How to protect SiC MOSFETs… the best way!

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What will I get out of this session?

- What are SiC MOSFET advantages compared with Si MOSFET and IGBT
- Different short circuit current sensing and protection methods
- How to safely turn off MOSFET under short circuit

- Relevant part numbers:
  - UCC2152x
  - ISO585X

- Relevant reference designs:
  - TIDA-01604&5
  - ISO5852SDWEVM-017
  - TIDA-00917

- Relevant applications:
  - Solar Inverter, HEV/EV Traction Inverter, EV On-Board Charger, Charging Pile
SiC MOSFET Application Positioning

- **EV charger:** 3.3kW - 22kW
- **Traction inverter:** 15kW - 400kW
- **PV Booster and Inverter:** 5kW - MW
SiC MOSFET Advantages over Si MOSFET

1) Lower specific $R_{ds(on)}$ especially for >650V devices; 2) Low body diode reverse recovery.

Use SiC, GaN devices or Si IGBT!

SJ-MOSFET Reverse Recovery at $V_{dd}=150V$, $I_{dd}=10A$
SiC MOSFET Advantages over Si IGBT: Conduction

1) No 0.5-1.0V knee voltage; 2) Has “body diode”; 3) 3rd quadrant operation mode.
SiC MOSFET Advantages over Si IGBT: Switching

- **Low switching loss:**
  MOSFET (unipolar) vs IGBT (bipolar)- fundamental difference;

- **Switch loss less increase at elevated temperatures:**
  For 1000V SiC MOSFET, Esw@25°C = Esw@150°C

- **Low reverse recovery for the body diode:**
  Silicon PiN diode has significant reverse recovery which has reverse recovery loss and also adds more turn on loss.

Typical switching waveforms
Overcurrent/Short Circuit Fault

Short circuit happens at t1:
Overcurrent/Short Circuit Fault Mechanism: Thermal limitation

- The short circuit withstand time $t_{sc}$ is determined by the critical energy
  - minimal dissipated energy leading to device failure for one short circuit pulse
    \[ E_c = \int_{t_i}^{t_f} V_{ds} \cdot I_d \cdot dt \]
  - $V_{ds}$ is the DC link voltage, $I_d$ will be the device saturation current.

- SiC MOSFET short circuit withstand time is shorter than IGBT due to smaller chip size, less thermal capacity.
Overcurrent/Short Circuit Fault Mechanism: Thermal limitation

- **IGBT self-limits the current increase with lower saturation current**
  - shape transient from saturation region to active region, collector current is limited to a constant value in active region
- **SiC MOSFET has large linear region with high saturation current**
  - In the case of SiC, \( I_d \) continues to increase with increase in \( V_{ds} \), eventually resulting in faster breakdown
- **For same rated current & voltage, IGBT reaches active region for significantly lower \( V_{CE} \) as compared to SiC MOSFET**
Question: From thermal limitation point of view, what is the typical SiC MOSFET short circuit withstand time (for example 1200V MOSFET in TO247 package used for 800V dc bus)?

- A) <1us
- B) 1-3us
- C) 3-10us
- D) >10us

Answer: B) 1-3us (under typical Vds and recommended Vgs conditions)
Overcurrent/Short Circuit Protection Method: DESAT

- Desaturation circuit detects the $V_{ds}$ of MOSFET or $V_{ce}$ of IGBT, protection is triggered when detected voltage is above pre-set reference voltage.

- Blanking time is needed to prevent false trigger during switching turn on transients

$$t_{DS\_BLK} = \frac{V_{DESAT} \times C_{BLK}}{I_{CHG}}$$

- Real detection voltage on the device terminals is lower than pre-set reference voltage

$$V_{DS\_DET} = V_{desat} - V_{D_{IV}} - I_{desat} \times R_{desat}$$

- DESAT threshold voltage varies between different devices due to the output characteristics, especially IGBT and SiC MOSFET.
Overcurrent/Short Circuit Protection Method: DESAT

- **Advantages**
  - Simple circuits
  - Low loss
  - Programmable protection time

- **Challenges of DESAT protection method**
  - High voltage fast reverse recovery diodes add cost
  - Multiple high voltage diodes are needed to share blocking voltage for above 1200V applications
  - Blanking time makes the protection time too long for SiC MOSFET
  - Parallel diode $D_{\text{desat}}$ is needed to prevent the negative voltage on DESAT pin
  - Indirect current sensing can be challenging for SiC MOSFET
Overcurrent/Short Circuit Protection Method: Shunt Resistor

- **Advantages**
  - Accurate for both AC and DC
  - Fast protection speed
  - Low cost
- **Challenges of shunt resistor**
  - High power loss in high power applications
  - Weak noise immunity due to gate loop noise caused by parasitic inductance of shunt resistor and PCB trace
Overcurrent/Short Circuit Protection Method: SenseFET / Current Mirror

- SenseFET / Current mirror is used to scale down main current, tens of mV voltage is measured on sense resistor
- Accuracy is determined by current scaling circuit and sensing resistor
- More commonly used in automotive applications
Overcurrent/Short Circuit Protection Method: **SenseFET / Current Mirror**

- **Advantages**
  - Fastest protection speed
  - Accurate for both AC and DC

- **Challenges of SenseFET / Current mirror**
  - Module needs to be customized to integrate SenseFET / Current mirror
  - Higher cost
### Overcurrent/Short Circuit Protection Method: Comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>DESAT</th>
<th>Shunt Resistor</th>
<th>SenseFET / Current Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Good for IGBT; Medium for SiC MOSFET</td>
<td>High, depends on shunt quality 3% without calibration, 1% with calibration</td>
<td>Medium, depends on scaling accuracy and external resistor selection</td>
</tr>
<tr>
<td>Losses</td>
<td>Negligible</td>
<td>High and depends on Rs value</td>
<td>Low</td>
</tr>
<tr>
<td>Cost</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

- Shunt Resistor method is not desired for high power applications due to high loss;
- SenseFET/Current Mirror works best for SiC MOSFET for its low noise and fast speed, but senseFET is not always available;
- Desat method works good for IGBT, but may have limitations for SiC MOSFET, especially for the drivers designed for IGBT.
Overcurrent/Short Circuit Safe Turn-off: Avalanche limitation

- **Voltage and avalanche limit:** Device avalanche can be caused by the overshoot voltage on $V_{ds}$. 

\[
\Delta V_{ds} = \Delta V_{g} + \Delta V_{d}
\]
SiC MOSFET Protection: **Soft Turn-Off (STO) & 2L Turn-Off**

- There are parasitic inductances in the power loop.
- Parasitic inductances together with \( di/dt \) cause voltage spikes.
- The \( di/dt \) rate is much higher under short circuit fault that a preventive turn-off measure needs to be taken in order to limit the loop inductance induced voltage spike.
- Effectively, there are two ways to slow down the turn-off process: *reduce di* or *extend dt*.
Short-Circuit Protection: **Hardware Validation**

**Evaluation Hardware**

**Schematic for Double-Pulse Test Setup**

- **High-side Isolated Driver (Upto ±15A)**
  - ISO5852S Based Driver Module

- **Low-side Isolated Driver (Upto ±15A)**
  - ISO5852S Based Driver Module

- DC Bus Caps
- Isolated Power Supplies

**IGBT Half-bridge Module**

- Isolated Half-bridge Drive Stage using ISO5852S-Q1 ± 15A Buffer Driver
- IGBT Half-bridge Module (FF450R12KT4)
Short Circuit Protection for SiC MOSFETs: with or without Soft turn-off

- Hard Turn-off
- Soft Turn-off for Hard SC
- Soft Turn-off for SC under Load
Summary and key takeaways

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

- There are mainly three methods for the fault current sensing and then protection, sense FET is good for SiC MOSFETs but cost is high;

- De-sat method used for Si IGBT needs to be re-designed for SiC MOSFETs;

- Soft/two level turn off is also desired for turning off SiC MOSFET under short circuit.