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

>10x faster than silicon
>5x faster than cascoded GaN
Proprietary design
5+ pending or issued patents

iDrive First & Fastest Integrated GaN Gate Drivers

>2x faster than any other gate driver
Proprietary design
15+ pending or issued patents

World’s First AllGaN™ Power IC

= 

Up to 40MHz switching, 5x higher density & 20% lower system cost
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

<table>
<thead>
<tr>
<th>Technology</th>
<th>V</th>
<th>Pack (mm)</th>
<th>F\text{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>

- 27.12MHz, φ2 Inverter, \(V_{ds}\) of GaN

- 20ns/div, 150V/div

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

![Power Loss Breakdown (Active Components)](image)
Removing Speed Limits: Navitas GaN Power IC

- **Monolithic** integration
- 20X lower drive loss than silicon
- Driver impedance matched to power device
- Shorter prop delay than silicon (10ns)
- Zero inductance turn-off loop
- Digital input (hysteretic)
- Rail-rail drive output
- Layout insensitive
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 – Fast & Efficient

- No overshoots, No spikes, No oscillations, S-curve’ transitions,
- Zero Loss Turn-on (Soft switching) Zero Loss Turn-off (Integrated Gate Drive)
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

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 $T_{CASE} = 53^\circ C$
The Road Ahead (as per APEC 2016...)

- LLC (BCM)
- PFC
- TOPOLOGY
- ACF
- TOTEM POLE
- SYNC REC
- INTEGRATION
- BIAS SUPPLIES
- INTEGRATION
- SENSING CIRCUITS
- INTEGRATION
- PROTECTION CIRCUITS
- INTEGRATION
dv/dt CONTROL
- INTEGRATION
- LOW-SIDE DRIVE

TOPOLOGY

NAVITAS
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

94% average per DoE Level VI

116 x 55 x 18 mm = 115 cc (1.31 W/cc, 21.4 W/in³) uncased
150W: Running Cool

**TOP VIEW**
- LLC Transf. 85°C
- SR FETs 90°C
- DM Choke 90°C
- PFC Inductor 85°C
- PFC diode 90°C
- PFC Switch (NV6117) 80°C

**SIDE VIEW**
- LLC Primary (2x NV6115) 65°C
AllGaN 2017: MHz 150W Totem-pole + LLC

GaN-based Power Density = 35 W/in\(^3\)

(Best commercial benchmark = 12W/in3)
45W Active Clamp Flyback & AllGaN Power ICs

- 94.5% efficient at 220 V (94.2% at 120 V\textsubscript{AC}, 93.1% at 90 V\textsubscript{AC})
- 23.7 W/in\textsuperscript{3} 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
45W → 65W ACF
Just 13% longer for 44% more power

45W = 59.1 x 33.5 x 15.7 mm = 24 W/in³ (uncased)
2x NV6115 (160mΩ)

65W = 66.7 x 33.5 x 15.7 mm = 30 W/in³ (uncased)
1x NV6115 (160mΩ) + 1x NV6117 (110mΩ)

ACF switching waveforms, 300 kHz

65W Efficiency (excluding EMI) vs. AC line
(25°C ambient, no airflow, full load)

65W Thermal Performance
(90VAC, 25°C ambient, no airflow, full load)
650V Half-Bridge AllGaN™ Power IC

- Proprietary AllGaN™ technology
- Monolithic integration of 650V eMode GaN FET, driver, logic
- Internal level-shift, bootstrap
- Ground-referenced, digital input
- High dV/dt immunity (200 V/ns)
- Zero inductance turn-off loops
- ESD, UVLO, shoot-through protection
- Flexible topologies: Active Clamp Flyback, Half-Bridge, LLC, etc.
66% Higher Power with Half-Bridge GaN Power IC

a) Original 15 W AC charger case

b) Original 15 W, Si-based QR Flyback, ~100 kHz

c) Upgraded 25 W, Half-Bridge GaN Power IC ACF, ~400 kHz
25W Cool Thermals (12.5V, 2A)

a) No case, 25°C ambient, full load, 90 V_{ac} input, no heatsinking.

b) Cased, 25°C ambient, full load, 90 V_{ac} input, no heatsinking.
Clean 600V ZVS switching at 2 MHz

- Demonstration board with half bridge AllGaN™ Power IC driving an LC resonant load
- Nearly perfect, loss-free half bridge switching up to 650V with a single part
- Only 5V PWM logic signals are needed
- No diode recovery losses
- No turn-on losses
- Nearly zero turn-off losses
1 MHz, 25 W ACF – Next Step

- Single-stage EMI
- 1x Navitas Half-Bridge GaN Power IC
- Planar transformer
- ACF IC
MHz+ 25 W ACF Prototype Performance

\[ F_{SW} = 1.5 \text{MHz} \]

\[ V_{GS} \text{(3 V/div)} \]

\[ V_{DS} \text{(50 V/div)} \]

**Efficiency vs. Load**

- **Load Current (A)**

  - 2.6 MHz: 0.876
  - 1.5 MHz: 0.921
  - 1.5 MHz: 0.933
  - 1.5 MHz: 0.931

*Exclude bridge and EMI filter loss*

1 MHz, 3.2 kW Server Supply – 65 W/in³

- 220 V\textsubscript{AC} (47-63 Hz) to 48 V, 3.2 kW
  - Target > 97.5% efficiency (<80W loss)
  - >99% efficiency demonstrated on PFC alpha version
- Multi-phase Totem-Pole CrCM
  - Variable frequency interleaving (500 kHz – 1.5 MHz)
- 2-phase full-bridge LLC with full-bridge SR
  - Fixed-frequency interleaved 1 MHz
Quasi-Square Wave PFC Full-range ZVS Operation

- Totem Pole Configuration
- Current Mode Control
- Constant ZVS current point
- Alpha version waveforms

\[ f_{sw}(\text{MHz}) \]

\[ 0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0 \]

\[ 0.00 \quad 0.24 \quad 0.28 \quad 0.32 \] Time (s)

\[ V_{DC}=385V \]
\[ V_{AC}=240V/RMS \]
\[ R_{load}=1020\text{ohm} \]
\[ P_{load}=1450W \]
Preliminary LLC Waveforms at 400V, 2.4kW
1 MHz, 3.2 kW – 100% GaN

Heatsink (PFC Boost Switch)

PFC choke (Hitachi ML91S)

3x paralleled input current-limiting relays

2x DM choke (in series)

2x + 2x X-caps

CM choke (no EMI test yet)

Full bridge SR (80V EPC GaN) (16 or 24 TBD in final test)

Isolated power supply for SR

48 V Output

Coupled LLC transformer

Full bridge LLC (1/2 on each card) (using paralleled NV6117s)

Coupled Res Inductor

AC input
We Have Arrived!

• GaN Power ICs are now delivering these desired features and more
• System designers are taking a major step forward to deliver more power with less loss in smaller form factors than ever before
• It’s time to go “GaN Fast”
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