The eGaN® FET Journey Continues

eGaN® FET based Wireless Energy Transfer Using New Zero Voltage Switching Class-D Topology

Efficient Power Conversion Corporation

Agenda

- Wireless Energy Transfer Overview
- Topology Overview
- eGaN® FET Family
- Wireless FET Figure of Merit
- Experimental performance
- Preliminary A4WP Results
- Summary

eGaN® is a registered trademark of Efficient Power Conversion Corporation

Why Wireless Energy

- Mobile device charging
  - Convenience
  - Extended battery life
- Medical Implants
  - Quality of life improvement
  - Life extender
- Hazardous environment systems
  - Explosive atmosphere
  - Corrosive locations
  - High Voltage

Wireless Energy Standards

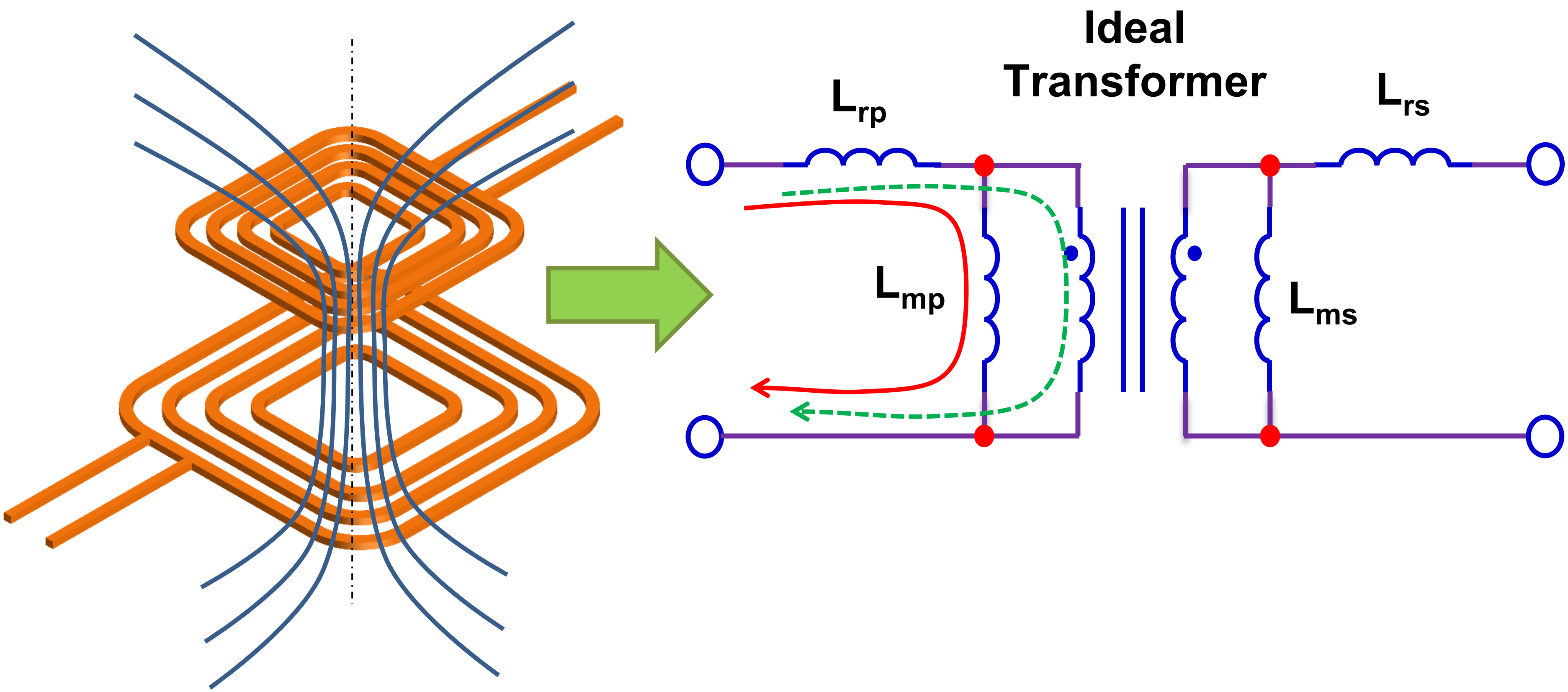
- Alliance for Wireless Power (A4WP / Rezence)
  - Highly resonant (6.78 MHz ISM band)
  - loosely coupled coils
- Wireless Power Consortium (WPC - Qi)
  - Low frequency (~ 100 - 205 kHz)
  - Tightly coupled (Inductive)
- Power Matters Alliance (PMA)
  - Low frequency (~ 201 - 315 kHz)
  - Tightly coupled (Inductive)
  - Joined with A4WP standard

Wireless System Overview

Comprises 4 main sections:

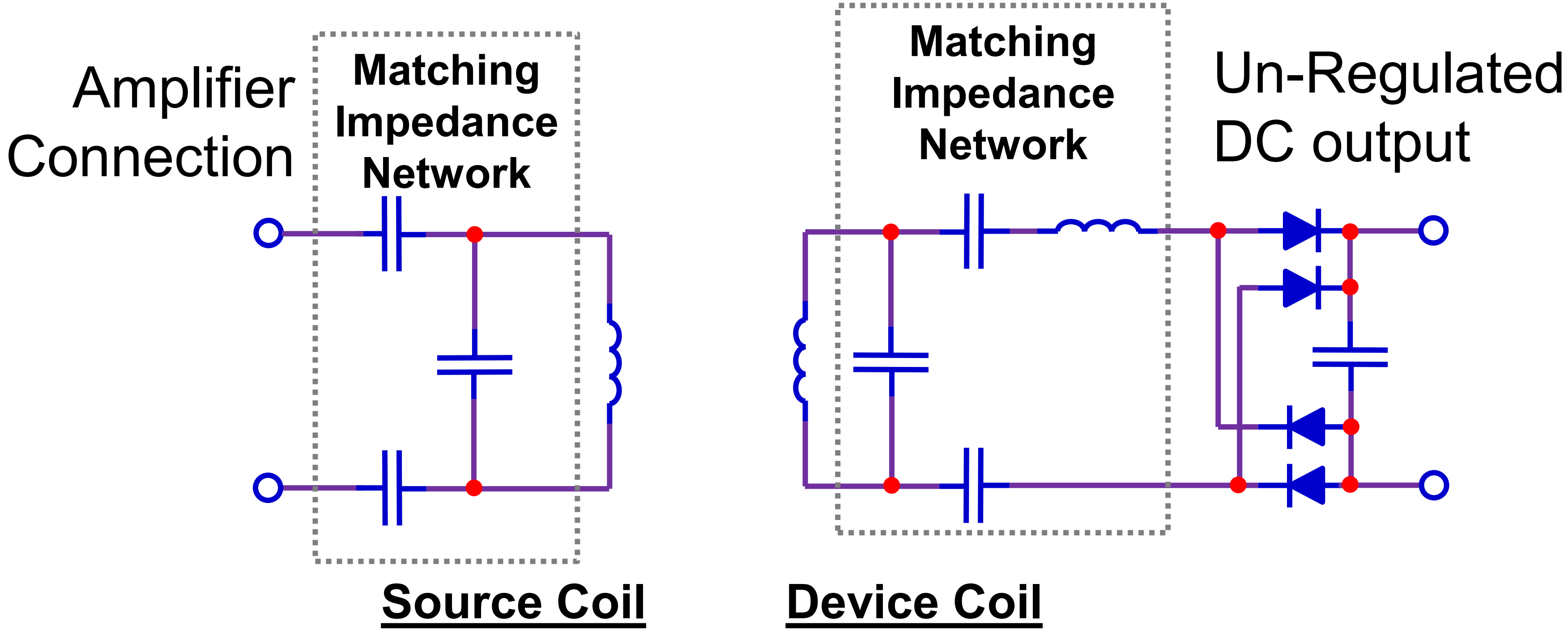
1. An amplifier (a.k.a. a power converter).
2. A Source coil (transmitter) with matching.
3. A Device coil (receiver) with matching.
4. A rectifier with high frequency filtering

Magnetic Field Wireless Transfer



Highly Resonant Wireless Transfer

- Coils tuned to resonate at 6.78 MHz
- Series and Shunt tuning can be used
- Coupling and load variation can shift resonance

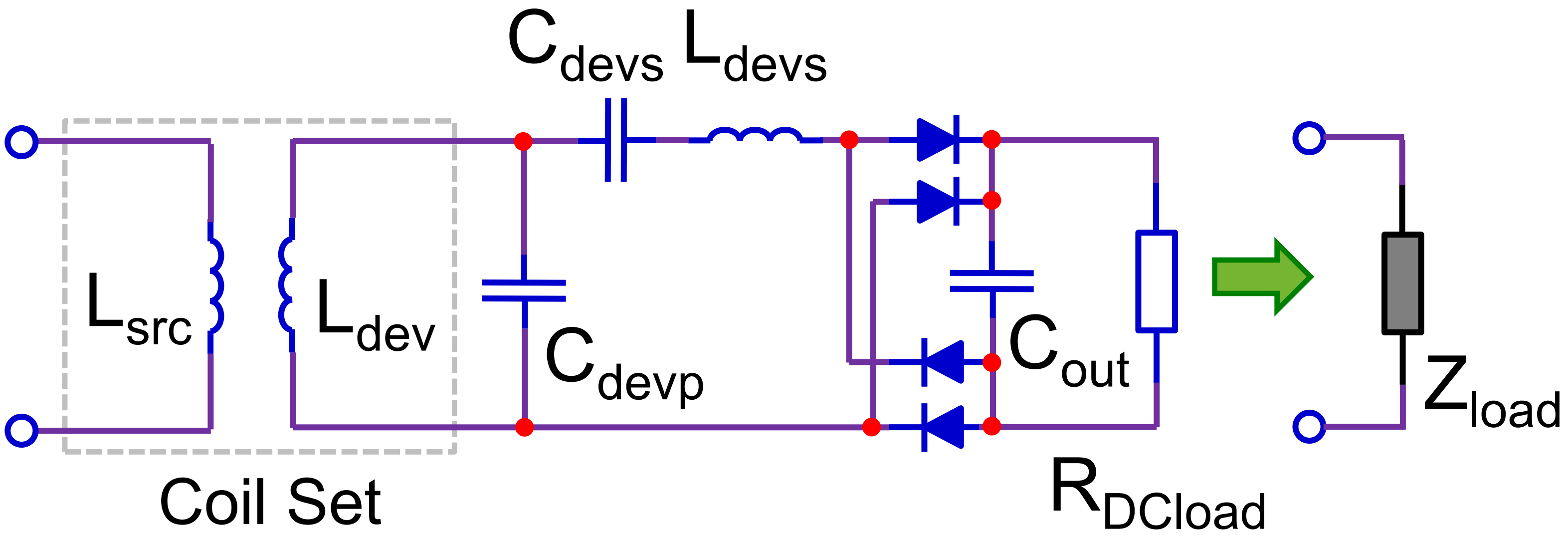


Challenges to Wireless Energy

- High Efficiency required
  - limited thermal dissipation budget
  - Energy Standards
- Low Profile – mobile market
- Robustness to dynamic operating conditions (convenience factor)
  - Load Profile – A4WP (inc. Foreign object)
- Regulatory compliance (e.g. FCC, EN, UL)

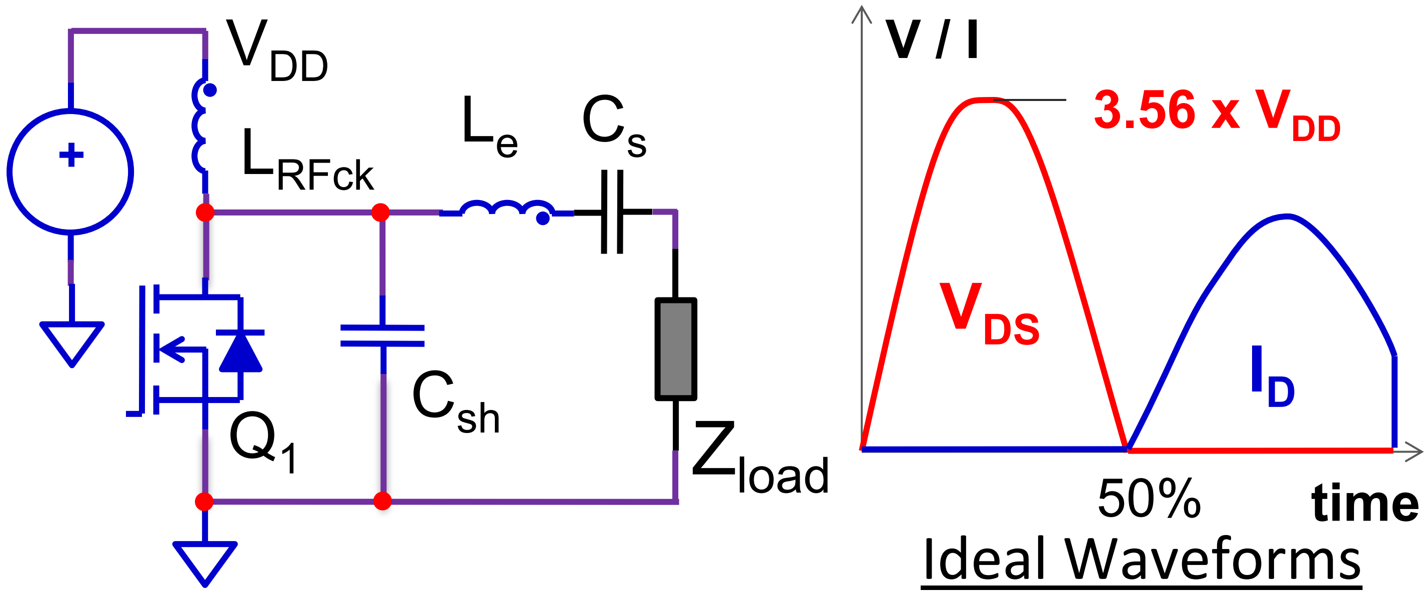
Wireless Coil-set Overview

Simplified representation of coil-set for easy comparison between topologies



Class-E Overview

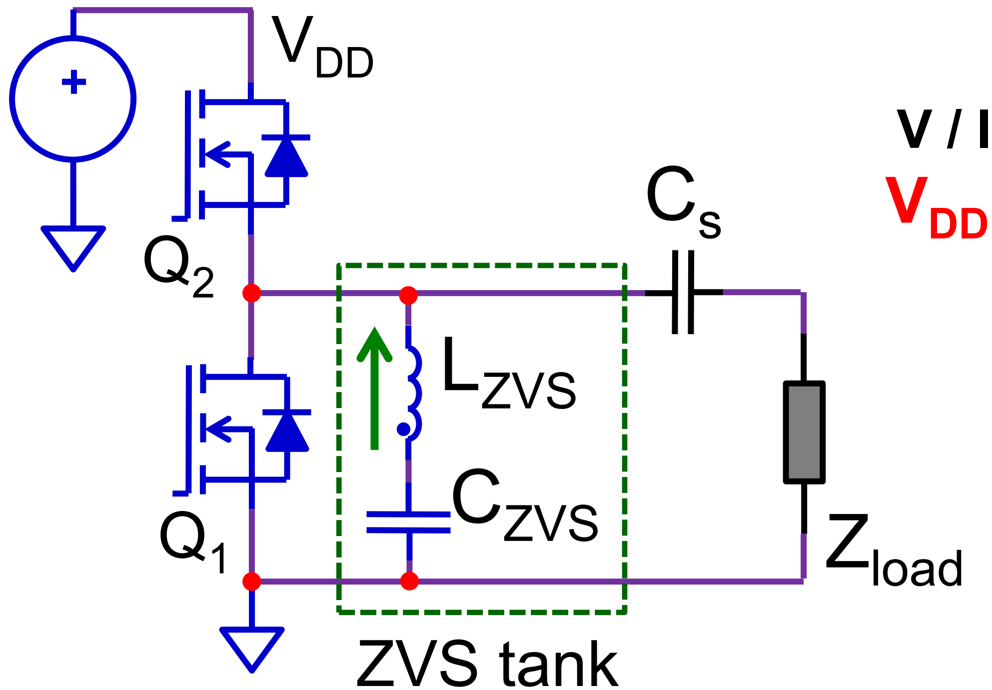
- Switch voltage rating ≥ 3.56·Supply (V_{DD}).
- C_{OSS} “absorbed” into matching network.
- Susceptible to load variation - high FET losses
- Tuned Coil Voltage ≈ 0.707·V_{DD} [V_{RMS}]

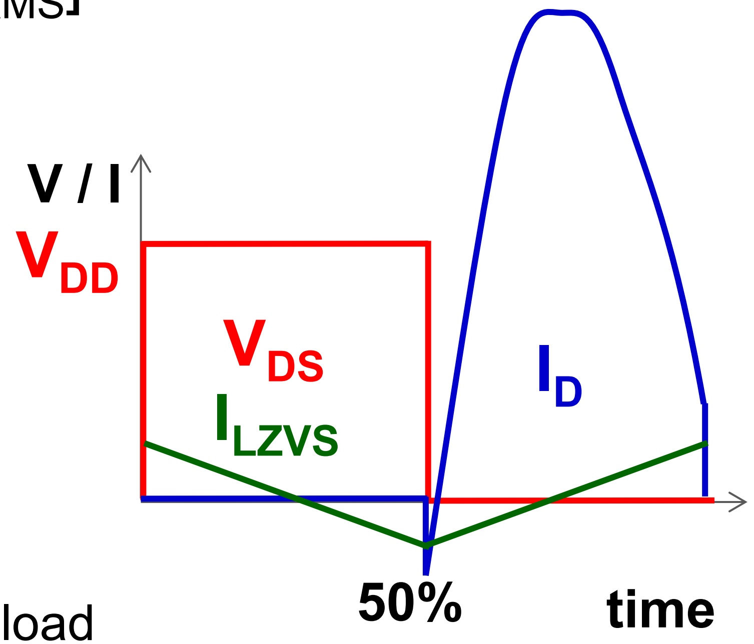


Ideal Waveforms

ZVS Voltage Mode Class-D*

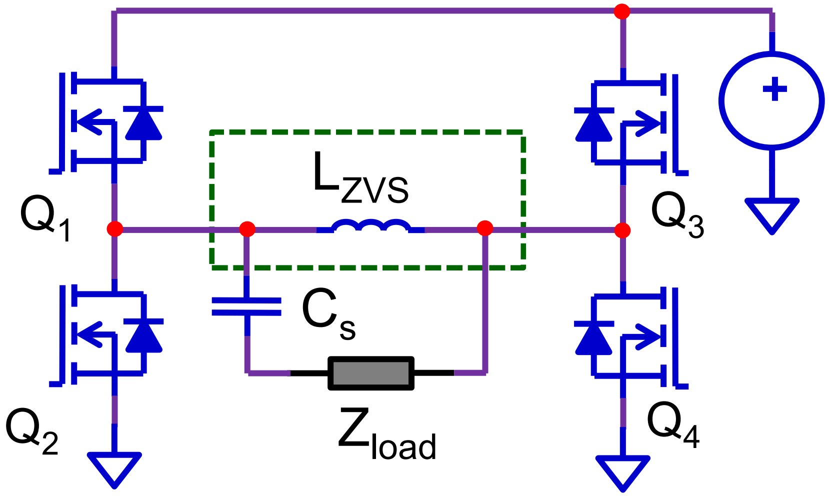
- Switch voltage rating = Supply (V_{DD}).
- ZVS tank current soft switches C_{OSS} Voltage
- ZVS tank circuit does not carry load current
- Tuned Coil Voltage = ½·V_{DD} [V_{RMS}]



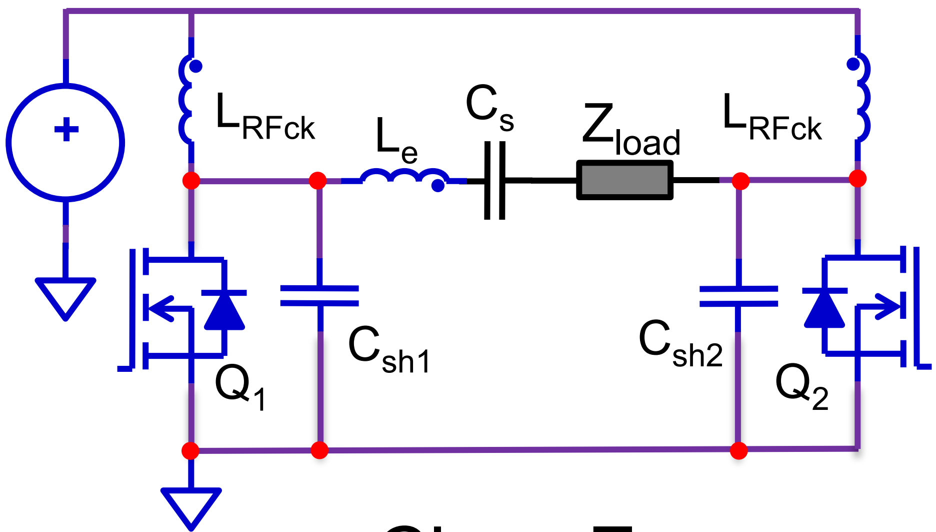


Ideal Waveforms

Differential Versions



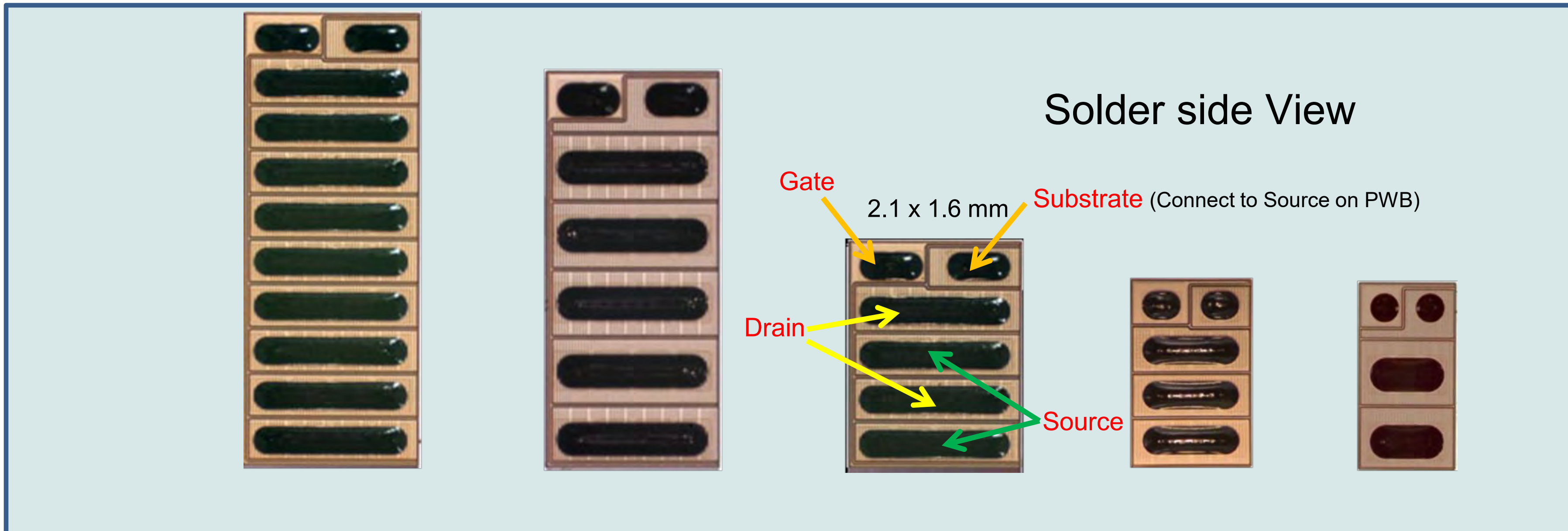
ZVS Class-D



Class-E

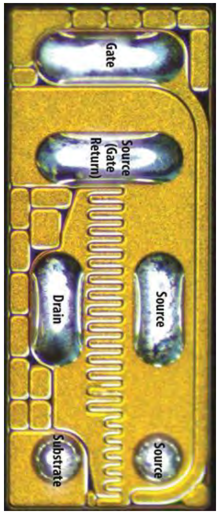
- ZVS Class-D simplifies with the removal of the ZVS Capacitor

eGaN FET Low Voltage Family



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 Gen 3 eGaN FETs

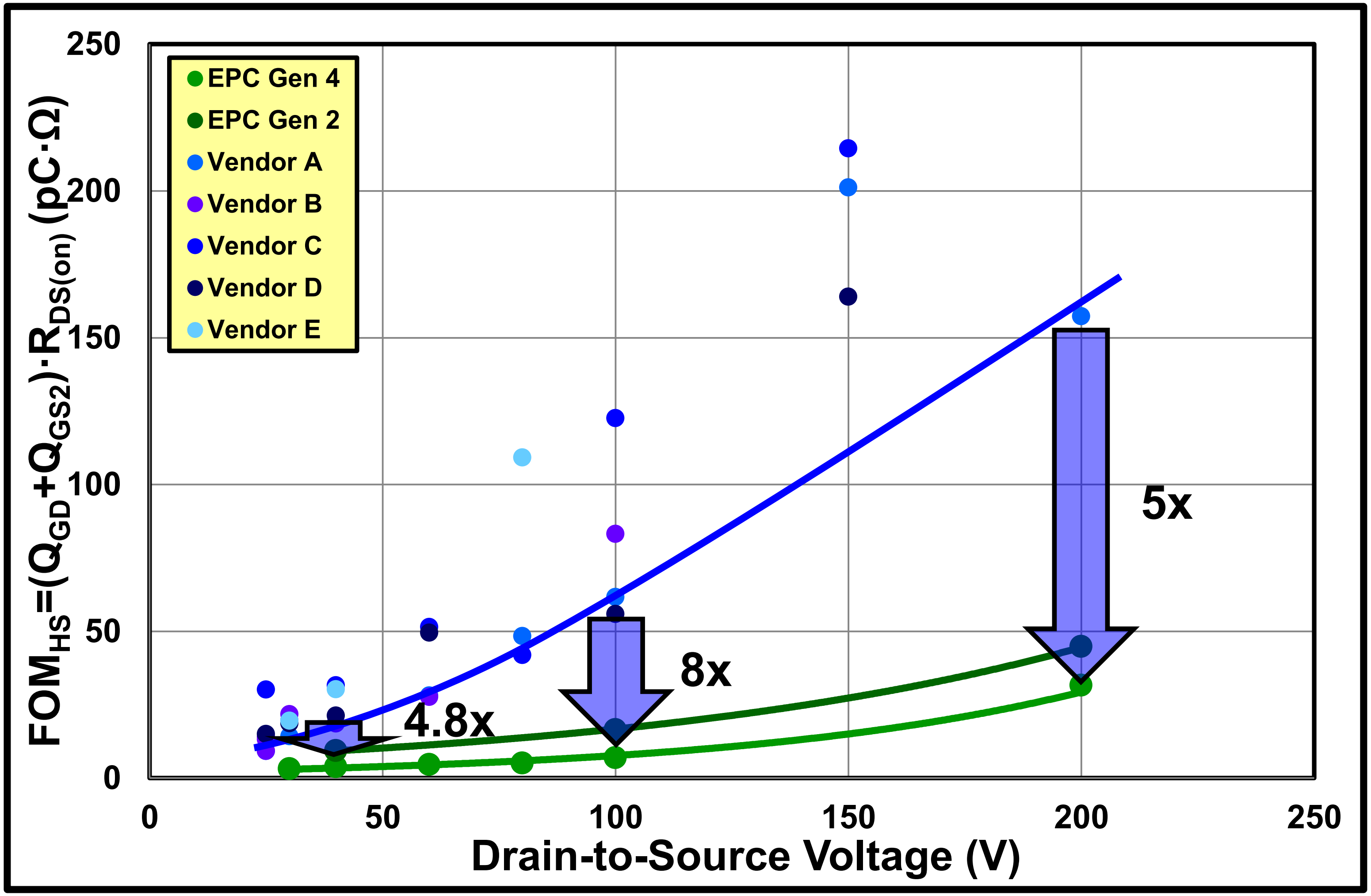


EPC Part No.	BV (V)	Max. $R_{DS(ON)}$ (mΩ) (V_{GS} = 5V, I_D = 0.5 A)	Min. Peak Id (A) (Pulsed, 25 °C, T_{pulse} = 300 µs)	Typical Charge (pC)					Typical Capacitance (pF) (V_{DS} = 20 V; V_{GS} = 0 V)		
				Q_G	Q_{GD}	Q_{GS}	Q_{OSS}	Q_{RR}	C_{ISS}	C_{OSS}	C_{RSS}
EPC8004	40	125	7.5	358	31	110	493	0	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

Gen 4 Datasheet Summary

Part Number	Gen	BV (V)	$R_{DS(on)}$ (mΩ) (V_{GS} = 5V, at I_D Cont.)		Peak I_D (A) (Pulsed 25˚C)	Max T_J	Typical Charge (nC) @ V_{ds}= BV/2;					Typ R_g (Ω)	Cont. I_D (A)
			Typ.	Max			Q_G	Q_{GD}	Q_{GS}	Q_{OSS}	Q_{RR}		
EPC2023	4	30	1.0	1.3	590 A	150˚C	27.5	1.9	5.8	27	0	0.3	60
EPC2024	4	40	1.2	1.5	550 A	150˚C	26	2.0	6.4	32	0	0.3	60
EPC2020	4	60	1.5	2.0	470 A	150˚C	22	2.0	5.0	42	0	0.3	60
EPC2021	4	80	1.8	2.5	420 A	150˚C	20	2.1	3.8	60	0	0.3	60
EPC2022	4	100	2.4	3.2	360 A	150˚C	17	2.0	3.7	60	0	0.3	60
EPC2019	4	200	33	43	42 A	125˚C	2	0.33	0.63	17.5	0	0.3	9
EPC2015	2	40	3.2	4	150 A	125˚C	10.5	2.2	3	18.5	0	0.3	33
EPC2001	2	100	5.6	7	100 A	125˚C	8	2.2	2.3	35	0	0.3	25
EPC2012	2	200	70	100	15 A	125˚C	1.5	0.57	0.33	11	0	0.3	3

Hard Switching FOM



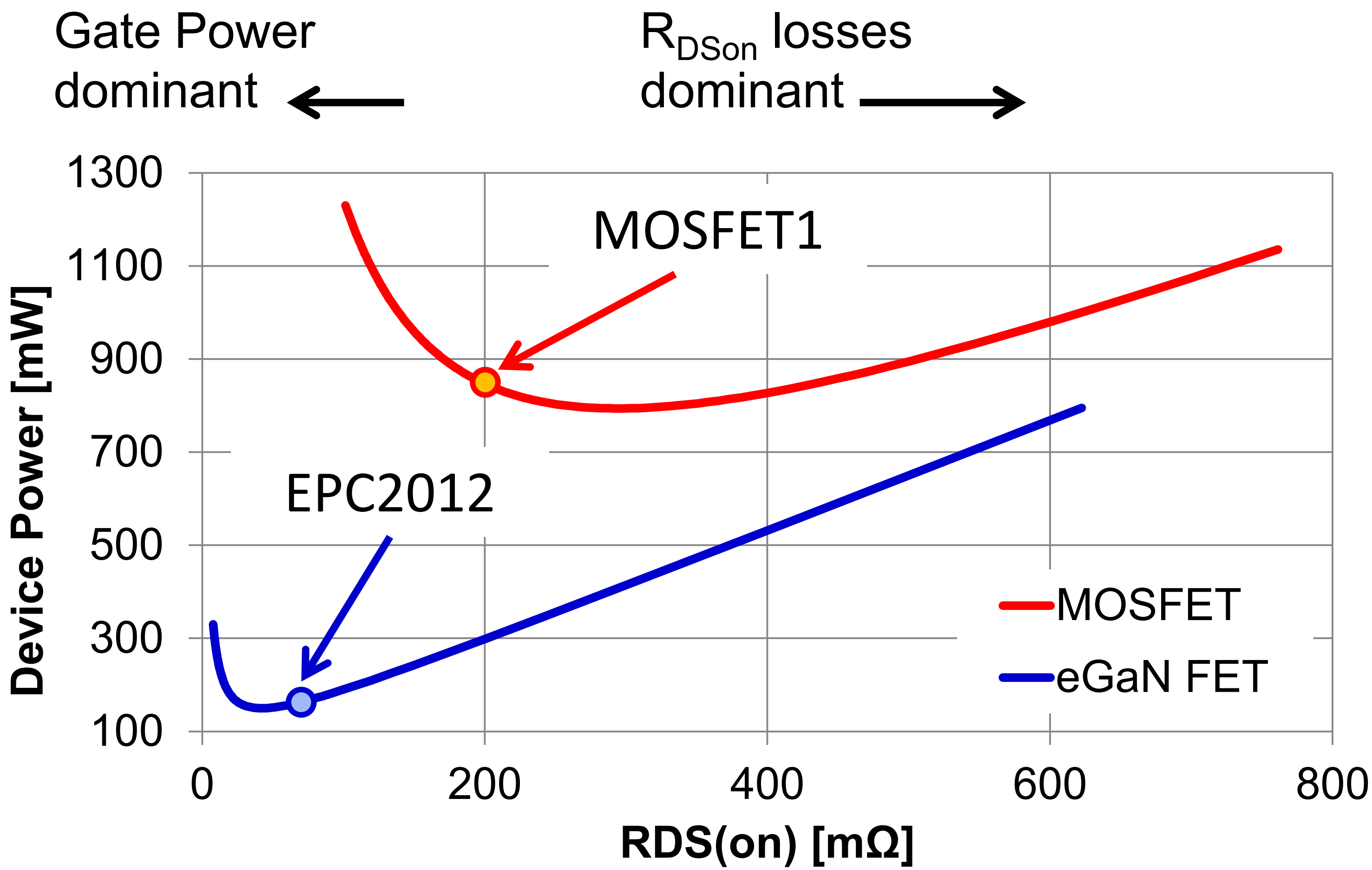
$V_{DS}=0.5\cdot V_{DSS}$, $I_{DS}=20$ A

Wireless Power Figure of Merit

- All topologies are ZVS: $Q_G - Q_{GD}$ only
- C_{OSS} is "absorbed" in matching – excluded
- C_{OSS} still important:
  - Drives off-resonance losses
  - Determines design-ability (Maximum C_{OSS})

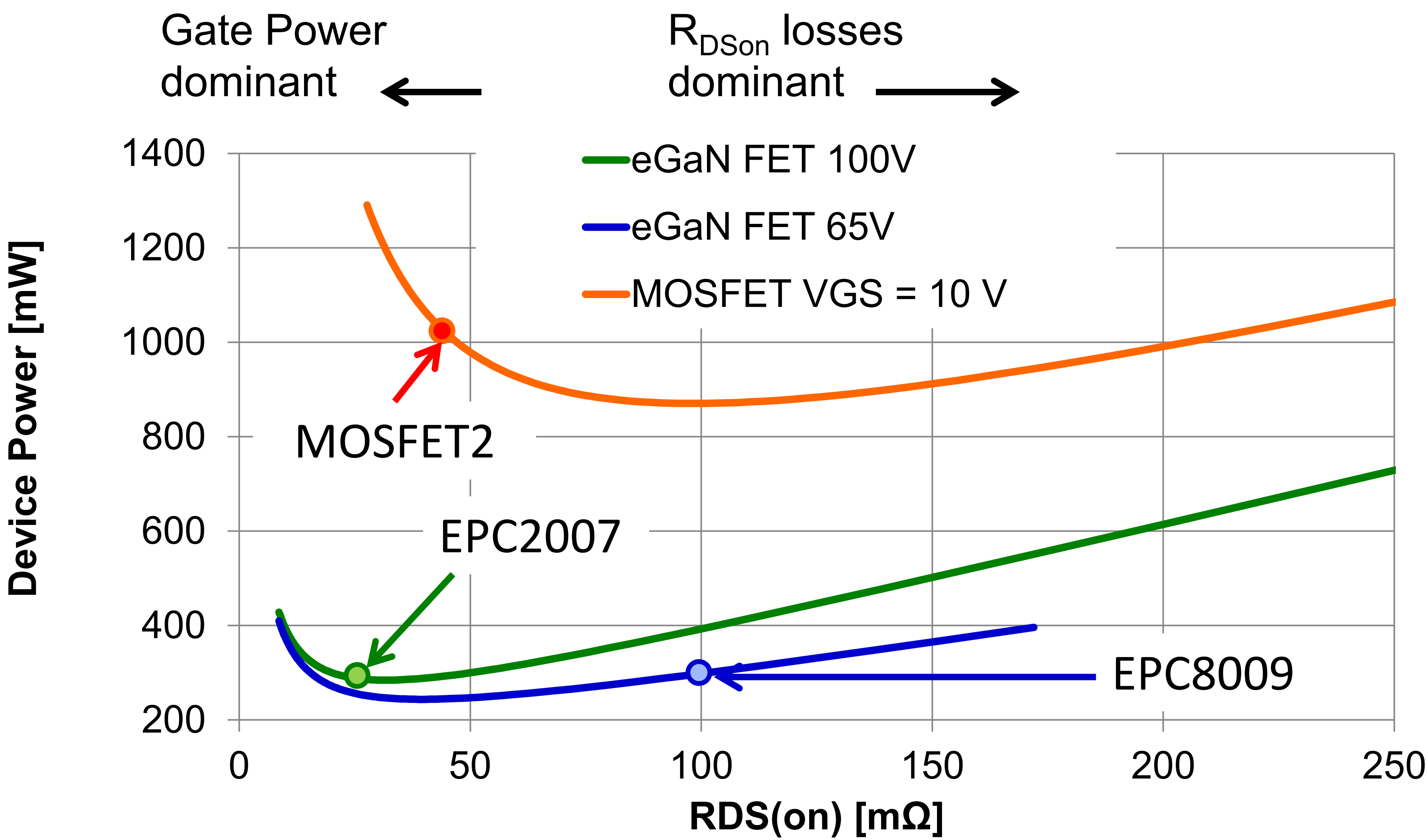
$$FOM_{WPT} = R_{DS(on)} \cdot (Q_G - Q_{GD})$$

Optimal Device – Class E

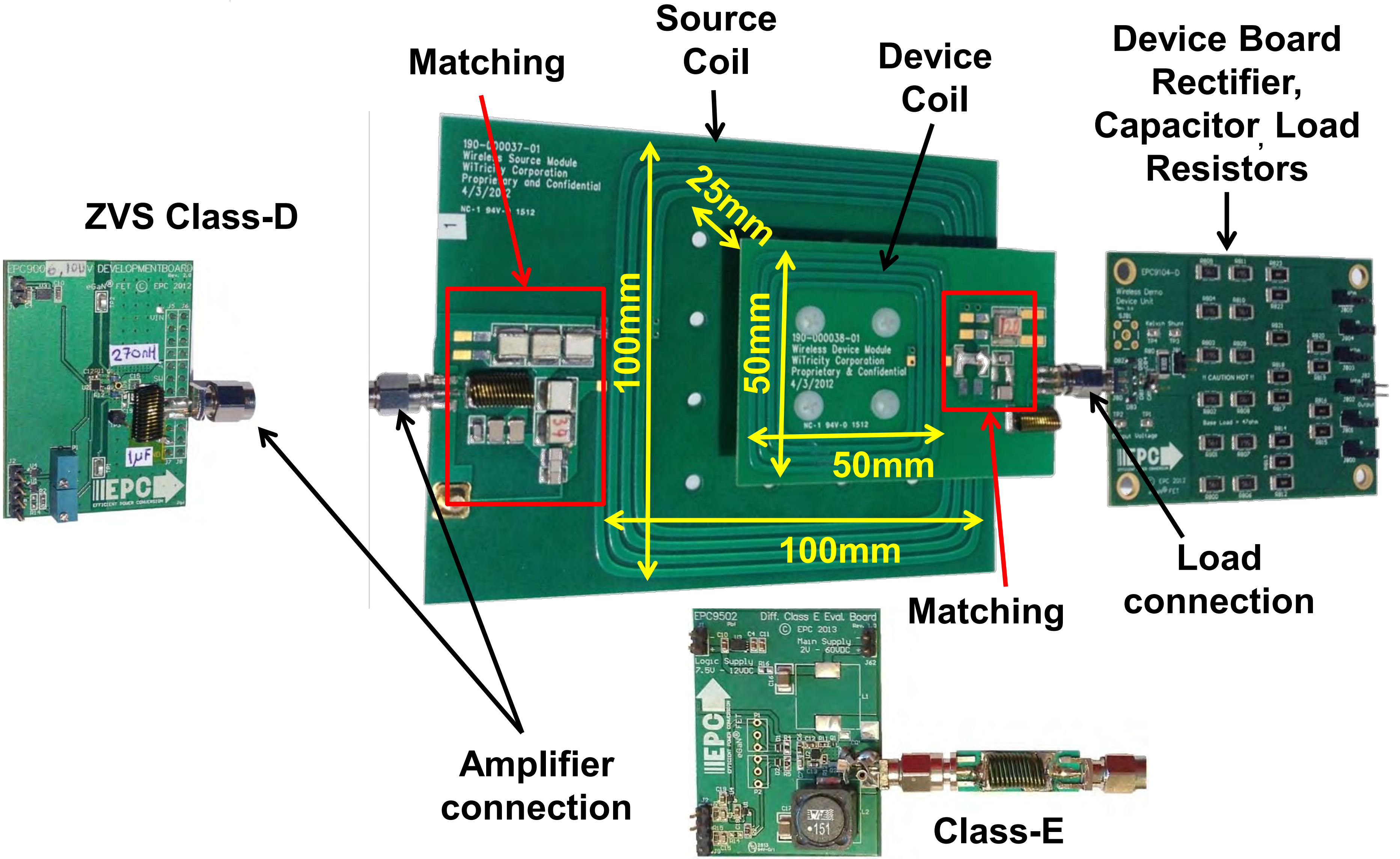


A too low R_{DSon} yields too high C_{OSS} to realize design!

Optimal Device – ZVS Class D



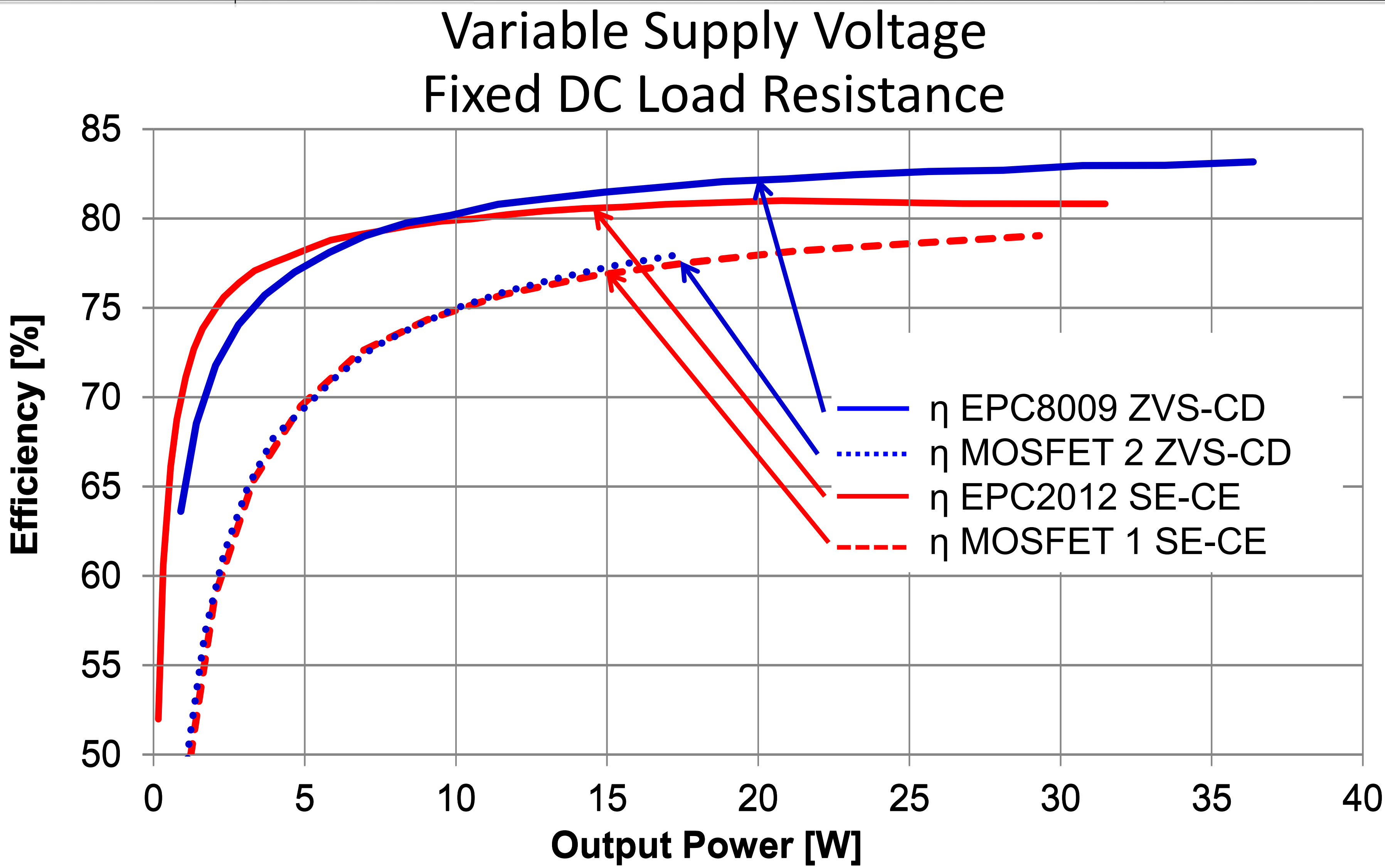
Experimental Setup



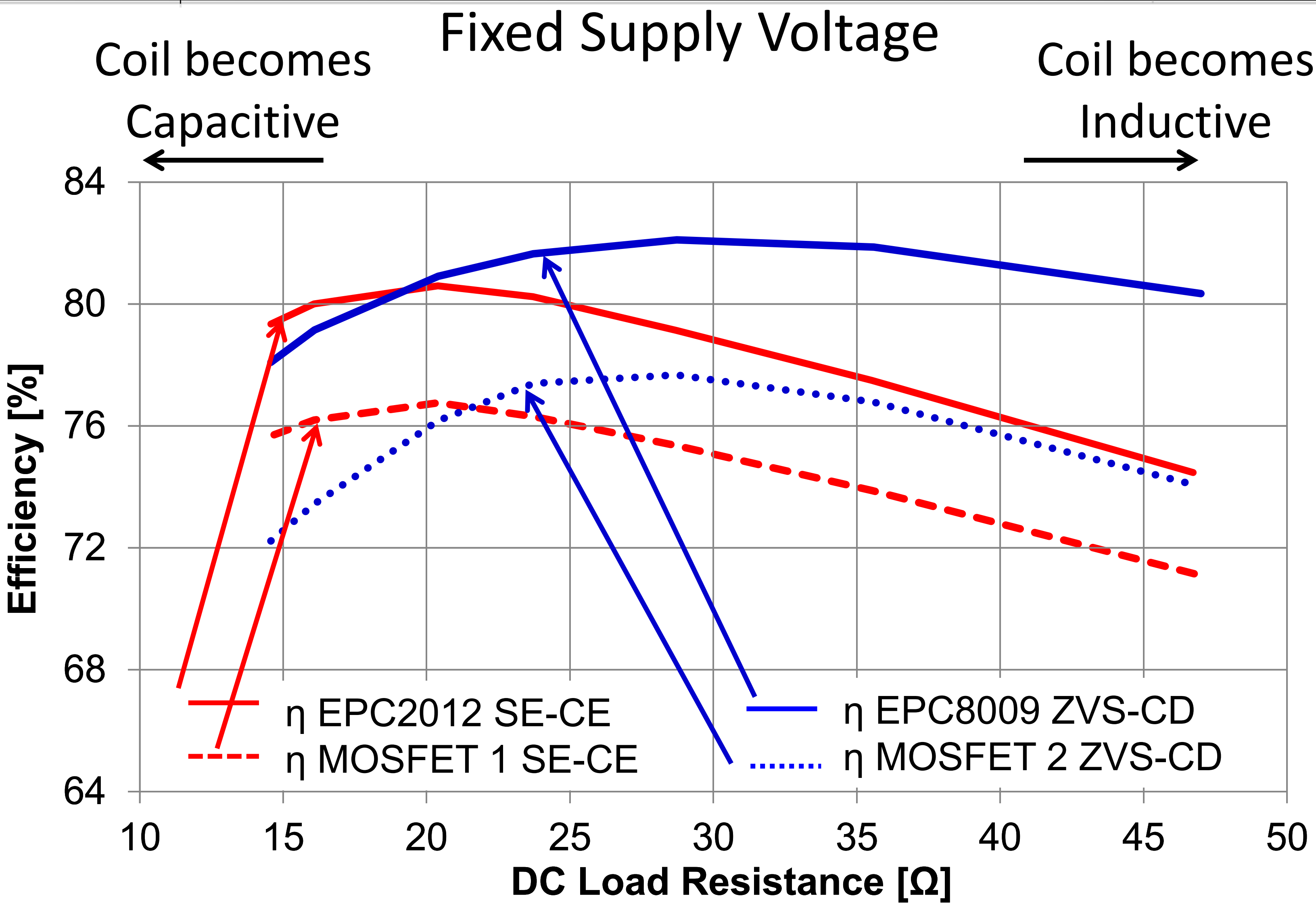
Experimental Background

- Operating setup:
  - On resonance tuned source coil
  - Device tuning is fixed
- Performance testing:
  - Fixed load, variable supply (Peak Performance)
  - Fixed supply, variable DC load (3:1 ratio) (Load Variation)
  - Fixed load voltage, variable DC load (3:1 ratio) (Load Regulation)
  - Fixed supply voltage, foreign object response

Peak Performance Results

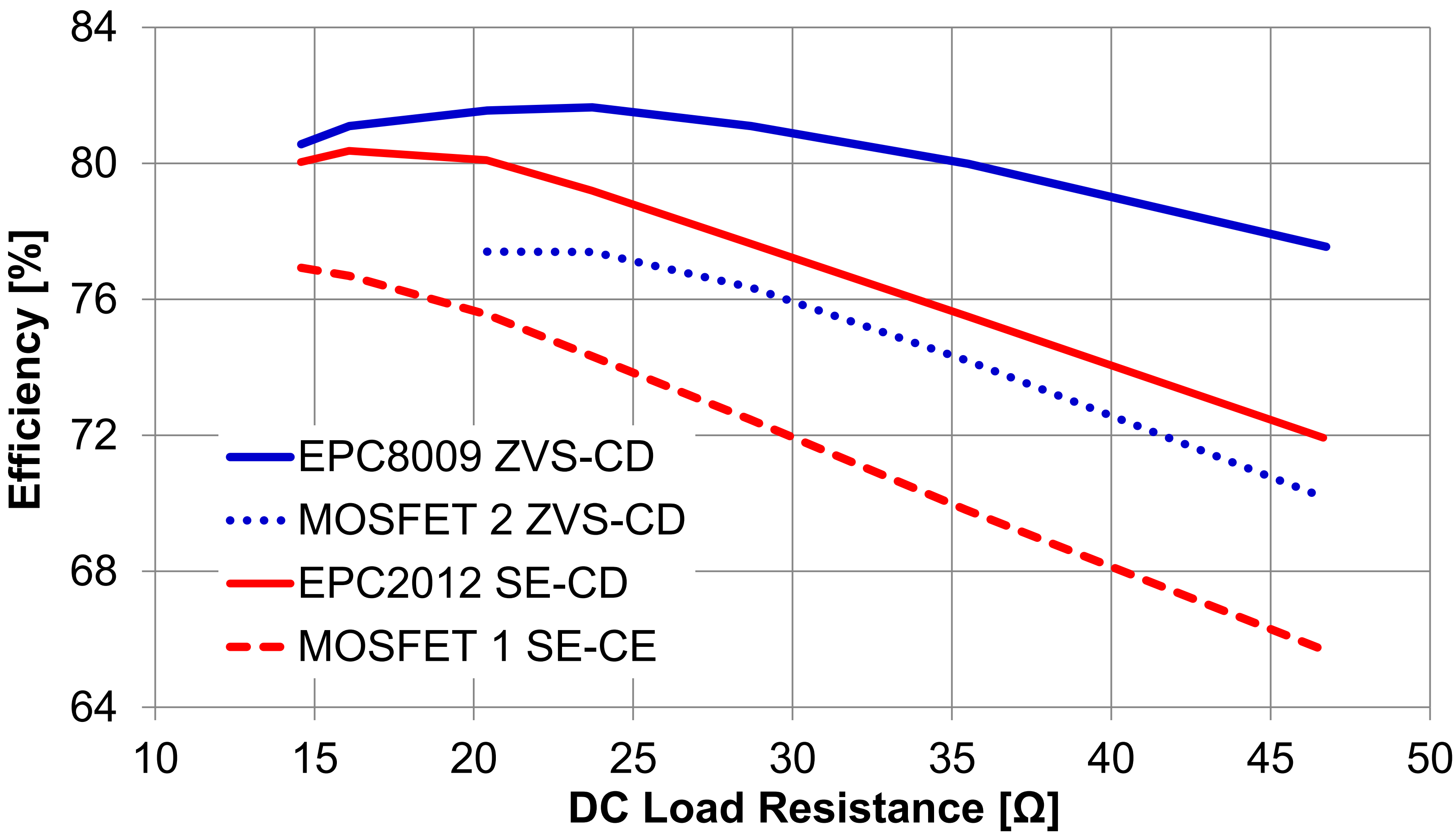


Load Variation Results



Load Regulation Comparison

Fixed DC load voltage, DC Load Resistance varied



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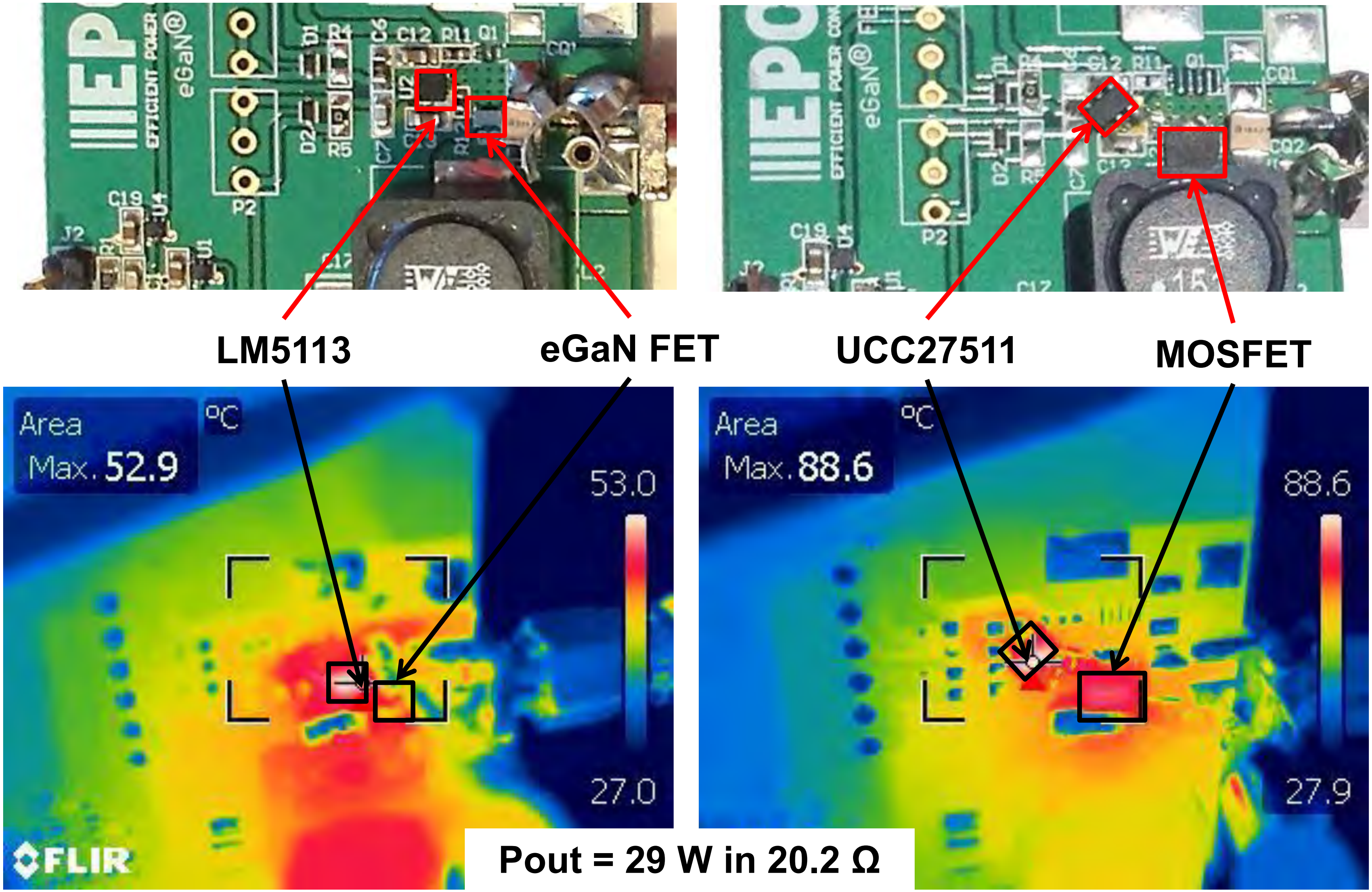
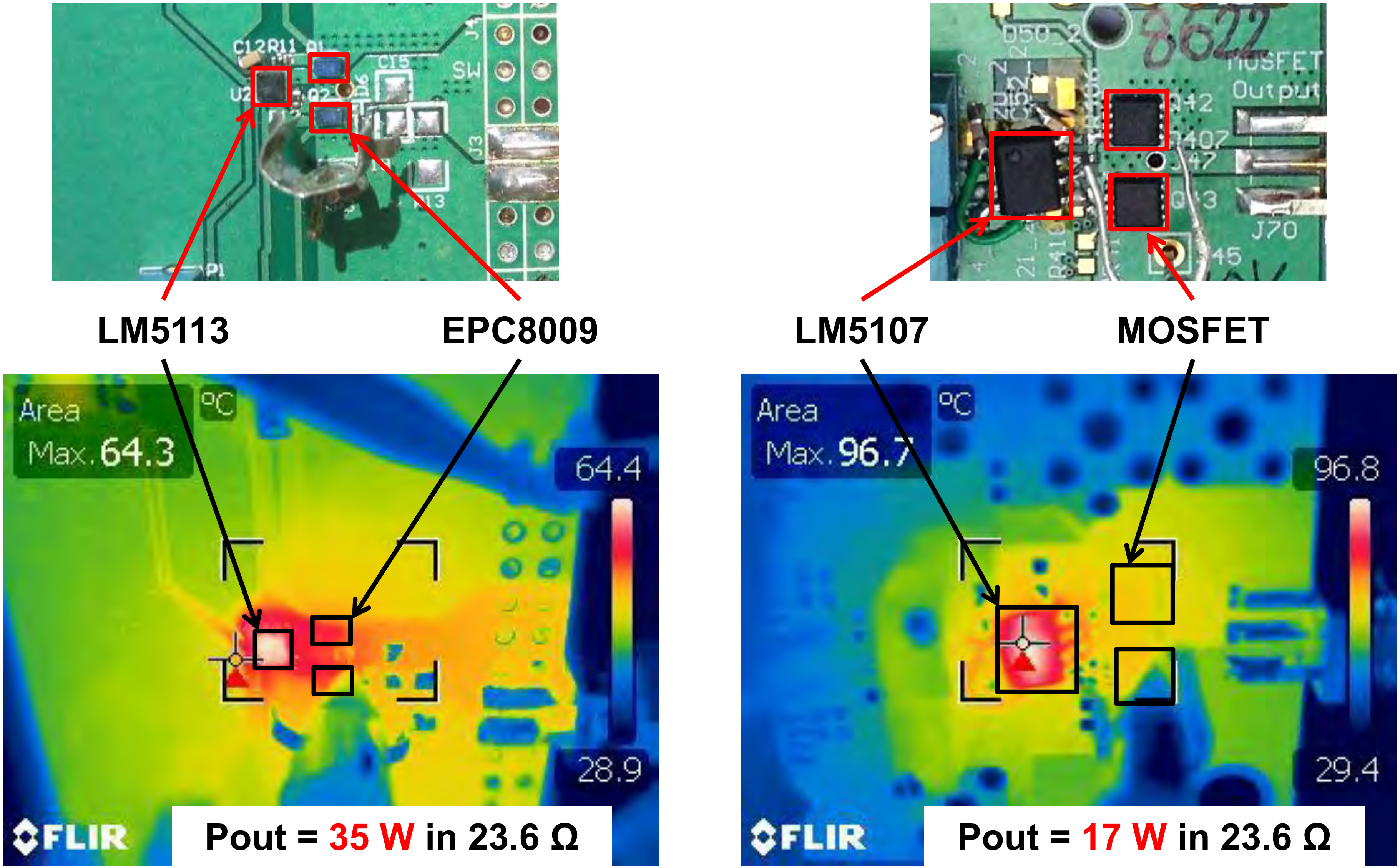
Class-E Thermal Performance

EPC EFFICIENT POWER CONVERSION



Pout = 29 W in 20.2 Ω

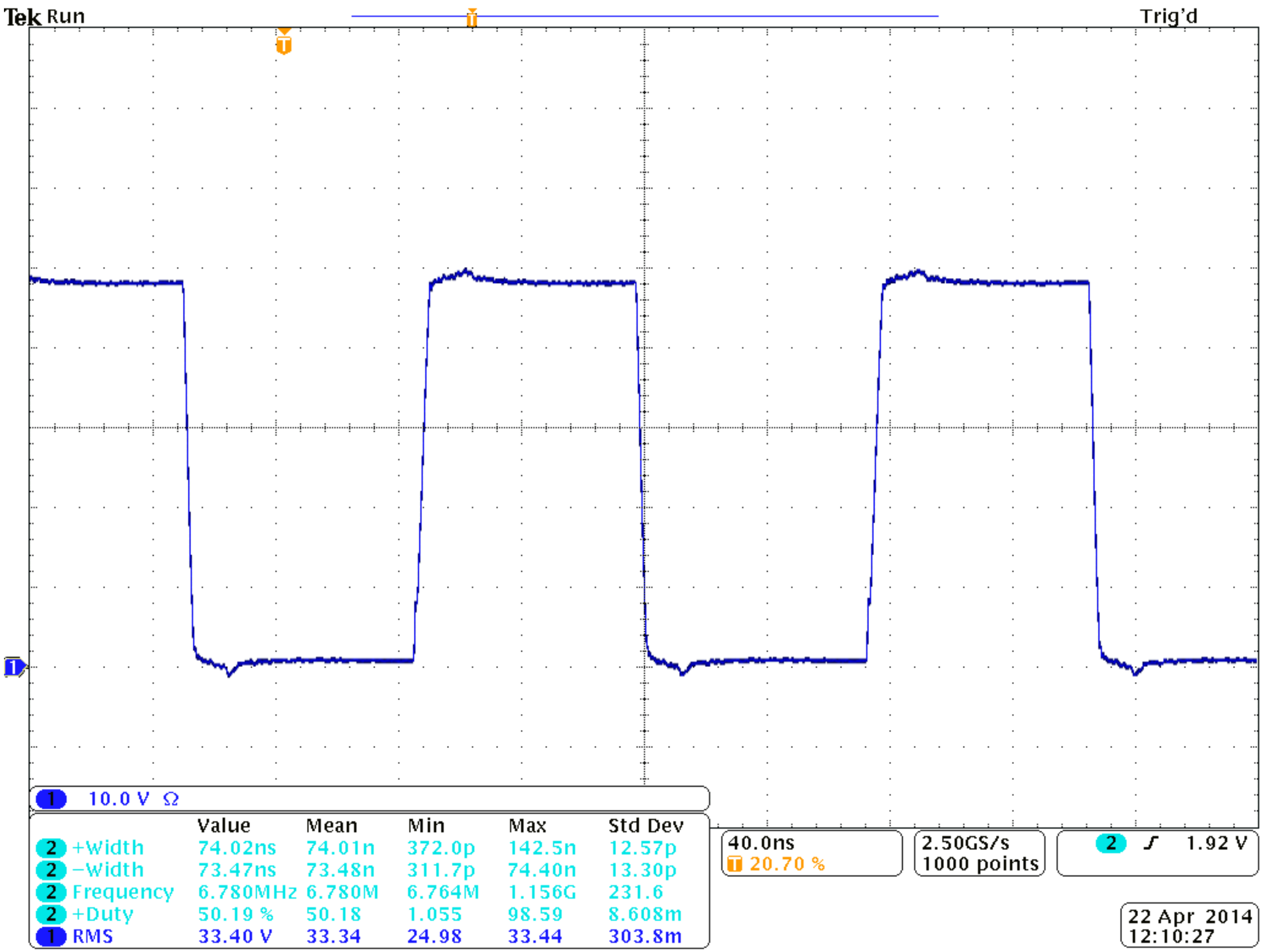
ZVS Class-D Thermal Performance



ZVS Class-D waveforms

EFFICIENT POWER CONVERSION

EPC8009 – 32.5 W into 23.6 Ω



Foreign Metal Object Response

- No simple means to detect a foreign object
- Ability to operate in presence of foreign metal object:
  - ZVS Class-D – very good
  - Class-E – very bad

Spacing	Voltage	Current	Temperature	Remarks	Severity
5 mm Class E	$6.4 \cdot V_{sup}$	$0.3 \cdot I_{nom}$*	FET Very High*	Capacitive switching losses	High
5 mm ZVS Class D	$1 \cdot V_{sup}$	$0.02 \cdot I_{nom}$	40˚C FET	Normal	Low

* Circuit cannot operate at full input voltage

Topology Comparison Summary

- Class-E:
  - Good for Small load variations
  - Cannot tolerate foreign objects well
- ZVS Class-D:
- Highest Efficiency
- Good foreign object operation
- Lowest impact on tuned coil impedance (Low Z_{out})
- Lower Z_{OUT} reduces impact of load variation

Next Steps

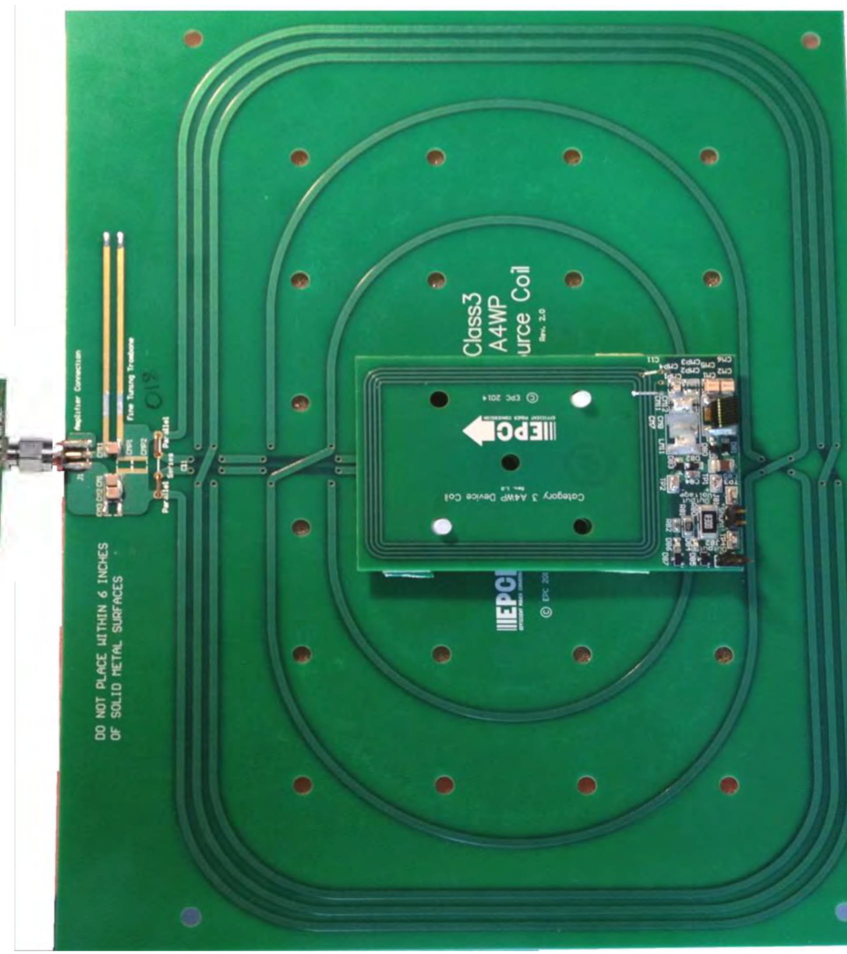
- New EPC Demo Boards
  - Single Ended and Differential ZVS Class-D
    - 6.78 MHz & 13.56 MHz
    - Includes Constant Current (CC) Pre-Regulator

EPC's New ZVS Class-D Demo

- Single Ended and Differential ZVS Class-D
- Tuned A4WP class 3 and 1x Category 3 Coil set
- 6.78 MHz Design
- Constant Current Pre-Regulator

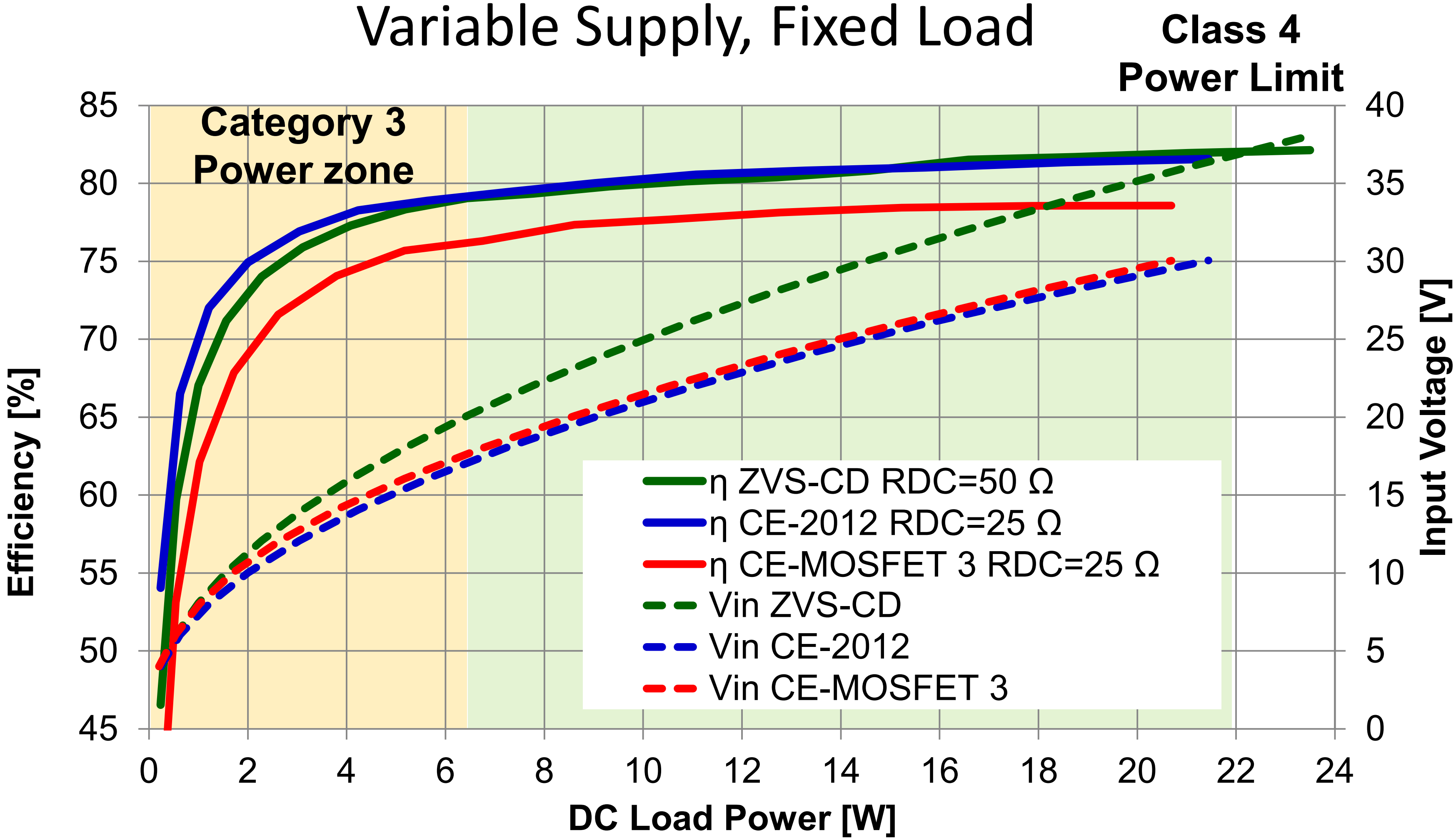
EPC9111 & EPC9112

EPC9506/7



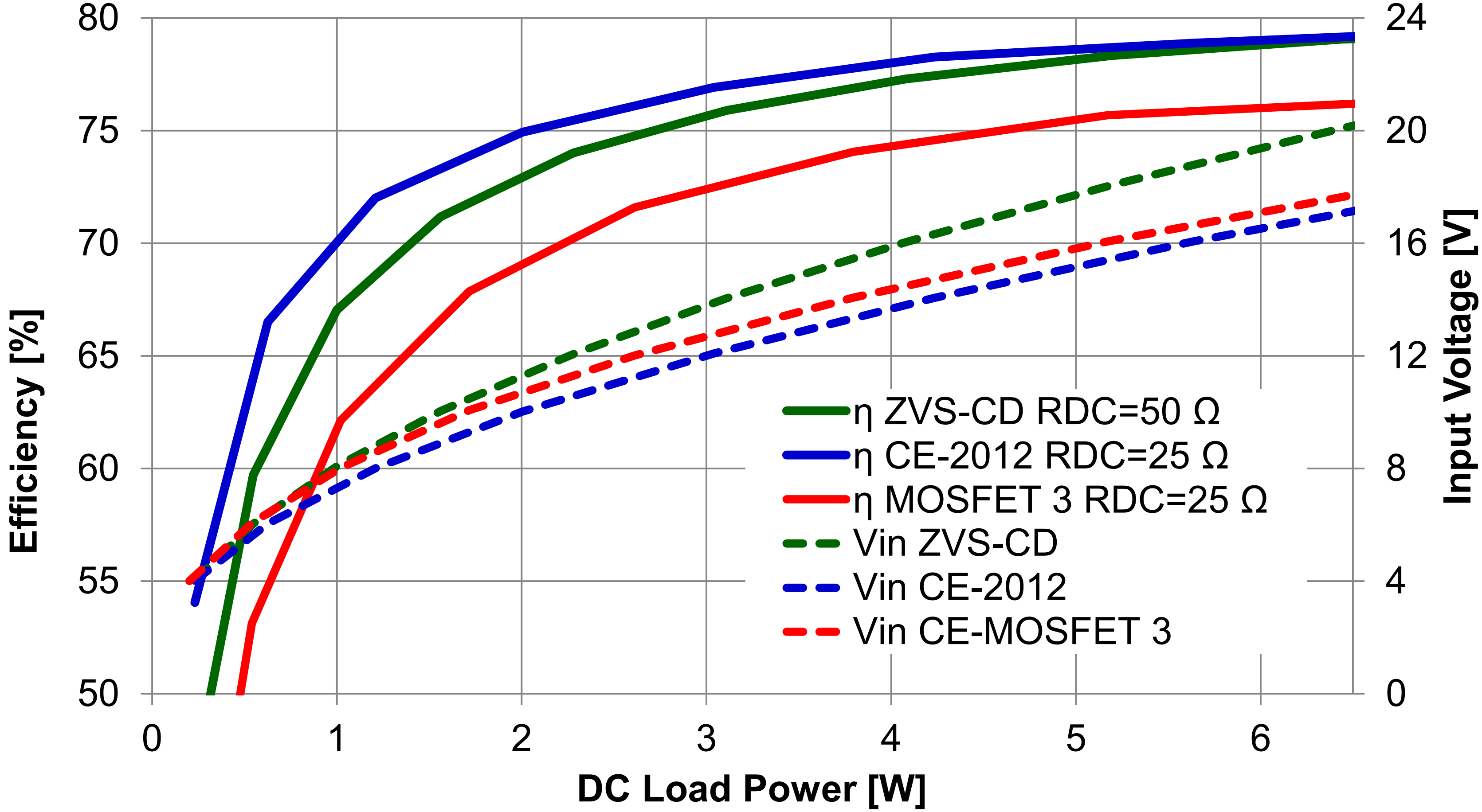
Peak Performance Results

Peak Efficiency, Single load capability
Variable Supply, Fixed Load



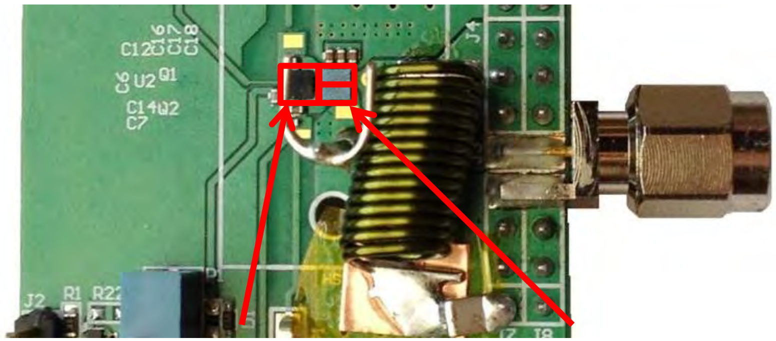
Peak Performance Results

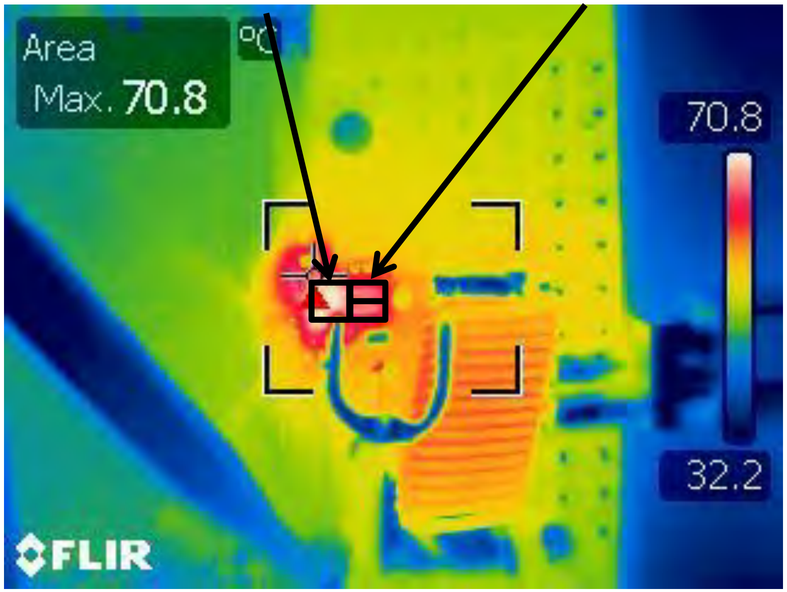
Peak Efficiency for Category 3 Load
Variable Supply, Fixed Load



EPC8009 ZVS Class D Waveforms & Thermal

V_{DC} = 38 V
P_{out} = 23.5 W
R_{DCload} = 50.3 Ω



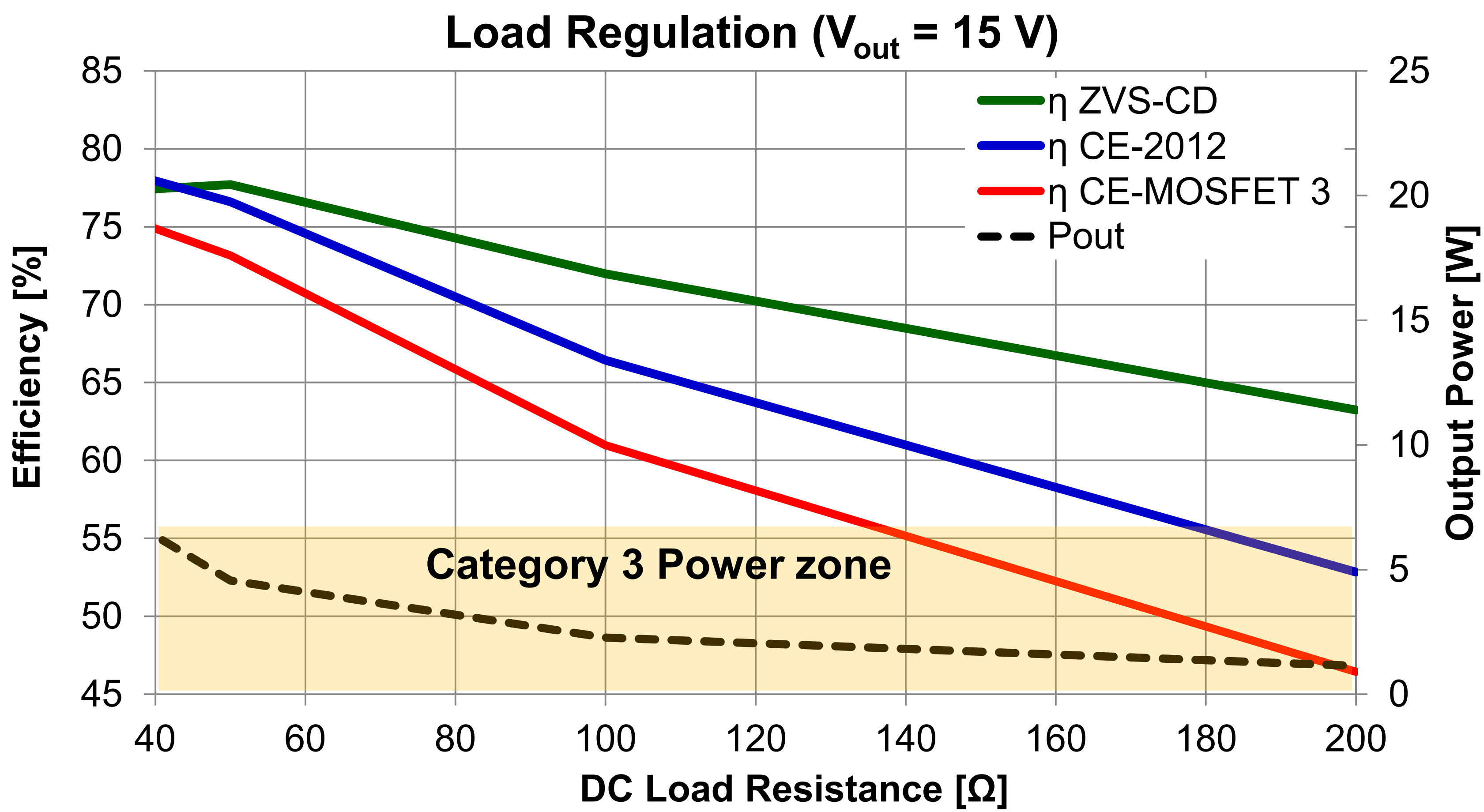


High Power, Peak Performance

Load Variation Results

EFFICIENT POWER CONVERSION

High Power Capability

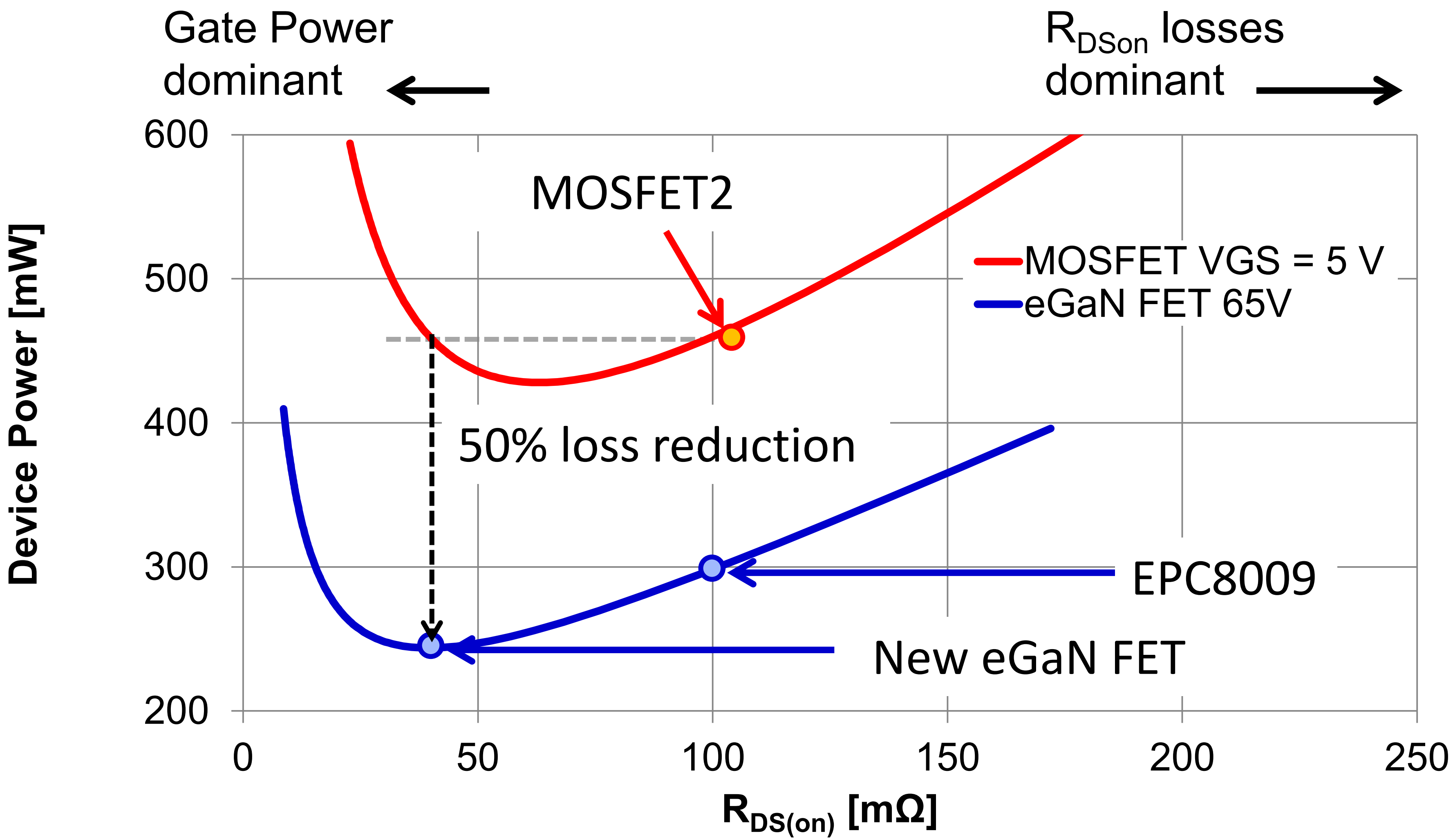


Next Steps

- Full A4WP impedance range testing
- Expand to Class 2 support
- eGaN FETs specifically designed for Wireless Power
  - ZVS Class-D – Optimized Half bridge device
  - Differential Class-E – Dual FET common source

Optimal eGaN FET Performance

ZVS Class D topology



Summary

- eGaN® FETs are disruptive in Wireless Energy:
  - Enable Wireless Power
  - Yield Higher Efficiency than MOSFETs
  - Can operate at 6.78 MHz
  - Are low profile
  - Easy to use
  - Drive new topologies e.g. ZVS Class-D
  - Increasing IC vendor support for eGaN FETs
  - Increasing customer adoption

EFFICIENT POWER CONVERSION

The end of the road
for silicon.....

is the beginning of
the eGaN FET
journey!