SiC User Forum

Use of SiC Components in Power Electronic Systems

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Outline

- SiC – Si Material Properties
- Reported SiC Device Performance
- Selected Application Areas
- SiC Systems Research at ETHZ
- Technology Gaps
- Outlook
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SiC Power Semiconductor Devices

Challenges

SiC Wafer Defects – Micropipes and Screw Dislocation Causing Low Processing Yield
<5/cm² Ultra-Low MP Density
<3/cm² Required for 1200V/100A Devices

2002 SiC Wafer Production Capacity
94% US Share

SiC / Si Material Properties Comparison

Wide Bandgap → High Operating Temperature
High Critical Field → Low On-Resistance
High \( V_{sat} \) → High Frequency
High Therm. Cond. → High Power/ Temperature

Biggest Device Performance Difference Resulting from 10 times Higher Critical Field \( E_c \)

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<tr>
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<tr>
<td>( \lambda ) (W/cmK)</td>
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<td>3 - 5</td>
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SiC Power Semiconductor Devices

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Biggest Device
Performance Difference
Resulting from 10 times
Higher Critical Field $E_c$
Influence of $E_c$ on Device Performance

Consider pn-Junction

Design for High Blocking Voltage / Low On-Resistance
Proper Selection of $N_D$ and $W \rightarrow E=0$ for $x=W$

FOM (Figure of Merit)

\[ V_B^2 \quad \frac{R_{on,sp}}{W} \]

\[ W = \frac{2eV_\pi}{\sqrt{qN_D}} \quad N_D = \frac{2eV_\pi}{qW^2} = \frac{\mu_e E^2}{2qV_A} \]

For 1 kV:

<table>
<thead>
<tr>
<th>Material</th>
<th>$W$ (\text{\micrometer})</th>
<th>$N_D$ (\text{\cubiccentimetre})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>100</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>SiC</td>
<td>10</td>
<td>$10^{16}$</td>
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</table>

\[ R_{on,sp} = RA \]

On-Resistance of Drift Zone Depends on $E_c^3$

FOM SiC 2 MW/cm²
Si 2 kW/cm²

Enables High Blocking Voltage Low On-State Loss
SiC Unipolar Devices

High Voltage (Unipolar) Devices
Influence of $E_c$ on Device Performance

Consider pn-Junction

Design for High Blocking Voltage / Low On-Resistance

Proper Selection of $N_D$ and $W \rightarrow E=0$ for $x=W$

FOM (Figure of Merit)

$$\frac{V_B^2}{R_{on,sp}}$$

Non punch-through

design for 1 kV:

<table>
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<tr>
<th>Material</th>
<th>$E_c$ (MV/cm)</th>
<th>$W$ ($\mu$m)</th>
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<tr>
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$$W = \frac{2eV_x}{\sqrt{qN_D}}$$

$$N_D = \frac{2eV_x}{qW^2}$$

$$E_x = \frac{1}{\varepsilon}qN_D$$

$$V_x = \frac{WE_x}{2}$$

$$R_{on,sp} = \frac{W}{q\mu_s N_D}$$

$$\frac{V_x^2}{R_{on,sp}} = \frac{W}{\varepsilon\mu_s E_x^2}$$

High Voltage (Unipolar) Devices

On-Resistance of Drift Zone Depends on $E_c^3$

FOM SiC 2MW/cm$^2$

Si 2 kW/cm$^2$

Enables High Blocking Voltage Low On-State Loss

SiC Unipolar Devices
SiC Power Switching Device Properties

High Frequency Devices

Transport through Depleted Region Causes Delay Time

\[ W_{\text{SiC}} = \frac{1}{10} W_{\text{Si}} \]
\[ v_{\text{sat SiC}} = 3 v_{\text{sat Si}} \]

\[ \tau = \frac{W}{2v_{\text{sat}}} \]
\[ C \propto \varepsilon_r \]

\begin{array}{|c|c|c|c|}
\hline
& Si & GaAs & 4H/6H-SiC & GaN \\
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E_c (MV/cm) & 0.25 & 0.3 & 2.2-2.5 & 3 \\
\varepsilon_r & 11.9 & 13 & 10 & 9.5 \\
v_{\text{sat}} (cm/s) & 1 \times 10^7 & 1 \times 10^7 & 2 \times 10^7 & 3 \times 10^7 \\
\hline
\end{array}

\[ N_i \text{ must not exceed } \langle N_d \rangle \]

Intrinsic Carrier Concentration \( N_i \) Exponentially Dependent on Bandgap \( E_g \)
SiC Power Switching Device Properties

High Frequency Devices

\[ \tau = \frac{W}{2v_{\text{sat}}} \quad C \propto e^{-} \]

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High Temperature Devices

Intrinsic Carrier Concentration \( N_i \) Exponentially Dependent on Bandgap \( E_g \)

\( N_i \) must not Exceed Doping Level
SiC Power Switching Device Properties

High Temperature Devices

SiC Rectifier Diode
Probe-Tested at 600°C

Junction Temperature Rise
Proportional to Power and Thermal Resistance

\[ \Delta T = R_{TH} \frac{P}{\lambda A} \]

\[ P_{SiC} \approx 10 \times P_{Si} \]
\[ \lambda_{SiC} \approx 2 - 3 \times \lambda_{Si} \]
\[ \Delta T_{SiC} \approx 5 \times \Delta T_{Si} \]

High Power Devices

SiC device

Heat sink

C.M. Zetterling/KTH
SiC Power Switching Device Properties

High Temperature Devices

SiC Rectifier Diode
Probed-Tested at 600°C

Junction Temperature Rise Proportional to Power and Thermal Resistance

\[ \Delta T = R_{TH} P = \frac{1}{\lambda A} P \]

\[ P_{SiC} \approx 10 \times P_{Si} \]

\[ \lambda_{SiC} \approx 2 - 3 \times \lambda_{Si} \]

\[ \Delta T_{SiC} \approx 5 \times \Delta T_{Si} \]

High Power Devices

\[ W_{SiC} = 1/10 W_{Si} \]

Low Thermal Resistance

High Device Temperature Requires Advanced Packaging / Cooling

C.M. Zetterling/KTH
Summary of SiC Power Switching Device Properties

High Blocking Capability
High Switching Frequency
High Operating Temperature
Low On-Resistance

Basic Types of SiC Power Switching Devices

SiC pn-Diode
Threshold is \( \approx 3\text{V} \) due to large Bandgap \( E_g=3.3\text{eV} \)

Potential of Bipolar Devices only for \( V_B > 4...5\text{kV} \)
Summary of SiC Power Switching Device Properties

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Progress in Blocking Voltage of SiC Power MOSFETs

MOSFET → IGBT
Conductivity Modulation Could Reduce On-Resistance but Minority Carrier Charge must be Removed before Blocking – Results in Switching Losses

Comparison of Unipolar and Bipolar SiC Power Switching Devices

20kV  N-Channel MOSFET
P-Channel IGBT
N-Channel IGBT

Significantly Higher Current of IGBTs at Package Limit
Progress in Blocking Voltage of SiC Power MOSFETs

Best Reported WBG Power Device Performance June 04

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SiC Power Switching Devices Performance Envelope

Status of 2004

Recent Development in DARPA Wide Bandgap (WBG) High Power Electronics (HPE) Program

SiC MOSFET 2A/10kV
SiC pin Diode 40A/10kV/200ns

SiC Schottky Diodes
- 600V 35A
- 1200V 25A
- 1700V 40A

SiC MPS Diodes
> 2kV 15A

SiC Bipolar Diodes
> 4kV 12A

SiC J-FETs
- 1200V 5A/10A
- 1800V 3A/8A

SiC Power Semiconductor Devices

600V SiC Schottky Diode
Positive Temp. Coefficient of $V_F$
No Reverse Recovery Current
SiC Power Switching Devices Performance Envelope

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SiC Power Semiconductors Devices

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- 600V 35A
- 1200V 25A
- 1700V 40A

SiC MPS Diodes
- > 2kV 15A
- > 4kV 12A

SiC J-FETs
- 1200V 5A / 10A
- 1800V 3A / 8A

Positive Temp. Coefficient of $V_F$
No Reverse Recovery Current

$T=120^\circ C, V_{C}=400$ V
$I_d=64$ A, $dI/dt=200$ A/s
SiC J-FET

SiC J-FET
Si Low-Voltage MOSFET
Cascode

TO-220 1300V / 4A
R_{DS(on)} = 0.47Ω @ 25°C, V_{gs}=0V
R_{DS(on)} = 1.47Ω @ 200°C, V_{gs}=0V

dv/dt_{max} = 50kV/µs

Pinch-Off Voltage

**SiC J-FET**

**SiC J-FET**

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\[
\begin{align*}
\text{D} & \quad \text{O} \\
\text{G} & \quad \text{E} \\
\text{S} & \quad \text{C} \\
\end{align*}
\]

**SiC JFET**

\[
\begin{align*}
\text{Source} & \quad \text{Gate} \\
\text{p-} & \quad \text{p+} \\
\text{n-} & \quad \text{n+} \\
\end{align*}
\]

\[
\begin{align*}
\text{Low } R_{DS(on)} & \quad \text{(a)} \\
\text{Fast Switching} & \quad \text{(b)} \\
\end{align*}
\]

**SiC J-FET Switching Characteristics**

\[ \frac{dv}{dt} \text{ max} = 50kV/\mu s \]

**Pinch-Off Voltage**

\[
\begin{align*}
\text{V}_{GON} & \quad \text{V}_{DS} \\
\text{V}_{ON} & \quad \text{V}_{DS} \\
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SiC J-FET Switching Characteristics

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Stacked High-Voltage SiC J-FET Switch

Alternative to Realization of a Single High Voltage Bipolar Switch - Problem of Thick Epi Layer Growth

4-Stack 8kV / 10A / 2Ω
SiC J-FET Switching Characteristics

\[ \frac{dv}{dt} \text{ max} = 50 \text{kV/\mu s} \]

Stacked High-Voltage SiC J-FET Switch

Alternative to Realization of a Single High Voltage Bipolar Switch - Problem of Thick Epi Layer Growth

4-Stack 8kV / 10A / 2Ω
High-Voltage High-Frequency SiC Devices

Future Target: 15kV / 20kHz, $T_J = 200^\circ$C  PiN Diode, MOSFET, IGBT

DARPA
Wide Bandgap (WBG) High Power Electronics (HPE) Program
15kV Class Devices for
2.5MVA Solid State Navy Ship Substations

EPRI
Intelligent Universal Transformer Program
Advanced Distribution Automation and Power Quality Enhancement
13.8kV – 120/240kV, 10...50kVA

SiC Power Semiconductor Application Areas

Low-Voltage
Mature Technology
Applications with High Potential Volumes
- SMPS
- Motor Integrated Drives (100kHz)
- Hybrid Cars
- More Electric Aircraft

High-Voltage
Rapid Development
- Utility / Power Distribution
- Military Research Platforms
High-Voltage High-Frequency SiC Devices

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Mature Technology Applications with High Potential Volumes

- SMPS
- Motor Integrated Drives (100kHz)
- Hybrid Cars
- More Electric Aircraft

**High-Voltage**
Rapid Development

- Utility / Power Distribution
- Military Research Platforms
Drive Systems

60% of Electric Energy Utilized in Germany consumed by Drives

5% Employing Electronic Speed Control
35% Possible Share / 40% Energy Saving Potential (16TWh)
400TWh Drives Energy Consumption in the EU
60% Energy Saving Potential
Drive Systems

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400TWh Drives Energy Consumption in the EU
60% Energy Saving Potential

Active Front-End

1200V SiC Schottky Diodes

Multi-Level Converter Topologies

High-Voltage High-Frequency Replacing 2-Level Systems Converters
Three-Phase PWM Inverter

- 8 mm x 8 mm Chip Size
- 6 mm x 6 mm PiN diode
- Metal Can Package
- Utilizing new high-temperature Resin (up to 300°C) for Dielectric Insulation
- 110kVA / Switching Frequency 2kHz
- 4.5kV/100A SiC Gate-Turn-Off Thyristors
- 2us Turn-Off Time
- No Snubber

SiC-J-FET PWM Inverter Stage

- Concept for Normally-On Inverter Operation
Three-Phase PWM Inverter

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SiC-J-FET PWM Inverter Stage

- Concept for Normally-On Inverter Operation
All-SiC-Sparse Matrix Converter

Switching Frequency: 100kHz
Output Power: 1.5kW
Efficiency: $\eta = 94\%$

1300V, 4A IXYS i4-Pack, SiCED
1200V, 5A CREE SiC CSD05120

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SiC-JFET
Si-MOSFET

1300V, 4A IXYS i4-Pack, SICED
1200V, 5A CREE SiC CSD05120

Switching Frequency: 100kHz
Output Power: 1.5kW
Efficiency: $\eta = 94\%$

DSP control
PWM generation
Measurement
Gate drive, auxiliary
Power circuit
Heat sink
Fan
All-SiC-Sparse Matrix Converter

Switching Frequency 100kHz
Output Power 1.5kW
Efficiency $\eta = 94\%$

Comparative Evaluation of Si-IGBT/SiC Diode BBC and IMC

Isolated Half-Bridge Packages Integrating Si-IGBTs and SiC Schottky Diodes

1200V SiC Schottky Diodes
**All-SiC-Sparse Matrix Converter**

- **Switching Frequency**: 100kHz
- **Output Power**: 1.5kW
- **Efficiency**: \( \eta = 94\% \)

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**Comparative Evaluation of Si-IGBT/SiC Diode BBC and IMC**

**Isolated Half-Bridge Packages Integrating Si-IGBTs and SiC Schottky Diodes**

- **1200V SiC Schottky Diodes**
- **IXYS FIO 50-12E**
Hybrid Car

Power System Architecture

300...500V High Voltage DC Bus
14V Battery

Electric Powered Air Conditioning
Windscreen Deicing
Electric Power Steering
(Med. & Large Cars)
Integrated Starter Alternator
- Stop/Start Operation
- Acceleration Boost
- Regenerative Braking
Emergency Vehicle (EV)
Electric Oil and Water Pumps
Electromechanical Brakes
Exhaust Aftertreatment
Suspension Control

High Voltage (e.g. 380V)
Storage System

Battery Charge/Discharge Unit
DC/AC Inverter
Propulsion System
Conventional Low-Power Loads
DC/DC Converter
12V Battery
12V Storage System

Electric Motors
Air Conditioning
Power Steering

Self-Commitment of EU Automotive Industry
Hybrid Car

Power System Architecture

300...500V High Voltage DC Bus
14V Battery
Future Motor-Integrated Power Electronics

Ambient Temperature – 125°C at ICE
105...115°C Coolant Inlet
Junction Temperature – 200°C (275°C/EU HOPE)
Simultaneously Increasing Reliability Requirements

High Temperature Power Electronics
Packaging Technology with Matched CTEs
High Power Density – 50kVA/l

State of the Art

<table>
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<tr>
<th>Power Electronics (inverter/controller)</th>
<th>2010 Target</th>
<th>2003 Status</th>
<th>Gap</th>
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<tbody>
<tr>
<td>Specific power at peak load (kW/kg)</td>
<td>&gt;1.2</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Volumetric power density (kW/l)</td>
<td>&gt;1.2</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Cost ($/kW peak)</td>
<td>&gt;0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>&gt;90 at 10% max. speed</td>
<td>90 at 5% max. speed</td>
<td>90-30% max. speed</td>
</tr>
<tr>
<td>Coolant inlet temperature, °C</td>
<td>105</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>Lifetime, years</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
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Status based on PNGV (Partnership for New Generation of Vehicles)
Automotive IPEM and Automotive Electric Motor Drive Program PNGV
Coolant Temp.: 70°C, Table shows Estimated Values for 105°C

Technology Gaps
Power Electronics

System Efficiency to be increased to 95% in 2015, other Parameters as for 2010

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<th>Propulsion System (Inverter &amp; Motor)</th>
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<td>Specific power at peak load (kW/kg)</td>
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<td>Cost ($/kW peak)</td>
<td>&gt;0.5</td>
<td>0.52</td>
<td>0.37</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>&gt;90 at 10% max. speed</td>
<td>90 at 5% max. speed</td>
<td>90-30% max. speed</td>
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<td>Lifetime, years</td>
<td>15</td>
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a) 2003 status based upon recent progress report from Semakron.
c) Approximated by adding inverter plus motor.
Future Motor–Integrated Power Electronics

Ambient Temperature – 125°C at ICE
105...115°C Coolant Inlet
Junction Temperature – 200°C (275°C/EU HOPE)
Simultaneously Increasing Reliability Requirements

High Temperature Power Electronics
Packaging Technology with Matched CTEs
High Power Density – 50kVA/l

State of the Art

System Efficiency to be increased to 95% in 2015, other Parameters as for 2010

Status based on PNGV (Partnership for New Generation of Vehicles) Automotive IPEM and Automotive Electric Motor Drive Program PNGV Coolant Temp.: 70°C, Table shows Estimated Values for 105°C

Technology Gaps

Power Electronics
Electric Machines

<table>
<thead>
<tr>
<th>Power Electronics (inverter/controller)</th>
<th>2010 Target</th>
<th>2003 Status</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific power at peak load (kW/kg)</td>
<td>&gt;12</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Volumetric power density (kW/l)</td>
<td>&gt;12</td>
<td>11.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cost/kW peak</td>
<td>&gt;55</td>
<td>56</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>97</td>
<td>97</td>
<td>0</td>
</tr>
<tr>
<td>Coolant inlet temperature, °C</td>
<td>105</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>Lifespan, years</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traction Motor</th>
<th>2010 Target</th>
<th>2003 Status</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific power at peak load (kW/kg)</td>
<td>&gt;1.3</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Volumetric power density (kW/l)</td>
<td>&gt;55</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Cost/kW peak</td>
<td>&gt;55</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>&gt;93% at 10% max. speed</td>
<td>&gt;90% at 35% to 100% max. speed</td>
<td>10-34% max. speed</td>
</tr>
<tr>
<td>Voltage, V</td>
<td>525</td>
<td>325</td>
<td>0</td>
</tr>
<tr>
<td>Maximum current, A</td>
<td>40</td>
<td>415</td>
<td>0</td>
</tr>
<tr>
<td>Peak power for 15 seconds, kW</td>
<td>55</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>Continuous power, 8.5–85 mph</td>
<td>30 kW</td>
<td>30 kW, 8.5–77 mph</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propulsion System (Inverter &amp; Motor)</th>
<th>2010 Target</th>
<th>2003 Status</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific power at peak load (kW/kg)</td>
<td>&gt;1.2</td>
<td>0.95</td>
<td>0.25</td>
</tr>
<tr>
<td>Volumetric power density (kW/l)</td>
<td>&gt;3.5</td>
<td>2.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Cost/kW peak</td>
<td>&gt;512</td>
<td>521</td>
<td>0</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>&gt;90% at 10% max. speed</td>
<td>90 at 35% to 100% max. speed</td>
<td>10-34% max. speed</td>
</tr>
<tr>
<td>Lifespan, years</td>
<td>15</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

a) 2003 status based upon recent progress report from Semakron.
c) Approximated by adding inverter plus motor.
Technology Gaps for Power Electronics and Integrated Propulsion System

Normalized Power Electronics Gaps
- Specific Power at Peak Load (>12 kW/kg), Status 11.5 kW/kg
- Volumetric Power Density (>52 kW/l), Status 11 kW/l
- Lifetime (19 Years)
- Cost (200 W/J), Status $167 WS
- Efficiency (97%)

Normalized Propulsion System Gaps
- Specific Power at Peak Load (<1.2 kW/kg), Status 0.95 kW/kg
- Volumetric Power Density (<2.0 kW/l), Status 2.5 kW/l
- Efficiency (>95%)
- Status 93%
- Cost (>42 W/J)
- Status 48 WS

More Electric Aircraft
- Air Traffic Growth 4.7%/a

Variable Frequency Power Generation
- 270VDC Power Distribution
- Replacement of Hydraulic by Electric System
Technology Gaps for Power Electronics and Integrated Propulsion System

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- Specific Power at Peak Load (>12 kW/kg), Status 11.5 kW/kg
- Volumetric Power Density (>52 kW/l), Status 11 kW/l
- Efficiency (97%)
- Cost (200 W/€), Status $167 W/S
- Lifetime (19 Years)
- Coolant inlet Temperature (105°C), Status 70°C

Normalized Propulsion System Gaps
- Specific Power at Peak Load (<1.2 kW/kg), Status 0.95 kW/kg
- Volumetric Power Density (<2.9 kW/l), Status 2.5 kW/l
- Efficiency (>90%)
- Cost (<42 W/€), Status 48 W/S
- Lifetime (15 Years)

More Electric Aircraft
Air Traffic Growth 4.7%/a

Variable Frequency Power Generation
270VDC Power Distribution
Replacement of Hydraulic by Electric System
More Electric Fighter Aircraft
Integrated Power Unit

Research Programs
Reduced Size and Mass Power Electronic Systems
High Temperature Electronics

Near Term (3 – 5 years)
250...300°C max Component Temp.
Eliminates need for Active Cooling

Far Term (5 – 9 years)
300...350°C max.
Supports ‘High Speed’ Aircraft

More Electric Aircraft
Flight Control
Surface Actuation

EHA  Electro-Hydrostatic Actuator
EMA  Electro-Mechanical Actuator
More Electric Fighter Aircraft
Integrated Power Unit

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Three-Phase AC/DC Power Conversion with Low Effects on the Aircraft Mains

Unidirectional Buck+Boost Converter

Unidirectional Three-Level Boost Converter

Three-Phase PMW Rectifier

Specifications

- 10 kW
- 3-Φ 480V<sub>AC</sub>
- 800 V<sub>DC</sub>
- 500 kHz
- 10 kW/dm<sup>3</sup>

Novel Technologies

- COOLMOS / SiC-Diodes
- Micro-Channel Heat Sink
- High-Speed DSP-Control
- Flat Magnetics
- HBW & CMR Current Sensing
More Electric Aircraft

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- High-Speed DSP-Control
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- HBW & CMR Current Sensing
Switching Loss Measurements

Turn-on
Turn-off

\[ P_0 = 10\text{kW} \]
\[ U_N = 185\text{V} \]

\[ \text{THD} = 2.06\% \]
\[ \eta > 96\% \text{, } P_0 = 3\text{...}10\text{kW} \]
Switching Loss Measurements

Turn-on

Turn-off

Three-Phase PMW Rectifier Performance

\[ THD = 2\% \text{ @ } P_0 = 10kW \]
\[ \eta > 96\%, P_0 = 3...10kW \]
Partitioning of the Converter Volume

Main Share of Passive Components
Increase of Switching Frequency

EMC Input Filter

30% Power Circuit / Cooling

30% Electrolytic Capacitors

Specifications
17.5kW
400V_{AC}
800V_{DC}

Free-Wheeling Diodes 2 x 10A SiC
Power Transistor CoolMOS 600V/45A

Novel Three-Phase PMW Rectifier Power Module
Partitioning of the Converter Volume

EMC Input Filter

30%

Power Circuit / Cooling

30%

- 30%

Electrolytic Capacitors

Main Share of Passive Components

Increase of Switching Frequency

Specifications

17.5kW
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Power Transistor CoolMOS 600V/45A
ETH Zurich
SiC Power Electronics Research

Three-Phase 10k/1 PWM Rectifier
Three-Phase All-SiC Matrix
Three-Phase All-SiC PWM Inverter
Autonomous Drilling Robot
High-Frequency Active Filter

Autonomous Deep Drilling Robot

120kW Down-Hole Electric Drilling Actuator
5kV<sub>dc</sub> Power Supply
5km Maximum Supply Length
250°C Max. Operating Temp.

Power & Data Transmission via Highly Flexible Composite Coiled Tube

NASA – Honeybee Robotics Inchworm Deep Surface Platform
ETH Zurich
SiC Power Electronics Research

Three-Phase 10k/l PWM Rectifier
Three-Phase All-SiC Matrix
Three-Phase All-SiC PWM Inverter
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Autonomous Drilling Robot

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5kV \text{p.c.} \quad \text{Power Supply}
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Inchworm Deep Subsurface Platform

Power & Data Transmission via Highly Flexible Composite Coiled Tube

NASA – Honeybee Robotics
Inchworm Deep Surface Platform
Autonomous Deep Drilling Robot

Ultra-Compact Drilling Actuator
Power Electronics

Input Stage
5kV$_{DC}$ → 800V$_{DC}$
20…50 kHz

Actuator Modules

6 GHZ.VA
Switching Frequency
Power Product for Ultra Compact System Realization
Autonomous Deep Drilling Robot

Ultra-Compact Drilling Actuator
Power Electronics

Input Stage
5kV_{DC} \rightarrow 800V_{DC}
20...50 kHz

6 GHZ.VA
Switching Frequency
Power Product for Ultra Compact System Realization
Highly Dynamic High-Voltage Active Filter

Si-Multi-Level Converter
Replaced by SiC-2-Level System
With Factor 10 Higher Switching Frequency

Technology Gaps

- High Temperature Packaging
- High Temperature Passives (Capacitors, Magnetics)
- High Temperature Control Circuits
- High Temperature Sensors

Advanced Cooling Systems

- High Frequency / High Current Interconnection Technology
- High dv/dt Gate Drive (Optically Controlled Switch)
- High Frequency High Voltage Passives
- Advanced EMI Filtering / Parasitics Cancellation
Highly Dynamic High-Voltage Active Filter

Si-Multi-Level Converter
Replaced by SiC-2-Level System
With Factor 10 Higher Switching Frequency

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Planar Power Polymer Packaging (P4TM)

Oriented to High Power Devices
< 2400V / 100...500A
< 200W Device Dissipations

Wire-bonded Die on Ceramic Substrate
Replaced with Planar Polymer-based Interconnect Structure
Direct High-conductivity Cooling Path

- Reduces Wire Bond Resistance by Factor 100
- Significantly Lower Switching Overvoltages
- Reduced Switching Losses
- No Ringing
- Reduces EMI Radiation
- Enables Topside Cooling
- No Mechanical Stress of Wire Bonding
- Reduces CTE Wire Bond Stress of Chip Pads
Planar Power Polymer Packaging (P4TM)

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CROSS SECTION OF A POWER OVERLAY MODULE

DOUBLE-SIDED COOLING OF A POWER OVERLAY MODULE
Future

Higher Temperatures
Higher Powers
Higher Frequencies
Higher Efficiencies

HOT
HARD
FAST
Future

Higher Temperatures
Higher Powers
Higher Frequencies
Higher Efficiencies

HOT
HARD
FAST