Improving Totem-Pole PFC and On Board Charger performance with next generation components

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UnitedSiC history

- **1999**: Company Founded
- **2009**: Built Pilot Production Fab
- **2010**: Established 4” foundry relationship
- **2011**: First foundry-based diodes and JFETs manufactured
- **2012**: Released the xR 1200V & 650V JBS diode series and the 1200V Normally-on JFETs
- **2013**: Initiated 6” Fab Transfer
- **2014**: Acquired and recapitalized by current board and management team
- **2015**: 6” wafer line qualification & production; Diode, Cascode 650V/1200V release
- **2017**: 1200V MOSFET release

UnitedSiC: Simply More Efficient
Replace IGBTs, SiC MOSFETs or Si Superjunction devices with no change to gate drive voltages

- UJC: Gen 1
- UJ3C: Gen 3 standard
- UF3C: Gen 3 fast
650V technologies compared

Silicon Superjunction
vertical current flow

GaN HEMT
lateral current flow

SiC
vertical current flow
### RDSA (active area) comparison: 650V class

<table>
<thead>
<tr>
<th>Technology</th>
<th>SiC Cascode 650V-45mΩ (UJC6505K)</th>
<th>Commercial SiC MOSFET</th>
<th>Commercial GaN HEMT</th>
<th>Commercial Si Superjunction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{DS_A}$</td>
<td>0.75 mΩ-cm²</td>
<td>2-3 mΩ-cm²</td>
<td>3-7 mΩ-cm²</td>
<td>10 mΩ-cm²</td>
</tr>
<tr>
<td>Normalized Die Area</td>
<td>1</td>
<td>2.6X</td>
<td>4X</td>
<td>13X</td>
</tr>
<tr>
<td>$E_{oss}$</td>
<td>7.5 μJ</td>
<td>32 μJ</td>
<td>12 μJ</td>
<td>14 μJ</td>
</tr>
<tr>
<td>Avalanche Capability</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
Comparison with Superjunction

TABLE I. KEY DATASHEET PARAMETERS OF USCI’S 650V CASCADE SWITCH COMPARED TO SUPERJUNCTION MOSFET

<table>
<thead>
<tr>
<th>Device</th>
<th>R&lt;sub&gt;DS&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;G&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;GS&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;GD&lt;/sub&gt;</th>
<th>Q&lt;sub&gt;rr&lt;/sub&gt;</th>
<th>E&lt;sub&gt;oss&lt;/sub&gt;</th>
<th>V&lt;sub&gt;TH&lt;/sub&gt;</th>
<th>TCR</th>
<th>Gate Drive</th>
<th>Die Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC Cascade UJC0650ST</td>
<td>34</td>
<td>58</td>
<td>15</td>
<td>15</td>
<td>0.15</td>
<td>8</td>
<td>5</td>
<td>1.8</td>
<td>0 to 12V</td>
<td>1</td>
</tr>
<tr>
<td>Si Superjunction IPP65R045C7</td>
<td>40</td>
<td>93</td>
<td>23</td>
<td>30</td>
<td>13</td>
<td>11.7</td>
<td>3.5</td>
<td>2.4</td>
<td>0 to 12V</td>
<td>7.3×</td>
</tr>
</tbody>
</table>

Fig. 3. Capacitance curves comparison between SiC Cascade UJC0650ST and superjunction MOSFET IPP65R045C7

Fig. 4. Eoss comparison between SiC Cascade UJC0650ST and superjunction MOSFET IPP65R045C7.

Fig. 5. Diode reverse recovery comparison between SiC Cascade and Super Junction MOSFET
SiC Cascode gate drive benefit

- Easy Drop-in
  12V turn-on makes SiC cascode an easy choice for drop-in replacement

- Extra Margin in VGS
  SiC cascode has higher margin in VGS design and requires no negative VGS for turn-off

Maximum VGS rating vs. recommended VGS
SiC MOSFET can be operated at Vgs=0V in some circuits
Totem pole PFC – UJC06505K

Fig. 1. CCM totem-pole PFC operation in positive half cycle with an active switch in conduction (top) and a freewheeling device in conduction (bottom).

Fig. 2. Soft start-up of totem-pole PFC with positive AC input voltage.

**TABLE I. DESIGN PARAMETERS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>115 V to 230 V (60 Hz AC)</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>400 V (DC)</td>
</tr>
<tr>
<td>Input Current</td>
<td>8.7 A (RMS)</td>
</tr>
<tr>
<td>Rated Power</td>
<td>1 kW at 115 Vac; 1.5 kW at 230 Vac</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>SiC Cascodes (Q1, Q2)</td>
<td>UJC06505K</td>
</tr>
<tr>
<td>Si MOSFETs (Q3, Q4)</td>
<td>IPW65R019C7</td>
</tr>
<tr>
<td>Input Inductor</td>
<td>300 μH at no load</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>560 μF, 500 V</td>
</tr>
</tbody>
</table>
Fig. 4. Average current control scheme for totem-pole PFC

Fig. 10. 230 V AC input voltage (top) and inductor current (bottom) at 1.3 kW load.

Fig. 11. Inductor current (light blue CH2) at zero crossing, from negative to positive (top), from positive to negative (bottom). (CH1: Vg4 potential to DC output ground; CH3: DSP gate signal of Q4; CH4: DSP gate signal of Q5)
Totem pole PFC – UJC06505K

Does not include auxiliary supply losses

Fig. 8. THD at high line and low line input with 100 kHz switching frequency.
650V Cascode vs. Superjunction

Test results of cascode drop-in replacement of super-junction MOSFET in phase shift full bridge

Efficiency versus Output Power

Greatly reduced capacitances = faster switching

Phase shift full bridge (PSFB) circuit with synchronous rectifier (SR) output
Cascode for soft switching

- Intrinsic loss mechanisms being studied for soft switched operation of cascodes for ultra-high frequency
- This manifests itself as the loss from ramping the voltage up and down with zero current.
- SiC Cascodes found to be superior in a comparative assessment
  - Near 0 Cds of JFET eliminates the capacitive divider problem
- Further refinements in technology needed to push >1MHz
- Will use logic level MOSFETs with ultra-low Qg Vth=2V, 5V gate drive and low inductance surface mount packaging. This type of operation is not possible with SiC MOSFET which needs a wider gate voltage swing with larger Qg.
SiC MOSFET landscape

**Standard Planar MOSFET**
- Gate oxide shielding – narrow JFET region
- Worse mobility Si face
- Adds to RdsA

**Rohm Trench MOSFET**

**Infineon Trench MOSFET**
- Trench bottom Gate oxide shielding – deep p regions. Adds to RdsA
- Better a-face/m-face mobility

**USCi Trench JFET**
<table>
<thead>
<tr>
<th>Feature</th>
<th>Normally Off USCi Cascode</th>
<th>Normally Off Typical SiC MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die Size</td>
<td>(Smaller) $R_{D_{\text{SA}}} \sim 1.75\text{mW-cm}^2$</td>
<td>(Larger) $R_{D_{\text{SA}}} \sim 3.1\text{-}4.5\text{ mW-cm}^2$</td>
</tr>
<tr>
<td>Gate Drive</td>
<td>(Standard) $V_{\text{GS}} = 0\text{V to }12\text{V OR}$</td>
<td>$V_{\text{GS}} = -5\text{V to }15/18/20\text{V}$</td>
</tr>
<tr>
<td></td>
<td>(SIC) $V_{\text{GS}} = -10\text{V to }20\text{V}$</td>
<td></td>
</tr>
<tr>
<td>Threshold</td>
<td>$V_{\text{GS(TH)}} = 5\text{V Typical}$</td>
<td>$V_{\text{GS(TH)}} = 2\text{-}3\text{V Typical}$</td>
</tr>
<tr>
<td>Intrinsic Diode</td>
<td>Low Qrr, +10% Over Temperature</td>
<td>High Qrr, High VF 3X Over Temperature</td>
</tr>
<tr>
<td>Avalanche</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>Yes</td>
<td>Low</td>
</tr>
</tbody>
</table>
Inductive switching, 800V, 30A

Turn-on $R_{\text{gon}} = 4.7\, \text{ohm}$

$E_{\text{on}} = 543\, \text{uJ}$

$\text{td}_{\text{on}} = 69\, \text{ns}$

$\text{tr} = 14\, \text{ns}$

Turn-off 800V, 30A $R_{\text{goff}} = 47\, \text{ohm}$

$E_{\text{off}} = 269\, \text{uJ}$

Use Higher $R_{\text{goff}}$ to control turn-off speed

Cascode Internal Schematic
It is important to follow guidelines for Rgoff for both the HS and LS FET in the half-bridge.

Vth is >3V at 175°C

UJC1206K temperature characteristics
Fresh 3φ rectifier designs

- Compact, efficient AFE made possible by low $R_{\text{DS(on)}}$ with 1200 V rating combined with excellent reverse conduction and recovery characteristic
- Low noise, low charge reverse recovery eliminates the need for bypass and blocking diodes as in Vienna rectifier with super-junction MOSFETs
- Extremely high efficiency is possible, especially with three-level topology, due to very low switching loss
- Can use switching algorithm with three-level topology to reduce or eliminate common-mode voltages

**USCi 1200V Cascode:**
- UJC1206K
- UJC1210K
- UJ3C120040K3S
- UJ3C120080K3S
- UJ3C120150K3S

**USCi 650V Cascode:**
- UJ3C065030K3S
- UJ3C065080K3S
- UJC06505K
Charge up with high power

- High power battery charger fed by three-phase grid connection
- Three-phase active front end (AFE) as rectifier yields efficient, compact design
- Phase shift full bridge (PSFB) with 700 to 800 V input, hundreds of Volts output
- Typical application: on or off-board electric vehicle charger

300V - 480V AC two-level active front end (rectifier)

400V - 600V AC three-level active front end (rectifier)
High voltage PSFB

- Previous technologies include IGBT, super-junction MOSFET, and SiC MOSFET
- IGBTs have very high turn-off switching power loss, slow-switching reverse diode
- Super-junction MOSFETs have larger chip size, slow-switching reverse diode
- SiC MOSFET has larger chip size, asymmetric gate drive (-5 to 18 V typically)
- USCi cascode is the best performing PSFB switch

**USCi 1200 V Cascode:**
- UJ3C120080K3S
- UJ3C120040K3S
- UJC1206K
- UJC1210K
United SiC 650V and 1200V SiC based transistors use standard gate drives.

With excellent diode recovery, high Vth at temperature and fast switching, they greatly improve hard and soft switching performance.

Examples in Totem-Pole PFC and On-board chargers (Rectifier and DC-DC) discussed in this presentation.

For more information, contact sales@unitedsic.com.