Novel Gate Driver for Normally-off SiC JFET and General High Temperature SiC Converter Technology

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Outline

- **Novel Gate Driver for Normally-off SiC JFET**
  - SiC normally-off 1200 V JFET
  - Existing Gate Driver Concepts
  - Novel Gate Driver
  - Experimental Results

- **General High Temperature SiC Converter Technology**
  - High Ambient Temperature Inverter System
  - High Temperature Current Measurement
  - High Temperature Fan
SiC Normally-off JFET

<table>
<thead>
<tr>
<th>SiC Normally-off JFET (SemiSouth)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>V\textsubscript{DS,BD}</strong></td>
</tr>
<tr>
<td><strong>I\textsubscript{D,cont}</strong></td>
</tr>
<tr>
<td><strong>R\textsubscript{DS,on}</strong></td>
</tr>
<tr>
<td><strong>A\textsubscript{chip}</strong></td>
</tr>
</tbody>
</table>

Vertical Channel

Source Contact

Gate (p-Type)

n\textsuperscript{-} Drift Region

n\textsuperscript{+} Substrate

Drain Contact
Specific Gate Driver Requirements – On-State

- pn-junction
- SiC diodes at the gate
- Operated in forward direction during on-state
Specific Gate Driver Requirements – On-State

Actual Choice:
\[ I_G = 300 \text{ mA} \\
V_{GS} = 2.5 \text{ V} \]

\[ I_{G,\text{min}} \text{ for } R_{\text{on, min}} \]

\[ I_{G,\text{min}} \text{ for } 1.1 \cdot R_{\text{on, min}} \]
Specific Gate Driver Requirements – Switching

- Turn-on and -off: ±15 V for fast charging of $R_{GS}C_{GS}$-circuit
- $C_{GD}$ is up to a factor of 10 higher for the JFET

SiC JFET vs. SiC MOSFET (1200V, 20 A @ 175 °C)
Specific Gate Driver Requirements – Off-State

- High $C_{GD}$ reinforces the Miller-Effect

Current Freewheeling in high side diode  

Turn-on of low side switch
Specific Gate Driver Requirements – Off-State

- High $C_{GD}$ reinforces the Miller-Effect

Current Freewheeling in high side diode

Turn-on off low side switch

Threshold voltage:

$V_{GS,th} = 1 \text{ V @ 25 °C}$

$V_{GS,th} = 0.75 \text{ V @ 175 °C}$
Specific Gate Driver Requirements – Off-State

- Low $V_{GS,th}$ requires negative bias
- Limited to -15 V due to leakage currents (2 mA)
Specific Gate Driver Requirements – Summary

- Voltage and current levels:
  - Turn-on: $V_{GS} = +15 \text{ V}$
  - Turn-off: $V_{GS} = -15 \text{ V}$
  - Off-state: $V_{GS} = -15 \text{ V}$ (during converter operation) and fast removal of Miller charge
  - On-state: $I_{G} = 300 \text{ mA}, V_{GS} = 2.5 \text{ V}$ for $I_{D} = 10 \text{ A} @ 175 ^\circ \text{C}$
    - $I_{G} = 100 \text{ mA}$ for 10% higher $R_{DS,\text{on}}$

- Standard requirements:
  - Wide operating frequency range
  - Arbitrary duty cycles
  - Conventional control with 1 signal per switch
  - Low circuit complexity and cost
## State-of-the-Art Gate Drivers

<table>
<thead>
<tr>
<th>Two-stage gate drivers</th>
<th>AC coupled gate driver</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>+ Required voltage and current levels</td>
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</tr>
<tr>
<td>– Significant power loss in $R_2$ and additional IC required</td>
<td>– Significant power loss in $R_{CL}$</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td>– No fast removal of Miller charge</td>
</tr>
<tr>
<td>+ Required voltage and current levels</td>
<td>– Duty cycle limitations due to discharge of $C_{BP}$</td>
</tr>
<tr>
<td>– Significant power loss in DC-DC conv. &amp; additional ICs required</td>
<td></td>
</tr>
</tbody>
</table>

1) SemiSouth Laboratories, Application Note AN-SS1, 2009
2) Kelley, Improved Two-Stage DC-Coupled Gate Driver for Enhancement-Mode SiC JFET, 2010
3) SemiSouth Laboratories, Application Note AN-SS1, 2009
Novel AC Coupled Gate Driver

Eliminating week points of conventional AC coupled driver by:

- 2 Zener diodes and 4 Schottky diodes
- Adjustment of supply voltage levels:
  - $V_{CC} \approx 4 \, V$
  - $V_{EE} \approx -25 \, V$
Novel AC Coupled Gate Driver – Principles of Operation

On-State

Gate Driver IC and Supply

- \( V_{CC} \)
- \( C_{CC} \)
- \( 0 \) V
- \( V_{EE} \)

Turn-off

Novel Gate Driver Circuit

- \( R_{GD} \)
- \( R_{DC} \)
- \( D_{AC} \)
- \( D_{1} \)
- \( D_{2} \)
- \( D_{3} \)
- \( D_{4} \)

Off-State

SiC Normally-Off JFET

- \( C_{GD} \)
- \( R_{D} \)
- \( D_{GD} \)
- \( D_{GS} \)
- \( C_{GS} \)
- \( R_{S} \)

Turn-on
Novel AC Coupled Gate Driver – Principles of Operation

**On-State**

- \( V_{CC} \approx 4 \text{ V} \Rightarrow \text{very small power loss in } R_{DC} \)

**Turn-off**

**Off-State**

**Turn-on**

\[ R_{GD} + R_{DC} \approx 1 \, \Omega \quad V_{D,DC} \approx 0.3 \, \text{V} \quad I_{RD,DC} \approx 3 \, \text{mA} \]
Novel AC Coupled Gate Driver – Principles of Operation

- $V_{EE} \approx -25 \text{ V}$ and $V_{Z,D3} \approx 15 \text{ V} \Rightarrow C_{AC}$ is charged to 10 V
- Low-impedance path for charging $C_{AC} \Rightarrow$ no duty cycle limitations

$C_{AC} \approx 6 \text{ nF}$  \quad  $V_{D,AC} \approx 0.2 \text{ V}$
Novel AC Coupled Gate Driver – Principles of Operation

- Only small leakage currents flowing
Novel AC Coupled Gate Driver – Principles of Operation

- Miller charge can flow into $C_{GS}$ (negative bias) and gate driver

$V_{Z,D1} \approx 10\, \text{V}$
Novel AC Coupled Gate Driver – Principles of Operation

- Voltage across $C_{AC}$ adds to $V_{CC} \Rightarrow V_{GS} \approx 14 \text{ V}$

- $C_{AC} \approx 6 \text{ nF}$
- $R_{AC} \approx 0 \Omega$
Novel Gate Driver – Experimental Results

- **Test setup:** Half-bridge with inductive load

- **Testing scenarios:**
  - 4 chips in parallel (symmetrical setup important for balanced currents)
  - Various drain currents, faster turn-off with higher $I_D$
  - $T_J$ up to 225 °C (30% slower turn-on at 225 °C)
  - Switching frequencies up to 50 kHz
Novel Gate Driver – Switching waveforms

- Switching times for 600 V and 8 A:

  Turn-on: 30 ns (20 kV/µs)
  Turn-off: 20 ns (30 kV/µs)
Novel Gate Driver – Experimental Verifications

Function of $C_{AC}$

Inductive voltage drop across TO-247 pin

$V_{GS}$ at $C_{AC}$

$V_{GS}$ at package

$> 5 \text{ V safety margin to accidental turn-on of switch}$
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  - High Temperature Current Measurement
  - High Temperature Fan
High Ambient Temperature Inverter System (1/2)

**DC-AC 3-ph Inverter System Specifications:**

- Ambient Temperature: $T_A = 120 \, ^\circ C$
- Switching frequency: $f_{SW} = 50 \, kHz$
- Output frequency: $f = 1000 \, Hz$
- Output power: $P = 10 \, kW$
- DC link voltage: $V_{DC} = 700 \, V$
High Ambient Temperature Inverter System (2/2)

① Ambient air intake
② Peltier heat sink
③ Switches heat sink
④ Heat input to signal PCB
⑤ Horizontal heat transfer
⑥ Heat output of box by Peltier Cooler
# Fast High Temperature Isolated DC and AC Current Measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. $T_A$ for Sensor</td>
<td>250</td>
<td>°C</td>
</tr>
<tr>
<td>Max. $T_A$ for Signal Electronics</td>
<td>120</td>
<td>°C</td>
</tr>
<tr>
<td>Measurement Range</td>
<td>-50...+50</td>
<td>A</td>
</tr>
<tr>
<td>Measurement Frequency</td>
<td>50</td>
<td>kHz</td>
</tr>
<tr>
<td>Max. Error</td>
<td>&lt; 1</td>
<td>%</td>
</tr>
</tbody>
</table>

![Image of electronic component]

![Graph showing current and error over time]

![Graph showing absolute error vs. current to be measured]
High Temperature Fan for Power Electronics Cooling (1/2)

- $T_{\text{max}} = 250\, ^\circ\text{C}$
- $n = 19'000\, \text{rpm}$
- $P_{\text{in}} = 15\, \text{W}$
- DC supply voltage: 12 V
High Temperature Fan for Power Electronics Cooling (2/2)

- Fan Housing: Titanium Grade 5
- Plain Bearing: Carbon
- Shaft (Ø 3 mm): Silver Steel (115CrV3)
- Bearing Case: Titanium Grade 5
- Yoke: Vacoflux 50
- Stator Iron Sheet Package: 0.1mm Sheets (Vacoflux 48)
- Permanent Magnets: radially anisotropic SmCo17
- Rotor with blades: Titanium Grade 5
Summary

- Novel Gate Driver for Normally-off SiC JFET
  - Detailed analysis of gate driver requirements of normally-off SiC JFET
  - Evaluative comparison of gate driver concepts
  - Presentation of novel AC coupled gate driver
    - Fast switching
    - Wide operating frequency range
    - Arbitrary duty cycles
    - Low circuit complexity and cost

- General High Temperature SiC Converter Technology
  - 120 °C Ambient Temperature Inverter System
  - 250 °C Fast Isolated DC and AC Current Measurement up to ±50 A
  - 250 °C High Performance Fan for Power Electronics Cooling
Thank you for your interest.

Please ask your questions!