Using integrated GaN FETs to achieve high power density and efficiency in power factor correction (PFC) and high-voltage DC/DC converters.
Outline

• TI GaN: Engineered for high-frequency operation
• Applications driving for higher efficiency and density
  – Information technology power supplies
  – Automotive onboard chargers
• TI GaN for power factor correction (PFC) design
• TI GaN for DC/DC converter design
• TI GaN reference design and tools
GaN device: key advantages

Low $C_G, Q_G$ gate capacitance/charge (1 nC-Ω vs Si 4 nC-Ω)
✓ faster turn-on and turn-off, higher switching speed
✓ reduced gate drive losses

Low $C_{OSS}, Q_{OSS}$ output capacitance/charge (5 nC-Ω vs Si 25 nC-Ω)
✓ faster switching, high switching frequencies
✓ reduced switching losses

Low $R_{DSON}$ (5 mΩ-cm² vs Si >10 mΩ-cm²)
✓ lower conduction losses

Zero $Q_{RR}$ No ‘body diode’
✓ No reverse recovery losses
✓ Reduces ringing on switch node and EMI
Low switching loss in TI GaN

- GaN offers best performance

**Hard switching Figure-of-Merit**
*(turn-on and turn-off losses)*

**Soft-switching Figure-of-Merit**
*(turn-off losses, ZVS at turn-on)*
High-frequency design challenges with discretes

- **Common Source Inductance (CSI)**
  - Slows $V_{DS}$ transitions.
  - Higher overlap losses (Hard-Switching).
  - Longer dead-times (Soft-Switching).

- **Gate Loop Inductance**
  - Limit peak gate current: slow down gate drive and induce high overlap losses in hard switching.
  - Gate over-stress reliability risk.
  - Miller shoot-through risk.

- **White paper:** Optimizing GaN performance with an integrated driver
TI GaN engineered for high-frequency

- SMD (QFN) multi-chip module package offers **lowest parasitic inductance** for high frequency operation.

<table>
<thead>
<tr>
<th>Standard Power Package</th>
<th>Kelvin Source Power Package</th>
<th>TI: GaN FET + Gate driver</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Standard Power Package" /></td>
<td><img src="image2.png" alt="Kelvin Source Power Package" /></td>
<td><img src="image3.png" alt="TI: GaN FET + Gate driver" /></td>
</tr>
<tr>
<td>Common Source: 2nH -10nH</td>
<td>Common Source: &lt;1nH</td>
<td>Common Source: &lt;1nH</td>
</tr>
<tr>
<td>Gate loop: 5nH – 20nH</td>
<td>Gate loop: 5nH – 20nH</td>
<td>Gate loop: 1nH – 4nH</td>
</tr>
</tbody>
</table>
TI GaN: Integrated for high frequency and robustness

Integrated GaN FET, gate driver, protection, reporting
- <1 nH common source inductance, <4 nH gate loop inductance
- On-chip V/I/T sensing, protections & reporting
- Advanced power management features

Compact SMD package
- Low parasitic lead inductance
- Enhanced thermal management with top/bottom-side cooling

Design simplicity & confidence
- Demonstrated \( \frac{dV}{ds} / dt \) capability of 150 V/ns
- \( \frac{dV}{ds} / dt \) adjustable between 30-150 V/ns for EMI vs efficiency
- Compact PCB footprint
TI GaN integration simplifies BOM and cost

**TI GaN**

- FETs + Driver + Protection
- Only single 12-V unregulated supply needed
- Min area: 24x29mm

**Discrete GaN**

- Gate drive circuitry
- External power supply needed
- External protection needed
- Min area: 50x40mm
TI GaN FET portfolio

Gen-I

2x the power

- RDS: 50/70/150 mΩ
- Size: 8mm x 8mm
- Cooling: Bottom
- $R_{\text{j-s}}$: <5.5 C/W
- Power Loop Inductance: <2.3 nH

https://www.ti.com/product/LMG3411R050

Gen-II Industrial

- RDS: 30/50 mΩ
- Size: 12mm x 12mm
- Cooling: Bottom
- $R_{\text{j-s}}$: <2.6 C/W
- Power Loop Inductance: <2.8 nH

https://www.ti.com/product/LMG3422R030

Gen II Automotive

- RDS: 30 mΩ
- Size: 12mm x 12mm
- Cooling: Top
- $R_{\text{j-s}}$: <2.3 C/W
- Power Loop Inductance: <2.1 nH

https://www.ti.com/product/LMG3522R030-Q1

https://www.ti.com/product/LMG3422R030

https://www.ti.com/product/LMG3522R030-Q1
LMG342x/352x: TI Gen-II GaN FETs

- >150 V/ns Drain-Source Slew rate capability; adjustable from 30 V/ns to 150 V/ns
- Integrated 2.2-MHz gate driver with industry lowest CSI
- Overcurrent protection Cycle-by-Cycle
- Short circuit protection Latched
- 5-V regulated output for powering digital isolator
- GaN FET temperature digital PWM reporting for active power management
- V/VT fault reporting
- LMG342x: 600-V GaN FET
- LMG352x: 650-V GaN FET
- LMG3425/3525 Ideal diode mode reduces reverse conduction losses
- Wettable flanks
- NEW
- NEW
- NEW

https://www.ti.com/product/LMG3422R030
https://www.ti.com/product/LMG3522R030-Q1
Outline

• TI GaN: Engineered for high-frequency operation
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  – Information technology (IT) AC/DC power supplies
  – Automotive onboard chargers
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• TI GaN for DC/DC converter design
• TI GaN reference design and tools
Multi-kW applications demanding high efficiency & density

AC/DC power supply for datacenter, telecom, medical and industrial (up to 10 kW)

Automotive HEV/EV powertrain
AC/DC trends in datacenter and telecom

Energy Efficiency
Beyond 80+ Titanium @ 50% & 100% load

<table>
<thead>
<tr>
<th>80 PLUS Certification</th>
<th>115V Internal Non-Redundant</th>
<th>230V Internal Redundant</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Rated Load</td>
<td>20%</td>
<td>50%</td>
</tr>
<tr>
<td>80 PLUS</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>80 PLUS Bronze</td>
<td>82%</td>
<td>85%</td>
</tr>
<tr>
<td>80 PLUS Silver</td>
<td>85%</td>
<td>88%</td>
</tr>
<tr>
<td>80 PLUS Gold</td>
<td>87%</td>
<td>90%</td>
</tr>
<tr>
<td>80 PLUS Platinum</td>
<td>90%</td>
<td>92%</td>
</tr>
<tr>
<td>80 PLUS Titanium</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

- **PSU efficiency spec 2021:**
  - ITE-level PSU >96.5%
  - Rack-level PSU peak efficiency > 97.5% @ 230Vac

High power & Power density
3kW/4kW/5kW & >100W/in³

**ITE-level PSU** going up to 3kW+ in same FF

**Rack-level PSU** going up to 4kW+ in same form factor
- Power density: >100W/in³ by Y23
# Automotive trends in onboard charger & HV DC/DC

<table>
<thead>
<tr>
<th>High power density</th>
<th>Lower cost</th>
<th>Faster to market</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-2 kW/L ➔ 3-5 kW/L)</td>
<td>Smaller and cheaper magnetic components</td>
<td>Solutions that easily scale from 3.3-22 kW and address both 400-V and 800-V battery systems, while delivering on performance metrics.</td>
<td>Component level and application level reliability</td>
</tr>
<tr>
<td>Requires new topologies and design approaches:</td>
<td>Integrated magnetics (eg, inductor + transformer)</td>
<td></td>
<td>Confidence for adopting new technologies or design approaches</td>
</tr>
<tr>
<td>• <strong>PFC:</strong> Totem-pole topology to achieve 2x density improvement</td>
<td>Lower BoM with highly integrated devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• <strong>DC/DC:</strong> &gt;10x increase in switching frequency to achieve significant reduction in magnetics</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outline

• TI GaN: engineered for high-frequency operation
• Applications driving for higher efficiency and density
  – Information technology power supplies
  – Automotive onboard chargers
• TI GaN for power factor correction (PFC) design
• TI GaN for DC/DC converter design
• TI GaN reference design and tools
Hard-switching loss breakdown: TI GaN solution

- Hard-switching loss occurs in CCM Totem Pole PFC.

Low $C_{\text{oss}}$ output capacitance in TI GaN given its better Figure of Merit (FOM).

Integrated gate drive that is capable of providing >150 V/ns switching speed for TI GaN.

No body diode conduction and there is no Reverse Recovery loss in TI GaN device.

Integrated gate drive that provides a strong gate drive to turn-off.

Ideal Diode Mode enables automatic synchronous FET operation, and adapts to load current.
Bridgeless PFC comparison: Si vs. SiC vs. TI GaN

- **Dual-boost bridgeless PFC with Si MOSFET + SiC Schottky diode**: Si MOSFET has high $C_{oss}$ loss and overlap loss, while SiC diode has high conduction loss.

- **SiC MOSFET totem-pole (TP) bridgeless PFC (w/o anti-parallel Schottky diode)**: SiC MOSFET still has reverse recovery loss and high dead time loss.

- **TI GaN totem-pole (TP) bridgeless PFC**: lowest loss, zero reverse recovery, minimal overlap.

Loss comparison at 1 kW, 100 kHz

Reduction in component count

Technical article: [Wide-bandgap semiconductors: Performance and benefits of GaN versus SiC](#)
Adjustable slew rate

- High slew-rates with minimal ringing and voltage overshoot
- Tested in Buck converter at 400 V, and the turn-on $dv/dt$ can be adjusted according to different $R_{drv}$ resistances.
- The slew rate is defined from 20% to 80% at a bus voltage of 400 V.
Impact of slew rate on device loss

- Analysis at 4 kW, 230 V $V_{ac\_RMS}$, 400 V bus, 55°C ambient and $f_{sw} = 200$ kHz
  - Full load (4 kW) is considered for thermal design, and the steady-state loss is obtained.
  - With TI GaN’s 150 V/ns slew rate, the device is cooler and the system is more efficient.

Impact of slew rate on device loss

- Conduction Loss $P_c(T_j)$ + Switching Loss $P_{sw}(T_j)$
- Thermal Model $R_{th,th} + R_{th,ha}$
- Total Power Loss
- Ambient Temperature $T_a$
- Steady State $T_j$ and Power Loss

38% loss reduction
Case study: CCM TP PFC $R_{ds,on}$ v.s $C_{oss}$ trade-off

- 30 mΩ and 50 mΩ comparison at different $f_{sw}$ with 100 V/ns slew rate
  - 230 V $V_{ac\_RMS}$ and 400 V bus. Ambient temperature is 55°C.
  - 30-mΩ device shows lower loss at full power (4 kW).
  - At 50% load, the 50-mΩ device indicate lower loss when the switching frequency is beyond 100 kHz.

Loss Comparison at 50% Load: 2kW

Loss Comparison at Full Load: 4kW

Thermal Design at Full Power
4-kW single-phase CCM totem-pole PFC

Key parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input range</td>
<td>200 V&lt;sub&gt;AC&lt;/sub&gt;-277 V&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Nominal input</td>
<td>230 V&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>400 V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>GaN HEMT (Q1/Q2)</td>
<td>LMG342xR030</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>50 kHz</td>
</tr>
</tbody>
</table>
Phase shedding for higher light load efficiency

**Features**

- **TI GaN-based** 3-phase interleaved totem pole bidirectional PFC
- Rated Power: 3.3 kW (at 230 V<sub>rms</sub>)
- Peak efficiency: 98.7% (at 230 V<sub>rms</sub>)
- Total Harmonic Distortion (THD) < 2% (at low line)
- PWM switching frequency: 100 kHz
- Phase shedding control for higher efficiency

**Bidirectional 3.3kW CCM Totem Pole PFC**
Summary: CCM TP PFC Design with TI GaN

- TI GaN provides different QFN package variants for optimized thermal design at full power and max $T_a$.
- TI GaN's 30 V/ns to 150 V/ns adjustable slew rate provides a design flexibility to optimize the system efficiency and help on thermal design.
- TI GaN provides a variety of on-resistance to optimize the system design at different switching frequency.

---

**Thermal Model**

\[
\text{Total Power Loss} = P_c(T_j) + P_{SW}(T_j)
\]

\[
R_{th,jh} + R_{th,ha}
\]

**Ambient Temperature** $T_a$

**Steady State?**

- No: Updated $T_j$ and Power Loss
- Yes: Steady State $T_j$

**TI GaN with Different $R_{ds,on}$**

Up to 150 V/ns Slew Rate
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TI GaN: superior solution for soft-switching DC/DC

- **Reduced output capacitance** $C_{OSS}$
  - Reduces dead-time, increasing the time when current delivered to the output
  - Low transformer magnetizing current to minimize circulating current loss & eddy loss.

- **Reduced gate driver losses**

- **High power density in system**
  - GaN enables higher switching frequency to reduce magnetic components, and enables further magnetic integration.
## 1-MHz Isolated LLC DC/DC converter with TI GaN

Compared with 100-kHz LLC design, the 1 kW transformer is **6X smaller**

### Design target

<table>
<thead>
<tr>
<th>Design target</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (V)</td>
<td>380 ~ 400 V</td>
</tr>
<tr>
<td>Output voltage (V)</td>
<td>48 V Nom unregulated</td>
</tr>
<tr>
<td>Power (W)</td>
<td>1000 W</td>
</tr>
<tr>
<td>Integrated Transformer size (mm)</td>
<td>33 x 53 x 43</td>
</tr>
<tr>
<td>Power density</td>
<td>140 W/in3 (8.5 W/cm3) High power density</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;97.5% High Efficiency</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>1 MHz High Frequency</td>
</tr>
</tbody>
</table>

**1 MHz Integrated transformer design**

**100 kHz transformer design**

>650 Grams  

<100 Grams

[Link to PMP20637]
6.6 kW Bidirectional On-Board Charger with TI-GaN

**Design Features**
- Single TI C2000 used for control (TMS320F28388D)
- Two phase Interleaved CCM totem-pole bridgeless PFC converter (125kHz)
- CLLLC DC-DC Converter (200-800 kHz), <100ns dead-time
- 250 to 450V output (battery voltage range)
- Liquid cooled heatsink
- Integrated active EMI filter circuit
- Total Size ~ 113mm (w) x 271mm (l) x 58.4mm (h)

**Design Benefits**
- Higher power density and lower solution cost than SiC.
- 59% smaller DC/DC magnetics offering lower cost.

<table>
<thead>
<tr>
<th>Typical Operating conditions</th>
<th>SiC</th>
<th>Ti-GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFC Switching Frequency (kHz)</td>
<td>67</td>
<td>125</td>
</tr>
<tr>
<td>DC-DC Switching Frequency (kHz)</td>
<td>&lt;300</td>
<td>~500</td>
</tr>
<tr>
<td>Open frame Power Density (W/in³)</td>
<td>54</td>
<td>62.5</td>
</tr>
<tr>
<td></td>
<td>(kW/liter)</td>
<td>3.3</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>96.5</td>
<td>97+</td>
</tr>
</tbody>
</table>

**Operation**

- CCM Totem Pole PFC
- Resonant CLLLC

**Magnetic volume**
- 65kHz Totem Pole PFC: 149 cm³
- 120kHz Totem Pole PFC: 119 cm³ (~25% smaller)
- 150-300kHz CLLLC: 166 cm³
- 200-800kHz CLLLC: 69 cm³ (~60% smaller)
Soft switching waveforms in CLLLC

- Conditions: \( V_{in} = 400 \, \text{V} \), \( V_{out} = 354 \, \text{V} \), \( I_{out} = 10 \, \text{A} \), \( f_{sw} = 500\, \text{kHz} \).

Low \( C_{OSS(tr)} \) of TI GaN enables ZVS with \( \sim 60 \, \text{ns} \) deadtime.
Cooling design for top-cooled device: 6.6kW OBC

- 12 GaN FETs (tsQFN12x12), 4 Si FET (TO-247), PFC inductor and DC/DC transformer are cooled by one aluminum coldplate.
Additional resources and tools

**App notes**
- Ti GaN Ideal Diode Mode ([Link](#))
- Ti GaN 3rd Quadrant Operation ([Link](#))
- Ti GaN Direct Drive ([Link](#))
- Thermal Design ([Link](#))

**Training videos**
- Ti GaN: Built for Lifetime Reliability ([Link](#))
- GaN: From Watts to Kilowatts ([Link](#))
- Ti GaN Enabling 900-V Multi-kW Grid Converters ([Link](#))
- Designing with GaN High Density Power Supplies ([Link](#))
- Motor Drive Training ([Link](#))

**Design tools**
- GaN reference designs
  - 99% efficient 3-phase inverter
  - 1MHz 1.6kW CrM Totem Pole PFC
  - Bidirectional 3.3kW CCM Totem Pole PFC
- GaN plug-in daughter cards
  - LMG3411R050 Daughter Card
  - LMG3422R030 Daughter Card
  - LMG3522R030 Daughter Card
- GaN Buck-Boost Motherboard

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