GaN Power Devices: From Watt to Kilo-Watt Power Applications

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Texas Instruments
TI training – summary

GaN: Watt to KW Power Applications

TI's Portfolio of GaN FETs with integrated driver and protection are in mass production and are enabling designers to reach unprecedented levels of power density and efficiency in every power level and end-equipment. These cost-competitive solutions are found in applications such as robotics, solar converters, telecom, grid infrastructure, AI servers, networking, industrial power supplies, and personal electronics.

What you’ll learn:

• Learn about how the LMG3410 can bring differentiation in a typical application
• Integration for system performance and reliability
• Overview of GaN applications: power supply, motor drive, wall adapter
Detailed Agenda

• GaN Overview
• Why LMG3410x GaN?
• Half-bridge Solutions
• GaN Applications:
  – High Density Power Supply Designs
  – High Efficiency Motor Drives
  – Ultra-Small USB PD and AC-DC Solutions
• Summary
GaN Overview
**GaN: Key Advantages Over Silicon FET**

- **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: Ready to Take you Beyond Silicon Today

- GaN devices are enabling solutions with twice the power density of what is possible with best-in-class superjunction FETs
- TI LMG3410x GaN devices are now in production with our customers ramping to mass production now.
  - 3kW Telecom Rectifier
  - Class-D Audio Amplifier
  - 3D Printer
  - Factory Robotics Drive
  - OLED TV PSU
LMG3410x: GaN performance beyond Silicon

2x Higher Power Density

98.8% efficient 1MHz CrM PFC

- 37 W/in³
- 1.6kW in ½ the space
- 70 W/in³

Loose the fan

99.2% efficient 1.2kW Servo Drive Inverter

- 85% Smaller Heat Sink
- No Fan!

Ultra small form factor

65W Pocket Sized USB Type-C Adapter

- >60% Smaller Volume
- >30 W/in³

TI Information – Selective Disclosure [TIDA-00961]
Why LMG3410x GaN?
**LMG3410x GaN: Ready to Use Now**

**Integrated**
- Complete GaN, driver and protection in single package
- Fast and easy system design

**Robust**
- 720V surge capability while switching
- 100ns short-circuit protection
- Thermal protection

**Reliable**
- >20 million hours of reliability testing to date
- <1 FIT rate for 10 year lifetime

**Ready**
- Available in 50, 70, and 150mΩ
- 100% TI internal HV GaN process, fab, and assembly
LMG3410x: Integrated Driver
Ease of Design & Higher Efficiency

Integrated gate driver with zero common source inductance

50mΩ, 70mΩ and 150mΩ 600V GaN

<25V voltage ringing
102V/ ns

Switching node voltage

Simple system interface

RDRV

IN

VDD

5V

FAULT

600V GaN

Slew Rate

Direct Drive

LDO, BB

OCP, OTP, UVD

<100ns Short Circuit Protection

TI Information – Selective Disclosure
LMG3410x: Integrated Driver
Design Simplicity & Smaller HB BOM

Complete Half-Bridge Design for any Power Level

High-Side GaN

Low-Side GaN

Bypass caps

Digital Isolator

Bootstrap diode/cap

Single 12V Unregulated Supply
Challenges of GaN Designs with External Driver and Protection

• **Driver Bias Voltage**: GaN gate bias is critical to its performance and long-term device reliability.

![](MTTF_vs_VGS.png)

- **MTTF vs. $V_{GS}$**

- **Mean Time to Failure (h)**
- **Gate Bias (V)**

- **10 yrs**

- **$5 \rightarrow 5.5 \rightarrow 6 \rightarrow 6.5 \rightarrow 7$**

• **Protection**: Designing a robust overcurrent protection circuit at high slew rate is difficult and costly.

• **Parasitic Inductance**: causes switching loss, ringing and reliability issues, especially at high GaN frequencies.

![](GaN_FET_Driver_ParInductance.png)
Parasitic Effect: Common Source Inductance

- Common Source inductance reduces the $\frac{di}{dt}$ during turn-on and turn-off.
  - Increases power dissipated during the $\frac{di}{dt}$ ramp
- 5nH common source inductance increases turn-on loss by 60%

High-side turn on versus common-source inductance:
red = 0 nH, green = 1 nH, blue = 5 nH
Parasitic Effect:
Gate Loop Inductance

- Gate loop inductance increases the impedance between the gate and the driver.
  - Limits the ability to hold off the GaN device during the Vds ramp
  - Shoot through increases the power dissipated in the high-side device and can cause it to fail due to SOA.

- Gate loop inductance increases ringing
  - Higher stress on gate
  - Ringing can cause the device to turn-on/off
  - Loop resistance is required to dampen ringing

Low-side hold-off versus gate-loop inductance
red = 2 nH, green = 4 nH, blue = 10 nH
Parasitic Effect: Power Loop Inductance

- Power loop inductance
  - Increases Ringing and EMI
  - Increases $V_{ds}$ voltage stress
  - Increase switching losses
- Package must be designed to enables low power loop inductance PCB layout
- GaN must be switched without snubber to have high efficiency

$V_{sw}$ ringing versus power loop inductance
red = 2nH, green = 5nH, blue = 10nH, orange = 20nH
Common Source & Gate Loop: Comparison

Standard Packages

Kelvin Source Packages

Integrated Driver Packages

<table>
<thead>
<tr>
<th></th>
<th>Standard Power Package</th>
<th>Kelvin Source Power Package</th>
<th>Integrated Driver Power Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Source</td>
<td>2nH -10nH</td>
<td>&lt;1nH</td>
<td>&lt;1nH</td>
</tr>
<tr>
<td>Gate Loop</td>
<td>5nH – 20nH</td>
<td>5nH – 20nH</td>
<td>1nH – 4nH</td>
</tr>
</tbody>
</table>

TI Information – Selective Disclosure
Discrete GaN: Limited Switching Performance

Expensive bias supply
With negative voltage

>10nH gate inductance

> 10nH gate inductance

> 250 mm² extra area
> 6 extra active comp.

Switching node voltage:

- 63.7V/ns
- 400V
- 0V

10ns/div

TI Information – Selective Disclosure
Integrated Driver Allows Faster Switching

LMG3410R070
IGOT60R070D1
GS66508T

**P_{SW} \sim \left( I_{RMS} \times V_{DC} \times t_R \times f_{PWM} \right)/2 + (V_{DC} \times Q_{oss} \times f_{PWM}) + (V_{DC} \times Q_{rr} \times f_{PWM})**

Switching Loss
100kHz, 1kW
TP CCM PFC

TI GaN: 100V/ns \rightarrow 0.95W
Discrete: 50V/ns \rightarrow 1.9W

2.3W at 387V
1.6W at 387V
0W
0W

* @turn-on at 400V V_{bus} 10A with default driving configuration on EVM
** dv/dt measured within 10%-90% V_{bus}
LMG341x: Robust to Surge

- The IEC 61000-4-5 standard specifies the surge waveform.
- The VDE 0884-11 standard specifies the application of 50 strikes.
- The TI test consists of an additional 50 strikes, to assure margin.
LMG341x: Robust 100ns Overcurrent Protection

- Latched (LMG3410Rxxx)
  In an OCP event, the device is turned off in less than 100ns and held off until the fault is reset by either holding the IN pin low for >350µs

- Cycle-by-Cycle (LMG3411Rxxx)
  In an OCP event, the device is turned off in less than 100ns and held off until the next PWM cycle
Discrete OCP Implementation: External Components

High side fault reporting requires level shifting

~20ns blanking time is required to prevent false trigger

Shunt resistor increases the power loop inductance and power losses

High-speed comparator
Discrete OCP Implementation: Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resistive Shunt 2X 12mΩ (25mΩ /2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Added PCB Area</td>
<td>233 mm²</td>
</tr>
<tr>
<td>Added Power Loop Inductance</td>
<td>1.2nH</td>
</tr>
<tr>
<td>dv/dt</td>
<td>80V/ns</td>
</tr>
<tr>
<td>Additional Power Loss at Po=1.2kW</td>
<td>0.9W</td>
</tr>
</tbody>
</table>

2 x Shunt resistors
Comparator w/ filters
GaN FET
Bypass caps
12.7mm x 6mm
6.35mm x 6.40mm
LMG341x: Reliable and In Mass Production

- Over 20 million hours of reliability testing to date
- < 1 FIT rate for 10 year lifetime
- JEDEC JESD47 qualification complete
- Hard-switching reliability complete
- Dynamic Rds-on testing complete
- Long term in-application testing complete
- Extreme Short-circuit and surge testing complete
- In mass production with 100% TI owned fab

Device Reliability Hours:

>20,000,000
LMG3410x GaN: Ready for Watts to 10kW

- LMG341XR150: 150mΩ
- LMG341XR070: 70mΩ
- LMG341XR050: 50mΩ

ACF, PFC, LLC, Inverter, Multi-Level

<65W → 10kW
High Density Power Supply Designs
Power Supply Architecture: PFC and LLC

85-265 V_AC → 400 V_DC → 12, 24, 48 V_DC

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

Resonance set up with Lr, Cr (& Lm), this network determines regulation characteristics.

Low-voltage Si or GaN synchronous rectifier.

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

PFC

400 V_DC

LLC

12, 24, 48 V_DC

T1 Information – Selective Disclosure

600V GaN

GaN

Si

Line frequency Silicon MOSFET active rectifier

600V GaN

TI Information – Selective Disclosure
LMG3410x GaN: Maximize Power Density

Silicon PFC @ 1.6kW

Power Density: 37 W/in$^3$

GaN PFC @1.6kW

Power Density: 70 W/in$^3$

- 2x higher density
- 50% reduction in magnetics
- 2 GaN replaces 2 SJ and 2 SiC diodes
- 2-3% Higher Efficiency

TIDA-00961
**GaN PFC Solution: Superior Power Supply Design**

- **Higher efficiency**
  - Reduced power loss by 36%

- **Higher power density**
  - 2X power density in Totem-pole PFC versus Silicon

- **Solution cost parity**
  - Reduced magnetics and external components bring total solution cost down

### Loss Mechanism

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Dual Boost PFC with Silicon</th>
<th>Totem-pole PFC with GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching FET Cond.</td>
<td>0.6 W</td>
<td>2.06 W</td>
</tr>
<tr>
<td>SiC Diode Cond.</td>
<td>2.75W</td>
<td>-</td>
</tr>
<tr>
<td>FET Eoss / SiC Diode Qoss</td>
<td>3.9 W</td>
<td>2.4W</td>
</tr>
<tr>
<td>I-V Overlap</td>
<td>1.47 W</td>
<td>0.95W</td>
</tr>
<tr>
<td>Rect. Diodes / FETs</td>
<td>0.45 W (FET)</td>
<td>0.45 W (FET)</td>
</tr>
<tr>
<td><strong>Total Power Losses</strong></td>
<td><strong>9.17W</strong></td>
<td><strong>5.86W</strong></td>
</tr>
</tbody>
</table>
GaN in LLC: Superior Power Supply Design

- **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
PMP20637: 1MHz Isolated LLC DCDC Converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>380 – 400V</td>
</tr>
<tr>
<td>Input Frequency</td>
<td>≤ 1MHz</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>48V</td>
</tr>
<tr>
<td>Output Power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>≤ 1MHz</td>
</tr>
<tr>
<td>Efficiency</td>
<td>97%</td>
</tr>
</tbody>
</table>

Power Density: 140 W/in³

GaN FETs (LMG3410-HB-EVM)

Power Density Improvement & Weight Reduction

PMP20637: 100 kHz transformer design

Integrated Transformer

94 x 84 mm
4x Density and 98% Efficiency
Comparison with MOSFET

Reduced capacitance & circulating currents dramatically improve light-load efficiency

Resistance Limited (slight improvement)
High Efficiency Motor Drives
Digital or analog communication (encoded angle) require high immunity against fast transient bursts, high-voltage surge and ESD.
New Trend: Integrated Motor Drives

Integrated Drives with GaN

✓ Compact form factor
✓ Fan-less operation
  • No fan failures, higher reliability
✓ Integrated design
  • High dv/dt operation
  • DC distribution saves cabling cost
  • Noise immunity on comm and encoder lines
  • Factory floor savings

6-axis 4.5kW robotic arm

- Max space for inverter
- 8cm
- 10cm
- 6-axis 4.5kW robotic arm
- Tamb= 70 to 90°C
- Integrated Motor Drive
- AC/DC Converter
- 140cm
- 70cm
- Integrated Motor Drive
- Integrated Motor Drive
- Integrated Motor Drive
- Grid
LMG3410R150: Enabling Integrated Motor Drive

Silicon Servo Drive @1.5kW

- 75% reduction Factory Floor Cabinets
- 90% less power and communication cabling
- 85% smaller heatsink and NO-FAN

Cooling Area: Fan + 145 x 82 x 42 mm

*in 6 axis robotic system

Integrated GaN based Motor Drive

Cooling Area: No Fan: 80 x 46 x 20 mm

TIDA-00915

Texas Instruments
TIDA-00915: 1.2kW 3Φ Integrated Drive

Solution Features
- Ultra-small form factor with power density of 150W/in³
  - 50°C ambient conditions up to 1.25kW
  - 85°C ambient conditions up to 550W
- Peak efficiency > 99%
- Natural convection cooling with 10mm heatsink
- Built-in short-circuit and over temperature protection
- 450V Max DC Operation

Applications
- Integrated motor drives
- Robotics
- Servo drivers
TIDA-00915: Natural Convection Cooling

Heatsink: 10mm fin height
Peak efficiency > 99.2%
**GaN: Enabling Smart Motor Drive**

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

TI Information – Selective Disclosure
Ultra-Small USB PD and ACDC Solutions
LMG3410x GaN: Achieve Ultra-Small Solutions

Silicon <100kHz

- QR flyback
- Size: 72 x 72 x 28 mm

GaN >500kHz

- Active clamp flyback
- Size: 65 x 30 x 22 mm
Active Clamp Flyback

Eliminates switching losses and reduces EMI with proper control of the clamp which allows zero voltage switching (ZVS) to be achieved.

Improves efficiency over traditional Flyback converters by recirculating the leakage energy and delivering it to the output instead of dissipating it.

Enables greater power density. Lower switching losses and corresponding temperature rise enables higher switching frequencies, which allows for smaller passive components and tighter packaging.
PMP21639: 65-W USB Type-C PD AC/DC Adapter Reference Design

Features

• 100% TI GaN solution, ACF, and SR controllers
• Requires only ONE GaN Device
• High efficiency (94% Peak)
• High power density (>30W/in³)
• Low light-load input power (0.5W), @20Vout/0.25W output
• Fully compatible with USB PD 2.0 standard, with 5V/3A, 9V/3A, 15V/3A, 20V/3.25A output
• Small size (62mm*28.6mm*18.4mm)
TI-GaN Active Clamp Flyback Solution

More power in less space

LMG3411R150 GaN Power Stage
- 600V 150mΩ single-chip GaN with driver and protection
- 100ns cycle by cycle short-circuit protection

UCC28780 Active Clamp Flyback
- Best in class efficiency and innovative ZVS algorithm
- Advanced protection features

UCC24612 Advanced Sync Rectifier
- Wide voltage range operation
- Intelligent control provides near ideal diode emulation
PMP21639: Why Si on the High-Side?

- 65W TM flyback high-side
  - High side $I_{\text{rms}}$ << low side $I_{\text{rms}}$
  - can tolerate $R_{\text{dson}} > 1\Omega$
  - $C_{\text{sw}}$ dominated by $C_{\text{oss}}$ of low side FET

- Trade offs of Si FET on high side:
  + Significant cost savings
  + Simplified drive for high side FET
  + Avoid any boot-strap issues at no load
  - Minor impact on efficiency
Key Takeaways

• TI GaN portfolio supports applications from Watts to 10kWs, enabling a new generation of power conversion designs with high power density and efficiency

• GaN enables 2X power density improvement on a PFC stage at system level cost parity

• 1MHz isolated LLC design delivers 6x reduction in size and weight of the solution

• GaN decreases USB PD Charger volume by 60%

• GaN based integrated motor drive eliminates cooling, and saves factory space and cabling costs

• For products, designs, and training material, visit Ti.com/GaN
Thank You