SiC – Status update and future outlook
Semiconductor Solutions for Automotive

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Drivers for SiC in automotive
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Power converters portfolio: From a few-watts to mega-watts

<table>
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<tr>
<th>Power supply and UPS</th>
<th>Solar inverter and EVCI</th>
<th>Drives and wind converter</th>
<th>STATCOM, FACTs, HVDC</th>
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Large portfolio of power converters for different applications
Applications for SiC devices
Recently launched products with SiC semiconductors

- **BORDLINE**
  - 10 kW battery charger for rail traction
  - 1200V SiC MOSFETs
  - **Main driver**: Volume reduction (factor 10) by smaller passive components (transformers, inductors, capacitors, and coolers)

- **Solar PV**
  - 1-ph and 3-ph solar PV string inverters with MPPT control
  - 1200V and 1700V SiC diodes, SiC MOSFET discretes and SiC modules in boost and inverter stages
  - **Main driver**: Volume and weight reduction

- **EV charging**
  - 50 kW isolated DC fast charger
  - 1200V SiC modules replacing discrete ISOTOP IGBTs
  - Extended DC capability up to 1000V
  - **Main driver**: Improved efficiency at lower system cost & acoustic noise emissions

MPPT: Maximum power point tracking
IEA projected vehicle stock in 2030:
- 130 – 250 million passenger EV / LCV
- 1.5 – 4.5 million e-buses
- 1.0 – 2.5 million e-trucks

- Driven by regulations
- Likely to develop to the largest power semiconductor market of the future

- **Traction inverter** to drive electrical machine (highest potential market)
- **On-board battery charger and DC/DC converter** to support auxiliary systems
- **SiC of high interest** for all PE converters in the drivetrain
  → Reduce losses, increase switching frequency, reduce size

- **System integration** to minimize cost, space, cables, connectors & cooling loops
- **New materials and manufacturing technologies**: WBG devices, laser welding, thermoplastic welding, cold forging, ...
- **More sensors, fusion, analytics and control**: Adaptive, predictive, fault-tolerant, life-extending, self-learning, ...
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Requirements for power semiconductor modules

Cost reduction
- Main driver and key development target
- Low-cost materials and interconnect technologies
- Processes for fast and automated volume production
- Powertrain system optimization, e.g., compromising component vs. system cost in drive cycle

Power density and integration
- Module design for mechanical integration into space-restricted inverters and engine compartments
  - Footprint reduction by current routing into 3D and by improved cooling
  - High-T operation of WBG devices
  - Elimination of mounting overhead on system level (screwing, clamping, …)

Reliability
- Understand physics-of-failure of new module innovations: Planar topside, new substrates, embedded power and heterogeneous integration
- Robustness margins fit-for-application in harsh environment (ambient temperature, vibrations, humidity, …)
- Different requirements for commercial vs. passenger EVs, e.g., 10 x lifetime
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Key drivers for SiC semiconductors

Reduce costs

<table>
<thead>
<tr>
<th>Drive cycle analysis</th>
<th>RoadPak SiC</th>
<th>RoadPak Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant $T_{\text{inlet}}$</td>
<td>50°C</td>
<td>50°C</td>
</tr>
<tr>
<td>$T_{\text{max}}$ during drive cycle</td>
<td>109°C</td>
<td>178°C</td>
</tr>
<tr>
<td>Switching losses</td>
<td>0.31 kWh</td>
<td>2.45 kWh</td>
</tr>
<tr>
<td>Conduction losses</td>
<td>0.63 kWh</td>
<td>1.36 kWh</td>
</tr>
<tr>
<td>3-phase module loss, 9.8 h E-truck profile</td>
<td>2.8 kWh</td>
<td>11.7 kWh</td>
</tr>
<tr>
<td>SiC battery saving</td>
<td>8.9 kWh</td>
<td>-</td>
</tr>
</tbody>
</table>

- ABB RoadPak in long-haul E-truck drive cycle → 9h 47min of driving
- SiC with < 4 times lower losses:
  → Save 8.9 kWh battery

Power density, reduce size

![Graph showing power density and switching frequency]

Increase reliability

- SiC with < 2 times $\Delta T_j$, $\Delta T_{\text{solder}}$:
  → Solder cycle life > ~ 30 times Si
- Advanced packaging to avoid de-rating for high-lifetime vehicles (trucks, buses)

Additional notes:

- $V_{\text{DC}} = 850$ V, $T_{\text{max}} = 175^\circ$C, $\text{mod} = 0.95$, $\text{cos}\psi = 0.85$, WEG coolant: 10 l/min, 60°C
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Advanced powertrain integration

Machine-inverter integration

Advanced cooling

Diagnostics and fault tolerance

- **Cooling** = most important factor to determine output power for any motor
- **Stator** direct slot cooling and fluid winding head cooling vs. housing cooling
- **Rotor spray mist cooling**
- **Hollow shaft** and bearing cooling

→ Combined power electronics and machine cooling, e.g., modules in oil

<table>
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<tr>
<th>Cooling</th>
<th>$\Delta T_{j, \text{RoadPak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEG 50/50</td>
<td>100%</td>
</tr>
<tr>
<td>Oil</td>
<td>121%</td>
</tr>
<tr>
<td>Oil w/o DBC</td>
<td>106%</td>
</tr>
<tr>
<td>Oil DSC w/o DBC</td>
<td>~ 75%</td>
</tr>
<tr>
<td>2-Φ DSC w/o DBC</td>
<td>~ 50%?</td>
</tr>
</tbody>
</table>

Source: Universitäts Karlsruhe

- **Fault prediction, detection, location and containment** enabled by on-board sensing, redundant architectures, re-routing and modified operation, e.g., for degraded or emergency operation for fail-safe vehicle stand-still
- Advanced sensing and multiphase machine approaches

Source: Schweizer

Source: TU Berlin

Source: Fraunhofer IISB
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Advanced packaging technologies

**Bonding**
- Ag, Cu & Ni sintering
- Pressure-less sintering (T, IR, bare Cu, polymer content)
- Ultrasonic welding of terminals
- Pressure contacts
- Laser bonding

**Topside interconnection**
- Cu wire bonding
- Sintered top plates & clips
- Electroplated vias for embedding and thru-mold
- Topside substrates (DBC, PCB, flex-foil, LTCC, ...)
- 3D printed interconnects

**Substrate & encapsulation**
- Thick-metal ceramic, low-thickness Al₂O₃, and organic insulated substrates
- Chip-on-leadframe approaches
- Integrated substrate / baseplate / cooler solutions
- Transfer and compression molded high-T compounds

**Cooling**
- Module with integrated coolers
- Double-side cooling
- Microchannel cooling
- Immersion cooling
- Jet impingement

Source: WOLVERINE
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Next generation semiconductors (besides Si IGBT)

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
<th>AlN</th>
</tr>
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<tbody>
<tr>
<td>6&quot;, 8&quot;, 12&quot;</td>
<td>4&quot;, 6&quot;, 8&quot; demonstrated</td>
<td>4&quot; - 8&quot; GaN-on-Si (2&quot; GaN-on-GaN)</td>
<td>2&quot;, 4&quot; epi wafers</td>
<td>Small square samples ~ 1cm$^2$</td>
<td>2&quot; substrates</td>
<td></td>
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<table>
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<tr>
<th>Material</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
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<thead>
<tr>
<th>Device</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
<th>AlN</th>
</tr>
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<tbody>
<tr>
<td>SJ MOSFET</td>
<td>Planar &amp; trench MOSFET</td>
<td>HEMT</td>
<td>MOSFET (w/o inversion channel)</td>
<td>MOSFET (w/o inversion channel)</td>
<td>tbd (MOSFET)</td>
<td></td>
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</tbody>
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<table>
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<tr>
<th>Key benefits</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
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<tr>
<td>Mature technology</td>
<td>Switching losses</td>
<td>Static losses</td>
<td>Very low losses (2DEG) (RF, OBC, DC/DC)</td>
<td>Static losses</td>
<td>Static losses</td>
<td>Static losses</td>
</tr>
<tr>
<td>Switching losses Body diode</td>
<td>Switching losses Body diode</td>
<td>Very low losses (2DEG) (RF, OBC, DC/DC)</td>
<td>Static losses</td>
<td>Very high $\lambda_{th}$</td>
<td>Static losses</td>
<td></td>
</tr>
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<tr>
<th>Challenges</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
<th>AlN</th>
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<tr>
<td>Reaching its limit</td>
<td>Switching loss ↑($T$) Limited to ~ 650 V</td>
<td>Static loss ↑($T$) Channel mobility</td>
<td>Ruggedness No body diode p-type activation</td>
<td>No p-type Low $\lambda_{th}$</td>
<td>Material availability n-type difficult</td>
<td>Material availability p-type difficult</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Cost potential</th>
<th>Si SJ</th>
<th>SiC</th>
<th>GaN</th>
<th>Ga$_2$O$_3$</th>
<th>Diamond</th>
<th>AlN</th>
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<tr>
<td>Low</td>
<td>Medium</td>
<td>Medium - Low</td>
<td>Medium - Low</td>
<td>Medium - Low</td>
<td>High</td>
<td>High</td>
</tr>
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Conclusions: SiC outlook - needs for the future

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<tr>
<th>SiC devices</th>
<th>SiC modules</th>
<th>SiC system design</th>
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- **Improved performance** $R_{DSon} \times A$ at given robustness ($V_{th}$ stability, GoX lifetime, cosmic ray, SOA and short-circuit)
- **Reduce device cost** by improved material quality & processing yield, larger wafer diameter and economies of scale
- **Research** to enable future step-change device designs, e.g., SJ, and to avoid expensive SiC substrates, e.g., SiC-on-Si?

- **Low-cost materials**, interconnect technologies and processes for automated volume production
- **Module design for mechatronics integration** into engine compartments, e.g., high-T operation, elimination of mounting overhead, immersion cooling, etc.

- **Holistic powertrain system optimization** (EM, thermal, reliability, costs)
- **Utilizing better modelling capability, simulation and virtual testing** to improve performance and shorten product cycles
- **Advanced control**, diagnostics and fault tolerance
- **Utilizing new manufacturing techniques**

- $R_{DSon}$: On-state resistance, $V_{th}$: Threshold voltage, GoX: Gate oxide, SOA: Safe operating area
- SJ: Super-Junction

Model predictive pulse pattern control