Get Your GaN PhD in Less Than 60 Minutes!
Detailed agenda

Why is GaN Exciting
GaN Fundamentals
Cost and Reliability

Totem Pole PFC
Isolated LLC
Motor Drive
LiDAR

Driving GaN
Choosing a GaN
Tools
Why GaN is exciting?
Why GaN: 3x power density from AC-to-POL

1kW GaN Solution

**COOLER:**
99% efficient Totem Pole PFC

**FASTER:**
1 MHz Isolated DC/DC LLC

**SMALLER:**
Single stage Stackable 48V-to-POL

GaN: 156 W/in³ (9.5 W/cm³)
Versus
Silicon: 55 W/in³ (3.4 W/cm³)
195 x 84 mm

GaN: 140 W/in³ (8.5 W/cm³)
Versus
Silicon: 95 W/in³ (5.8 W/cm³)
94 x 84 mm

GaN: 140 W/in³ (8.5 W/cm³)
Versus
Silicon: 40 W/in³ (2.4 W/cm³)
102 x 102 mm

230V

AC

230V

AC

400V

DC

48V

DC

48V

DC

1V

DC

1V

DC

GaN Solution
TI-GaN: maximizing density, speed, and power

High-Density
270W/in³ 1.6KW CrM PFC switching at 1MHZ

High-Speed
50MHz DCDC Converter & 1ns 100W Lidar Driver

High-Power
8kW Multi-Level Converter Developed Jointly by Siemens and TI
HV GaN power stage: designed and made by TI

TI GaN Process
Fully qualified by TI for production

Built-in Protection
<100ns Short circuit, and thermal protection

Integrated Driver
Optimal gate bias, and 100V/ns performance

Packaging
Low inductance easy to use QFN Package

Reliability
Over 10M device and application reliability hours
TI-GaN power stage: fast and “perfect” switching

Switching node voltage

<25V voltage ringing

102V/ns

Zero to 400V in <4ns
With TI-GaN

Captured with 1GHz Passive Voltage Probe – Tektronix TPP1000
GaN Fundamentals
Power devices: mapping power and frequency

- IGBT / GTO
- Si SJ
- SiC
- GaN
GaN: key advantages over Silicon

- **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
GaN: higher frequency – lower loses

- Improved FOM allows both lower $R_{DS(on)}$ and lower switching loss
- High efficiency and/or higher switching frequency

Diagram showing the comparison between Si and GaN in terms of device losses vs. frequency.
GaN solutions: 6X smaller and lighter solutions

Example based on 1kW 480V:48V Isolated DCDC Design

Si Solution: >650 Grams

100 kHz transformer design

GaN Solution: <100 Grams

1 MHz Integrated transformer design
GaN: watts to kilowatts

Energy Delivery
- Solar Inverter
- Telecom AC/DC Rectifier
- 48V:POL
- Server / Network AC Power Supply
- UPS

Consumer
- Wireless Charger
- HDTV Power Supply
- Audio Amplifier

Emerging
- 5G Envelope Tracking
- LiDAR
- Augmented Reality

Industrial
- DCDC Converters
- Factory Automation
- Imaging Power Supply
- Motor Drive and Drones

Defence and Space
- Imaging Power Supply
- Motor Drive and Drones
Cost and Reliability
GaN cost: demystifying the myth

• GAN is not a drop-in replacement for silicon MOSFET. FET to FET cost comparison is misleading.

• GaN achieves new levels of power density not possible by silicon, and by enabling:
  – **New topologies** eliminates costly power components
  – **10x switching frequencies** reduce the cost and size of magnetics and cooling
  – **New architectures** cuts component count by half

• In these applications GaN enables solution cost parity with silicon at a minimum 2X increase in power density.

• Example: PFC designs, GaN delivers total cost on par with silicon at double the power density

![Graph showing cost comparison between Silicon and GaN for different applications.](image)
GaN reliability: not a science fiction

• After years of work by industry leaders, GaN is delivering the reliability and the ruggedness that engineers expect.

• For instance TI has long implemented a comprehensive methodology to ensure reliable operation and lifetime of GaN under the harshest operating conditions

• Our >10 million device reliability includes:
  – JEDEC JESD47I test conditions for temperature, bias, and operating life test
  – Accelerated hard-switching testing
  – Power supply system-level operation

• New JEDEC committee, JC70, is working on releasing a standard on GaN reliability and qualification procedures
GaN in Practical Applications
CCM Totem Pole PFC
PFC: applications and topology

Typical AC/DC PSU for industrial, medical, telecom and server applications.

PFC inductor is used to regulate input current in phase with the input voltage

Line frequency Silicon MOSFET active rectifier

600V GaN half-bridge
CCM PFC: topologies

- **Diode-bridge PFC**
  - Low cost
  - Good EMI performance
  - Moderate power density
  - Low efficiency
  - Heat not distributed

- **Dual-boost PFC**
  - Good EMI performance
  - Distributed heat
  - Good efficiency
  - Low power density

- **Totem-pole PFC**
  - High power density
  - High efficiency
  - Distributed heat
  - EMI performance
# CCM PFC: Power Loss Comparison

## Semiconductor Power Losses of PFC Topologies

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Diode-bridge Boost - SJ</th>
<th>Dual Boost - SJ</th>
<th>Dual Boost - GaN</th>
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</thead>
<tbody>
<tr>
<td><strong>Switching FET - Conduction</strong></td>
<td>0.6 W</td>
<td>0.6 W</td>
<td>0.6 W</td>
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<tr>
<td><strong>SiC Diode Conduction</strong></td>
<td>3.5W</td>
<td>3.5W</td>
<td>3.5W</td>
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<tr>
<td><strong>Rect Diodes / FETs</strong></td>
<td>8.19 W (Diode)</td>
<td>0.45 W (FET)</td>
<td>0.45 W (FET)</td>
</tr>
<tr>
<td><strong>FET E_{oss} / SiC Diode Q_{oss}</strong></td>
<td>3.1 W</td>
<td>3.1 W</td>
<td>2.56W</td>
</tr>
<tr>
<td><strong>I-V Overlap</strong></td>
<td>1.47 W</td>
<td>1.47 W</td>
<td>0.95W</td>
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<tr>
<td><strong>Total Losses</strong></td>
<td><strong>16.86W</strong></td>
<td><strong>9.12W</strong></td>
<td><strong>8.06W</strong></td>
</tr>
</tbody>
</table>

### Switching Losses

- **I-V Overlap Losses:** \((I_{\text{RMS}} \times V_{DC} \times t_{SW} \times f_{PWM})/2\)
- **Output Charge Losses:** \((V_{DC} \times Q_{\text{OSS}} \times f_{PWM})\)
- **Reverse Recovery Losses:** \((V_{DC} \times Q_{rr} \times f_{PWM})\)

### Notes

- Same heat sinking and RDSon for superjunction (SJ) and GaN - both 70mΩ
- Switching frequency is 100 kHz. \(V_o=400V, P_o=1kW\)
- \(Q_{\text{oss}}\) of SJ=360nC; \(E_{\text{oss}}\) of SJ=13µJ
- \(Q_{\text{oss}}\) of TI GaN=60nC; \(E_{\text{oss}}\) of TI GaN=7.6µJ
- \(Q_{\text{oss}}\) of SiC diode=65nC
Totem-pole PFC: operation

Positive half cycle

Active GaN FET is on

Synch GaN FET is on

Negative half cycle

Active GaN FET is on

Synch GaN FET is on
### GaN Totem-pole PFC: 2X power density of SJ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Input Voltage</td>
<td>85 – 265 V&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Input Frequency</td>
<td>50 – 60 Hz</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>385 V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Output Power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Input Inductance</td>
<td>481 μH</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>100 kHz / 140 kHz</td>
</tr>
<tr>
<td>GaN</td>
<td>LMG3410</td>
</tr>
</tbody>
</table>

#### 156 W/in<sup>3</sup>  
99% Efficiency

GaN FET Daughter Card LMG3410-HB-EVM

Switching Stage and Inductor

PMP20873
Totem-pole PFC: getting to >99% efficiency

- GaN Losses
- Thermal design
  - Use high thermal conductivity TIM
  - Board thickness and Thermal vias – number of vias, diameter
- PCB design
  - Minimize power loop
  - Minimize switch node overlap
- Control
  - Minimize dead-time through adaptive and predictive digital control
- Passive Component Selection
  - Inductor – core and wire size
  - EMI inductors – low DCR
  - DC bus capacitor – low ESR
Totem-pole PFC: loss breakdown and efficiency

Loss breakdown of 1kW PFC

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Power Loss</th>
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</thead>
<tbody>
<tr>
<td>EMI Inductor Loss</td>
<td>0.4W</td>
</tr>
<tr>
<td>PFC Inductor Copper Loss</td>
<td>1.2W</td>
</tr>
<tr>
<td>PFC Inductor Core Loss</td>
<td>1.64W</td>
</tr>
<tr>
<td>DC Capacitor Loss</td>
<td>0.54W</td>
</tr>
<tr>
<td>GaN Conduction Loss</td>
<td>1.76W</td>
</tr>
<tr>
<td>GaN Q&lt;sub&gt;oss&lt;/sub&gt; + Switch Node Cap Loss</td>
<td>2.6W</td>
</tr>
<tr>
<td>GaN I-V Overlap Loss</td>
<td>0.9W</td>
</tr>
<tr>
<td>Relay + Si FET + PCB Losses</td>
<td>0.95W</td>
</tr>
<tr>
<td><strong>Total Power Losses</strong></td>
<td><strong>9.98W</strong></td>
</tr>
</tbody>
</table>

*<sub>T<sub>amb</sub>=25°C, fs=100kHz, V<sub>dc</sub>=387V</sub>*

99% efficiency 60% to 100% load

Note: Excludes bias losses
1MHz LLC
**LLC: Applications and topology**

- **Typical AC/DC PSU** for industrial, medical, telecomm and server applications.

- **Resonance set up with** $L_r$, $C_r$ ($&$ $L_m$), **this network determines** regulation characteristics.

- **600V Superjunction** or GaN half-bridge

- **Low-voltage Si** or GaN synchronous rectifier

- **85-265 V_{AC}**

- **PFC** 400V_{DC}

- **LLC** 12, 24, 48V_{DC}
**LLC: key benefits**

- Soft-switching over entire load range
- Low component stresses
- Easy magnetic integration

```
Waveform @f_{sw} < f_r
```

```
Low MOSFET turn-off current
Primary ZVS
Secondary ZCS
```
GaN: superior solution for LLC

• Reduced Output Capacitance $C_{OSS}$
  – reduces dead-time, increasing the time when current delivered to the output
  – allows larger magnetizing inductance and lower circulating current losses as well as transformer fringe-field losses

• Reduced Gate Driver Losses

• System Optimization
  – GaN enables higher switching frequency to reduce magnetic components significantly
  – GaN enables LLC converter with higher efficiency and higher power density
**LLC solution: 1MHz isolated DC-DC converter**

**Specification**

<p>| | |</p>
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<tr>
<td>Input voltage (V)</td>
<td>380 ~ 400</td>
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<tr>
<td>Output voltage (V)</td>
<td>48V Nom unregulated</td>
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<tr>
<td>Power (W)</td>
<td>1000</td>
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<tr>
<td>Size (in)</td>
<td>2 x 2.1 x 1.7</td>
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<tr>
<td>Power density (W/in^3)</td>
<td>140 High power density</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;97% High Efficiency</td>
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<tr>
<td>Switching frequency</td>
<td>1 MHz</td>
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</table>
LLC solution: 1MHz isolated DC-DC converter

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<thead>
<tr>
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<th>GaN</th>
<th>Silicon</th>
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<tbody>
<tr>
<td>Topology</td>
<td>LLC</td>
<td>LLC</td>
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<tr>
<td>Frequency</td>
<td>1MHZ</td>
<td>100-200 kHz</td>
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<tr>
<td>Density  (W/in$^3$)</td>
<td>140</td>
<td>95* commercial server LLC</td>
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</tbody>
</table>

![Image of LLC solution with dimensions and components highlighted]
1MHz LLC: integrated transformer design details

- PCB windings integrated with SR FETs & output capacitors for low interconnect and leakage loss
- Interleaved structure for lower winding loss
- “∞” shaped winding structure to achieve high power density
- Better thermal performance
Test results: measured efficiency
Motor Drive
GaN: advantages in motor drives

• GaN reduces or eliminates heatsink
• GaN reduces or eliminates switch node oscillations
  – Lower radiated EMI, no additional snubber network (space, losses) required
• GaN increases PWM frequency and reduces switching losses
  – Drive very low inductance PM synchronous motors or BLDC motors
  – Precise positioning in servo drives/steppers through minimum torque ripple
  – High-speed motors (e.g. drone) achieves sinusoidal voltage above 1-2kHz frequency
• GaN eliminates dead-time distortions of phase voltage
  – Better light load and THD performance
TIDA-00909: 48V/10A high frequency 3-phase GaN inverter

Design features
- Inverter w/ three 80V/10A half-bridge GaN power modules LMG5200
- Interfaced with C2000 MCU LaunchPad
- Up to 100-kHz PWM inverter with wide input voltage range 12-60V\(_{\text{DC}}\)

Design benefits
- Very low switching losses, efficiency up to 98.5% at 100-kHz PWM
- No heatsink
- Tested up to 100kHz PWM to drive low inductance/high-speed motors
GaN inverter: 100kHz 3-phase design

48V/10A with 98.5% efficiency

Natural Convection

Board dimension 54mm * 79mm

No heatsink!
LiDAR
High accuracy LiDAR enabled by GaN

• Next generation scanning LiDAR requires:
  – Increased range (300m): need more power (>40A/ 75W)
  – Eye safety: <2ns pulse width
  – Depth accuracy of <10cm: <2ns pulse, <500ps rise time

• GaN and the LMG1020 LiDAR GaN driver enables optimal power and speed in the laser design, not possible with MOSFET drivers
LMG1020: 1ns 100W light output

Light output, 1ns ½ power peak power >100W

Receiver falling edge BW limited
Driving GaN
Parasitics: limits system performance

- Parasitic inductances cause switching loss, ringing and reliability issues, especially at higher frequencies
- Why pay for GaN if you cannot get best system performance?
**Integrated driver: for best total solution**

- Integrating the driver eliminates common-source inductance and significantly reduces the inductance between the driver output and GaN gate, as well as the inductance in driver grounding.
LMG3410 GaN: driver integration eliminates ringing

Switching node voltage

<25V voltage ringing

Zero to 400V in <4ns
With TI-GaN

Captured with 1GHz Passive Voltage Probe – Tektronix TPP1000
Choosing a GaN
LMG3410: 600V/70mΩ 12A GaN power stage

- Slew rate control by one external resistor: 30 V/ns to 100 V/ns
- Digital PWM input
- Only +12V unregulated supply needed
- Built-in 5V LDO to power external digital Isolator
- Low power mode for standby conditions
- Fault feedback to system controller
- Integrated direct gate driver with zero common source inductance
- 70mΩ-600V GaN FET for 12A continuous operation
- High speed over current protection with <100ns response time
- Integrated temperature protection and UVLO
- 600V/70mΩ GaN power stage

LMG3410: 600V/70mΩ 12A GaN power stage

- LDO, BB UVLO, OC, TEMP
- VDD 5V
- LPM IN
- RDRV Current
- Direct- Drive
- Slew Rate
- Enable Switch
- 600V GaN
- S
- VNEG
- IN
- VDD
- 5V
- LPM
- FAULT
- Current
- Fault feedback to system controller
- Integrated temperature protection and UVLO
- Only +12V unregulated supply needed
- Built-in 5V LDO to power external digital Isolator
- Low power mode for standby conditions
- Fault feedback to system controller
- Integrated temperature protection and UVLO

Texas Instruments
TI-GAN: more than just high voltage

Easy and Compact

- Fully integrated HB GaN
  - LMG5200
  - 6x8mm QFN

Fast and Robust

- Up to 50MHz Operation
  - LMG1210
  - CMTI >300V/ns

Small and Mighty

- 0.8 x 1.2 mm WCSP
  - LMG1020
  - 1ns Pulse -500ps rise time

- 80V Half Bridge GaN Power Stage

- 50MHz 200V Half Bridge GaN Driver

- RF Envelope Tracking
- High Frequency DCDC
- High-Side driver

- Motor Drive
- Wide Vin DCDC
- Audio Amp

- 60MHz Low Side GaN Driver

- LiDAR
- Time of Flight Laser Driver
- Class E wireless charging
Tools
## Sub 200V design tools

<table>
<thead>
<tr>
<th>Solution</th>
<th>Devices</th>
<th>Type</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>48V to POL DCDC Converter</td>
<td>LMG5200</td>
<td>EVM</td>
<td>LMG5200POLEVM-10</td>
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<td></td>
<td>TPS53632G</td>
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<td>48V to POL DCDC Converter</td>
<td>LMG5200</td>
<td>TIDA</td>
<td>PMP4497</td>
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<td>UCD3138</td>
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<td>Triple Rail 48V DCDC Converter</td>
<td>LMG5200</td>
<td>TIDA</td>
<td>PMP4486</td>
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<td>UCD3138</td>
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<tr>
<td>48V 3-Phase 10A Motor Drive</td>
<td>LMG5200</td>
<td>TIDA</td>
<td>TIDA-00909 EVM</td>
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<td></td>
<td>C2000</td>
<td>EVM</td>
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<td>3-Phase 200V AC Servo Drive</td>
<td>LMG3410</td>
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<td>Nanosecond LiDAR Solution</td>
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<td>TIDA-01573 EVM</td>
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<td>Multi-MHz GaN Power Stage</td>
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# 600V Design Tools

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<th>Solution</th>
<th>Devices</th>
<th>Type</th>
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<tbody>
<tr>
<td>HV GaN Evaluation Platform</td>
<td>LMG3410</td>
<td>EVMs</td>
<td>LMG3410-HB-EVM</td>
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<td>LMG34XX-BB-EVM</td>
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<td>500W LLC (400/12V)</td>
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<td>PMP20289</td>
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<td>UCD3138</td>
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<td>1KW CCM Totem Pole PFC</td>
<td>LMG3410</td>
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<td>3KW Interleaved CCM Totem Pole PFC</td>
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Summary

• GaN is enabling a new generation of power conversion designs not possible before.
• These designs allow systems to reach unprecedented levels of power density and efficiency
• Integration of driver and GaN in a low inductance package provides an optimal solution for fast and reliable switching
• GaN enables 1MHz isolated LLC designs with over 6x reduction in size and weight of the power transformer
• GaN enables the integrations of 100kHz drive and motor by reducing the solutions size and eliminating heatsink.
• Learn more at ti.com/gan