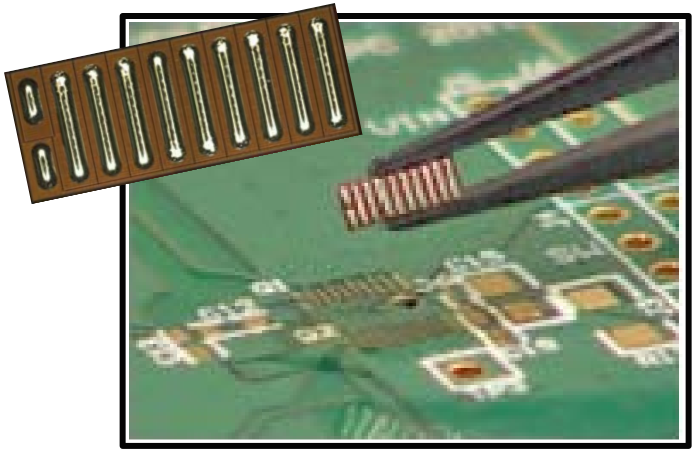
GaN is Crushing Silicon



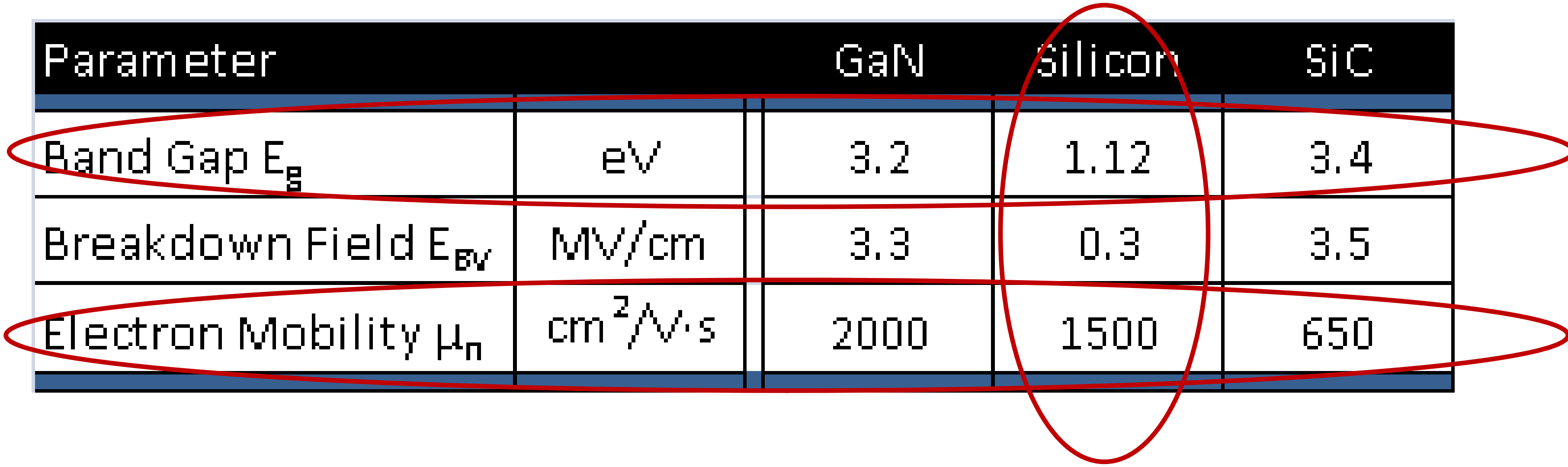
Agenda

- How eGaN® FETs work
- Hard Switched DC-DC converters
  - High Efficiency point-of-load converter
  - Envelope Tracking buck converter
- Resonant DC-DC Converters
  - Bus Converter
  - ZVS Class D Wireless Power Transmission
- A Look into the Future
- Q & A

Power Switch Wish List

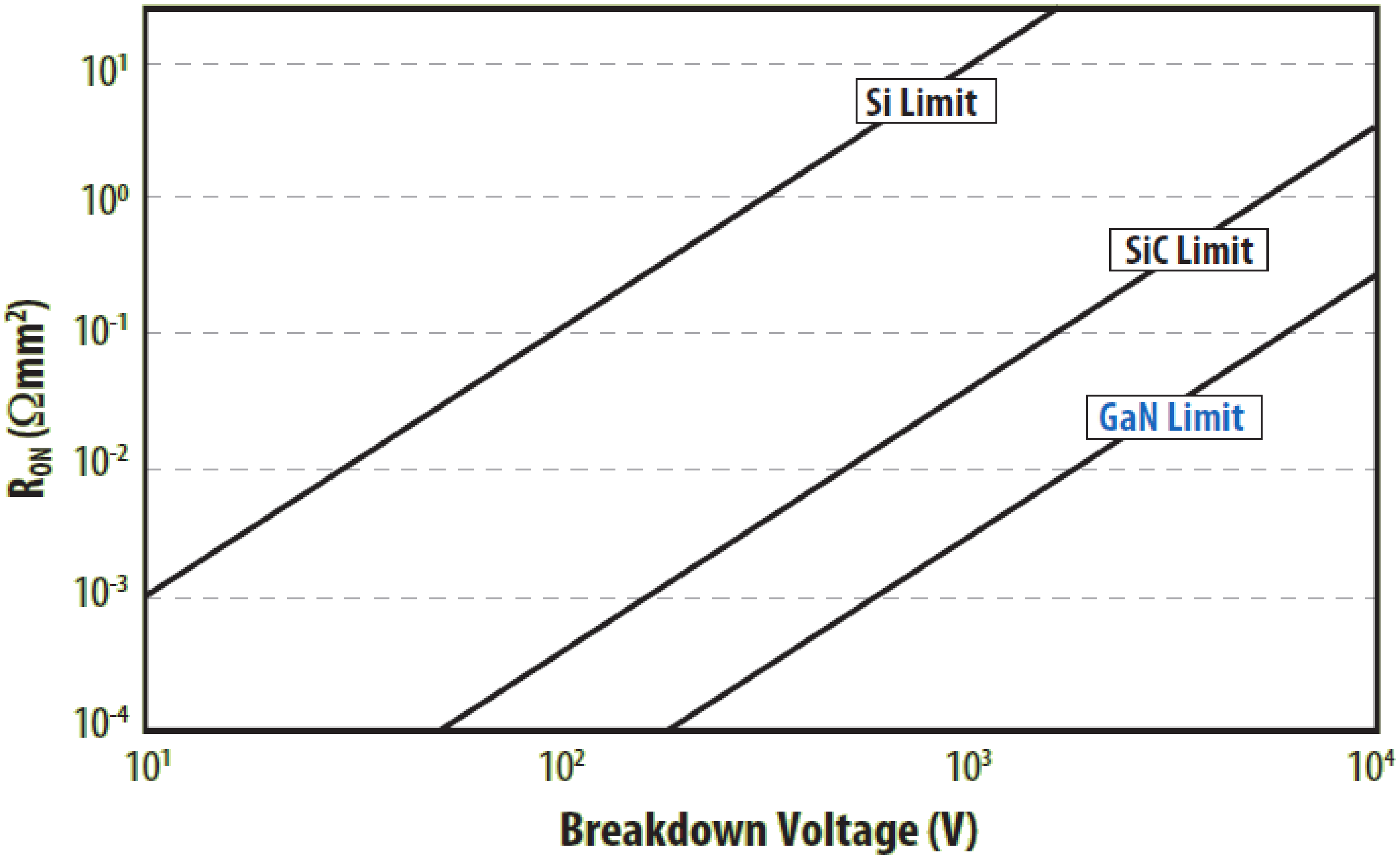
- Lower On Resistance
- Faster
- Less Capacitance
- Smaller
- Lower Cost

Material Comparison



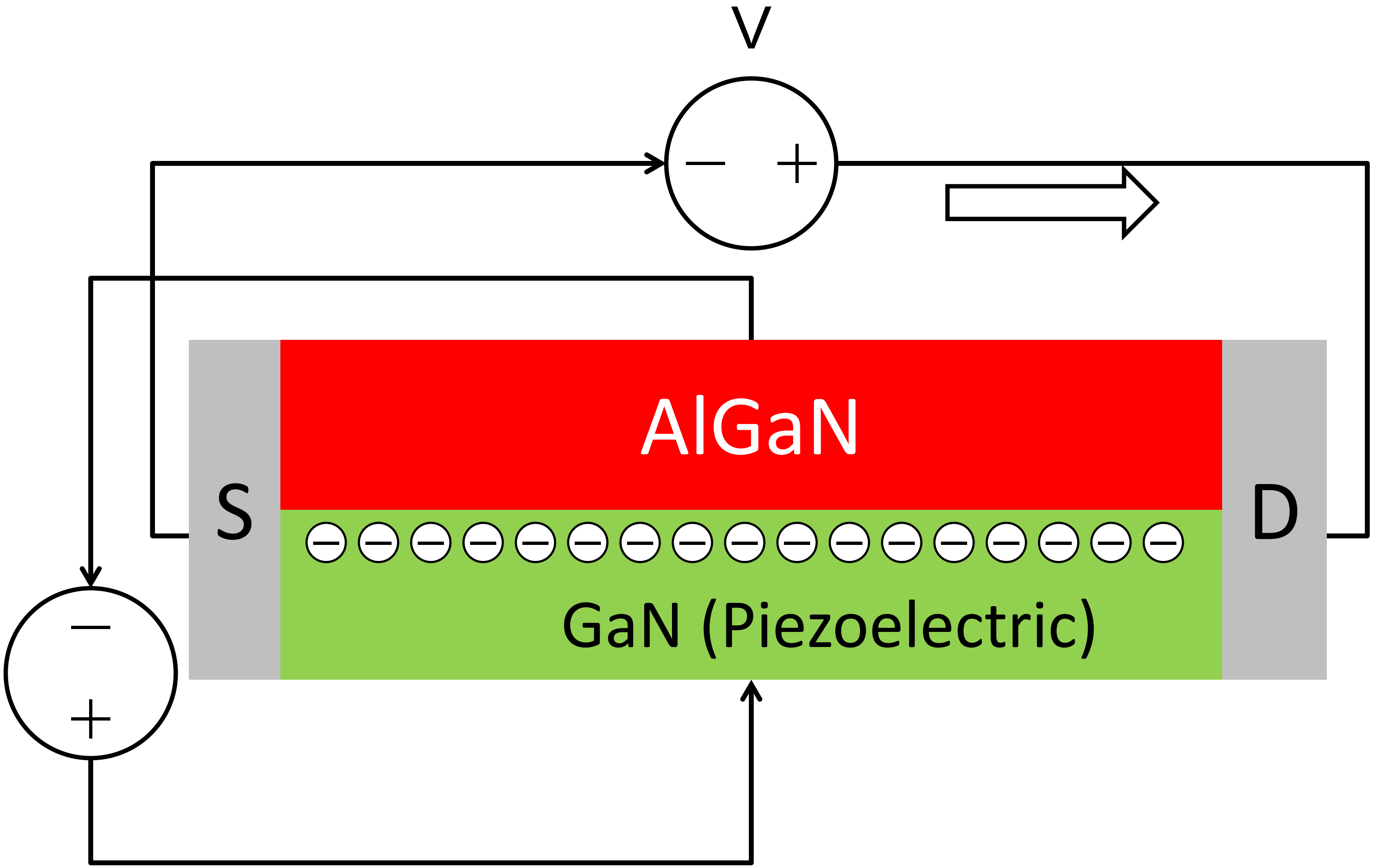
Parameter		GaN	Silicon	SiC
Band Gap E_g	eV	3.2	1.12	3.4
Breakdown Field E_{BV}	MV/cm	3.3	0.3	3.5
Electron Mobility μ_n	$cm^2/V{\cdot}s$	2000	1500	650

State of the Art

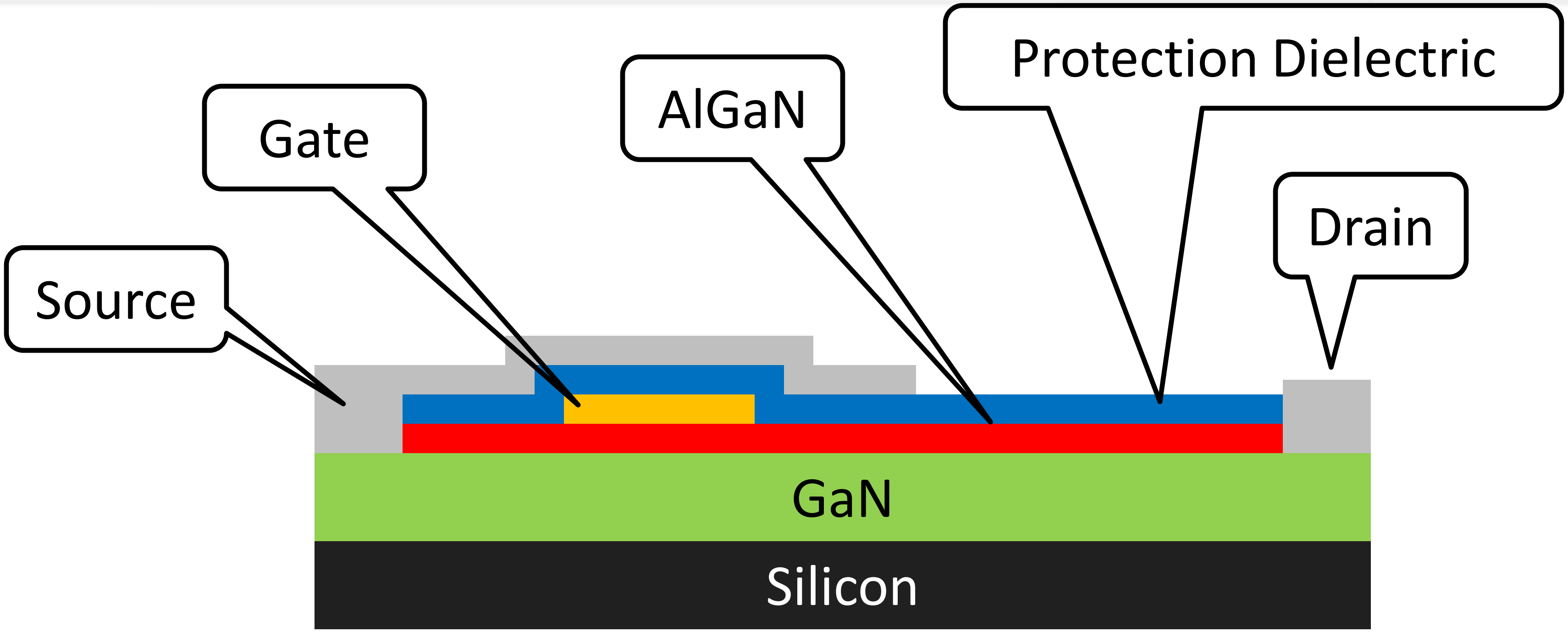


Theoretical on-resistance vs. blocking voltage capability for silicon, silicon carbide, and gallium nitride.

GaN Magic

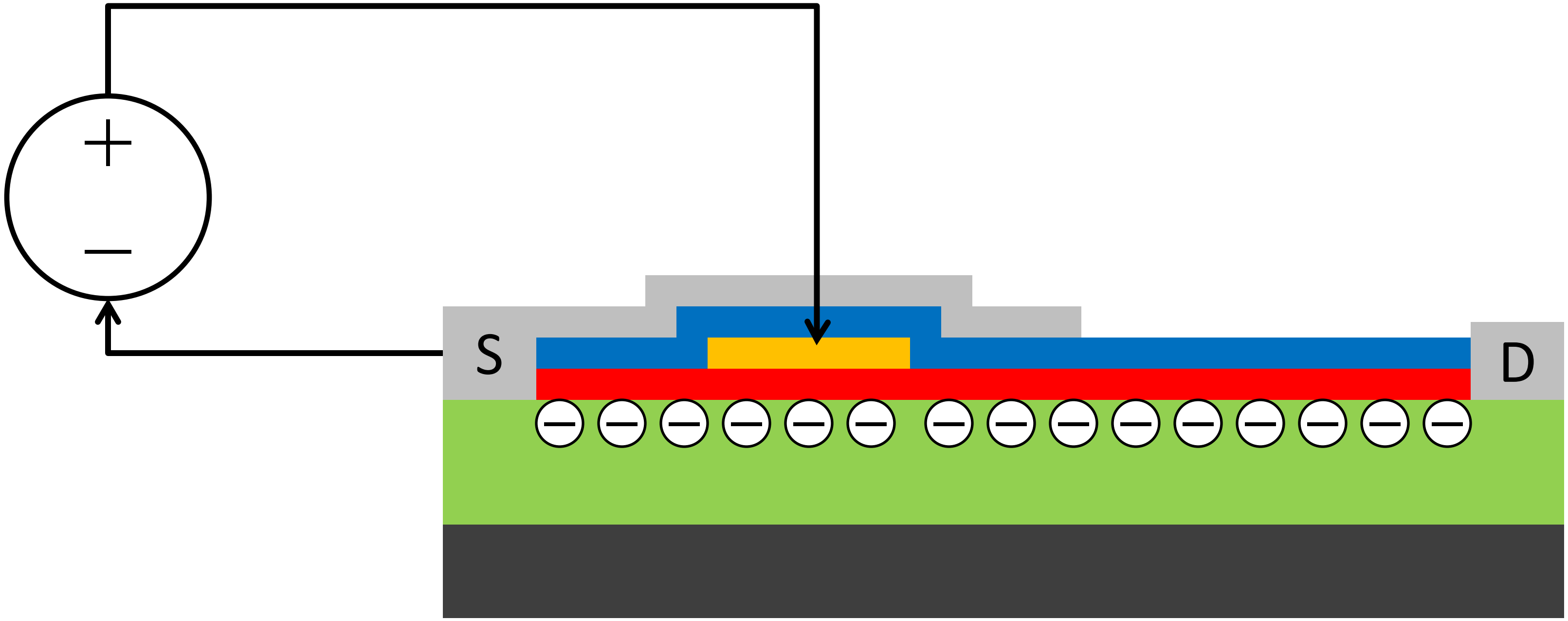


Device Construction Concept



Forms the foundation for a Depletion Mode device

Enhancement Mode – eGaN FET

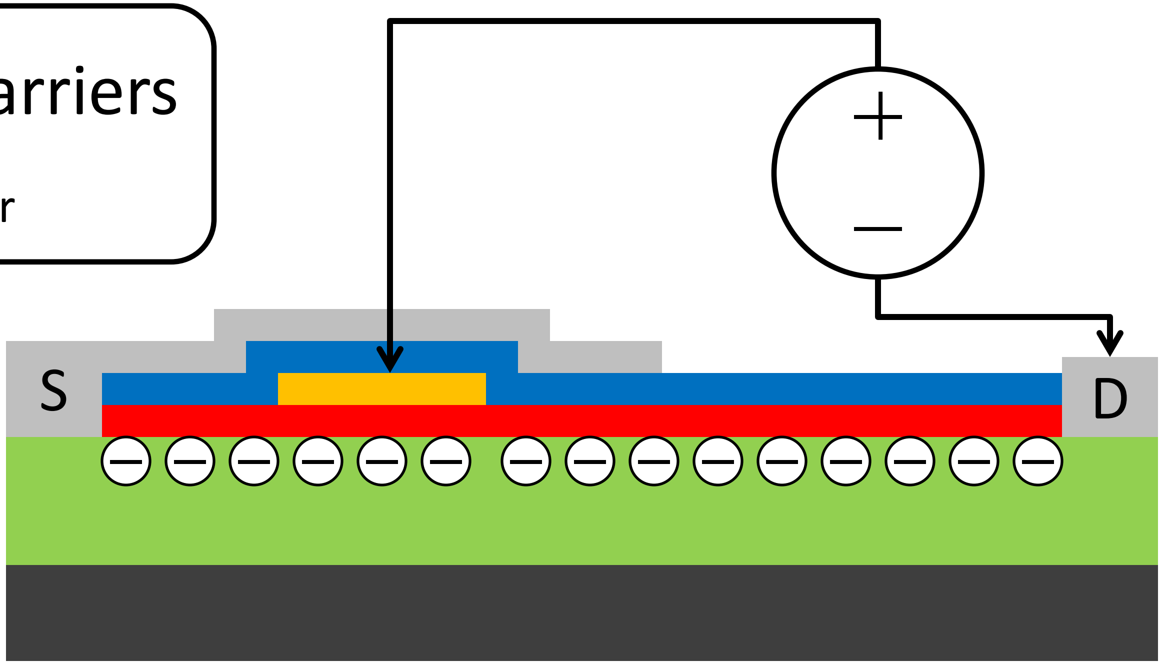


A positive voltage from Gate-To-Source establishes an electron gas under the gate

Body Diode?

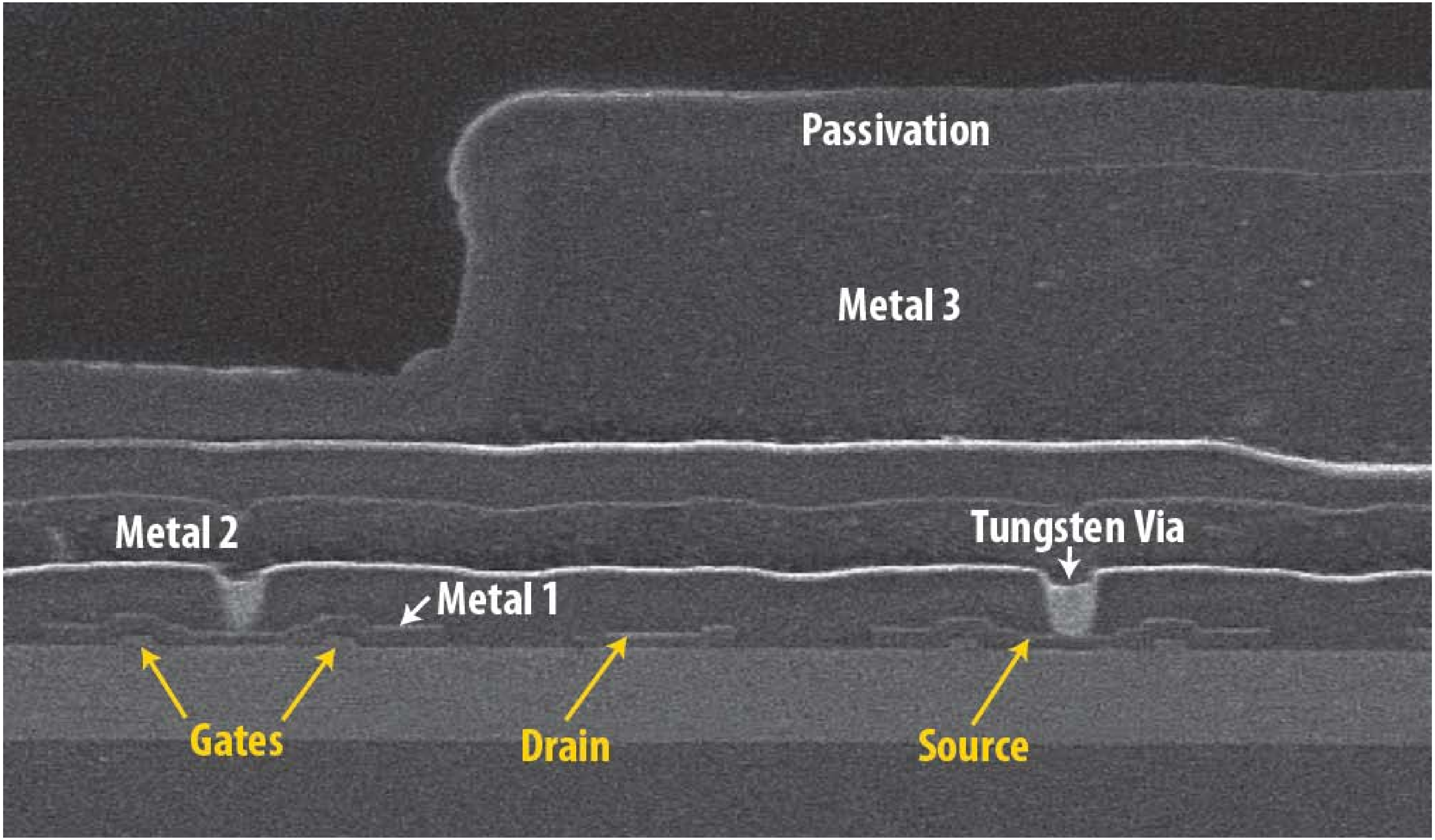
No Minority Carriers

= Zero Q_{rr}

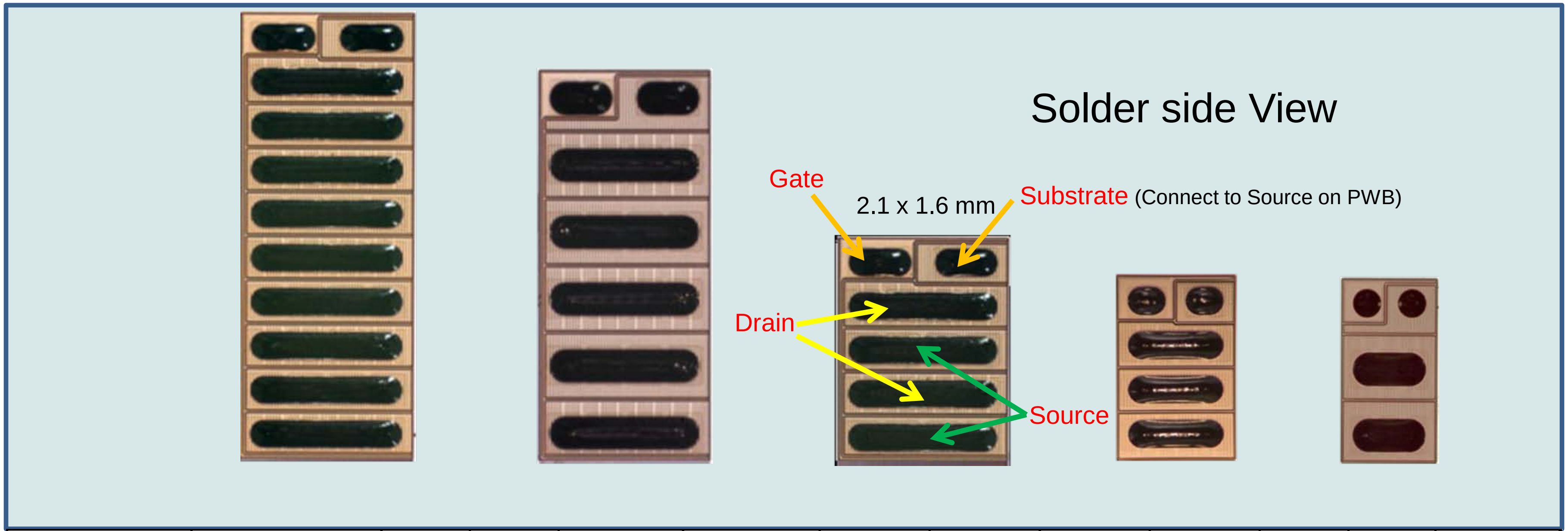


A positive voltage from Gate-To-Drain also establishes an electron gas under the gate enabling reverse conduction

Cross Section of an eGaN FET



eGaN FET Low Voltage Product Family



Solder side View

Gate

2.1 x 1.6 mm

Substrate (Connect to Source on PWB)

Drain

Source

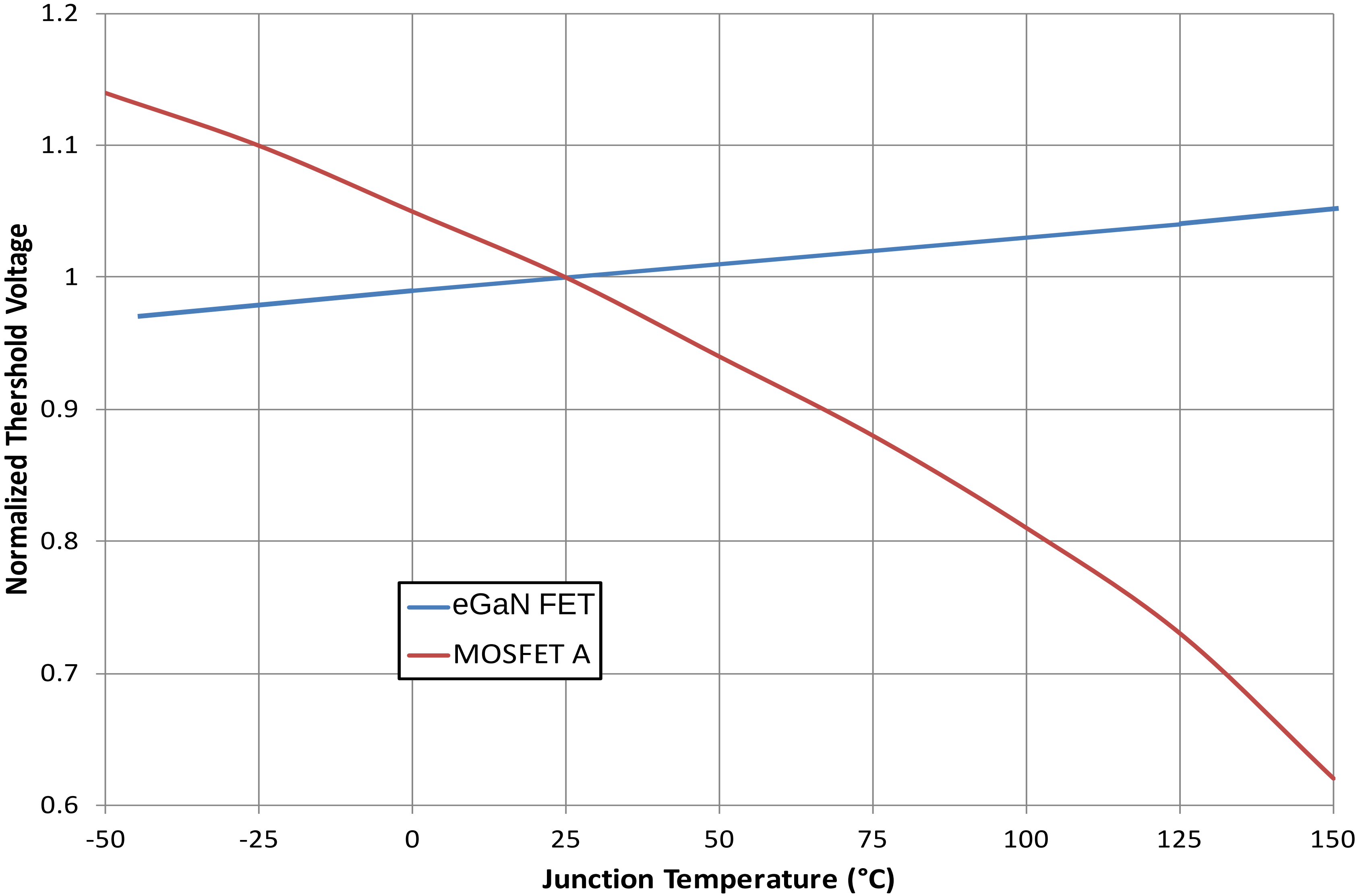
Part Number	Package (mm)	V_{DS} (V)	V_{GS} (V)	$R_{DS(on)}$ @5V (mΩ)	Q_G @5 V Typ. (nC)	Q_{GS} Typ. (nC)	Q_{GD} Typ. (nC)	R_G Typ. (Ω)	V_{th} Typ. (V)	Q_{RR} (nC)	I_D (A)	T_J Max. (°C)
EPC2015	LGA 4.1x1.6	40	6	4	10.5	3	2.2	0.6	1.4	0	33	150
EPC2014	LGA 1.7x1.1	40	6	16	2.5	0.67	0.48	0.6	1.4	0	10	150
EPC2001	LGA 4.1x1.6	100	6	7	8	2.3	2.2	0.6	1.4	0	25	125
EPC2016	LGA 2.1x1.6	100	6	16	4.1	0.93	0.75	0.6	1.4	0	11	125
EPC2007	LGA 1.7x1.1	100	6	30	2.1	0.5	0.6	0.6	1.4	0	6	125
EPC2010	LGA 3.6x1.6	200	6	25	5	1.3	1.7	0.6	1.4	0	12	125
EPC2012	LGA 1.7x0.9	200	6	100	1.5	0.33	0.57	0.6	1.4	0	3	125

Ultra High Frequency eGaN® FETs

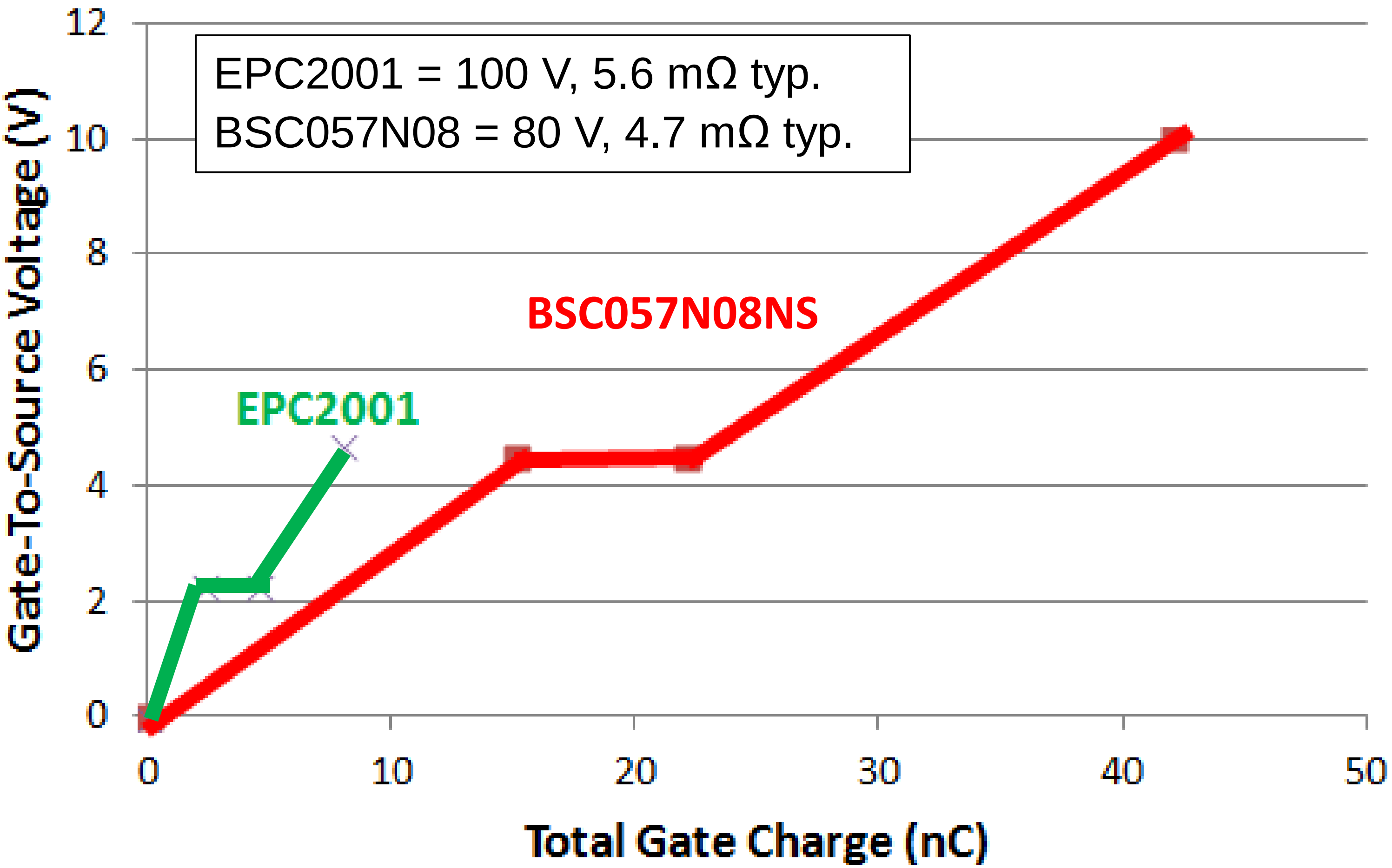
EPC Part No.	**BV (V)**	**Max. $R_{DS(ON)}$ (mΩ) (V_{GS} = 5V, I_D = 0.5 A)**	**Min. Peak Id (A) (Pulsed, 25 °C, T_{pulse} = 300 µs)**	Typical Charge (pC)					**Typical Capacitance (pF) (V_{DS} = 20 V; V_{GS} = 0 V)**		
				Q_G	**Q_{GD}**	**Q_{GS}**	**Q_{OSS}**	**Q_{RR}**	**C_{ISS}**	**C_{OSS}**	**C_{RSS}**
EPC8004	40	125	7.5	358	31	110	493	0	45	17	0.4
EPC8007	40	160	6	302	25	97	406	0	39	14	0.3
EPC8008	40	325	2.9	177	12	67	211	0	25	8	0.2
EPC8009	65	138	7.5	380	36	116	769	0	47	17	0.4
EPC8005	65	275	3.8	218	18	77	414	0	29	9.7	0.2
EPC8002	65	530	2	141	9.4	59	244	0	21	5.9	0.1
EPC8003	100	300	5	315	34	110	1100	0	38	18	0.2
EPC8010	100	160	7.5	354	32	109	1509	0	47	18	0.2

* Preliminary Data – Subject to Change without Notice

Threshold vs. Temperature

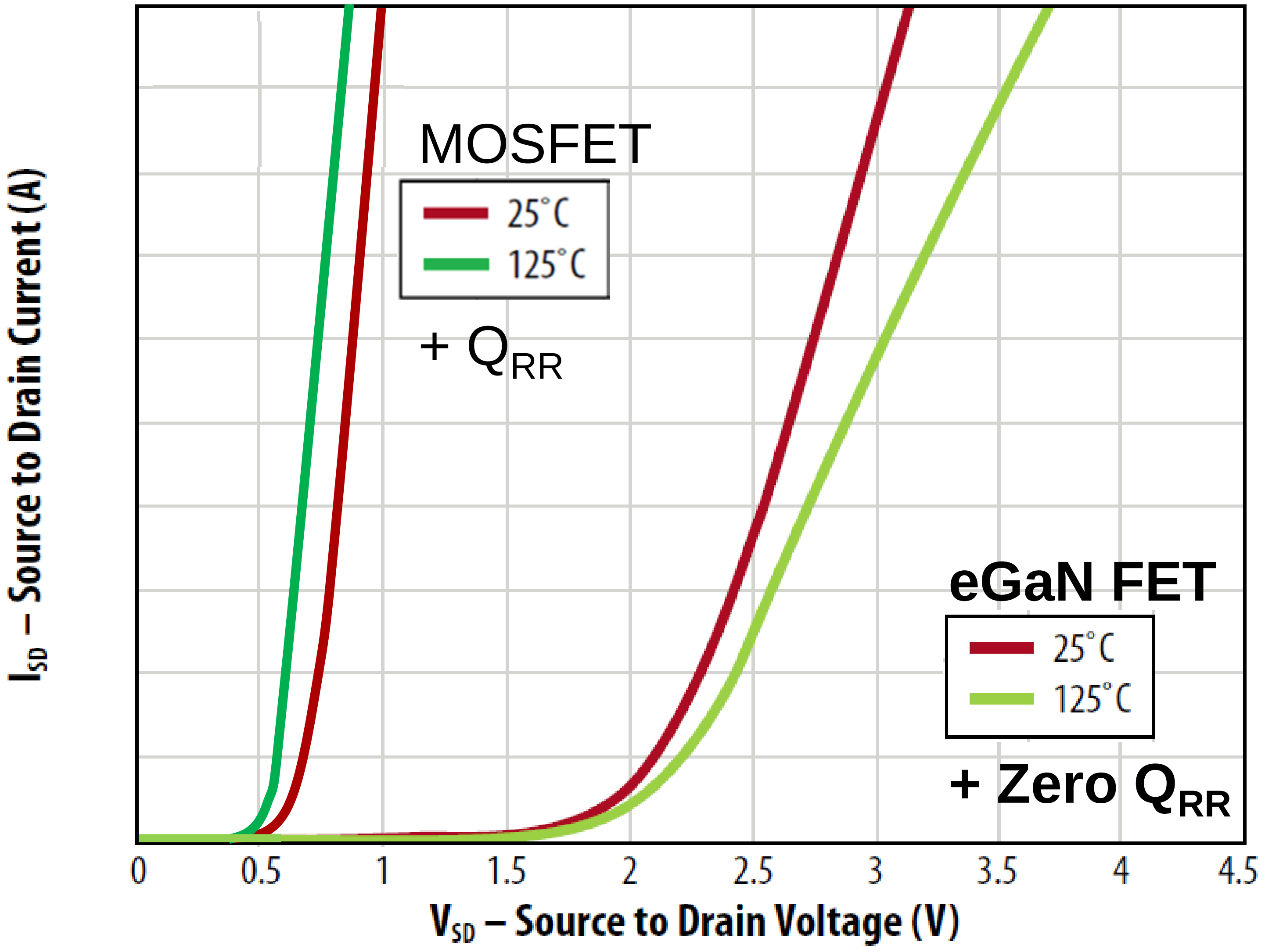


Total Gate Charge

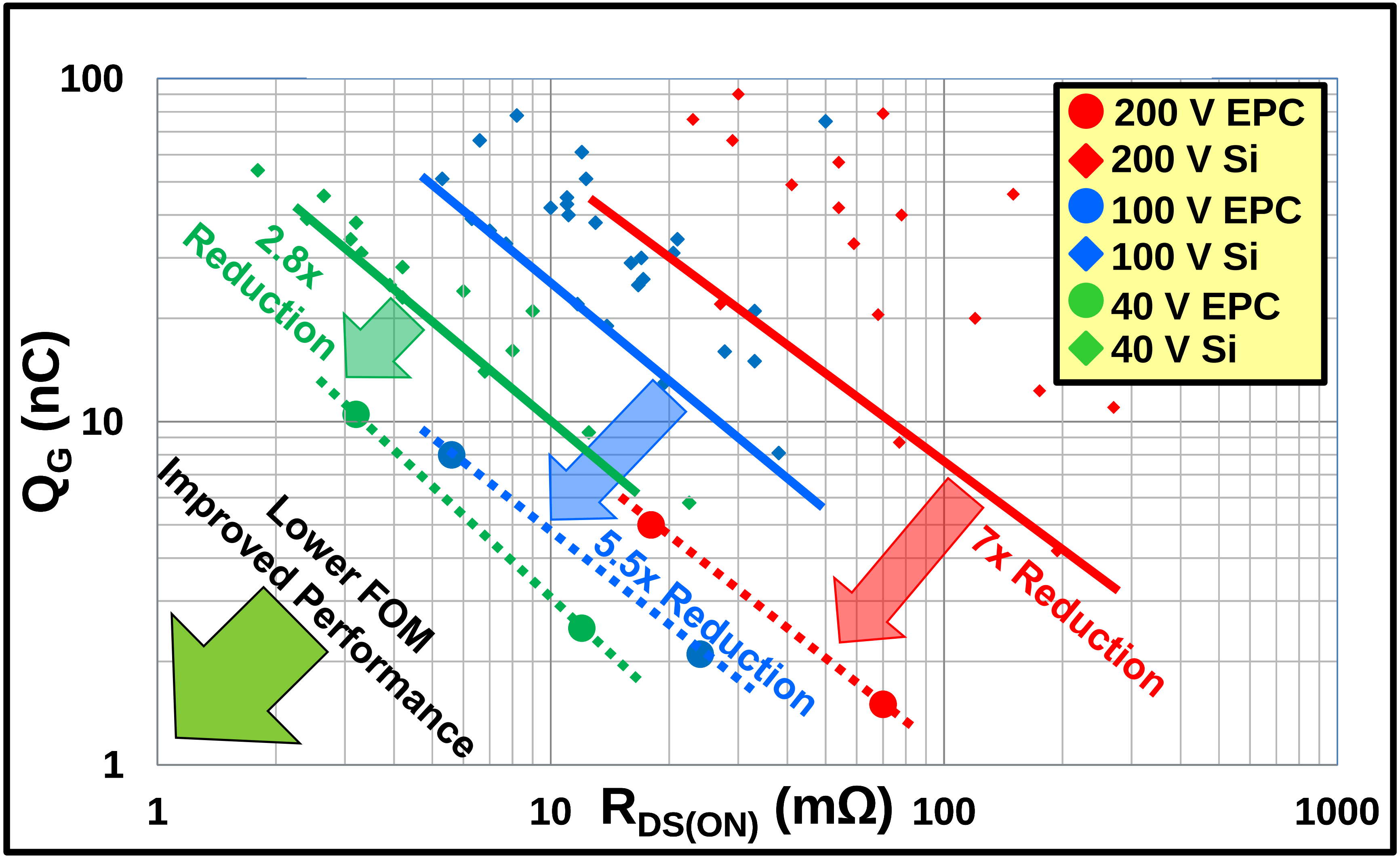


EPC2001 = 100 V, 5.6 mΩ typ.
BSC057N08 = 80 V, 4.7 mΩ typ.

eGaN FET Reverse Conduction



Conduction Figure of Merit



eGaN FET Loss Mechanisms

Like A MOSFET

- I^2R Conduction Loss
- Capacitive Switching Losses
- Gate Drive Losses
- V×I Switching Loss

Not Like A MOSFET

- High Reverse Conduction Loss
- No Body Diode Reverse Recovery Loss

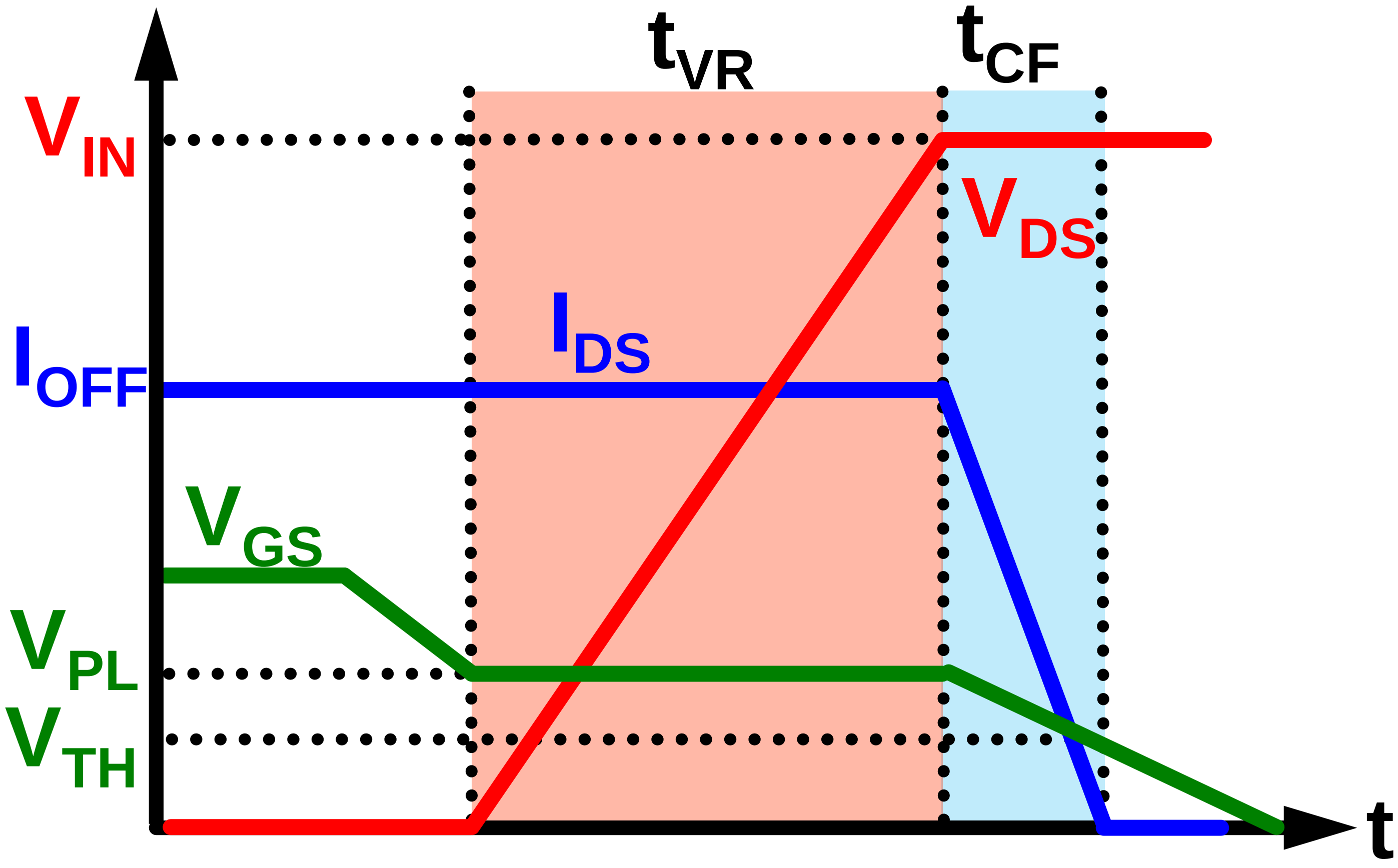
Can be much, much better than comparable silicon MOSFET

Design Examples

Design Example

- Hard-Switched DC-DC Conversion
  - Buck Converter
  - Envelope Tracking
- Resonant DC-DC Conversion
  - Resonant Bus Converter
  - Wireless Power

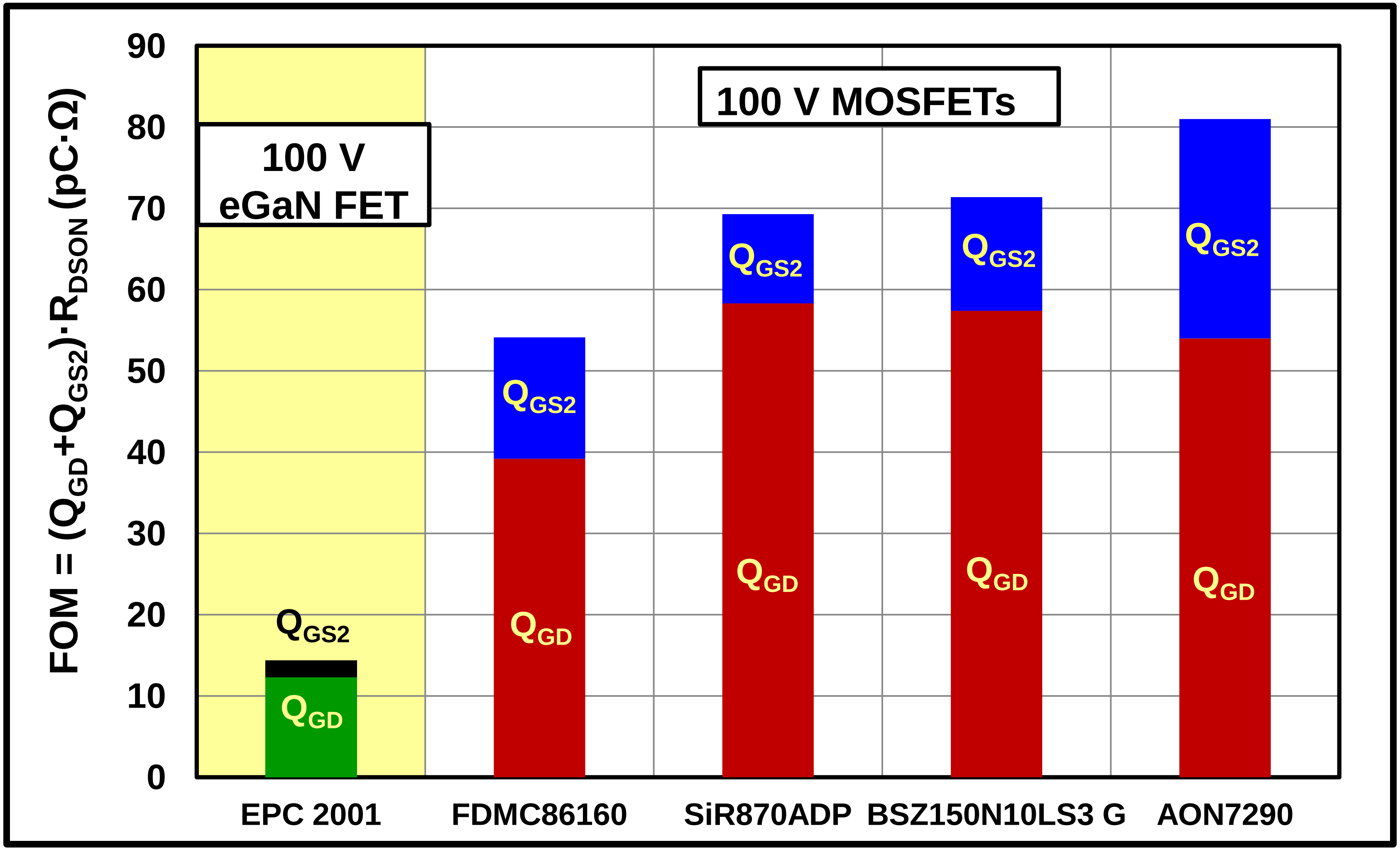
Ideal Hard Switching



$$P_{t_{VR}} \approx \frac{V_{IN} \cdot I_{OFF} \cdot Q_{GD} \cdot f_{SW}}{2 \cdot I_G}$$

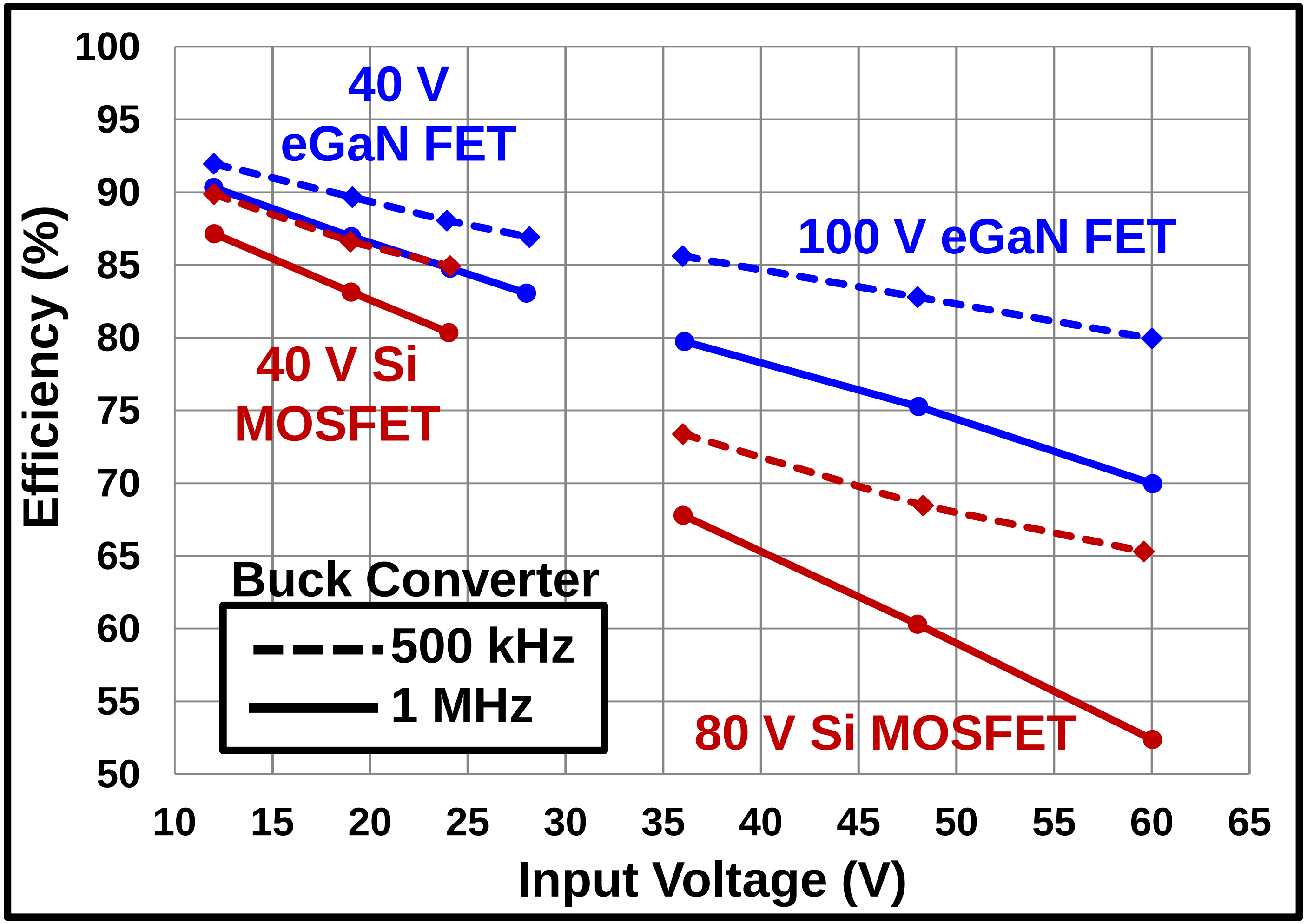
$$P_{t_{CF}} \approx \frac{V_{IN} \cdot I_{OFF} \cdot Q_{GS2} \cdot f_{SW}}{2 \cdot I_G}$$

100 V Device Comparison



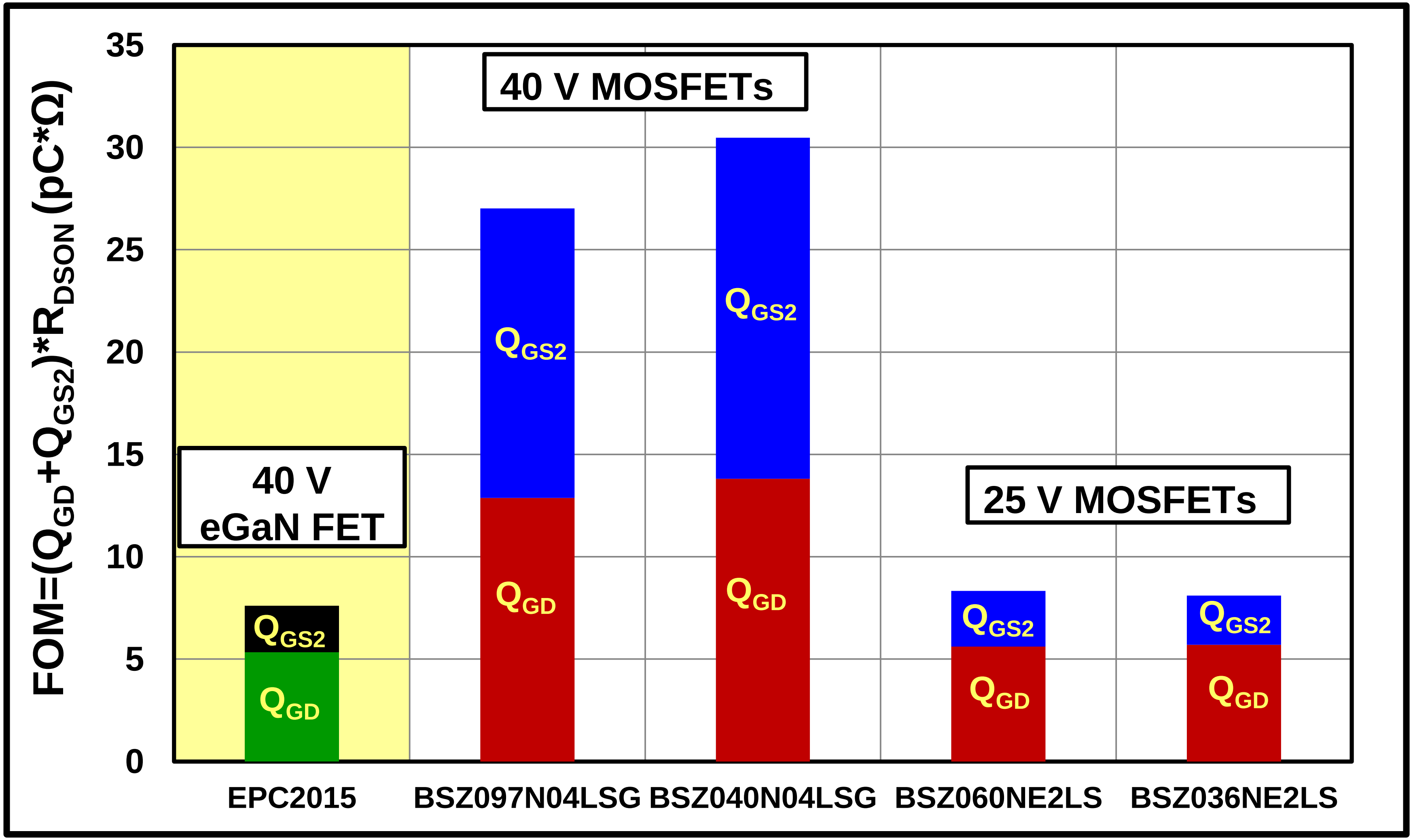
V_{DS}=0.5*V_{DS}, I_{DS}= 10 A

eGaN FET vs MOSFET



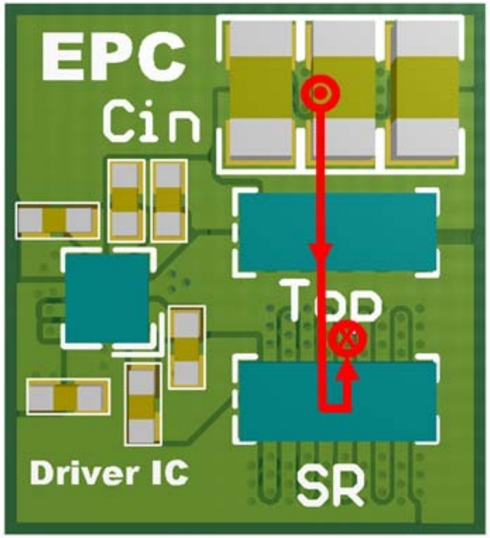
Measured Efficiency V_{OUT}=1.2 V I_{OUT}=10 A

Low Voltage Device Comparison



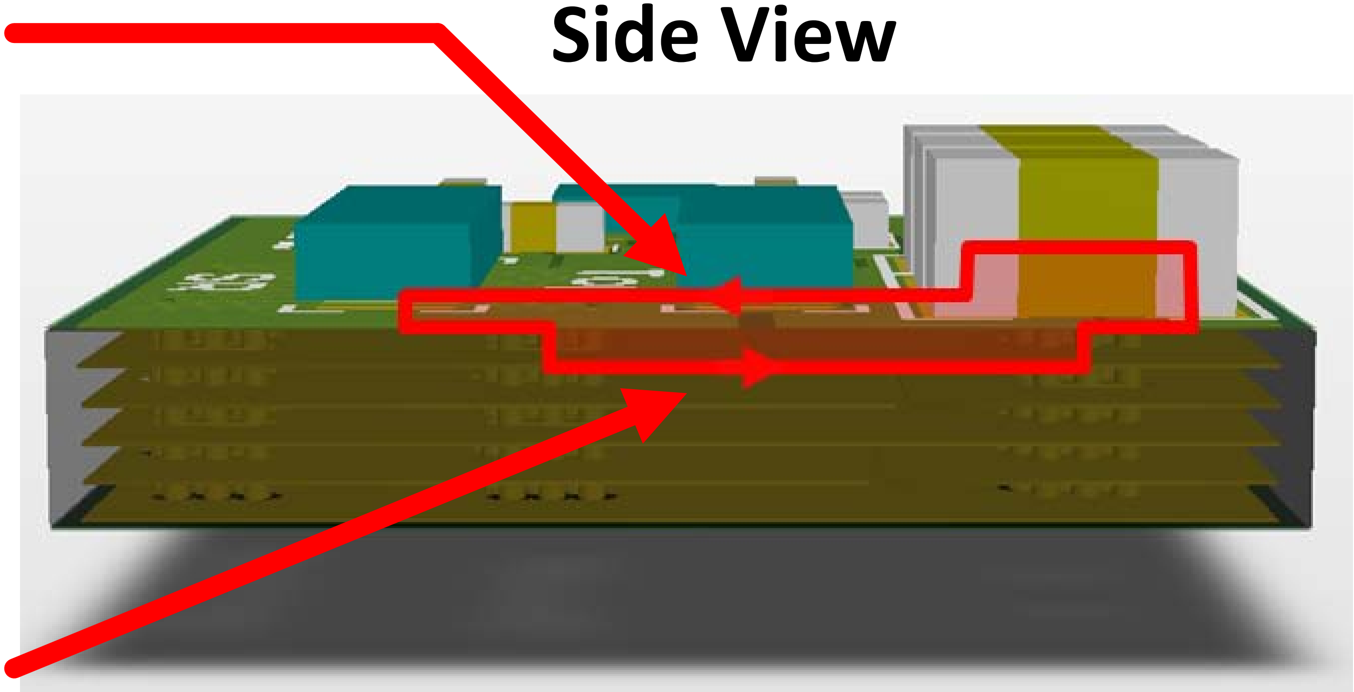
V_{DS}=12 V, I_{DS}= 20 A

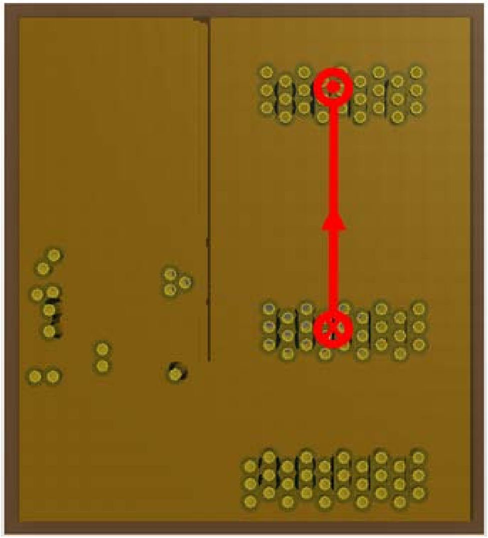
Optimal Layout



Top View

Side View

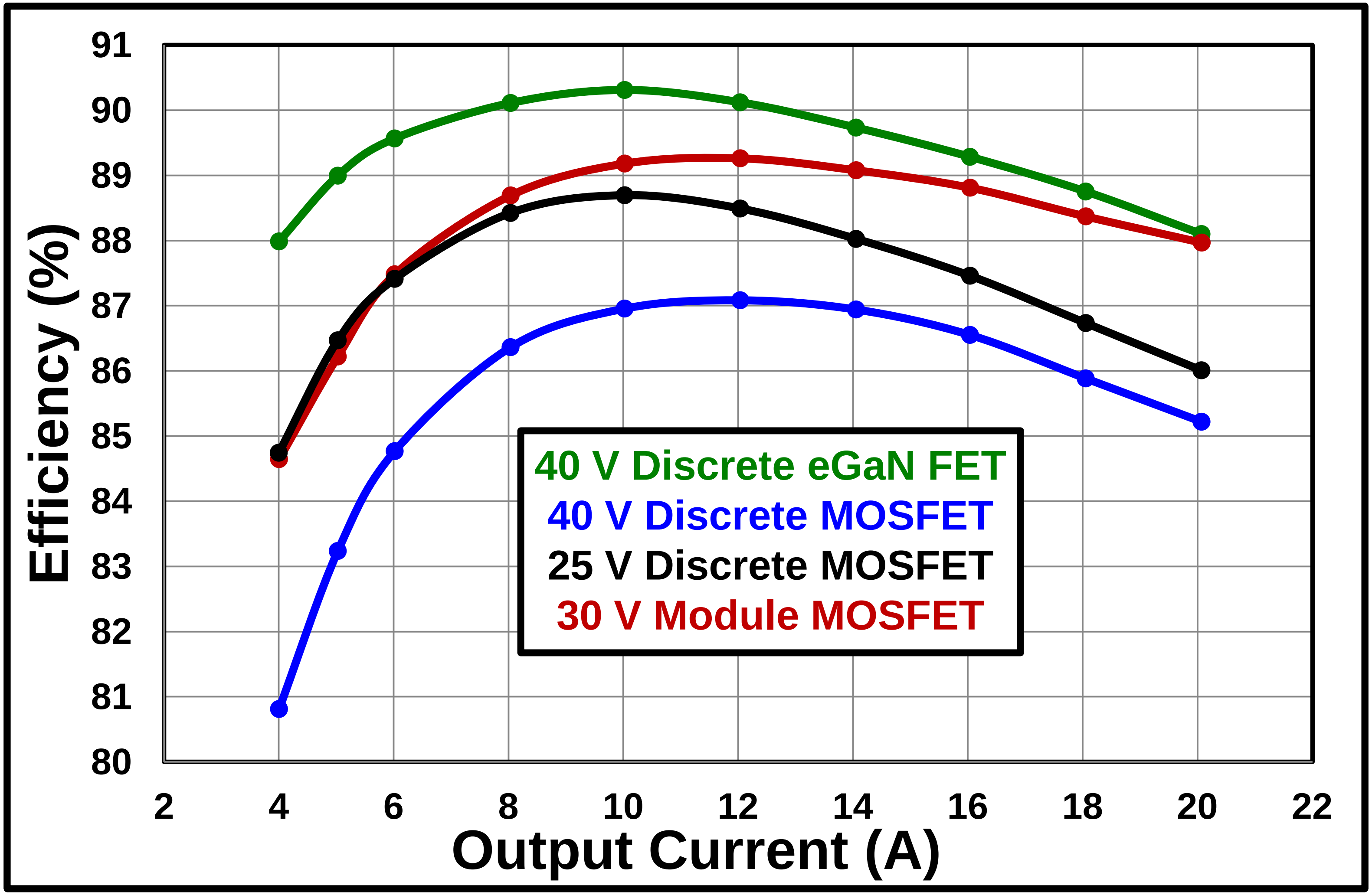




Top View
Inner Layer 1

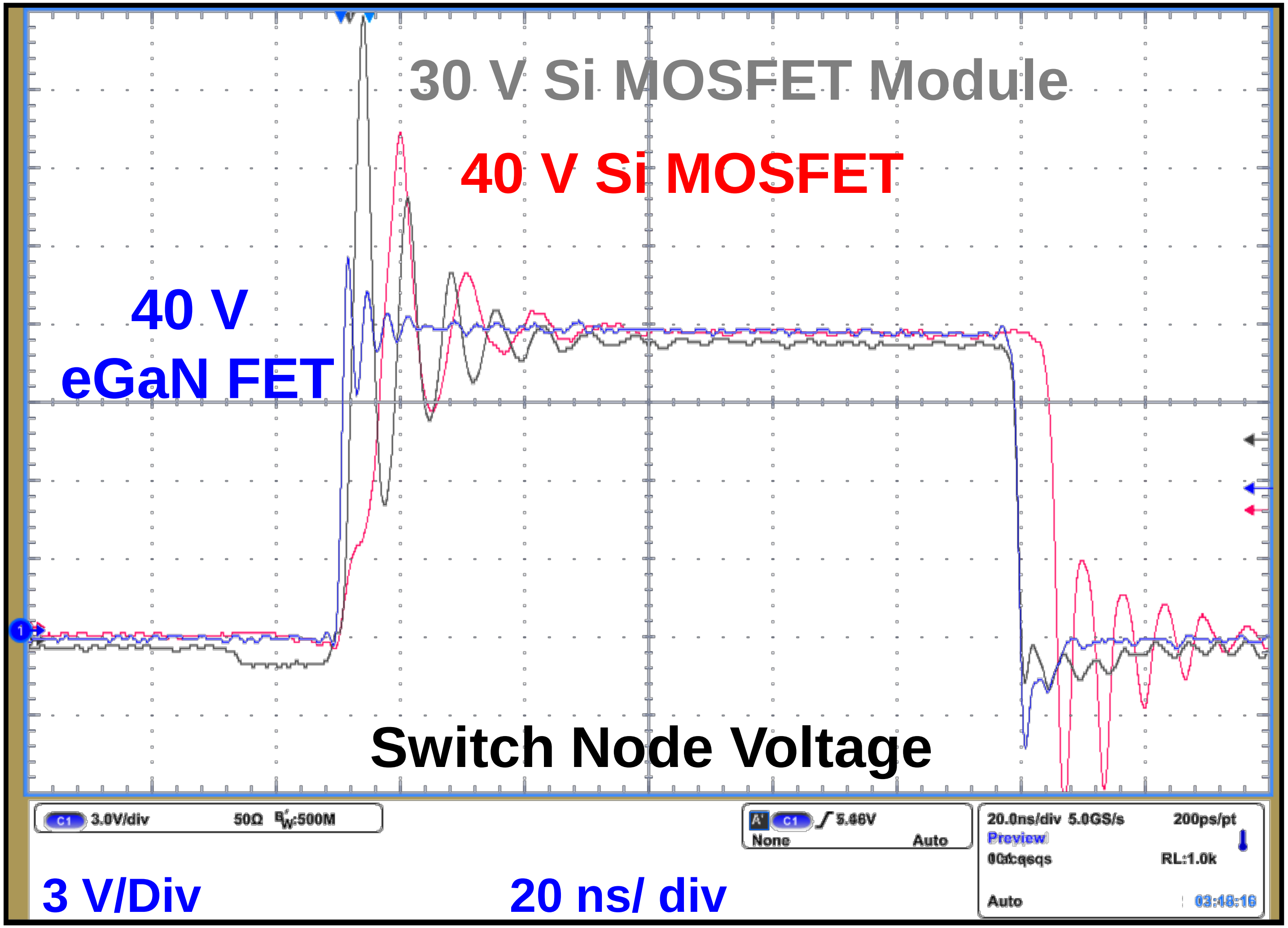
Ref: D. Reusch, J. Strydom, "Understanding the Effect of PCB Layout on Circuit Performance in a High Frequency Gallium Nitride Based Point of Load Converter," APEC 2013

eGaN FET vs. MOSFET Efficiency



V_{IN}=12 V V_{OUT}=1.2 V f_{sw}=1 MHz L=300 nH

Impact of Parasitics on Overshoot



30 V Si MOSFET Module

40 V Si MOSFET

40 V eGaN FET

Switch Node Voltage

3 V/Div

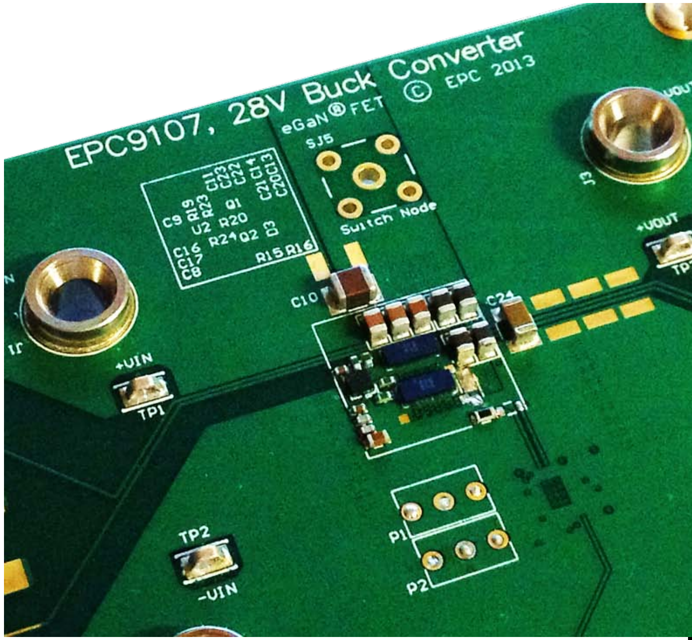
20 ns/ div

V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A f_{sw}=1 MHz L=300 nH eGaN FET T/SR: EPC2015

MOSFET T:BSZ097N04 SR:BSZ040N04 MOSFET Module: CSD97370Q5M

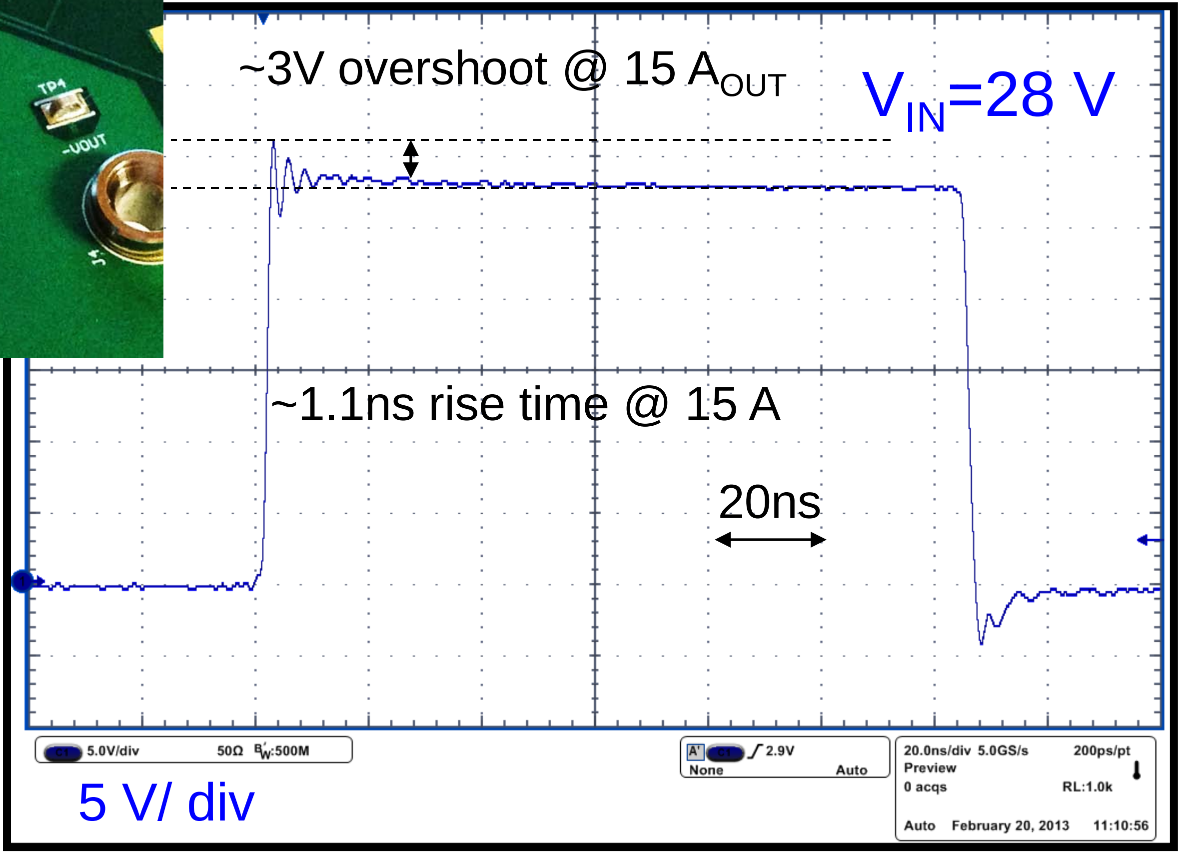
EPC9107 Demonstration Board

V_{IN}=12-28 V V_{OUT}=3.3 V
I_{OUT}=15 A f_{sw}=1 MHz
2 x EPC2015



Switching Node Voltage

V_{IN}=28 V, I_{OUT}=15 A


~3V overshoot @ 15 A_{OUT}

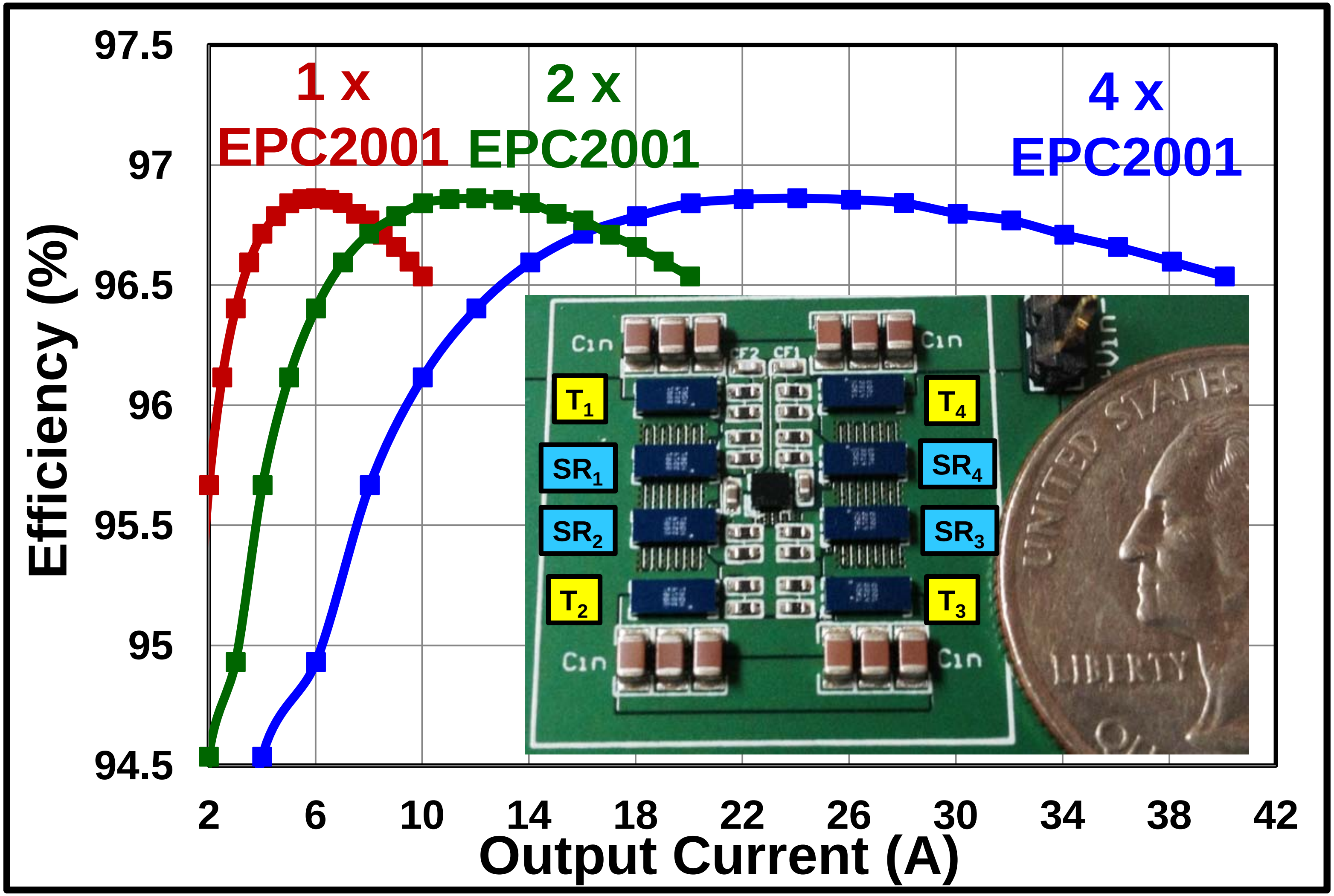
V_{IN}=28 V

~1.1ns rise time @ 15 A

20ns

5 V/ div

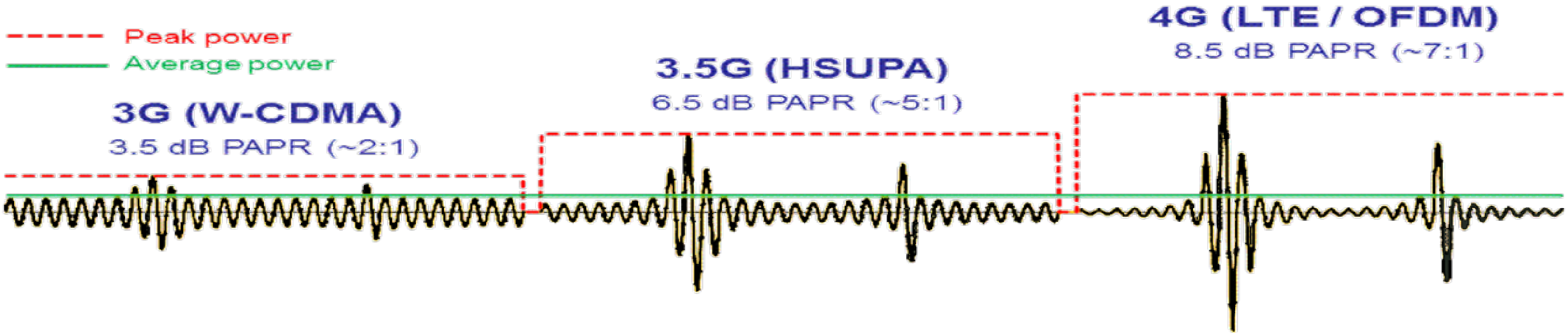
Higher Current?...Parallel

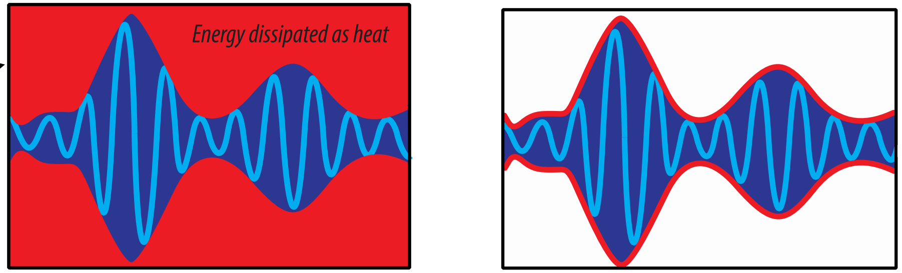


V_{IN}=48 V, V_{OUT}=12 V, f_{sw}=300 kHz

Envelope Tracking (ET)

Envelope Tracking





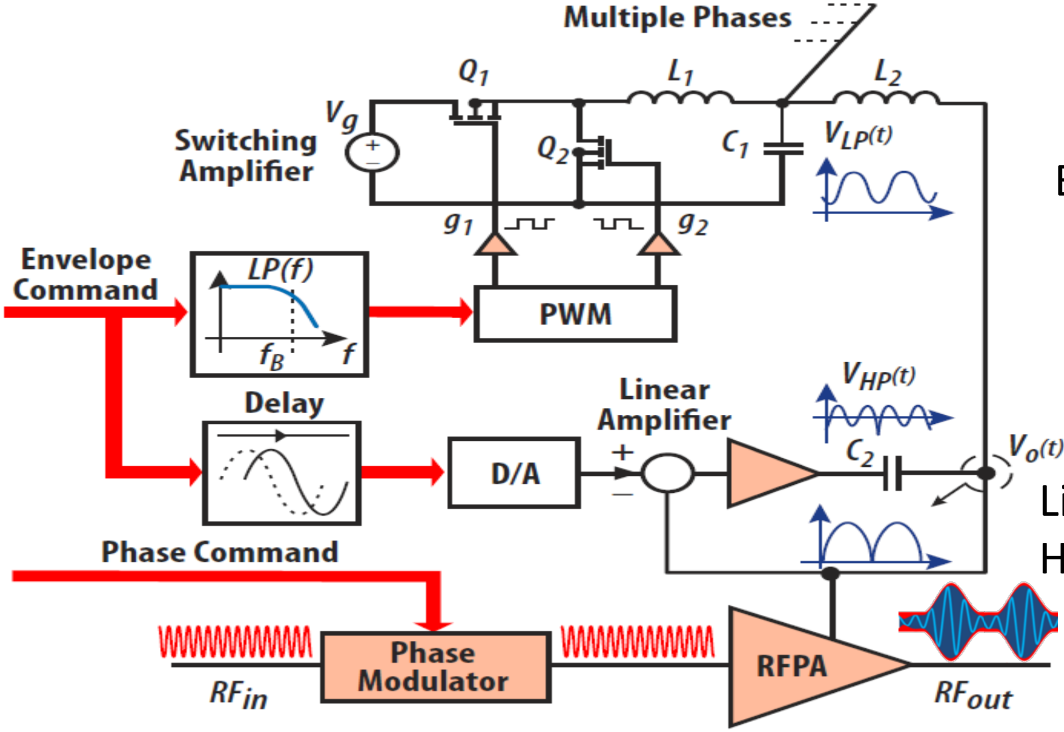
W/O ET **With ET**

Red represents wasted energy dissipated as heat

- **Envelope Tracking can *double* base station efficiency.**

Envelope Tracking Supply

- ET power supply topologies vary
  - Hybrid / linear-assisted Buck* (one option)

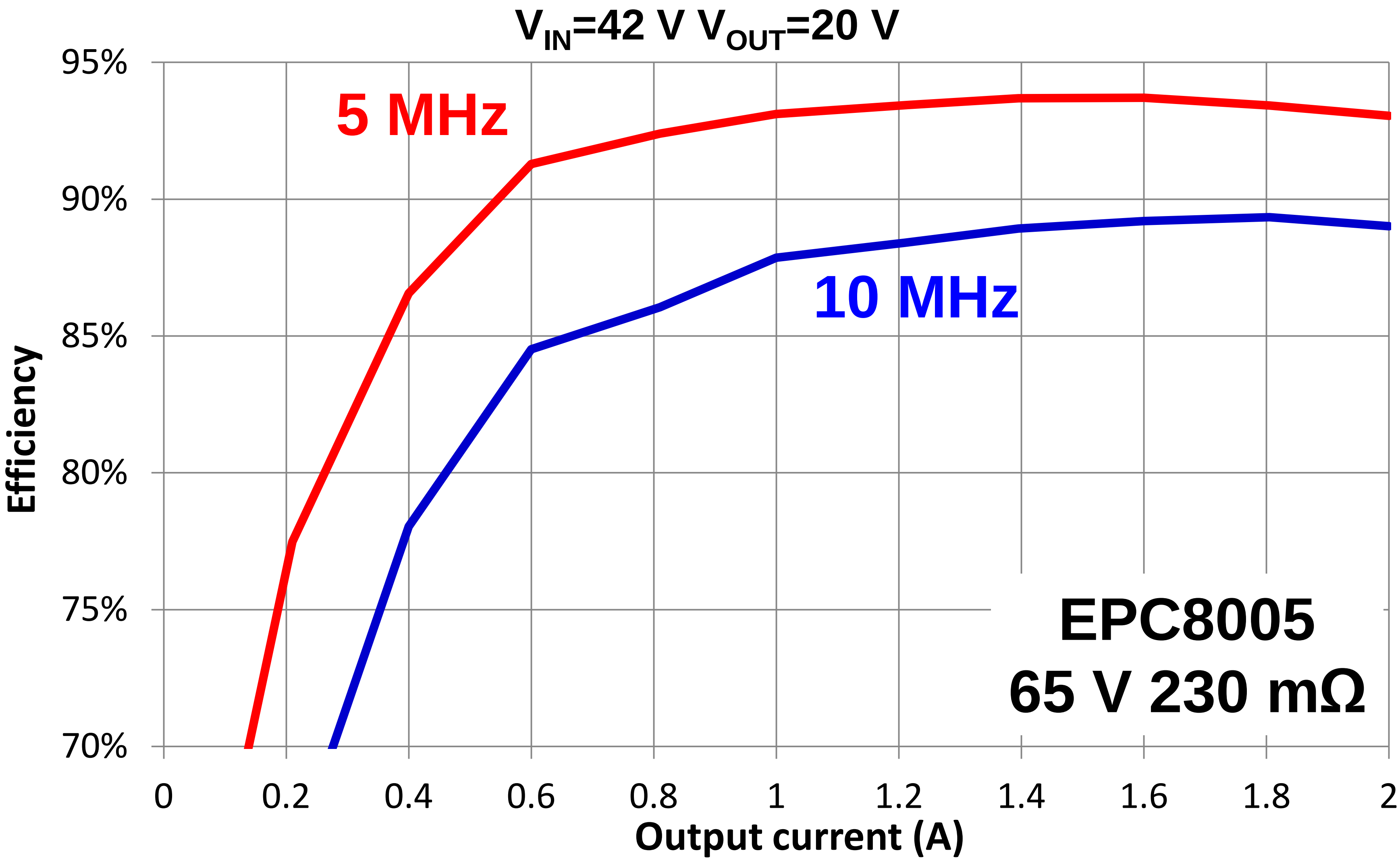


Buck ~10% Bandwidth
~ 90% Power

Linear AMP ~ 10% Power
Highest 90% of Bandwidth

* V. Yousefzadeh, et. al, "Efficiency optimization in linear-assisted switching power converters for envelope tracking in RF power amplifiers," ISCAS 2005

Efficiency

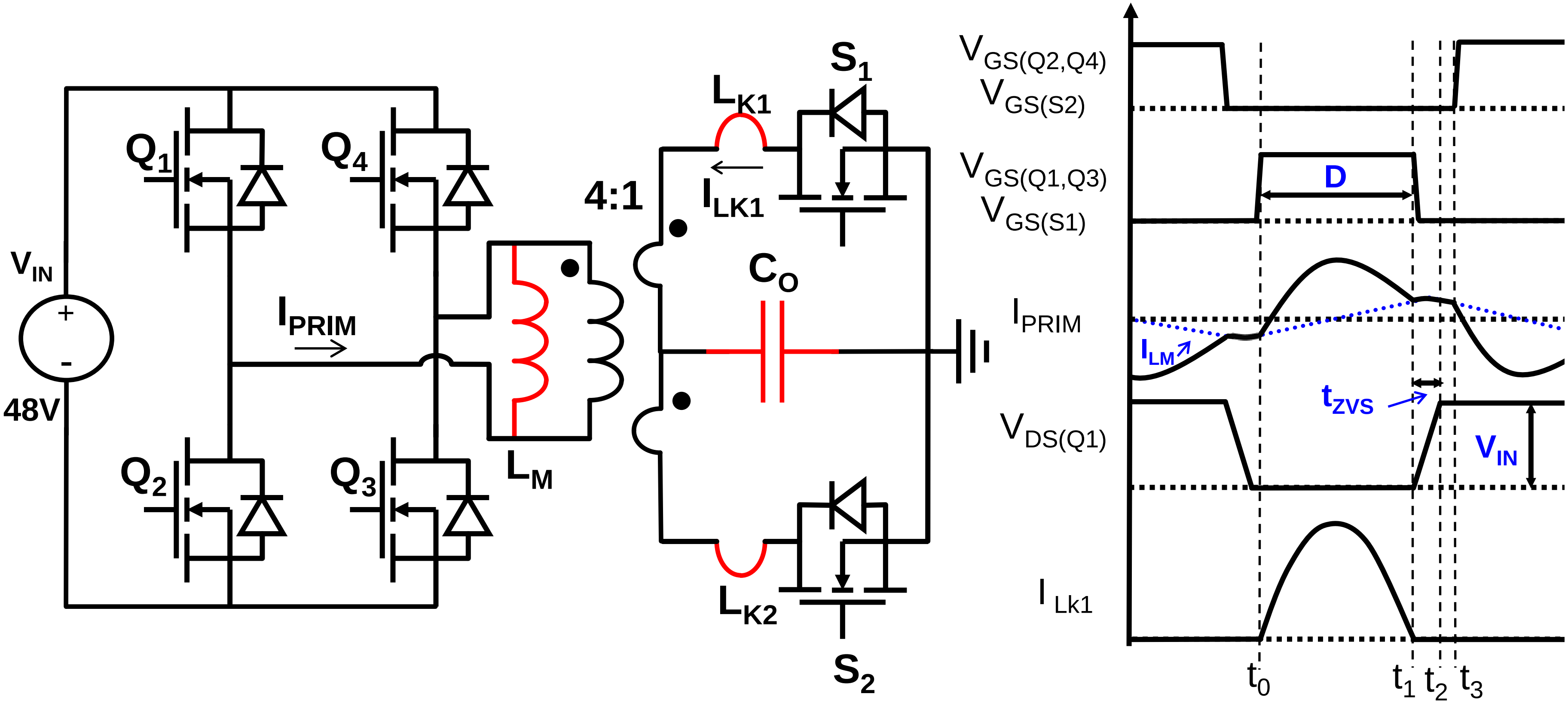


V_{IN}=42 V V_{OUT}=20 V
5 MHz
10 MHz
EPC8005
65 V 230 mΩ
Efficiency
95%
90%
85%
80%
75%
70%
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Output current (A)

Resonant Converters

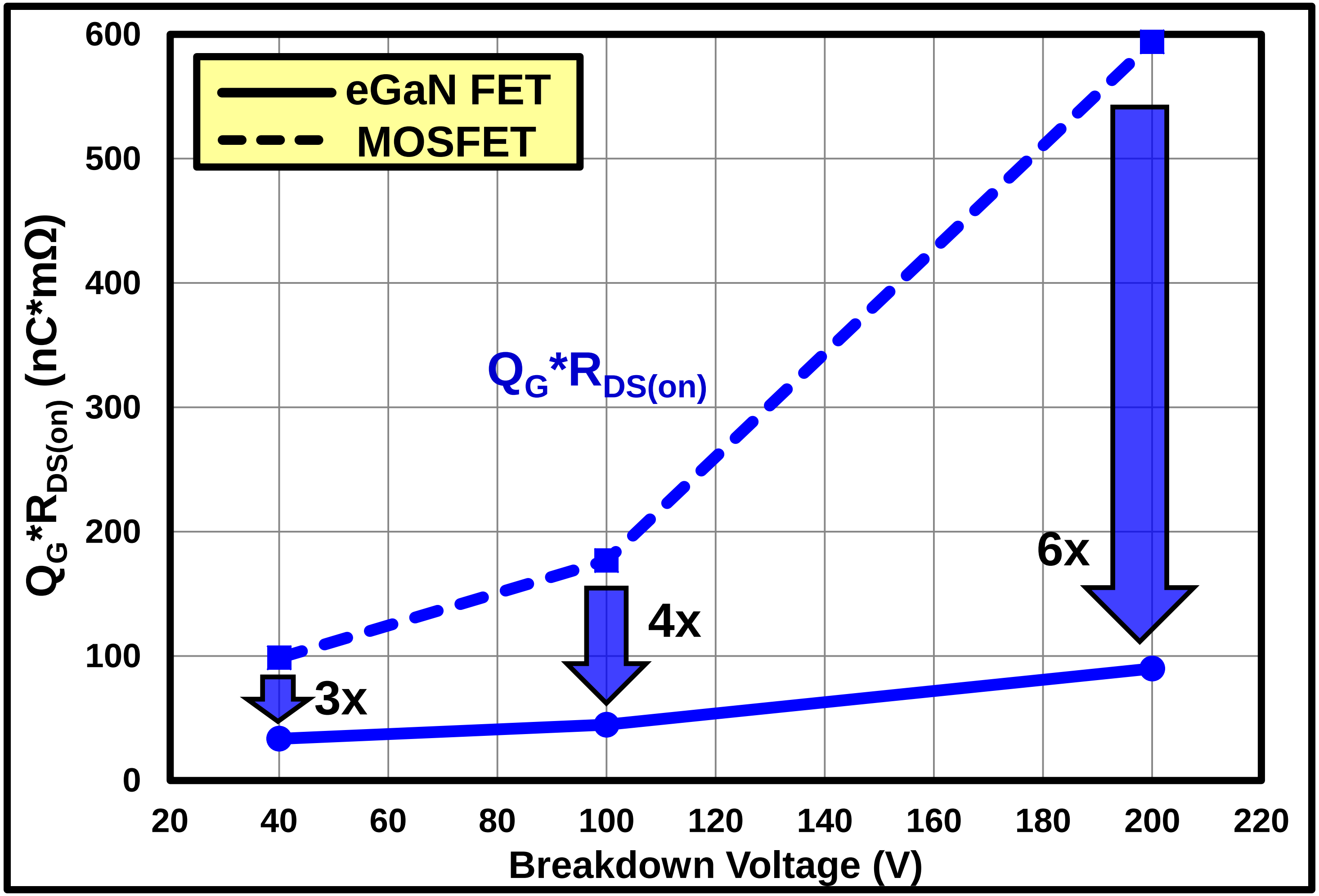
Resonant Bus Converter

High Frequency DC/DC Transformer

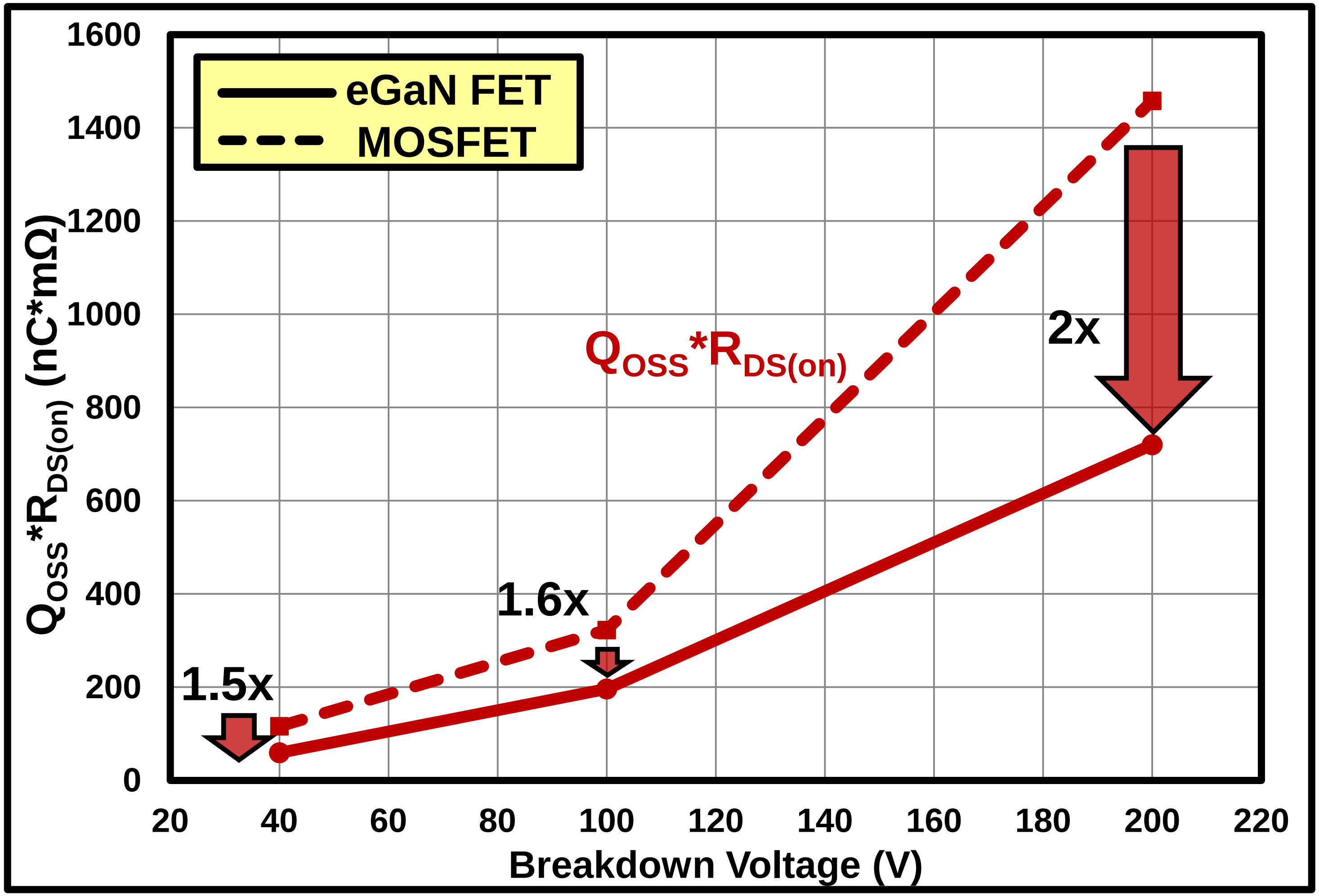


Ref: Y. Ren, M. Xu, J. Sun, and F. C. Lee, “A family of high power density unregulated bus converters,” IEEE Trans. Power Electron., vol. 20, no. 5, pp. 1045–1054, Sep. 2005.

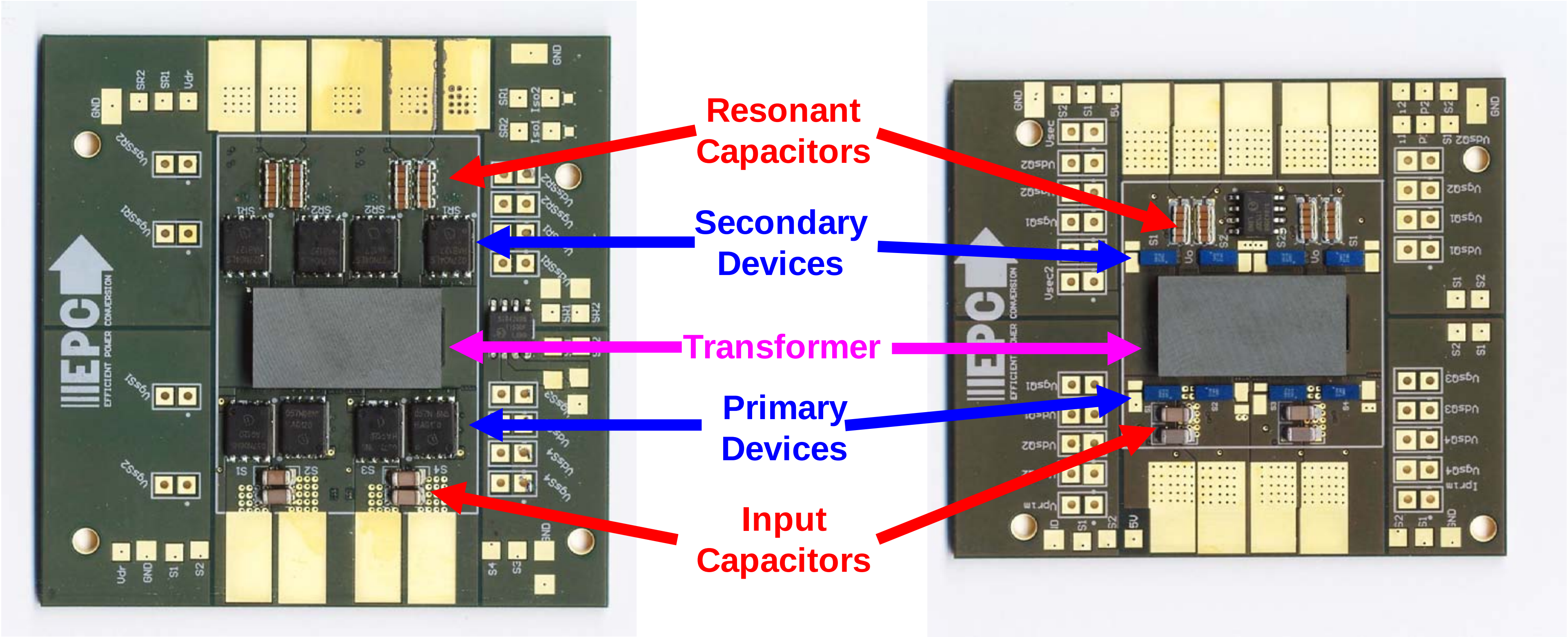
Gate Charge


eGaN FET
MOSFET
Q_G*$R_{DS(on)}$
3x
4x
6x
600
500
400
300
200
100
0
20
40
60
80
100
120
140
160
180
200
220
Breakdown Voltage (V)
Q_G*$R_{DS(on)}$ (nC*mΩ)

Output Charge



eGaN FET vs. MOSFET



Resonant Capacitors

Secondary Devices

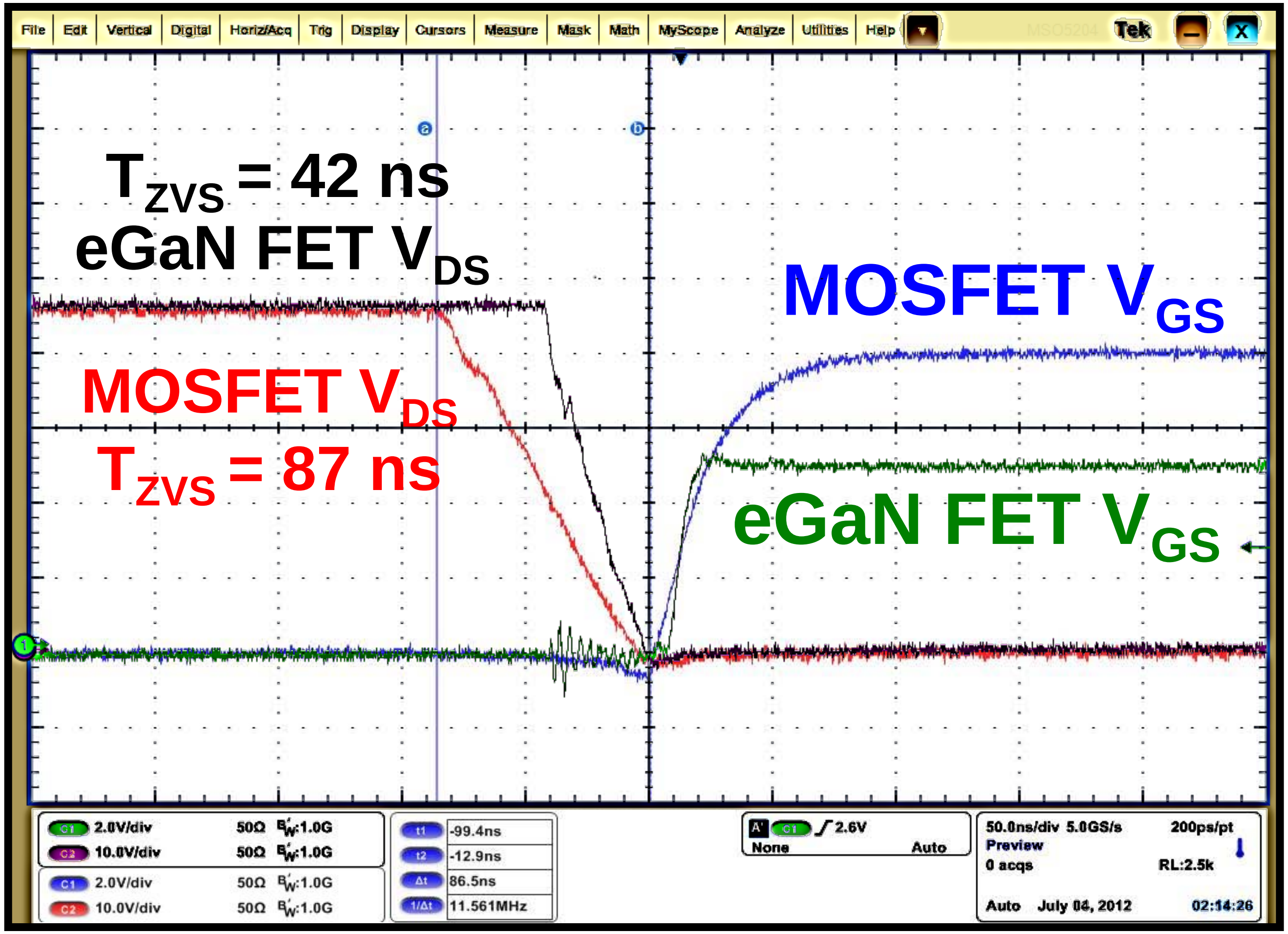
Transformer

Primary Devices

Input Capacitors

MOSFET **vs.** **eGaN$^{®}$FET**

ZVS Switching Comparison



C1 2.0V/div 50Ω B_W:1.0G
C2 10.0V/div 50Ω B_W:1.0G
C1 2.0V/div 50Ω B_W:1.0G
C2 10.0V/div 50Ω B_W:1.0G

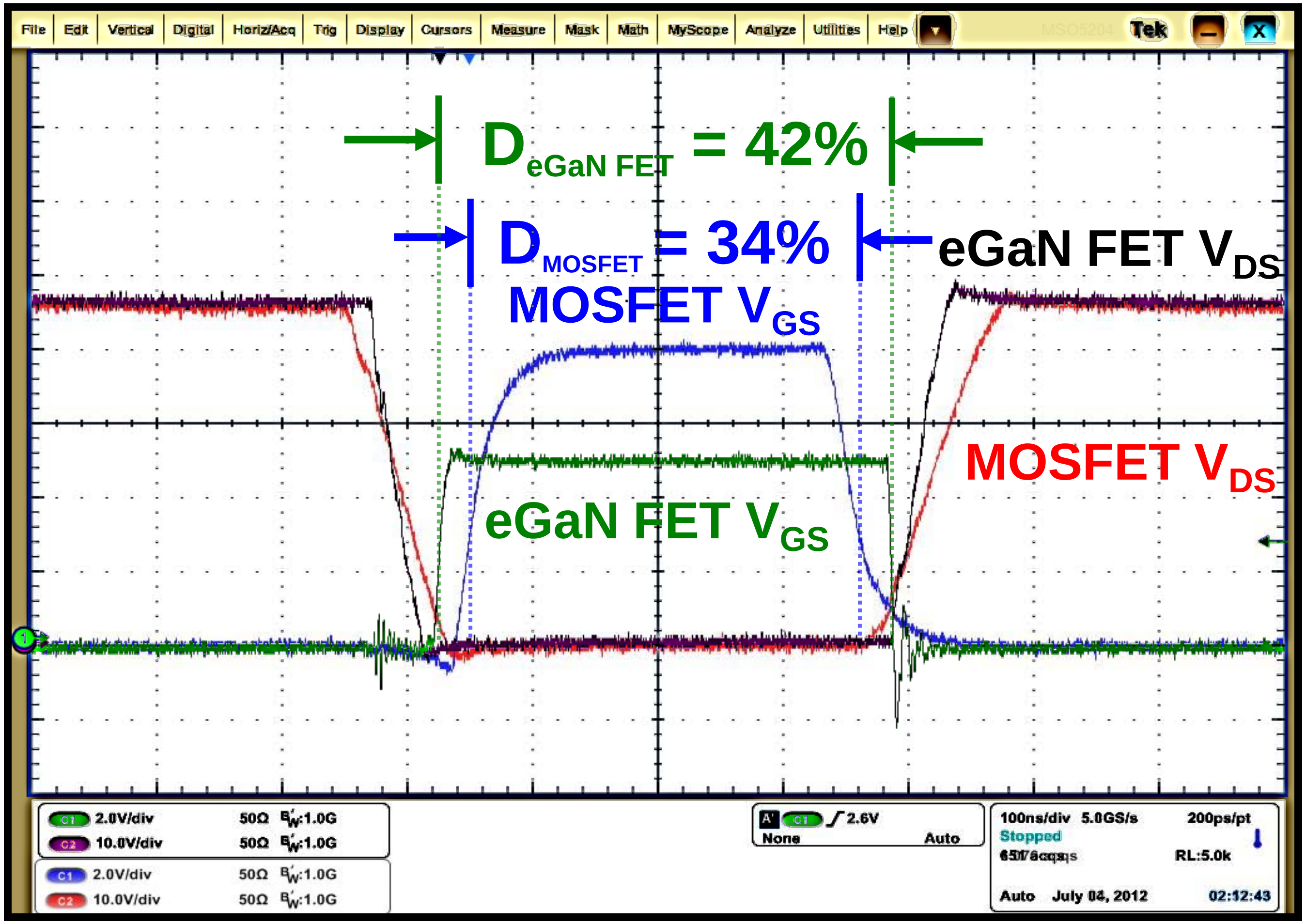
t1 -99.4ns
t2 -12.9ns
Δt 86.5ns
1/Δt 11.561MHz

A' C1 ∫ 2.6V
None Auto

50.0ns/div 5.0GS/s 200ps/pt
Preview
0 acqs RL:2.5k
Auto July 04, 2012 02:14:26

f_{sw} = 1.2 MHz, V_{IN} = 48 V, and $V_{OUT} \approx$ 12 V

Duty Cycle Comparison



$D_{\text{eGaN FET}}$ = 42%

D_{MOSFET} = 34%

eGaN FET V_{DS}

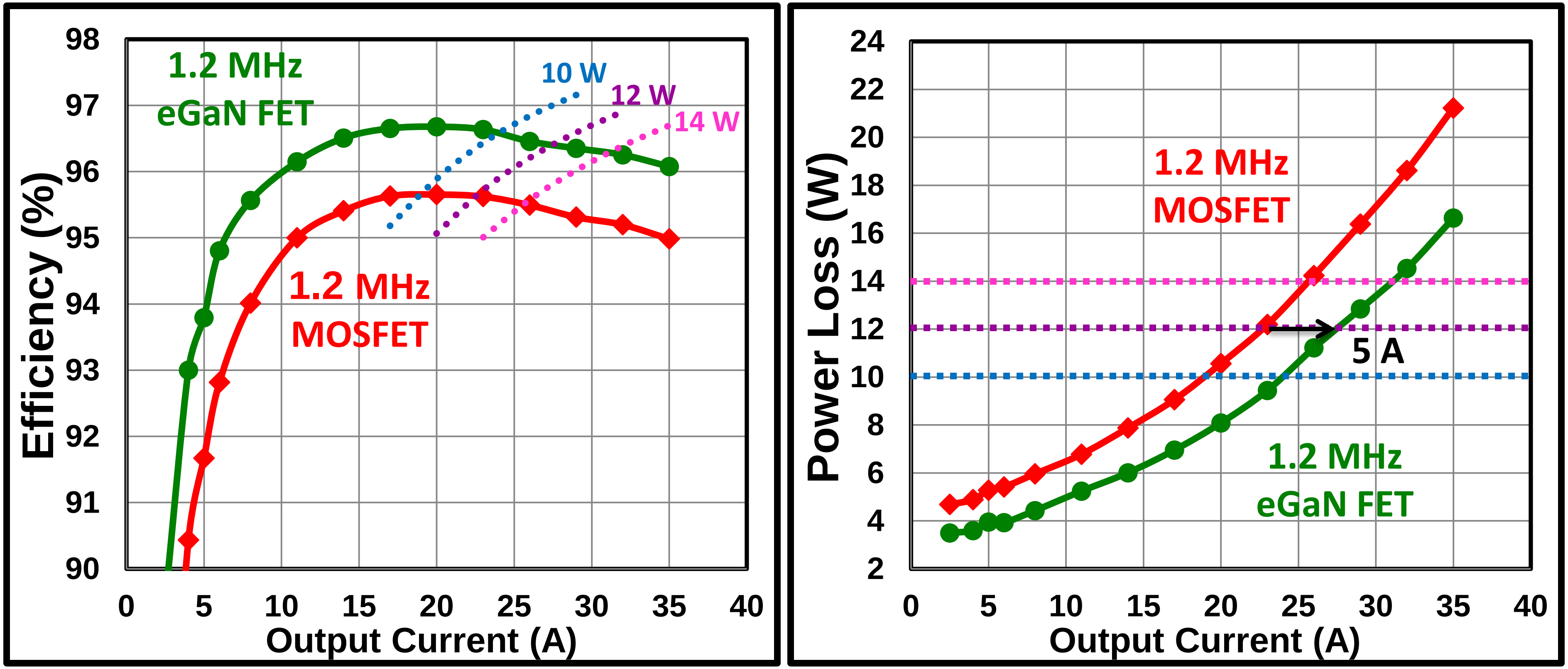
MOSFET V_{GS}

MOSFET V_{DS}

eGaN FET V_{GS}

f_{sw} = 1.2 MHz, V_{IN} = 48 V, and V_{OUT} = 12 V

Efficiency Comparison



f_{SW} = 1.2 MHz, V_{IN} = 48 V, and $V_{OUT} \approx 12$ V

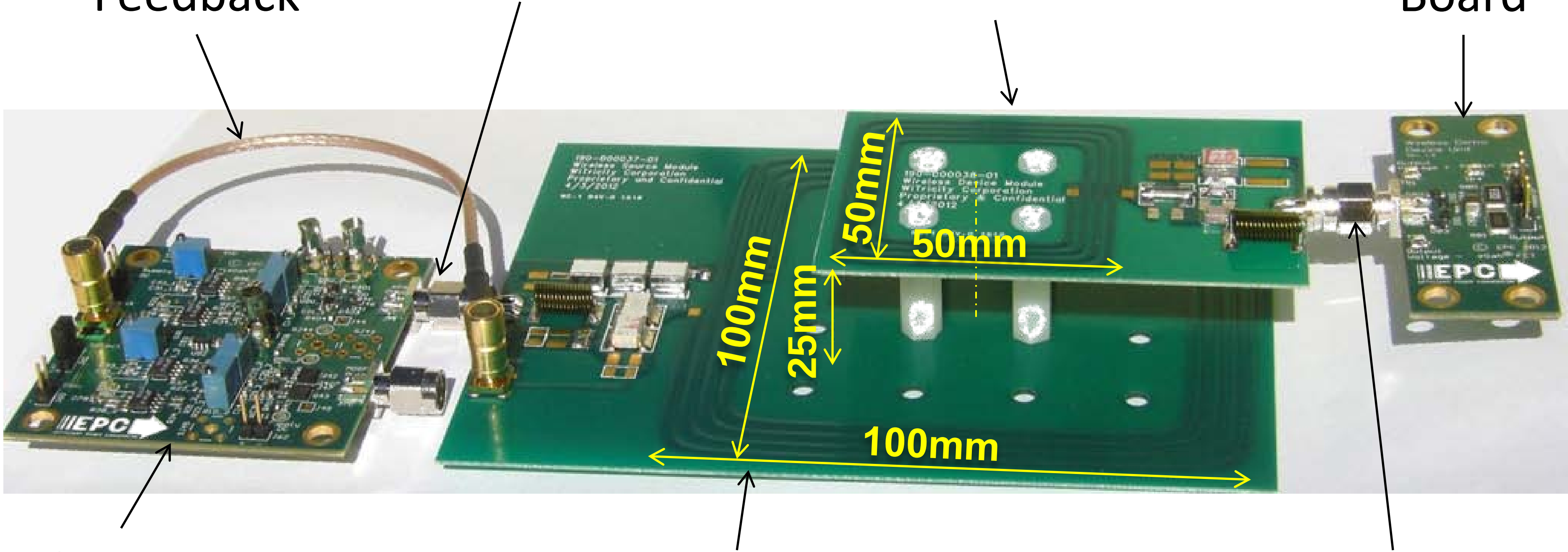
Resonant Converter Summary

- eGaN FETs improve high frequency resonant converter performance
  - Lower output charge
  - Lower gate charge
  - More power delivery per cycle

Why Wireless Power?

- eGaN FETs enable higher efficiency and operation at safer frequencies
- The global wireless charging market is estimated to grow to $10B by 2018, a CAGR of 42.6%

Experimental System Setup



Coil Feedback

eGaN FETs RF connection

Device Coil

Device Board

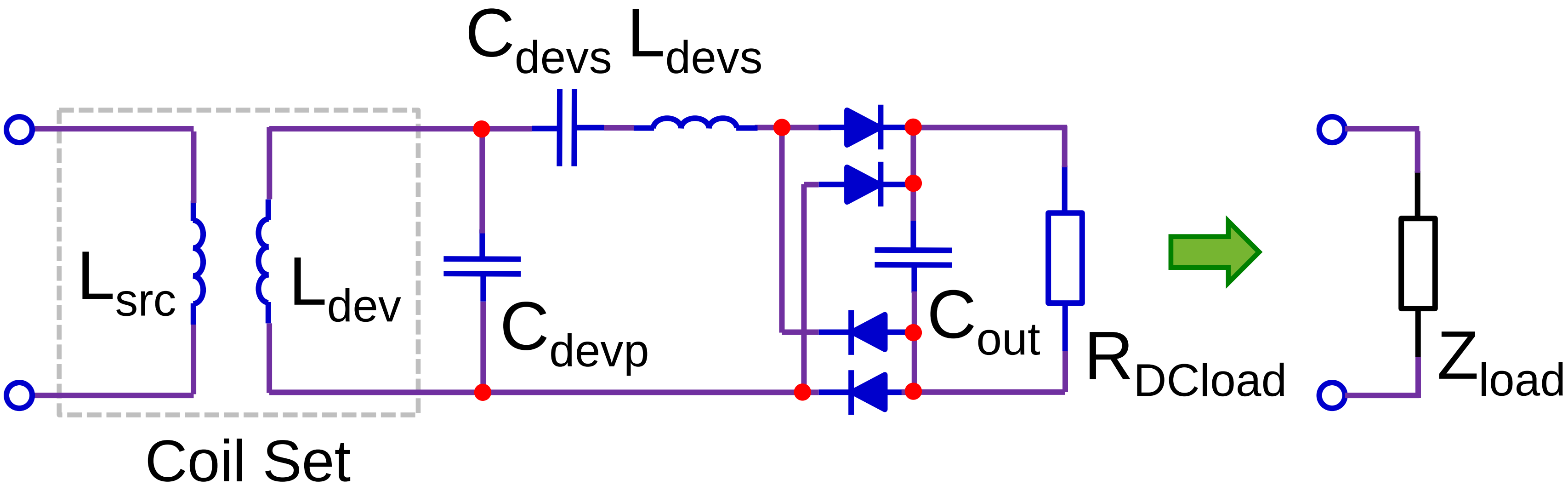
Source Board

Source Coil

RF connection

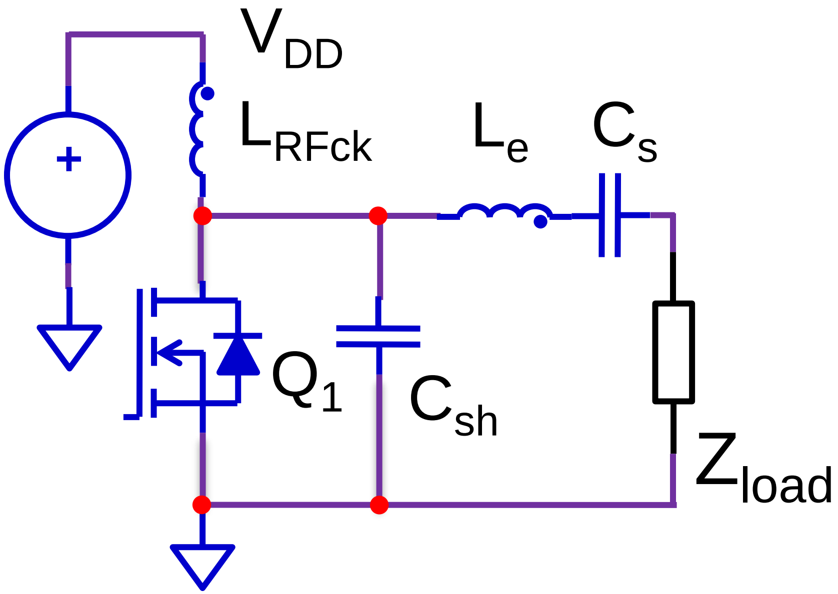
Wireless Coil-set Overview

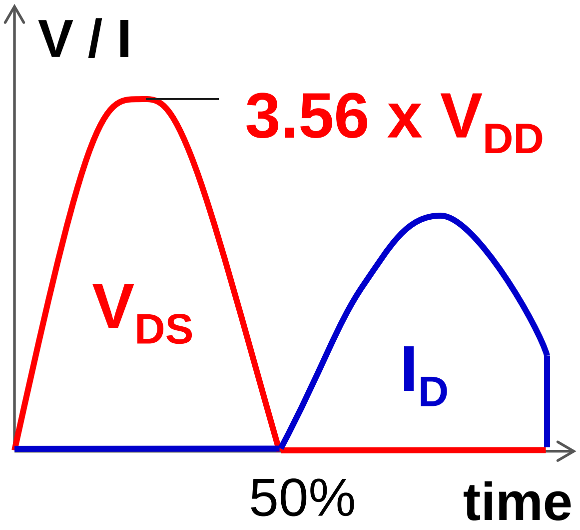
Simplified representation of coil-set for easy comparison between topologies



Class E Overview

- Switch voltage rating = > 3.56·Supply (V_{DD}).
- C_{OSS} "absorbed" into matching network.

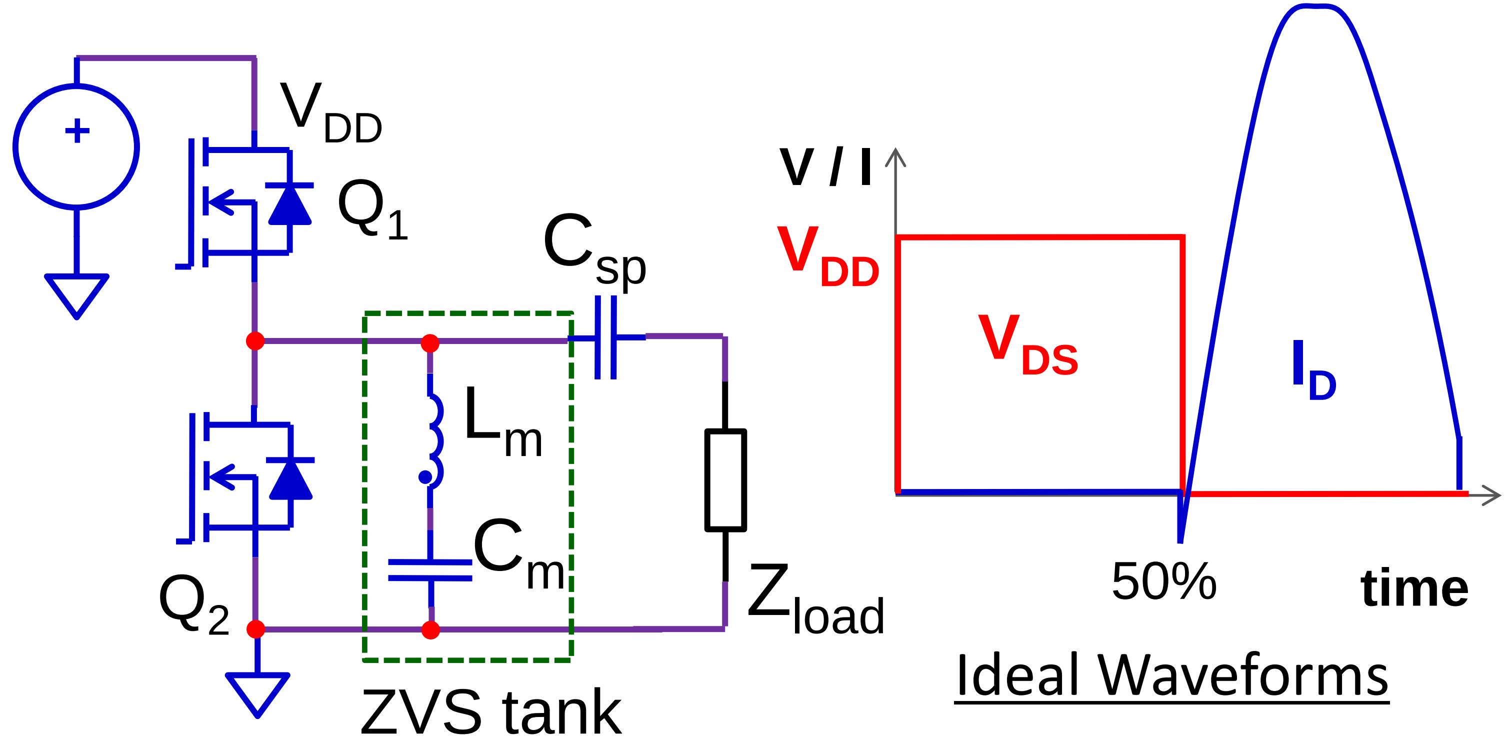




Ideal Waveforms

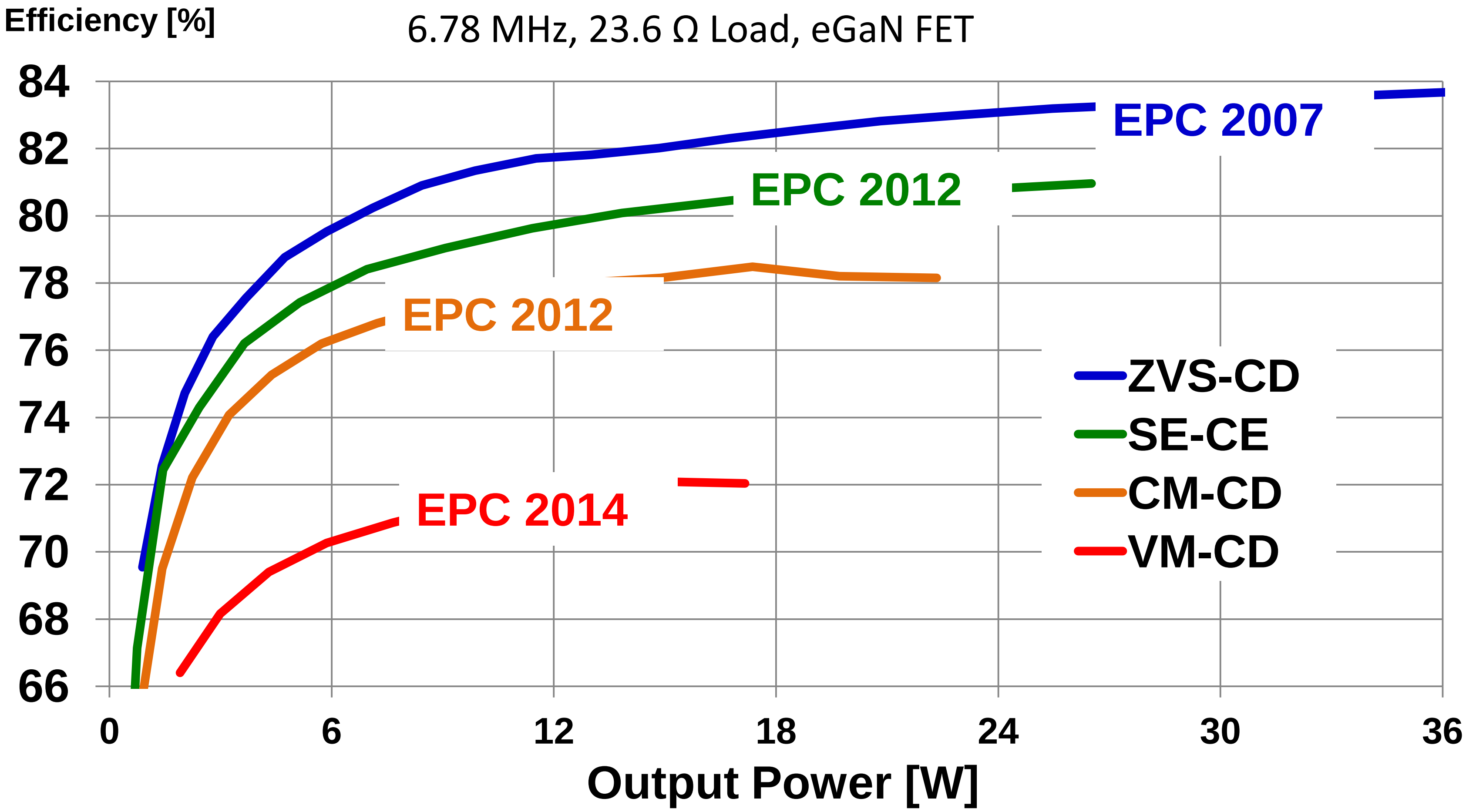
ZVS Voltage Mode Class D

- C_{OSS} Voltage is transitioned by the ZVS tank
- Lower eGaN FET C_{OSS} leads to higher available duty cycle
- Highest system efficiency



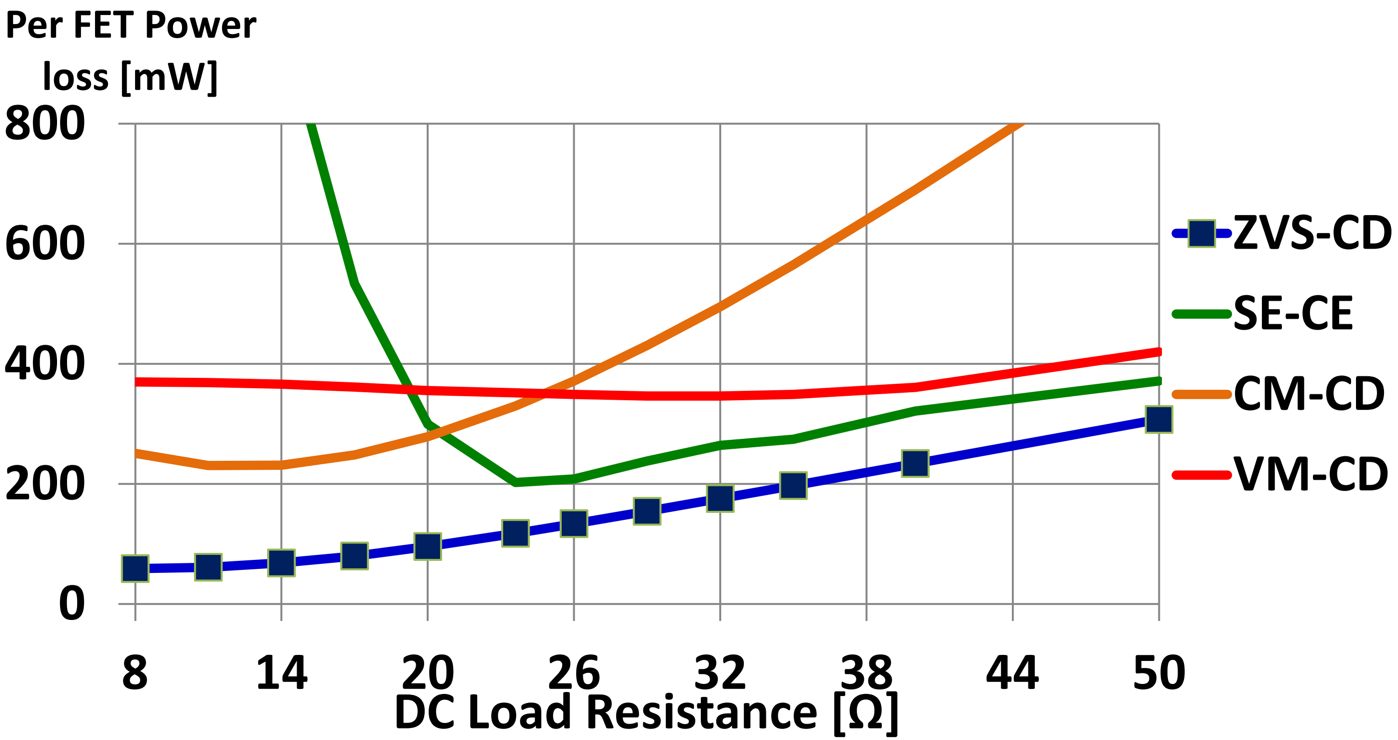
Ideal Waveforms

Efficiency



eGaN FETs enable the highest efficiency in all topologies using 6.78 MHz and 13.56 MHz frequencies.

Impact of Load



ZVS class D has higher efficiency and a broader operating range than class E.

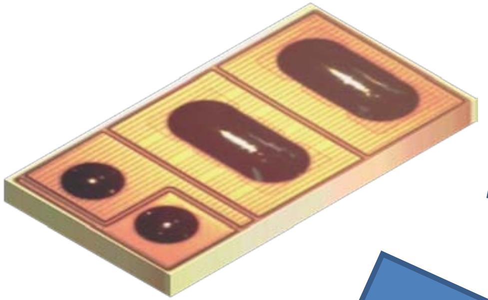
A Look into the Future

Silicon vs. eGaN Transistor Costs

	2013	2016
Starting Material	lower	lower
Epi Growth	***higher***	***~same?***
Wafer Fab	lower	lower
Test	same	same
Assembly	lower	lower
OVERALL	**higher**	***lower!***

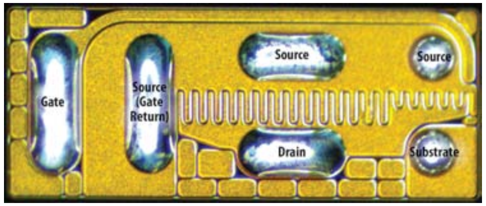
EPC Into the Future

Mass Production
40 V - 200 V
~500 MHz



Ultra High Frequency Family
1 - 3 GHz

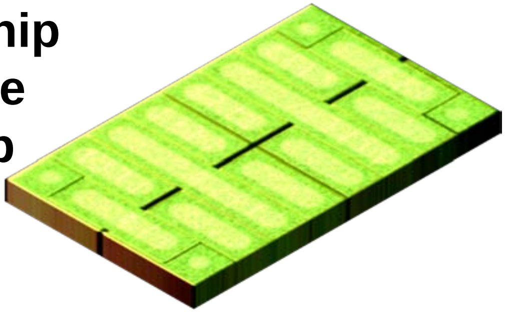
Launched Sept 2013



Higher Current
45 A

Higher Voltage
600 V

More functions on a chip
Monolithic half bridge
Driver on power chip



Next Generation Devices
2 x FOM Improvement

Summary

eGaN FETs…

- enable exciting new applications
- have the potential to replace silicon power MOSFETs
- are straightforward to use, but they can't just drop them into a MOSFET socket. Some R&D is needed – **start today**!