IS2.3-6 Wide Bandgap (WBG) Power Devices for High-Density Power Converters - Excitement and Reality

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Industry Session Paper – IS2.3-6
Wednesday, March 19, 2014
2:00 pm – 5:30 pm
Implications of WBG Materials on Transportation Power Electronics

Current state of a traction drive rated at 55 kW peak for 18 sec., 30 kW continuous and 15 years lifetime

<table>
<thead>
<tr>
<th>Year</th>
<th>Reduce Cost ($/kW)</th>
<th>Reduce Weight (kW/kg)</th>
<th>Reduce Volume (kW/l)</th>
<th>Reduce Energy Storage Requirements</th>
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</thead>
<tbody>
<tr>
<td>2010*</td>
<td>19</td>
<td>1.08</td>
<td>2.60</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>2013</td>
<td>14.8</td>
<td>1.14</td>
<td>3.16</td>
<td>&gt;92%</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>1.17</td>
<td>3.53</td>
<td>&gt;93%</td>
</tr>
<tr>
<td>2020</td>
<td>8</td>
<td>1.44</td>
<td>4.00</td>
<td>&gt;94%</td>
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Power Electronics

<table>
<thead>
<tr>
<th></th>
<th>($/kW)</th>
<th>(kW/kg)</th>
<th>(kW/l)</th>
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</thead>
<tbody>
<tr>
<td>2010*</td>
<td>7.9</td>
<td>10.8</td>
<td>8.7</td>
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<tr>
<td>2013</td>
<td>6.16</td>
<td>11.5</td>
<td>10.7</td>
</tr>
<tr>
<td>2015</td>
<td>5</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>2020</td>
<td>3.3</td>
<td>14.1</td>
<td>13.4</td>
</tr>
</tbody>
</table>

Electric Motors

<table>
<thead>
<tr>
<th></th>
<th>($/kW)</th>
<th>(kW/kg)</th>
<th>(kW/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010*</td>
<td>11.1</td>
<td>1.2</td>
<td>3.7</td>
</tr>
<tr>
<td>2013</td>
<td>8.64</td>
<td>1.26</td>
<td>4.48</td>
</tr>
<tr>
<td>2015</td>
<td>7</td>
<td>1.3</td>
<td>5</td>
</tr>
<tr>
<td>2020</td>
<td>4.7</td>
<td>1.6</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Source: DOE VTO

An example of traction inverter cost breakdown
G. Cameron et al, *Proc. EVS26, 2012*

Compact energy-efficient power train and EV charging systems
Design for Reliability

Power Electronics Systems Should be **Built-to-Last** Under Appropriate Field-Operating Conditions.

**WBG data sheet statement:**

“This product has not been designed or tested for use in, and is not intended for use in, applications implanted into the human body nor in applications in which the failure of the product could lead to death, personal injury or property damage, including but not limited to equipment used in the operation of nuclear facilities, life-support machines, cardiac defibrillators or similar emergency equipment, aircraft navigation or communication or control systems, air traffic control systems, or weapons systems.”
What does this mean?

High-end computer server power supplies demand an MTBF $\sim 1,000,000$ hours.
How are today’s power converters designed?

Automotive traction inverters and battery chargers demand MTBF > 500,000 hours
Power Semiconductor Switching Stresses

\[ v_{\text{SUP}} \]

\[ i_L(t), \quad di_L(t)/dt \]

\[ v_{\text{AB}}(t), \quad dv_{\text{AB}}(t)/dt \]
Power Semiconductor Switch Module

Chip $T_{j\text{max}}$ Interface $T_c$
Heatsink $T_s$

$T_a$ 

Conduction

(a)

Convection

(b)

$Z_{jc}$ $Z_{cs}$ $Z_{sa}$

$P_{\text{loss}}$
“Industry-Best” SiC Power MOSFETs

1,200V Cree MOSFET
\[ R_{sp} = 3.7 \text{ m}\Omega \cdot \text{cm}^2 \]

1,200V Rohm MOSFET
\[ R_{sp} = 2.6 \text{ m}\Omega \cdot \text{cm}^2 \]
“Industry-Best” GaN Power Switches

600V Panasonic GIT

\[ R_{sp} = 2.5 \text{ m}\Omega\cdot\text{cm}^2 \]
SiC and GaN power devices will make converters more compact and energy-efficient, and will enable new applications.
Vertical vs. Lateral Power Switches

Vertical

Lateral
Unipolar Power Switch

Vertical

Lateral
“Industry Standard”

\[ R_{sp} = \frac{4V_B^2}{\varepsilon S \mu E_C^3} \quad (1a) \]

\[ Q_g = C_{iss} V_{gs} \quad (1b) \]

\[ R_{spl} = \frac{V_B^2}{q \mu_s n_s E_C^2} \quad (3) \]

Specific On-State Resistance

Thermal Failures in Electronics

(a) Pie chart showing percentages of thermal failures due to different factors: Temperature (54%), Humidity (22%), Dust (19%), Vibration (6%).

(b) Graph showing failure rate per 100,000 hours against junction temperature in °C. The failure rate increases significantly with temperature.

Avionics Integrity Program (AVIP), MIL-STD-1796A (USAF), October 13, 2011
Localized Failure in Power Semiconductors

Thermal “Figure of Merit”

\[ Q_{F2} = \kappa \sigma_{sp} E_c \]

Why WBG Power Semiconductors are not in the Transportation Sector?

- Reality!
**On-State Resistance**

**C2M0080120D**

**Typical Output Characteristic (T_j = 25 °C)**

**Typical Output Characteristic (T_j = 150 °C)**

On-resistance data is inconsistent with I-V data

**On Resistance vs. Temperature (V_{GS} = 20 V)**
Body Diode Characteristics

Typical Body Diode Characteristic ($T_j = 25^\circ C$)

Strong indication of the Influence of gate oxide charge
Measured $dv/dt$ of SiC Power Diodes

WBG data sheets do not provide $dv/dt$ ratings

Manufacturer Report on $dv/dt$

Turn-on $dv/dt = 75$ V/ns
Turn-off $dv/dt = 100$ V/ns
Cree Report # CPWR-RS01, Rev A

Does not make any sense!
Measured Avalanche Energy of Diodes

600V/8A 4H-SiC JBS diode

600V/6A silicon MPS diode

WBG data sheets do not provide *avalanche energy* ratings

Safe Operating Area (SOA)

IXFB30N120P

\[ V_{DS} = 1200V \]
\[ I_{D25} = 30A \]
\[ R_{DS(on)} \leq 350m\Omega \]
\[ t_{rr} \leq 300ns \]

Why SiC SOA is smaller than silicon?

C2M0080120D

- \[ V_{DS} = 1200V \]
- \[ I_D @ 25^\circ C = 31.6A \]
- \[ R_{DS(on)} = 80m\Omega \]

TO-247-3

Graphs showing SOA limits and drain-source voltage vs. drain-source current for different pulse durations.
Silicon Carbide MOSFET Gate Oxide Failures

- Pre-screening or burn-in difficult
  - Extrinsic population is Poisson-distributed in area
  - Can’t predict next failure during useful life of device
- Critical reliability issue

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**Figure 9.** Uncensored Weibull distribution of $4 \times 10^{-4} \text{ cm}^2$ 4H-SiC capacitors at a temperature of 230 °C and under electric field of 8.9 MV/cm.


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SiC MOS gate oxide charge and poor reliability originate from material defects in the epitaxial region.
Substrate Effect on Heat Removal

Package Layout

Thermal Model
Preliminary Results

(a) Thermal impedance and (b) $T_{j_{\text{max}}}$ vs. substrate thickness for 600V/24A silicon SJT, and (c) estimated $T_{j_{\text{max}}}$ for 1,200V power transistors fabricated on various substrate materials when dissipating 10W power in the on-state.
Where do we go from here?

- Need a New Approach!
Present PVT SiC Crystal Growth Process

Growth in the c-axis direction, enabled by screw-dislocations providing steps!

Vertical (c-axis) 4H-SiC boule growth proceeds from top surface of large-area seed via hundreds to thousands of threading screw dislocations (TSDs).

Contention: Elimination of screw dislocations from power devices not possible while maintaining commercially viable crystal quality and growth rate and via this approach.

Crystal grown at $T > 2200^\circ C$ --> High thermal gradient & stress --> More dislocations


Threading screw dislocation growth spirals (THE sources of steps for c-axis growth) found at top of grown 4H-SiC boule.
Defects in SiC Material
Joint OSD/Army/Navy
SiC HEPS ManTech

M. Loboda, DOW CORNING, ICSCRM 2011
Industry Session

100 mm wafers
Micropipe Density ~ 0 cm\(^{-2}\)
Threading Screw Dislocation Density < 1,000 cm\(^{-2}\)
Basal Plane Dislocation Density < 1,000 cm\(^{-2}\)

100 mm wafers
Micropipe Density ~ 0 cm\(^{-2}\)
Threading Screw Dislocation Density < 1,000 cm\(^{-2}\)
Basal Plane Dislocation Density < 1,000 cm\(^{-2}\)

Key Objectives:

- Increase wafer dia. from 4” to 6”
- Increase voltage ratings by 2-3X of Si rating
- Bring down die cost to within 2-2.5X of Si cost
- Reliable operation up to \(T_C = 150\degree C\) (vs. 70\degree C for Si)

Si and SiC IGBTs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline (4” dia. median)</th>
<th>Best R&amp;D in FY13 (6” dia.)</th>
<th>Commercial (6” dia. median)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-pipes (cm(^{-2}))</td>
<td>&lt; 0.8</td>
<td>&lt; 0.8</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>TEDs and TSDs (cm(^{-2}))</td>
<td>275</td>
<td>2,000</td>
<td>800</td>
</tr>
<tr>
<td>BPDs in epi (cm(^{-2}))</td>
<td>&lt; 2 (50 (\mu)m)</td>
<td>&lt; 50 (75 (\mu)m)</td>
<td>&lt; 1 (160 (\mu)m)</td>
</tr>
<tr>
<td>Epi thickness/doping uniformity/thickness</td>
<td>2%/5%/75 (\mu)m</td>
<td>2%/20%/75 (\mu)m</td>
<td>1%/6%/160 (\mu)m</td>
</tr>
</tbody>
</table>

TED and TSD densities are higher for 6 in. dia. wafers

- Role of TEDs and TSDs not investigated
- Radically new bulk and epi crystal growth processes may be needed in order to further reduce and/or eliminate TEDs and TSDs
- Yield and cost metrics are not well-defined
- Not directly applicable to commercial power devices
Key Device Challenge

Consequences:

- Voltage De-Rating
- Limited Die Size
- Poor Wafer Yield
- High Cost
- Less Than Optimal Performance
- Field-Reliability Unknown
- Bipolar power switch questionable

There are other challenges

High starting Wafer Cost
Epi Uniformity
Gate Dielectrics
Contacts
HV Passivation
Carreer Lifetime Control

Material - Device - Module - Converter Interaction

1c density (cm$^2$):
- 4% >000
- 14% 500-2000
- 27% 250-500
- 55% 50-200

Median 1c density: 175 cm$^2$
Key Material Challenge

**Bulk Material Defect Density**

- SiC: Median 1c density 175 cm$^2$
- GaN: 1c density (cm$^2$)
  - 4% >2000
  - 14% 500-2000
  - 27% 200-500
  - 55% <200

**Reliable Switching Current Density**

- > 200 A/cm$^2$

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$T_{J\text{MAX}} > 200^\circ \text{C}$

Summary and Recommendations

• WBG power devices have the potential for transformative advances in transportation sector.

• Progress is severely hampered by a high density of crystal defects in WBG semiconductors.

• Need reliability-driven application engineering with improved data sheets in order to infuse WBG power electronics into the transportation sector.

• This is a challenge especially since the power electronics industry supply chain is highly fragmented.