A Robust Gate Driver Solution for High Power Density EV On-Board Chargers using Silicon Carbide (SiC) MOSFETs

Gangyao Wang, System Engineer, APP-HVP-HPD
Detailed Agenda

- SiC Material Properties + Characteristics of SiC MOSFET compared with Si power devices

- SiC Applications Landscape;

- SiC MOSFET based 6.6kW Totem-pole PFC for EV on-board charger (TIDA-01604);

- How to drive SiC MOSFET

- SiC MOSFET gate driver design with UCC21521C (TIDA-01605)
SiC Material Properties + Power System Benefits

### Intrinsic Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
<th>Si</th>
<th>GaN</th>
<th>SiC – 4H</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_G ) (eV)</td>
<td>Bandgap Energy</td>
<td>1.12</td>
<td>3.4</td>
<td>3.26</td>
</tr>
<tr>
<td>( E_{BR} ) (MV/cm)</td>
<td>Critical Field Breakdown Voltage</td>
<td>0.3</td>
<td>3.3</td>
<td>3.0</td>
</tr>
<tr>
<td>( v_s ) (x10^7 cm/s)</td>
<td>Saturation Velocity</td>
<td>1.0</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>( \mu ) (cm²/V.s)</td>
<td>Electron Mobility</td>
<td>1400</td>
<td>990-2000</td>
<td>900</td>
</tr>
<tr>
<td>( \lambda ) (W/cm.K)</td>
<td>Thermal Conductivity</td>
<td>1.3</td>
<td>1.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

### Properties leading to System Benefits

- **Impact on Operation**
  - High-Voltage operation
  - Lower Switching Losses

- **Impact on Power Stage**
  - Higher Switching Frequency + Smaller Filters & Passives
  - Fewer Cooling Needs

- **Impact on End Equipment**
  - System...
    - (1) Size,
    - (2) Cost,
    - (3) Weight Reduction

TI Information – Selective Disclosure
Ideal specific on-resistance of drift regions in 4H-SiC and Silicon

\[ R_{on, sp} = \frac{4(BV)^2}{\varepsilon_s \mu_n (E_{br})^3} \]

Structure of MOSFET

Ideal specific on-resistance

~2000X
What’s the limitation for Si IGBT compared with SiC MOSFET?

- A) 0.5 - 1.0V knee voltage
- B) No “body diode”
- C) No 3\textsuperscript{rd} quadrant operation mode
- D) High switching loss
- E) Much higher switching loss at elevated temperatures
- F) High reverse recovery loss for the paralleled Si diode
TIDA-01604
6.6kW Totem-Pole PFC with SiC MOSFETs for 400V-800V EV On-Board Charger

Design Features
- 6.6kW Totem-pole PFC using SiC MOSFETs
- System Specifications:
  - Input: 85-264 Vac, 50/60Hz
  - Output: 400V-600V DC
  - Power: 6.6KW at 240Vrms
  - Efficiency: > 96.20% peak efficiency
  - PWM frequency: 100kHz
- Uses UCC21520-Q1 gate driver & C2000 MCU controller
- Low total harmonic distortion (THD) ~ 2-3%
- Soft start + Short circuit protection with 2-level turn off
- High Common Mode Transient Immunity (CMTI) of >100 V/ns
- Phase shedding to enable higher efficiency
- Variable output voltage for optimizing DC/DC stage efficiency

Tools & Resources
- TIDA-01605 Tools Folder
- Test Data/Design Guide
- Design Files: Schematics, BOM and BOM Analysis, Design Files
- Key TI Devices: UCC21520-Q1, SN6501-Q1, TMS320F28004x, ISO7721-Q1, UCC28700-Q1

Design Benefits
- High power, high efficiency PFC design with liquid cooling for powering the systems up to 6.6kW
- SiC MOSFETs with TI Drivers offering higher integration for the customers
- Full digital control with high performance C2000 controller enabling advanced control scheme
- High power factor and low total harmonic distortion (THD)
- 3Phase Interleaved operation with phase shedding control.

Size: 235mm X 85mm X 85mm

6.6kW EV OBC Benchmarking
<table>
<thead>
<tr>
<th>Company</th>
<th>Product 1</th>
<th>Product 2</th>
<th>TI Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch</td>
<td>Si</td>
<td>GaN</td>
<td>SiC</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95%</td>
<td>95%</td>
<td>96.20%</td>
</tr>
<tr>
<td>Power Density</td>
<td>0.88 kW/L</td>
<td>1.19 kW/L</td>
<td>1.66 kW/L</td>
</tr>
</tbody>
</table>
Single Phase OBC PFC topology evolution

- Traditional Boost PFC
- Dual Boost Bridgeless PFC
- Totem-Pole Bridgeless PFC
- Semi-Boost Bridgeless PFC
Totem-Pole Bridgeless PFC

Use SiC or GaN devices!

SJ-MOSFET Reverse Recovery at Vdd=150V, Idd=10A

Ti Information – Selective Disclosure
Bidirectional Totem-Pole Bridgeless PFC

- Bidirectional power flow capability
- Further reduce conduction loss
Interleaved Bidirectional Totem-Pole Bridgeless PFC

- Three phases interleaved design with 120° phase shift to reduce input current ripple
Interleaved Bidirectional Totem-Pole Bridgeless PFC

![Graphs showing inductor and total input currents](image)

- Inductor Current (A) for IL1, IL2, IL3
- Total Input Current (A) for In

4A
Bidirectional Totem-Pole Bridgeless PFC without interleaving
6.6kW Totem-Pole PFC Architecture

3-Phase Interleaved Totem-Pole Architecture

System Specifications

<table>
<thead>
<tr>
<th>SYSTEM PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>85-264 Vac, 50/60Hz</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>400V-600V DC</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>6.6kW at 240Vrms</td>
</tr>
<tr>
<td>Efficiency Target</td>
<td>&gt;98.5% (peak)</td>
</tr>
<tr>
<td>PWM Frequency</td>
<td>100kHz</td>
</tr>
<tr>
<td>THD</td>
<td>&lt;3%</td>
</tr>
</tbody>
</table>
6.6kW Totem-Pole PFC Hardware

Total Size: 235mm x 85mm x 85mm
6.6kW Totem-Pole PFC Measurements

Measured Waveforms

Vin=240Vac, Pout=6.6kW, Fsw=100 kHz

Vout: 100V/div
Vac: 200V/div
Iac: 50A/div

Measured Efficiency (vs) Load

98.67% Peak Efficiency at Half Load (3.3kW)
How to driver SiC MOSFET?

Driver Board

SiC MOSFET
# SiC Driver: Key Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>High output drive voltage: 25V-35V</td>
<td>Higher Efficiency: Lower conduction loss</td>
</tr>
<tr>
<td>• Tight voltage control</td>
<td>Gate-oxide protection</td>
</tr>
<tr>
<td>• Margin to accommodate noise</td>
<td>Gate-oxide protection</td>
</tr>
<tr>
<td>• Negative supply voltage</td>
<td>Fast turn-off &amp; Miller turn-ON immunity</td>
</tr>
<tr>
<td>Active miller clamp</td>
<td>Miller turn-ON immunity</td>
</tr>
<tr>
<td>High drive strength</td>
<td>Higher Efficiency: Lower switching loss</td>
</tr>
<tr>
<td>High $dV_{DS}/dt$ immunity (CMTI)</td>
<td>Robustness for higher efficiency</td>
</tr>
</tbody>
</table>

**TI’s Industry-best Capacitive Isolation Technology**

- Industry-leading Integrated Capacitive Isolation
- SiO₂ is the most stable dielectric over temperature & moisture
- Leverage advantages of TI’s customized CMOS process:
  - High precision
  - Tight part-to-part skew
  - No wear out mechanisms
  - Low defect levels
  - Highest lifetime in the industry: >1.5 kV<sub>RMS</sub> for 40 years
  - Superior transient protection for harsh environments: >12.8kV peak

[Link to ti.com/isolation]
## SiC Driver: Key Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High output drive voltage: 25V-35V</strong></td>
<td>Higher Efficiency: Lower conduction loss</td>
</tr>
<tr>
<td>- Tight voltage control</td>
<td>Gate-oxide protection</td>
</tr>
<tr>
<td>- Margin to accommodate noise</td>
<td>Gate-oxide protection</td>
</tr>
<tr>
<td>- Negative supply voltage</td>
<td>Fast turn-off &amp; Miller turn-ON immunity</td>
</tr>
<tr>
<td><strong>Active miller clamp</strong></td>
<td>Miller turn-ON immunity</td>
</tr>
<tr>
<td><strong>High drive strength</strong></td>
<td>Higher Efficiency: Lower switching loss</td>
</tr>
<tr>
<td><strong>High (dV_{BS}/dt) immunity (CMTI)</strong></td>
<td>Robustness for higher efficiency</td>
</tr>
<tr>
<td><strong>Fast short-circuit protection</strong></td>
<td>Lower short-circuit capability</td>
</tr>
<tr>
<td><strong>Small propagation delay &amp; variation</strong></td>
<td>Higher Efficiency + Faster System Control</td>
</tr>
<tr>
<td><strong>Switch Temperature Sensing</strong></td>
<td>Advanced switch protection</td>
</tr>
</tbody>
</table>

### SiC: Need for Fast Short-Circuit Protection

- For same ON resistance, IGBT die is larger than SiC MOSFET die
  - SiC MOSFET die has lower thermal dissipation capability than IGBT

- For same rated current & voltage, IGBT reaches active region for significantly lower \(V_{CE}\) as compared to SiC MOSFET
  - IGBT self-limits the current increase
  - In the case of SiC, \(I_C\) continues to increase with increase in \(V_{DS}\), eventually resulting in faster breakdown

[NOTE: Drawings not to scale.]

---

TI Information – Selective Disclosure
TIDA-01605
Automotive Dual-Channel Isolated SiC Gate Driver with Short-Circuit Protection

Design Features
• 6-A peak sink and 4-A source output drive current
• Up to 25V output drive voltage suitable for SiC MOSFETs with operating PWM frequency up to 5MHz
• 18ns prop delay (typ), < 5ns delay matching, <5ns Max PWM Distortion
• 5.7kVrms reinforced isolation capability
• Up to 12.8kV isolation surge Immunity
• Short circuit protection with two-level turn off circuit
• High Common Mode Transient Immunity (CMTI) of >100V/ns (Min)
• Built-in compact push-pull architecture-based isolated bias supplies
• Adjustable negative gate voltage for SiC MOSET turn-off
• Short circuit fault and reset diagnostic function
• Programmable dead-time control & Enable feature

Design Benefits
• Compact/small form factor dual channel gate drive solution (40mm × 40mm)
• Discrete short circuit protection with easily adjustable current limit and delay(blanking) time
• Flexible in optimizing mid-level turn off voltage and delay time
• Easy interface with both digital and analog controllers

Tools & Resources
• TIDA-01605 Tools Folder
• Test Data/Design Guide
• Design Files: Schematics, BOM and BOM Analysis, Design Files
• Key TI Devices: UCC21520-Q1, SN6501-Q1, ISO7721-Q1, TPS7B6950-Q1
SiC Driver Board Short-Circuit Protection

Half-Bridge Isolated Driver Board using UCC21520/1C Driver

- Discrete short-circuit protection with easily adjustable current limit & blanking time
- Flexible in optimizing mid-level turn off voltage and delay time
- Easy interface with both digital and analog controllers

Fast Short Circuit Protection 2-Level Turn OFF Implementation
(Turn ON into short)

Time Scale: 500ns/div

0µs 0.6µs 1.6µs

Gate Control Input (3V/div)
VGS (10V/div)
VDS (100V/div)
ID (100A/div)

60V 102V

Texas Instruments

TI Information – Selective Disclosure
TIDA-01605 2-Level turn off implementation

1: De-sat;
2: Mid-level voltage generator;
3: Disable through input pin;
TIDA-01605 driver voltages
TIDA-01605 driver voltages: 12V UVLO for SiC MOSFETs

UVLO is referenced to Vss

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Recommended Vgs (V)</th>
<th>VDD-VSS (V)</th>
<th>UVLO for Vgs High (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C250080120D</td>
<td>+20 / -5</td>
<td>25</td>
<td>7 (12V-5V)</td>
</tr>
<tr>
<td>C3M0065090D</td>
<td>+15 / -4</td>
<td>19</td>
<td>8 (12V-4V)</td>
</tr>
<tr>
<td>SCT50N120</td>
<td>+20 / -5</td>
<td>25</td>
<td>7 (12V-5V)</td>
</tr>
<tr>
<td>FF23MR12W1M1</td>
<td>+15 / -5</td>
<td>20</td>
<td>7 (12V-5V)</td>
</tr>
</tbody>
</table>
UCC21521C: 2-Channel, Reinforced Isolation (5.7kVrms)

Features

- +4A peak source & -6A peak sink output drive currents
- 19ns Prop Delay (typ)
- <5ns Delay Matching
- 5ns Max PWM Distortion
- 5.7kVrms Isolation Capability Input-to-Output
- >12.8kV Surge Immunity
- Programmable Overlap and Dead-time Control
- CMIT: 100V/ns (min)
- 3V to 18V Input Supply Voltage
- 6.5V to 25V Output Drive Supply Voltage
- 12V UVLO
- TTL Compatible, Independent Inputs for Each Channel
- Operating range from -40 to 125°C
- Wide Body SOIC-16 (DW) Package
- Drop-in replacement for Si823X and ADuM4223

Benefits

- Drop-in replacement with better performance
- Higher drive could eliminate buffer stages and meet the requirements of a wide range of applications
- UL 1577 recognized; VDE certified
- Flexible settings to prevent shoot-through in ½ bridge applications
- Provides high noise immunity for fast/high current designs
Summary

- SiC MOSFET has superior performance than Si devices for both conduction and switching;

- SiC MOSFETs are used for EV/HEV on-board/off-board chargers as well as solar applications;

- SiC MOSFET based 6.6kW on-board charger totem-pole PFC has specifically been discussed;

- SiC MOSFET driver has special requirements;

- UCC21521C with 12V UVLO is the right driver for high frequency switched SiC MOSFET.
Thank you