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

![Diagram of magnetic field wireless transfer with inductances L_{rp}, L_{mp}, L_{ms}, and L_{rs}.]
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

![Diagram of coil-set with labels: L_{src}, L_{dev}, C_{devs}, L_{devs}, C_{devp}, C_{out}, R_{DCload}, Z_{load}](image)
Class-E Overview

- Switch voltage rating $\geq 3.56 \cdot \text{Supply} (V_{DD})$.
- $C_{OSS}$ “absorbed” into matching network.
- Susceptible to load variation - high FET losses.
- Tuned Coil Voltage $\approx 0.707 \cdot V_{DD} [V_{RMS}]$
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 = $\frac{1}{2} \cdot V_{DD} \cdot [V_{RMS}]$
Differential Versions

- **ZVS Class-D** simplifies with the removal of the ZVS Capacitor
## eGaN FET Low Voltage Family

### Table

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Package (mm)</th>
<th>V(_{DS}) (V)</th>
<th>V(_{GS}) (V)</th>
<th>R(_{DS(on)}) @5V (mΩ)</th>
<th>Q(_{GS}) @5 V Typ. (nC)</th>
<th>Q(_{GD}) Typ. (nC)</th>
<th>R(_{G}) Typ. (Ω)</th>
<th>V(_{th}) Typ. (V)</th>
<th>Q(_{RR}) (nC)</th>
<th>I(_D) Max. (A)</th>
<th>T(_J) Max. (°C)</th>
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<td>EPC2015</td>
<td>LGA 4.1x1.6</td>
<td>40</td>
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<td>4</td>
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</table>

**Solder side View**

- **Gate**
- **Drain**
- **Source**
- **Substrate** (Connect to Source on PWB)

**Diagram**

- **2.1 x 1.6 mm**
- **Connect to Source on PWB**

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**Package**: LGA 4.1x1.6, LGA 1.7x1.1, LGA 4.1x1.6, LGA 2.1x1.6, LGA 1.7x1.1, LGA 3.6x1.6, LGA 1.7x0.9

**V\(_{DS}\)**: 40, 40, 100, 100, 100, 200, 200

**V\(_{GS}\)**: 6, 6, 6, 6, 6, 6, 6

**R\(_{DS(on)}\) @5V (mΩ)**: 4, 16, 7, 16, 30, 25, 100

**Q\(_{GS}\) @5 V Typ. (nC)**: 10.5, 2.5, 8, 4.1, 2.1, 5, 1.5

**Q\(_{GD}\) Typ. (nC)**: 3, 0.67, 2.3, 0.93, 0.5, 1.3, 0.33

**R\(_{G}\) Typ. (Ω)**: 2.2, 0.48, 2.2, 0.75, 0.6, 1.7, 0.57

**V\(_{th}\) Typ. (V)**: 0.6, 0.6, 0.6, 0.6, 0.6, 0.6, 0.6

**Q\(_{RR}\) (nC)**: 1.4, 1.4, 1.4, 1.4, 1.4, 1.4, 1.4

**I\(_D\) Max. (A)**: 33, 10, 25, 11, 6, 12, 3

**T\(_J\) Max. (°C)**: 150, 150, 125, 125, 125, 125, 125
# Ultra High Frequency Gen 3 eGaN FETs

<table>
<thead>
<tr>
<th>EPC Part No.</th>
<th>BV (V)</th>
<th>Max. R&lt;sub&gt;DS(ON)&lt;/sub&gt; (mΩ)</th>
<th>Min. Peak Id (A) (Pulsed, 25 °C, T&lt;sub&gt;pulse&lt;/sub&gt; = 300 μs)</th>
<th>Typical Charge (pC)</th>
<th>Typical Capacitance (pF) (V&lt;sub&gt;DS&lt;/sub&gt; = 20 V; V&lt;sub&gt;GS&lt;/sub&gt; = 0 V)</th>
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<td>Q&lt;sub&gt;GD&lt;/sub&gt;</td>
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eGaN® is a registered trademark of Efficient Power Conversion Corporation
## Gen 4 Datasheet Summary

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<tr>
<th>Part Number</th>
<th>Gen</th>
<th>BV (V)</th>
<th>$R_{DS(on)}$ (mΩ) $(V_{gs} = 5V, \text{ at } I_D \text{ Cont.})$</th>
<th>Peak $I_D$ (A) (Pulsed 25°C)</th>
<th>Max $T_J$</th>
<th>Typical Charge (nC) @ $V_{ds} = BV/2$</th>
<th>Typ $R_g$ (Ω)</th>
<th>Cont. $I_D$ (A)</th>
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<td>EPC2023</td>
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<td>125°C</td>
<td>1.5 0.57 0.33 11 0 0.3 3</td>
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</tbody>
</table>
Hard Switching FOM

\[ FOM_{HS} = \left( Q_{GD} + Q_{GS2} \right) \cdot R_{DS(on)} \]

Drain-to-Source Voltage (V)

\[ V_{DS} = 0.5\cdot V_{DSS}, \quad I_{DS} = 20 \text{ A} \]
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 $C_{OSS}$)

$$FOM_{WPT} = R_{DS(on)} \cdot (Q_G - Q_{GD})$$
A too low $R_{DSon}$ yields too high $C_{OSS}$ to realize design!
Optimal Device – ZVS Class D

- Gate Power dominant
- $R_{DSon}$ losses dominant

Device Power [mW] vs. RDS(on) [mΩ]

- eGaN FET 100V
- eGaN FET 65V
- MOSFET VGS = 10 V

- MOSFET2
- EPC2007
- EPC8009
- EPC8009
Experimental Setup

ZVS Class-D

Source Coil

Device Coil

Device Board
Rectifier, Capacitor, Load Resitors

Matching

25mm

100mm

50mm

100mm

50mm

Matching

Amplifier connection

Class-E

Load connection
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

Variable Supply Voltage
Fixed DC Load Resistance

Efficiency [%] vs. Output Power [W]

- η EPC8009 ZVS-CD
- η MOSFET 2 ZVS-CD
- η EPC2012 SE-CE
- η MOSFET 1 SE-CE
Load Variation Results

Coil becomes Capacitive

Fixed Supply Voltage

Coil becomes Inductive

Efficiency [%] vs DC Load Resistance [Ω]

η EPC2012 SE-CE
η MOSFET 1 SE-CE
η EPC8009 ZVS-CD
η MOSFET 2 ZVS-CD

Coil becomes Inductive

Fixed Supply Voltage

Coil becomes Capacitive

η EPC2012 SE-CE
η MOSFET 1 SE-CE
η EPC8009 ZVS-CD
η MOSFET 2 ZVS-CD
Load Regulation Comparison

Fixed DC load voltage, DC Load Resistance varied

![Graph showing load regulation comparison for different MOSFETs. The graph plots efficiency (%) against DC load resistance (Ω). The curves represent:
- EPC8009 ZVS-CD (solid blue line)
- MOSFET 2 ZVS-CD (dotted blue line)
- EPC2012 SE-CD (solid red line)
- MOSFET 1 SE-CE (dotted red line).]
Class-E Thermal Performance

LM5113  eGaN FET  UCC27511  MOSFET

Pout = 29 W in 20.2 Ω
ZVS Class-D Thermal Performance

LM5113
EPC8009
LM5107
MOSFET

Pout = 35 W in 23.6 Ω

Pout = 17 W in 23.6 Ω
ZVS Class-D waveforms

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

<table>
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<tr>
<th>Spacing</th>
<th>Voltage</th>
<th>Current</th>
<th>Temperature</th>
<th>Remarks</th>
<th>Severity</th>
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<td>6.4\cdot V_{sup}</td>
<td>0.3\cdot I_{nom}^*</td>
<td>FET Very High(^*)</td>
<td>Capacitive switching losses</td>
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<td>0.02\cdot I_{nom}</td>
<td>40°C FET</td>
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<td>Low</td>
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\(^*\) 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

Class 4
Power Limit

Category 3
Power zone

Peak Efficiency, Single load capability
Variable Supply, Fixed Load

Efficiency [%] vs. DC Load Power [W]

- η ZVS-CD RDC=50 Ω
- η CE-2012 RDC=25 Ω
- η CE-MOSFET 3 RDC=25 Ω
- Vin ZVS-CD
- Vin CE-2012
- Vin CE-MOSFET 3

Input Voltage [V] vs. Efficiency [%]
Peak Performance Results

Peak Efficiency for **Category 3 Load**
Variable Supply, Fixed Load

![Graph showing peak efficiency for different load conditions.](image)

**Key Points:**
- Efficiency as a function of DC load power and input voltage for different load configurations:
  - η ZVS-CD RDC=50 Ω
  - η CE-2012 RDC=25 Ω
  - η MOSFET 3 RDC=25 Ω
- Vin ZVS-CD
- Vin CE-2012
- Vin CE-MOSFET 3
EPC8009 ZVS Class D Waveforms & Thermal

\[ V_{DC} = 38 \, V \]
\[ P_{out} = 23.5 \, W \]
\[ R_{DC\text{load}} = 50.3 \, \Omega \]

High Power, Peak Performance
Load Variation Results

High Power Capability

Load Regulation ($V_{out} = 15$ V)

- η ZVS-CD
- η CE-2012
- η CE-MOSFET 3
- Pout

Category 3 Power zone
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

Gate Power dominant

R_{DS(on)} losses dominant

Device Power [mW]

R_{DS(on)} [mΩ]

MOSFET2

50% loss reduction

MOSFET VGS = 5 V

eGaN FET 65V

EPC8009

New eGaN FET

50% loss reduction
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
The end of the road for silicon.....
is the beginning of the eGaN FET journey!