SiC MOSFET Performance in a Bidirectional DC-DC converter
• **Why 650V SiC MOSFET?**
  ✓ Compactness even in Single-Switch topologies: exceptional and flat \( R_{DS(on)} \times \text{Area} \)
  ✓ Ideal Reverse Recovery body diode benefits

• **Isolated Bidirectional DC-DC converter**
  ✓ Field of Application and Preferred Topologies

• **650V ST SiC MOSFETs in Isolated Bidirectional DC-DC converter for HEVs**
Why 650V SiC MOSFET?
ST 650V 2\textsuperscript{nd} GEN SiC MOSFET

$R_{DS(on)} \times \text{chip Area (FOM)}$ vs. Temperature

- ST is the only supplier to guarantee max Tj as high as 200°C in a plastic package (HiP247\textsuperscript{TM})
- ST SiC 2\textsuperscript{nd} Gen (planar) show a better Ron*A FOM at very high temperature
650V SiC vs. Silicon MOSFET

Conduction losses

<table>
<thead>
<tr>
<th>DUT</th>
<th>BV [V]</th>
<th>Ron @25°C [mΩ]</th>
<th>Ron @100°C [mΩ]</th>
<th>Normalized Die size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 650V SiC MOS (SCTW35N65G2V)</td>
<td>650</td>
<td>54</td>
<td>54</td>
<td>1</td>
</tr>
<tr>
<td>STW57N65M5</td>
<td>650</td>
<td>52.4</td>
<td>91</td>
<td>4.1</td>
</tr>
<tr>
<td>STW69N65M5</td>
<td>650</td>
<td>33</td>
<td>58</td>
<td>5.8</td>
</tr>
<tr>
<td>STW75N60M6</td>
<td>600</td>
<td>31</td>
<td>53</td>
<td>8.3</td>
</tr>
</tbody>
</table>

To notice:
The $R_{DS(on)}$ values are measured at:
a) 10V for the Si MOSFET
b) 20V for SiC MOSFET
650V SiC vs. Silicon MOSFET
Cutting switching losses

ST 650V SiC MOSFET

E_{off} = 16\mu J

STW75N60M6

E_{off} = 29.8\mu J

Turn-off halved!!

<table>
<thead>
<tr>
<th>T_{C} (°C)</th>
<th>E_{ON} (\mu J)</th>
<th>E_{OFF} (\mu J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>150</td>
<td>190</td>
</tr>
<tr>
<td>150</td>
<td>140</td>
<td>195</td>
</tr>
</tbody>
</table>

Ron*Area ~ 4 m\Omega \ cm^2 @ 650V

Switching losses flat vs. Tj

*V_{DD}=400V, I_{D}=50A, V_{GS}=-5V/20V, R_{G}= 2.2\Omega
650V SiC vs. Silicon MOSFET

Application results: 2kW DC-DC BOOST converter

Efficiency@ Full Load

![Graph showing efficiency comparison between Si and SiC MOSFETs at 100 kHz and 200 kHz]

- $\Delta \eta = 0.44\%$ for Si vs. SiC at 100 kHz
- $\Delta \eta = 1.2\%$ for Si vs. SiC at 200 kHz
650V SiC vs. Silicon MOSFET

Application results: 2kW DC-DC BOOST converter

\[
\Delta T = 25°C \\
\Delta T = 60°C
\]
Ideal reverse recovery diode benefits

Example: Totem-pole Bridgeless PFC

Main Benefits

- increasing the efficiency
- Only 4 devices are used
- Decreasing common-mode noise

Large reverse recovery charge ($Q_{\text{rr}}$) of existing silicon MOSFET makes the CCM operation of the totem-pole bridgeless PFC impractical. Since this topology requires a fast switching device with ultra-fast free-wheeling diode, SiC MOSFET is the best candidate.
Isolated Bidirectional DC-DC converter
IBDCs (Isolated Bidirectional DC-DC converters)

- Most DC-to-DC converters are designed to move power in only one direction. However, all switching regulator topologies can be made able to move power in either direction by replacing all diodes with active switches;

- A bidirectional converter is useful, for example, in applications requiring regenerative braking of vehicles, where power is supplied from the wheels while driving;

- Bidirectional DC-DC converters (IBDCs) with galvanic isolation have been proposed as the interface between high-voltage busses with distributed energy resources and low-voltage busses with energy storage devices in microgrids;

- In HEVs There are needs of galvanically isolated bidirectional DC-DC converter to link different DC voltage bus and transfer energy back and forth. For example one isolated DC-DC converters convert the high voltage in the main battery to low voltage (~12V) for use in electrical equipment.
Topologies for IBCDs

- **Push Pull**
  - 2 switches driven alternately with a dead time
  - Easy gate driving
  - Each switch must withstands $2 \times V_{in}$
  - Output stage can also be a Full-Bridge Rectifier

$$\frac{V_{out}}{V_{in}} = 2 \cdot \frac{N_s}{N_p} \cdot \delta \text{ with } \delta < 0.5$$
Topologies for IBCDs

- **Full-Bridge**

\[
\frac{V_{out}}{V_{in}} = 2 \cdot \frac{N_S}{N_p} \cdot \delta \quad \text{with} \quad \delta < 0.5
\]
Topologies for IBCDs: Rectification Stage

**LLC output stage – Center tap rectifier**

- **Synchronous Rectification** doesn’t need an isolated gate driver
- Twice copper losses and Half of total diode conduction losses compared to Full-Bridge rectifier
- 2 diodes (or MOSFETs) in output stage with twice of voltage rating compared to Full-Bridge rectifier
- Same diode average current of Full-Bridge rectifier

- **LLC output stage – Full Bridge rectifier**
- **Synchronous Rectification** needs an isolated gate driver
- Transformer with one secondary winding (half copper losses) and Twice total diode (or MOSFETs) conduction losses compared to center tap rectifier
- 4 diodes (or MOSFETs) in output stage with half of voltage rating compared to center tap rectifier
650V ST SiC MOSFETs in Isolated Bidirectional DC-DC converter for HEVs
DC-DC converter for HEV

Key features

- Vin = 200-400 Vdc
- Vout = 12.5 Vdc Nominal (Max 16 Vdc)
- Iout = 140A
- Control strategies (Phase Shift Modulation + Synchronous rectification and active clamp)
- Switching frequency = 70kHz

Order code: STEVAL-ISA157V1
Implementation of Bidirectional DC-DC converter for HEV

**FULL BRIDGE with Phase Shift modulation**

**CENTER TAP RECTIFIER with active clamp**

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HV battery pack

Gate Driver

M1 → M3

M2 → M4

T1

L

C1o

C2o

M1c

M2c

M3c

M4c

M5c

M6c

Gate Driver

Opto

Microcontroller

Galvanic Isolation

Aux LV battery 12V

Service Battery Charge

High Voltage Battery Charge
Power stage control strategies

- **Auxiliary battery (16V) charge:**
  - Phase shift modulation (PSM) for HV H-bridge
  - No needing to bypass the resonant capacitor of the LLC when the current flow is inverted (No relay)
  - Synchronous rectification for LV Rectifier
  - Active clamp to protect LV switches (if needed)

- **High voltage battery (up to 480V) charge:**
  - Pulse width modulation (PWM) for LV Isolal
  - Active clamp to protect LV switches (if needed)
Ideal reverse recovery diode benefits
HV-LV bidirectional DC-DC converter for EV

The HV-LV bidirectional DC-DC converter behaves like an isolated BOOST converter with full-wave rectifier in HV battery charging mode. SiC MOSFET and Si counterpart are used in the full-bridge portion (Q1, Q2, Q5 and Q6). In boost mode the MOSFETs of the high voltage side are not driven with a PWM signal and the intrinsic diodes simply perform a voltage rectification at 70kHz.

Q1, Q2, Q5 and Q6 position of devices under test.
The two PWM signals, shifted by 180°, always have a duty cycle above 50%. This is because an overlapping period where the two switches are simultaneously ON is necessary to magnetize the BOOST inductor.

**Ideal reverse recovery diode benefits**

HV-LV bidirectional DC-DC converter for EV

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**Static Characteristics of MOSFETs under test**

<table>
<thead>
<tr>
<th>DUT</th>
<th>Vth[V] @ 1mA</th>
<th>R&lt;sub&gt;DS(on)&lt;/sub&gt; [mΩ] @ 17A</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST 600V Si MOS STW48N60DM2</td>
<td>4.29</td>
<td>64.7</td>
</tr>
<tr>
<td><strong>ST 650V SiC MOS SCTW35N65G2V</strong></td>
<td>3.68</td>
<td>78.4</td>
</tr>
</tbody>
</table>

* Early prototypes with higher R<sub>DS(on)</sub>, final product shows 55mΩ typically
Ideal reverse recovery diode benefits
HV-LV bidirectional DC-DC converter for EV

1kW electrical waveforms

**Intrinsic diode conduction losses** can be calculated using an approximation with a series connection of DC voltage source representing on-state zero-current anode-cathode voltage ($u_D$) and a anode-cathode on-state resistance ($r_D$):

$$P_D = u_D I_{av} + r_D I_{RMS}^2$$

<table>
<thead>
<tr>
<th></th>
<th>SiC MOSFET</th>
<th>Si MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_D$</td>
<td>1.85</td>
<td>0.7</td>
</tr>
<tr>
<td>$r_D$</td>
<td>0.103</td>
<td>0.053</td>
</tr>
</tbody>
</table>
Ideal reverse recovery diode benefits
HV-LV bidirectional DC-DC converter for EV

Si MOSFET: detail of reverse recovery diode at 1kW

SiC MOSFET: Detail of reverse recovery diode at 1kW

SiC MOSFET has much lower $Q_{rr}$ than Si counterpart $\rightarrow$ much lower switching losses.

@ $V_r=60V$, $I_{SD}=34A$, $di/dt=100A/\mu s$, double pulse test

<table>
<thead>
<tr>
<th>Device</th>
<th>$I_{rr}$ (A)</th>
<th>$T_{RR}$ (ns)</th>
<th>$Q_{RR}$ (nC)</th>
<th>$T_c$ (°C)</th>
<th>$I_{rr}$ (A)</th>
<th>$T_{RR}$ (ns)</th>
<th>$Q_{RR}$ (nC)</th>
<th>$T_c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STW48N60DM2</td>
<td>9</td>
<td>127</td>
<td>718</td>
<td>25</td>
<td>21</td>
<td>251</td>
<td>2715</td>
<td>150</td>
</tr>
<tr>
<td>SCTW35N65G2V</td>
<td>3.4</td>
<td>40</td>
<td>85</td>
<td>25</td>
<td>5.1</td>
<td>52</td>
<td>155</td>
<td>150</td>
</tr>
</tbody>
</table>
### Ideal reverse recovery diode benefits

**HV-LV bidirectional DC-DC converter for EV**

<table>
<thead>
<tr>
<th>Load [W]</th>
<th>Pcond</th>
<th>Psw</th>
<th>Ptot</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si MOSFET</td>
<td>SiC MOSFET</td>
<td>Si MOSFET</td>
<td>SiC MOSFET</td>
</tr>
<tr>
<td>150</td>
<td>0.26W</td>
<td>0.67W</td>
<td>2.6W</td>
<td>0.42W</td>
</tr>
<tr>
<td>230</td>
<td>0.34W</td>
<td>0.87W</td>
<td>2.75W</td>
<td>0.46W</td>
</tr>
<tr>
<td>400</td>
<td>0.63W</td>
<td>1.57W</td>
<td>3.08W</td>
<td>0.46W</td>
</tr>
<tr>
<td>600</td>
<td>1.06W</td>
<td>2.6W</td>
<td>3.43W</td>
<td>0.48W</td>
</tr>
<tr>
<td>1000</td>
<td>2.17W</td>
<td>5.2W</td>
<td>3.84W</td>
<td>0.58W</td>
</tr>
</tbody>
</table>

SiC MOSFET has the highest conduction losses, however its outstanding diode performance makes it the best choice, especially at low load.

Looking at the results when the load is higher than 1kW, the conduction losses dominate over switching ones, consequently in **this case the synchronous rectification is mandatory.**
**Ideal reverse recovery diode benefits**

**HV-LV bidirectional DC-DC converter for EV**

With HV Synchronous Rectification

<table>
<thead>
<tr>
<th>Load [W]</th>
<th>Si MOSFET</th>
<th>SiC MOSFET</th>
<th>Si MOSFET</th>
<th>SiC MOSFET</th>
<th>Si MOSFET</th>
<th>SiC MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conduction</td>
<td>PSW</td>
<td>Ptot</td>
<td>Conduction</td>
<td>PSW</td>
<td>Ptot</td>
</tr>
<tr>
<td>150</td>
<td>0.26W</td>
<td>2.6W</td>
<td>2.86W</td>
<td>0.21W</td>
<td>0.42W</td>
<td>0.63W</td>
</tr>
<tr>
<td>230</td>
<td>0.34W</td>
<td>2.75W</td>
<td>3.09</td>
<td>0.25W</td>
<td>0.46W</td>
<td>0.71W</td>
</tr>
<tr>
<td>400</td>
<td>0.63W</td>
<td>3.08W</td>
<td>3.714W</td>
<td>0.43W</td>
<td>0.46W</td>
<td>0.89W</td>
</tr>
<tr>
<td>600</td>
<td>1.06W</td>
<td>3.43W</td>
<td>4.49W</td>
<td>0.71W</td>
<td>0.48W</td>
<td>1.19W</td>
</tr>
<tr>
<td>1000</td>
<td>2.17W</td>
<td>3.84W</td>
<td>6W</td>
<td>1.26W</td>
<td>0.58W</td>
<td>1.84W</td>
</tr>
</tbody>
</table>

* Values based on estimation

Conduction and Total SiC MOSFET (SCTW35N65G2V) achievable by using final 55mΩ SCTW35N65G2V prototypes with HV Synchronous Rectification

>3 times lower losses than Silicon up to 1kW
SiC MOSFET offers significant advantages over Silicon one, in particular the main benefit deriving from the use of SiC MOSFET when the bidirectional DC-DC converter works in BOOST mode is the strong reduction of reverse recovery charge leading to lower switching losses.

No modulation on HV side prevent SiC MOSFET from achieving very high efficiency when load increases (above 1kW SiC conduction losses are too high without HV Synchronous Rectification).

In BOOST mode the Synchronous Rectification on HV side is necessary to fully exploit the potential of SiC (3rd quadrant operation) and achieve the highest efficiency even at full load.
Thanks

For additional information, please visit:

www.st.com