GaN: the path to high power density
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What will I get out of this session?

**Purpose:**
- Advantages of LMG3410 Self-Protected GaN Power Stage
  - A tutorial on PCB layout when using GaN Power Stages to achieve best performance and reliability.
  - GaN-based CCM Totem-Pole PFC design with 2X power density.
  - GaN-based 1MHz LLC isolated DC/DC converter design with integrated transformer and 97.6% peak efficiency

**Part numbers mentioned:**
- LMG3410
- UCD3138, UCD7138
- UCC28740, UCC27714

**Reference designs mentioned:**
- PMP20873
- PMP20637

**Relevant End Equipment:**
- Industrial/Telecom/Server
Question #1: Why is GaN so exciting?

A) It enables 2x Power density of Silicon
B) It’s reliable
C) You can make your magnetics 6x smaller
D) All of the above
Agenda

• GaN technology
  - Advantages of GaN FET
  - Why GaN Power Stage?

• System design of LMG3410 half-bridge daughter card
  - Layout and thermal design and trade-offs

• System design of 1kW CCM totem-pole PFC
  - Hard switching loss calculation
  - System design considerations

• System design of 1kW 1MHz LLC
  - Advantage of GaN in high frequency soft-switching application
  - Magnetics design considerations
GaN FET Advantages

- **$C_G, Q_G$** Low gate capacitance/charge:
  - Faster turn-on and turn-off, higher switching speed
  - Reduced gate drive losses

- **$C_{OSS}, Q_{OSS}$** Low output capacitance/charge:
  - Faster switching, high switching frequencies
  - Reduced switching losses

- **Zero $Q_{RR}$** No ‘body diode’, zero reverse recovery:
  - Almost eliminate over-/under-shoot and ringing on switch node and hence reduce EMI
  - Smaller over-/under-shoot and ringing increase device reliability
Discrete GaN: Limits System Performance

- Parasitic inductances cause switching loss, ringing and reliability issues, especially at higher frequencies
- Why use a solution that limits your system performance?
Integrated Driver: For Best Total Solution

GaN FET/Driver Integrated Package

- 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.
TI-GaN Power Stage: LMG3410

- 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
- Integrated direct gate driver with zero common source inductance
- Integrated gate drive bias supply for reliable GaN switching
- 70mΩ-600V GaN for 12A continuous operation
- High speed over current protection with 100ns response time
- Fault feedback to system controller
- Integrated temperature protection and UVLO
- Only +12V unregulated supply needed
- Integrated 5V LDO to power external digital Isolator
- Fault feedback to system controller
- Integrated temperature protection and UVLO
Question #2: What’s the biggest challenge of your high frequency power supply design?

- A) Layout
- B) Magnetics
- C) EMI
- D) Other
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Question #3: How many places in the layout can be improved?

- A) 2
- B) 3
- C) 4
- D) >4
TI-GaN LMG3410-HB-EVM

Switching node voltage < 25V

102V / ns

Zero to 400V in <4ns

Captured with 1GHz Passive Voltage Probe – Tektronix TPP1000
High Side Level and Power Shifting

High side device level and power shifting are critical due to high dv/dt (>100V/ns)

- Signal level shifting: isolator with high common mode transient immunity (CMTI) are required. ISO7831 is recommended
- High side Aux. power supply: low intra-winding capacitance transformer and extra common-mode choke are recommend to minimize dv/dt noise to digital ground
- Optimize layout to reduce switching node to controller ground capacitive coupling
- Bootstrap: Fast recovery or SiC diode is recommended
Minimize power loop impedance and parasitic capacitance

Small Return Path Minimizes Power Loop Impedance

\[ V = L_{lk} \frac{di}{dt} \]

Added capacitance to SW 17 pF with 50mm²
Thermal design

- Increase copper thickness (2-3 oz copper)
- Reduced FR4 thickness (5 mil)
- Increase thermal vias numbers and optimized pattern
- Filled thermal vias for better thermal conduction

<table>
<thead>
<tr>
<th>TIM NAME</th>
<th>MATERIAL</th>
<th>THERMAL PERFORMANCE</th>
<th>ELECTRICAL ISOLATION</th>
<th>ASSEMBLY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Grease</td>
<td>High-thermal conductivity particles (Al₂O₃ or BN) dispersed in silicone or non-silicone matrix</td>
<td>High</td>
<td>No</td>
<td>Moderate</td>
</tr>
<tr>
<td>Phase Change Material</td>
<td>High-thermal conductivity particles (Al₂O₃ or BN) dispersed in phase-change polymer (polyolefin, epoxy, polyesters, or acrylics) Can be laminated on carriers (Al foil, polyimide, or fiberglass) for mechanical or dielectric strength</td>
<td>High</td>
<td>Yes</td>
<td>Difficult</td>
</tr>
<tr>
<td>Thermal Gel</td>
<td>High-thermal conductivity particles (Al₂O₃ or BN) dispersed in silicone or non-silicone matrix</td>
<td>Medium</td>
<td>No</td>
<td>Moderate</td>
</tr>
<tr>
<td>Adhesive Tape</td>
<td>High-thermal conductivity particles dispersed in silicone or non-silicone matrix and reinforced by glass fiber carrier or PET liner</td>
<td>Low</td>
<td>Yes</td>
<td>Easy</td>
</tr>
<tr>
<td>Filled Polymer Pad</td>
<td>High-thermal conductivity particles (Al₂O₃ or BN) dispersed in silicone or non-silicone matrix Reinforced by glass fiber or polyimide film for improved mechanical and dielectric strength</td>
<td>Medium</td>
<td>Yes</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
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Half-bridge hard switching loss calculation

- GaN FET driver losses (high & low-side):
  \[ P_{\text{GATE}} \approx 2 \times Q_G \times V_{\text{DD}} \times f_{\text{PWM}} \]

- GaN FET (high & low-side)
  - Conduction losses: \( P_{\text{COND}} = I_{\text{RMS}}^2 \times R_{\text{DSON}} \)
  - Dead time losses: \( P_{\text{DB}} \approx I_{\text{RMS}} \times V_{3Q} \times (t_{\text{DBR}} + t_{\text{DBF}}) \times f_{\text{PWM}} \)
  - Switching losses: \( P_{\text{SW}} \approx (I_{\text{RMS}} \times V_{\text{DC}} \times t_{\text{SW}} \times f_{\text{PWM}})/2 \)
    + \( (V_{\text{DC}} \times Q_{\text{OSS}} \times f_{\text{PWM}}) \)
    + \( (V_{\text{DC}} \times Q_{\text{rr}} \times f_{\text{PWM}}) \)

\[ E_{\text{OSS}} \times f_{\text{PWM}} + E_{\text{ch}} \times f_{\text{PWM}} = V_{\text{DC}} \times Q_{\text{OSS}} \times f_{\text{PWM}} \]

Typical Si FET, \( Q_{\text{rr}} = 2 \, \mu\text{C} \quad 2 \, \mu\text{C} \times 400\text{V} \times 100\text{kHz} = 80\text{W} ! \]
1kW GaN-based Totem-Pole CCM PFC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<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>HL Efficiency</td>
<td>99%</td>
</tr>
</tbody>
</table>

GaN FET Daughter Card LMG3410-HB-EVM

Switching Stage and Inductor

156 W/in<sup>3</sup> 2X power density

PMP20873
Specifications
- Universal AC line input
- High voltage DC bus output
- 1 kW output across universal input
- Continuous conduction mode

Features
- LMG3410 GaN FET implemented with LMG3410-HB-EVM
- Controlled with UCD3138
  - Highly integrated digital solution offering superior performance
  - Advanced control algorithm
  - Adaptive dead time control
  - Excellent THD and PF
Adaptive Dead-Time Control for SyncFET to Turn On

\[ Td = \frac{2C_{sw} \times V_o}{I_{L_peak}} \]

Switching node capacitance = top and bottom device \( C_{oss_{tr}} \) + PCB, heatsink, inductor coupling capacitance \( C_{oss_{tr}} \) is equivalent charge-related \( C_{oss} \) when Vds changes between 0V and Vo
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GaN – A Superior Solution for LLC

• Reduced Switching Losses
  • GaN superior switching characteristics significantly reduce gate driver loss and turn-off loss for LLC application

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>1MHz Isolated DC DC Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage (V)</td>
<td>380 ~ 400</td>
</tr>
<tr>
<td>Output voltage (V)</td>
<td>48V Nom unregulated</td>
</tr>
<tr>
<td>Power (W)</td>
<td>1000</td>
</tr>
<tr>
<td>Size (in)</td>
<td>2 x 2.1 x 1.7</td>
</tr>
<tr>
<td>Power density (W/in³)</td>
<td>140 1.5X power density</td>
</tr>
<tr>
<td>Peak Efficiency</td>
<td>&gt;97.5% High Efficiency</td>
</tr>
<tr>
<td>Switching freq</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>
Compared with 100kHz LLC design, the integrated transformer is 6X smaller.
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
Primary Deadtime for ZVS is small with GaN 3rd quadrant conduction time is minimized by digital controller

SR FET Body diode conduction time is minimized by UCD7138 with UCD3138A
Thank you for your attention!

References for more information:

1) Texas Instruments, Gallium Nitride (GaN) Solutions, [www.ti.com/gan](http://www.ti.com/gan)
4) Texas Instruments, Using the LMG3410-HB-EVM Half-Bridge and LMG34XXBB-EVM Breakout Board EVM, User Guide (SNOU140A)
5) Texas Instruments, Optimizing GaN Performance with an Integrated Driver, White Paper (SLYY085)
6) Texas Instruments, GaN FET Module Performance Advantage over Silicon, White Paper (SLYY071)
7) Texas Instruments, 99% Efficient 1kW GaN-based CCM Totem-pole Power Factor Correction (PFC) Converter Reference Design, TI design (PMP20873)
8) Texas Instruments, High Efficiency and High Power Density 1kW Resonant Converter Reference Design with TI HV GaN FET, TI design (PMP20637)