GaN Power ICs at 1 MHz+:
Topologies, Technologies and Performance

PSMA Industry Session, Semiconductors

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Power Electronics: Speed & Efficiency are Key

- **Speed** enables *small size*, *low-cost* and *faster charging*

- **Efficiency** enables *energy savings*

- With Silicon or Discrete GaN power devices, you can get one *or* the other

- With GaN power ICs, you get *both at the same time* with unequaled Speed & Efficiency
World’s First AllGaN™ Power ICs

Fastest, most efficient GaN Power FETs
>20x faster than silicon
>5x faster than cascoded GaN
Proprietary design
15+ pending or issued patents

*iDrive* First & Fastest Integrated GaN Gate Drivers
>3x faster than any other gate driver
Proprietary design
8+ pending patents

World’s First AllGaN™ Power IC

Up to 40MHz switching, 5x higher density & 20% lower system cost
The Power of GaN Power ICs
... Unequaled Speed & Efficiency

- **Driver Circuits**
- **Power Devices**
- **Passive Components**
- **Switching Frequency**
- **Energy Efficiency**

- **Silicon**
  - **Discrete GaN**
  - **GaN Power ICs**

- **Switching Frequency**
  - 100kHz: 85-90%
  - 500kHz: 88-92%
  - 1-10MHz: 90-95%
GaN Power IC – *Fast & Efficient*

- No overshoots, No spikes, No oscillations, S-curve’ transitions,
- Zero Loss Turn-on (Soft switching) Zero Loss Turn-off (Integrated Gate Drive)
External drivers
• Just 1-2 nH of gate loop inductance can cause unintended turn-on
• Gate resistors reduce spikes but create additional losses

Integrated GaN drivers (iDrive™)
• Eliminate the problem
• Negligible turn-off losses
GaN Power IC: Hi-Speed FET, Drivers & More

- Proprietary AllGaN™ technology
- **Monolithic** integration of GaN FET, GaN Driver, GaN Logic
- 650 V eMode
- 20x lower drive loss than silicon (<35 mW at 1 MHz)
- Driver impedance matched to power device
- Very fast (prop delay and turn-on/off of 10-20 ns)
- Zero inductance turn-off loop
- High dV/dt immunity (200 V/ns) with control
- Digital input
- Complete layout flexibility

Fast Chargers ... going “GaN Fast”
3x Fast Charging with 50% Energy Savings

**Existing Si-based**
- **15W**
  - **100 kHz**
  - Up to 6.5 W/in³
  - 88%

**AllGaN™ 2016**
- **25W**
  - **300-500 kHz**
  - 11 W/in³
  - >92%
  - **2x Faster Charging**

**AllGaN™ 2017**
- **25W**
  - **>1 MHz**
  - 17.5 W/in³
  - >95%
  - **3x Faster Charging**

45W Active Clamp Flyback & AllGaN Power ICs

- 94.5% efficient at 220 V (94.2% at 120 V<sub>AC</sub>, 93.1% at 90 V<sub>AC</sub>)
- 23.7 W/in<sup>3</sup> density (uncased)
- 15.7 mm profile

For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang
45W CrCM ACF Operation

- Switch-node voltage ($V_{SW}$), SR FET voltage ($V_{SR}$), leakage current ($i_{LK}$) and magnetizing current ($I_{Lm}$)
- 120V$_{AC}$, 0.2A load, $F_{SW} = 210$kHz, Circulating Current minimized using Secondary Resonance

For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang
45 W ACF: High Efficiency, Cool Temperatures

For further details of ACF, please see APEC 2017 technical paper “Active Clamp Flyback Using GaN Power IC for Power Adapter Applications”, Xue, Zhang
AllGaN 2017: 1 MHz, 25 W ACF in 5W Size

- Single-stage EMI
- Navitas GaN Power ICs
- Planar transformer
- DSP (for prototype)

MHz+ 25 W ACF Prototype Performance

\( F_{SW} = 1.5 \text{MHz} \)

\( V_{GS} \) (3 V/div)

\( V_{DS} \) (50 V/div)

**Efficiency vs. Load**

*Exclude bridge and EMI filter loss*

GaN Power ICs enable Hi-Density Adapters
3x Higher Density with 50% Energy Savings

Existing Si-based 150W

AllGaN™ 2016 150W

AllGaN™ 2017 150W

2x Higher Density

3x Higher Density

100 kHz
5-10 W/in³
88%

300-500 kHz
17 W/in³
>93%

>1 MHz
26.5 W/in³
>95%

150W

150W

### 150 W, 19 V: GaN Power IC vs. Si

<table>
<thead>
<tr>
<th>Part#</th>
<th>Technology</th>
<th>V</th>
<th>Pack</th>
<th>$R_{DS(ON)}$ (typ. mΩ)</th>
<th>$Q_G$ (typ. nC)</th>
<th>$C_{OSS}(er)$ (typ. pF)</th>
<th>$R \times Q_G$ (mΩ.nC)</th>
<th>$R \times C_{OSS}(er)$ (mΩ.pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STL34N65M5</td>
<td>Si FET</td>
<td>650</td>
<td>8x8</td>
<td>99</td>
<td>62.5</td>
<td>63</td>
<td>6,187</td>
<td>6,237</td>
</tr>
<tr>
<td>IPL60R199CP</td>
<td>Si FET</td>
<td>600</td>
<td>8x8</td>
<td>180</td>
<td>32</td>
<td>69</td>
<td>5,760</td>
<td>12,420</td>
</tr>
<tr>
<td>IPL60R299CP</td>
<td>Si FET</td>
<td>600</td>
<td>8x8</td>
<td>270</td>
<td>22</td>
<td>46</td>
<td>5,940</td>
<td>12,420</td>
</tr>
<tr>
<td>NV6115</td>
<td>GaN Power IC</td>
<td>650</td>
<td>5x6</td>
<td>160</td>
<td>2.5</td>
<td>30</td>
<td>400</td>
<td>4,800</td>
</tr>
<tr>
<td>NV6117</td>
<td>GaN Power IC</td>
<td>650</td>
<td>5x6</td>
<td>110</td>
<td>4</td>
<td>45</td>
<td>440</td>
<td>4,950</td>
</tr>
</tbody>
</table>

**GaN Benefit**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Navitas GaN Power ICs (5x6mm QFN)</td>
<td>14x 1.5-2.5x</td>
</tr>
<tr>
<td>Si FETs (8x8mm QFN)</td>
<td></td>
</tr>
</tbody>
</table>

PFC = 1x NV6117, LLC = 2x NV6115

Si FETs: a) PFC = 1x IPL60R299CP, LLC = 2x IPL60R299CP

For further details of the 150 W, 21 W/in3 board, please see APEC 2017 Industry Session “State-of-the-Art Mobile Charging: Topologies, Technologies and Performance” (Mobile Applications)
Frequency-related Loss Kills Si

PFC = free-running 63-200 kHz, LLC = 300 kHz

- **GaN**: PFC = 110mΩ, LLC = 160mΩ
- **Si #1**: PFC = 270mΩ, LLC = 270mΩ

**Efficiency vs. Output Power, AC Line Voltage**

**Efficiency vs. AC Line Voltage (150W Full Load)**

<table>
<thead>
<tr>
<th>Powertrain</th>
<th>GaN</th>
<th>Si #1</th>
<th>Si #2</th>
<th>Si #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFC (mΩ)</td>
<td>110</td>
<td>270</td>
<td>180</td>
<td>99</td>
</tr>
<tr>
<td>LLC (mΩ)</td>
<td>160</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
</tbody>
</table>
GaN-based Power Density
= 35 W/in$^3$

(Best commercial benchmark
= 12W/in3)
1 MHz, 3.2 kW Server Supply – 70 W/in³

- Multi-phase Totem-Pole CrCM + 2-phase Full-Bridge LLC
- Input: 220 V<sub>AC</sub> (47-63 Hz)
- Output: 48 V, 3.2 kW
- Target Size: 200 x 80 x 41.5 mm (uncased)

PFC Beta version

<table>
<thead>
<tr>
<th>650V GaN Power ICs</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC1</td>
</tr>
</tbody>
</table>

LLC converter

<table>
<thead>
<tr>
<th>650V GaN Power ICs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>80V GaN FETs</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 VDCOUT</td>
</tr>
</tbody>
</table>

Target Frequency:
- PFC = Variable frequency interleaving (500 kHz – 1.5 MHz)
- LLC = Fixed-frequency interleaved 1 MHz

Target Efficiency:
- PFC: >99% peak (1)
- LLC: >98% peak (2)

(1) Achieved on Alpha prototype (2) Estimated

650V GaN Power ICs

80V GaN FETs

Bulk Caps

EMI Filter

2x interleaved Totem-Pole PFC Daughtercards

2x interleaved LLC Daughtercards (coupled planar transformer)
Quasi-Square Wave PFC Full-range ZVS Operation

- Totem Pole Configuration
- Current Mode Control
- Constant ZVS current point
- Simple rule: only change the current reference waveforms

\[ V_{DC} = 385V \]
\[ V_{AC} = 240V/\text{RMS} \]
\[ R_{load} = 102\,\text{ohm} \]
\[ P_{load} = 1450\,\text{W} \]

\[ V_{DC} \]
\[ V_{AC} \]
\[ R_{load} = 102\,\text{ohm} \]
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\[ f_{sw}(\text{MHz}) \]
\[ V_{DC} \]
\[ V_{AC} \]
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\[ f_{sw}(\text{MHz}) \]
\[ V_{DC} \]
\[ V_{AC} \]
\[ R_{load} = 102\,\text{ohm} \]
\[ P_{load} = 1450\,\text{W} \]
AllGaN Achieves Over 99% PFC Efficiency

3 GaN in Parallel, Vdd=6V

9.5uH, 7 Turns, Litz 46/660

Efficiency at 385V/DC, 240V/AC

f_{max}=1.6MHz

f_{max}=1.2MHz

f_{max}=0.85MHz
Wireless Power ... Accelerated

Existing Silicon-based multi-stage wireless power

- AC-DC Adapter 88% Efficiency
- DC-DC 94% Efficiency
- Power Amplifier 93% Efficiency
- Wireless Transfer 90% Efficiency

- Single-Stage Amplifier 90% Efficiency
  - 650V GaN Power ICs
  - 3-stages integrated in 1-stage
  - 6.78MHz Operation
  - High-Efficiency

- Multi-stage Efficiency: 77%
- GaN-enabled single stage: 90%
- 20% lower system cost
- 3x faster charging
AC-RF Single Stage, Efficient & Cost-effective

400V Phase-shifted Full Bridge with ZVS Coupled Inductors

6.78 MHz Output Direct to Transmitter Antenna

47-63 Hz AC Input

GaN Phase-Shift vs. Load

Meets Key System Requirements:
Constant output current vs. load reactance

For further details, please see APEC 2017 technical paper “Single-Stage 6.78 MHz Power-Amplifier Design Using High-Voltage GaN Power ICs for Wireless Charging Application”, Xue, Zhang
Cool AllGaN, No Chance for Silicon

Efficiency from AC line to Transmitter Coil

Device Speed

ZVS Current-Induced Loss

50W Prototype Board:

a) Significant potential for further integration (control & GaN Power IC)
b) Thermal performance (50W):
   Max GaN Power IC $T_{\text{CASE}} = 53^\circ\text{C}$
27 MHz, 40 MHz...

Class Phi-2 DC/AC converter

- 50% less loss than RF Si
- 16x smaller package
- Air-core inductors
- Minimal FET loss
- Negligible gate drive loss

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![Diagram of Class Phi-2 DC/AC converter](image)

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**Power Loss Breakdown (Active Components)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>V (V)</th>
<th>Pack (mm)</th>
<th>$F_{SW}$ (MHz)</th>
<th>Eff. (%)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Si (ARF521)</td>
<td>500</td>
<td>M174 22x22</td>
<td>27.12</td>
<td>91%</td>
<td>150</td>
</tr>
<tr>
<td>Navitas</td>
<td>650</td>
<td>QFN 5x6</td>
<td>27.12</td>
<td>96%</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40.00</td>
<td>93%</td>
<td>115</td>
</tr>
</tbody>
</table>

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27.12MHz, φ 2 Inverter, $V_{DS}$ of GaN

- 20ns/div, 150V/div

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