Ultra-low resistance SiC FETs for high power applications

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VP Engineering
Capitalizing on megatrends in power electronics

**Automotive**
- On Board Chargers
- DC-DC Converters
- Traction Inverters

**Battery Charging**
- Fast DC Charging
- Wireless Charging
- Industrial Chargers

**IT Infrastructure**
- Power Factor Correction
- DC-DC Converters

**Renewables**
- Solar Inverters
- Energy Storage
- Wind

**Circuit Protection**
- AC/DC circuit breakers
- MV circuit breakers
- SS power controllers
UnitedSiC Product Portfolio

- **Schottky Diodes**
- **JFETs**
- **FETs**

### FETs
- **UJ3C**
  - Slower Switching
  - Co-packaged high-performance Gen3 SiC JFETs with cascode-optimized Si MOSFET
  - Only standard gate drive SiC device in the market today
  - 650V and 1200V
  - Low on-resistance RDS(on)
  - Excellent reverse recovery
  - Excellent body diode performance ($V_f < 2V$)
  - Drive with any Si and/or SiC gate drive voltage
  - Superior thermal performance
  - ESD protection
- **UF3C**
  - Faster Switching
  - Adding 4 new UF devices 9m, 16m 1200V 7m, 650V
Flagship devices

**650V-6.7mΩ SiC Cascode**

**Description**

United Silicon Carbide’s cascode products co-package its high-performance F3 SiC fast JFETs with a cascode optimized MOSFET to produce the only standard gate drive SiC device in the market today. This series exhibits very fast switching using a 4-terminal TO-247 package and the best reverse recovery characteristics of any device of similar ratings. These devices are excellent for switching inductive loads, and any application requiring standard gate drive.

**Features**

- Typical on-resistance $R_{DS(on)}$ of 6.7mΩ
- Maximum operating temperature of 175°C
- Excellent reverse recovery
- Low gate charge
- Low intrinsic capacitance
- ESD protected, HBM class 2
- TO-247-4L package for faster switching, clean gate waveforms

**Typical applications**

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**1200V-8.6mΩ SiC Cascode**

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United Silicon Carbide’s cascode products co-package its high-performance F3 SiC fast JFETs with a cascode optimized MOSFET to produce the only standard gate drive SiC device in the market today. This series exhibits very fast switching using a 4-terminal TO-247 package and the best reverse recovery characteristics of any device of similar ratings. These devices are excellent for switching inductive loads, and any application requiring standard gate drive.

**Features**

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- Maximum operating temperature of 175°C
- Excellent reverse recovery
- Low gate charge
- Low intrinsic capacitance
- ESD protected, HBM class 2
- TO-247-4L package for faster switching, clean gate waveforms
UnitedSiC low Rds devices

- Lowest on-resistance devices in TO-packages
- Sub 10mohm 650V and 1200V
- Features the latest stack cascode technology
- Low thermal resistance (Ag sintered)
- Well suited for inverters, high powered DC-DC converters, and circuit protection applications
- Drop in compatible with Si IGBTs, Si MOSFETs and SiC MOSFET gate drive voltages
- Excellent paralleling behavior

*Includes a 5ohm, 680pF snubber loss

<table>
<thead>
<tr>
<th>Device</th>
<th>Package</th>
<th>$V_{DS,(\text{MAX})}$</th>
<th>$I_{D,(100\text{C})}$</th>
<th>$R_{TH,(C\text{MAX})}$</th>
<th>$R_{DS,(\text{ON},(25\text{C})}$</th>
<th>$R_{DS,(\text{ON},(125\text{C})}$</th>
<th>$R_{DS,(\text{ON},(175\text{C})}$</th>
<th>$C_{DS,(\text{ER})}$</th>
<th>$E_{\text{ON}}$</th>
<th>$E_{\text{OFF}}$</th>
<th>Switching Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF3S C120009K4S</td>
<td>TO247-4L</td>
<td>1200</td>
<td>120</td>
<td>0.19</td>
<td>8.6</td>
<td>13.3</td>
<td>18.2</td>
<td>395</td>
<td>3.5</td>
<td>0.7</td>
<td>100A, 800V HB 150C</td>
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<tr>
<td>UF3S C120016K4S</td>
<td>TO247-4L</td>
<td>1200</td>
<td>77</td>
<td>0.29</td>
<td>16</td>
<td>24.8</td>
<td>33</td>
<td>243</td>
<td>2.82</td>
<td>0.15</td>
<td>80A, 800V HB 150C</td>
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<td>TO247-3L</td>
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<td>77</td>
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<td>16</td>
<td>24.8</td>
<td>33</td>
<td>243</td>
<td>3.35</td>
<td>0.67</td>
<td>80A, 800V* HB 150C</td>
</tr>
<tr>
<td>UF3S C065007K4S</td>
<td>TO247-4L</td>
<td>650</td>
<td>120</td>
<td>0.19</td>
<td>6.7</td>
<td>8.7</td>
<td>11</td>
<td>856</td>
<td>1.08</td>
<td>0.1</td>
<td>80A, 400V HB 150C</td>
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</table>
On-resistance vs temperature for the UF3SC065007K4S vs. best available Superjunction MOSFETs and UF3SC120009K4S vs best SiC MOSFET alternatives.

### On-resistance vs. temperature comparison

<table>
<thead>
<tr>
<th>Temperature</th>
<th>UF3SC065007K4S</th>
<th>Superjunction A</th>
<th>Superjunction B</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>6.7</td>
<td>17</td>
<td>12</td>
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<tr>
<td>125°C</td>
<td>8.8</td>
<td>34</td>
<td>23.4</td>
</tr>
<tr>
<td>150°C</td>
<td>9.7</td>
<td>40</td>
<td>26.4</td>
</tr>
<tr>
<td>175°C</td>
<td>11</td>
<td></td>
<td></td>
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### On-resistance vs temperature comparison 1200V

<table>
<thead>
<tr>
<th>Temperature</th>
<th>UF3SC120009K4S TO247-4L</th>
<th>UF3SC120016K4S TO247-4L</th>
<th>SiC MOSFET A</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>8.6</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>125°C</td>
<td>13.3</td>
<td>24.8</td>
<td>24</td>
</tr>
<tr>
<td>150°C</td>
<td>15</td>
<td>28</td>
<td>27.5</td>
</tr>
<tr>
<td>175°C</td>
<td>18.2</td>
<td>33</td>
<td>28.8</td>
</tr>
</tbody>
</table>
On-state characteristics: These devices are fully enhanced beyond Vgs=8-10V, with minimal further change in Rds(on). Therefore, positive gate drive voltages down to 10V may be used.
On-state characteristics: These devices are fully enhanced beyond $V_{gs}=8-10\,V$, with minimal further change in $R_{ds(on)}$. Therefore, positive gate drive voltages down to 10V may be used.
Body diode on-state characteristics (left), and $Q_{RR}$ (right) vs temperature for the UF3SC065007K4S. Note the low conduction drop at $V_{gs} = 0, -5V$ of $<1.5V$ at 100A along with a low $Q_{RR}$ of 840-880nC nearly independent of temperature.
Body diode on-state characteristics (left), and $Q_{RR}$ (right) vs temperature for the UF3SC120009K4S. Note the low conduction drop at $V_{gs}=-5V$ of 1.65V at 100A along with a low $Q_{RR}$ of 1200-1300nC nearly independent of temperature.
Switching Waveform Evaluation

- Device snubber is applied to reduce excessive VDS spike during turn-off
- Bus snubber is used to reduce bus voltage swing and VDS ringing
- Snubber losses are very low

<table>
<thead>
<tr>
<th>Device</th>
<th>Temp</th>
<th>VDS</th>
<th>ID</th>
<th>VGS</th>
<th>Rgon/Rgoff</th>
<th>Device Snub</th>
<th>Bus Snub</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF3SC120009K4S</td>
<td>25°C</td>
<td>800V</td>
<td>20-100A</td>
<td>15/-4V</td>
<td>5Ω/5Ω</td>
<td>680pF, 10Ω</td>
<td>0.1uF, 5Ω</td>
</tr>
<tr>
<td>UF3SC065007K4S</td>
<td>25°C</td>
<td>400V</td>
<td>20-100A</td>
<td>15/-4V</td>
<td>5Ω/5Ω</td>
<td>680pF, 10Ω</td>
<td>0.1uF, 5Ω</td>
</tr>
</tbody>
</table>
**UF3SC120009K4S 25C 100A**

**ON**

- $V_{GS} 10V/div$
- $I_D 50A/div$
- $V_{DS} 200V/div$

$\frac{di}{dt} = 3.23A/ns$

$\frac{dv}{dt} = -20V/ns$

**OFF**

- $V_{GS} 10V/div$
- $I_D 50A/div$
- $V_{DS} 200V/div$

$\frac{di}{dt} = -4.09A/ns$

$\frac{dv}{dt} = 48.9V/ns$
Snubber Rs = 10 Ohm, Cs = 680 pF
DC link 800V

<table>
<thead>
<tr>
<th>ID (A)</th>
<th>E_sr_ON (μJ)</th>
<th>E_sr_OFF (μJ)</th>
<th>E_sr_Total (μJ)</th>
<th>P_sr_Total (W) @ 10kHz fsw</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>57.87</td>
<td>31.95</td>
<td>90</td>
<td>0.9</td>
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<tr>
<td>40</td>
<td>57.15</td>
<td>53.67</td>
<td>111</td>
<td>1.11</td>
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<tr>
<td>60</td>
<td>53.45</td>
<td>81.82</td>
<td>135</td>
<td>1.35</td>
</tr>
<tr>
<td>80</td>
<td>51.43</td>
<td>104.03</td>
<td>155</td>
<td>1.55</td>
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<tr>
<td>100</td>
<td>46.78</td>
<td>119.29</td>
<td>166</td>
<td>1.66</td>
</tr>
</tbody>
</table>
**UF3SC065007K4S 25C 100A**

**ON**
- $V_{GS}$ 10V/div
- $V_{DS}$ 100V/div
- $I_D$ 50A/div

$\text{didt} = 2.62 \text{ A/ns}$
$\text{dvdt} = -10.3 \text{ V/ns}$

**OFF**
- $V_{GS}$ 10V/div
- $V_{DS}$ 100V/div
- $I_D$ 50A/div

$\text{didt} = -5.46 \text{ A/ns}$
$\text{dvdt} = 46.4 \text{ V/ns}$
Slowing the dV/dt down to 4-8V/ns: external $C_{GD}$

- A method to achieve low dV/dt waveforms for motor drive applications.
- Switching at 75A/800V, with 33Ω $R_g$ and 68pF external $C_{gd}$ capacitor.
- Half-bridge switching waveforms on the UnitedSiC double-pulse demo board.
Parallel switching of the UF3SC120009K4S

Two UF3SC120009K4S devices switched in parallel at 60A each (total 120A) with Vgs=+15/-5V, using a 15ohm Rg on each gate and 1ohm in the gate return path. Excellent sharing is achieved under high speed switching conditions. No snubbers were used.
Dimensions of the 8.6mohm, 1200V stack cascode.
The device in yellow is the SiC JFET, and the LV MOSFET in blue stacked on it.
The devices are rated at 175C for continuous operation but the on-state and blocking characteristics of this device show that operation at 200C is possible to handle overstress conditions safely.
Stack cascode technology

Stack cascode using the Silicon low voltage MOSFET stacked on the source pad of a high voltage SiC normally-on JFET, to make a composite normally-off device.

The final configuration of the cascoded SiC FET.
DC thermal model of Cascode in discrete packages

Electrical

Thermal network Stack cascode

Ag sinter die attach

Cu Drain Tab of Package
Stack cascode equivalent DC thermal resistance

\[ P_{\text{LVMOS}} = I^2 R_{\text{mos}} \]
\[ P_{\text{JFET}} = I^2 R_{\text{JFET}} \]

\[ T_{J2} - T_{J1} = P_{\text{LVMOS}} R_{\text{thLV}} \]
\[ T_{J1} - T_C = (P_{\text{LVMOS}} + P_{\text{JFET}}) R_{\text{thJC-JFET}} \]

Define \( R_{\text{EQ}} \) such that
\[ T_{J2} - T_C = (P_{\text{LVMOS}} + P_{\text{JFET}}) R_{\text{EQ}} \]

Then,
\[ R_{\text{EQ}} = (R_{\text{mos}} / (R_{\text{mos}} + R_{\text{JFET}})) R_{\text{thLV}} + R_{\text{thJC-JFET}} \]

The first term adds thermal resistance. To minimize it, \( R_{\text{mos}} \ll R_{\text{JFET}} \)
Usually, a factor of \( >10 \) is chosen.

\textit{In actual switching operation, since most of the switching loss occurs in the JFET, the effective thermal resistance becomes closer to} \( R_{\text{thJC-JFET}} \).
Benefits in high powered EV inverters

- EV inverter designs can be based on power modules, or can be done at significantly reduced cost with paralleled TO247-4L devices from UnitedSiC.
- Switching frequencies can be raised to >20kHz vs 4-8kHz for high powered IGBTs.
- Loss estimates for inverters designs with 4x and 6x paralleled devices are shown in the table. For 8kHz, 200KW operation, losses are reduced nearly 3X using 6x paralleled SiC FETs per switch.
- Inverter efficiencies >99% easily achieved, even while switching at twice the frequency of IGBTs.

<table>
<thead>
<tr>
<th>Voltage Class</th>
<th>Device Type</th>
<th>Chips/Switch</th>
<th>Bus Voltage</th>
<th>Frequency</th>
<th>Loss Type</th>
<th>Power Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>IGBT+Diode</td>
<td>100A X4 each</td>
<td>800V</td>
<td>8kHz</td>
<td>Pcondution (W)</td>
<td>193 440 742 1097</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pswitching (W)</td>
<td>823 1191 1559 1927</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Ptotal (W)</td>
<td>1016 1631 2301 3024</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Semi Efficiency</td>
<td>97.97% 98.37% 98.47% 98.49%</td>
</tr>
<tr>
<td>1200</td>
<td>SiC FET</td>
<td>UF3SC120009K4S X 4</td>
<td>800V</td>
<td>8kHz</td>
<td>Pcondution (W)</td>
<td>67 270 608 1080</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pswitching (W)</td>
<td>185 218 261 313</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Ptotal (W)</td>
<td>252 488 869 1393</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Semi Efficiency</td>
<td>99.50% 99.51% 99.42% 99.30%</td>
</tr>
<tr>
<td>1200</td>
<td>SiC FET</td>
<td>UF3SC120009K4S X 6</td>
<td>800V</td>
<td>8kHz</td>
<td>Pcondution (W)</td>
<td>45 180 405 720 1127 1621</td>
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<tr>
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<td>Pswitching (W)</td>
<td>265 293 327 368 415 469</td>
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<td>Ptotal (W)</td>
<td>310 473 732 1088 1542 2090</td>
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<td></td>
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<td></td>
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<td>Semi Efficiency</td>
<td>99.38% 99.53% 99.51% 99.46% 99.23% 98.96%</td>
</tr>
<tr>
<td>1200</td>
<td>SiC FET</td>
<td>UF3SC120009K4S X 4</td>
<td>800V</td>
<td>16kHz</td>
<td>Pcondution (W)</td>
<td>67 270 608 1080</td>
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<td>Pswitching (W)</td>
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<td>Ptotal (W)</td>
<td>437 706 1129 1705</td>
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<td></td>
<td></td>
<td></td>
<td>Semi Efficiency</td>
<td>99.13% 99.29% 99.25% 99.15%</td>
</tr>
</tbody>
</table>
Loss evaluation for a 60KVA Solar inverter with 800V DC link at 3 operating frequencies for a 2-level, NPC and TNPC topology. This power level is usually accomplished with power modules, but can now be done with UnitedSiC discrete devices.

- 2-Level: 1X UF3SC120009K4S per switch, i.e. 2/phase. (6 devices total)
- TNPC: 2X UF3Sc120009K4S and 2X UF3SC075007K4S per phase. (12 devices total)
- NPC: 4X UF3SC065007K4S per phase (12 devices total)
Benefits in high current battery chargers

- For lower battery voltage systems, use the UF3SC065007K4S to obtain much higher efficiencies than with IGBT based systems.
- Ultra-low losses reduce the cooling burden.
- Use of this device as a synchronous rectifier to replace the secondary side diodes can dramatically cut the total losses and heat burden.
- For e.g., at a 100A operating current with 50% duty cycle, the conduction loss of a JBS diode may be nearly 100W (2V drop@125C) at operating temperatures, but just 45W (0.9V drop@125C) with the UF3SC065007K4S using synchronous rectification.
- And this makes the converter usable for bi-directional power transfer.
Solid-state circuit breaker

- Ultra-low conduction loss simplifies the design and cooling of solid state circuit breakers, and battery disconnect switches in EVs.
- Ability to safely turn-off very high currents is demonstrated in the adjacent short circuit test waveform.
- Excellent paralleling behavior allows scaling to much higher current applications where modules are traditionally required – cost effective.
- Ability to switch stably allow very low ramp rates for switching to avoid voltage overshoots.
Managing slow switching transitions with the UF3SC120009K4S for power controllers/ load switches. Resistive load RL = 9.4Ohm, V_{DD} = 800V, Tj = 25°C, DUT switch with: V_{GS} = -5V/15V.
Solid State Circuit Breakers

- High performance DBC for improved $R_{thJC} < 0.033 \text{C/W}$
- Ag sinter interfaces
- Au plated bottom
- Package can be sintered to heat sink

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Package</th>
<th>Marking</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF3SC120002SNS</td>
<td>SOT-227</td>
<td>UF3SC120002SNS</td>
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