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Validating Duty Cycle-Based Repetitive Gate and Drain Transient Overvoltage Specifications for GaN HEMTs

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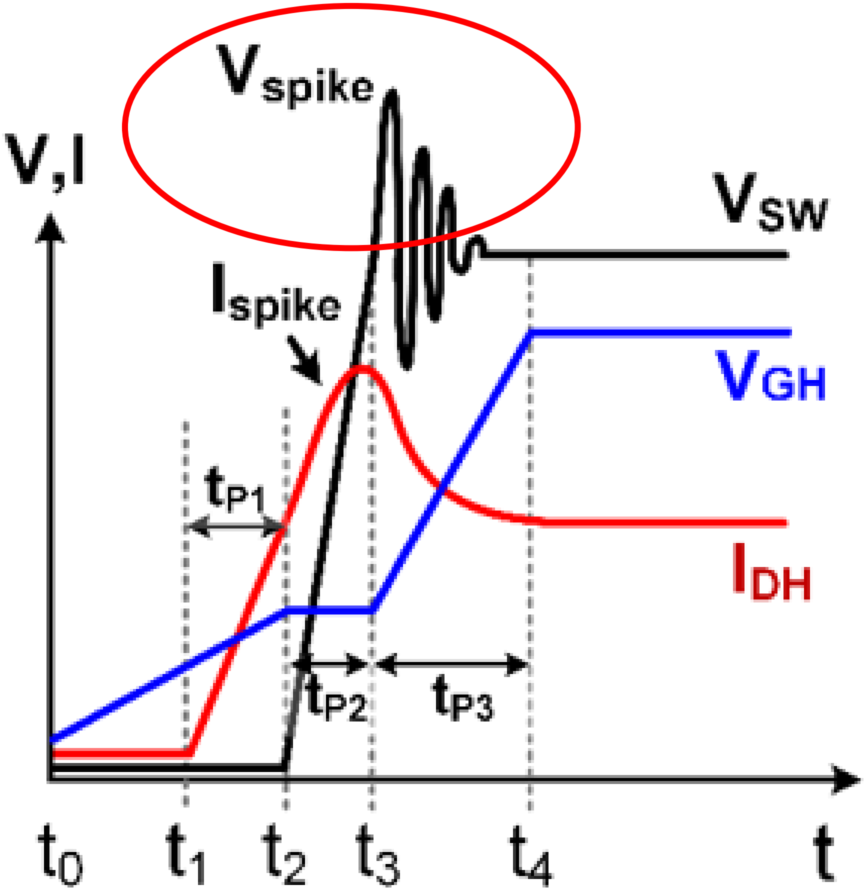
Efficient Power Conversion

Introduction

- Motivation
- Definition of Duty Cycle-based Overvoltage Specifications
- Drain Repetitive Transient Overvoltage
- Gate Repetitive Transient Overvoltage
- Conclusions

Motivation

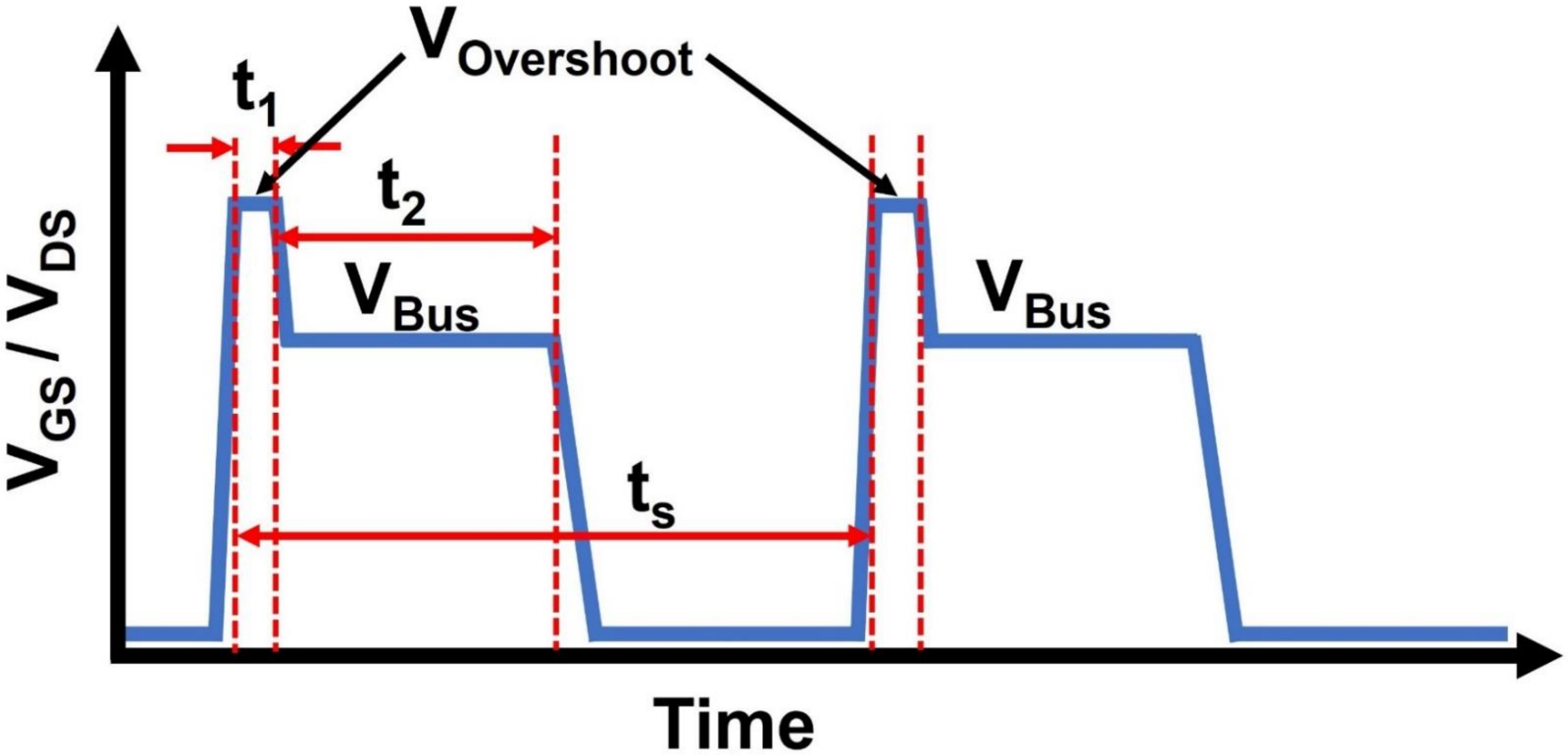
Transient Overvoltage Ringing in GaN-based Applications [1]



[1] Ke et al, “A Tri-Slope Gate Driving GaN DC–DC Converter With Spurious Noise Compression and Ringing Suppression for Automotive Applications” in IEEE Journal of Solid-State Circuits, vol. 53, no. 1, pp. 247-260, Jan. 2018

What is Duty Cycle-based Overvoltage Specification?

$$\text{Duty Cycle Factor} = t_1/t_S \leq 1\%$$



Drain Repetitive Transient Overvoltage Specification

Drain Wearout Mechanism: Dynamic $R_{DS(on)}$

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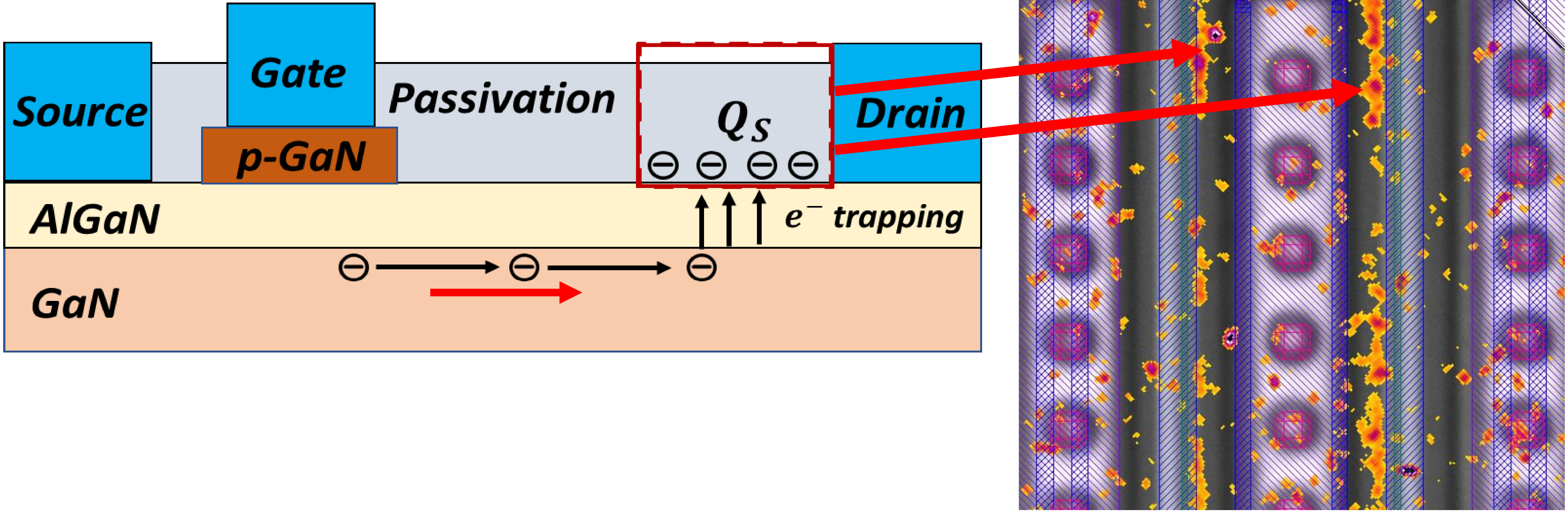
Hot Carrier Trapping Mechanism



Lifetime Model for Drain Wearout Mechanism

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

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

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

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

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

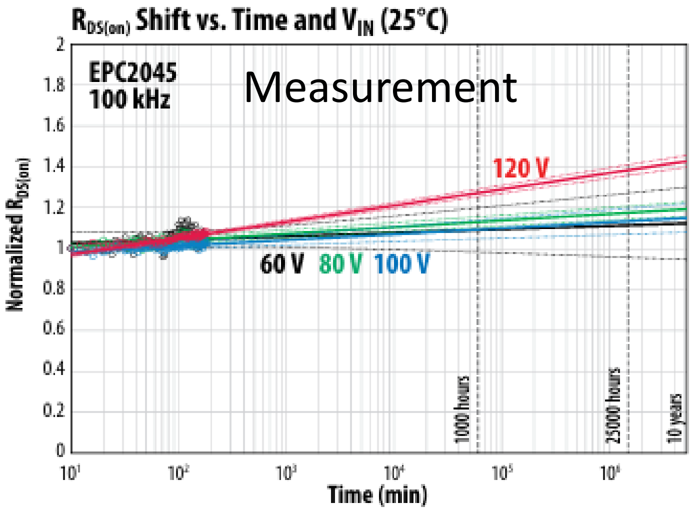
$$R(t) \approx R_0 + \frac{C}{Q_P}\left[1 + \frac{qF\lambda}{Q_P\beta} \log\left(1 + \frac{B\beta}{qF\lambda} t\right)\right]$$

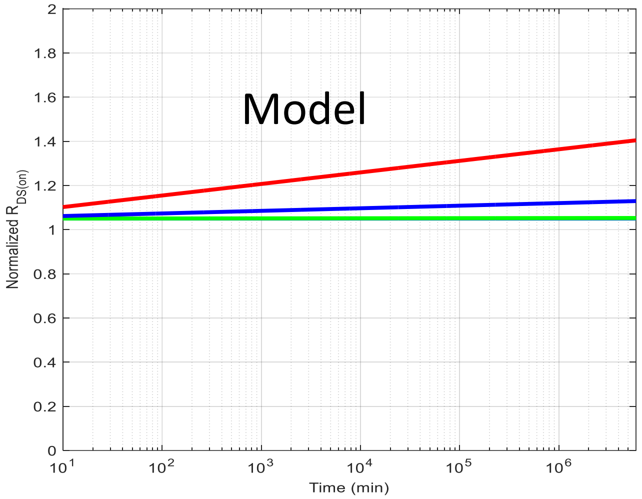
$$\tau_{LO} \propto exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$$

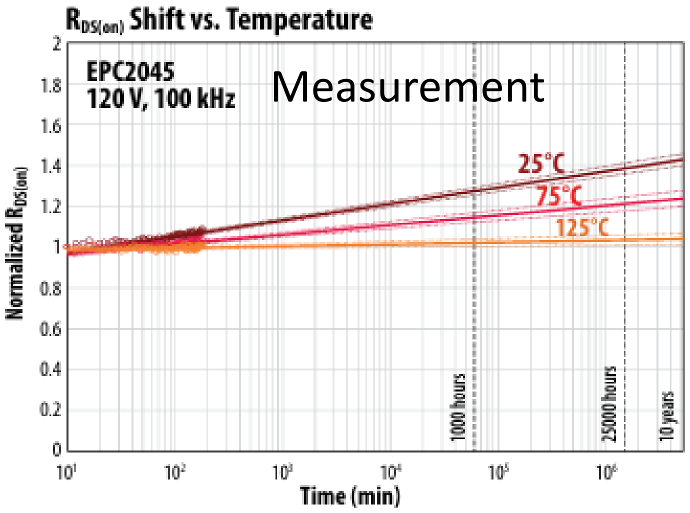
$$\lambda = v_{th}\tau_{LO} \propto A\sqrt{kT} exp\left(\frac{\hbar\omega_{LO}}{kT}\right)$$

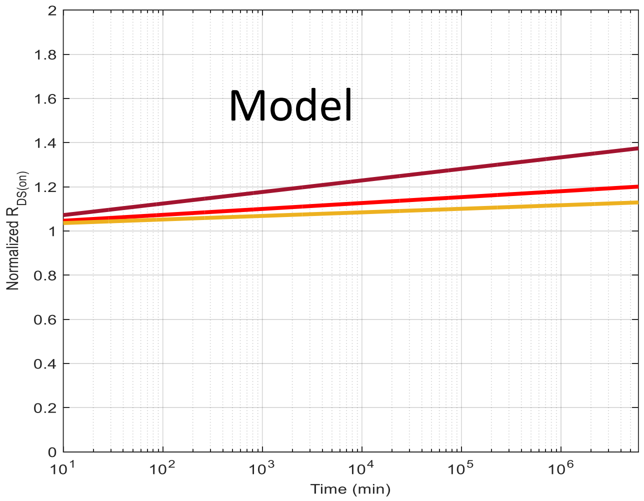
$$\frac{\Delta R}{R} = \frac{R(t) - R(0)}{R(0)} \approx a + bF \exp\left(\frac{\hbar\omega_{LO}}{kT}\right)\sqrt{T}\,\boxed{\log(t)}$$

Model vs Measurement

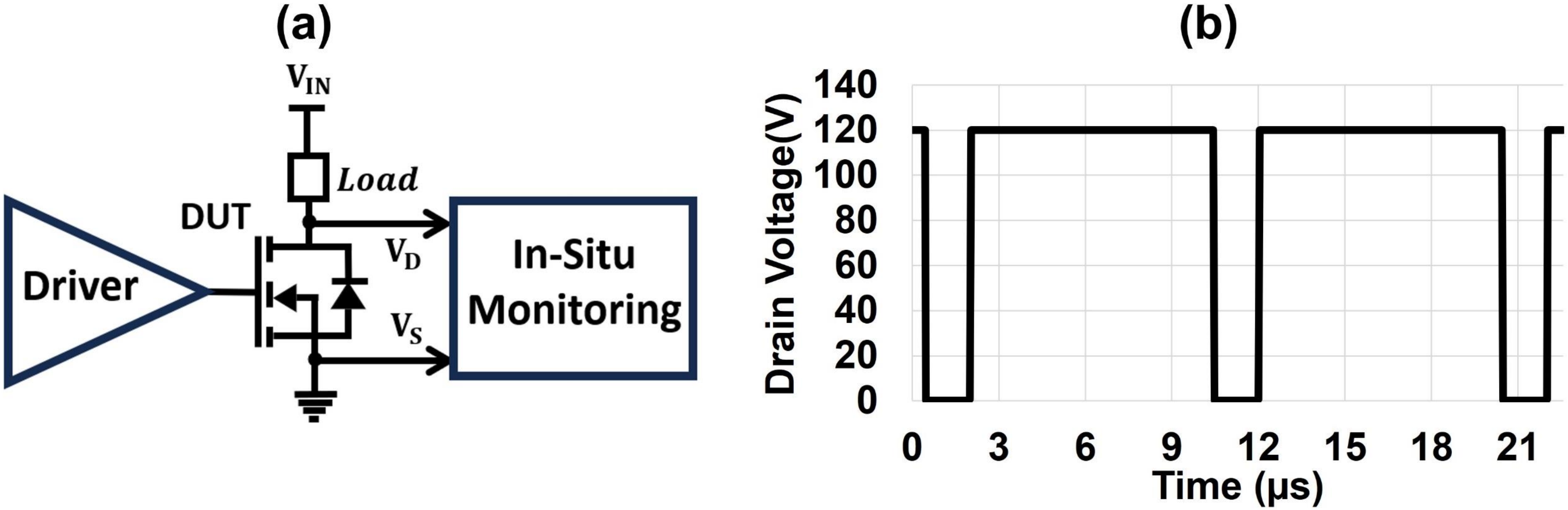








Resistive Hard Switching Circuit



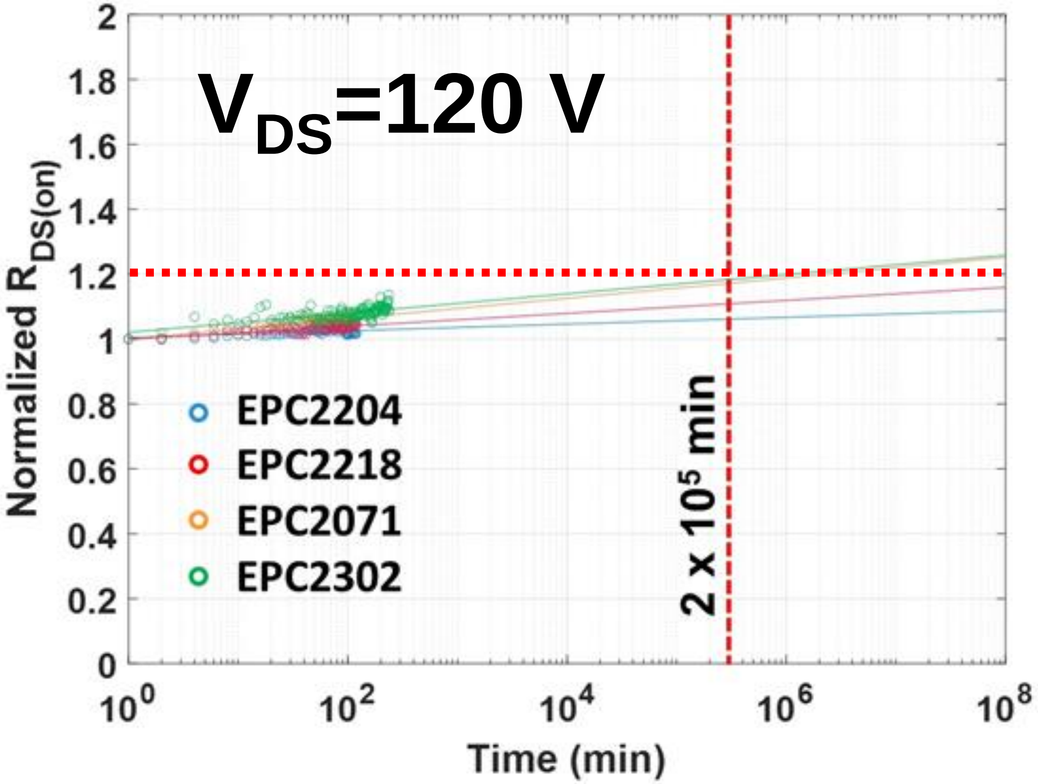
- V_{DS}=120 V for 100 V maximum rated devices
- 85% of the time, the device is OFF with V_{DS}=120 V applied
- 15% of the time, the device is ON

Developing Duty Cycle Factor for Drain Overvoltage

- Criteria: <20% Projected $R_{DS(on)}$ Shift

- 2 x 10^5 min x 85% (device off-time) = 1.7 x 10^5 min

- 1.7 x 10^5 mins / 25 years = ~1.3%
  - 25 years = 1.3 x 10^7 mins

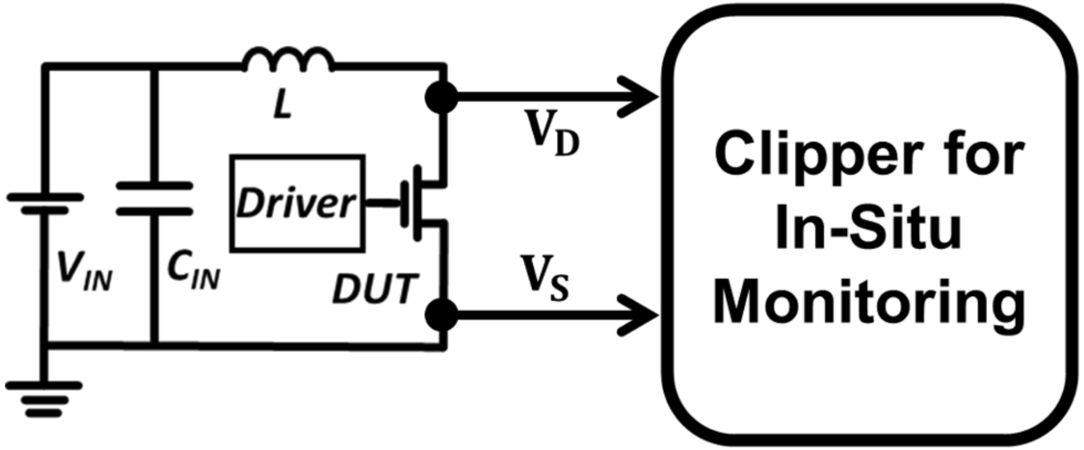


$V_{DS,Max}$=100V for all devices

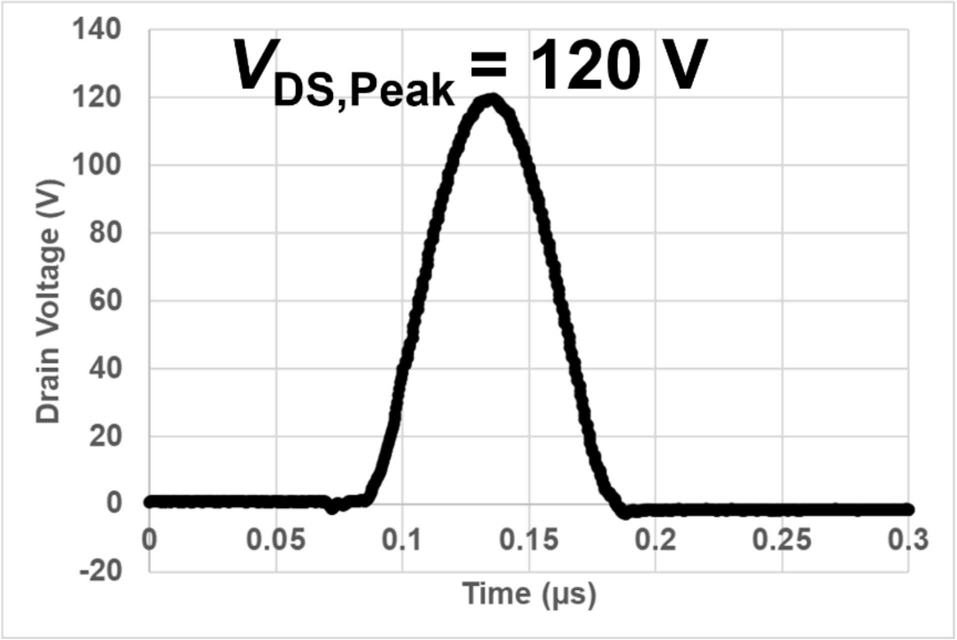
1% DC_{Factor} of the total lifetime when V_{DS}=120V

Validation: Drain Unclamped Inductive Switching

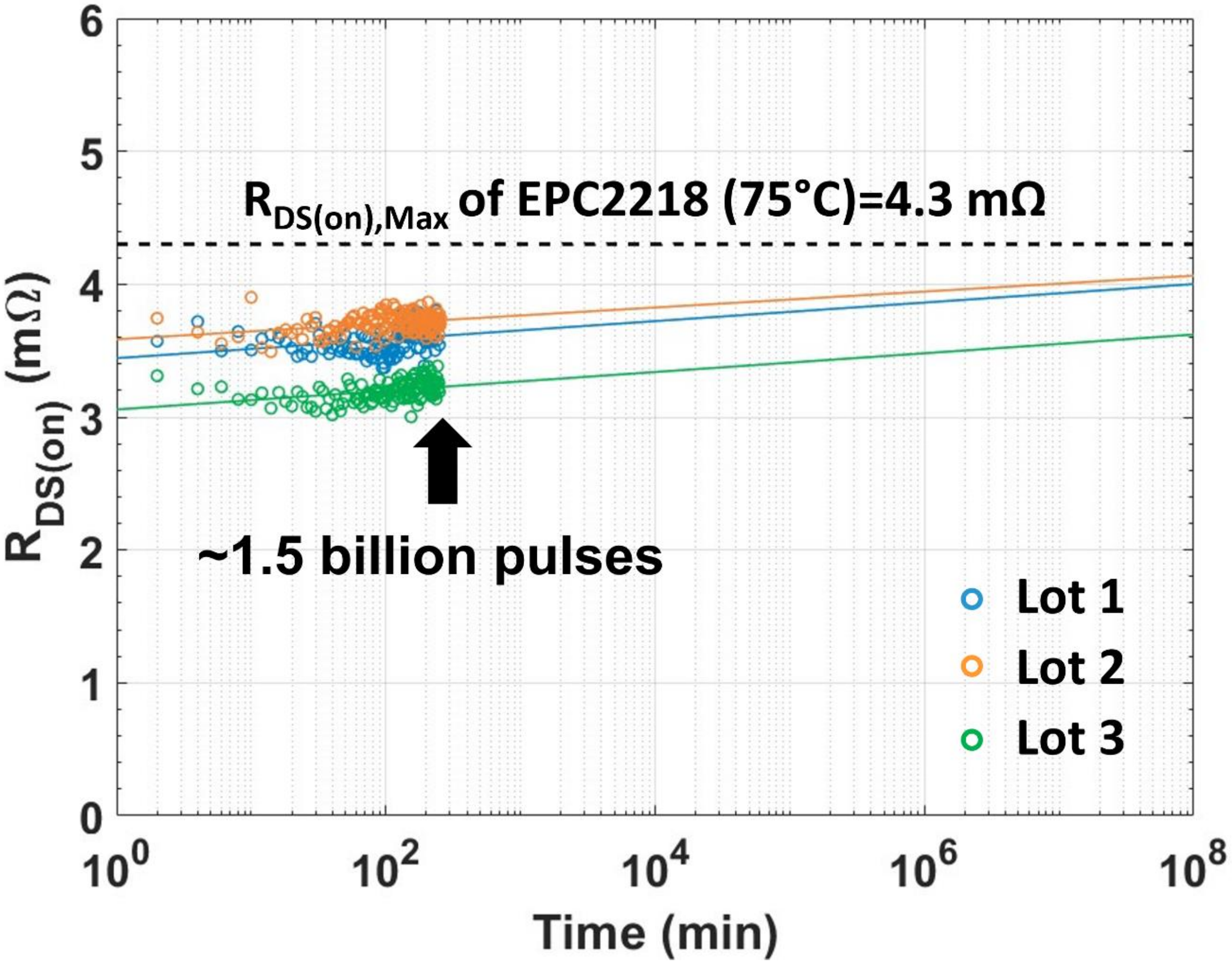
(a)



(b)

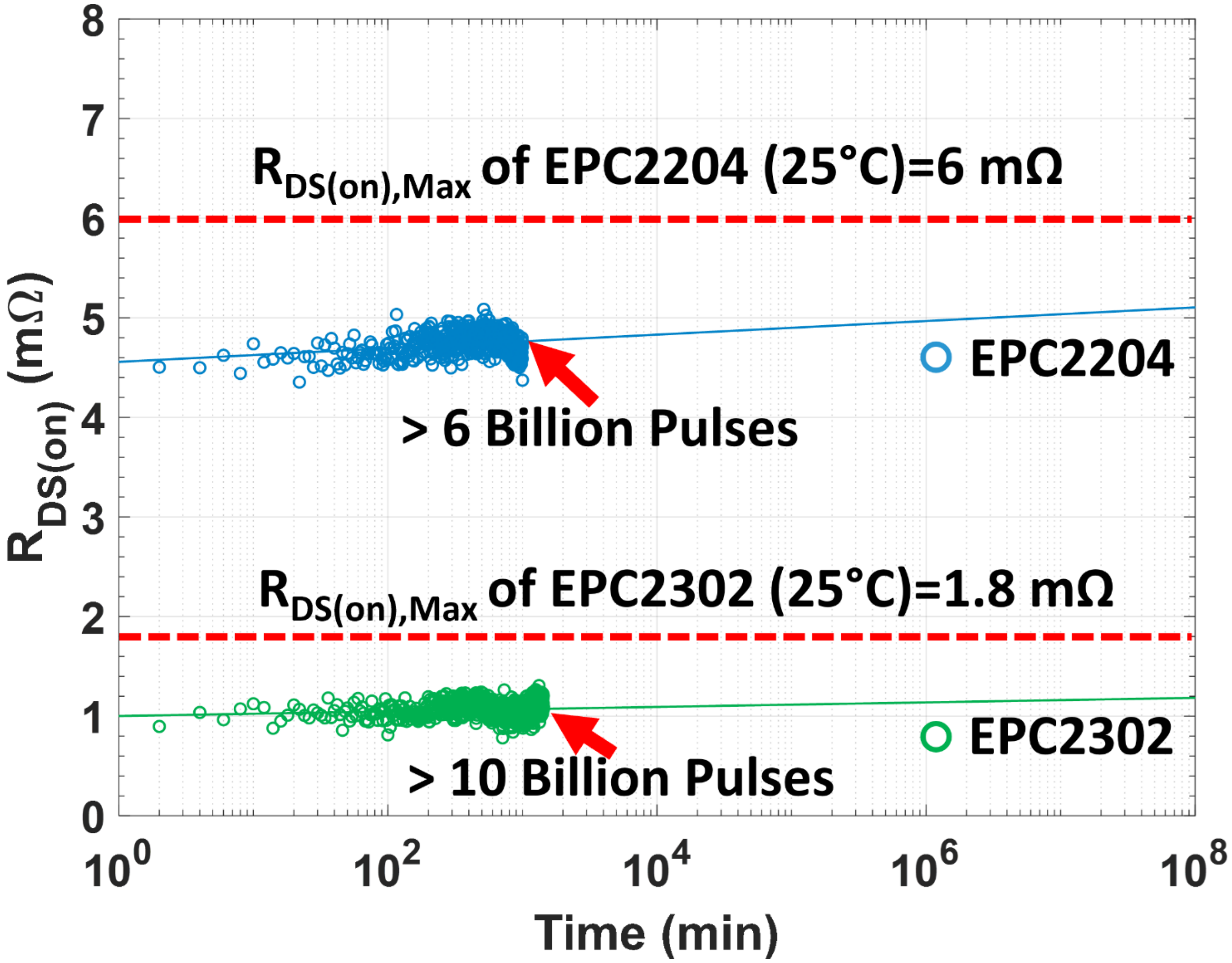


Validation of 120 V Repetitive Drain Transient Overvoltage



EPC2218: $V_{DS,Max}$=100V

Validation of 120 V Repetitive Drain Transient Overvoltage



EPC2204 and EPC2302: $V_{DS,Max}$=100V

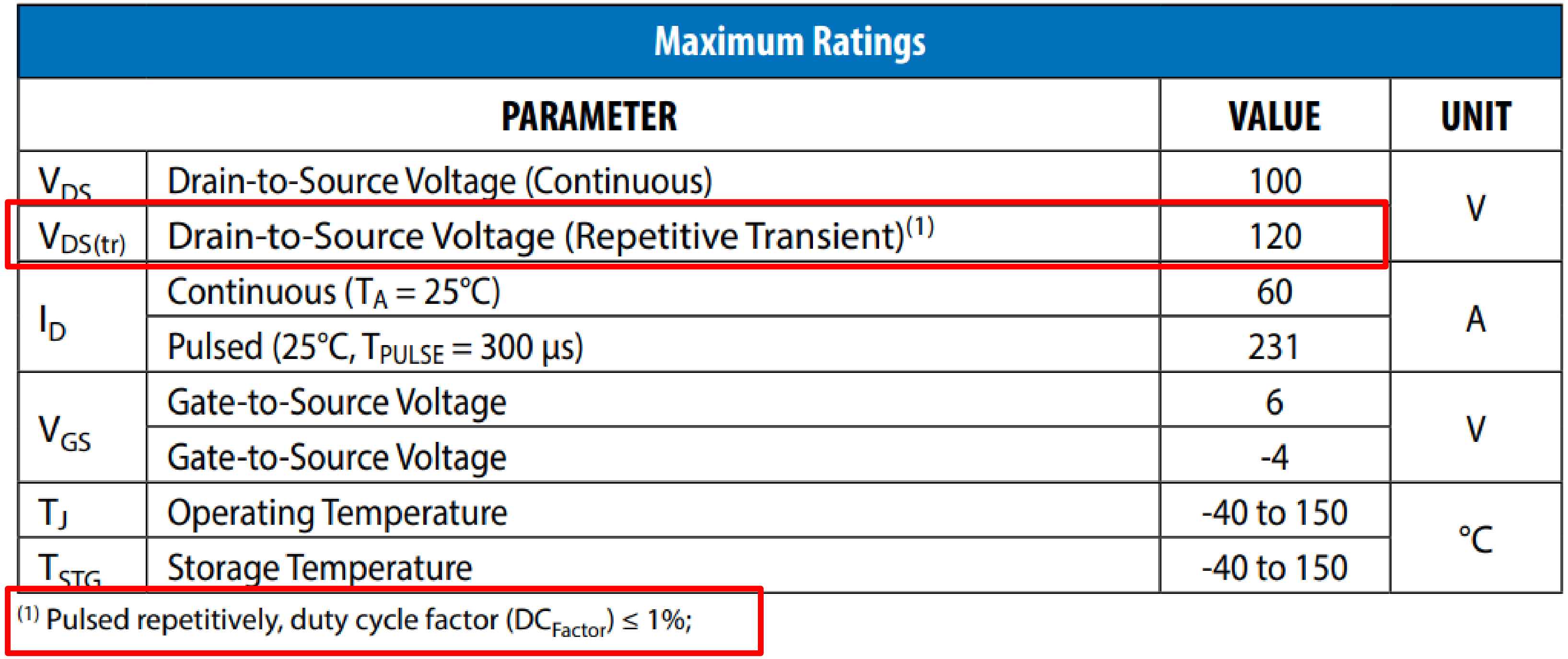
How to Use 1% DC_{Factor} in Applications

- A converter featuring 100 V max-rated GaN FETs operating at 1 MHz (period = 1 µs)

- It shows a repetitive 120 V_{DS} spike measured with ~10 ns pulse width.

- 10 ns/1 µs = 1% ≤ 1% → Low reliability risk

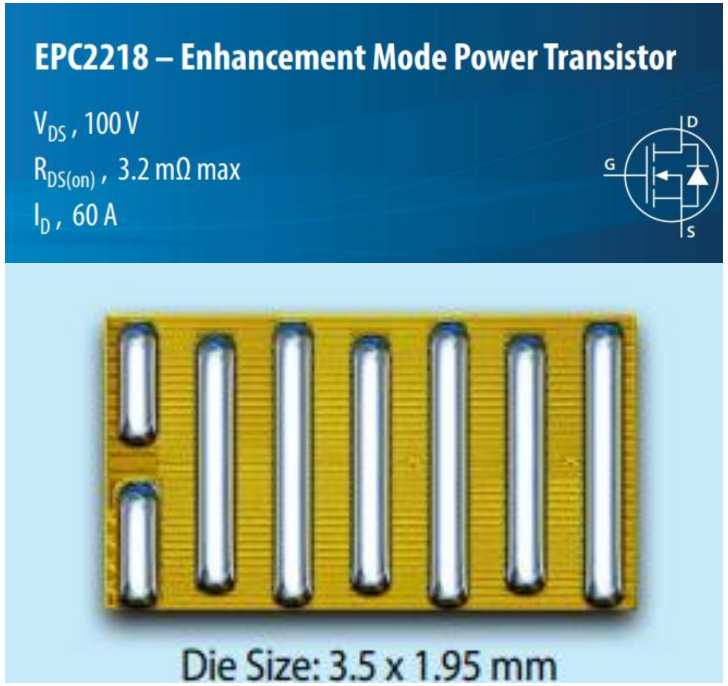
EPC’s Repetitive Transient Overvoltage Specification



Maximum Ratings

PARAMETER		VALUE	UNIT
V_{DS}	Drain-to-Source Voltage (Continuous)	100	V
$V_{DS(tr)}$	Drain-to-Source Voltage (Repetitive Transient)(1)	120	
I_D	Continuous ($T_A = 25°C$)	60	A
	Pulsed (25°C, $T_{PULSE} = 300\ \mu s$)	231	
V_{GS}	Gate-to-Source Voltage	6	V
	Gate-to-Source Voltage	-4	
T_J	Operating Temperature	-40 to 150	°C
T_{STG}	Storage Temperature	-40 to 150	

(1) Pulsed repetitively, duty cycle factor (DC_{Factor}) ≤ 1%;



EPC2218 – Enhancement Mode Power Transistor

V_{DS}, 100 V
$R_{DS(on)}$, 3.2 mΩ max
I_D, 60 A

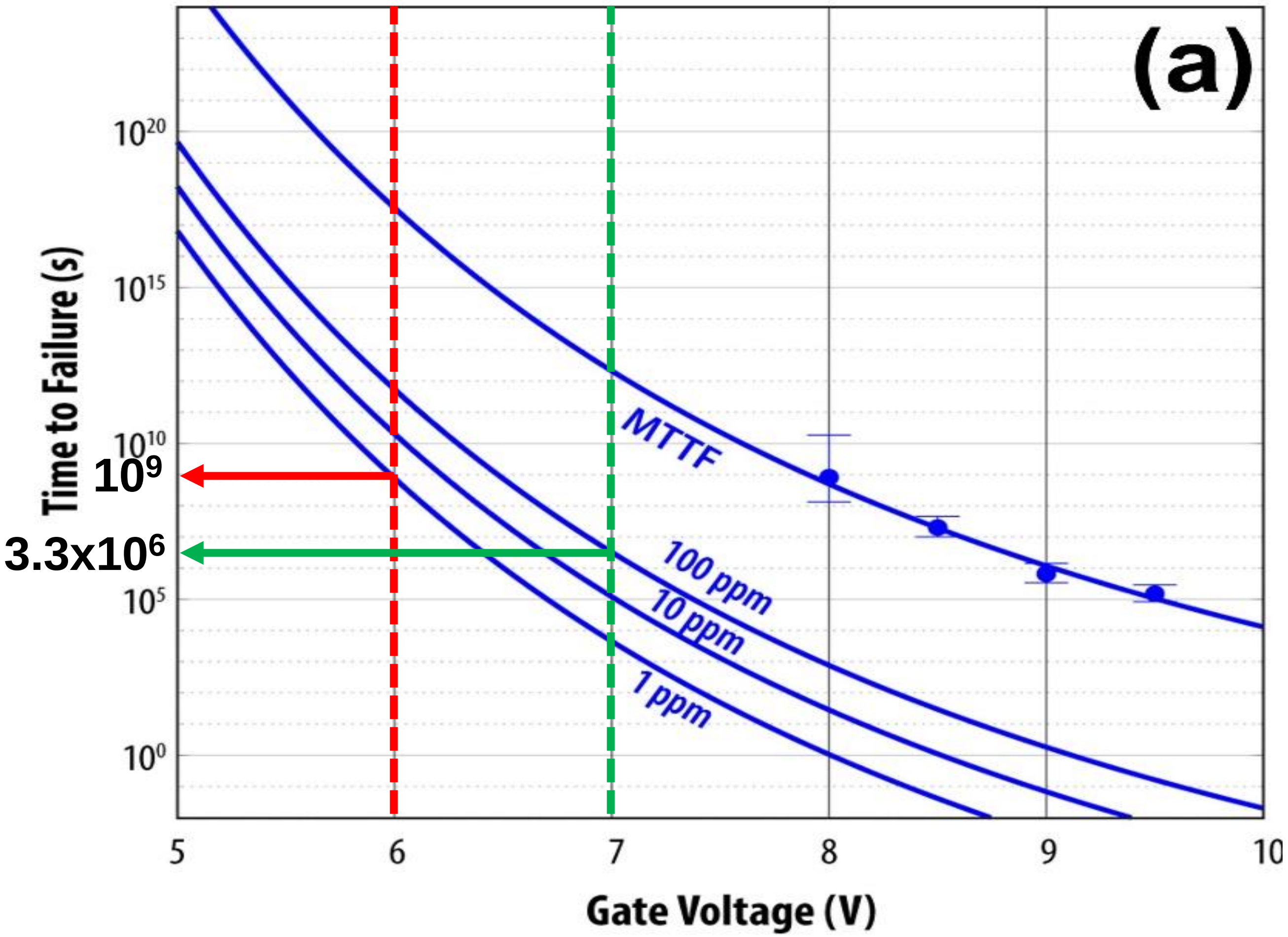
Die Size: 3.5 x 1.95 mm

Gate Repetitive Transient Overvoltage Specification

Developing Duty Cycle Factor for Gate Overvoltage

- Project ~30 years ($1x10^9$ seconds) lifetime with 1-ppm failure rate when $V_{GS} \leq 6$ V (max-rated V_{GS})

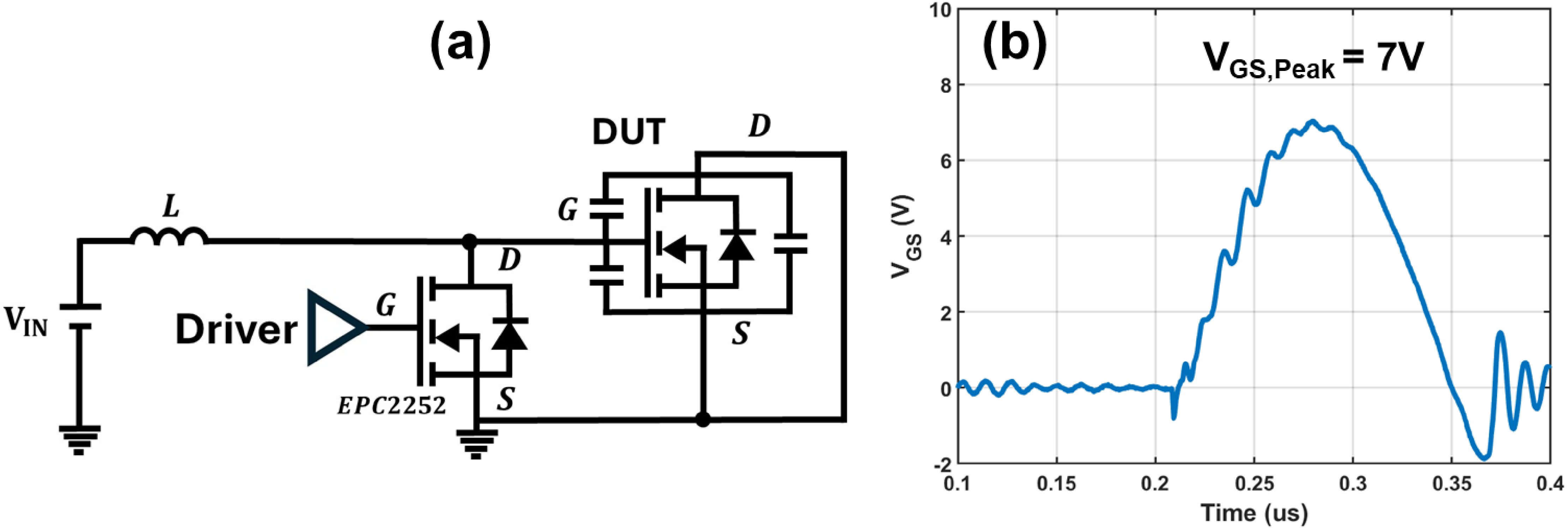
- At V_{GS}=7 V, projected lifetime (100-ppm) = ~3.3 x 10^6 seconds > 1% of 10 years lifetime



ppm: # failure of 1 million devices tested

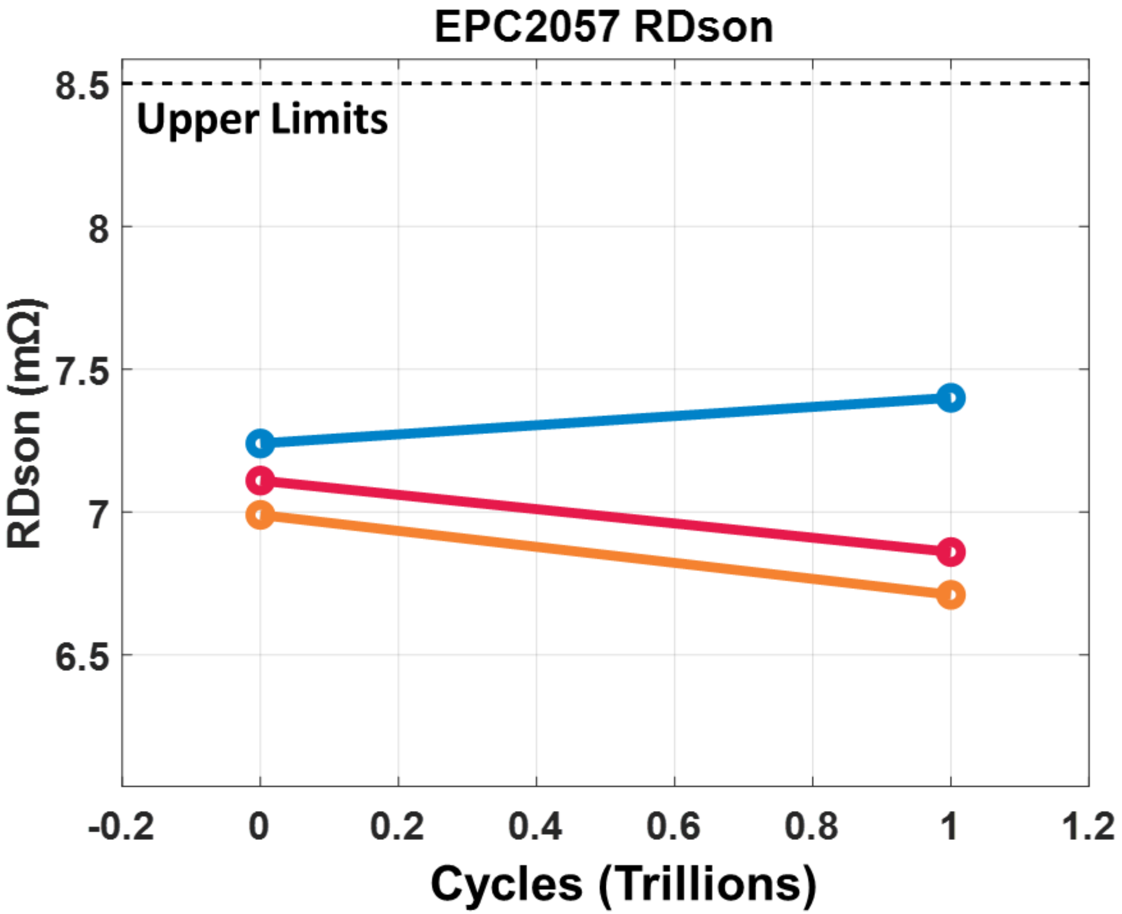
1% DC_{Factor} of the total lifetime when V_{GS}=7V

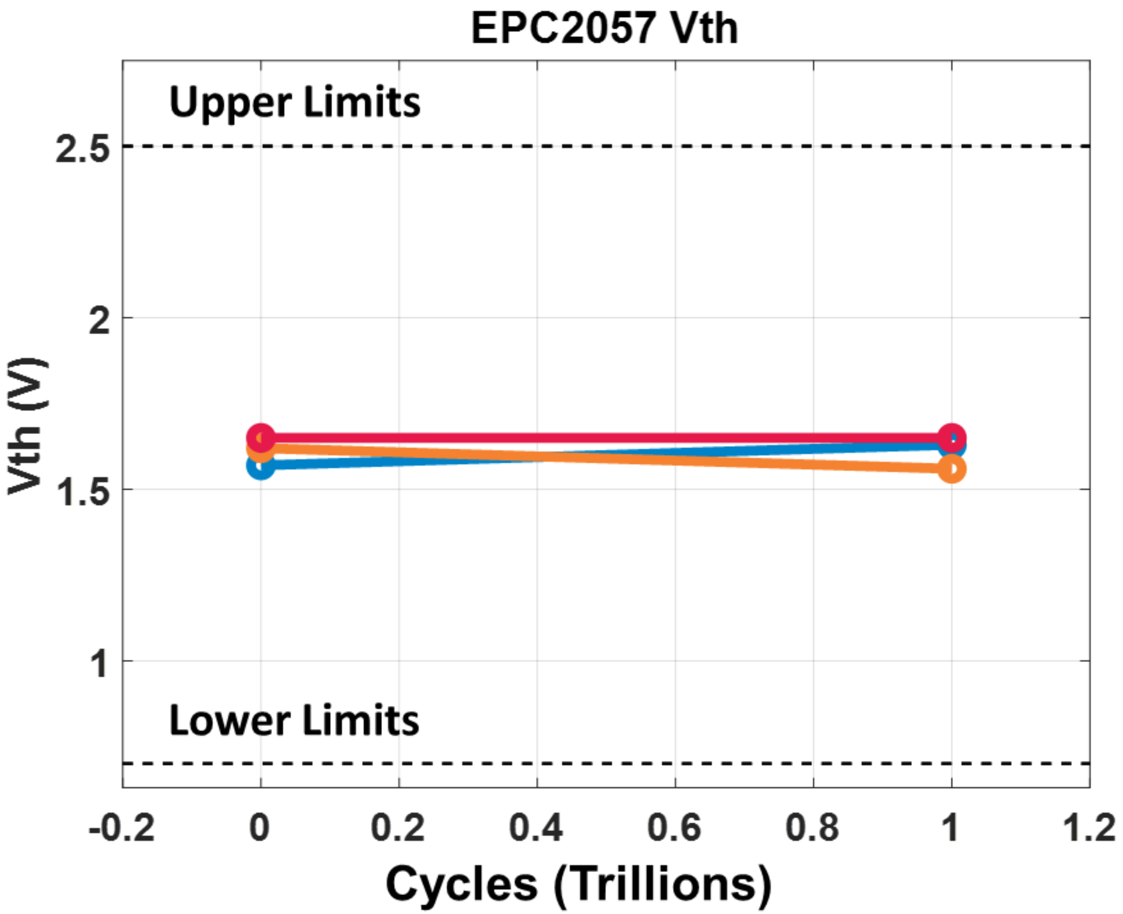
Validation: Gate Unclamped Inductive Switching



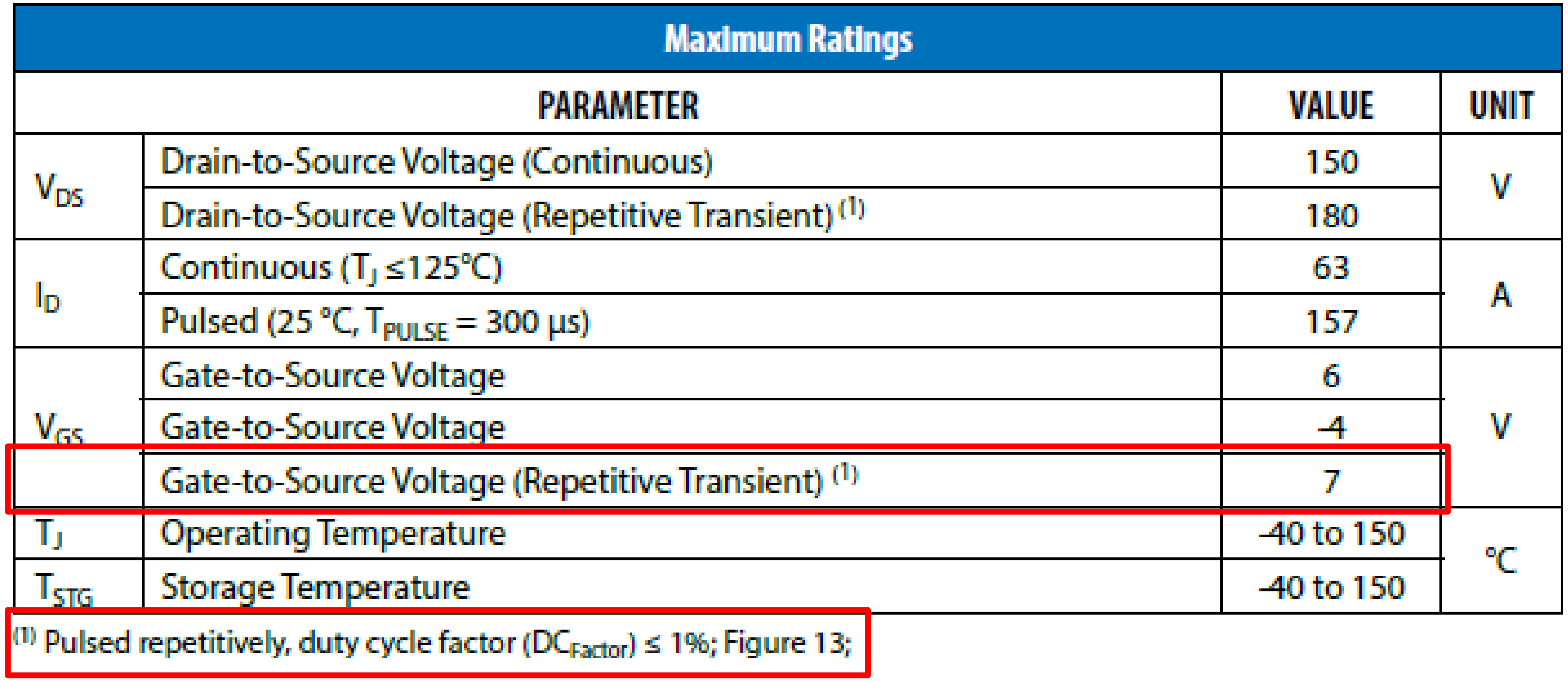
Validation of 7 V Repetitive Drain Transient Overvoltage

No issues found after 1 trillion pulses with $V_{GS,Peak}$=7V!





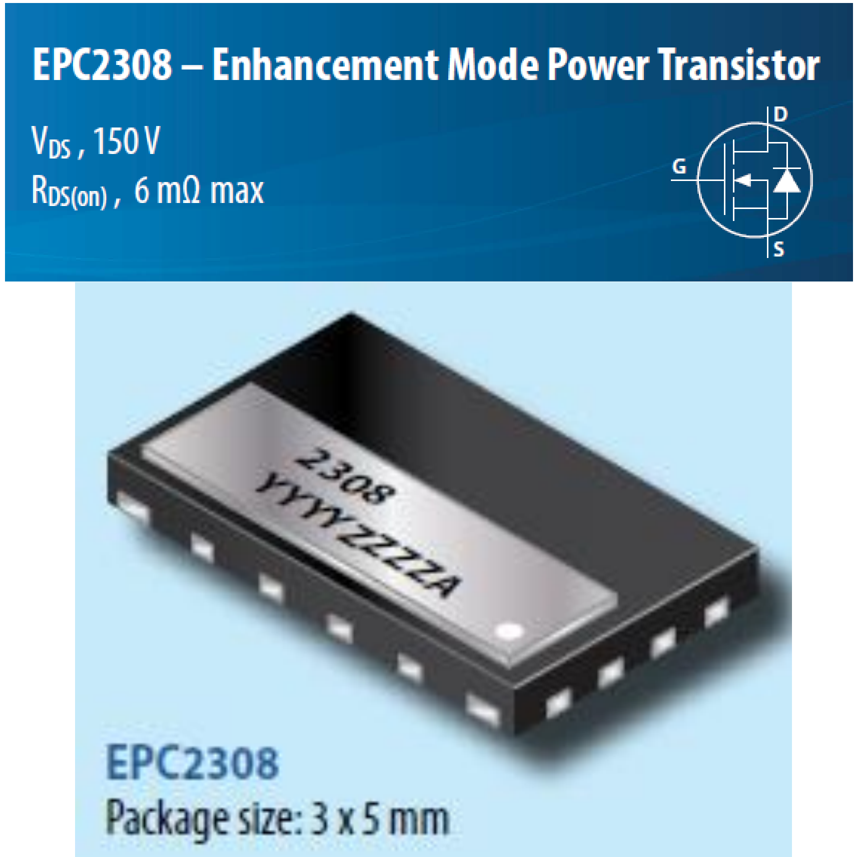
EPC’s Repetitive Transient Overvoltage Specification



Maximum Ratings

	PARAMETER	VALUE	UNIT
V_{DS}	Drain-to-Source Voltage (Continuous)	150	V
	Drain-to-Source Voltage (Repetitive Transient) (1)	180	
I_D	Continuous ($T_J \leq 125°C$)	63	A
	Pulsed (25 °C, T_{PULSE} = 300 µs)	157	
V_{GS}	Gate-to-Source Voltage	6	V
	Gate-to-Source Voltage	-4	
	Gate-to-Source Voltage (Repetitive Transient) (1)	7	
T_J	Operating Temperature	-40 to 150	°C
T_{STG}	Storage Temperature	-40 to 150	

(1) Pulsed repetitively, duty cycle factor (DC_{Factor}) ≤ 1%; Figure 13;



EPC2308 – Enhancement Mode Power Transistor

V_{DS} , 150 V
$R_{DS(on)}$, 6 mΩ max

EPC2308
Package size: 3 x 5 mm

How to Use 1% DC_{Factor} in Applications

- A converter featuring 100 V max-rated GaN FETs operating at 1 MHz (period = 1 µs)
- It shows a repetitive 6.8 V_{GS} spike measured with 10 ns pulse width.
- 10 ns/1 µs= 1% ≤ 1% and V_{GS}=6.8 V < 7 V → Low reliability risk

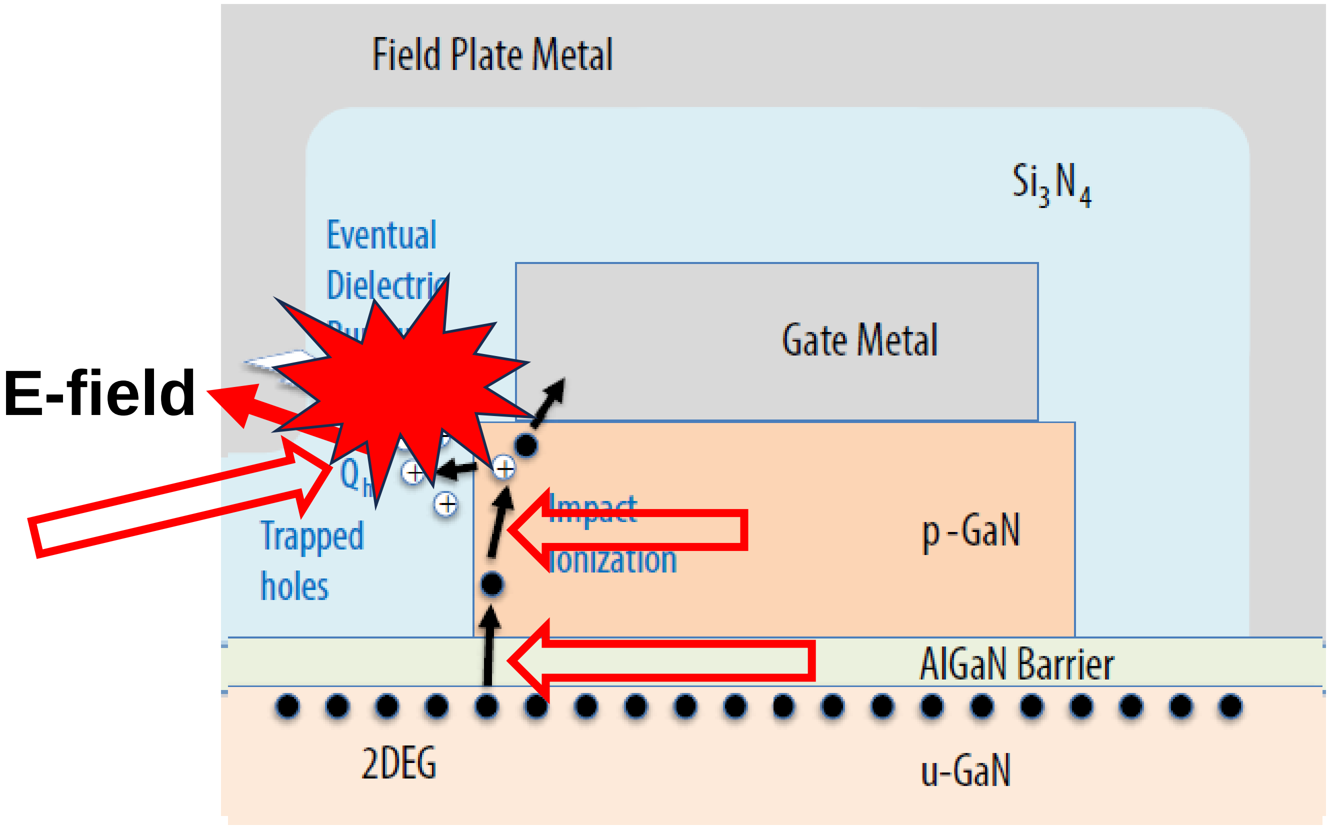
Conclusions

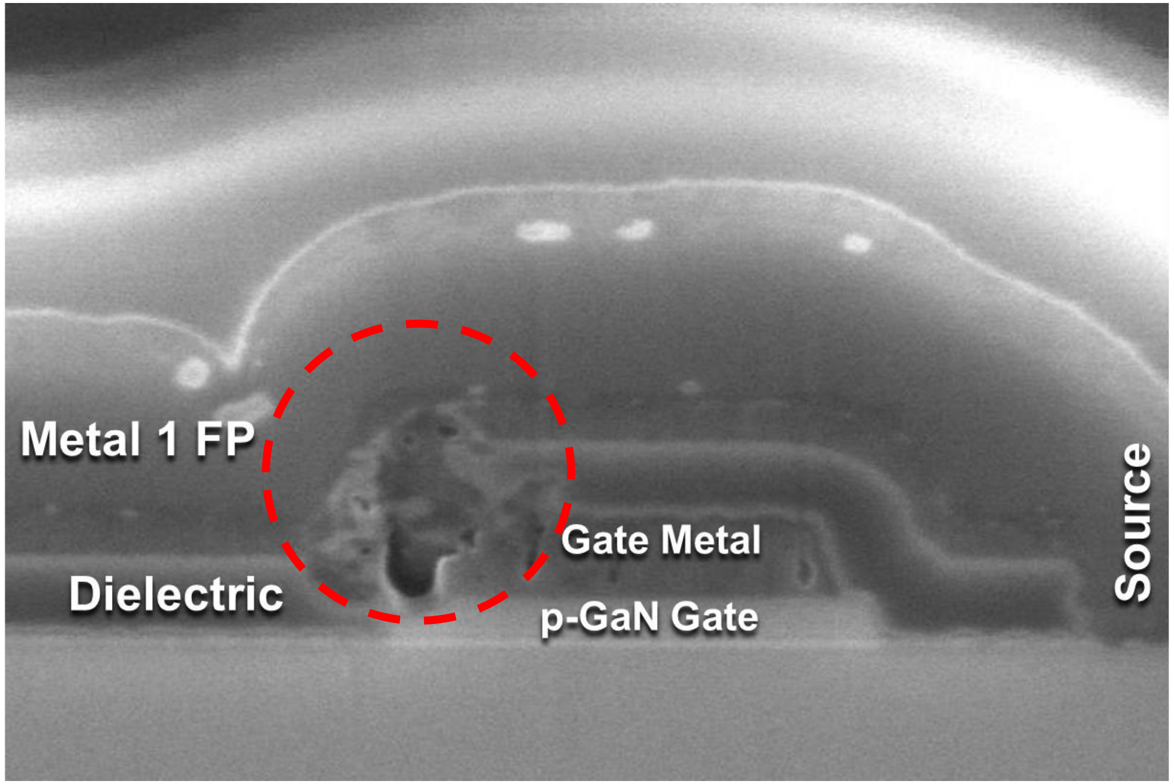
- Repetitive transient overvoltage ringing is commonly observed in GaN-based applications.
- The wearout mechanisms responsible for gate and drain stress are identified and the corresponding lifetime models are derived.
- A 1% duty cycle-based repetitive overvoltage specification is developed for both gate turn-on transients and drain turn-off transients.
- Different switching circuits are developed to validate the proposed overvoltage specifications for gate and drain.

Thank You!

Backup

Gate Wearout Mechanism: Impact Ionization





Lifetime Model for Gate Wearout Mechanism

MTTF: Mean Time to Failure

$$MTTF = \frac{Q_c}{G}$$

Q_C is the critical charge density of SiN layer

Q is the electron-hole pair generation rate from impact ionization

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

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

Impact Ionization coefficient

$$\alpha_n = a_n e^{-\left(\frac{b_n}{E}\right)^m}$$

Temperature dependence of impact ionization coefficient

$$a_n = a_{n.0}(1 + c\Delta T)$$

$$b_n = b_{n.0}(1 + d\Delta T)$$

$$MTTF = \frac{qQ_c}{J_n a_{n.0}(1 + c\Delta T)} e^{\left(\frac{b_{n.0}(1+d\Delta T)}{E}\right)^m}$$