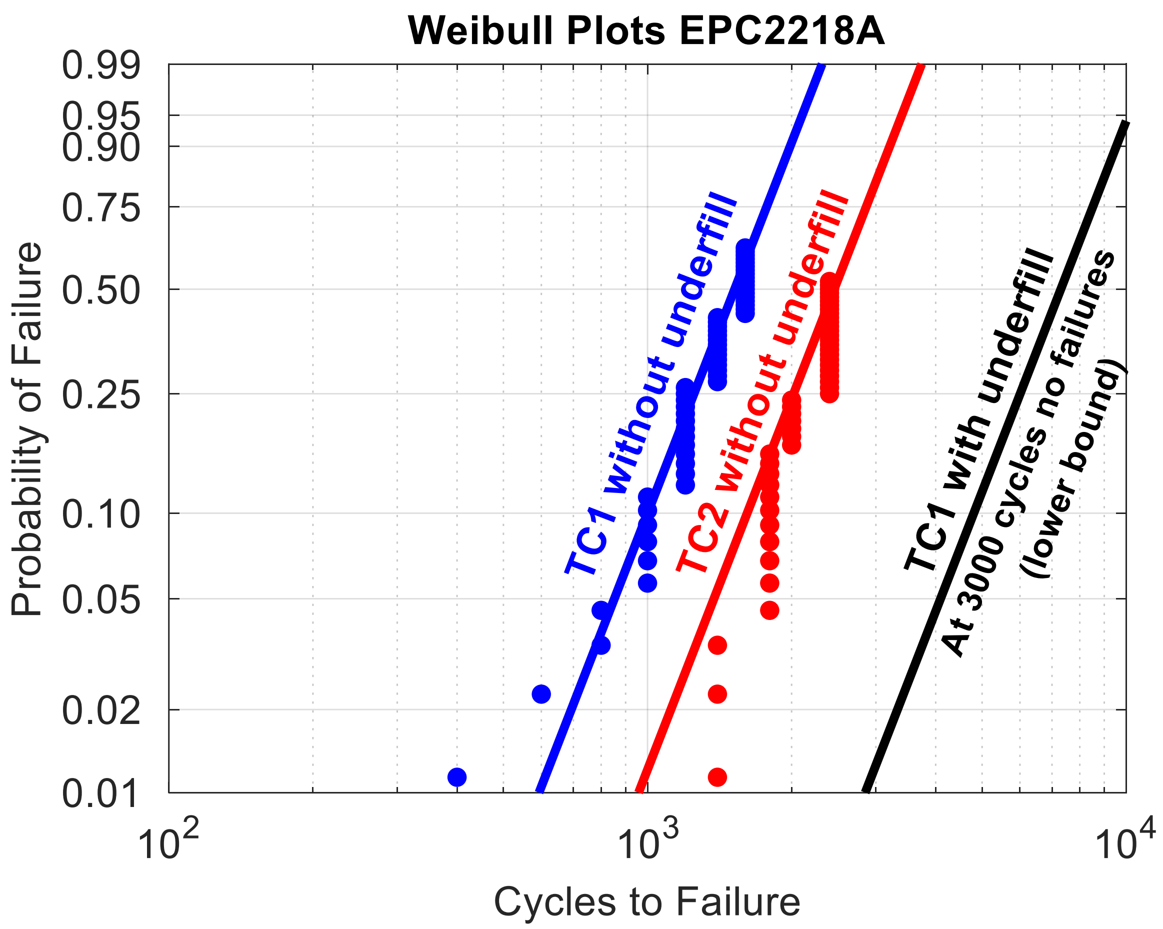
Drain Bias: Full Bridge Topology for Solar

- EPC2218 (100V V_{DSMax}) eGaN FET is a good fit
- A representative EPC2218 device was tested under continuous hard switching at 100 kHz and 80V (80% V_{DSMax})



Temperature Cycling (TC)

Board Level TC of EPC2218A (100V eGaN transistor)



- TC1: -40°C to 125°C
  - Without underfill, 88 devices
  - With underfill, 88 devices
- TC2 : -40°C to 105°C
  - Without underfill, 88 devices

Development of Lifetime Model for TC

Frequency term:

No. of cycle/day

ΔT term:

Solder Fatigue

Arrhenius term:

Solder Creep

$$N = A \cdot f^{-\alpha} \cdot \Delta T^{-\beta} \cdot \exp\left(\frac{E_a}{kT_{Max}}\right)$$

For EPC2218A using SAC305 solder: α = -1/3; β = 2.0; E_a = 0.2 eV

1. B. Han , Y. Guo, “Determination of an Effective Coefficient of Thermal Expansion of Electronic Packaging Components: A Whole-Field Approach,” IEEE TRANSACTIONS ON COMPONENTS, PACKAGING. AND MANUFACTURING TECHNOLOGY-PART A, VOL. 19, NO. 2, JUNE 1996
2. Automotive Electronics Council, “FAILURE MECHANISM BASED STRESS TEST QUALIFICATION FOR DISCRETE SEMICONDUCTORS IN AUTOMOTIVE APPLICATIONS”, AEC-Q101-Rev E, March 2021
3. Norris, K. C., & Landzberg, A. H., “Reliability of Controlled Collapse Interconnections”, IBM Journal of Research and Development, 13(3), pp. 266–271, 1969
4. Vasudevan, V., and Fan, X., “An Acceleration Model for Lead-Free (SAC) Solder Joint Reliability Under Thermal Cycling,” ECTC, pp. 139–145, 2008

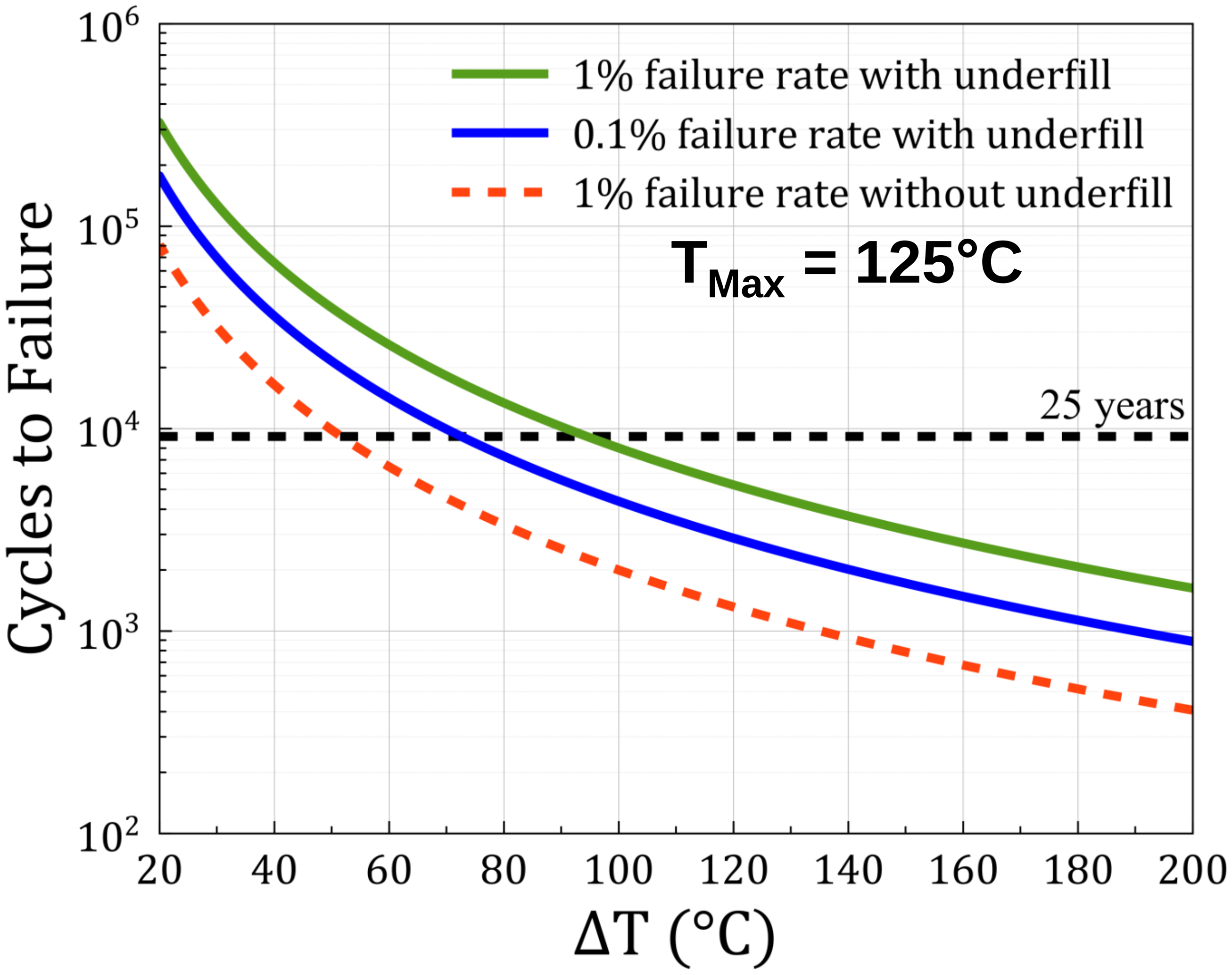
Temperature Cycling of EPC2218A (100V eGaN transistor)

1% of failure rate:

- With underfill - ΔT of 95°C
- Without underfill - ΔT of ~50°C

0.1% of failure rate:

- With underfill - ΔT of ~73°C



Apply the TC Lifetime Model to Real-world Scenarios

Estimate Lifetimes in Real-World Scenarios

Each mission profile

$$\frac{1}{N_{Total}} = \boxed{\frac{a}{N_{\Delta T_a}}} + \boxed{\frac{b}{N_{\Delta T_b}}} + \cdots + \boxed{\frac{i}{N_{\Delta T_i}}}$$

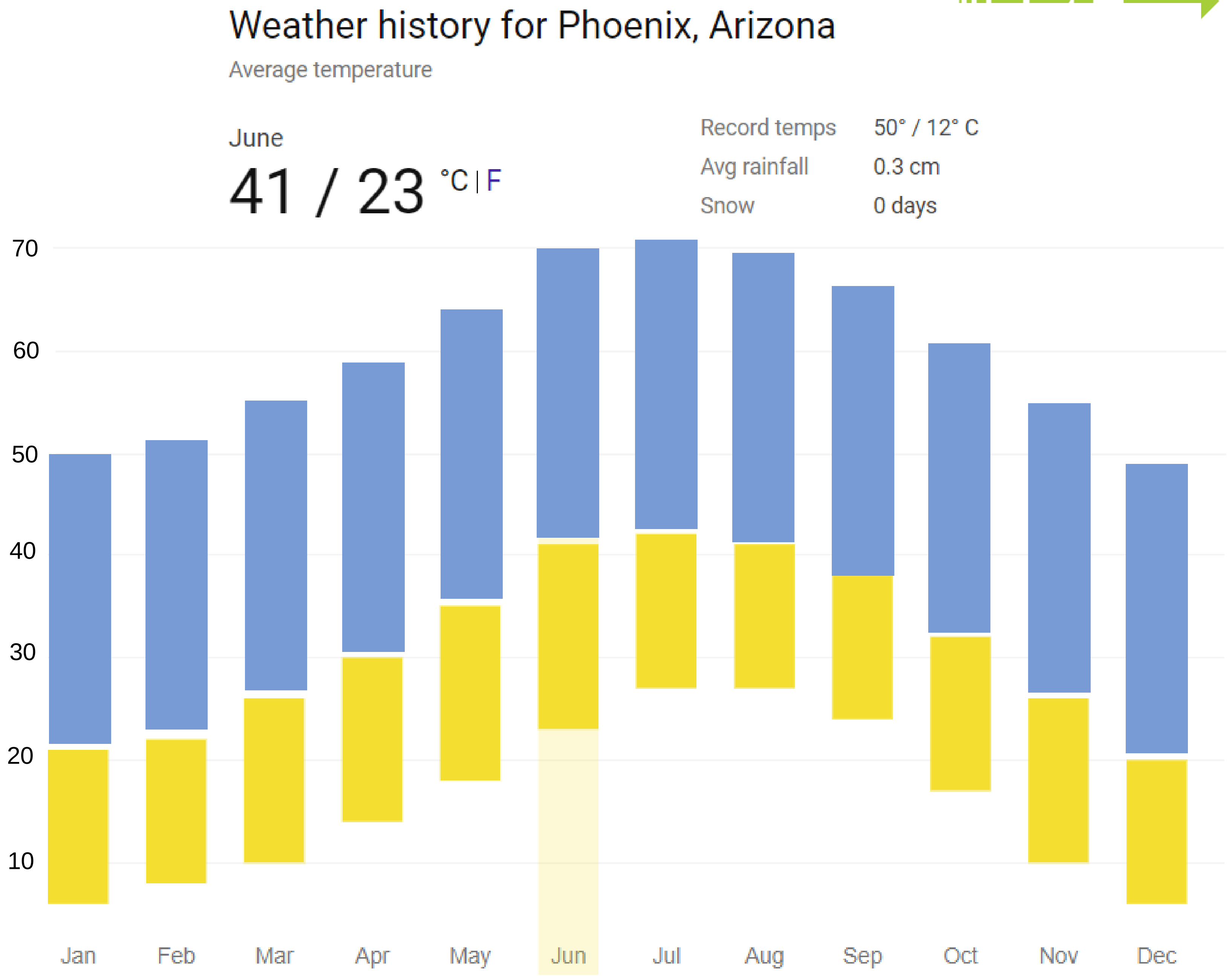
a, b, … i = the factional lifetime of each mission profile

$N_{\Delta Ti}$ = No of cycles-to-failure for a given mission profile

The most stringent mission profile ($N_{\Delta Ti}$) dominates the overall lifetime (N_{Total})

Predict Lifetime in a Real-world Scenario

N_{total} at Phoenix, AZ is estimated to be 10,971 cycles (10ppm failure rate), equivalent of *~30 years of continuous operation*



Weather history for Phoenix, Arizona

Average temperature

June

41 / 23 °C | F

Record temps	50° / 12° C
Avg rainfall	0.3 cm
Snow	0 days

🟦 **Self Heating (30°C)**

🟨 **Ambient Temperature**

The detailed study for GaN in Solar is published in our latest phase 15 reliability test report

Reliability Report Phase 15 (epc-co.com)

Thank you!