Enhancement Mode GaN on Silicon Enables Increased Performance and New Applications

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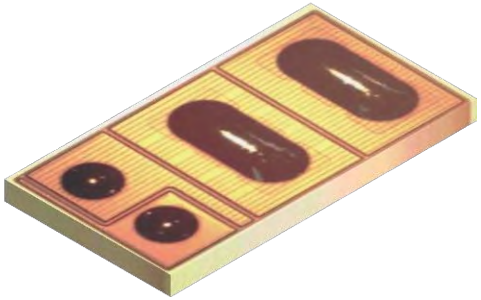
Efficient Power Conversion

Agenda

- How eGaN FETs work
- Design Basics
- Design Examples
- A Look into the Future
- Q & A

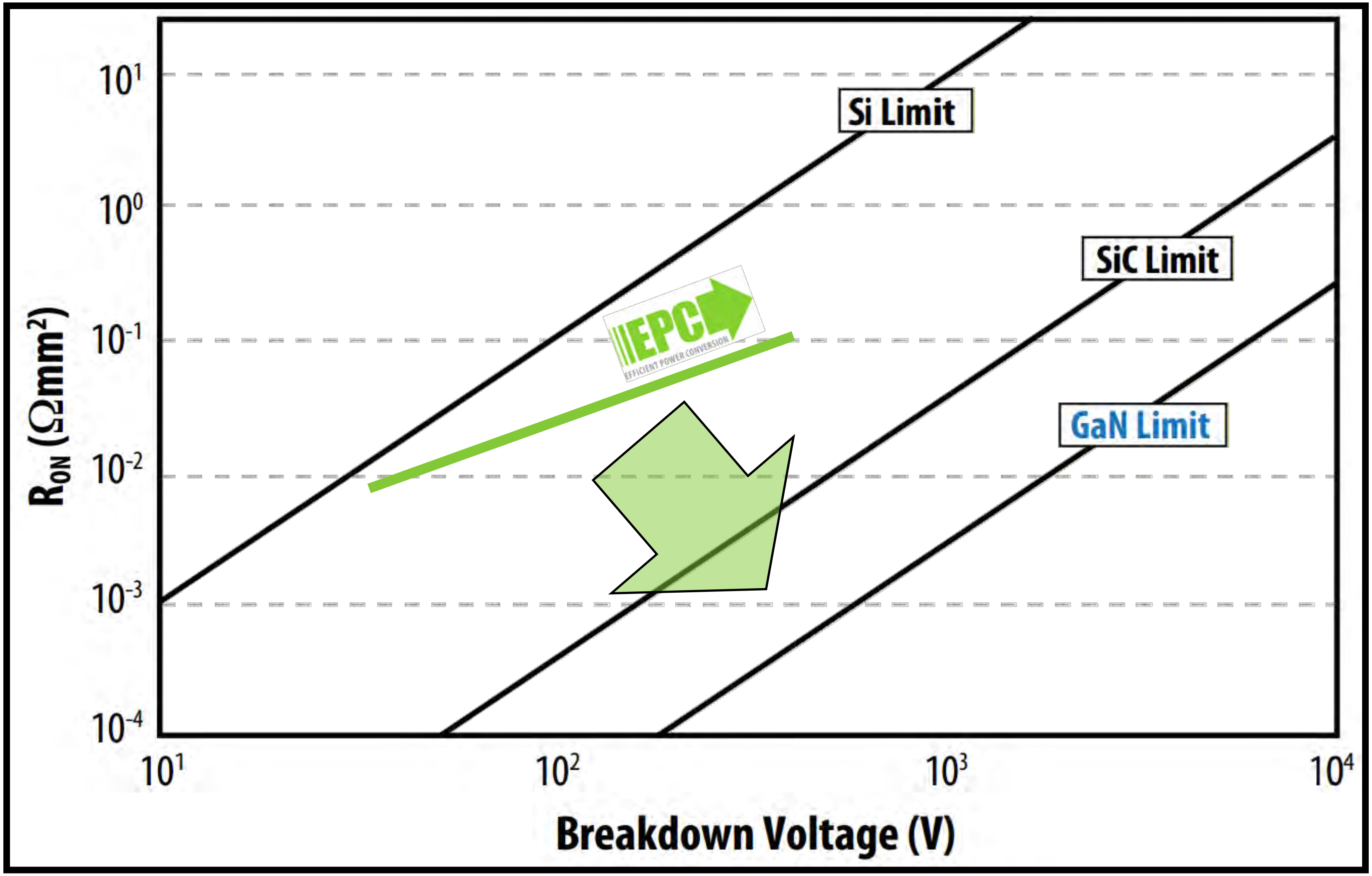
How eGaN FETs Work
and
State-of-the-Art Technology



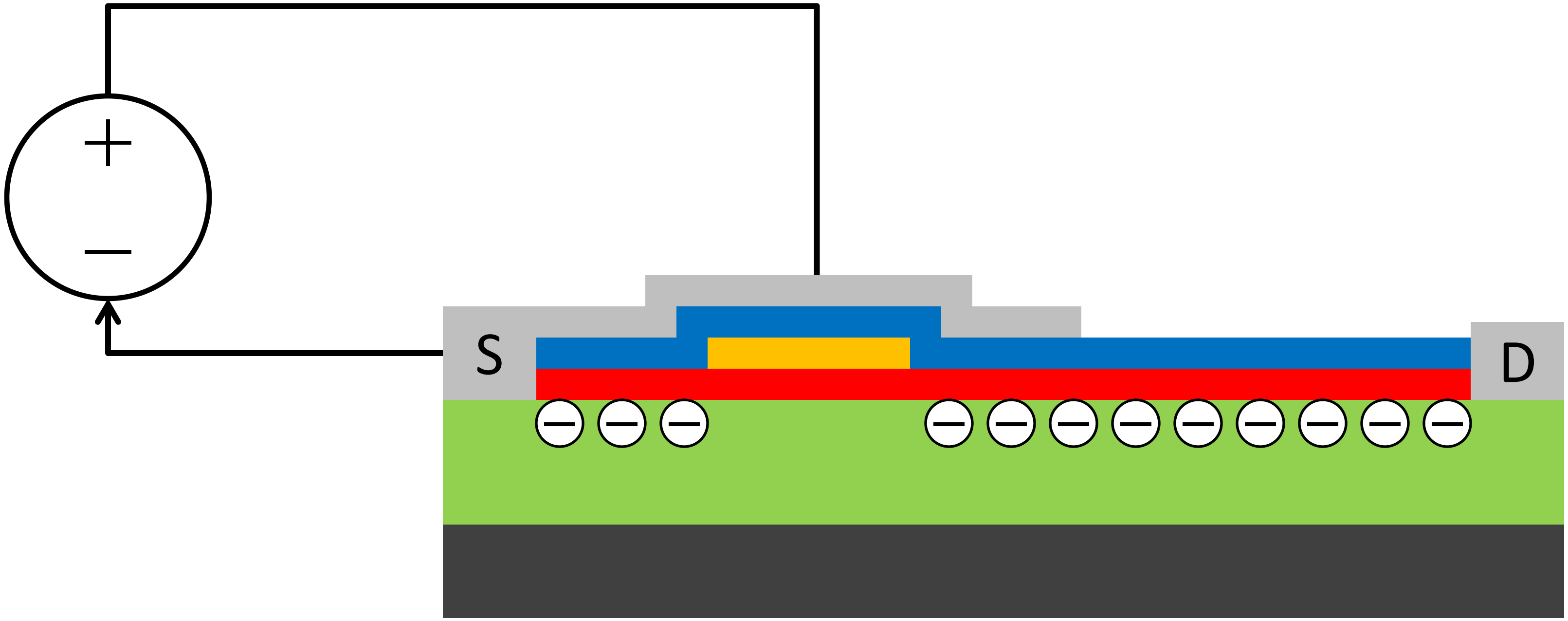
Power Switch Wish List

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

Why Gallium Nitride?



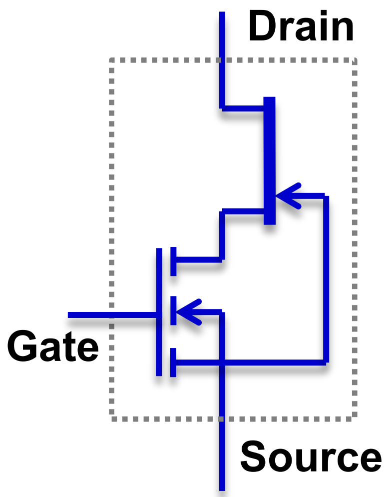
Enhancement Mode – eGaN FET

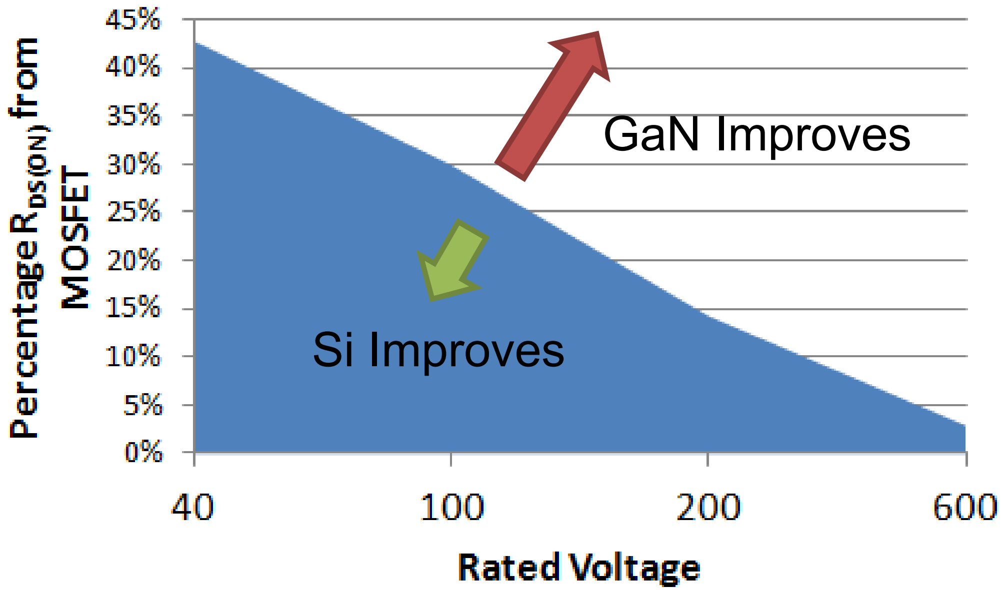


A positive voltage from Gate-To-Source establishes an electron gas under the gate

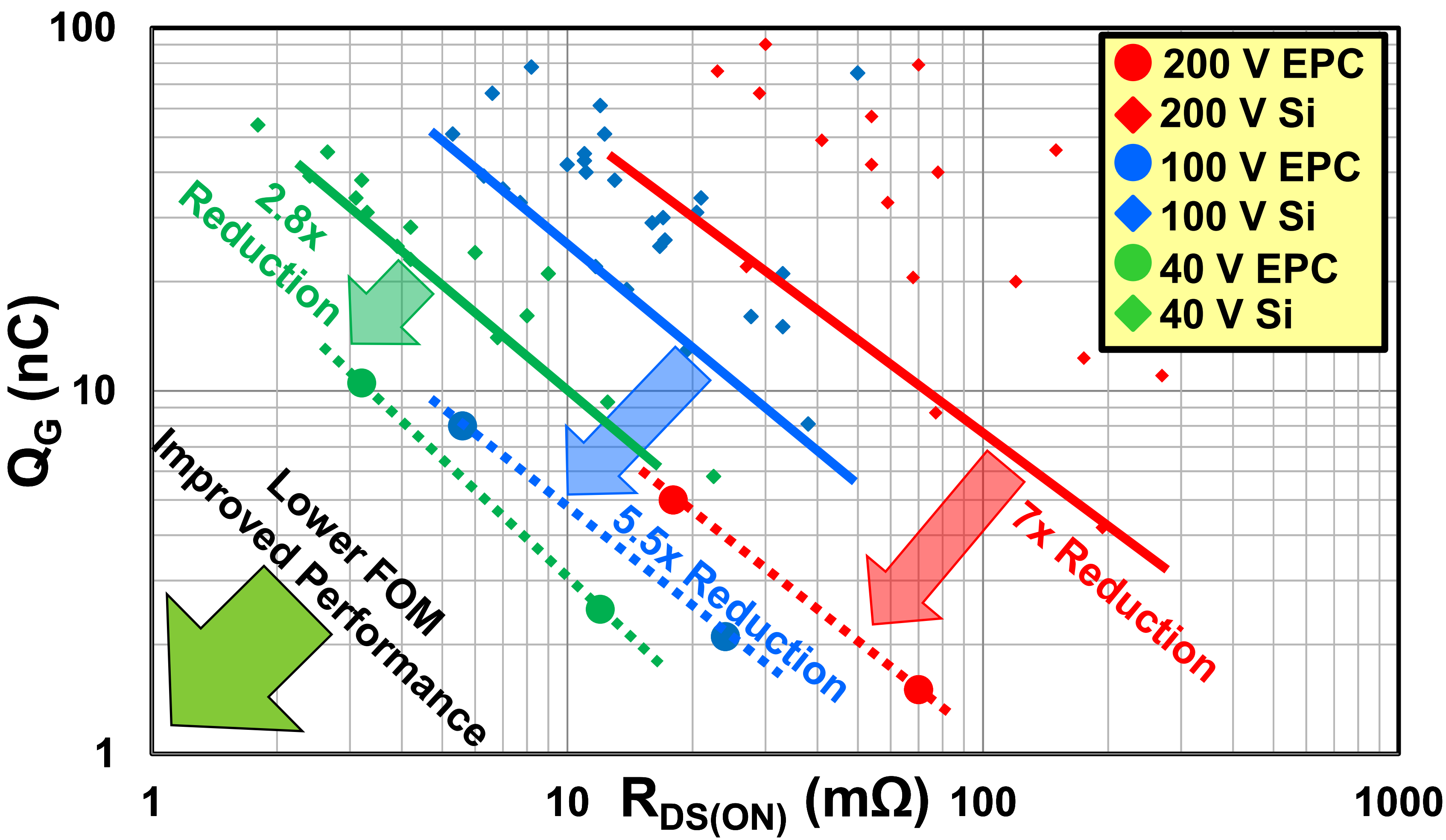
Cascode GaN Device

Cascode devices combine a depletion mode GaN transistor with a low voltage enhancement mode MOSFET

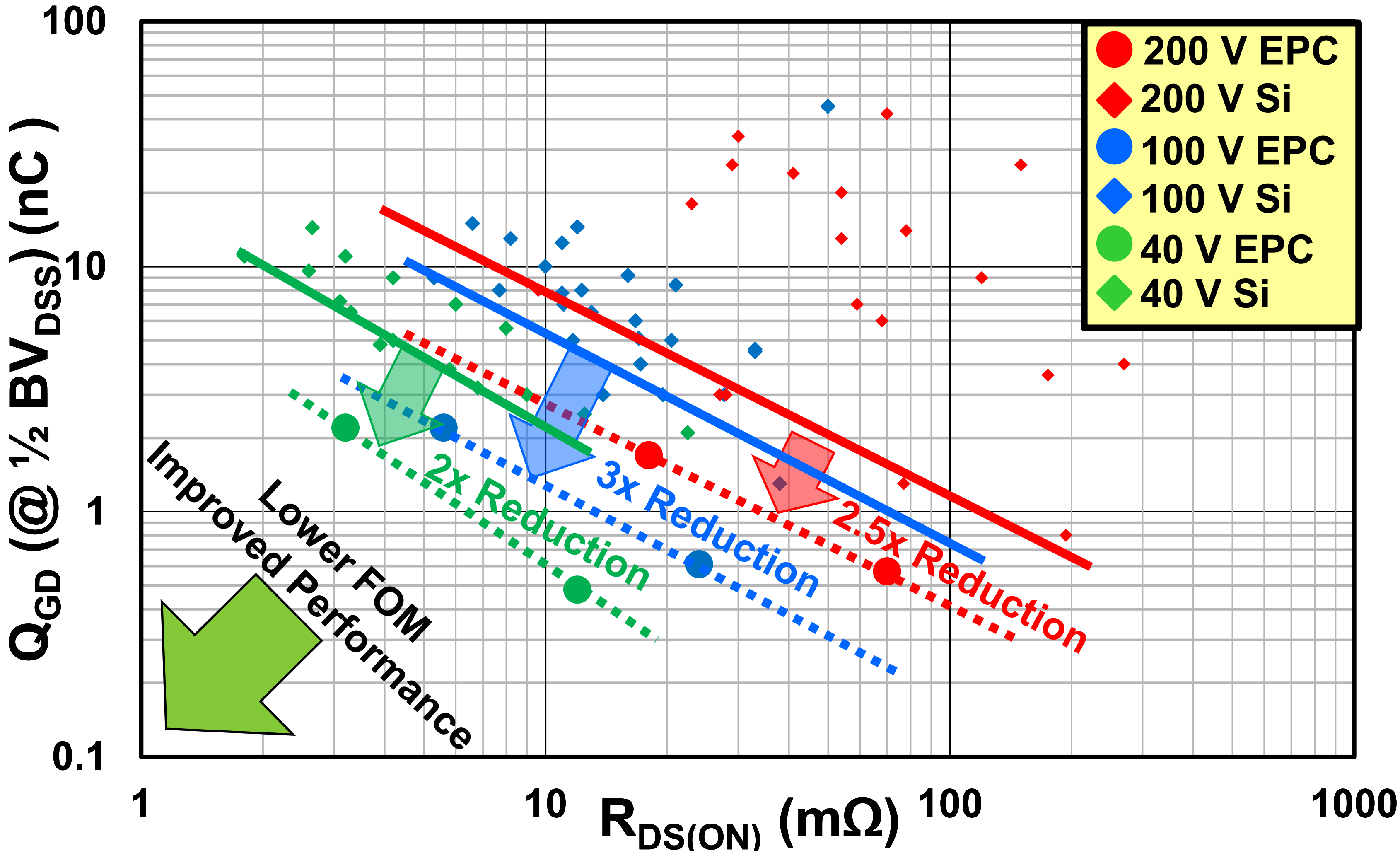




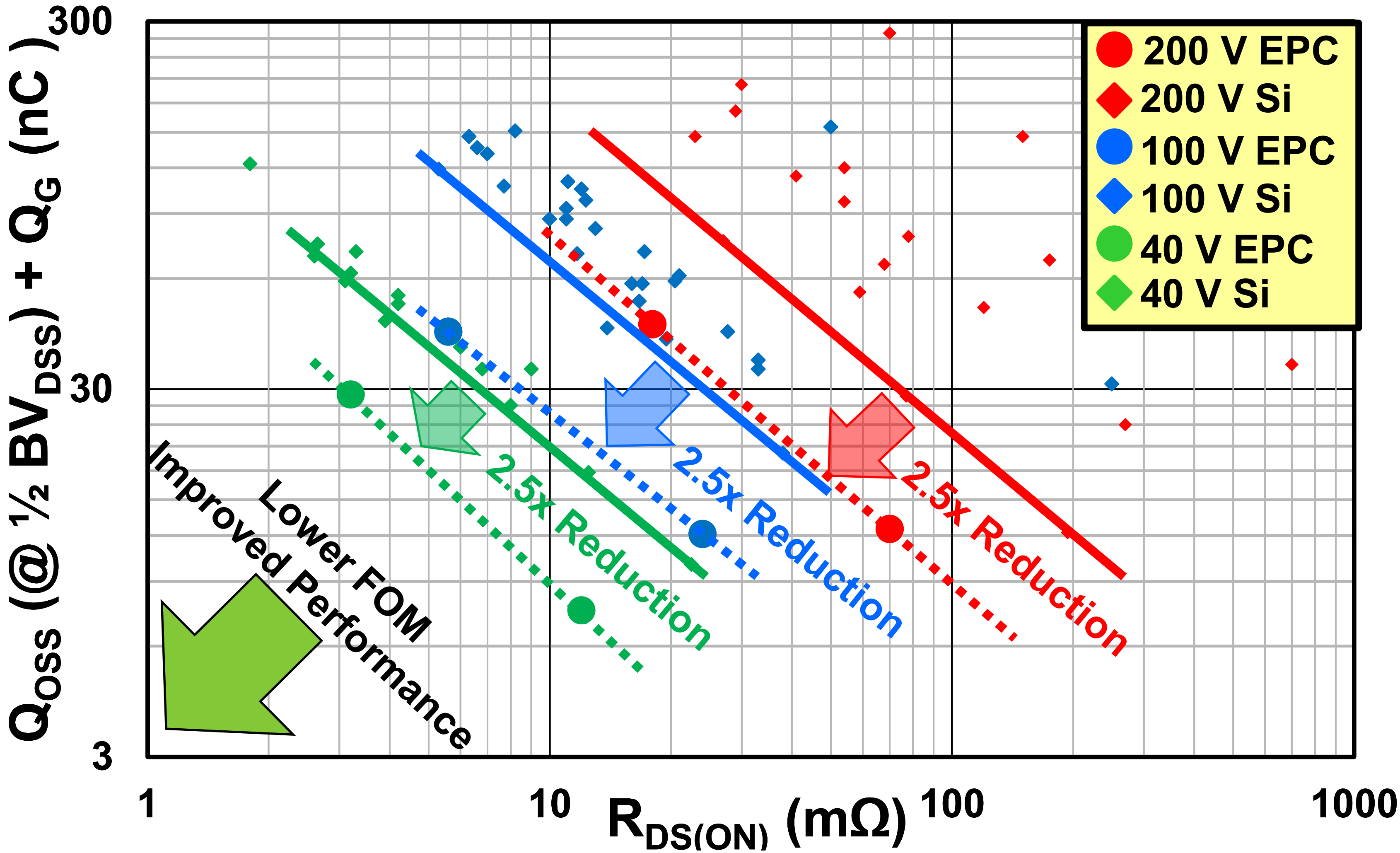
Conduction Figure of Merit



Hard-Switching Figure of Merit



Soft-Switching 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

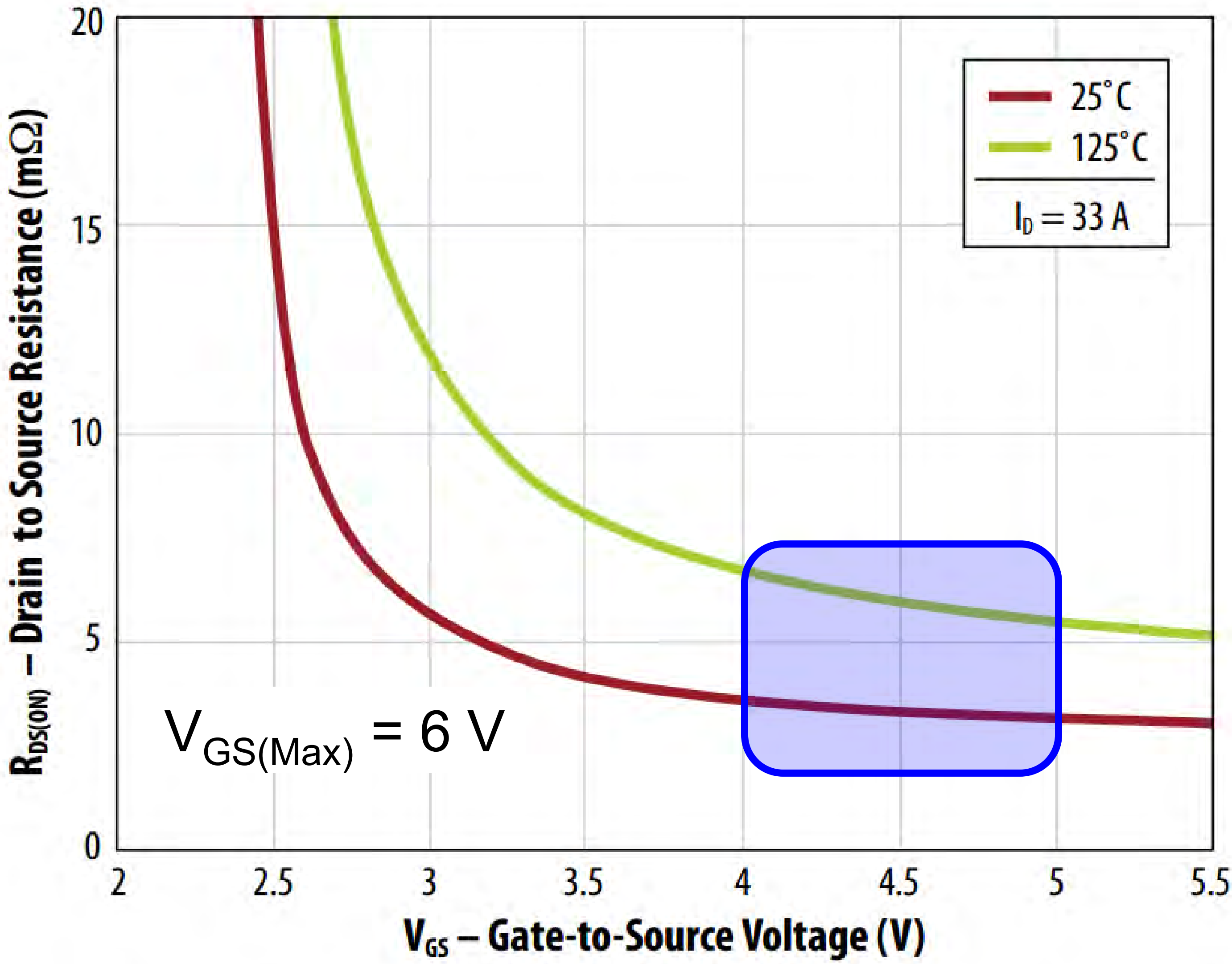
- High Reverse Conduction Loss
- No Body Diode Reverse Recovery Loss

Can be much, much better than comparable silicon MOSFET

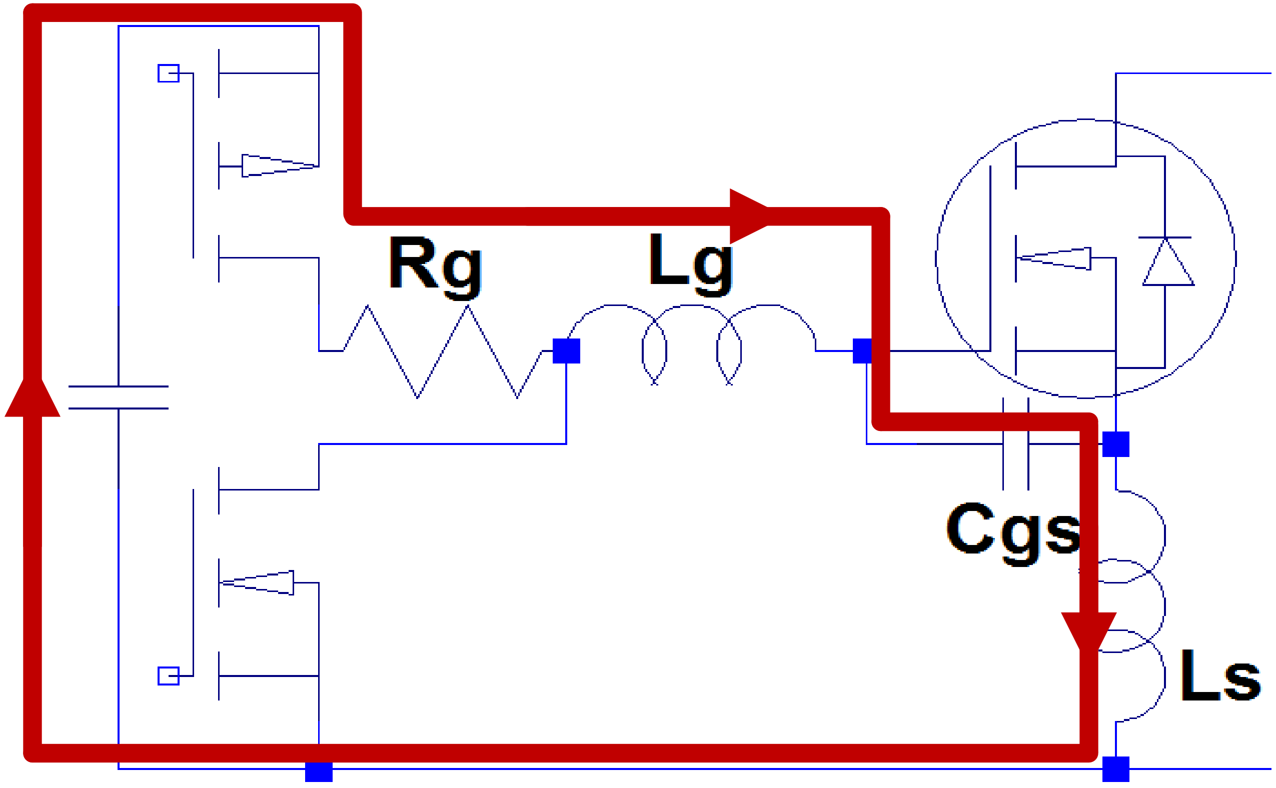
Design Basics

Gate Drive

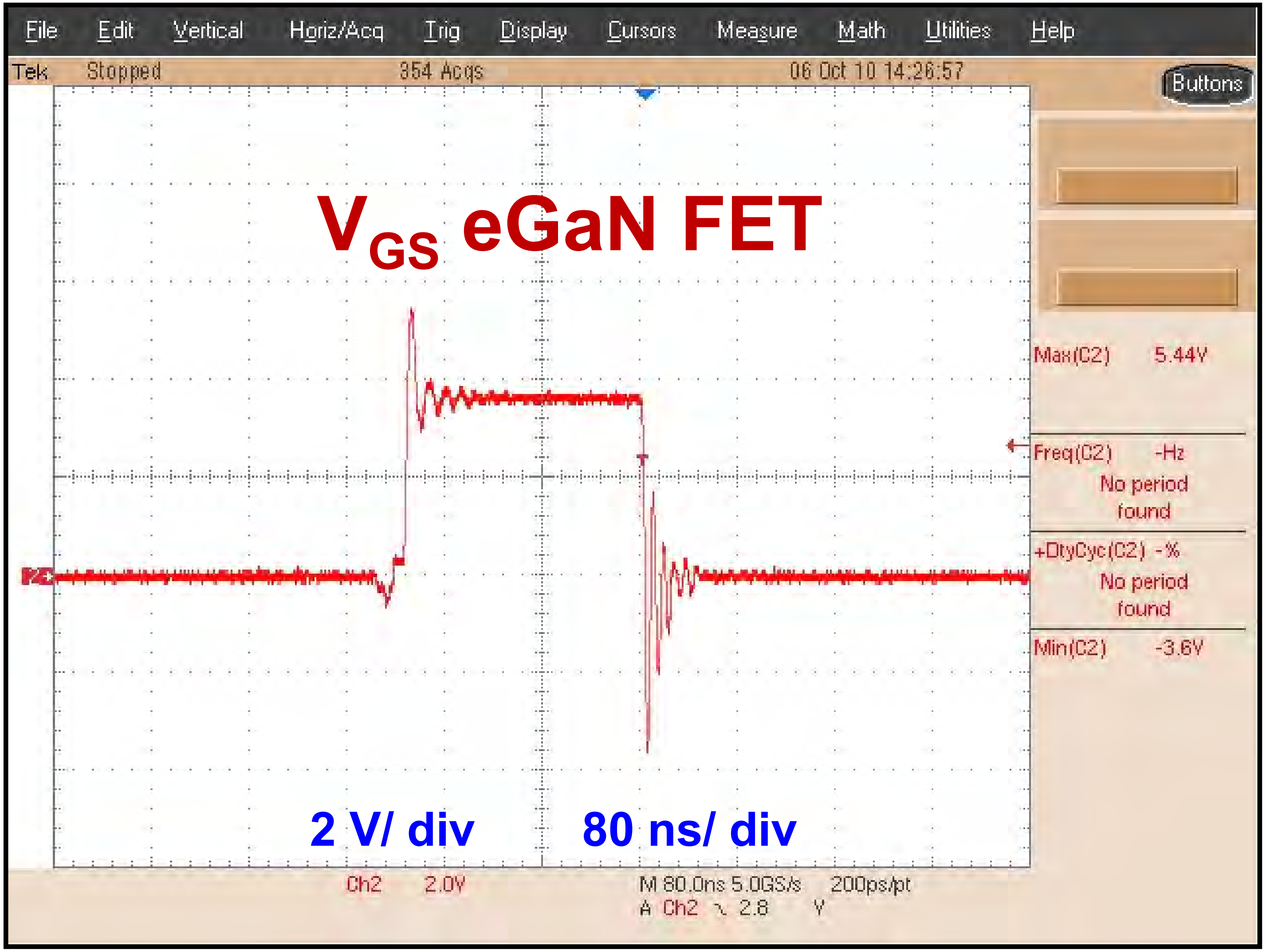
eGaN FET Driving Voltage Range



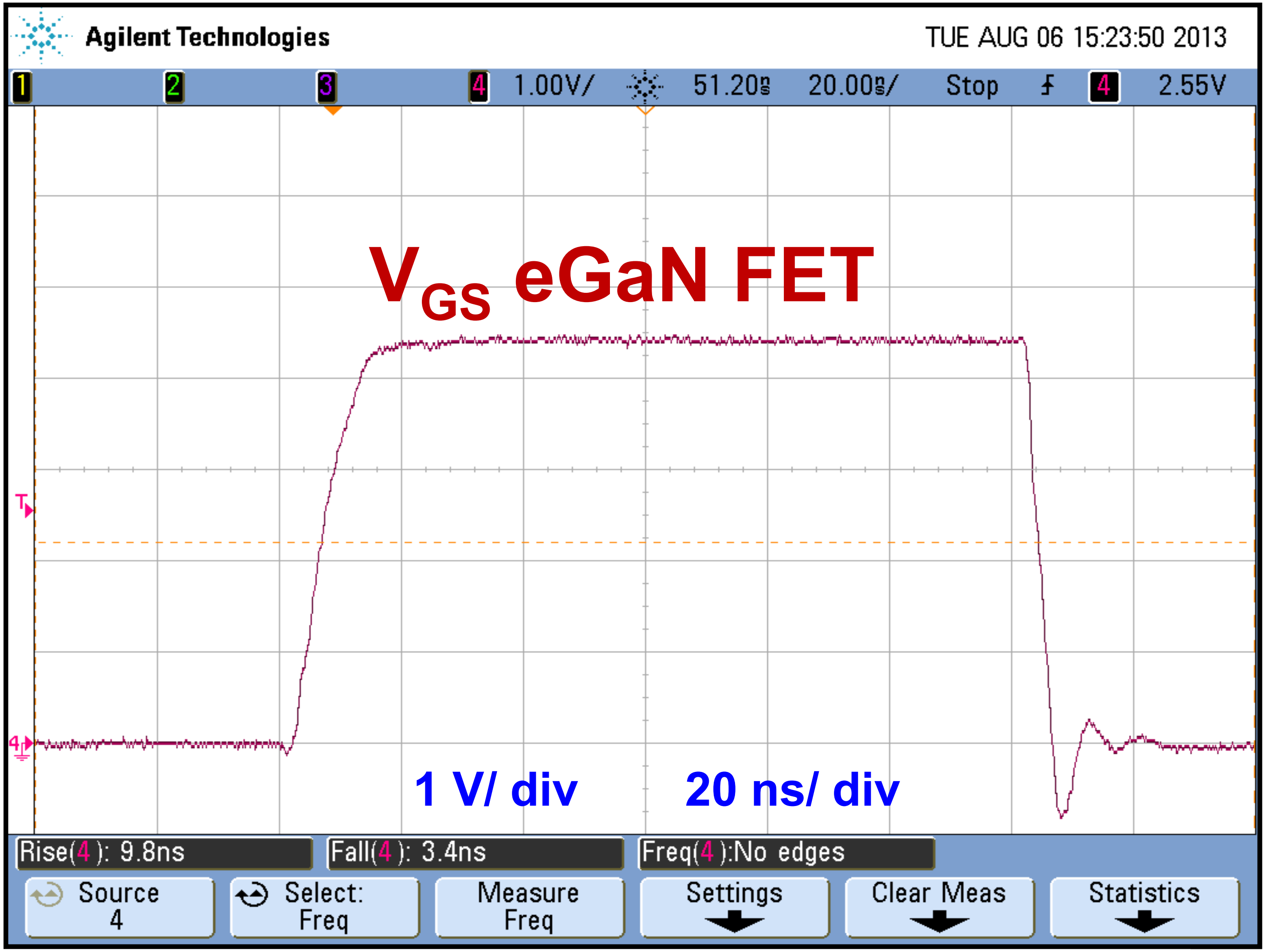
Minimizing Overshoot



Minimizing Overshoot

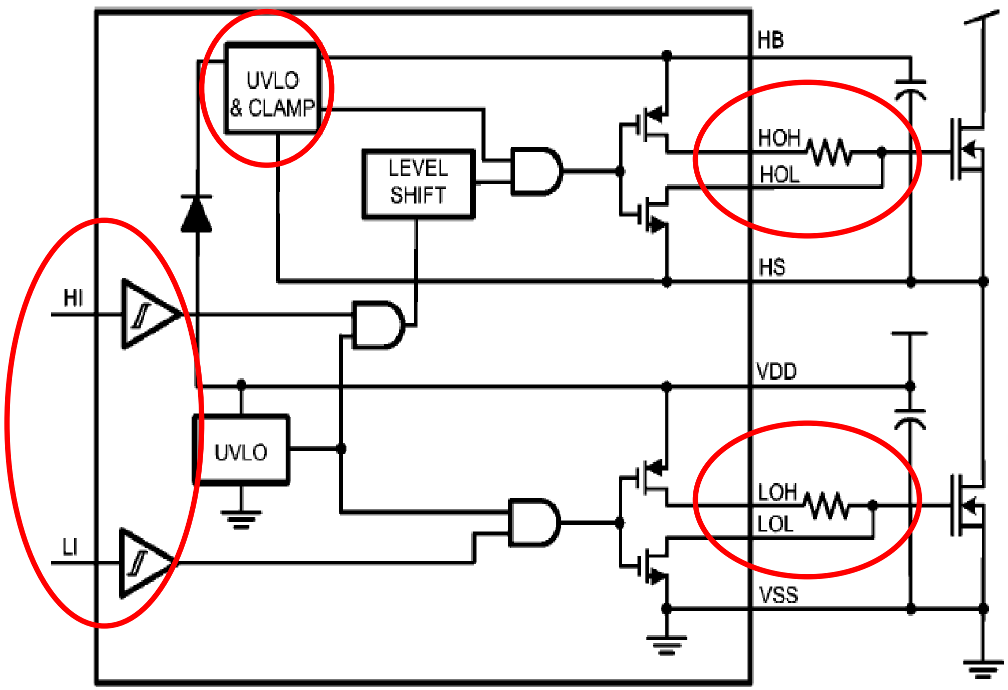


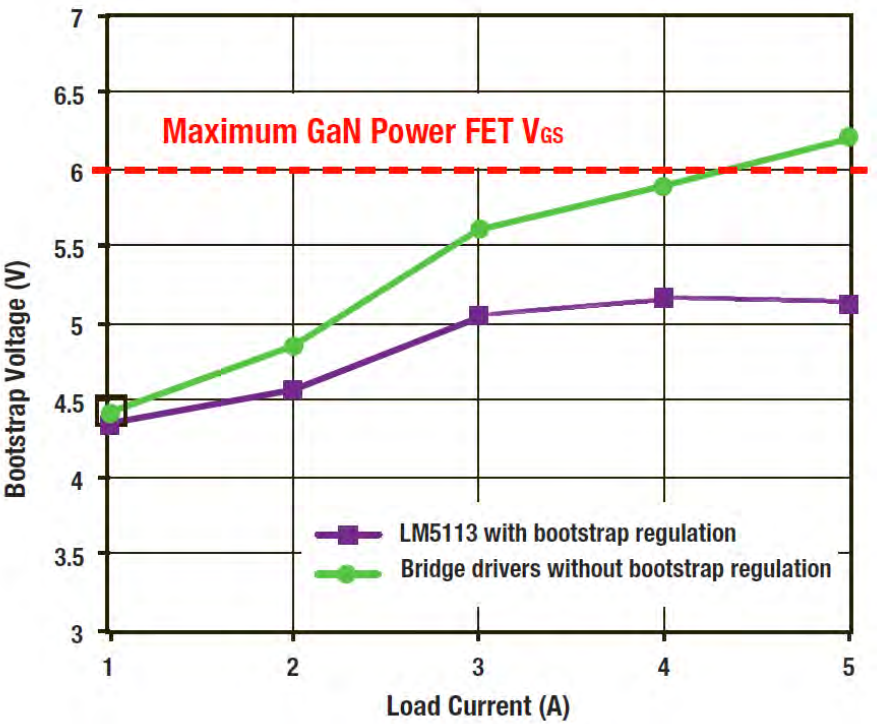
Minimizing Overshoot



eGaN FET Driver IC

LM5113

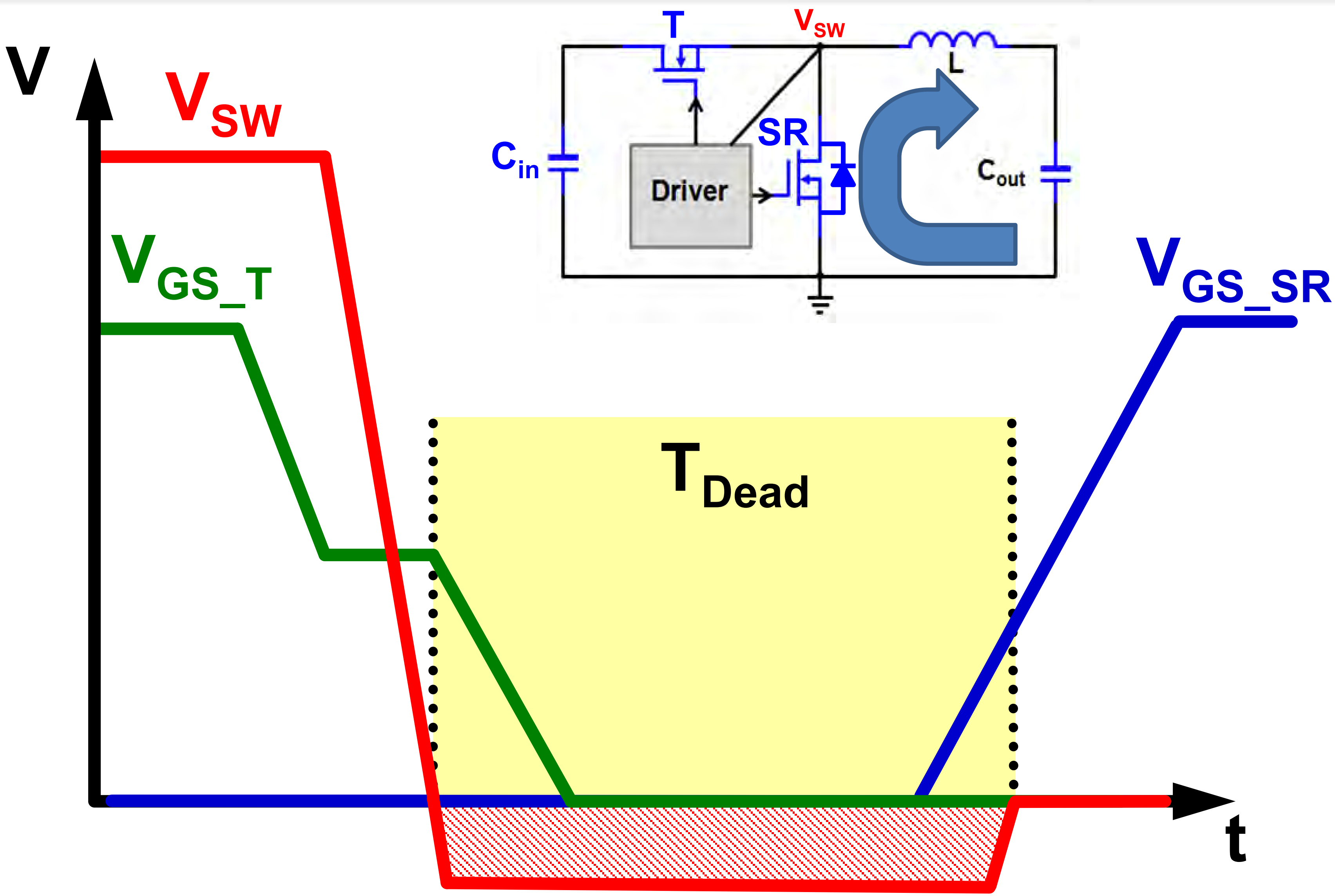




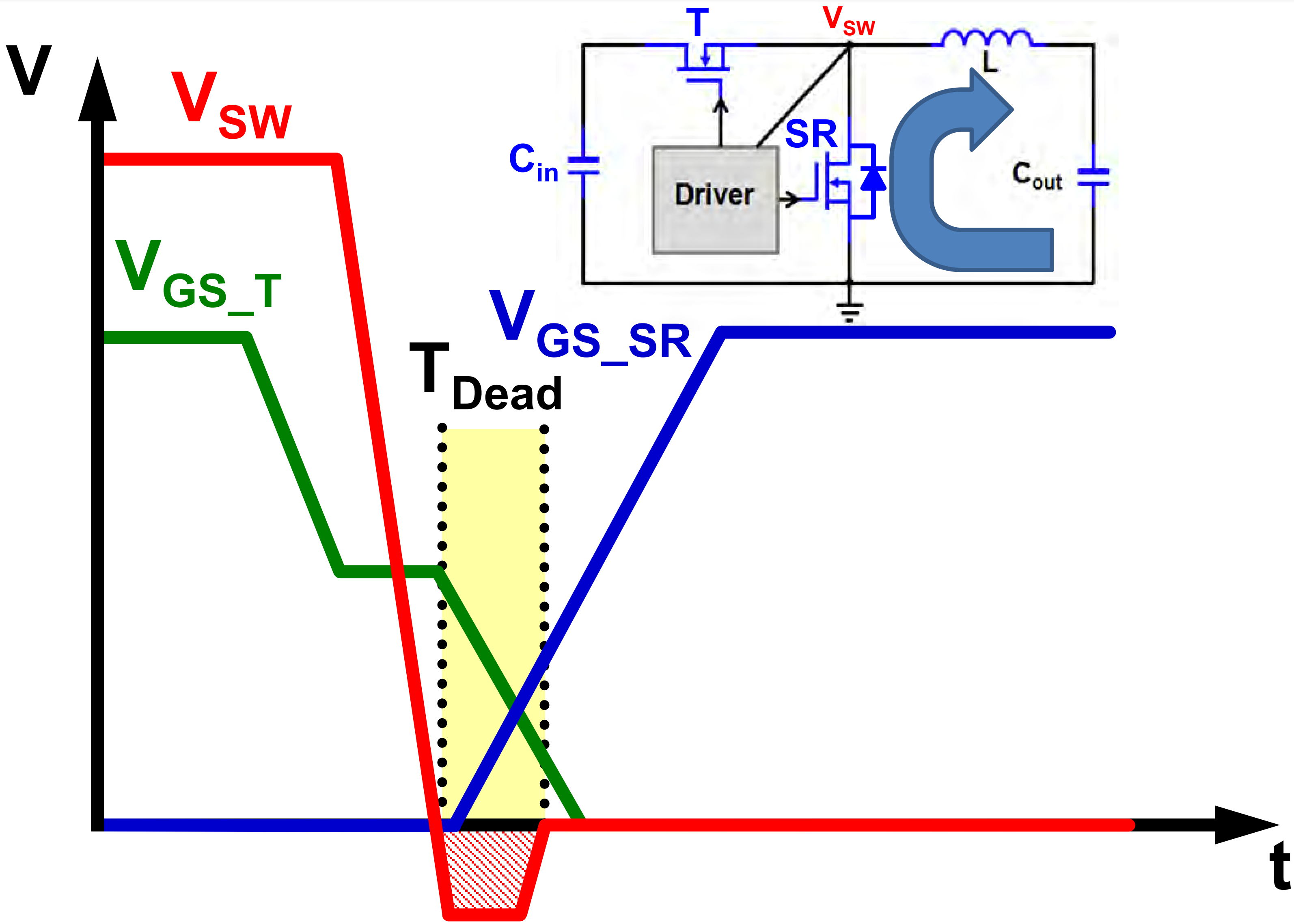
Reference: Texas Instruments, "Gate Drivers for Enhancement Mode GaN Power FETs 100V Half-Bridge and Low-Side Drivers Enable Greater Efficiency, Power Density, and Simplicity," SNVB001

Dead-time Requirements

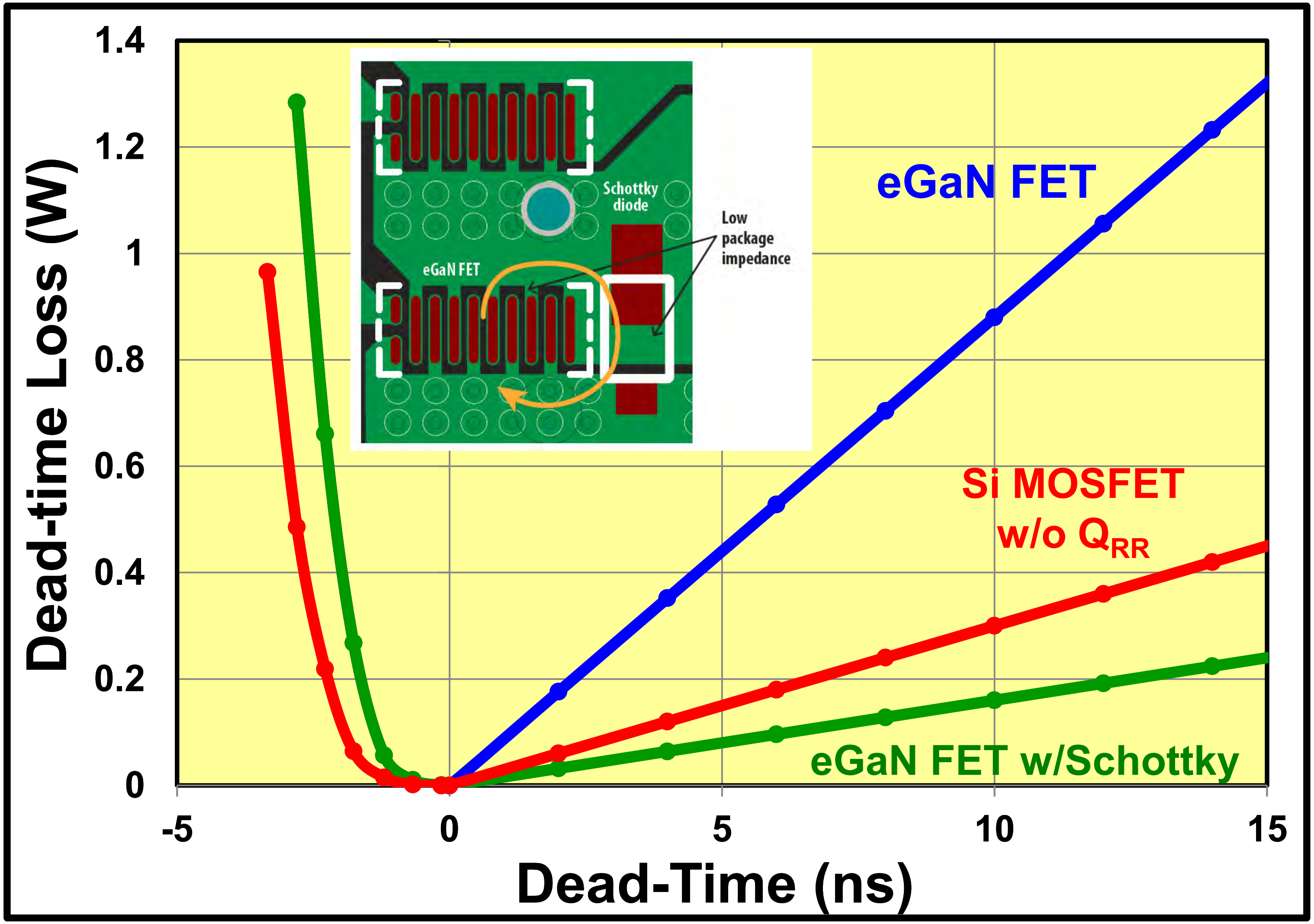
Reverse Conduction Period



Reverse Conduction Period

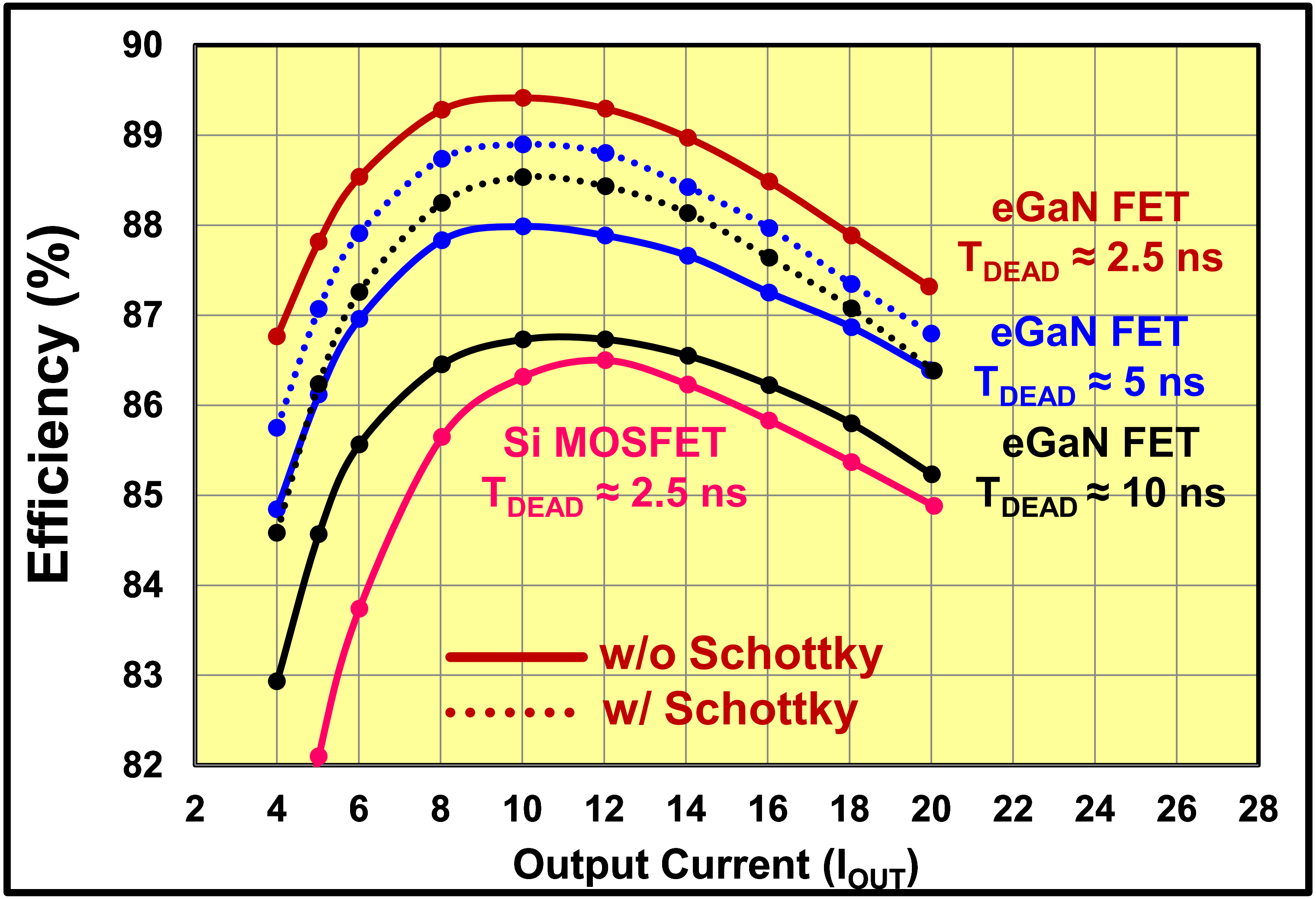


Impact of Dead-time



V_{IN} =12 V, V_{OUT} =1.2 V, I_{OUT}=20 A, and F_S =1 MHz

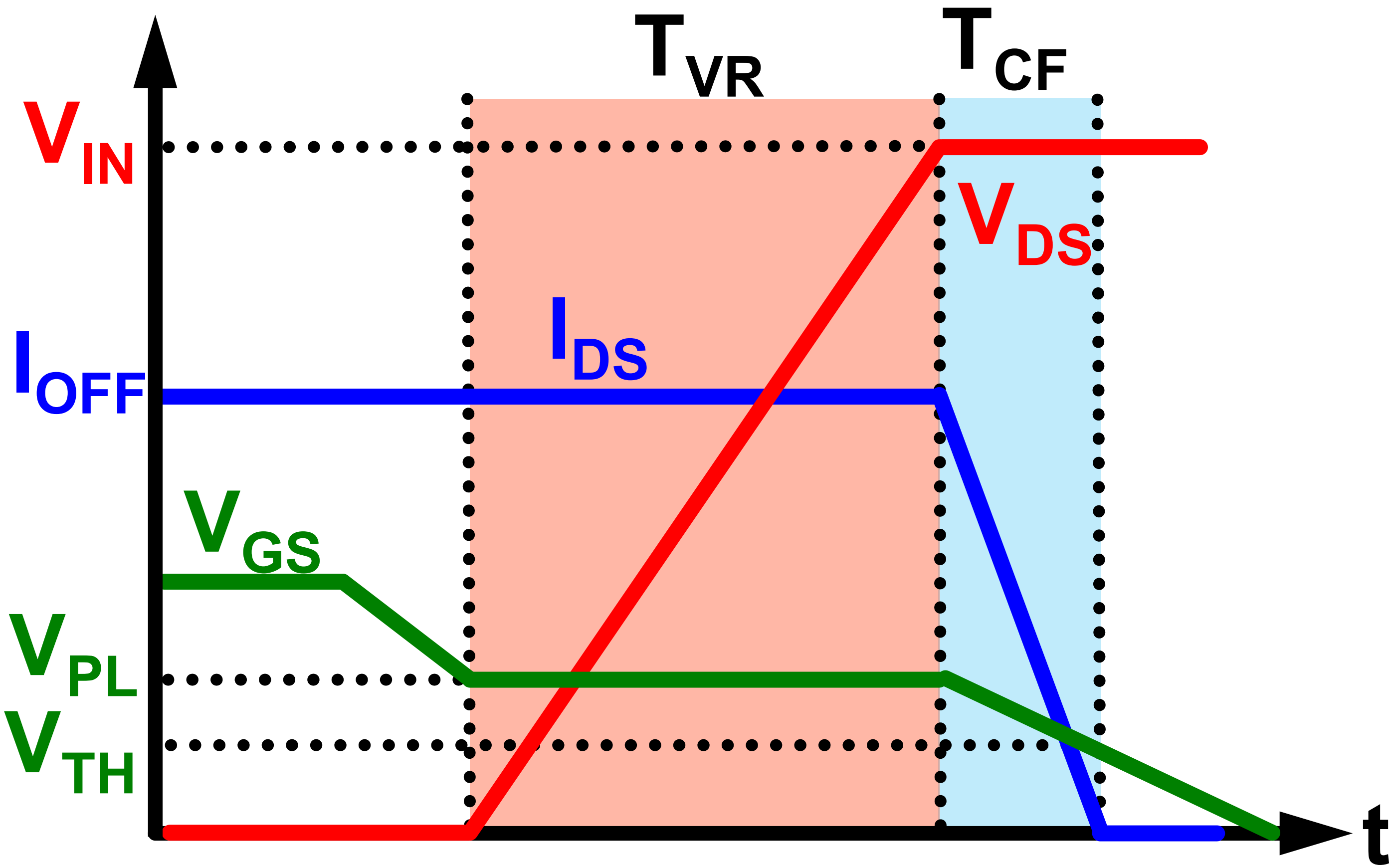
Impact of Dead-time



V_{IN} =12 V, V_{OUT} =1.2 V, and F_S =1 MHz

PCB Layout

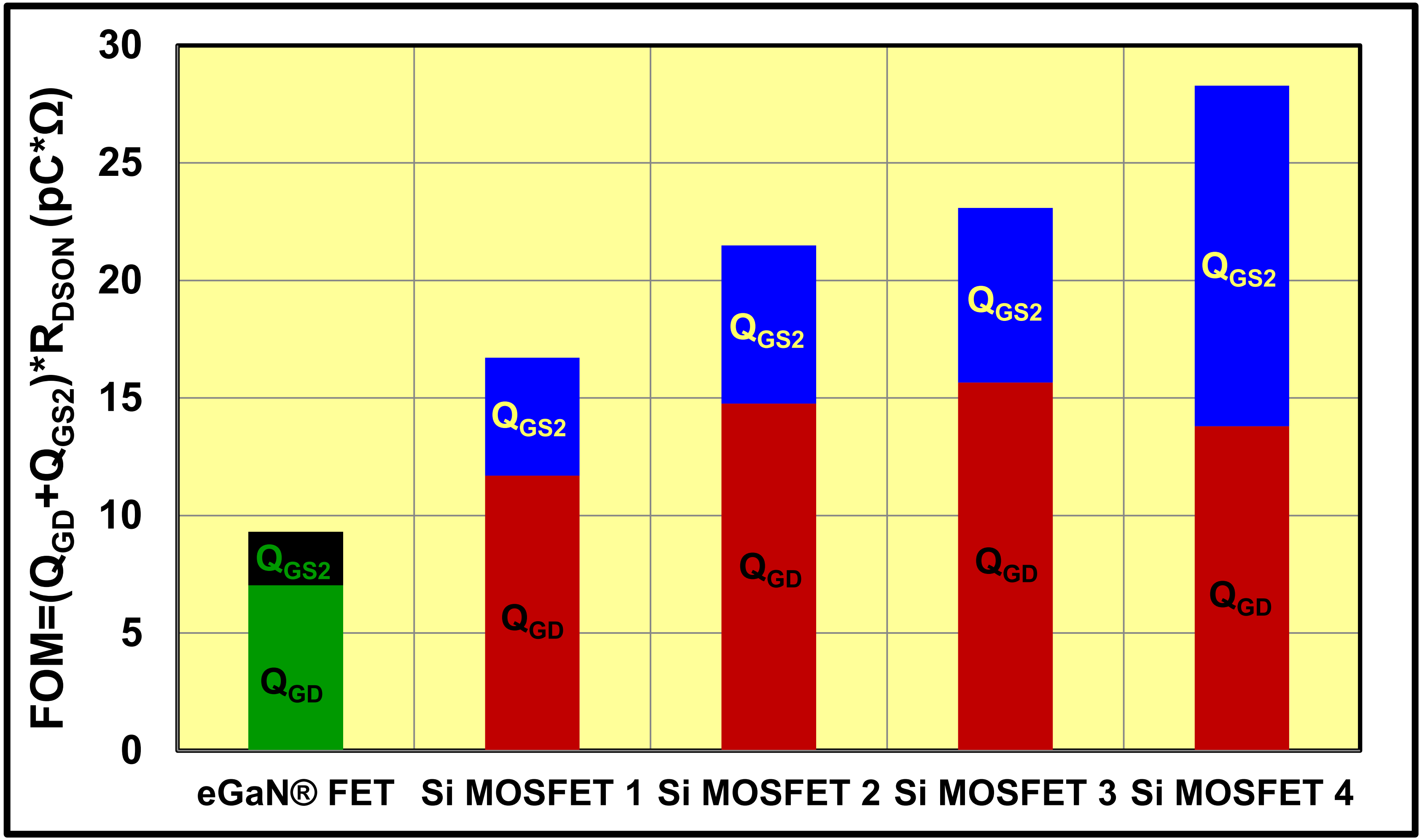
Ideal Hard Switching



$$P_{T_{VR}} \approx \frac{V_{IN} * I_{OFF} * Q_{GD}}{2 * I_G}$$

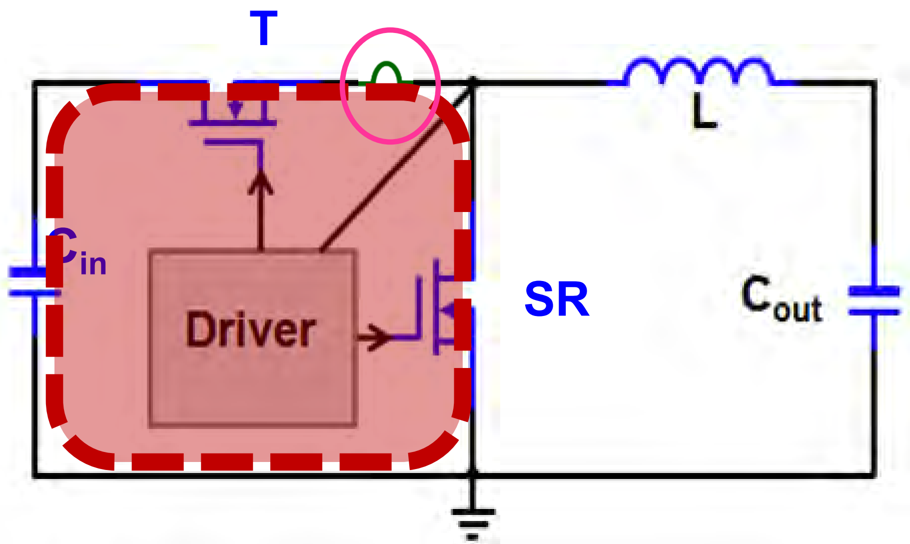
$$P_{T_{CF}} \approx \frac{V_{IN} * I_{OFF} * Q_{GS2}}{2 * I_G}$$

40V Device Comparison



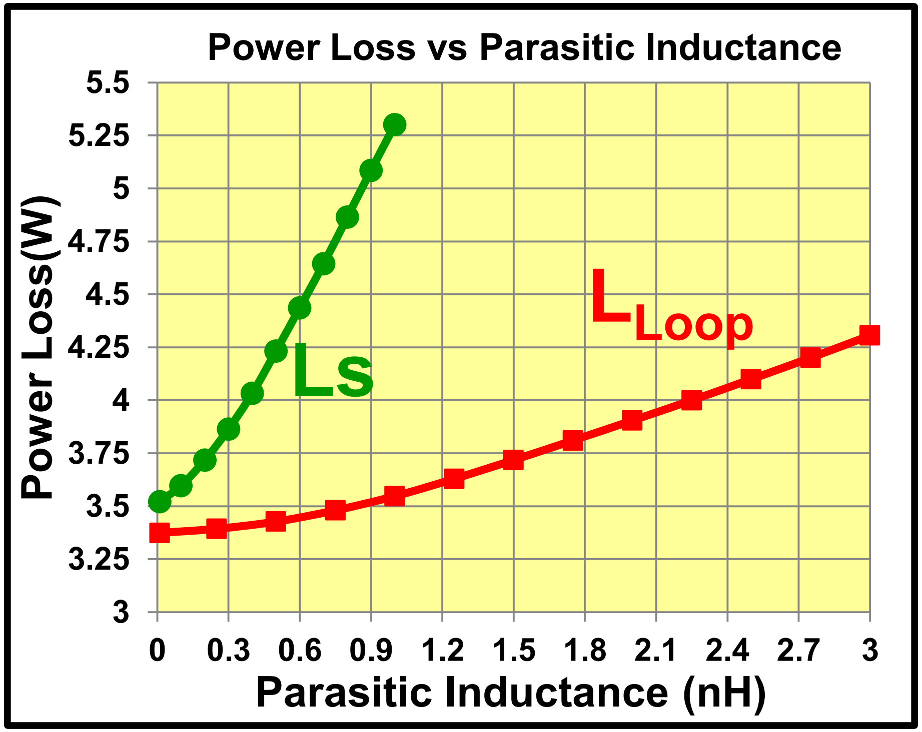
V_{DS}=20 V, I_{DS}= 20 A

Buck Converter Parasitics



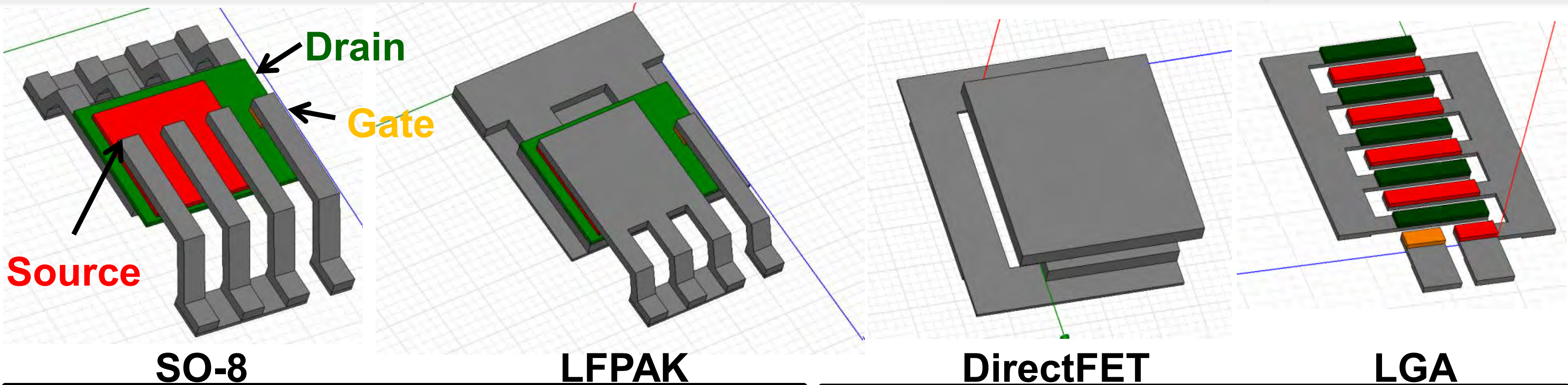
L_S: Common Source Inductance

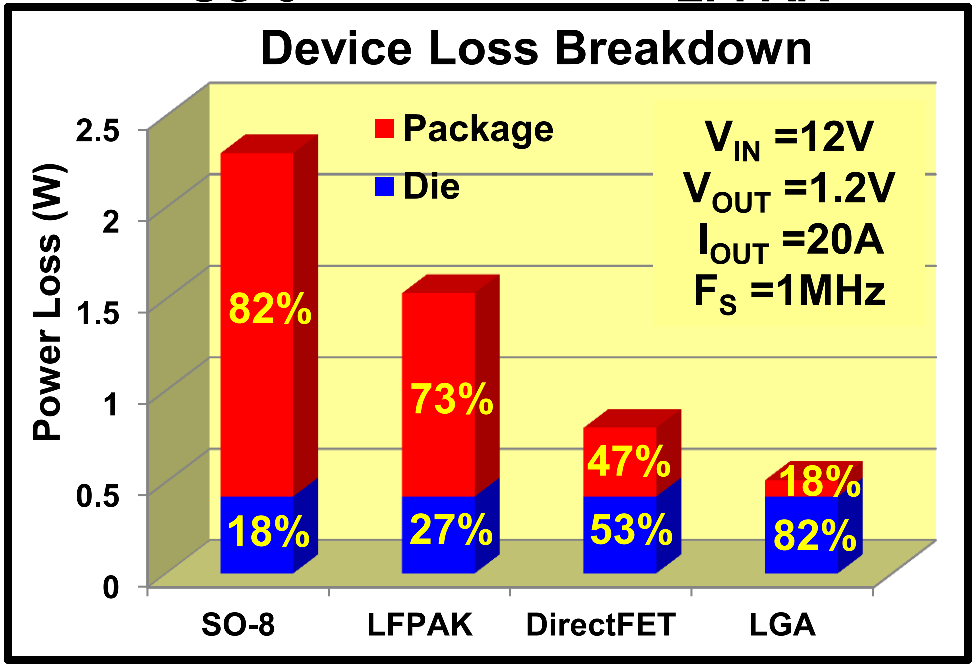
L_{Loop}: High Frequency Power Loop Inductance

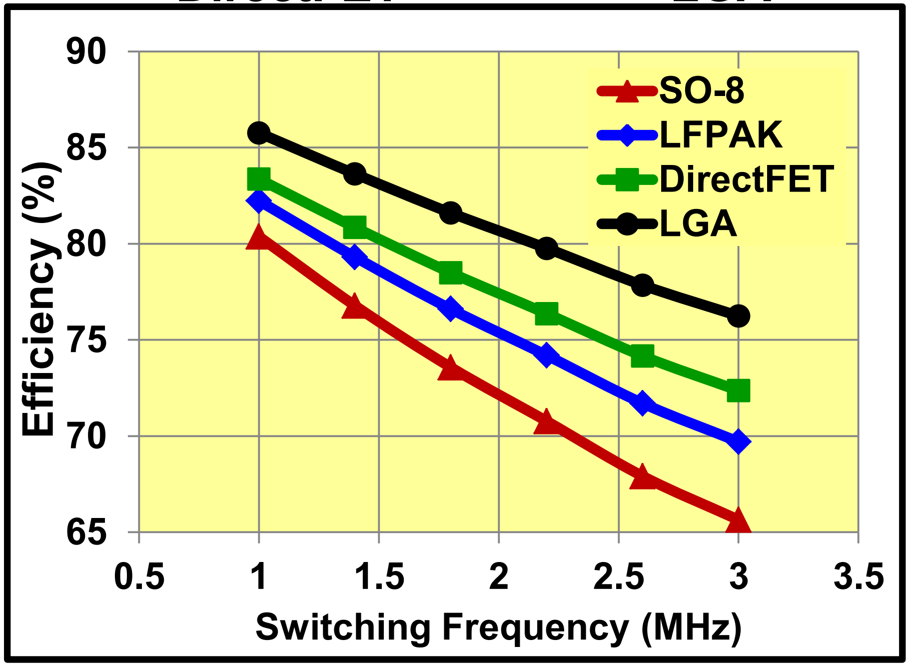


V_{IN}=12 V, V_{OUT}=1.2 V, F_S=1 MHz, I_{OUT}= 20 A

Packaging Evolution

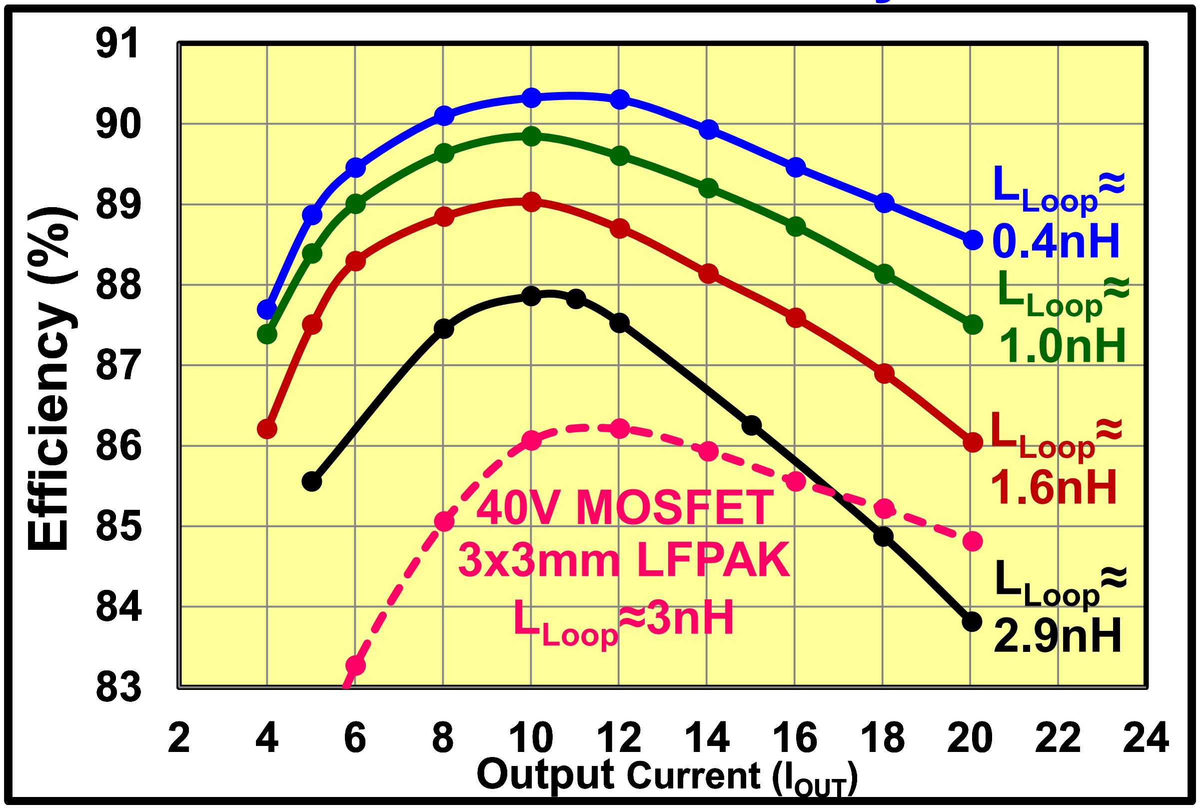






Layout Impact on Efficiency

Measured Efficiency



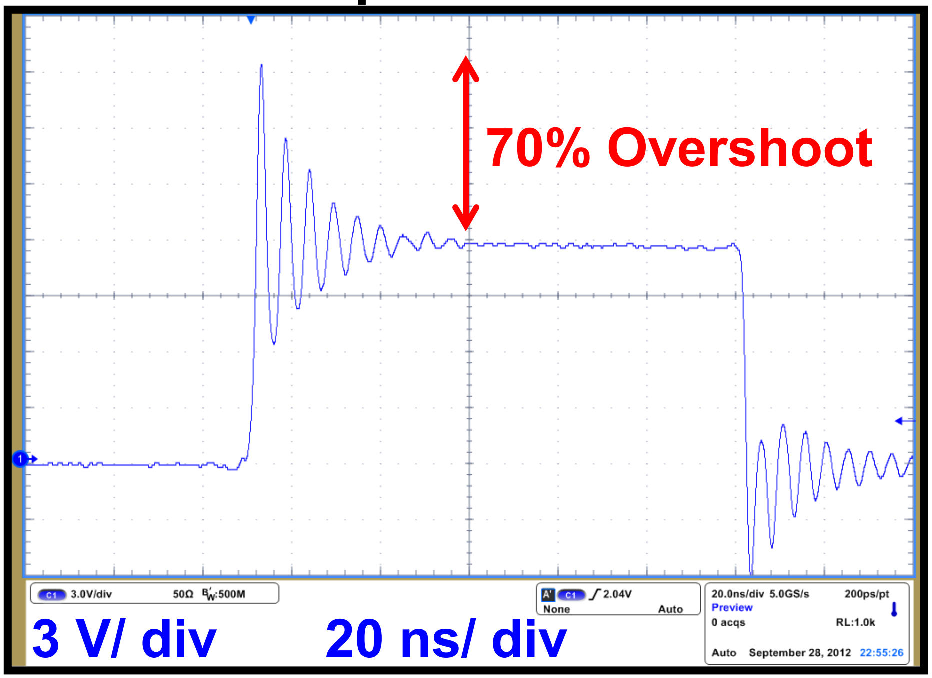
V_{IN}=12 V, V_{OUT}=1.2 V, F_S=1 MHz, L=150 nH

Experimental Prototype

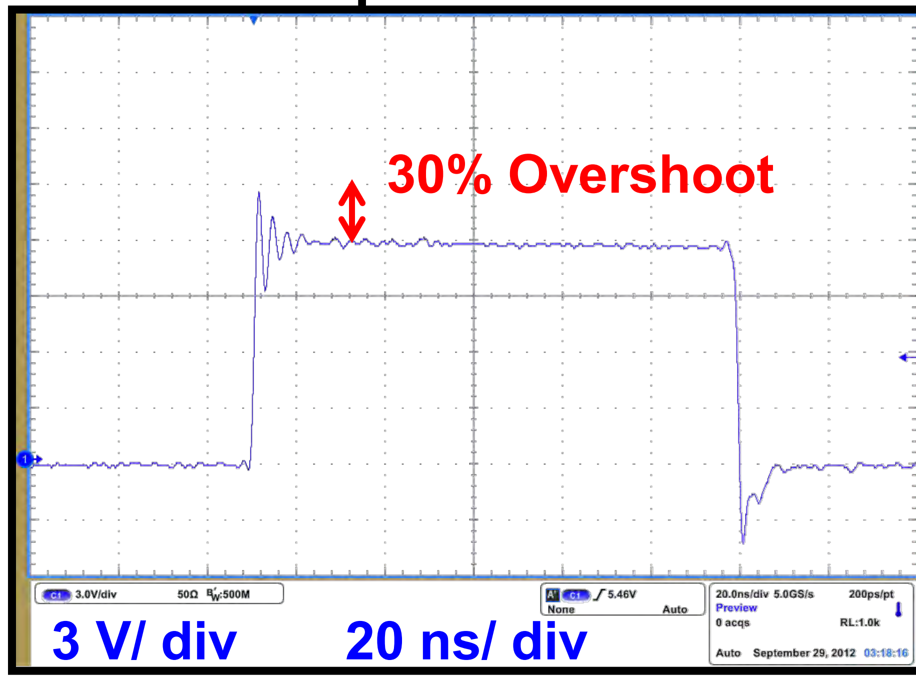
L_{LOOP}≈0.4 nH

Layout Impact on Peak Voltage

L_{Loop}≈1.0 nH



L_{Loop} ≈ 0.4 nH



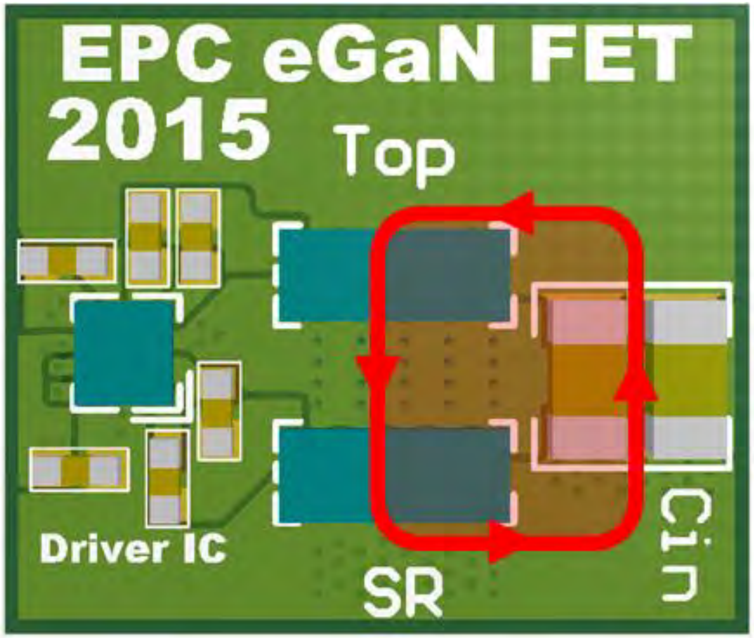
Switching Node Voltage

V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A F_S=1 MHz L=150 nH

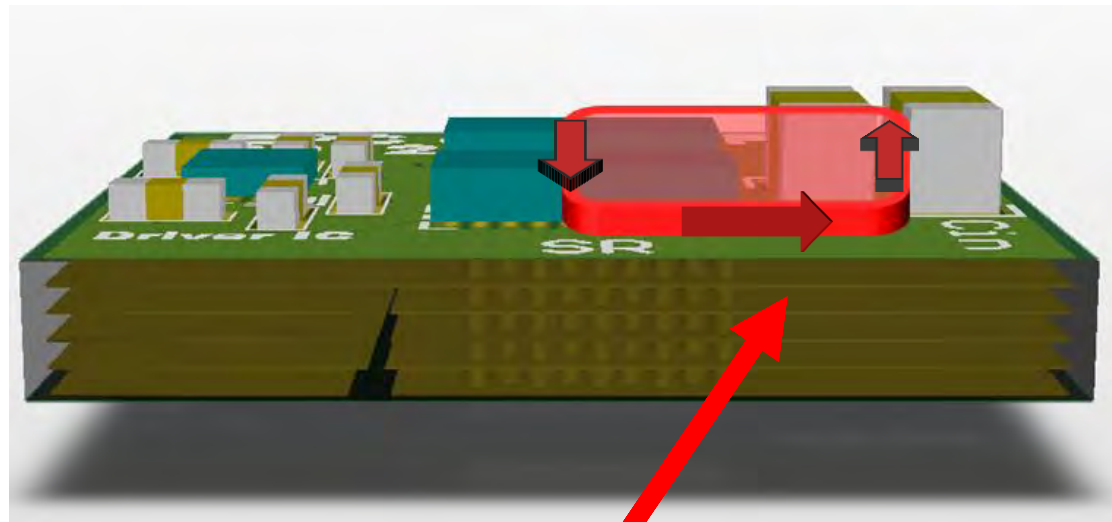
Conventional Lateral Layout

EFFICIENT POWER CONVERSION

Top View

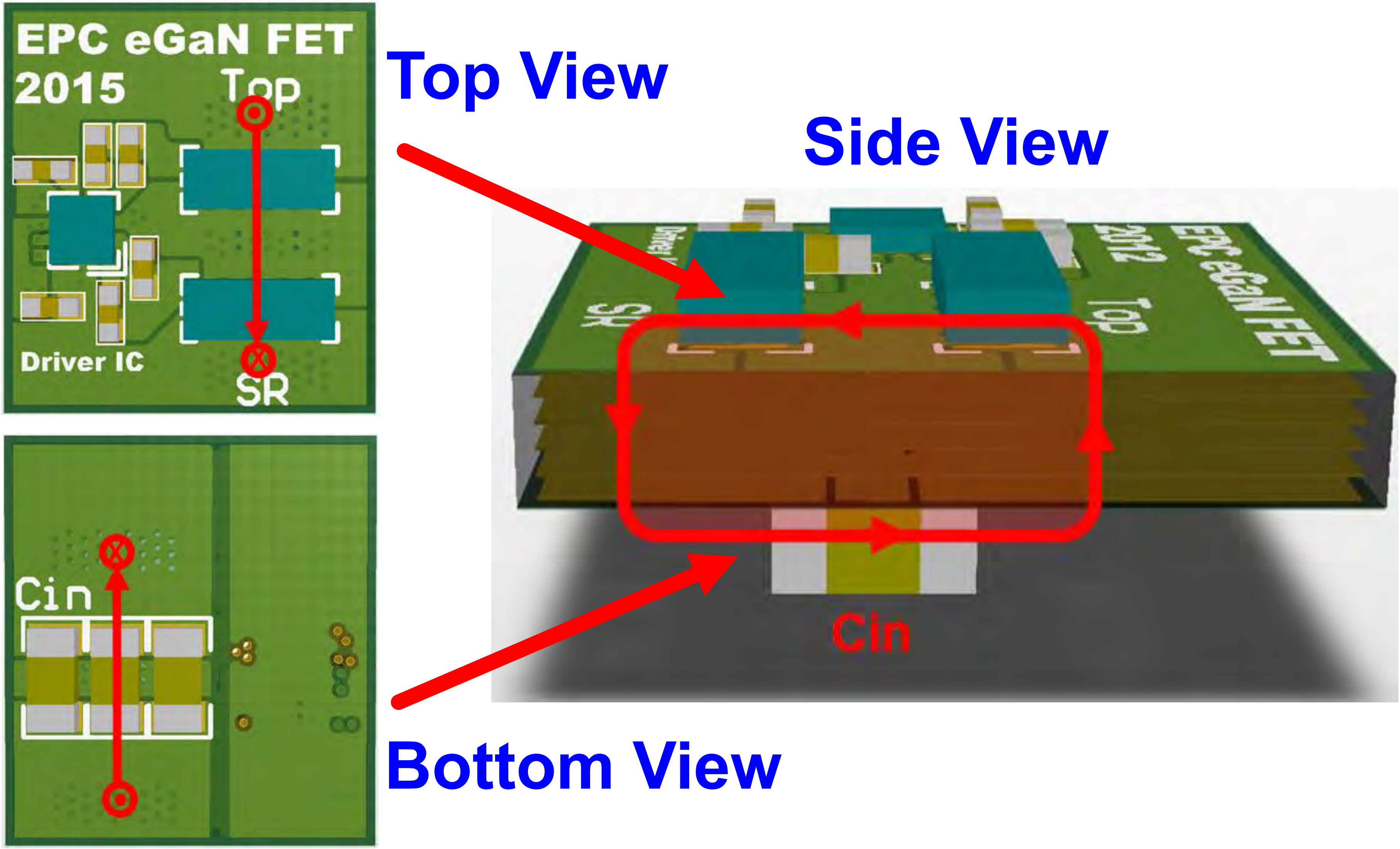


Side View

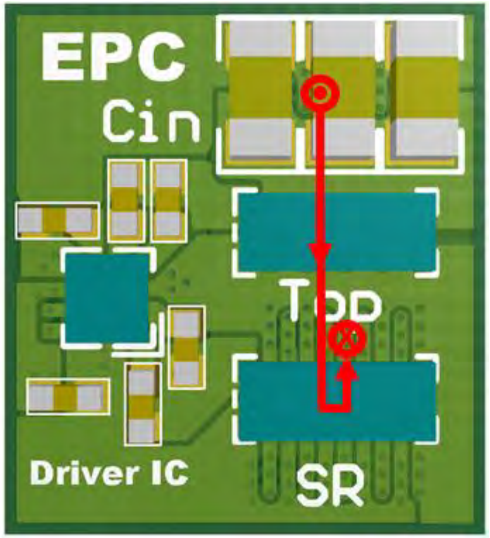


Shield Layer

Conventional Vertical Layout

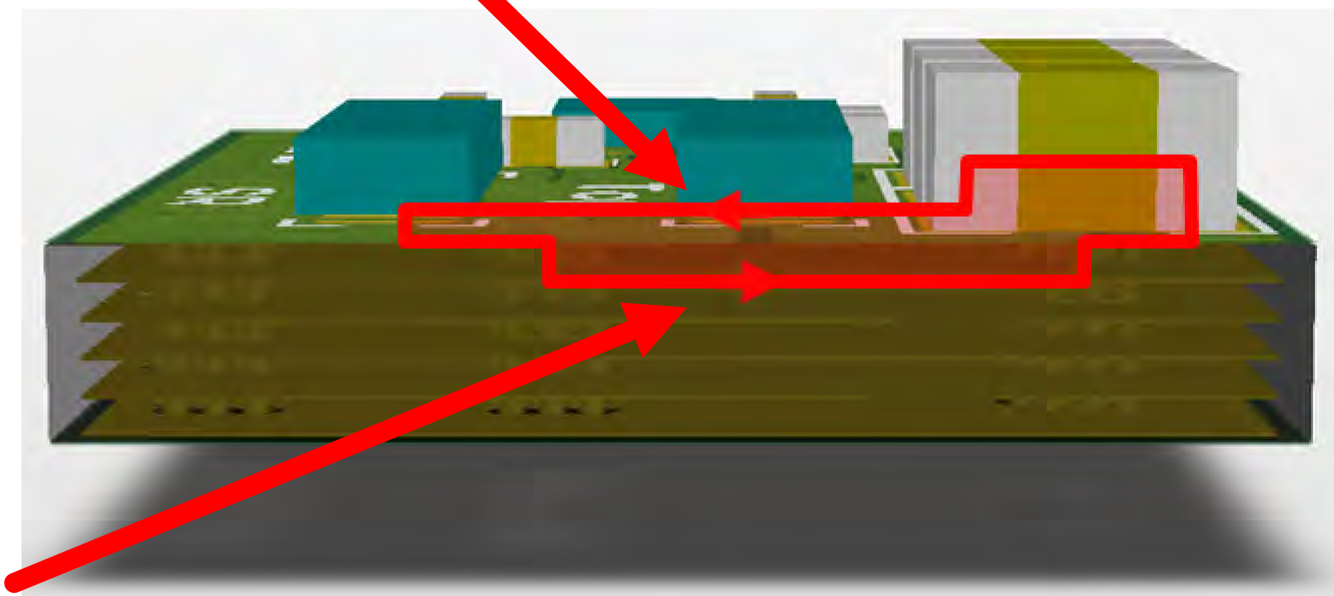


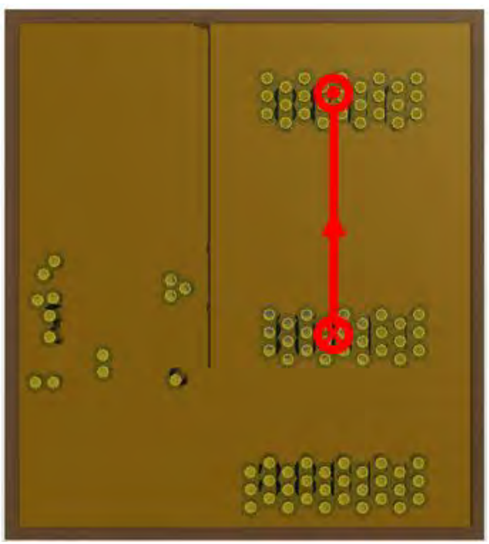
EPC Optimal Layout



Top View

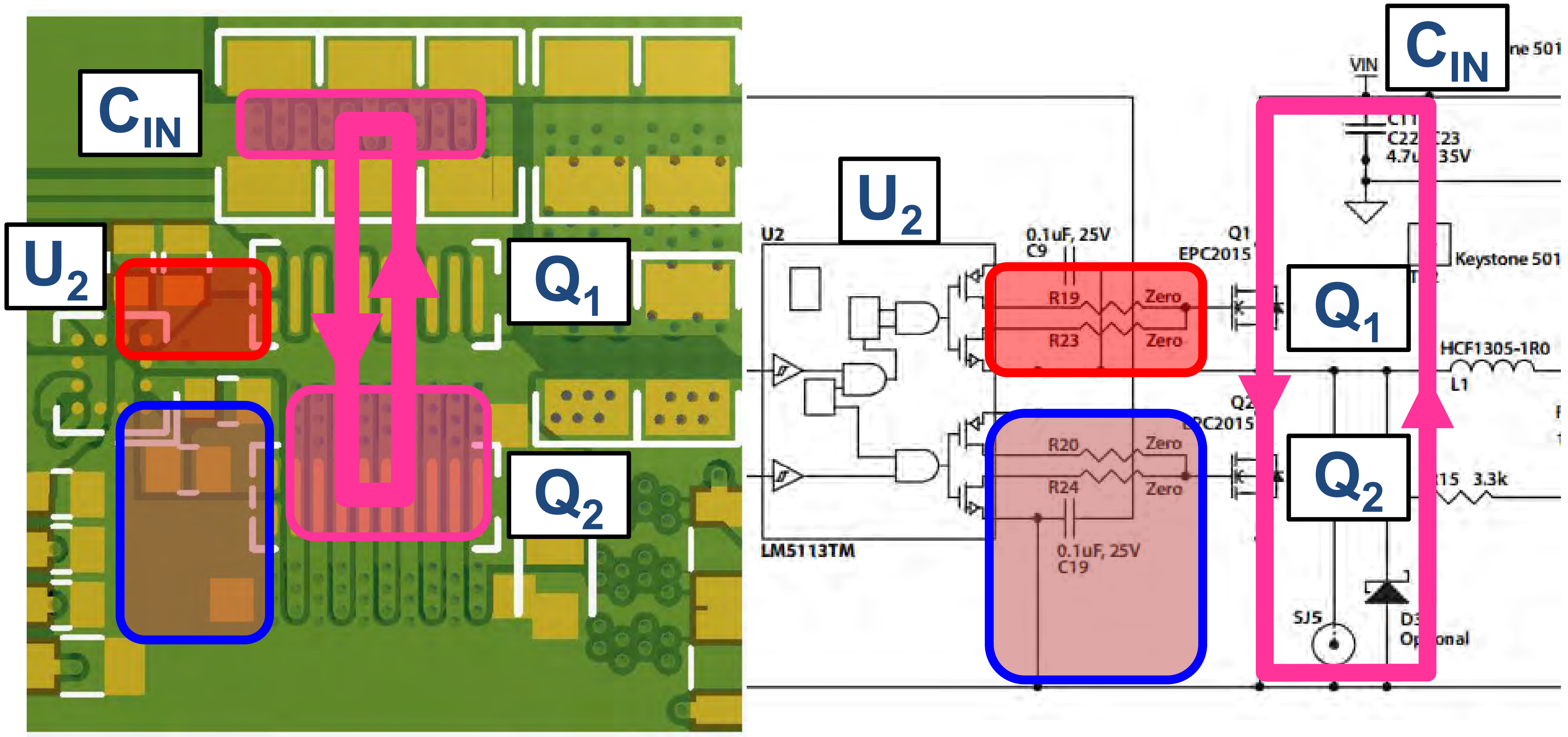
Side View





Top View
Inner Layer 1

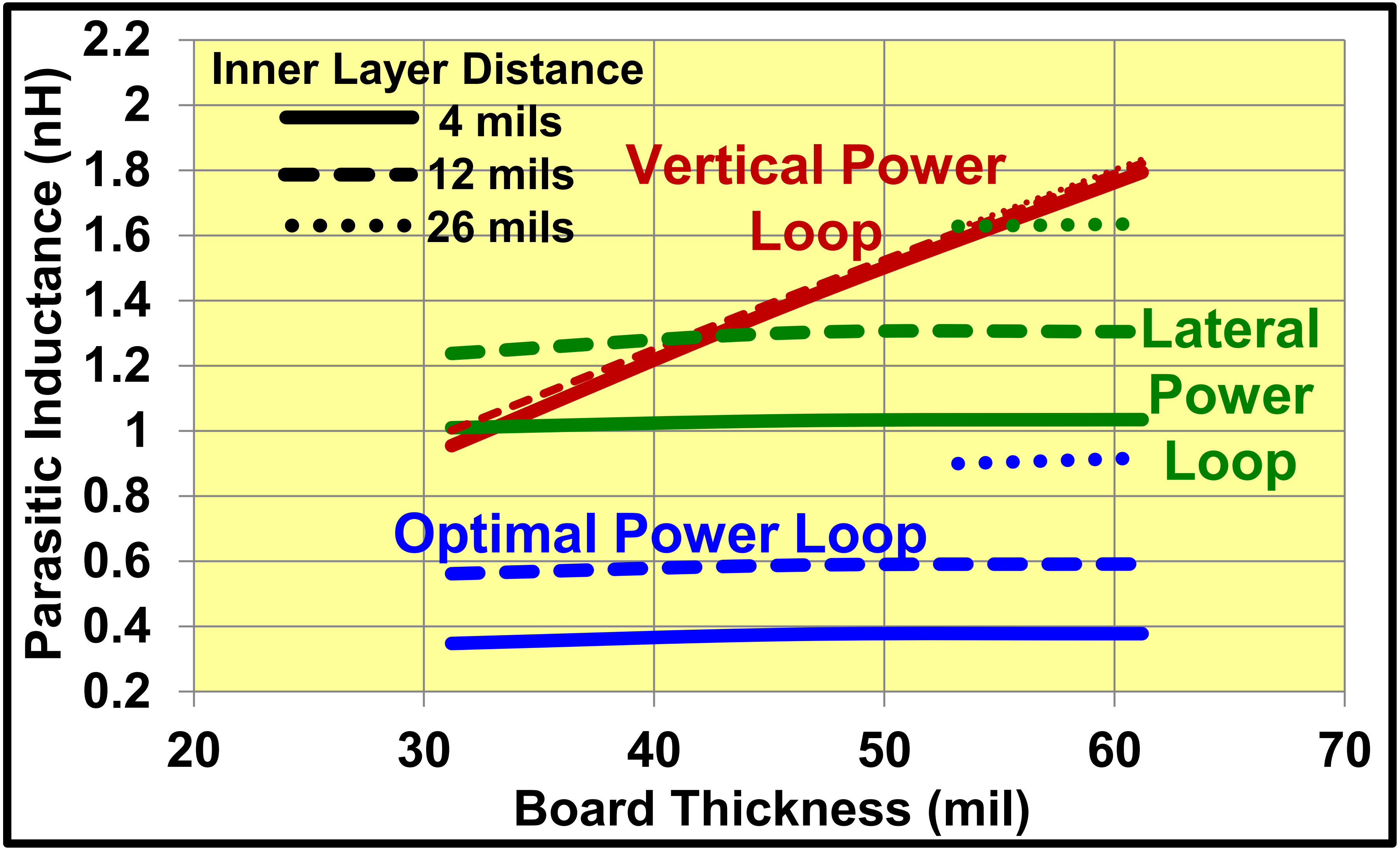
Optimal Layout Implementation



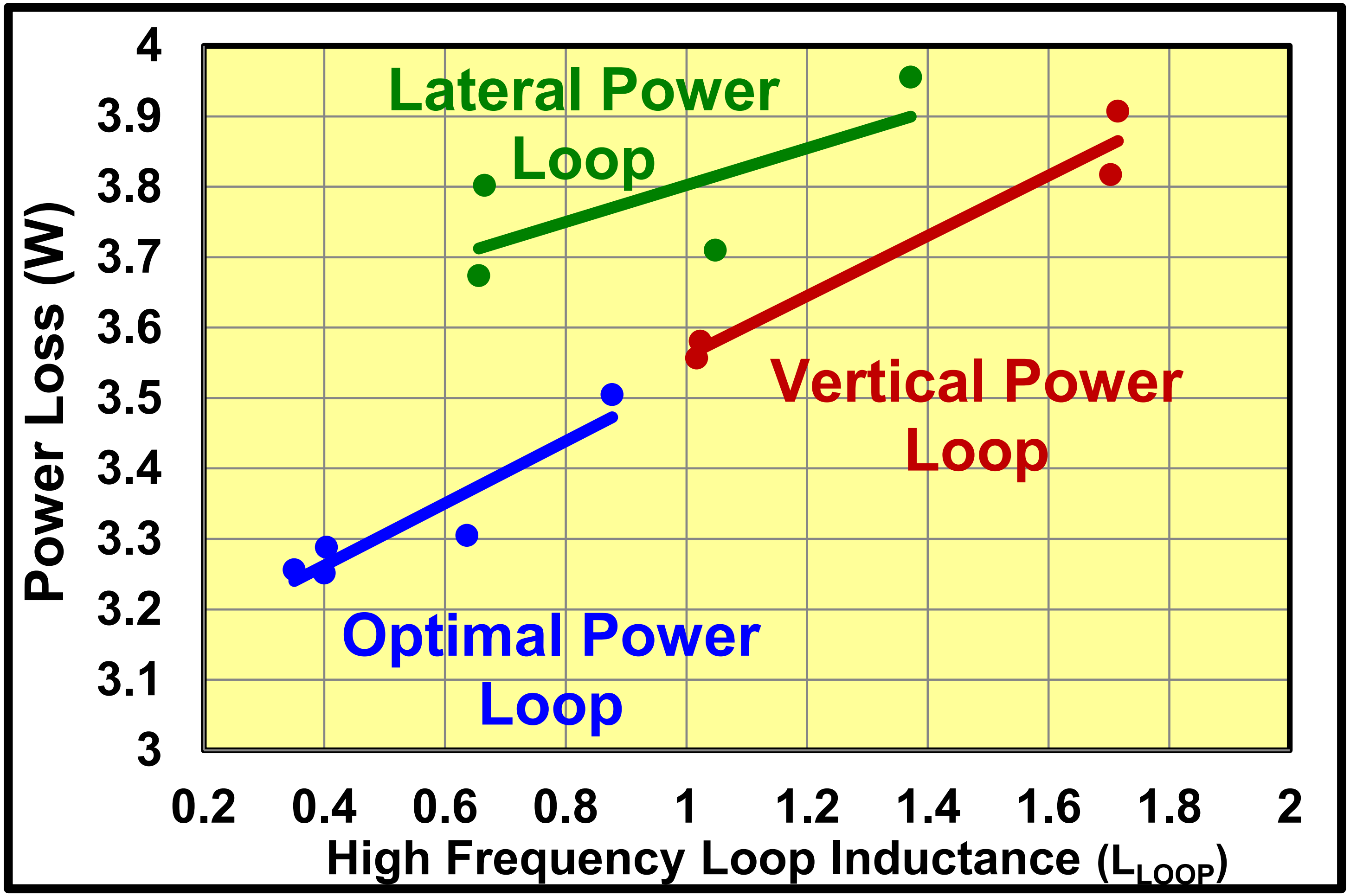
Layout Comparisons

	Lateral Loop	Vertical Loop	Optimal Loop
Single Sided PCB Capability	Yes	No	Yes
Field Self Cancellation	No	Yes	Yes
Inductance Independent of Board Thickness	Yes	No	Yes
Shield Layer Required	Yes	No	No

Layout Inductance Comparison

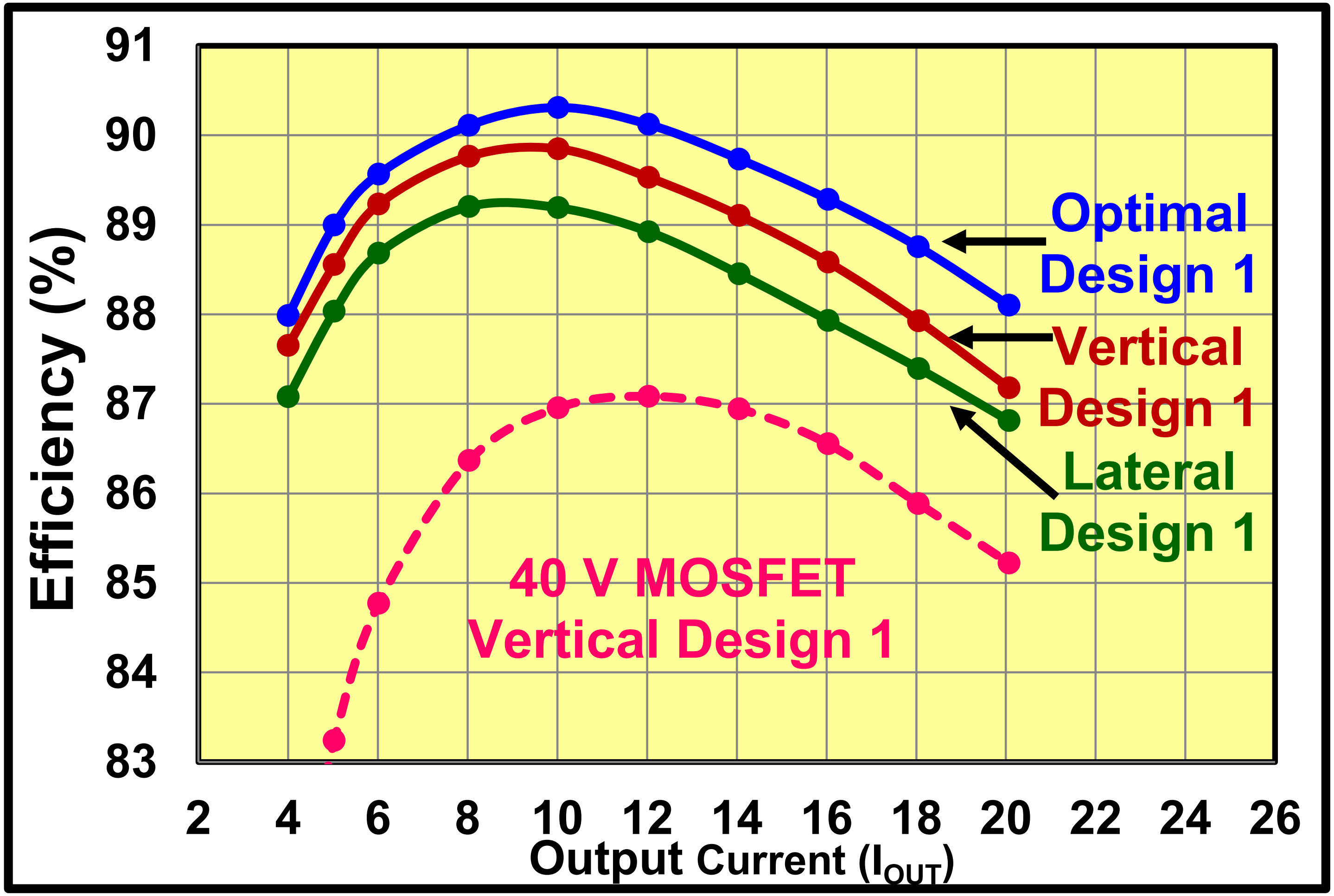


Power Loss Comparison



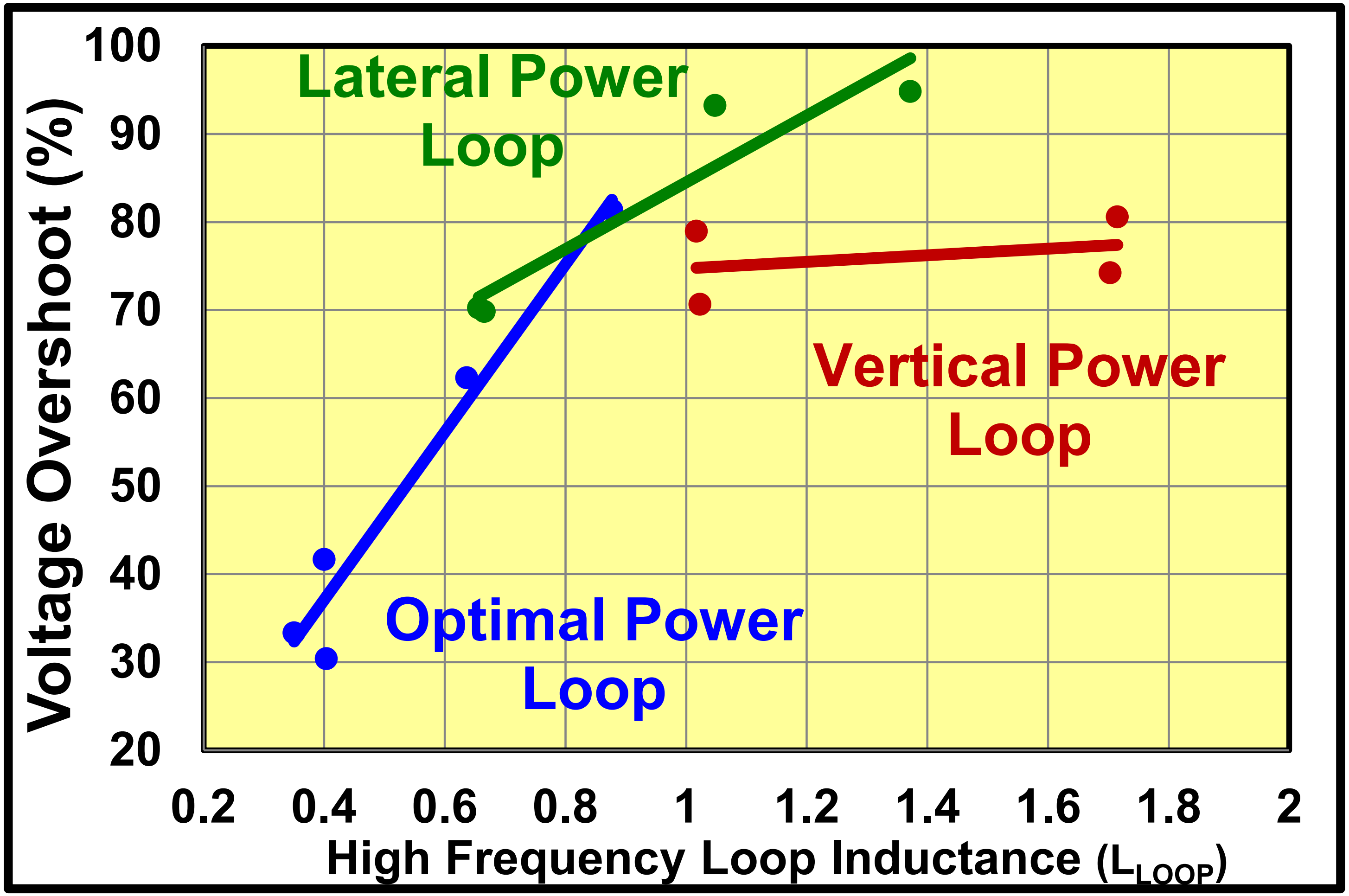
V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A F_S=1 MHz L=300 nH
T/SR: EPC2015 Driver LM5113

Efficiency Comparison



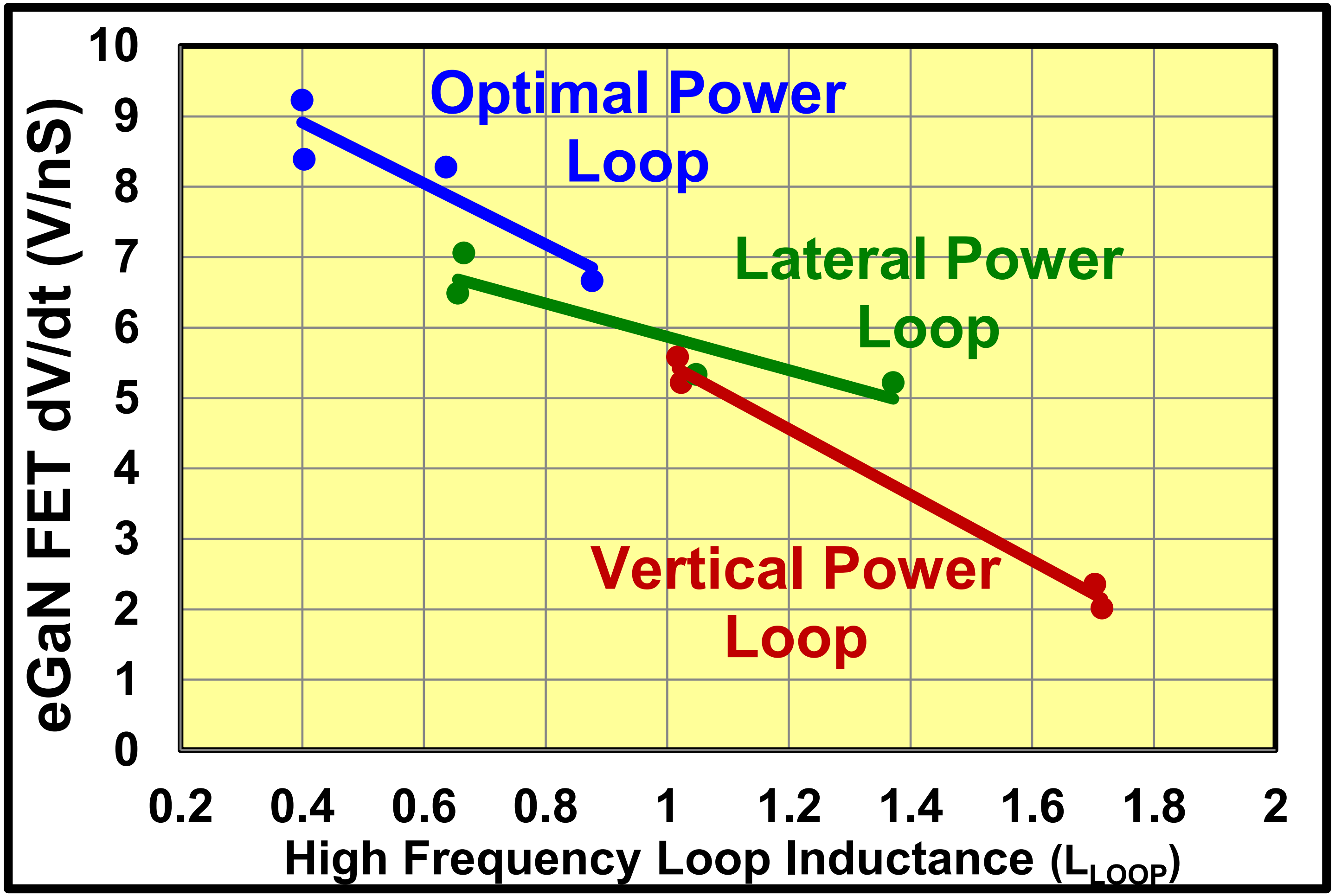
V_{IN}=12 V V_{OUT}=1.2 V F_S=1 MHz L=300 nH
GaN T/SR: EPC2015 Driver LM5113

Voltage Overshoot Comparison



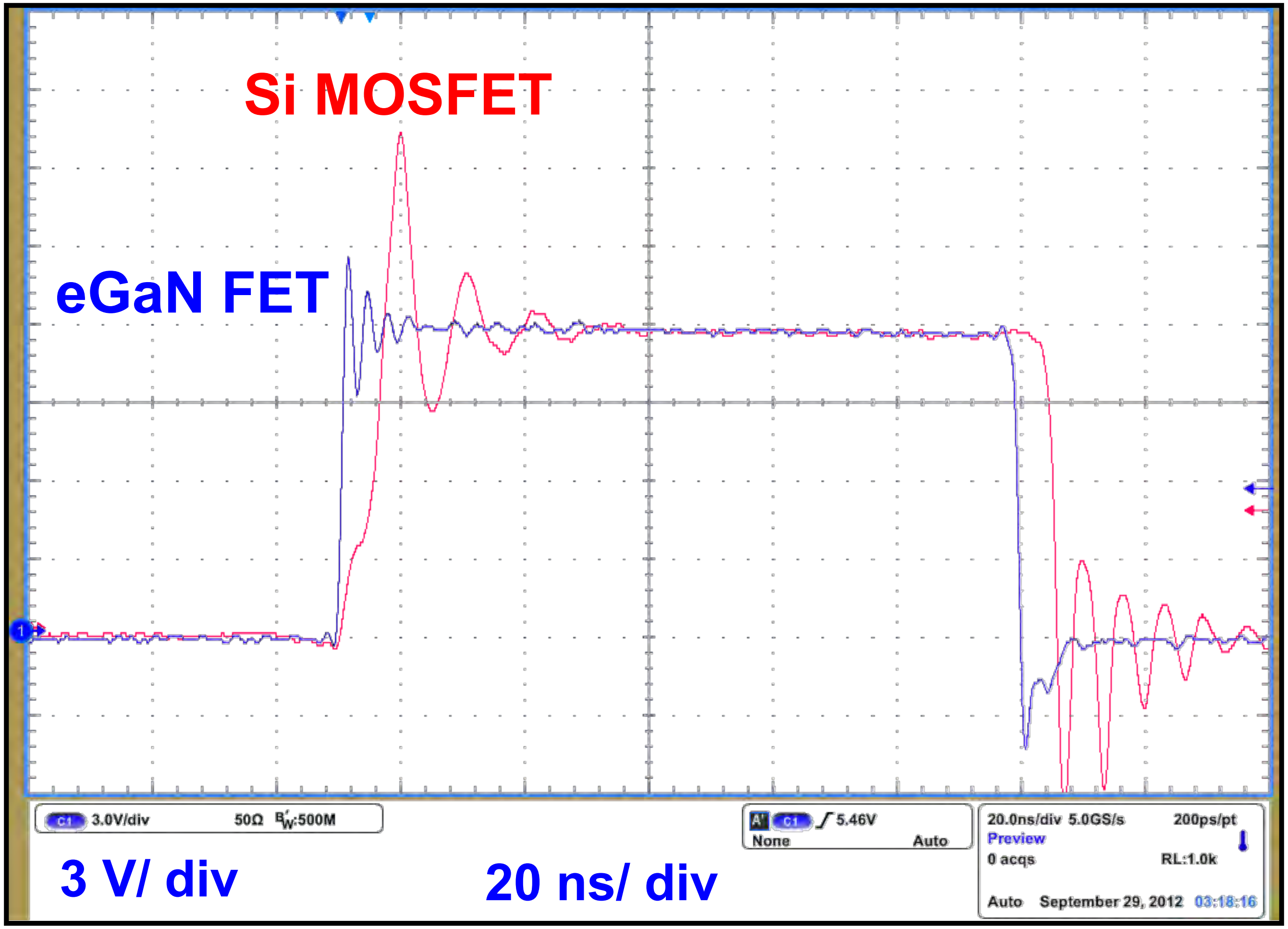
V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A F_S=1 MHz L=300 nH
T/SR: EPC2015 Driver LM5113

Switching Speed Comparison



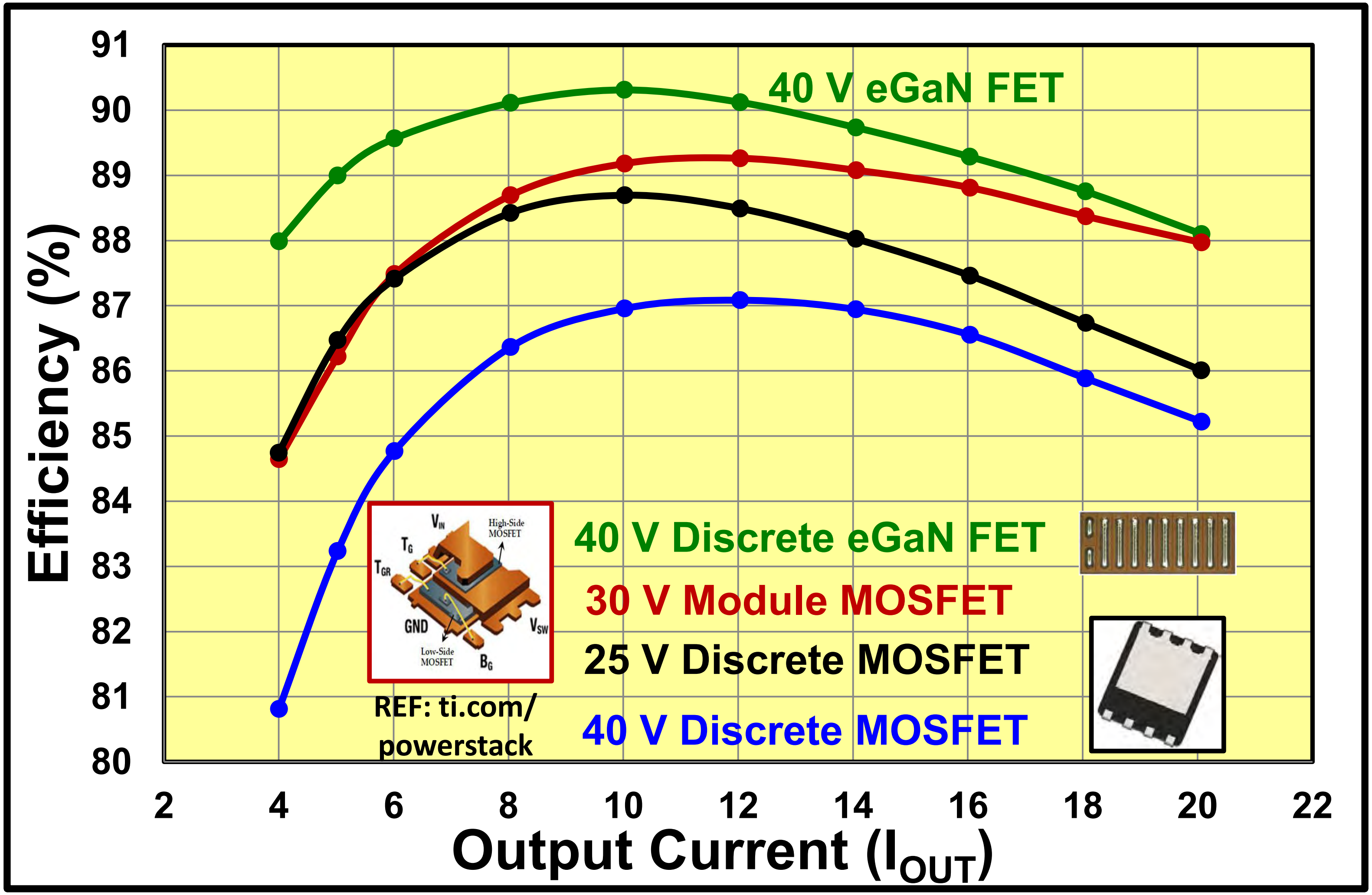
V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A F_S=1 MHz L=300 nH
T/SR: EPC2015 Driver LM5113

eGaN FET vs. MOSFET



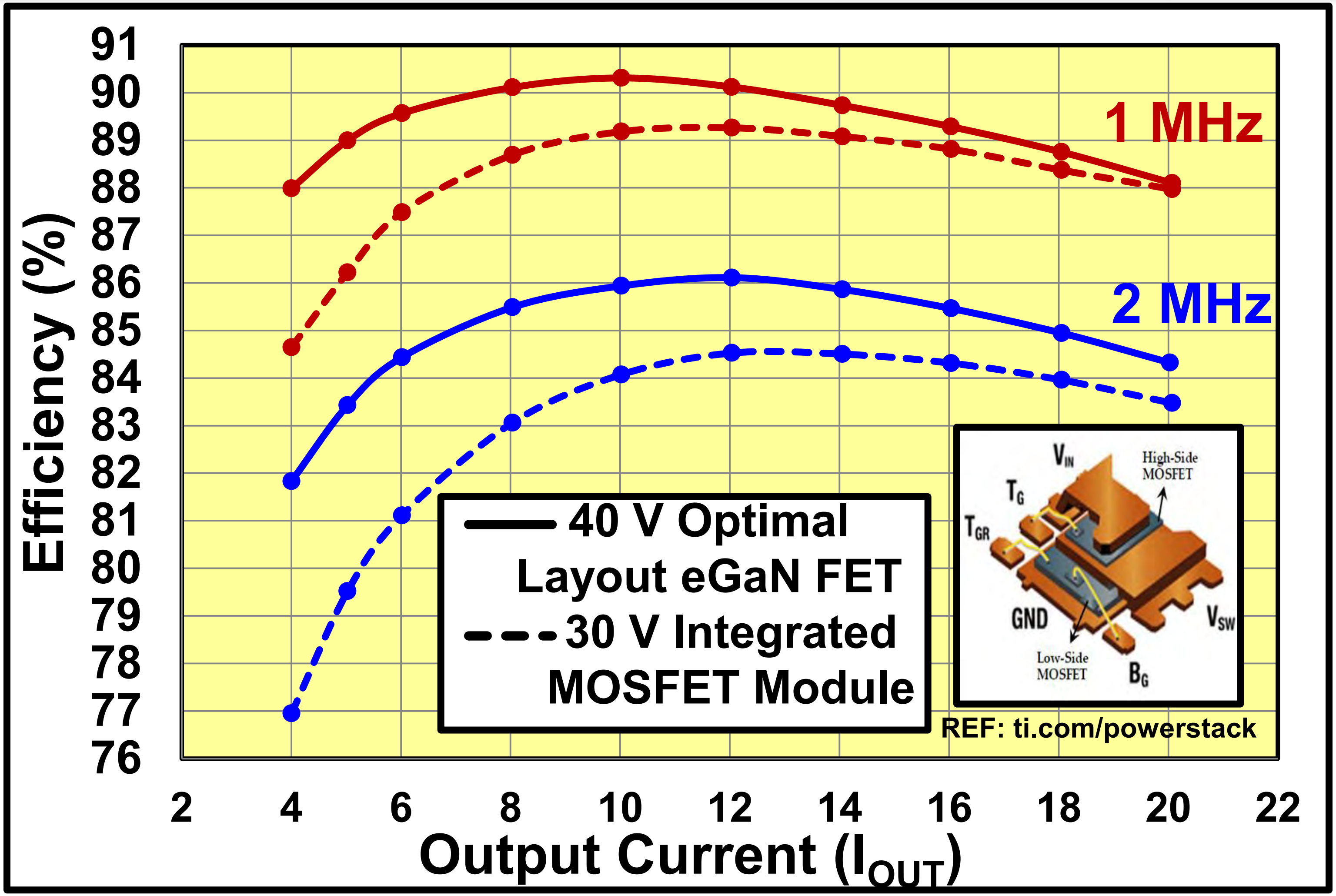
V_{IN}=12 V V_{OUT}=1.2 V I_{OUT}=20 A F_S=1 MHz L=300 nH eGaN FET T/SR: EPC2015
MOSFET T:BSZ097N04 SR:BSZ040N04

eGaN FET vs. MOSFET Efficiency



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

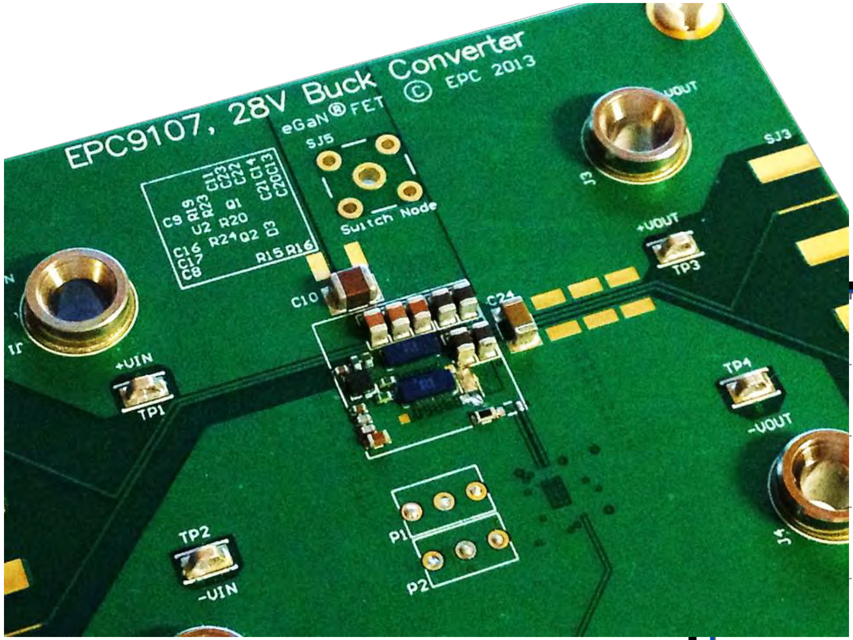
Pushing Frequency with eGaN FETs

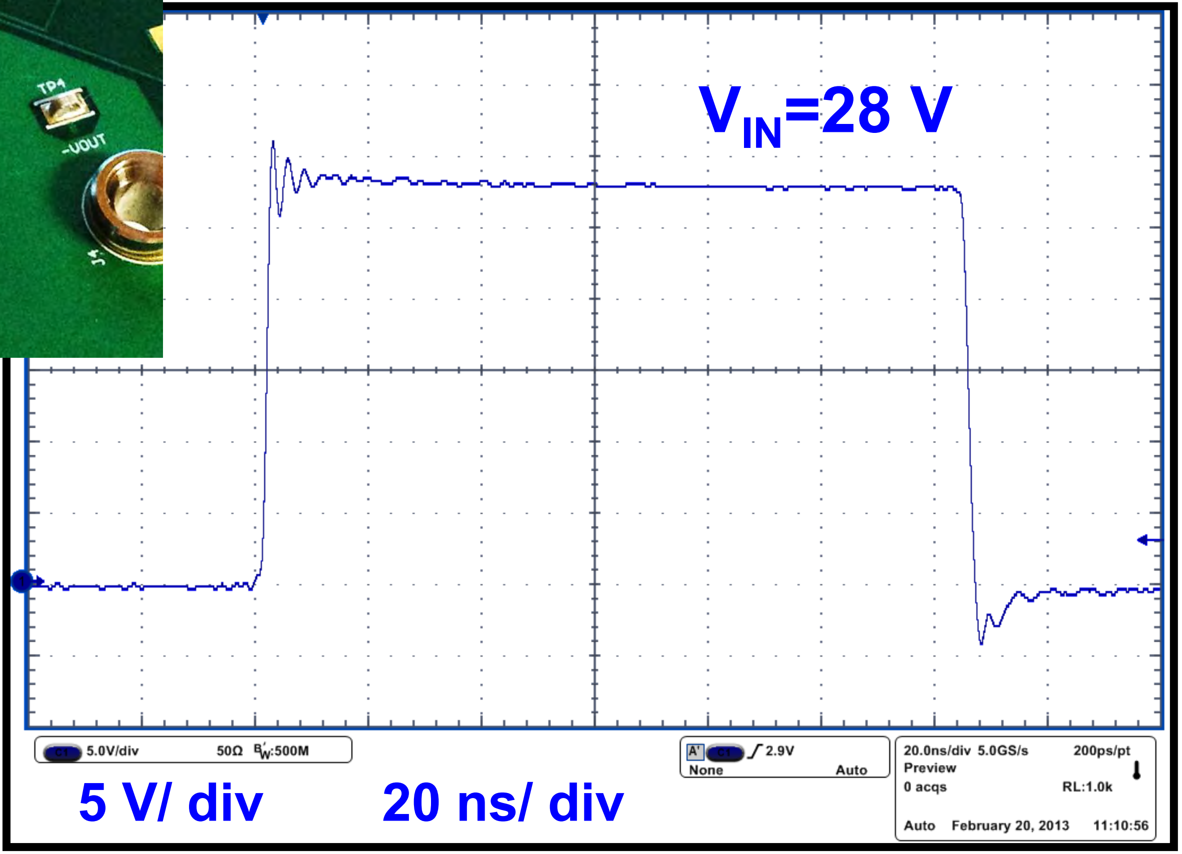


V_{IN}=12 V V_{OUT}=1.2 V L=300 nH

EPC9107 Demonstration Board

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





5 V/ div 20 ns/ div

Switching Node Voltage

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

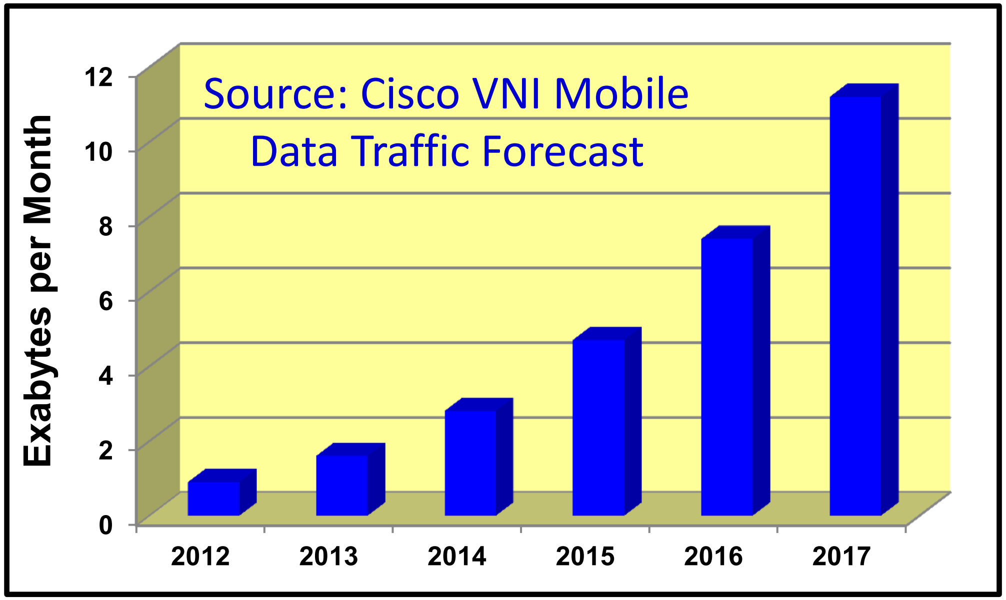
Design Example Agenda

- Envelope Tracking
- 48 V- 12 V Power Conversion
  - Hard Switching Brick
  - Resonant Bus Converter
  - High Current Non-Isolated Buck
- Wireless Power

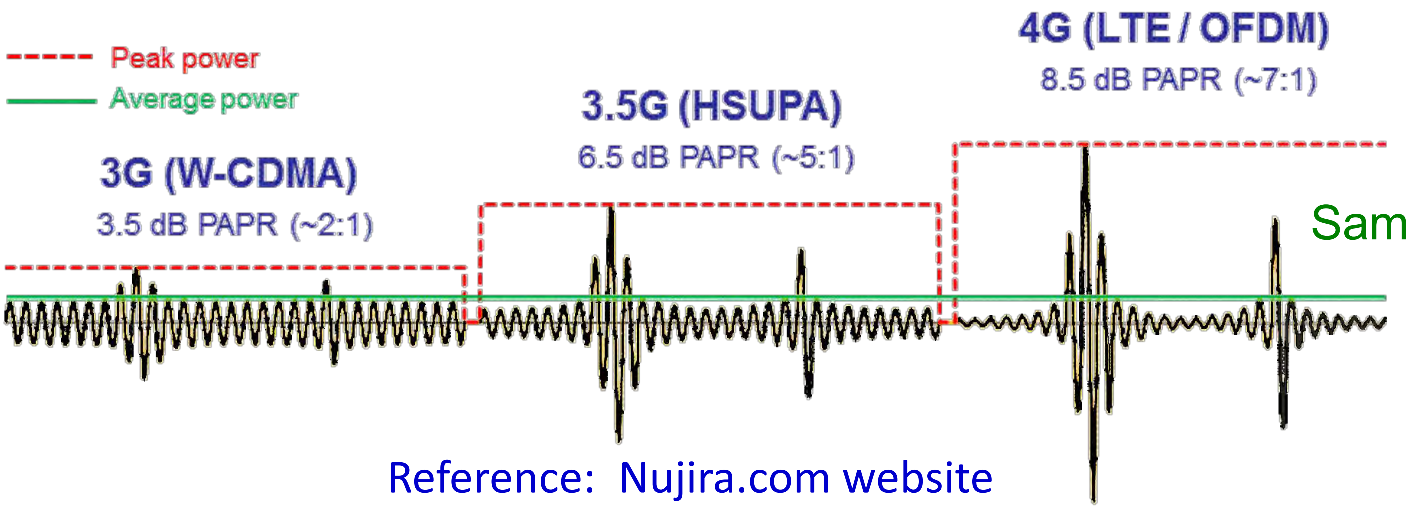
Envelope Tracking (ET)

Why Envelope Tracking?

EFFICIENT POWER CONVERSION



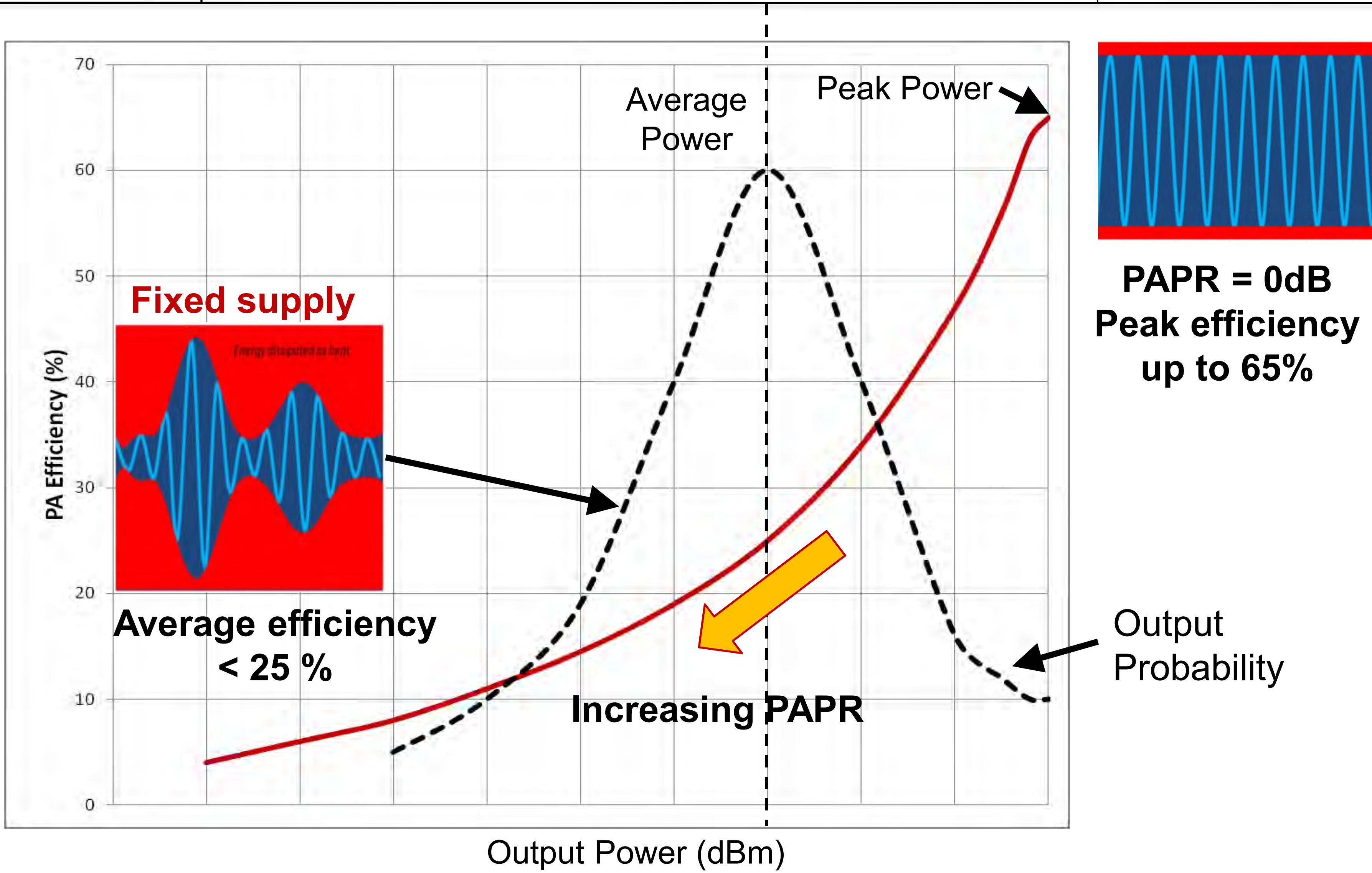
66% Compound annual growth rate (CAGR)



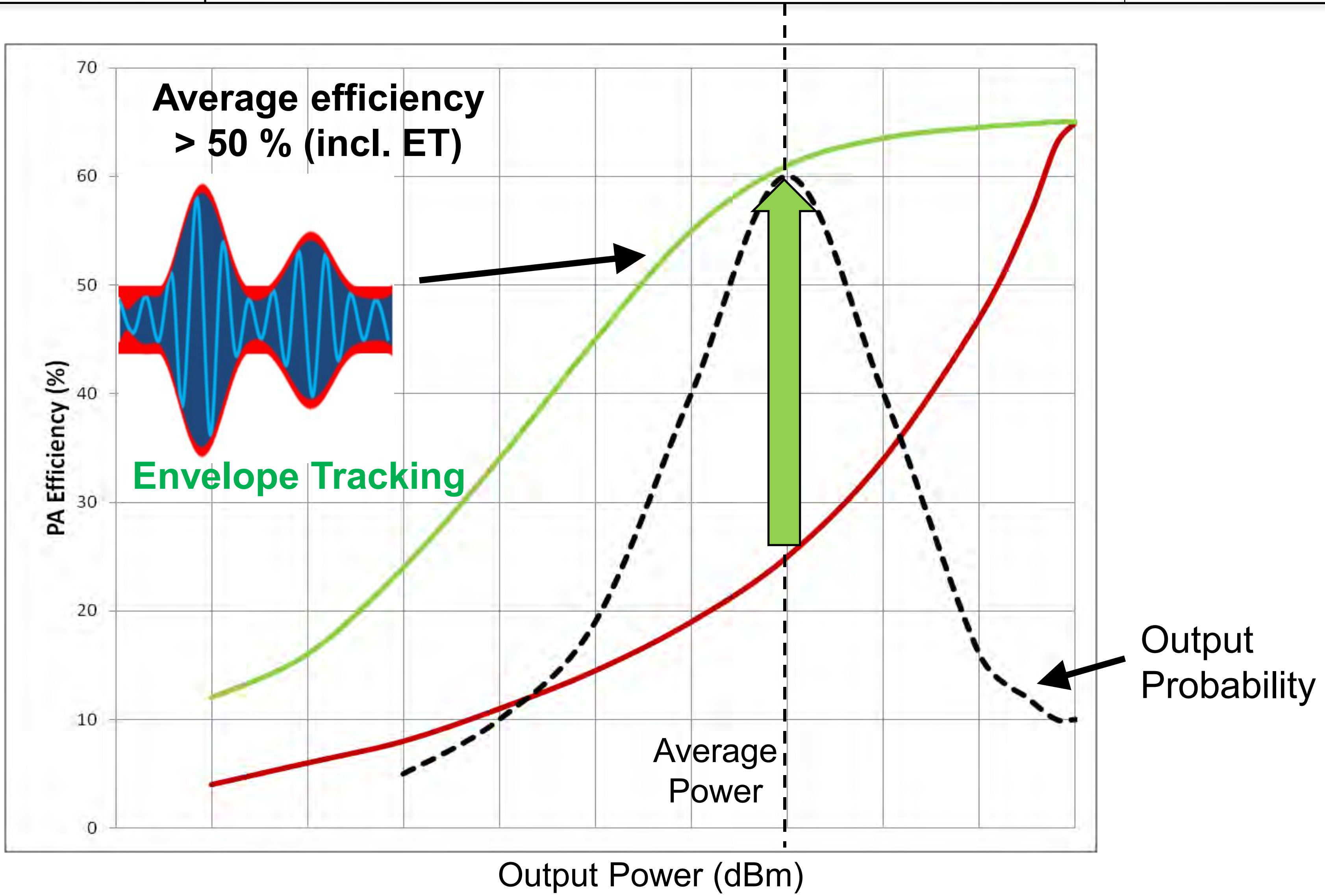
Same average

Reference: Nujira.com website

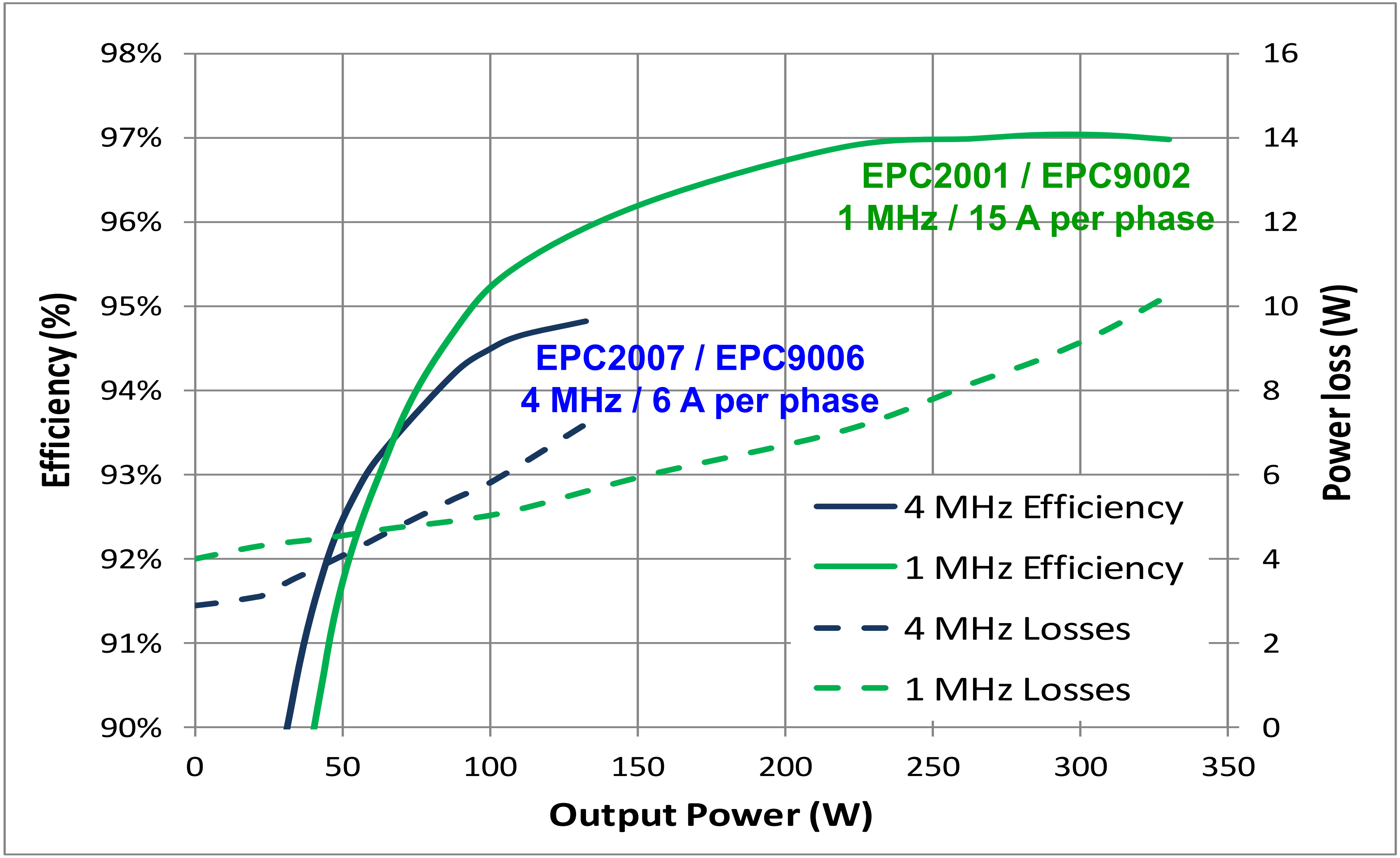
Peak to Average Power Ratio (PAPR)



Effect of Envelope Tracking

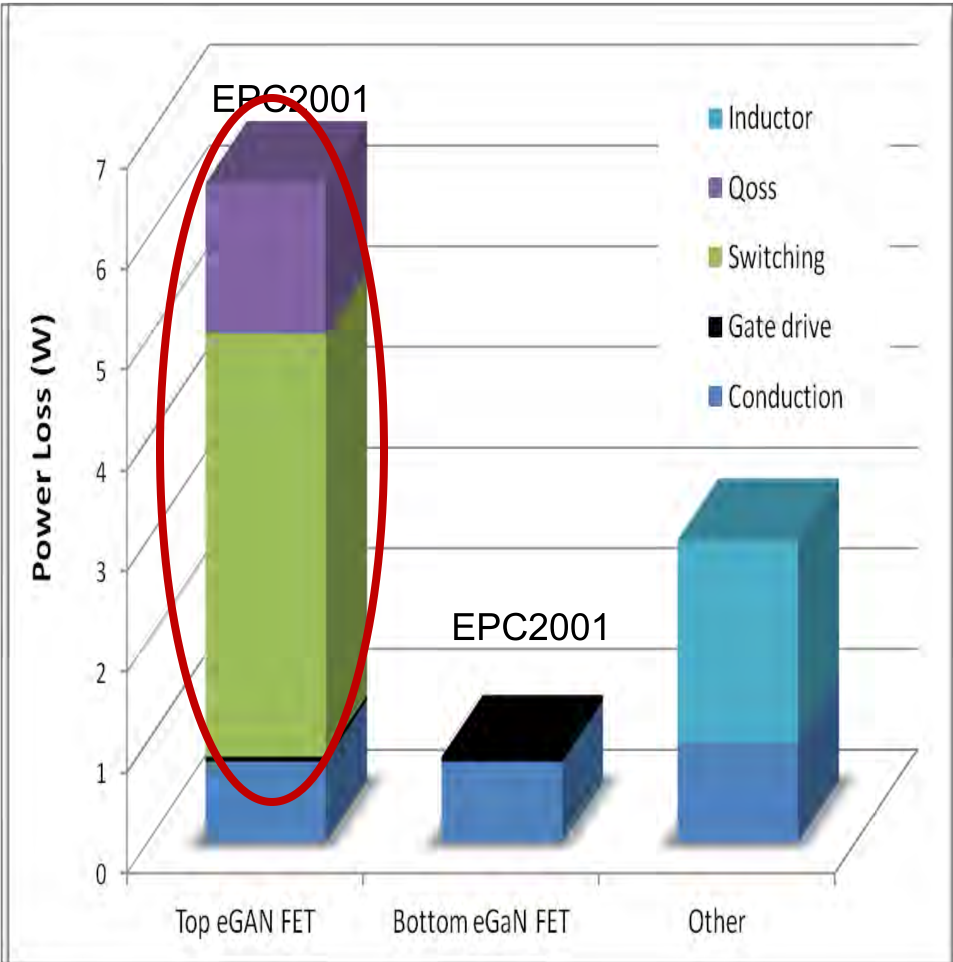


Efficiency Results

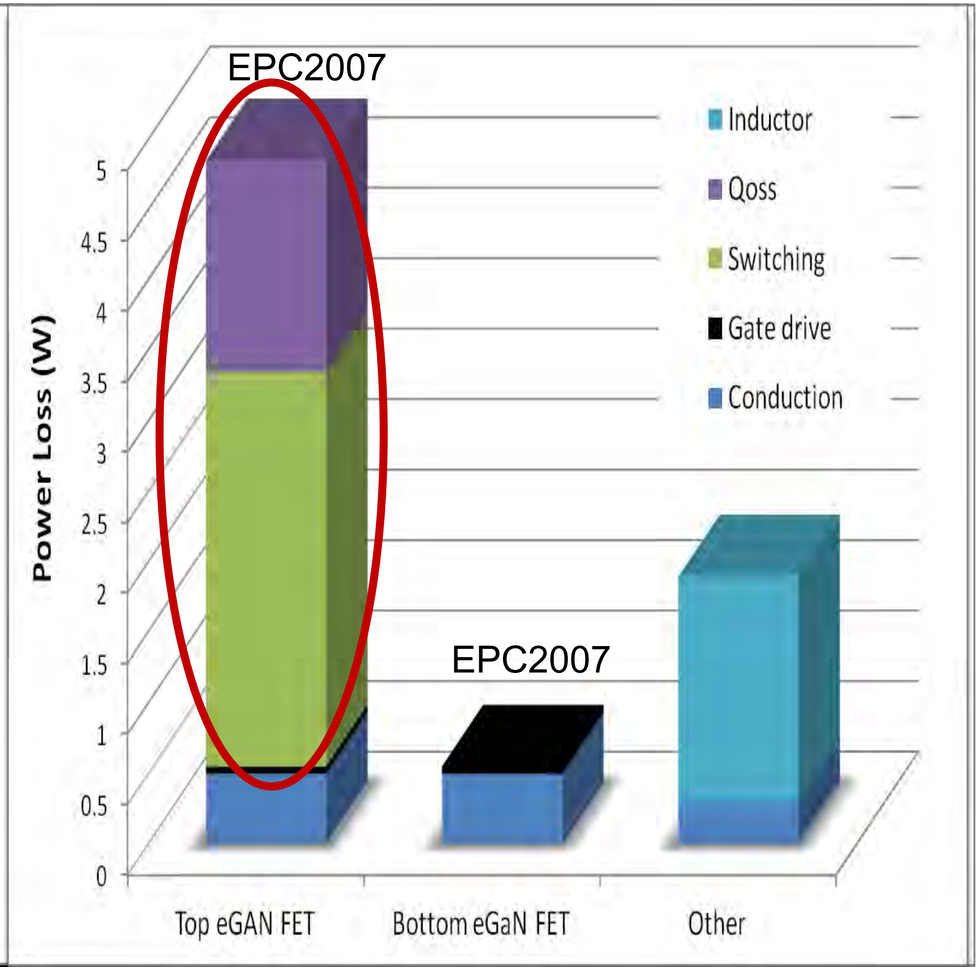


V_{IN}=45 V, V_{OUT}=22 V

Loss Breakdown

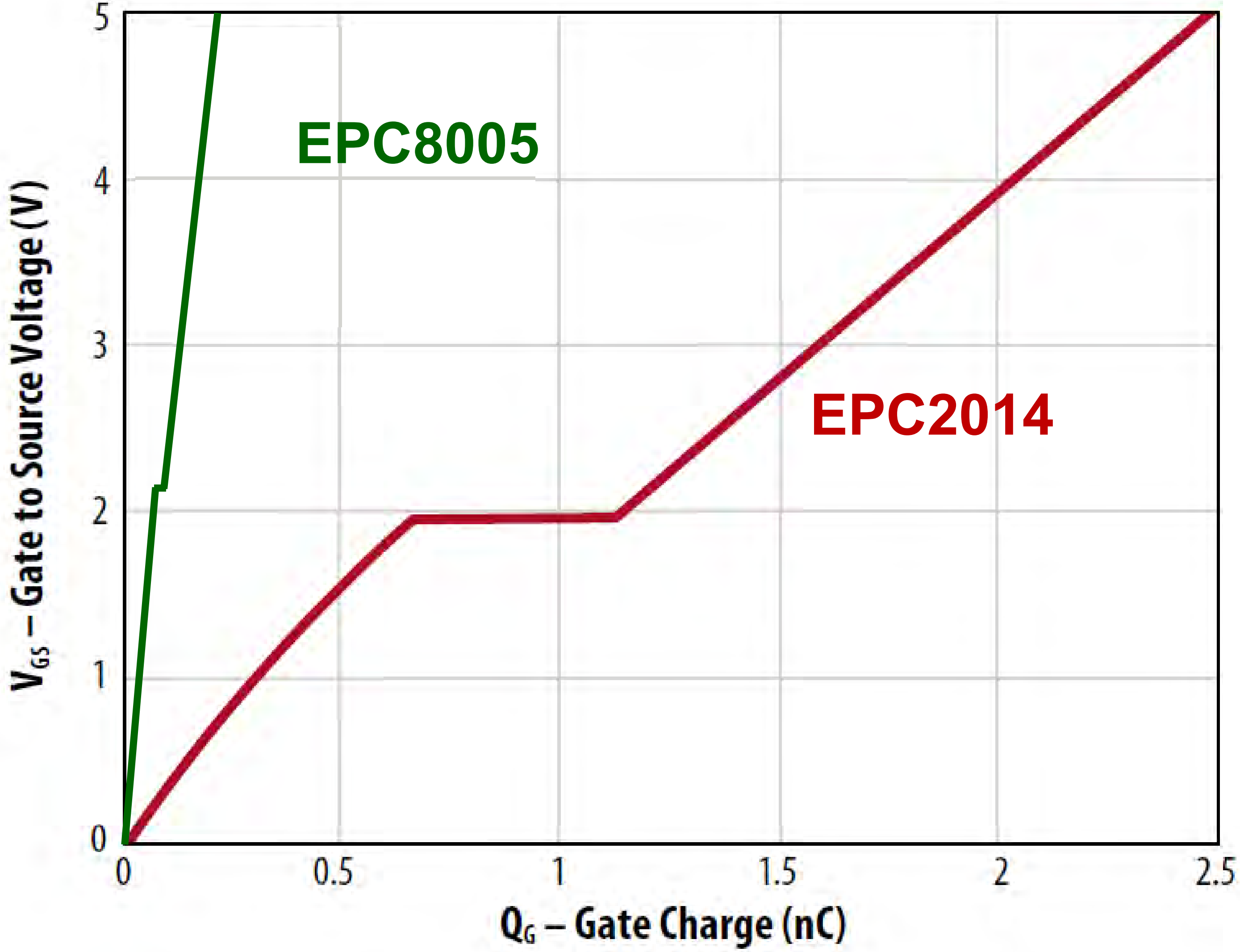


1 MHz EPC9002

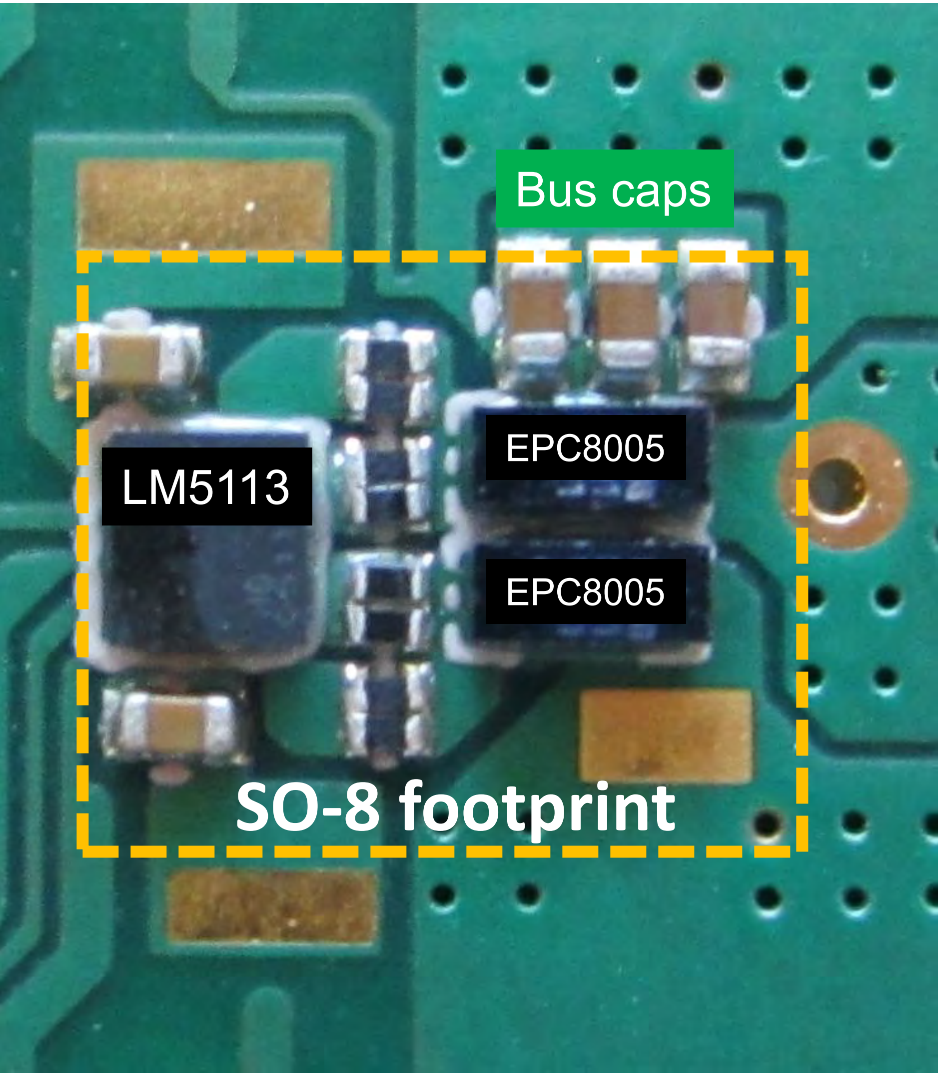


4 MHz EPC9006

High Frequency Device



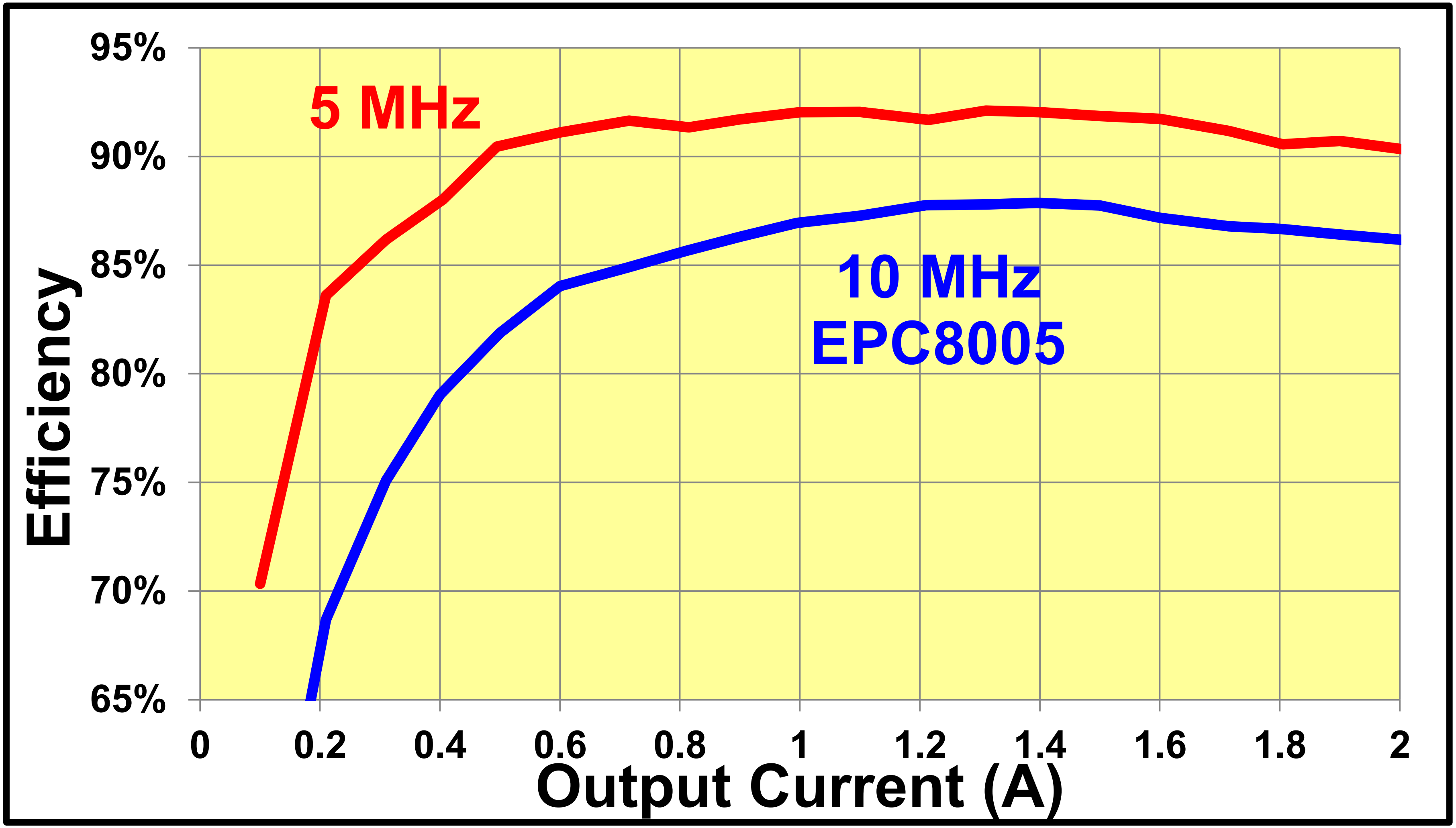
High Frequency Evaluation



- LM5113 BGA driver
- 2x 0201 resistors in parallel to minimize gate inductance
- Optimum gate and power loops

42 V to 20 V / 2 A buck

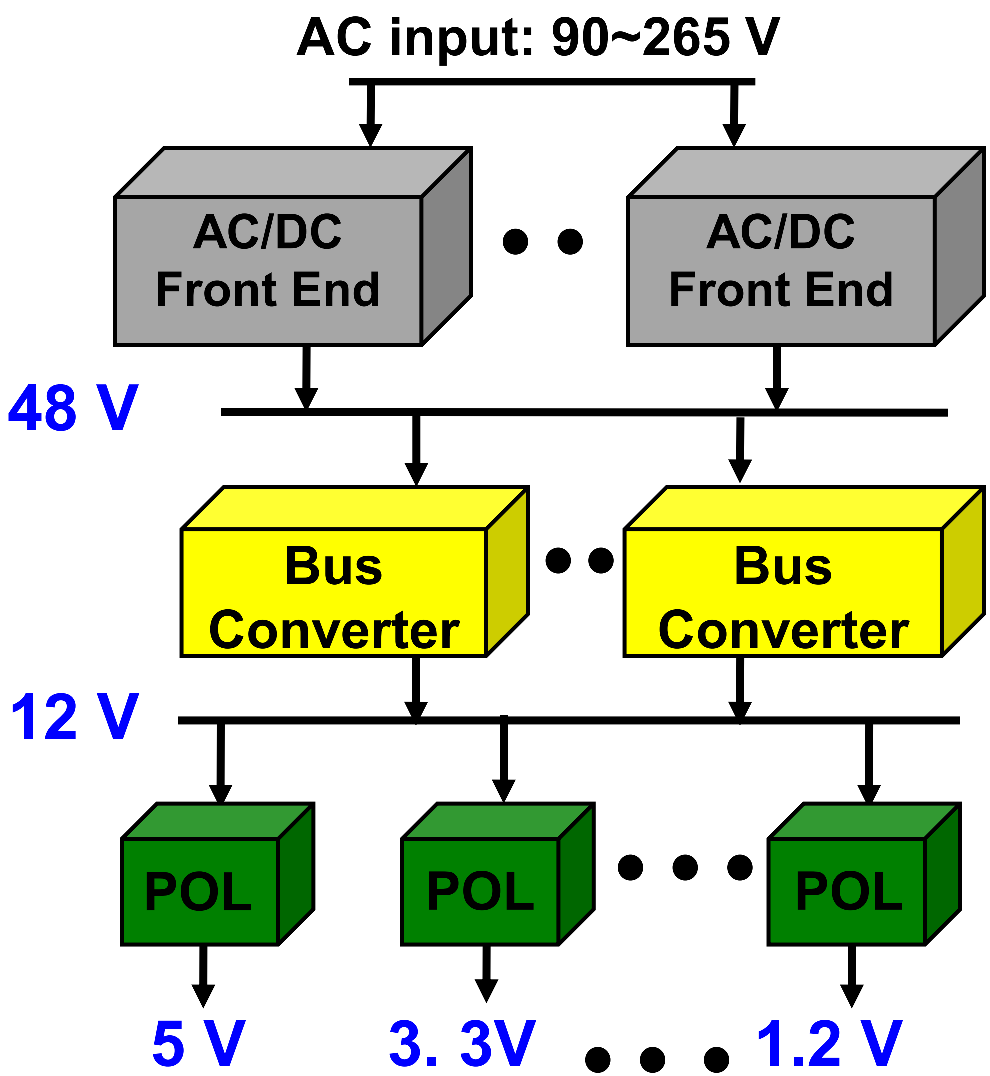
High Frequency Efficiency



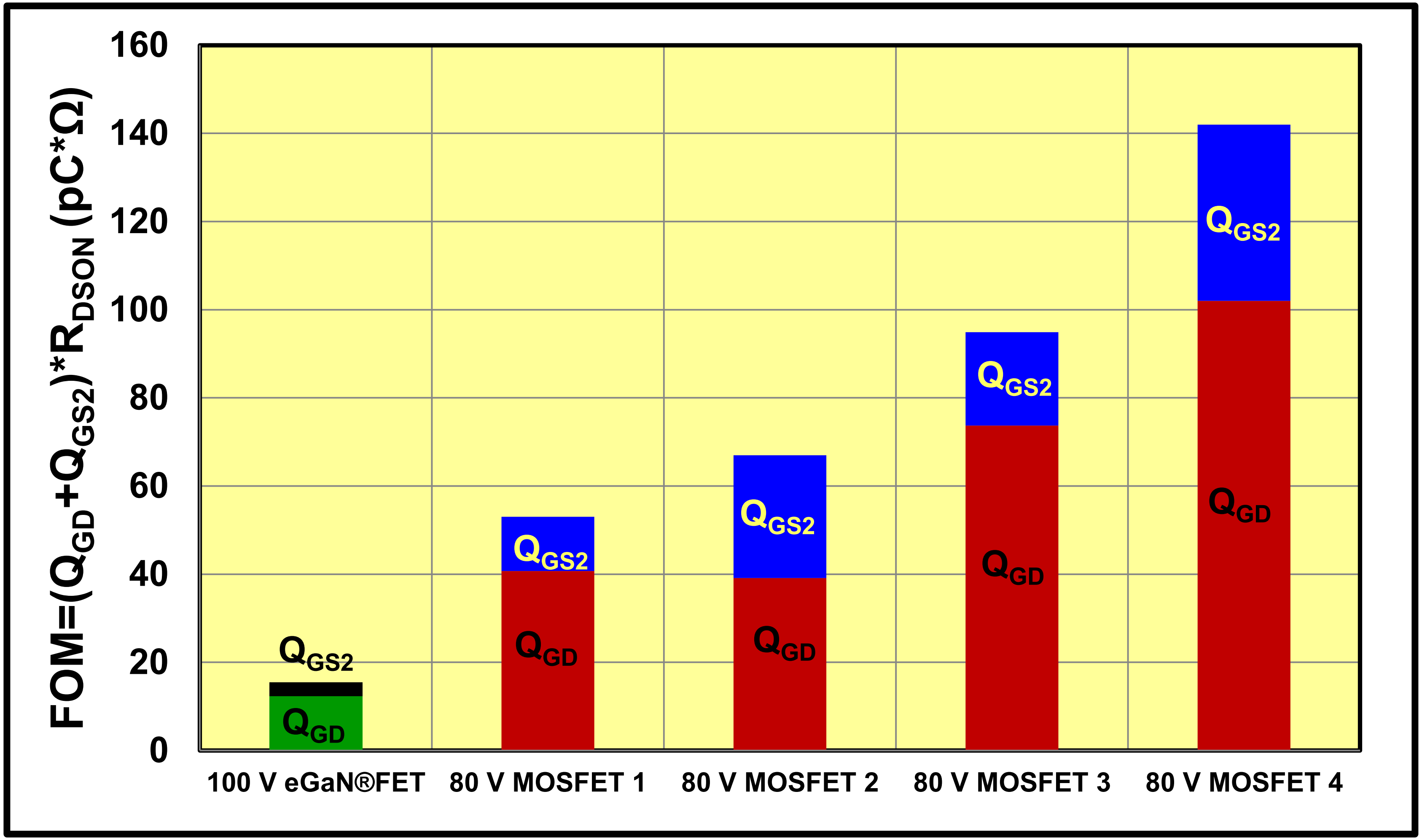
V_{IN}=42 V V_{OUT}=20 V

48 V to 12 V Power Conversion

Intermediate Bus Architecture

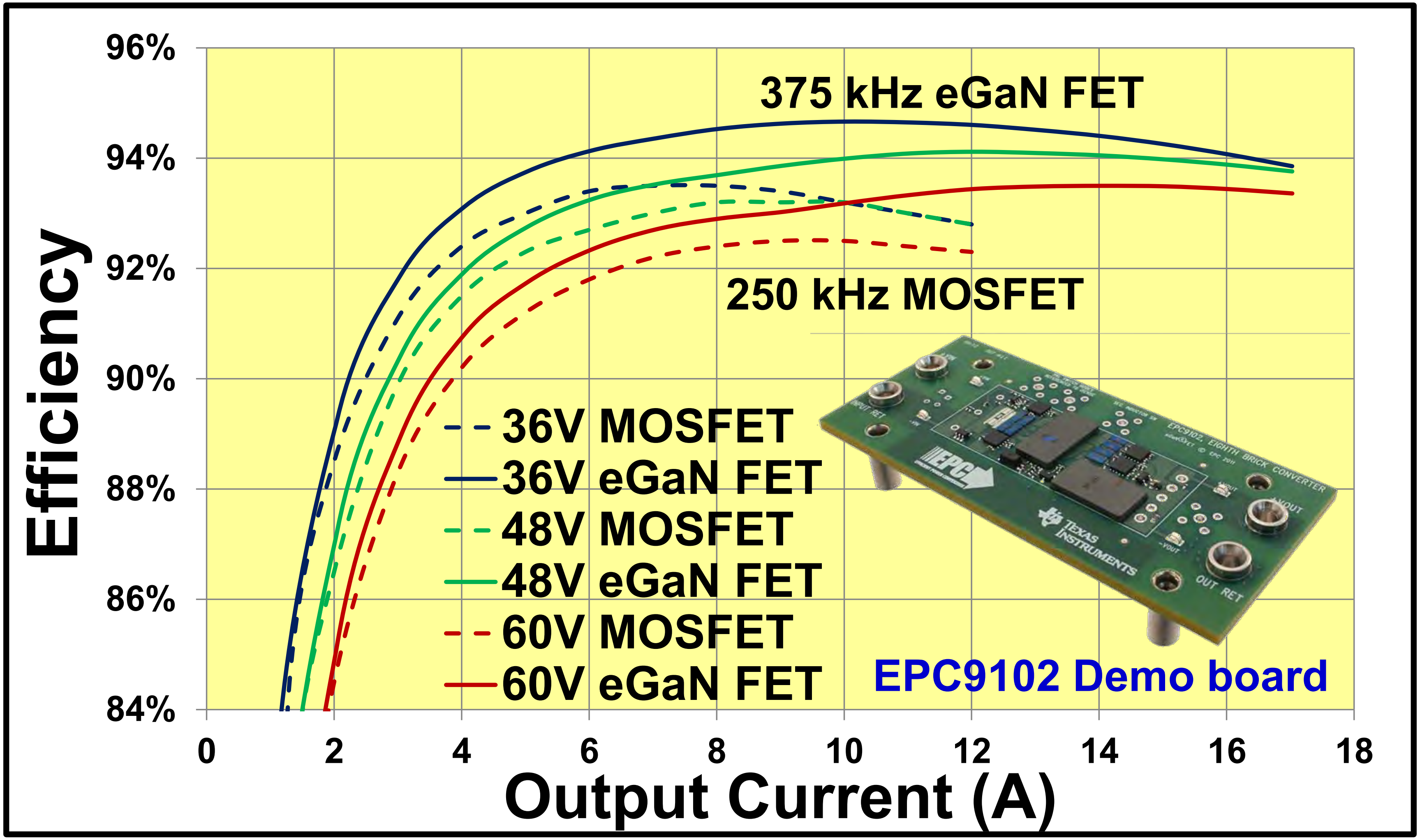


100 V Hard Switching FOM



V_{DS}=0.5*V_{DS} , I_{DS}= 15 A

Hard Switching Brick

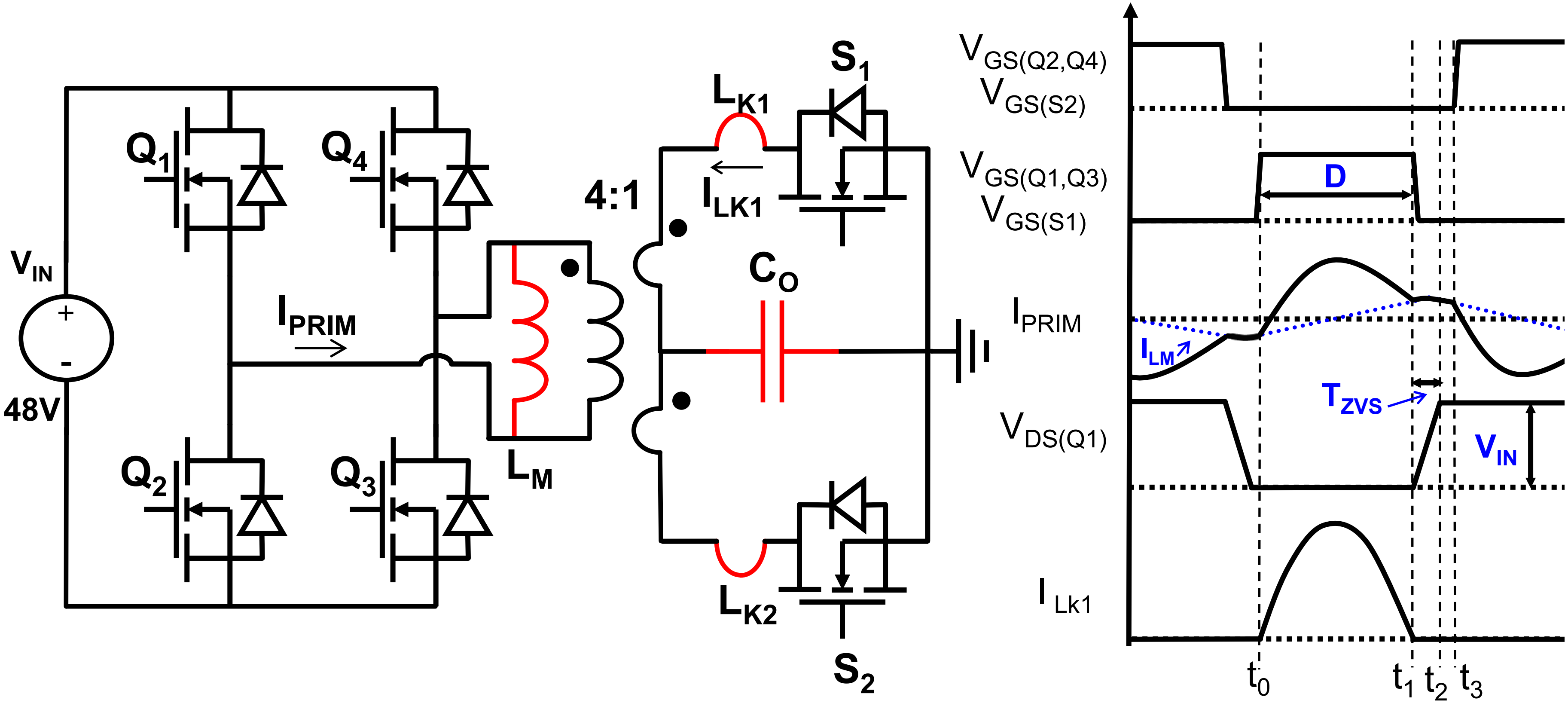


36 - 60 Vin, 12 Vout, 200 W, 375 kHz

Resonant Bus Converter

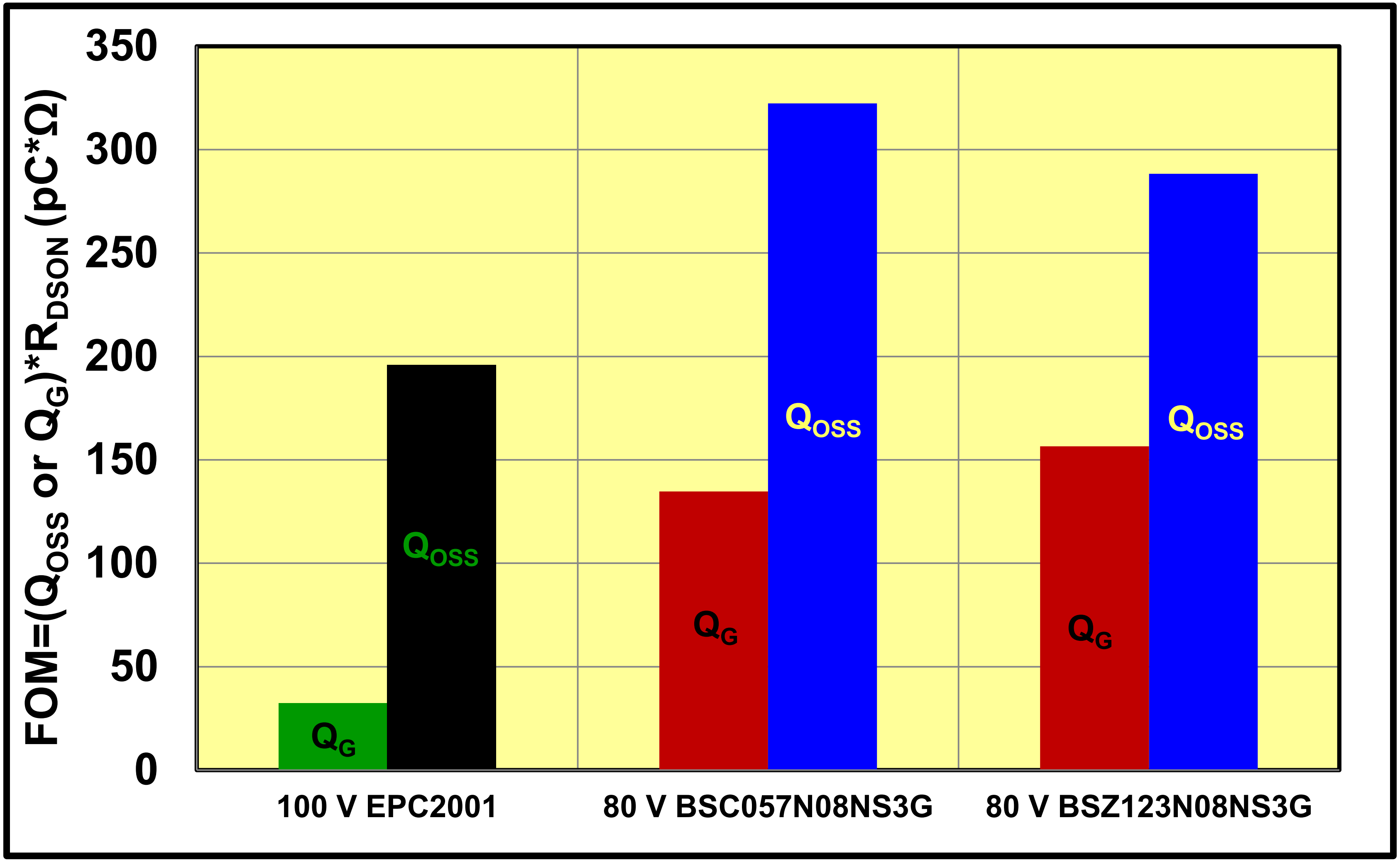
Resonant Bus Converter

High Frequency DC/DC Transformer



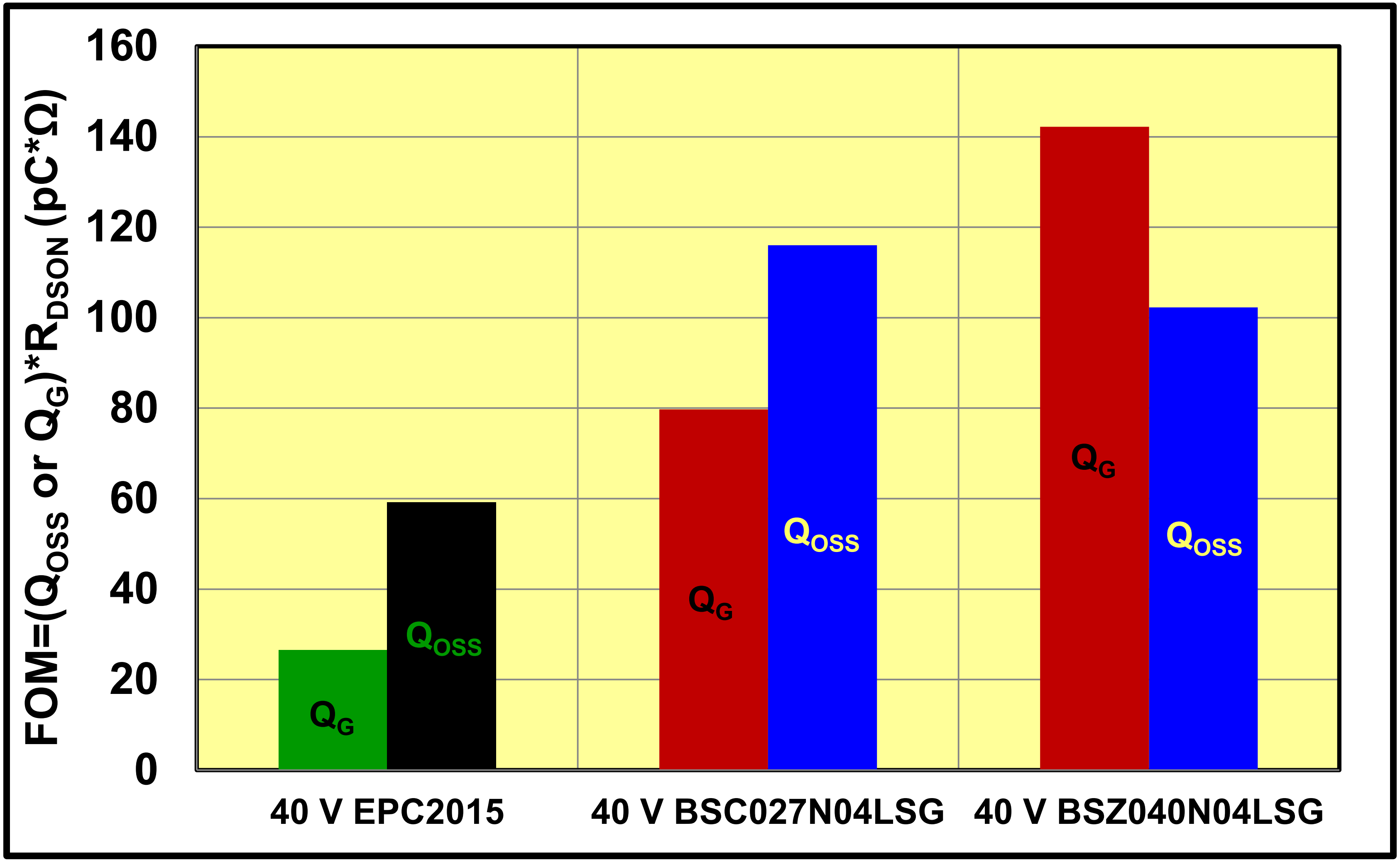
Ref: Y. Ren, M. Xu, J. Sun, and F. C. Lee, "A family of high power density unregulated bus converters," IEEE Trans. Power Electron., vol. 20, no. 5, pp. 1045–1054, Sep. 2005.

100 V Soft Switching FOM



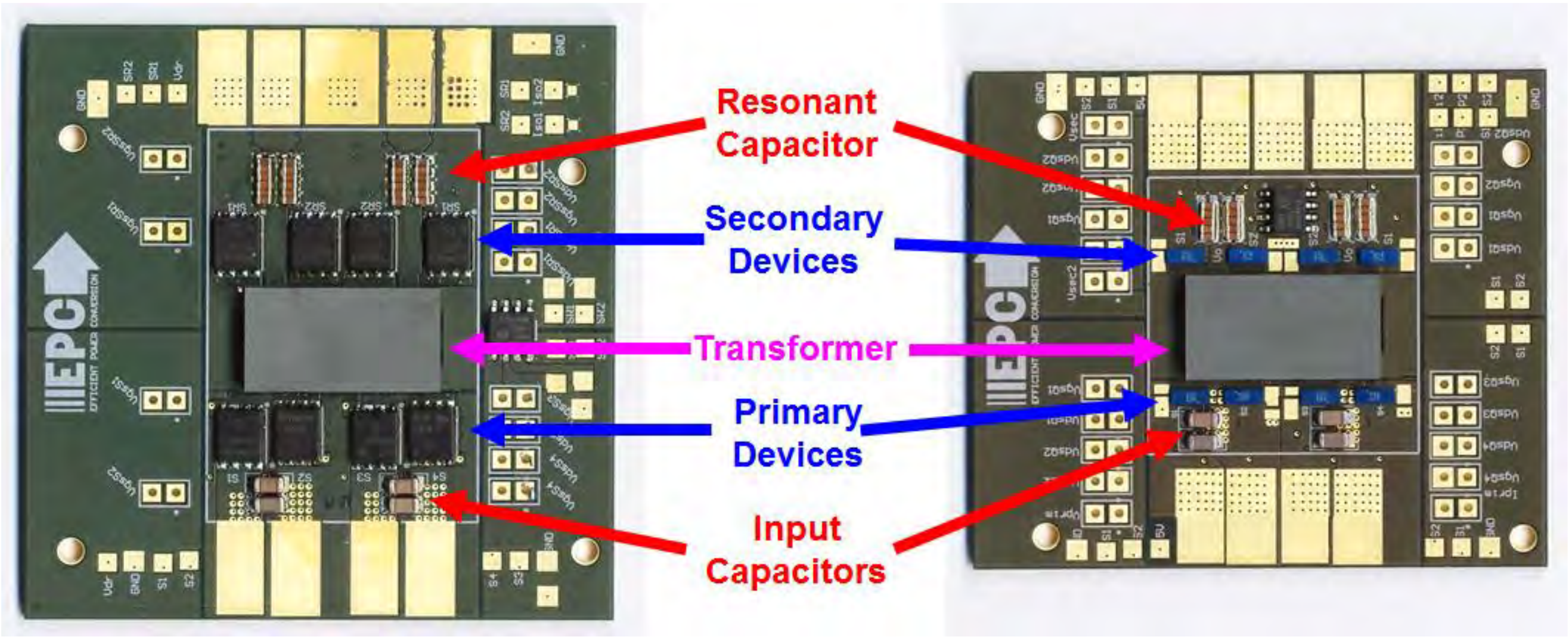
V_{DS}=48 V

40 V Soft Switching FOM



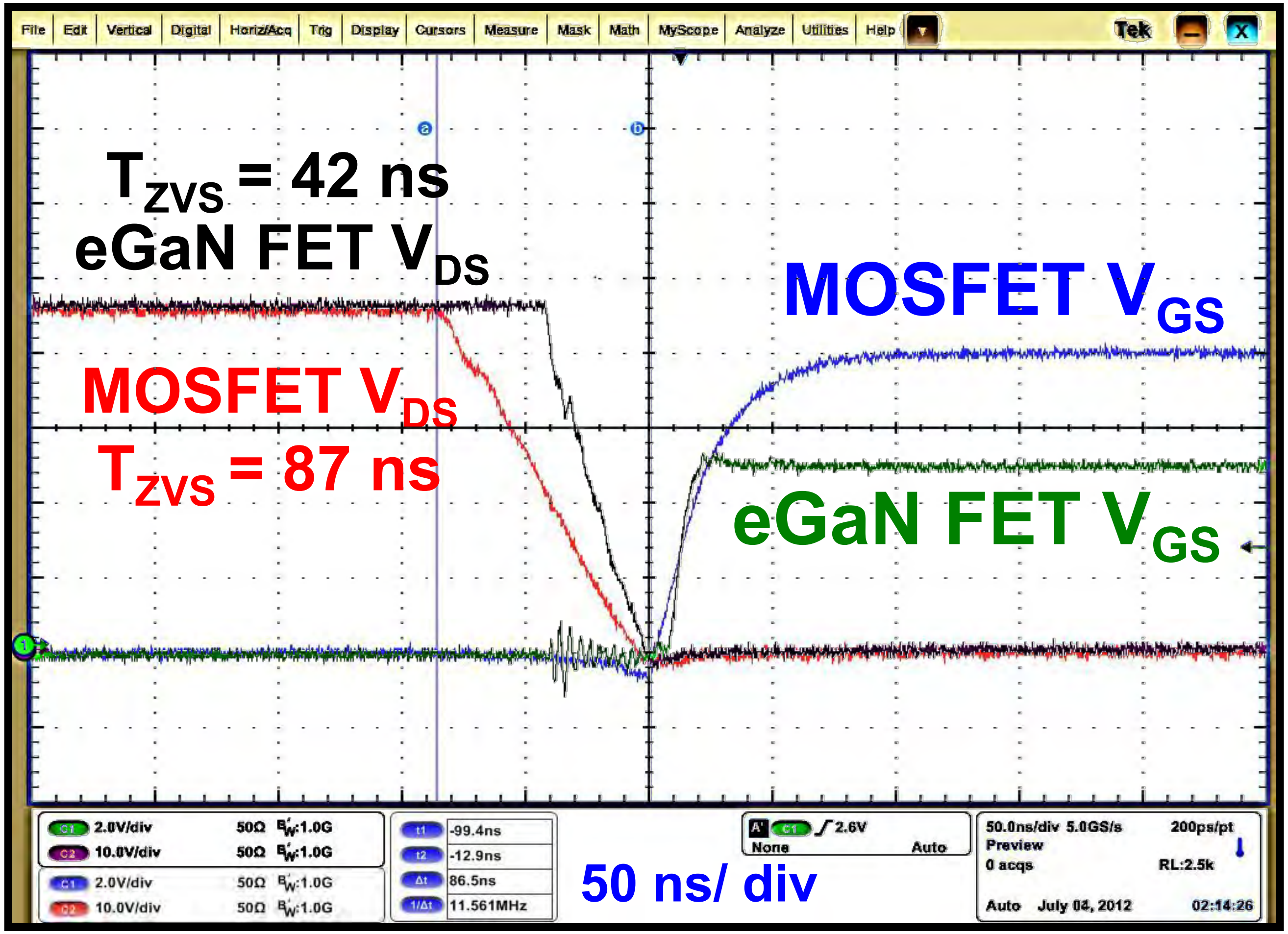
V_{DS}=20 V

eGaN® FET vs. MOSFET



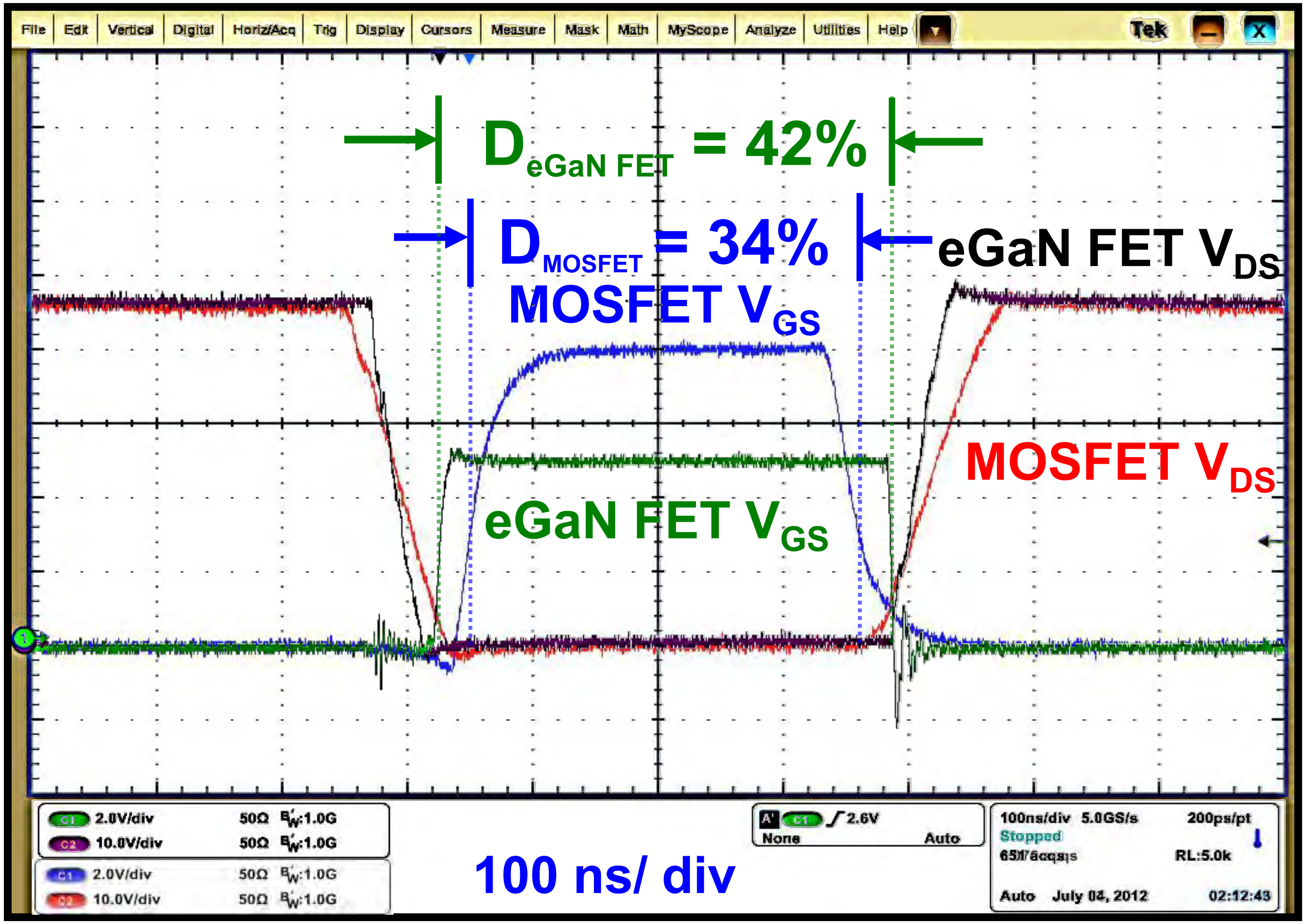
MOSFET **vs.** **eGaN® FET**

ZVS Switching Comparison



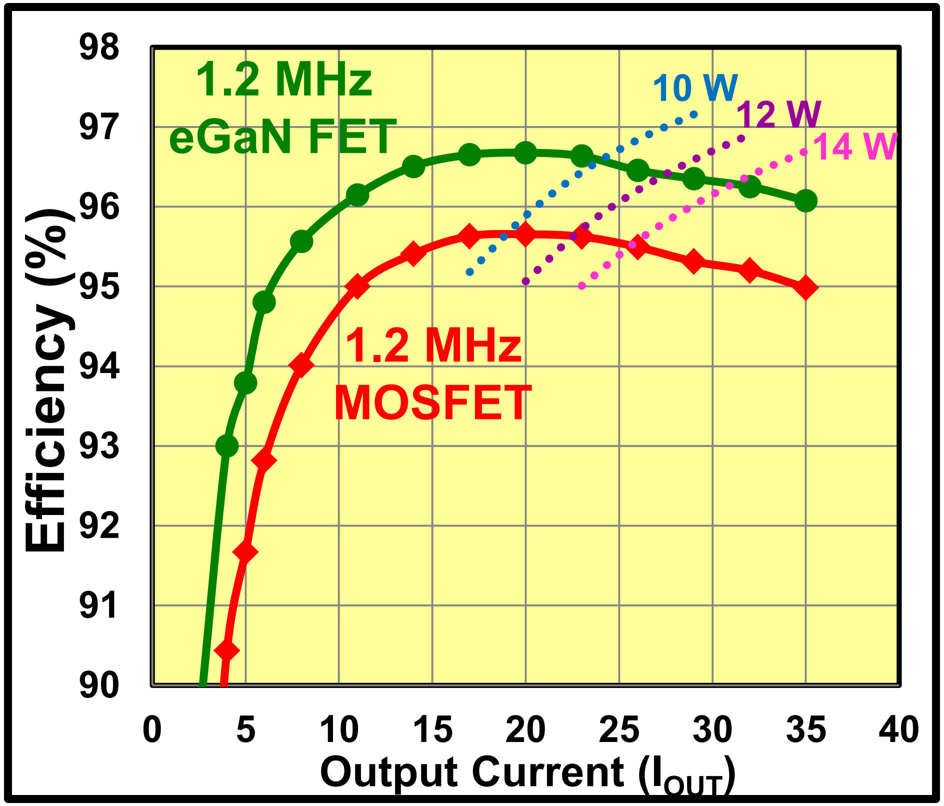
F_S = 1.2 MHz, V_{IN} = 48 V, and $V_{OUT} \approx$ 12 V

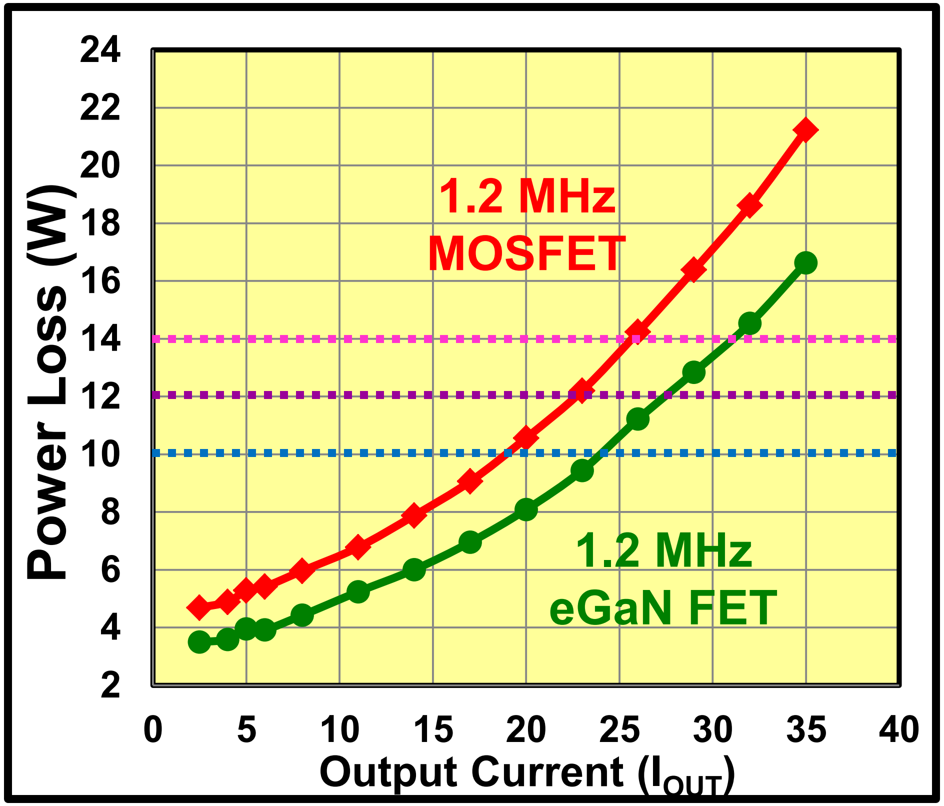
Duty Cycle Comparison



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

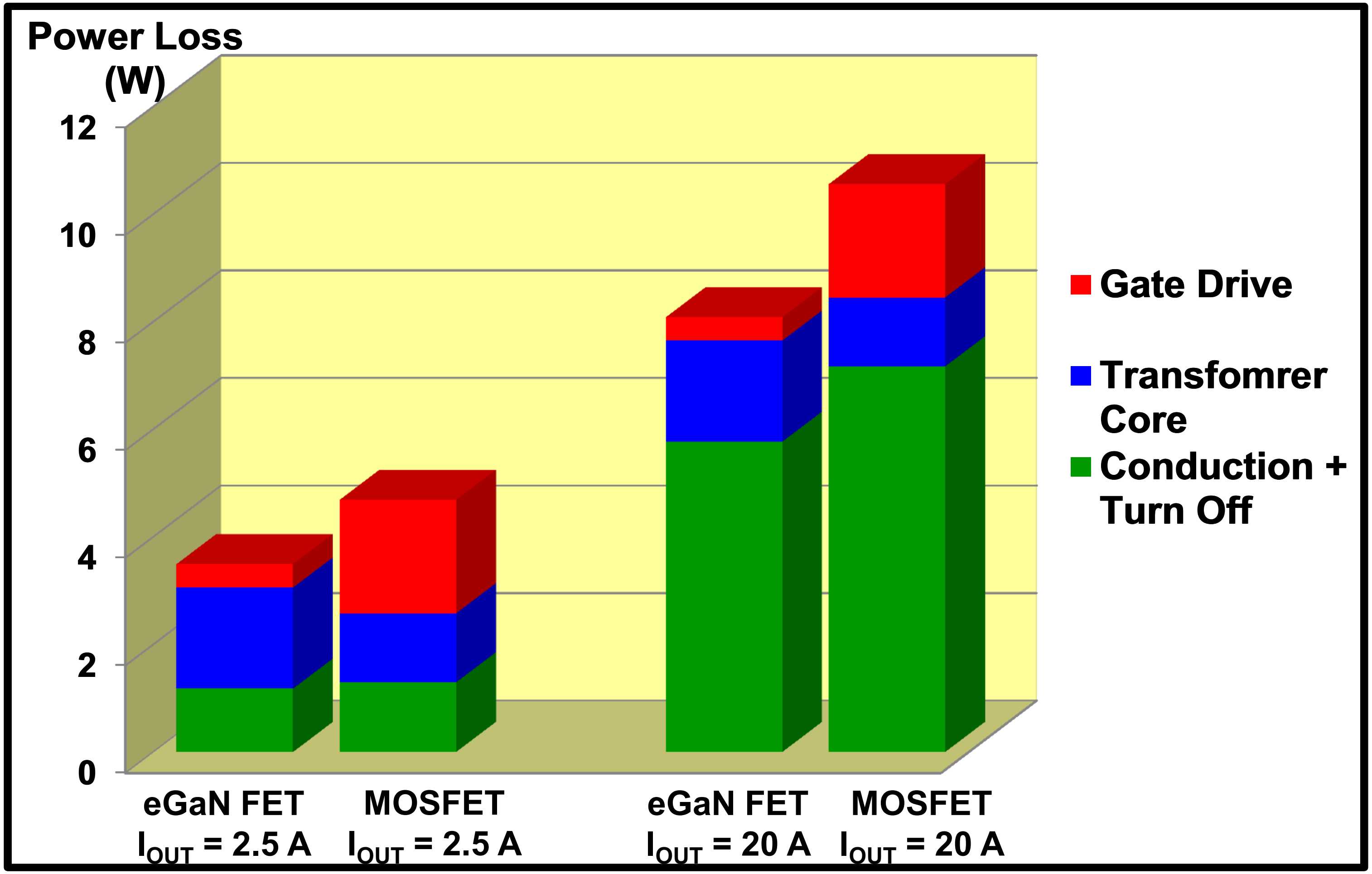
Efficiency Comparison





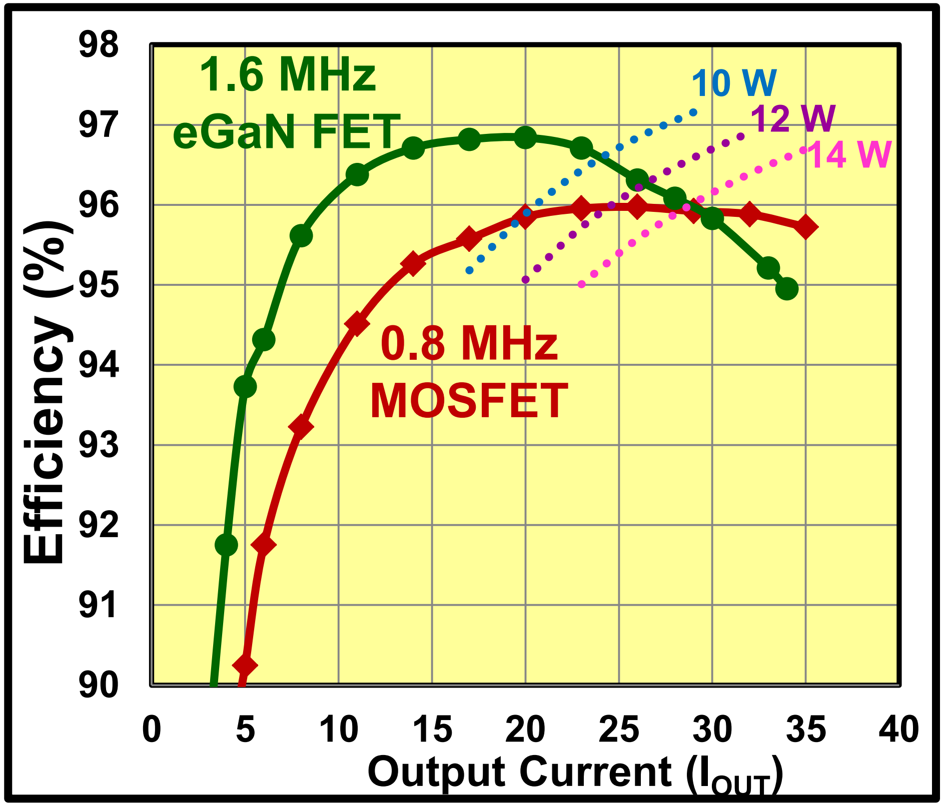
F_S = 1.2 MHz, V_{IN} = 48 V, and $V_{OUT} \approx$ 12 V

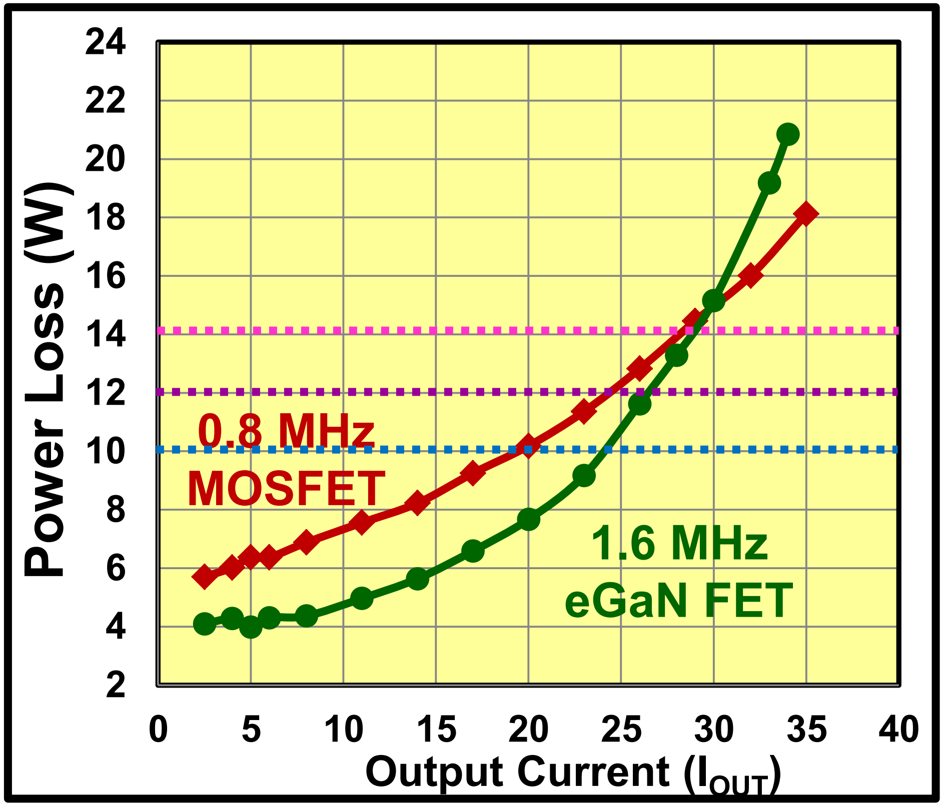
Loss Breakdown



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

Frequency Capability



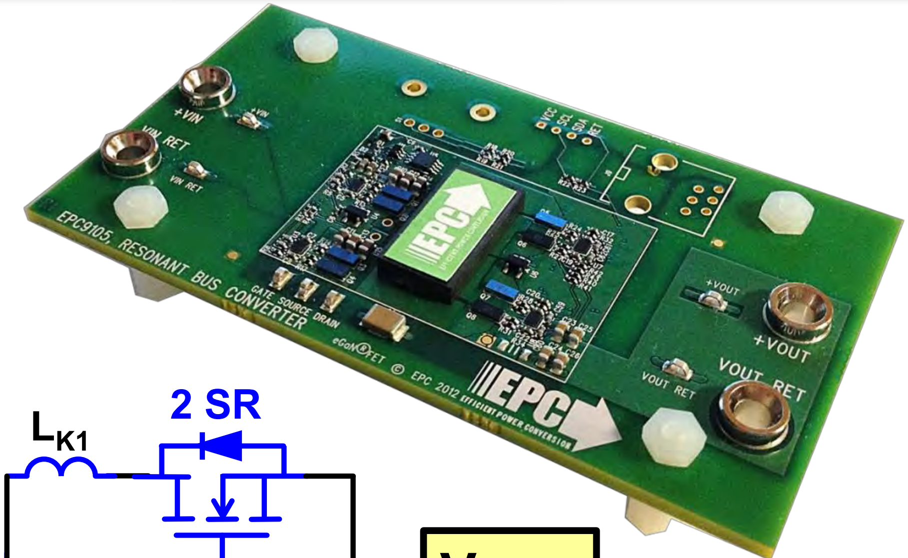


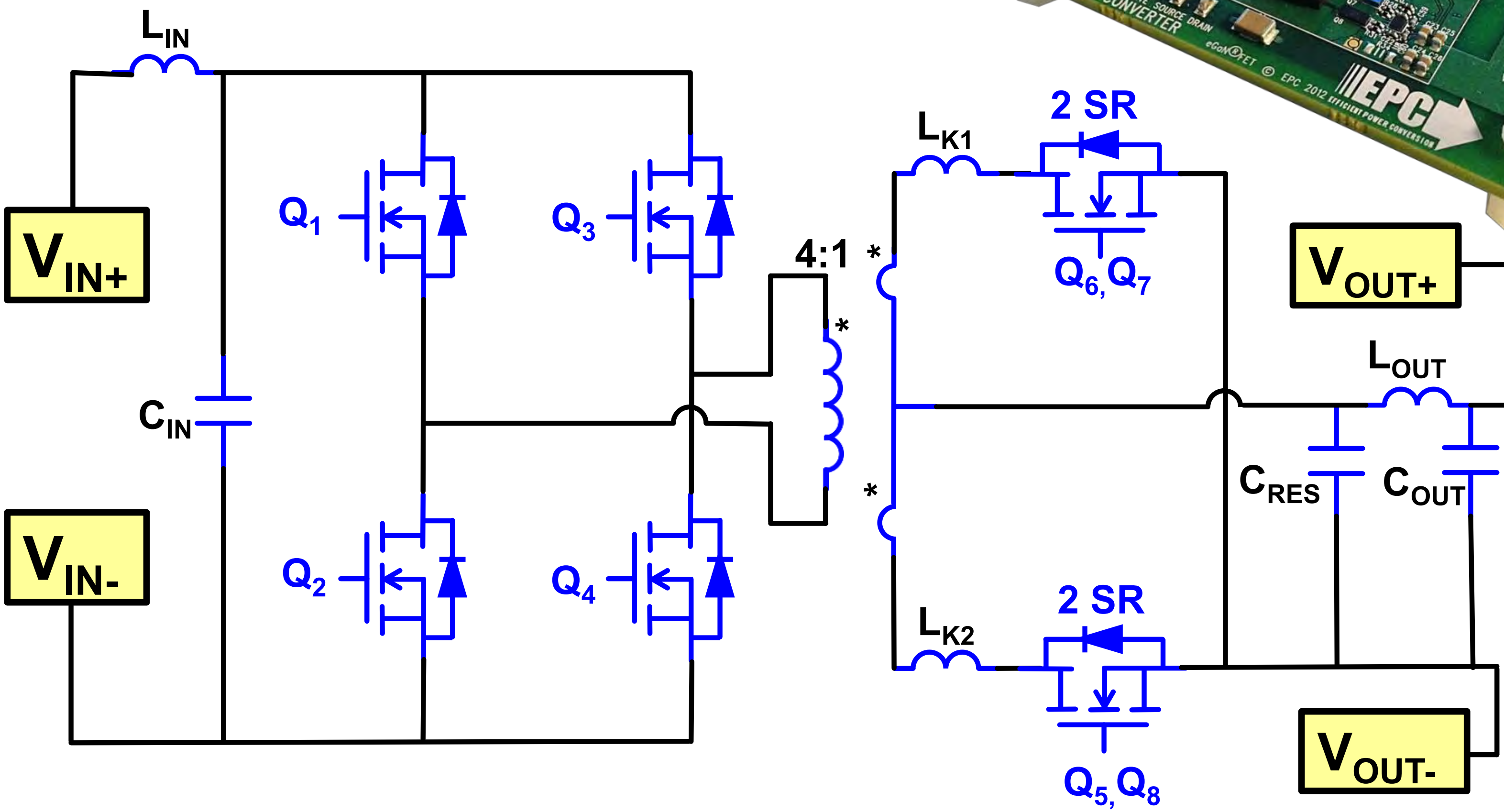
V_{IN} = 48 V, and $V_{OUT} \approx$ 12 V

EPC9105 Bus Converter

EPC9105 Demonstration Board

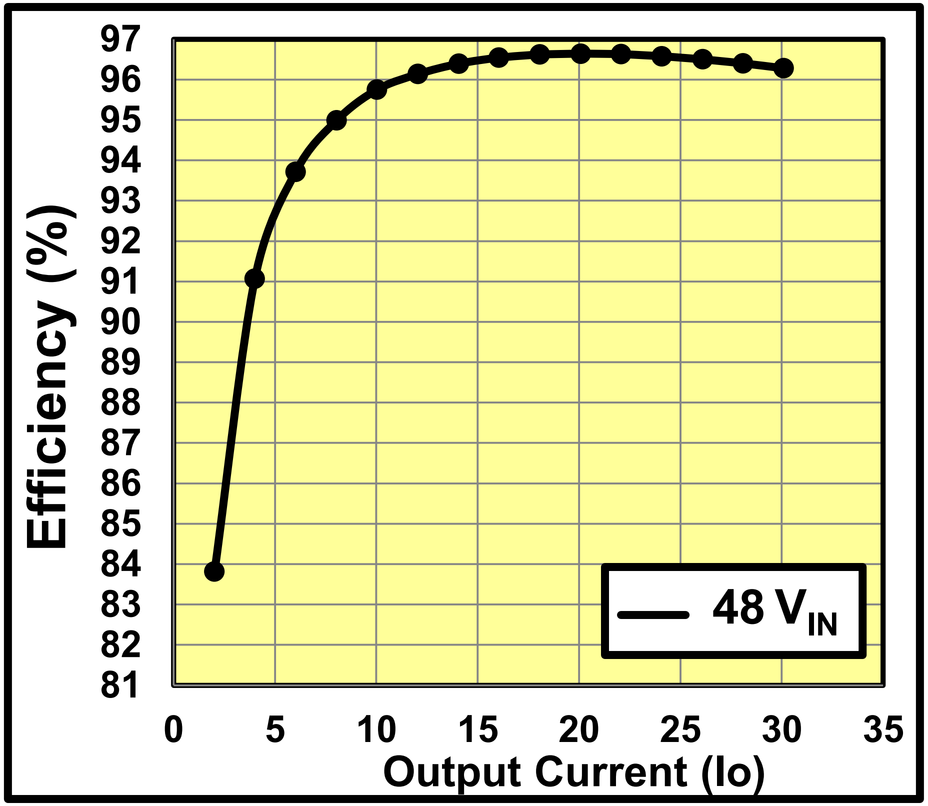
36 - 60 V_{IN}, 12 V_{OUT}, 350 W, 1.2 MHz

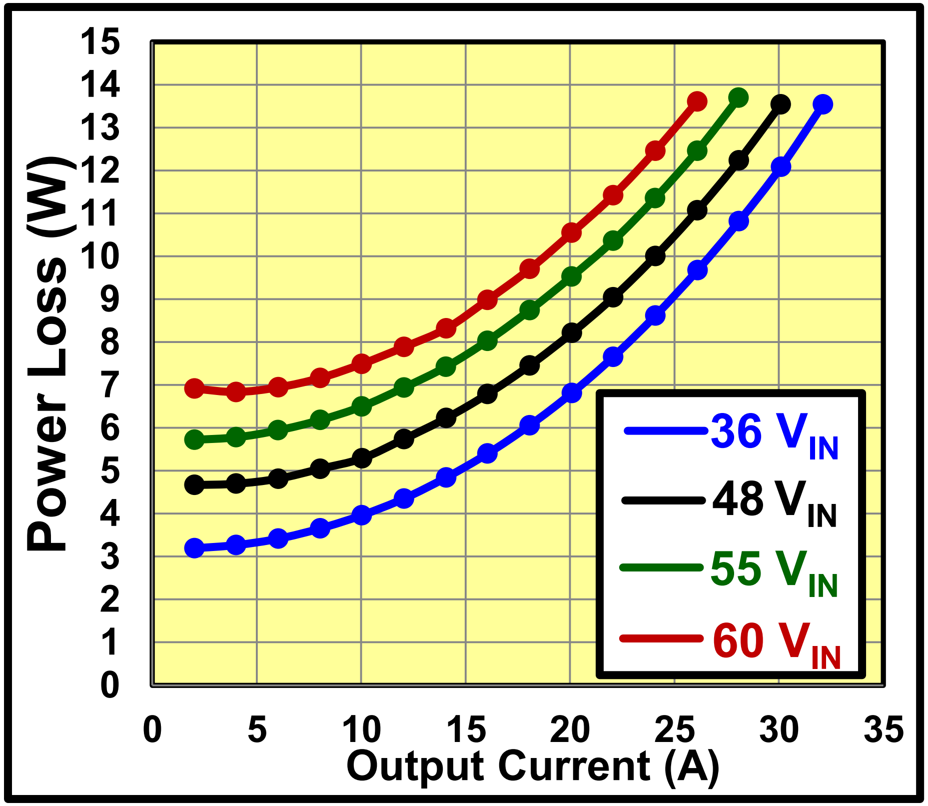




EPC9105 Bus Converter

EFFICIENT POWER CONVERSION





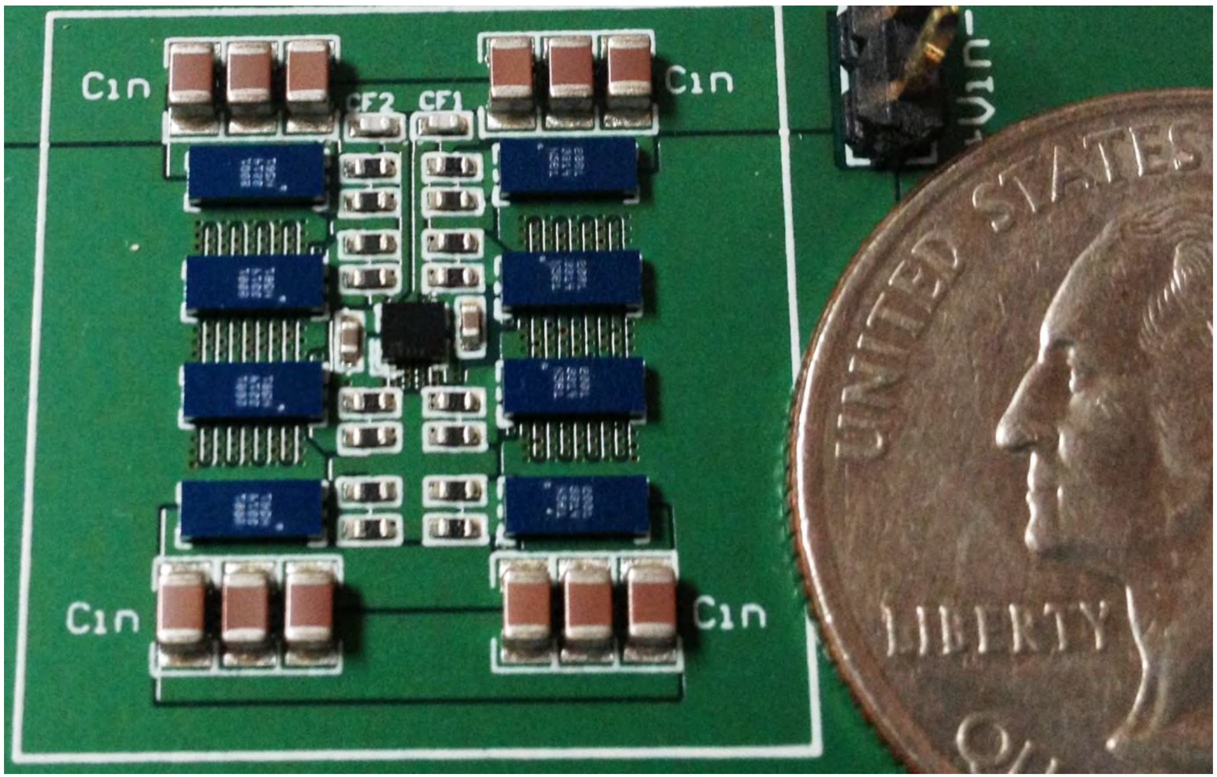
F_S = 1.2 MHz, V_{IN} = 36-60 V, and $V_{OUT} \approx V_{IN}/4$

High Current Non-Isolated Buck Converter

48 V Buck Power Stage

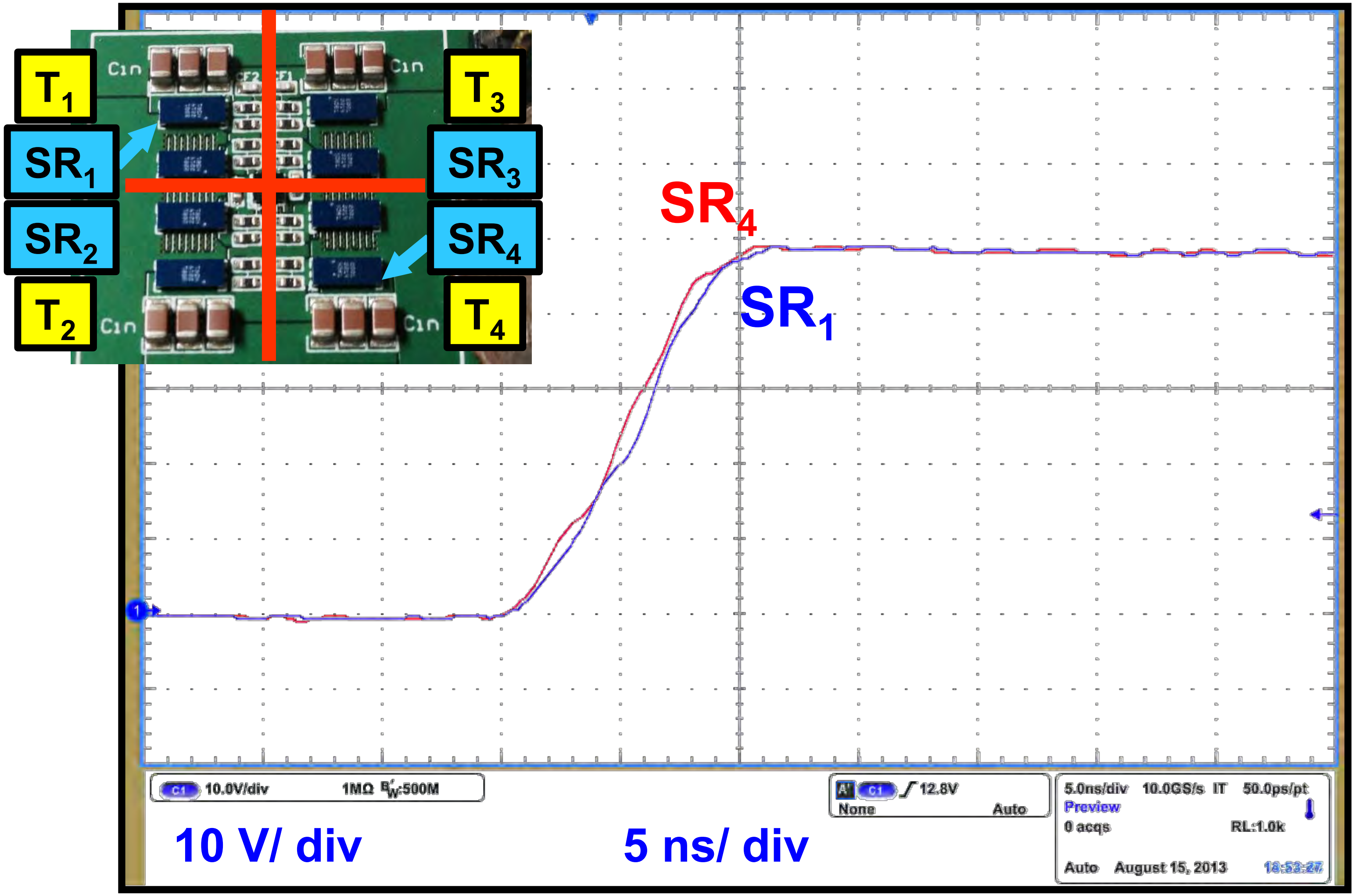
22.8mm
1/8th Brick Width

22.8mm
40% of 1/8th Brick Length



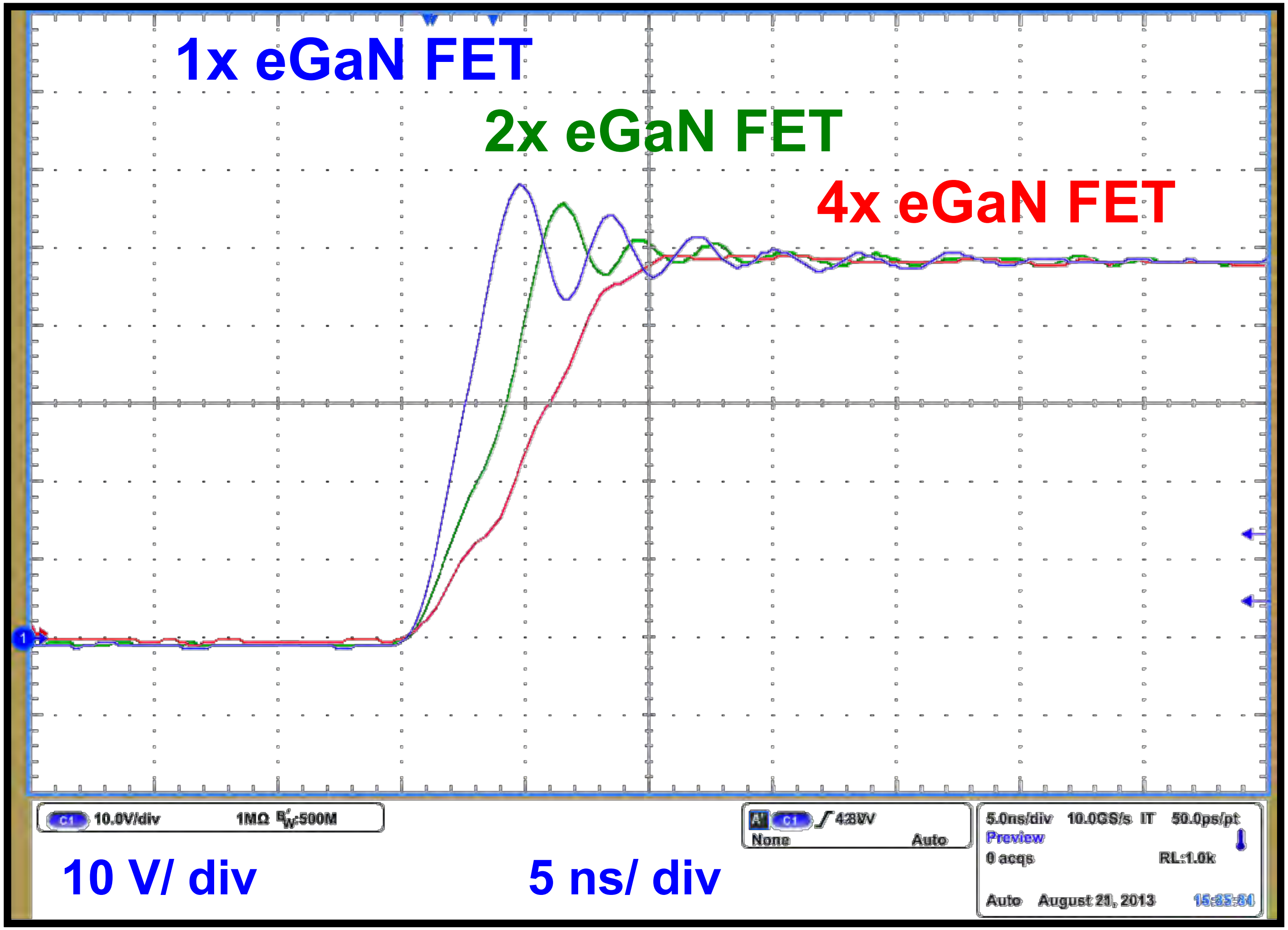
8 x EPC2001
4 Top Devices and 4 SR in parallel

Parallel Loop Optimal Layout



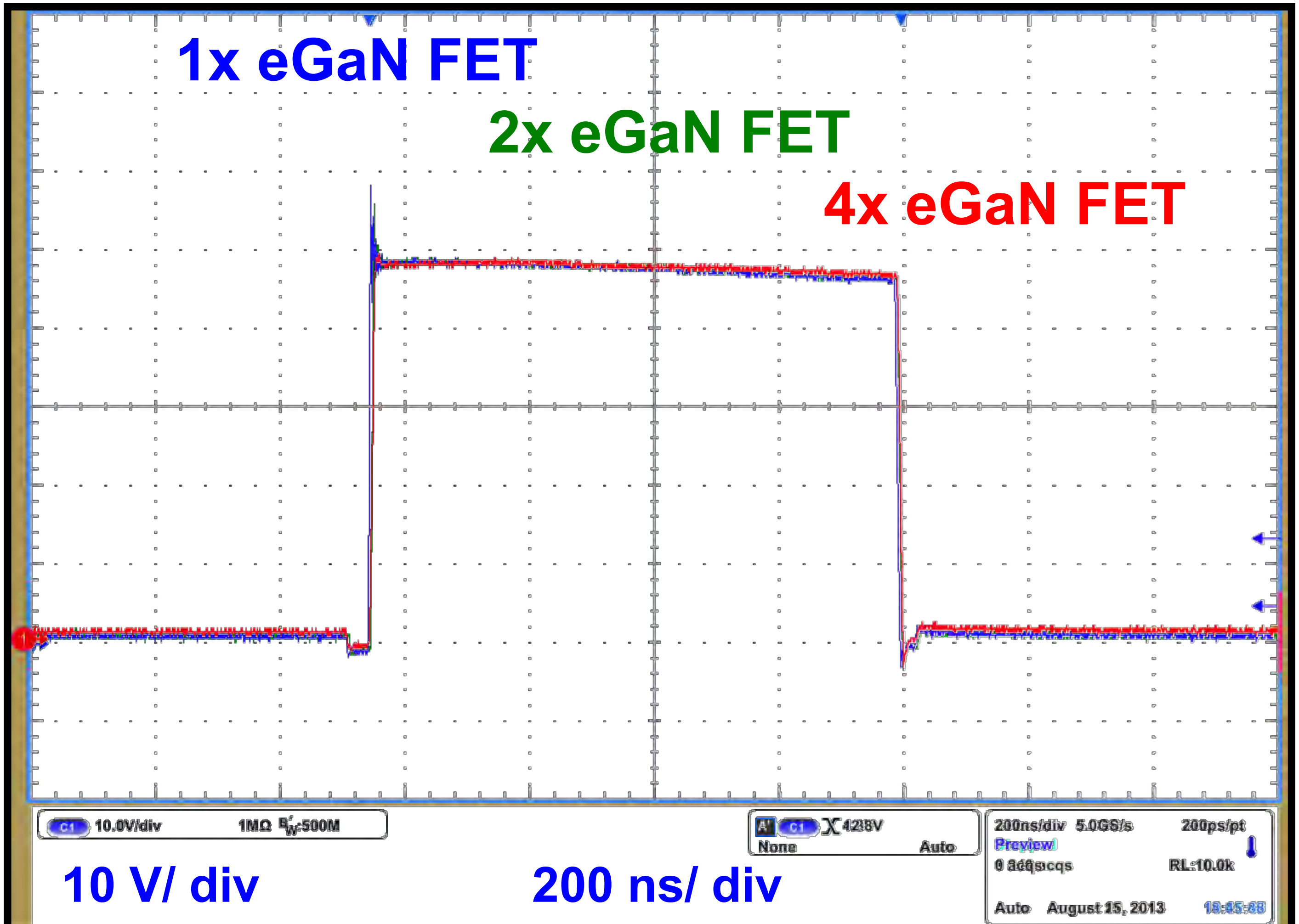
V_{IN}=48 V V_{OUT}=12 V I_{OUT}=30 A F_S=300 kHz L=3.3 uH GaN FET T/SR: 100 V EPC2001

Parallel eGaN FET Swithcing



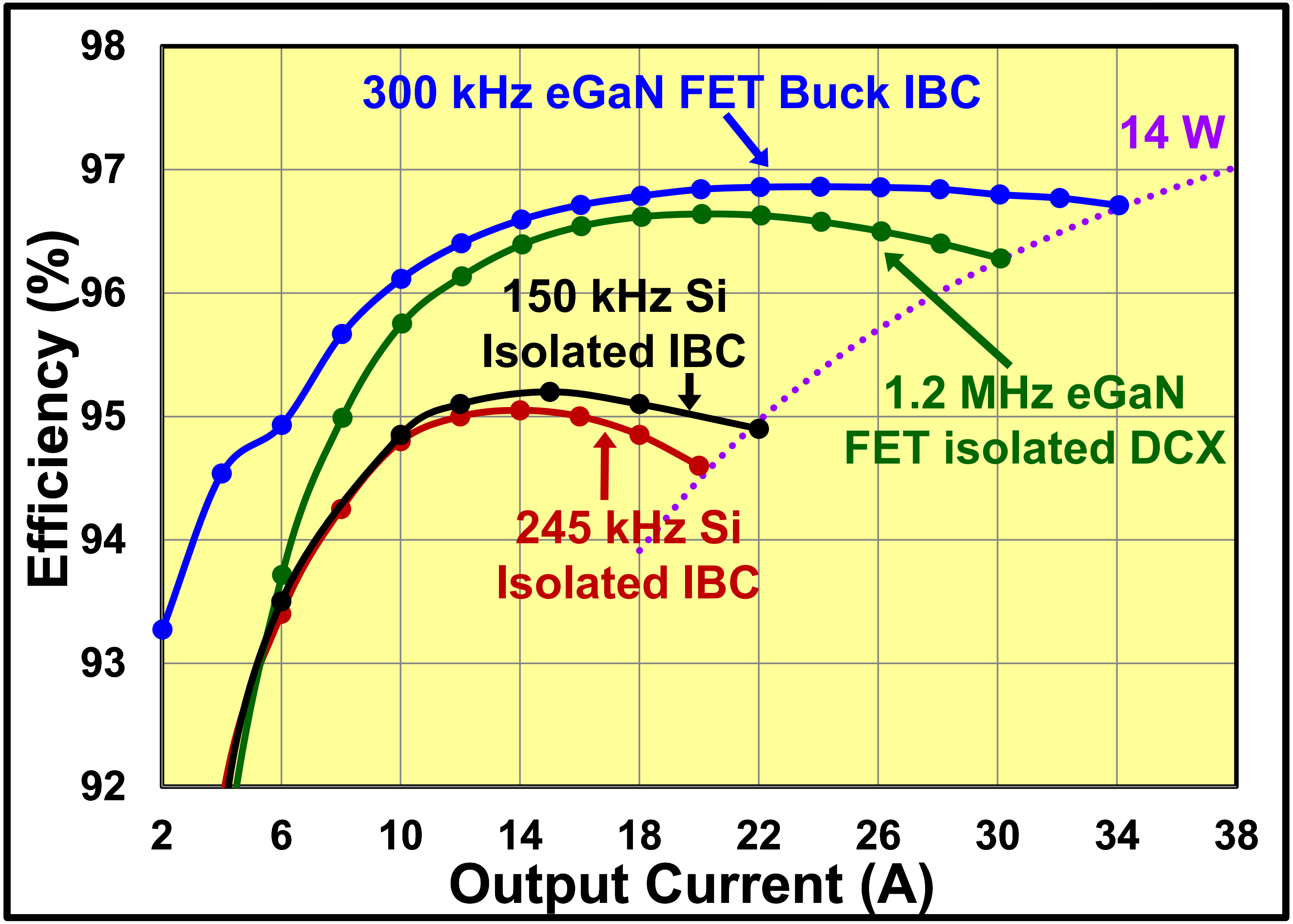
V_{IN}=48 V V_{OUT}=12 V I_{OUT}=30 A F_S=300 kHz L=10 uH GaN FET T/SR: 100 V EPC2001

Parallel eGaN FET Swithcing



V_{IN}=48 V V_{OUT}=12 V I_{OUT}=30 A F_S=300 kHz L=10 uH GaN FET T/SR: 100 V EPC2001

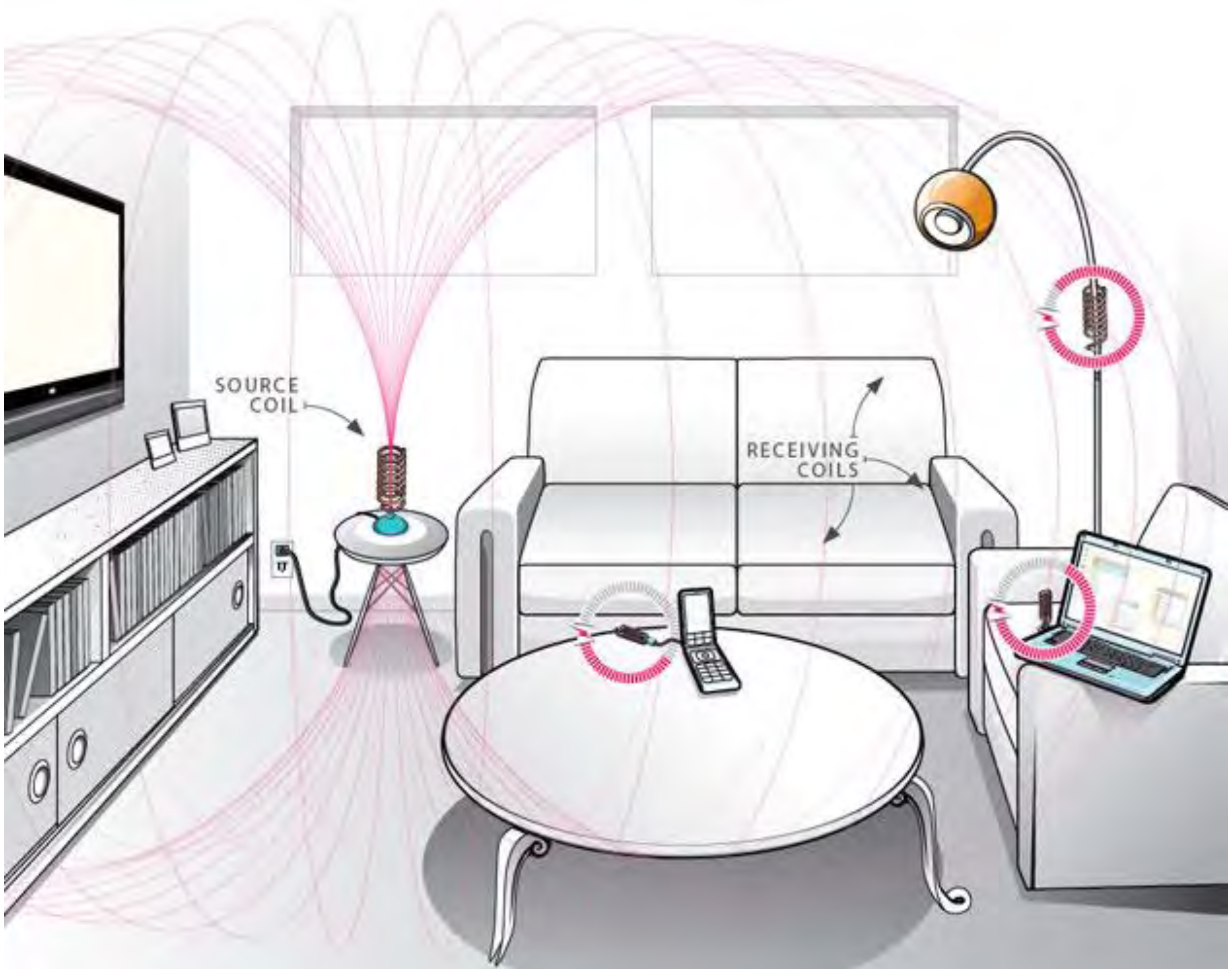
Intermediate Bus Improvements



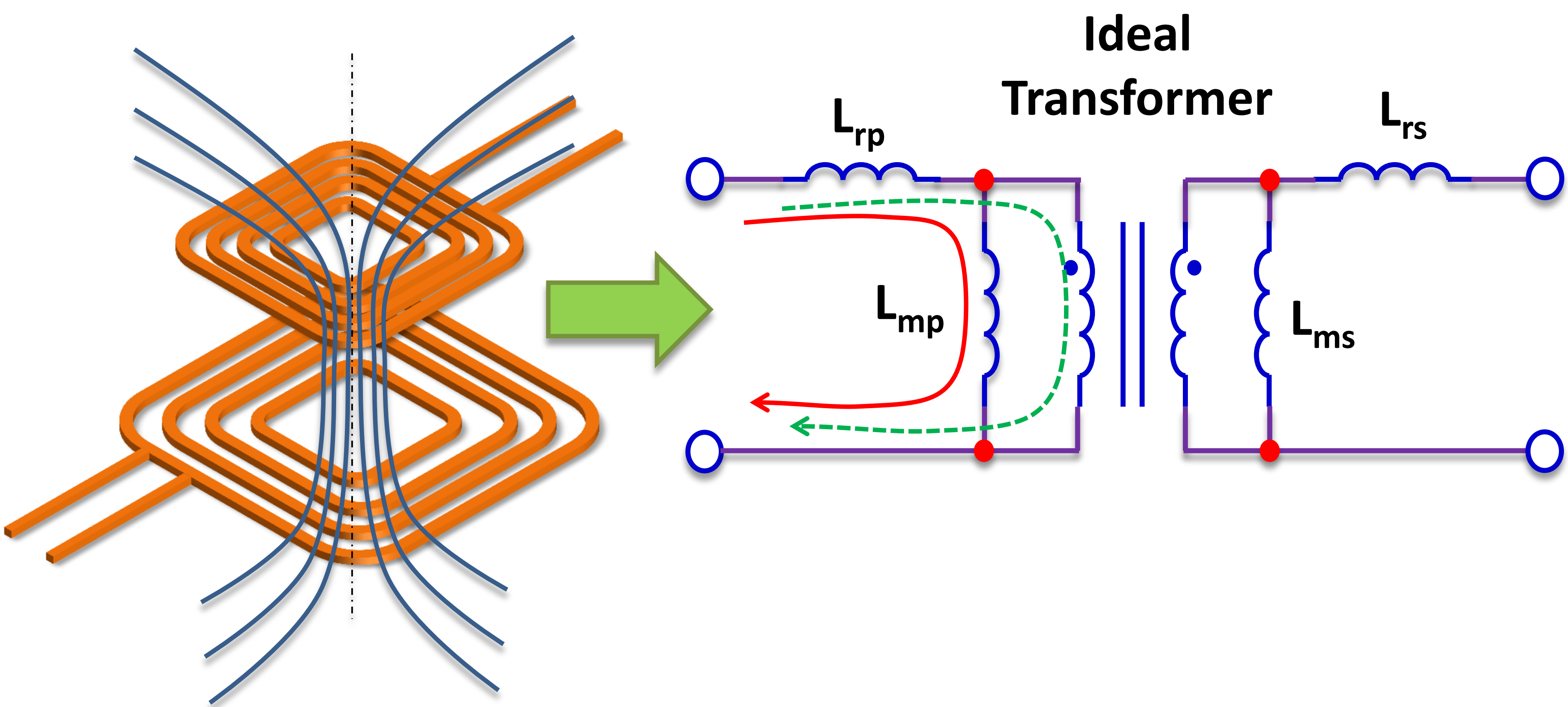
V_{IN}=48 V V_{OUT}=12 V

Wireless Power

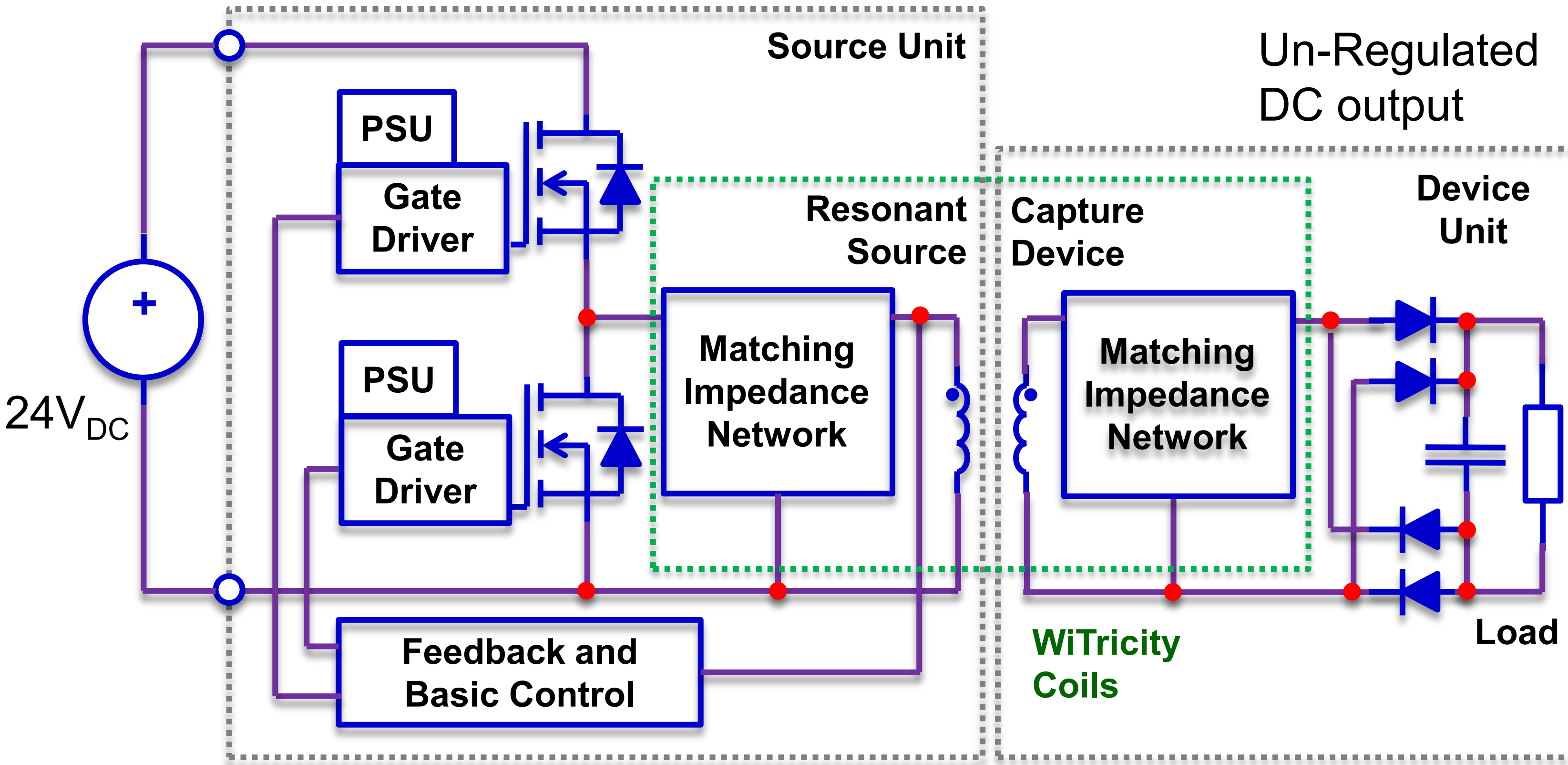
Wireless Power



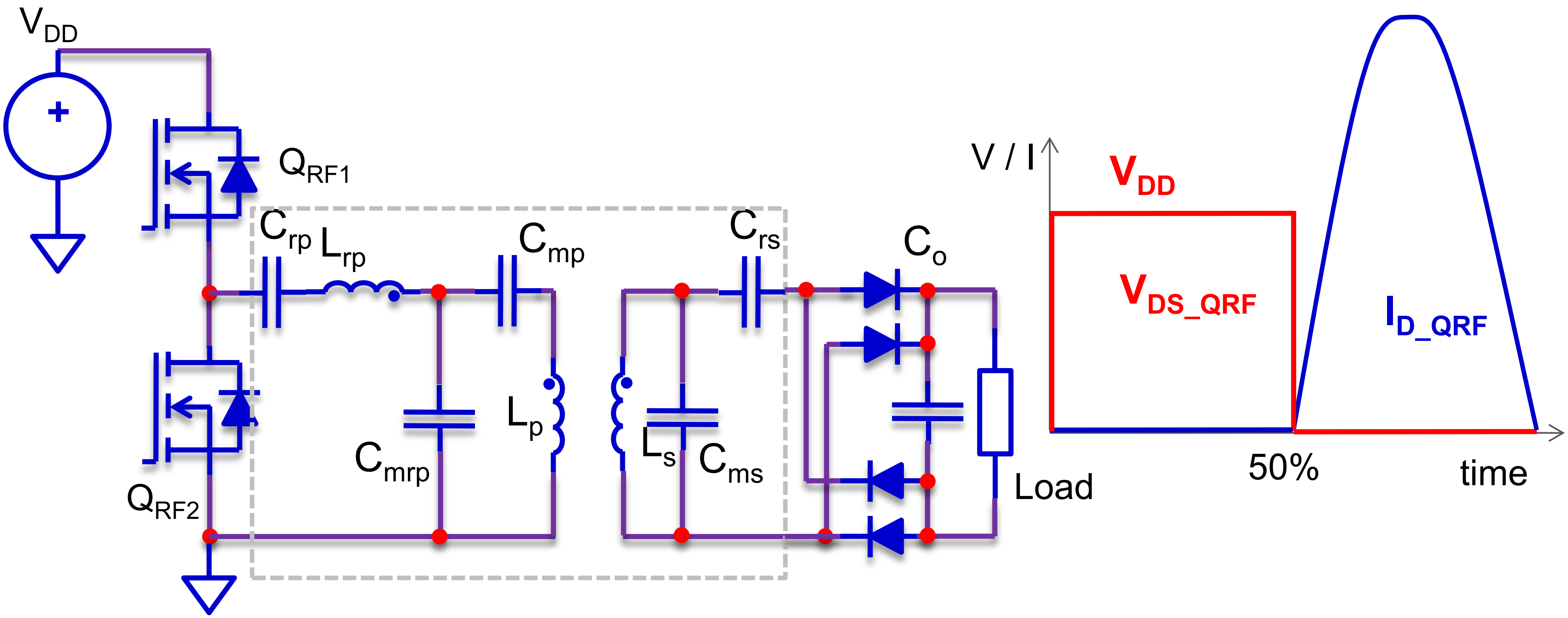
Equivalent Circuit Model for the Coils



Wireless Power



Class D Wireless Power Transfer Overview



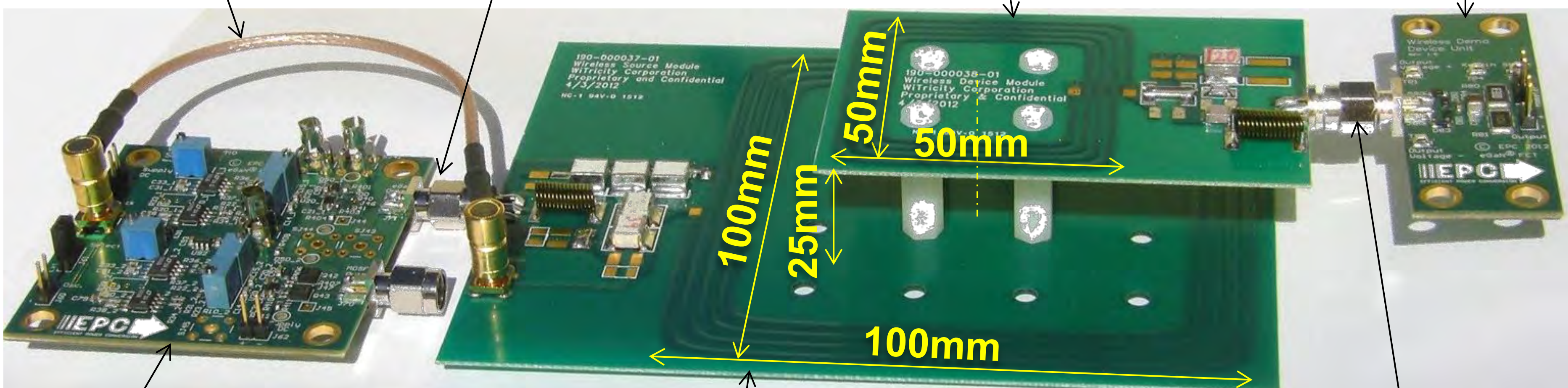
Experimental System Setup

Coil Feedback

eGaN FETs RF connection

Device Coil

Device Board

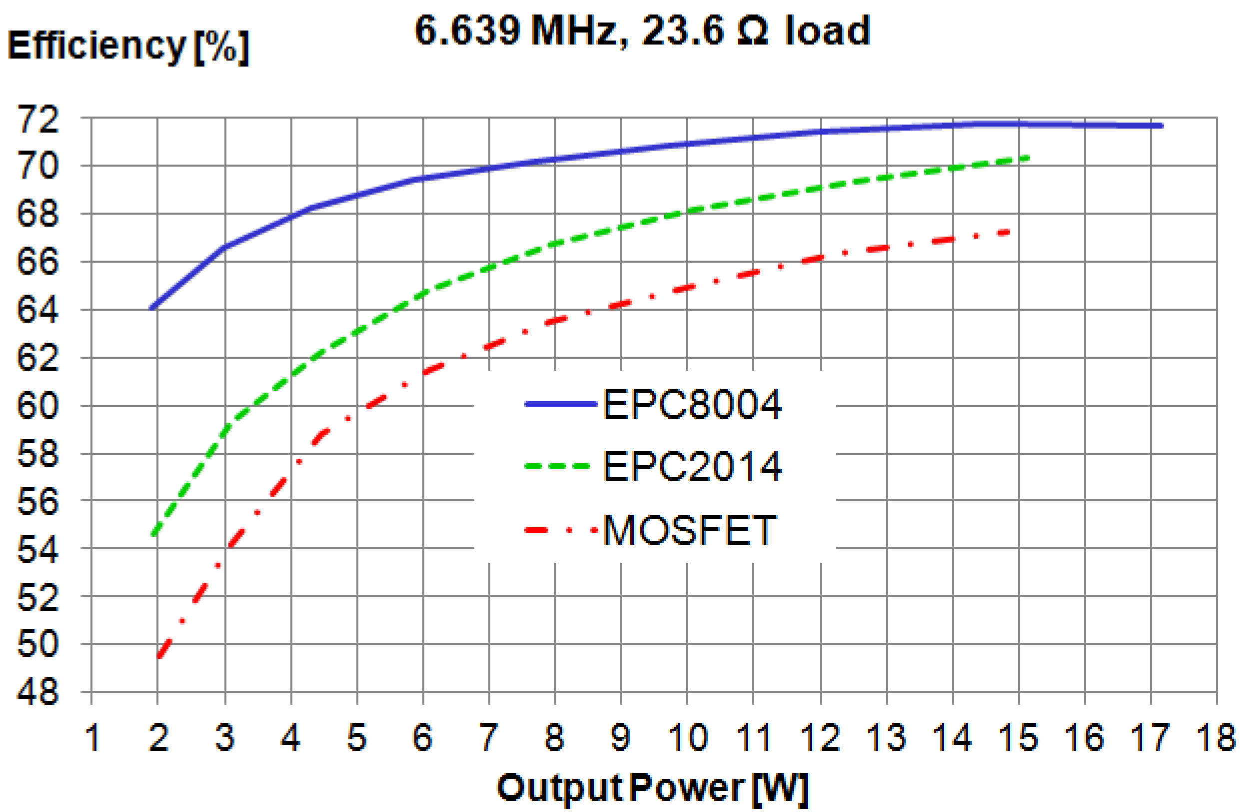


Source Board

Source Coil

RF connection

Efficiency as Function of Load Power



Voltage Mode Class D Operation

A Look into the Future

Breaking Down the Barriers

- Does it enable significant new capabilities?
- Is it easy to use?
- Is it VERY cost effective to the user?
- Is it reliable?

Breaking Down the Barriers

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- Is it easy to use?
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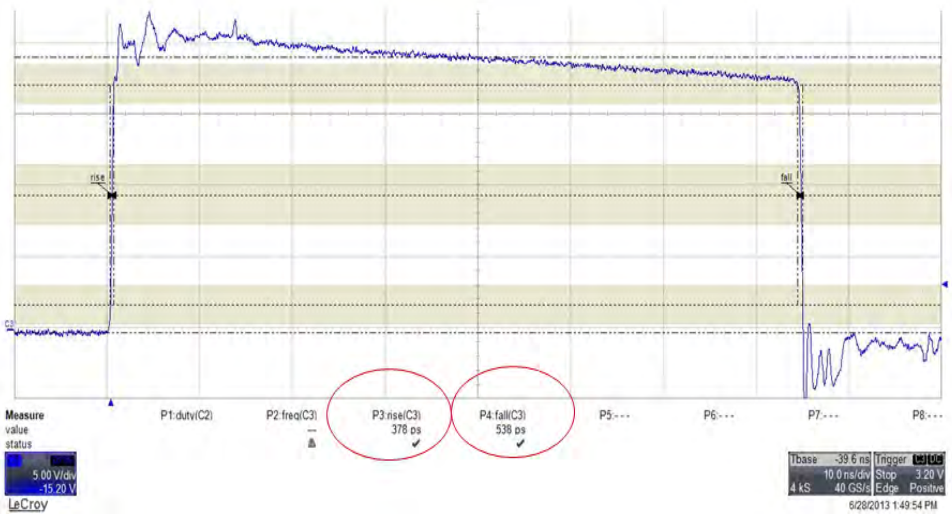
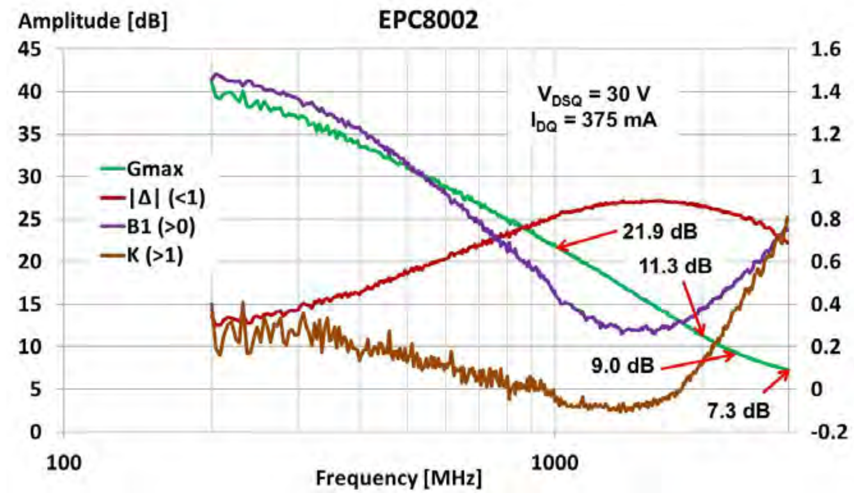
eGaN FETs are *FAST!*

- **20 V**
- 4 A load, 1 MHz
- 380 ps rise, 540 ps fall



EPC8007 driven by LM5113



Small signal Performance

Breaking Down the Barriers

- Does it enable significant new capabilities?
- Is it easy to use?
- Is it VERY cost effective to the user?
- Is it reliable?

Is an eGaN FET Easy to Use?

It's just like a MOSFET

except

The high frequency capability makes circuits using eGaN FETs sensitive to layout

The lower $V_{G(MAX)}$ of 6 V makes it advisable to have V_{GS} regulation in your gate drive circuitry

Universities With GaN Transistor Programs

Universities all over the world are graduating well-trained engineers experienced in the use of GaN Transistors

- Virginia Tech
- Ohio State University
- University of Tennessee
- Florida State University
- Auburn University
- University of California at Santa Barbara
- Rensselaer Polytechnic Institute
- Hong Kong University of Science and Technology
- Cornell University
- Katholieke Universiteit Leuven
- University of Bristol
- University of Glasgow
- University of Sheffield
- University of Warsaw
- University of Sydney
- Massachusetts Institute of Technology
- Cambridge University
- National Central University of Taiwan
- National Taiwan University
- Yale University
- Chang Gung University
- University of Florida
- Case Western University
- University of Toledo
- Kyushu Institute of Technology
- National Chiao Tung University
- University of Texas
- Yamaguchi University
- Universitat Kassel
- National Tsinghua University
- Mid Sweden University
- New Mexico State University
- University of Johannesburg
- University of Toronto
- Universita di Padova
- Delft University of Technology
- Missouri University of Science and Technology
- University of Maryland
- Insitituto Italiano di Technologia

Breaking Down the Barriers

- Does it enable significant new capabilities?
- Is it easy to use?
- Is it VERY cost effective to the user?
- Is it reliable?

Silicon vs. eGaN Wafer Costs

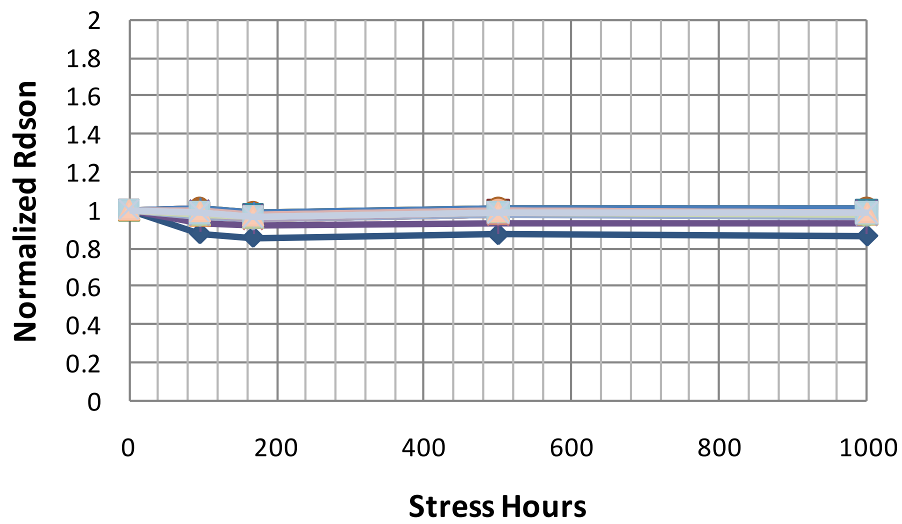
	2012	2015
Starting Material	same	same
Epi Growth	***higher***	***~same?***
Wafer Fab	same	lower
Test	same	same
Assembly	lower	lower
OVERALL	**higher**	***lower!***

Breaking Down the Barriers

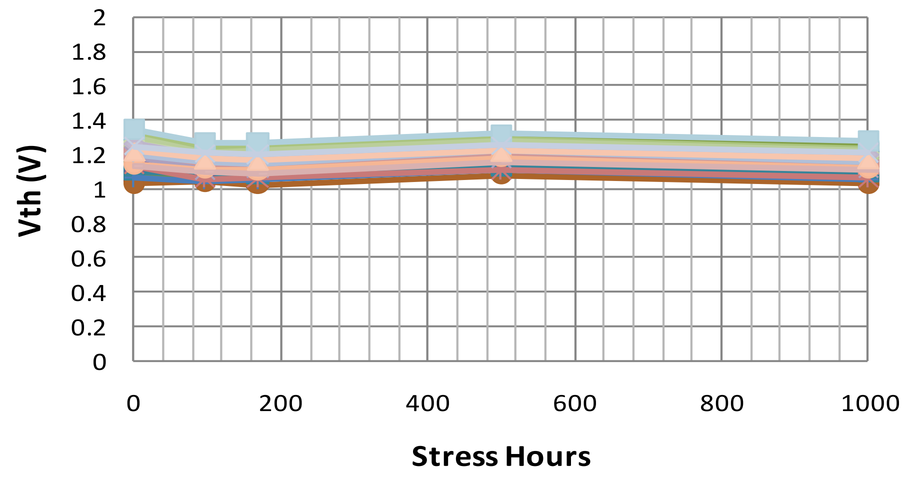
- Does it enable significant new capabilities?
- Is it easy to use?
- Is it VERY cost effective to the user?
- Is it reliable?

eGaN FETs are Reliable

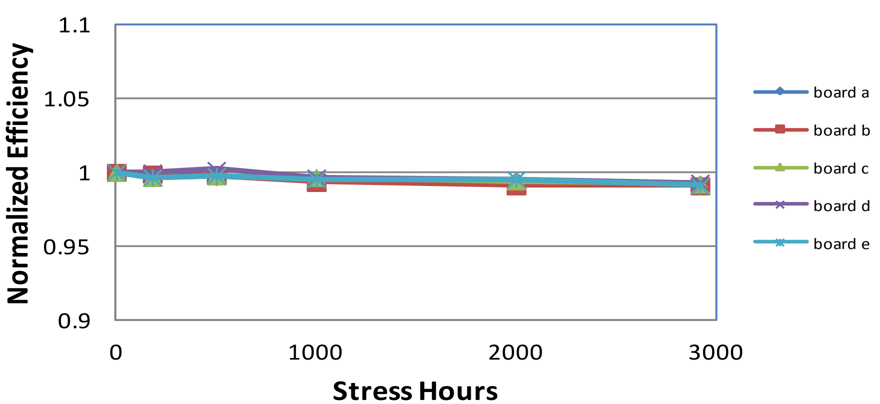
EPC2001 $R_{DS(ON)}$ after $100V_{DS}$ HTRB at 125ºC



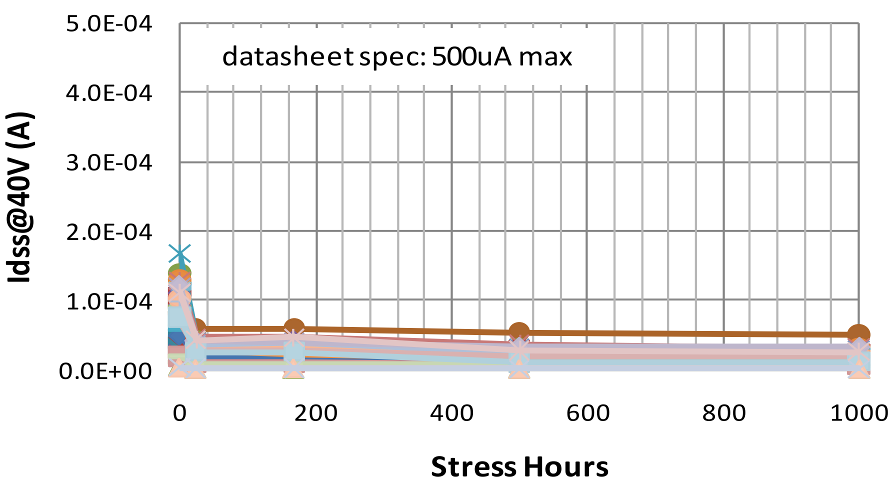
EPC2001 $V_{GS(TH)}$ after $100V_{DS}$ HTRB at 125ºC



EPC9001 Efficiency after Op Life Test at 85ºC T_J



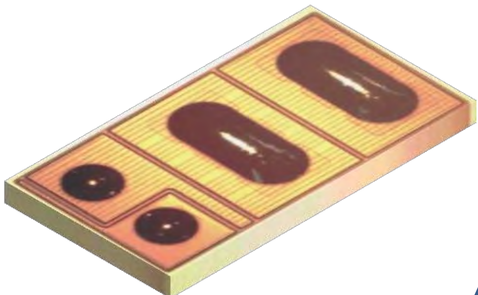
EPC2015 Idss after 40V H3TRB at 85ºC/85%RH



New Technology in the Future

EPC Into the Future

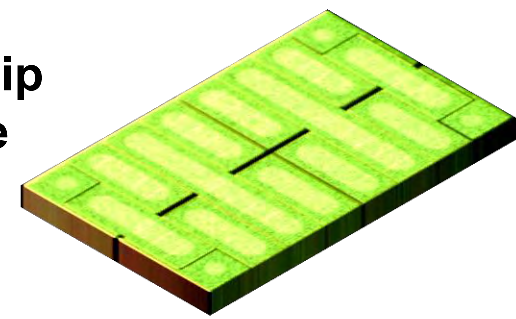
2010-2013
40 V - 200 V
~500 MHz



Generation 3
Higher Frequency
1 -3 GHz
Available Now

Higher Voltage
600 V

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



Generation 4
2 x FOM Improvement

Summary

- eGaN FETs enable exciting new applications such as RF Envelope Tracking and Wireless Power Transmission
- eGaN FETs have the potential to replace silicon power MOSFETs in power conversion applications with a low-cost and higher efficiency solution
- eGaN FETs are straightforward to use, but you can't just drop them into a MOSFET socket. Some R&D is needed – start today!