Monolithic GaN Device Integration Drives Efficiency, Density and Reliability in Power Conversion

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August 16th 2018
Navitas Semiconductor Inc.

- World’s first & only GaN power IC company
- Mass production, qualified “Beyond JEDEC”
- Founder member JEDEC JC-70.1 GaN Reliability
- www.navitassemi.com
The Si Landscape

Si FETs

- 1kW
- 10kW
- 600V
- 1,200V
- 30V
- 100V
- Micro-inverters
- Commercial Solar String Inverters
- Laptop Adapters
- Smartphone, Tablet Chargers
- TV, Game Players
- Mobile Wireless Power
- Class D Audio
- Server Power

Si IGBTs

- 10W
- 100W
- 100kW
- 1MW+
- 30V
- 100V
- 300V
- 600V
- 1,200V
- 3,300V
- 6,500V+
- On-board Battery Chargers & DC/DC Converters
- EV Inverters
- Industrial Drives, Welders, UPS, Inverters
- Wind Turbines
- Traction
- Utility
- LED Lighting
- TV, Game Players
- Smartphone, Tablet Chargers

Device Voltage (V)

Application Power
The GaN / SiC Landscape

- **GaN (Lateral)**
  - Mobile Wireless Power
  - On-board Battery Chargers & DC/DC Converters
  - LED Lighting
  - Micro-inverters
  - TV, Game Players
  - Smartphone, Tablet Chargers

- **SiC (Vertical)**
  - EV Inverters
  - Commercial Solar String Inverters
  - Server Power
  - Industrial Drives, Welders, UPS, Inverters
  - Wind Turbines
  - Traction
  - Utility

- **Application Power**
  - 1MW+
  - 100kW
  - 10kW
  - 1kW
  - 100W
  - 10W

- **Device Voltage (V)**
  - 30V
  - 100V
  - 300V
  - 600V
  - 1,200V
  - 3,300V
  - 6,500V+
The Next Revolution in Power Systems

- Linear Regulators
- Switching Regulators
- Switching Regulators
- HF Switching Regulators

Power Density (W/in³) (AC-DC converters ~300 W)

- 50 Hz
- 30 kHz
- 65 kHz
- 1 MHz+

Efficiency:
- Linear Regulators: 40%
- Switching Regulators: 80%
- HF Switching Regulators: 96-98%

Loss:
- Linear Regulators: 3x Lower Loss
- Switching Regulators: 3x Lower Loss
- HF Switching Regulators: 3x Lower Loss

- 1977: 40% efficiency
- 1987: 80% efficiency
- 2017: 90% efficiency
- 2027: 96-98% efficiency

- 5x Increase (18%/yr) in 10 years
- 3x Lower Loss
- 3x Lower $/W

- New GaN Power ICs
- New Magnetics
- New Controllers
- New Topologies

<6%/yr improvement over 30 years

3x Lower Loss
3x Lower $/W

5x Increase (18%/yr)
in 10 years

96-98%
Market Demands

• Legislative
  • US DoE VI, Euro CoC Tier 2

• Features
  • Type C, USB PD 3.0 / PPS / QC 4.0

• Performance
  • Fast charging, size, weight, low profile

• Cost
  • Premium vs old, slow designs?
• **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*, unequalled Speed & Efficiency

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**Navitas**

Gan Power IC

- Up to *5x* Energy Savings
- Up to *100x* faster Shrink size, weight & cost

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**SPEED (FREQUENCY)**

- 100kHz
- 1MHz
- 10MHz

**EFFICIENCY**

- Silicon
- Discrete GaN
High-Frequency Eco-System

GaNFast power ICs plus...

- HF Controllers
- HF Magnetics
- HF SR FETs
- HF Architectures
Modified Performance factor

\[ F_{3/4} = \frac{Bf^{3/4}}{(T \cdot Hz^{3/4})} \]

- **ML91S** (Hitachi Metal) ~2010s
- **3C90** (Ferroxcube) ~1990s
- **3F35** (Ferroxcube) ~2000s
- **67** (Fair-Rite) ~2015s

**Future**

\[ P_v = 500 \text{ mW/cm}^3 \]

**Magnetics: 10x Faster Every Decade**


World’s First GaNFast™ Power ICs

Fastest, most efficient GaN Power FETs

- >20x faster than silicon
- >5x faster than cascoded GaN
- Proprietary design

First & Fastest Integrated GaN Gate Drivers

- >3x faster than any other gate driver
- Proprietary design
- 30+ patents granted/applied

World’s First GaNFast™ Power ICs

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

- Monolithic integration, 650V
  - GaN FET
  - GaN Driver
  - GaN Logic
- Mass production

5 x 6 mm QFN

10...30V

DC IN(+)

DC OUT(+)

DC IN(-)

DC OUT(-)
Clean, Controlled FET Gate

- **Discrete driver**
  - Gate-loop inductance creates overshoot (even with good layout)
  - Reliability concern

- **GaNFast Power IC**
  - No gate loop parasitic
  - Clean and fast gate signal
  - No CdV/dt turn-on
  - No IV crossover turn-off switching losses
- Monolithic integration, 650V
  - 2x GaN FETs
  - 2x GaN drivers
  - GaN Logic (level-shift, bootstrap, UVLO, shoot-through, ESD)
Robust GaNFast Half-Bridge

Non-Overlapping Logic Input
(Typical Operation)

Overlapping Logic Input
(GaNFast Power IC Protection)

5 V digital input, 6.2 V gate output, 80 ns/div
## ‘Beyond’ JEDEC Qualification

**GaN-Based Qual Plan**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Test Conditions</th>
<th>Duration</th>
<th>Lots</th>
<th>S.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>JESD22-A113 J-STD-020</td>
<td>Preconditioning (MSL1): Moisture Preconditioning + 3x reflow: HAST, UHAST, TC &amp; PC</td>
<td>N/A</td>
<td>3</td>
<td>308</td>
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<tr>
<td>JESD22-A104</td>
<td>Temperature Cycle: -55°C / 150°C</td>
<td>1,000cy</td>
<td>3</td>
<td>77</td>
</tr>
<tr>
<td>JESD22-A122</td>
<td>Power Cycle: Delta Tj = 100°C</td>
<td>10,000cy</td>
<td>3</td>
<td>77</td>
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<tr>
<td>JESD22-A110</td>
<td>Highly Accelerated Stress Test: 130°C / 85%RH / 100V V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>96hrs</td>
<td>3</td>
<td>77</td>
</tr>
<tr>
<td>JESD22-A108</td>
<td>High Temperature Reverse Bias: 150°C / 520V V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>1,000hrs</td>
<td>3</td>
<td>77</td>
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<tr>
<td>JESD22-A108</td>
<td>High Temperature Gate Bias: 150°C / 6V V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>1,000hrs</td>
<td>3</td>
<td>77</td>
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<tr>
<td>JESD22-A108</td>
<td>High Temperature Operating Life</td>
<td>1,000hrs</td>
<td>3</td>
<td>77</td>
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<tr>
<td>JS-001-2014</td>
<td>Human Body Model ESD</td>
<td>N/A</td>
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<tr>
<td>JS-002-2014</td>
<td>Charged Device Model ESD</td>
<td>N/A</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

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**Lifetime Models (HTOL, HTRB)**

**Failure Modes Established**

**Application Specific HTOL Test Bench**
ZVS HTOL at Statistical Sample Sizes

- Matches all elements of application profile
  - FET & IC
- Many cells in parallel
  - Statistical sample sizes
- Low total power consumption
- Conditions changeable to develop lifetime and acceleration models

HTOL Mother Board

Qualification
3 Lots x 77

Lifetime Models
Voltage Current Frequency Temperature

Early Life Failure Rate
3 Lots x 1,000
### HTOL-based Lifetime Model

<table>
<thead>
<tr>
<th>Voltage/Temperature</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>575</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>625</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>650</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**T=150 °C, Voltage Acceleration**

\[
\text{Time to Fail (hrs)} \propto \frac{1}{(\text{Voltage})^{n=17.2}}
\]

**V= 650 V, Temperature Acceleration**

\[
\text{Time to Fail (hrs)} \propto e^{\frac{E_0}{kT}}
\]

where \( E_0 = 0.71 \text{eV} \)
**Lifetime Estimation: ACF Charger**

**Temperature Acceleration Factor**

\[ AF_{\text{temp}} = e^{E_a \times \left( \frac{1}{T_{\text{application}}} - \frac{1}{T_{\text{reliability}}} \right)} \]

\[ E_a = 0.71 \text{eV} \]

**Voltage Acceleration Factor**

\[ AF_{\text{voltage}} = \left( \frac{V_{\text{reliability}}}{V_{\text{application}}} \right)^n \]

\[ n = 17.2 \]

**Total Acceleration Factor**

\[ AF_{\text{total}} = AF_{\text{temp}} \times AF_{\text{voltage}} \]

**Lifetime estimate in application =**

\[ AF_{\text{total}} \times \text{Time to failure in reliability (TTF_{reliability})} \]

<table>
<thead>
<tr>
<th>AC line Voltage (V)</th>
<th>Rectified AC voltage (V)</th>
<th>Reflected Voltage (V)</th>
<th>Switch Voltage (V)</th>
<th>Full power Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>170</td>
<td>120</td>
<td>290</td>
<td>85</td>
</tr>
<tr>
<td>240</td>
<td>340</td>
<td>120</td>
<td>460</td>
<td>85</td>
</tr>
</tbody>
</table>

\[ Ea = 0.71 \text{eV} \quad n = 17.2 \]

**Lifetime**

\[ Lifetime = AF_{\text{total}} \times TTF_{\text{reliability}} = 233 \text{ years} \quad @ \ 240V \ \text{AC input} \]

Predicted lifetime in charger application (ACF) exceeds 10yr lifetime requirement.
GaNFast Applications
EMI? Si QR @65 kHz vs. GaN ACF @300 kHz

Si 45 W

Si: Overshoot/ringing: Need low-frequency to pass EMI

GaNFast 45 W

GaN: No overshoot/ringing: good EMI
Smaller, cheaper EMI filter
Quiet Power: GaNFast ACF at 1 MHz

- High frequency + Soft-switching + Pre-emptive EMI design

![Diagram showing noise level comparison between W/O Shielding and With Shielding for CM and DM noise.]

Conducted EMI Analysis and Filter Design for MHz Active Clamp Flyback Front-end Converter

Xinchen Xu, Junjie Feng, Fred C. Lee, Qiong Li, and Yuksun Yang
Center for Power Electronics Systems, the Bradley Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University, Blacksburg, VA, 24061, USA

978-1-4673-9550-2/16/$31.00 ©2016 IEEE 1534
## World’s Smallest 27 W USB-PD

**Available now**

- **Power, Output**: 27 W USB-PD
- **Topology**: ACF with UCC28780 and NV6252 GaNFast Power IC
- **Frequency**: 300 kHz
- **Size**: 23 cc (39 cc with case)
- **Density**: 1.2 W/cc (19 W/in³)
  
  (0.7 W/cc (11 W/in³) cased)
- **Efficiency**: >93% peak, 92.8% at 90 V_{AC}, full load

DoE Level VI, Euro CoC (EuP) Tier 2
27 W Clean Design

Transformer RM6
SR FET
CM Choke
AC Plug
DM Choke
Bulk Caps
Type-C Receptacle
SR IC
AC Bridge
GND
V_{SW}
NV6252
ACF IC
27 W High Efficiency

- Full Load:
  - VOUT = 5V
  - 90 VAC
  - 230 VAC

- 10% Load:
  - VOUT = 5V
  - 9V
  - 11V

- 4-Pt Average:
  - VOUT = 5V
  - 9V
  - 11V

- CoC Tier 2
27 W Cool Operation

90 V\textsubscript{AC}, 27 W, 25 °C, uncased, no airflow

- AC Bridge 80°C
- GaNFast Half-Bridge 75°C
- V\textsubscript{CC} LDO 80°C
- Transformer 75°C
- SR IC 80°C
World’s Thinnest Universal 45 W

- In mass production, see [www.kickstarter.com](http://www.kickstarter.com), search “Mu One”
- Size: 29 cc (41 cc with case)
- Density: 1.7 W/cc (27 W/in³), 1.1 W/cc (18 W/in³) cased
45 W Mu One: Major Components

- Planar Transformer
- Type-C Receptacle
- EMI Filter
- Bulk Caps
- AC Bridge
- NV611x Power ICs
- ACF IC UCC28780
- PD IC
- SR FET
90 V<sub>AC</sub>, 45 W, 25 °C, uncased, no airflow
45 W Mu One: Efficiency

**Full Load, 20V**

- Input $V_{AC}$ (V)
  - 90 V
  - 115 V
  - 140 V
  - 165 V
  - 190 V
  - 215 V
  - 240 V
  - 265 V

**4-Point Average**

- 5 V
- 9 V
- 15 V
- 20 V

CoC Tier 2

$V_{AC}$
45W Mu One: Radiated EMI

Data Reduction Result 1 [1]

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>MaxPeak,MaxFold (dB)</th>
<th>Height (km)</th>
<th>Polarization</th>
<th>Azimuth (deg)</th>
<th>Corr. (dB)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>172,211,256</td>
<td>55.1</td>
<td>189.8</td>
<td>H</td>
<td>179.3</td>
<td>26.1</td>
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<tr>
<td>285.965750</td>
<td>79.5</td>
<td>200.0</td>
<td>V</td>
<td>87.5</td>
<td>26.8</td>
<td></td>
</tr>
</tbody>
</table>
### World’s Smallest 65 W USB-PD Adapter

**Power, Output**: 65 W USB-PD

**Topology**: ACF with UCC28780 and NV6115, NV6117 GaNFast Power ICs

**Frequency**: 300 kHz

**Size**: 27 cc (45 cc with case)

**Density**: 2.4 W/cc (39 W/in3) (1.5 W/cc (24 W/in3) cased)

**Efficiency**: >93% peak, 92.8% at 90 V~AC, full load

DoE Level VI, Euro CoC (EuP) Tier 2

---

Proprietary; Authorized Use with Navitas License
• Peak efficiency = 94.3% at 230 V<sub>AC</sub>, full load (20V/3.25A)
• Lowest line efficiency = 93.4% at 90 V<sub>AC</sub>, full load
• Standby: 25 mW at 115 V<sub>AC</sub>, 40 mW at 230 V<sub>AC</sub>
  • CoC Tier 2 spec is < 75mW, DoE Level VI spec <= 210 mW
Cool Performance

- Meets customer case specification of <=50°C
- Conditions: $115V_{AC}$, $20V_{DC}$, 65W, 25°C ambient, no airflow, no heatsink
100W: Topology?

- Fixed or variable output?
  - LLC best for fixed output
  - ACF best for variable (PD) output

**Block Schematic**

**Example 100 W Output**

<table>
<thead>
<tr>
<th>PFC CrCM</th>
<th>LLC</th>
<th>DC-DC (PD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td></td>
<td>97.5%</td>
</tr>
<tr>
<td>#1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19 V fixed

<table>
<thead>
<tr>
<th>PFC CrCM</th>
<th>ACF (PD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td></td>
</tr>
</tbody>
</table>

USB-PD, Type C 96.5%

93.6%

<table>
<thead>
<tr>
<th>PFC CrCM</th>
<th>LLC</th>
<th>DC-DC (PD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td></td>
<td>97.5%</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

USB-PD, Type A 15 W 97%

92.6%

<table>
<thead>
<tr>
<th>Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Full load, 90 VAC, 25°C, no airflow, includes PD loss)</td>
</tr>
</tbody>
</table>

94.5%

93.6%

92.6%
# World’s Smallest 100 W USB-PD

![Image showing the board with GaNFast components and dimensions.

- **GaNFast** Power IC (PFC)
- **GaNFast** Power ICs (ACF)
- Height = 14 mm

## Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Power, Output</td>
<td>100 W USB-PD</td>
</tr>
</tbody>
</table>
| Topology                 | CrCM PFC with NCP1615 and NV6115 GaNFast Power IC  
                          | ACF with UCC28780 and NV6115, NV6117 GaNFast Power ICs |
| Frequency                | PFC min. 200 kHz, ACF 300 kHz |
| Size                     | 40 cc (65 cc with case) |
| Density                  | 2.5 W/cc (41 W/in³) (1.5 W/cc (25 W/in³) cased |
| Efficiency               | >93.7% peak, 92.1% (target >93%) at 90 VAC, full load, DoE Level VI, Euro CoC (EuP) Tier 2 |

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100 W USB-PD

Light Load (20 V, 500 mA)

Heavy Load (20 V, 4.8 A)

Light Load (20 V, 500 mA, zoom)

Half Load (20V, 2.5A)
150 W, 19 V: 200/500 kHz

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, Output</td>
<td>150 W, 19 V</td>
</tr>
<tr>
<td>Topology</td>
<td>CrCM PFC NCP1615 &amp; LLC NCP13992AB with NV6115 GaNFast Power ICs</td>
</tr>
<tr>
<td>Frequency</td>
<td>PFC min. 200 kHz, LLC typ. 500 kHz</td>
</tr>
<tr>
<td>Size</td>
<td>63 cc (101 cc with case)</td>
</tr>
<tr>
<td>Density</td>
<td>2.4 W/cc (39 W/in³)</td>
</tr>
<tr>
<td></td>
<td>1.5 W/cc (24 W/in³) cased</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95% peak, 93% at 90 VAC, full load</td>
</tr>
<tr>
<td></td>
<td>DoE Level VI, Euro CoC (EuP) Tier 2</td>
</tr>
</tbody>
</table>
150 W Highest Efficiency

![Graph showing efficiency vs. output power for different voltages: 115V, 230V, and 90V.](image)

- Efficiency [%]
- P_OUT [W]
150 W Cool Operation

90 V\textsubscript{AC}, 150 W, 25 °C, uncased, no airflow
Let’s go GaNFast™