SiC User Forum

Use of SiC Components in Power Electronic Systems

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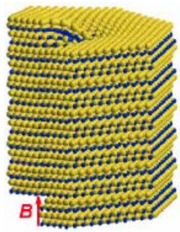
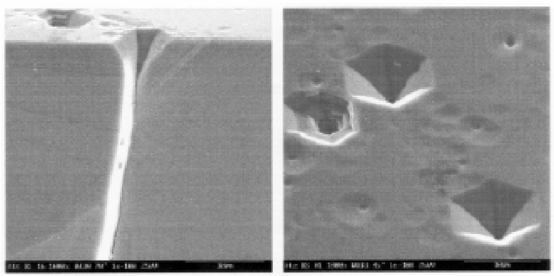
Outline

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

SiC Power Semiconductor Devices

Challenges





Cross section   Top view

SiC Wafer Defects – Micropipes and Screw Dislocation Causing Low Processing Yield
<5/cm^2 Ultra-Low MP Density

<3/cm^2 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

C.M. Zetterling/KTH

at 300 K	Si	GaAs	4H/6H-SiC	GaN
Eg (eV)	1.12	1.4	3.0-3.2	3.4
Ec (MV/cm)	0.25	0.3	2.2-2.5	3
μn (cm²/Vs)	1350	8500	100-1000	1000
εr	11.9	13	10	9.5
Vsat (cm/s)	$1x10^7$	$1x10^7$	$2x10^7$	$3x10^7$
λ (W/cmK)	1.5	0.5	3 - 5	1.3

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

Influence of E_c on Device Performance

Consider pn-Junction

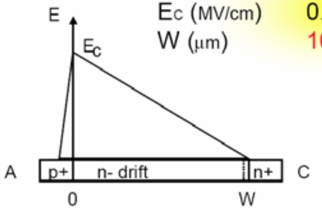
Design for High Blocking Voltage / Low On-Resistance
Proper Selection of N_D and $W \longrightarrow$ $E=0$ for $x=W$

FOM (Figure of Merit) $\dfrac{V_B^2}{R_{on,sp}}$

C.M. Zetterling/KTH

Non punch-through design for 1 kV:

	Si	SiC
Ec (MV/cm)	0.25	2.5
W (μm)	100	10



$$V_B = \frac{W E_C}{2}$$

$$\frac{E_C}{W} = \frac{1}{\varepsilon} q N_D$$

$$W \approx \sqrt{\frac{2\varepsilon V_B}{q N_D}} \qquad N_D = \frac{2\varepsilon V_B}{q W^2} = \frac{\varepsilon E_C^2}{2 q V_B}$$

For 1 kV:	Si	SiC
W (μm)	100	10
ND (cm^{-3})	10^{14}	10^{16}

$$R_{on,sp} = R.A$$

$$R_{on,sp} = \frac{W}{q \mu_n N_D} = \frac{4 V_B^2}{\varepsilon \mu_n E_C^3}$$

$$\frac{V_B^2}{R_{on,sp}} = \frac{\varepsilon \mu_n E_C^3}{4}$$

Influence of E_c on Device Performance

High Voltage (Unipolar) Devices

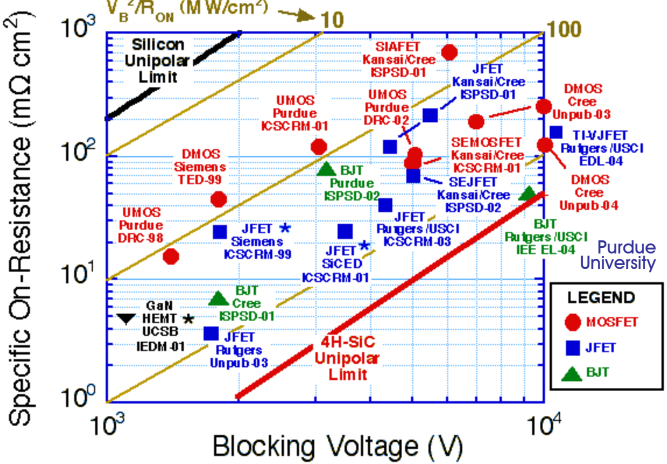
$$R_{on,sp} = R.A$$

A... *area*

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

$W_{SiC} = 1/10\ W_{Si}$
$v_{sat\ SiC} = 3\ v_{sat\ Si}$

$$\tau = \frac{W}{2 v_{sat}} \qquad C \propto \varepsilon_r$$

C.M. Zetterling/KTH

at 300 K	Si	GaAs	4H/6H-SiC	GaN
Ec (MV/cm)	0.25	0.3	2.2-2.5	3
ε_r	11.9	13	10	9.5
Vsat (cm/s)	1×10^7	1×10^7	2×10^7	3×10^7

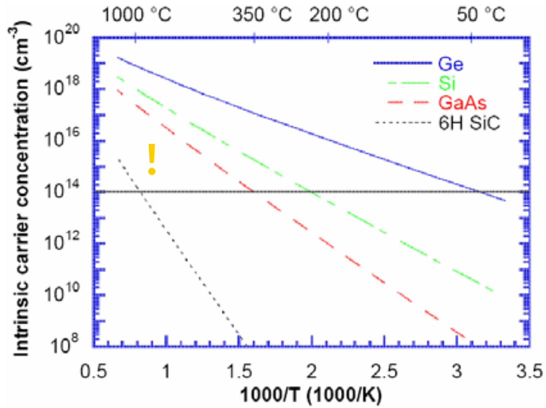
SiC Power Switching Device Properties

High Temperature Devices

Intrinsic Carrier Concentration N_i Exponentially Dependent on Bandgap E_g

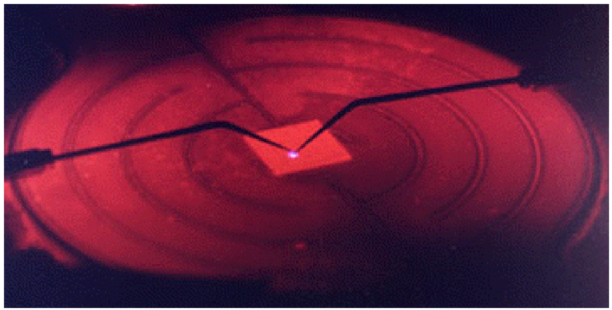
N_i must not Exceed Doping Level

C.M. Zetterling/KTH



SiC Power Switching Device Properties

High Temperature Devices



SiC Rectifier Diode Probe-Tested at 600ºC

SiC Power Switching Device Properties

High Power Devices

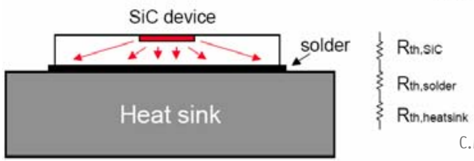
$$\boxed{\Delta T = R_{TH}\, P = \frac{l}{\lambda\, A} P}$$

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

Junction Temperature Rise Proportional to Power and Thermal Resistance

W_{SiC} = 1/10 W_{Si}
Low Thermal Resistance

High Device Temperature Requires Advanced Packaging / Cooling

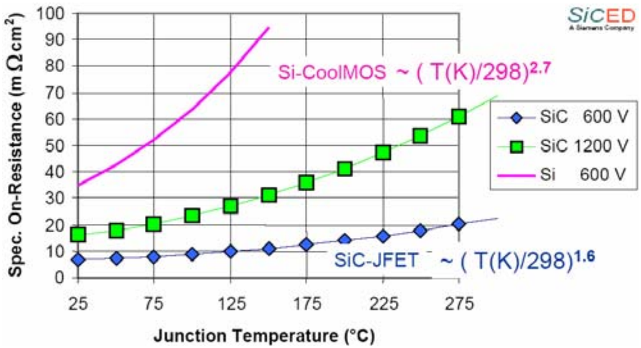


C.M. Zetterling/KTH

Summary of SiC Power Switching Device Properties

High Blocking Capability
High Switching Frequency
High Operating Temperature

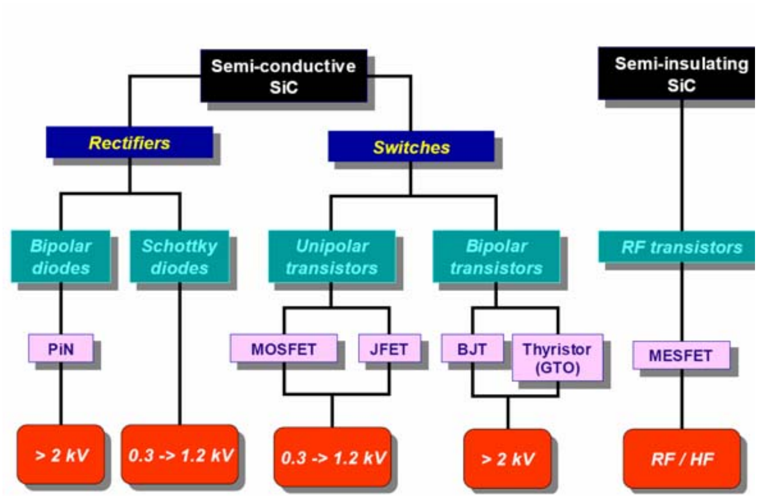
Low On-Resistance



Basic Types of SiC Power Switching Devices

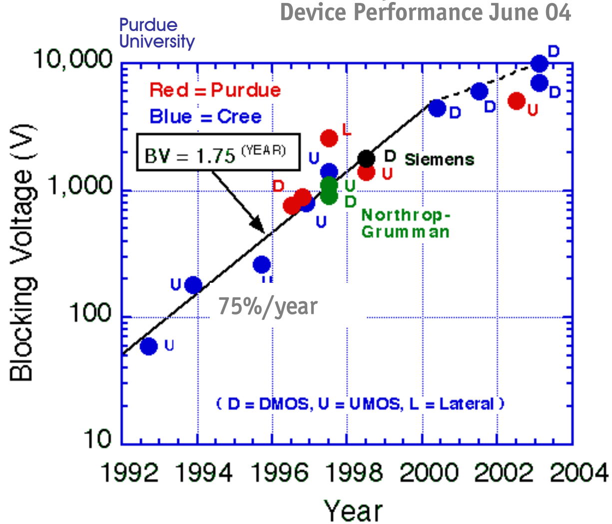
SiC pn-Diode Threshold is ≈*3V* due to large Bandgap *Eg=3.3eV*

Potential of Bipolar Devices only for V_B> 4...5kV



Progress in Blocking Voltage of SiC Power MOSFETs

Best Reported WBG Power
Device Performance June 04

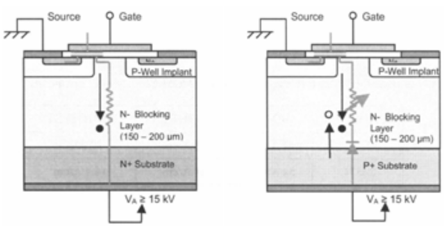


MOSFET → IGBT
Conductivity Modulation Could Reduce On-Resistance but Minority Carrier Charge must be Removed before Blocking – Results in Switching Losses

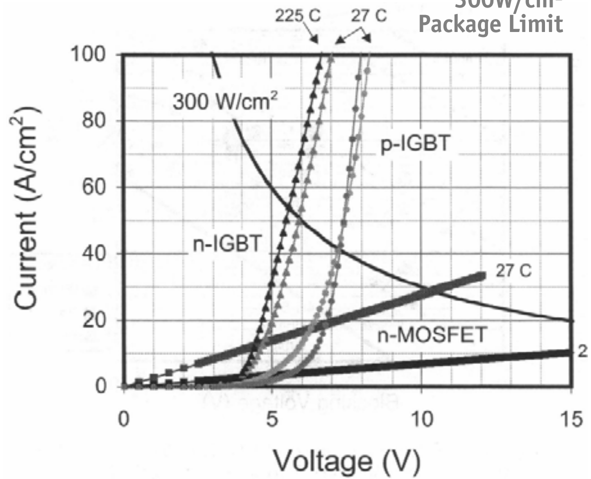
Comparison of Unipolar and Bipolar SiC Power Switching Devices

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

Significantly Higher Current of IGBTs at Package Limit



300W/cm² Package Limit



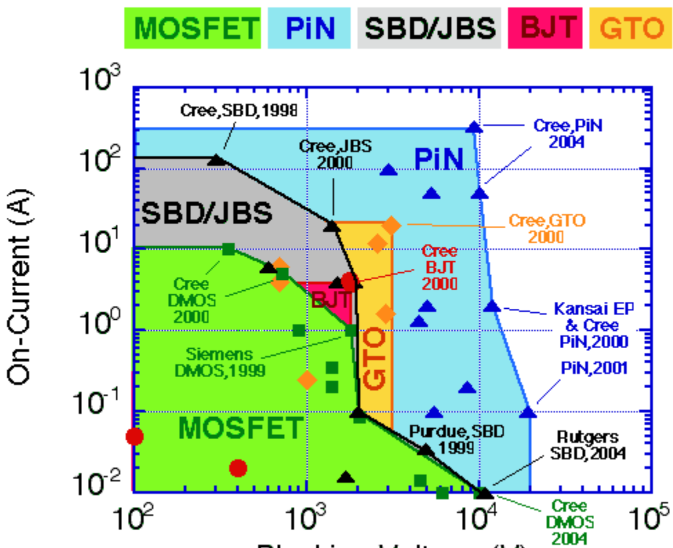
SiC Power Switching Devices
Performance Envelope

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

Purdue University



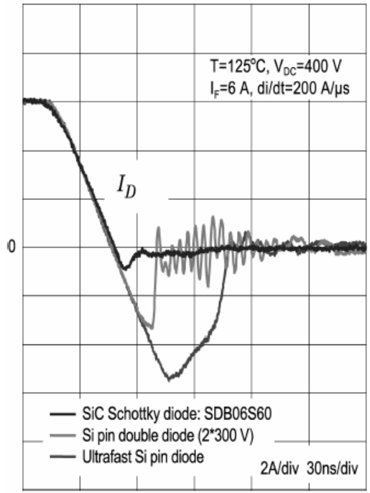
SiC Power Semiconductor Devices

SiCED
A Siemens Company

SiC Schottky Diodes	600V 1200V 1700V	35A 25A 40A
SiC MPS Diodes	> 2kV	15A
SiC Bipolar Diodes	> 4kV	12A
SiC J-FETs	1200V 1800V	5A /10A 3A / 8A

600V SiC Schottky Diode

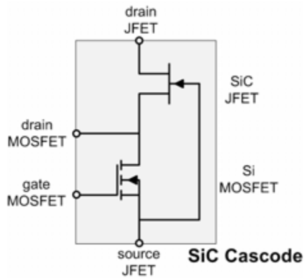
Positive Temp. Coefficient of V_F
No Reverse Recovery Current

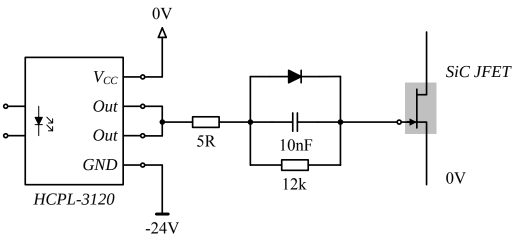


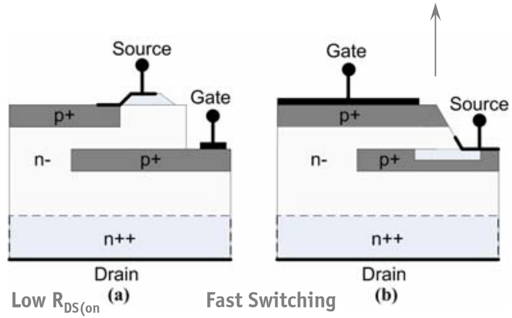
SiC J-FET

SiC J-FET
Si Low-Voltage MOSFET
Cascode

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

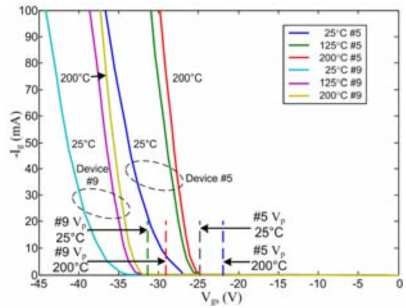




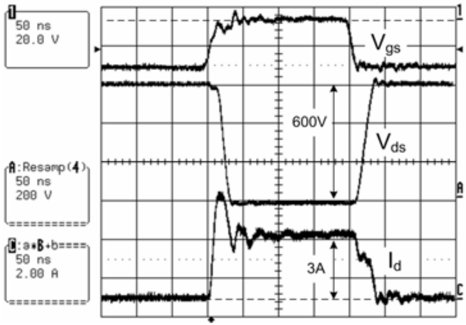


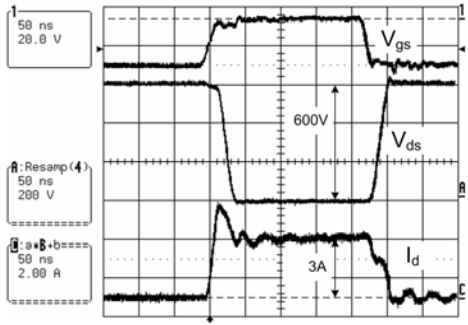
SiC J-FET Switching Characteristics

Pinch-Off Voltage



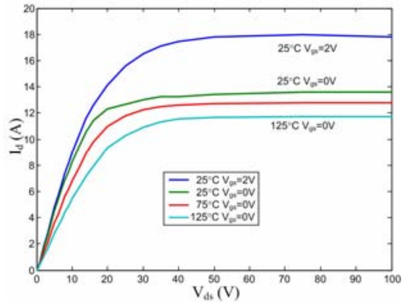
dv/dt $_{max}$ = 50kV/μs





SiC J-FET Switching Characteristics

Output Transfer Characteristic



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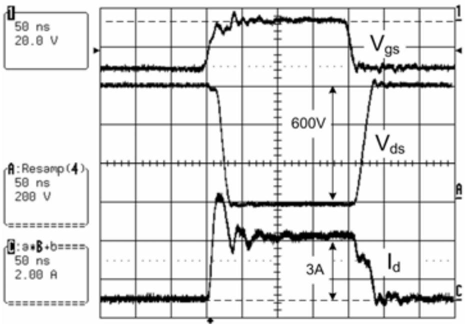
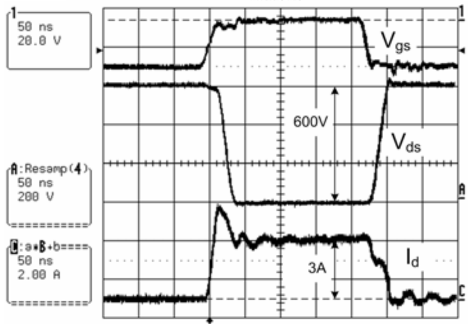
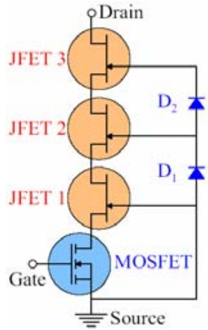




Stacked High-Voltage SiC J-FET Switch

SiCED
A Siemens Company

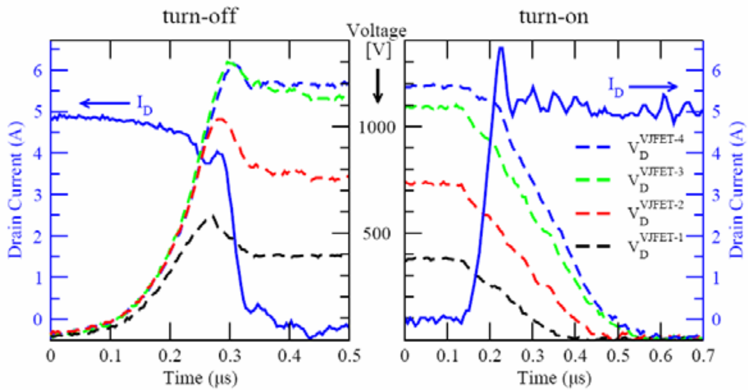


Alternative to Realization of a Single High Voltage Bipolar Switch - Problem of Thick Epi Layer Growth

Si Diodes with Stable Avalanche Determine Static Blocking Voltage Distribution

4-Stack 8kV / 10A / 2Ω

SEMIKRON
innovation+service



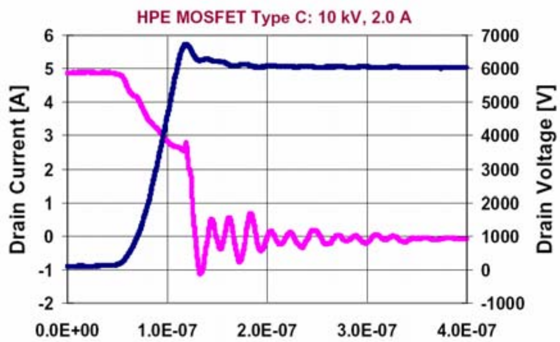
High-Voltage High-Frequency SiC Devices

Defense Advanced
Research Project Agency
Hefner /NIST

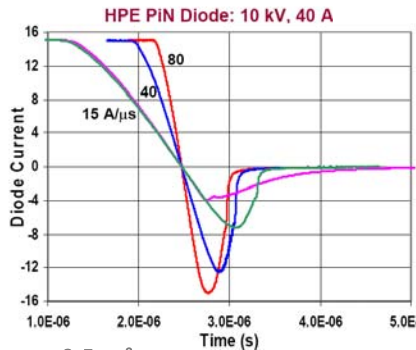
Future Target 15kV / 20kHz, T_j=200°C PiN Diode, MOSFET, IGBT

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



0.048cm² Time [s]



0.5cm²

SiC Power Semiconductor Application Areas

Low-Voltage

Mature Technology
Applications with High Potential Volumes

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

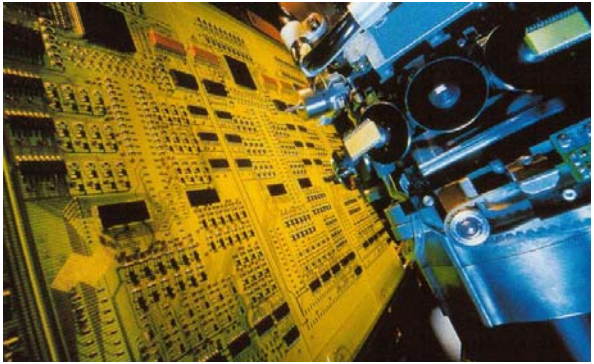
High-Voltage

Rapid Development

- Utility / Power Distribution
- Military Research Platforms

Drive Systems

60% of Electric Energy Utilized in Germany consumed by Drives



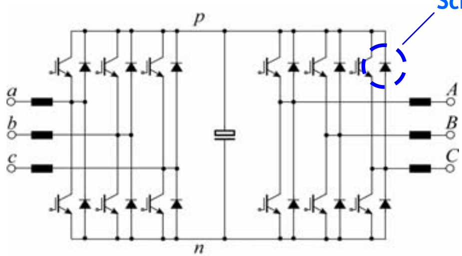
5%   Employing Electronic Speed Control
35% Possible Share / 40% Energy Saving Potential (16TWh)

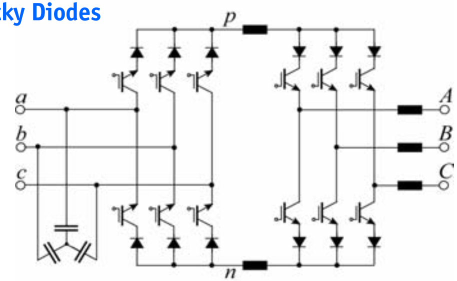
400TWh Drives Energy Consumption in the EU
60% Energy Saving Potential

Drive Systems

Active Front-End

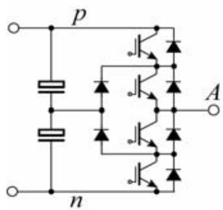
1200V SiC
Schottky Diodes

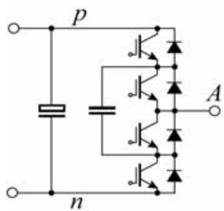


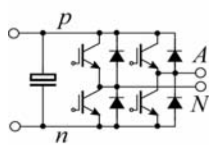


Multi-Level Converter Topologies

High-Voltage High-Frequency Replacing
2-Level Systems Converters







Three-Phase
PWM Inverter

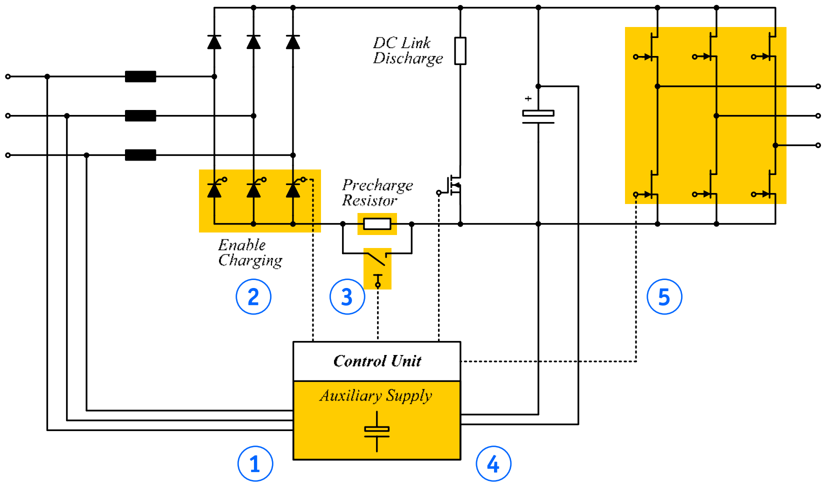
Inverter Phase-Leg as demonstrated by KEPCO (Kansai Electric Power Company,Osaka/Japan) and CREE in Feb. 2006

8 mm x 8 mm Chip Size
6 mm x 6mm PiN diode

Metal Can Package Utilizing New High-Temperature Resin (up to 300°C) for Dielectric Insulation

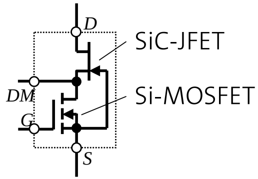
110kVA / Switching Frequency 2kHz
4.5kV/100A SiC Gate-Turn-Off Thyristors
2us Turn-Off Time
No Snubber

SiC-J-FET PWM Inverter Stage



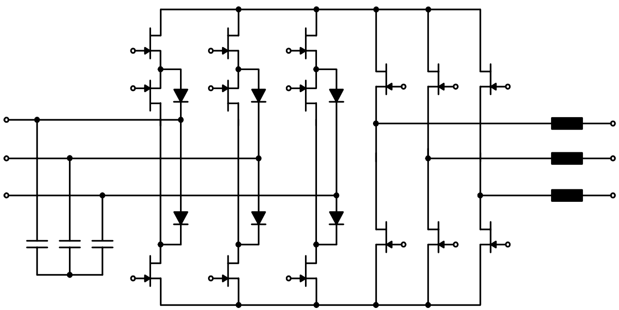
Concept for Normally-On Inverter Operation

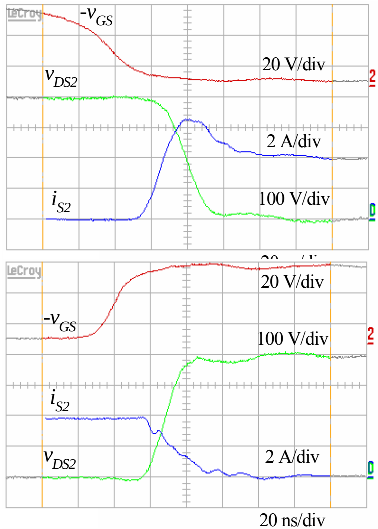
All-SiC-Sparse Matrix Converter



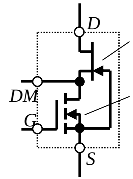
1300V, 4A IXYS i4-Pack, SiCED
1200V, 5A CREE SiC CSD05120

Switching Frequency	100kHz
Output Power	1.5kW
Efficiency	η = 94%





All-SiC-Sparse Matrix Converter



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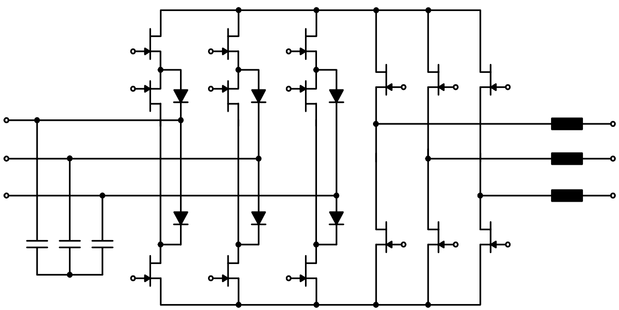
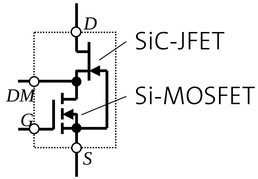


All-SiC-Sparse Matrix Converter



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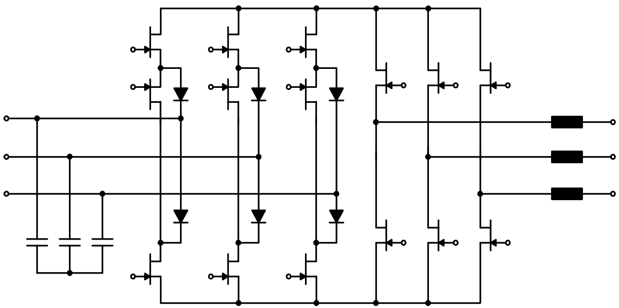
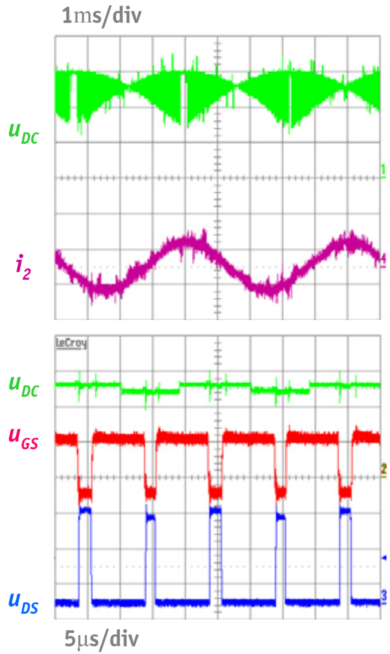
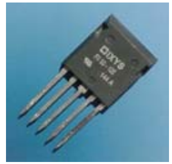




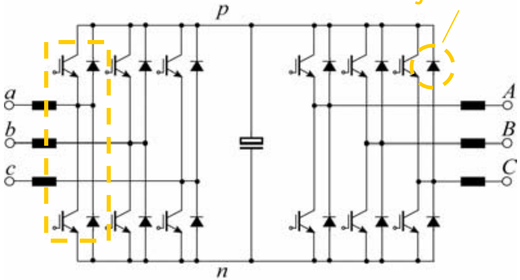
Comparative
Evaluation of Si-IGBT/SiC Diode
BBC and IMC

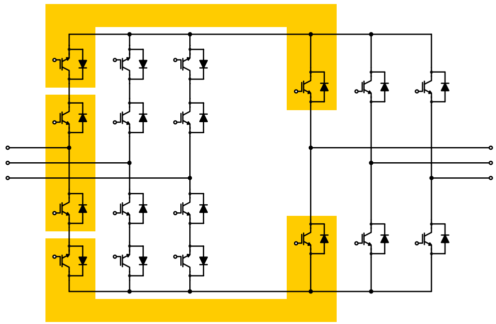
Isolated Half-Bridge
Packages Integrating Si-IGBTs and
SiC Schottky Diodes



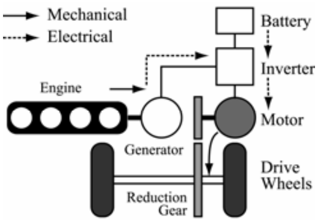
IXYS
FIO 50-12E

1200V SiC
Schottky Diodes

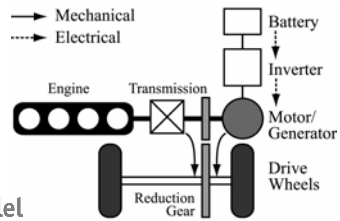




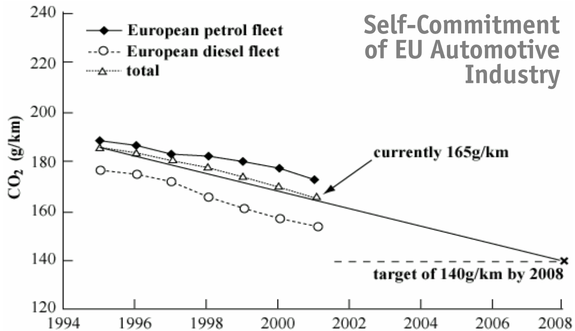
Hybrid Car



Series



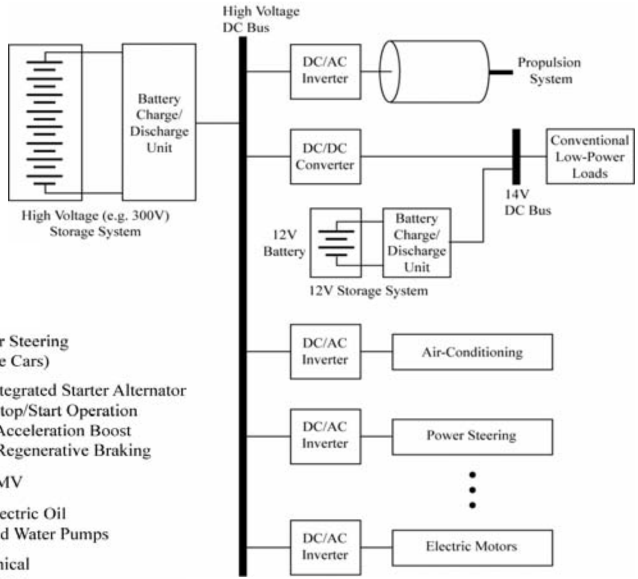
Parallel

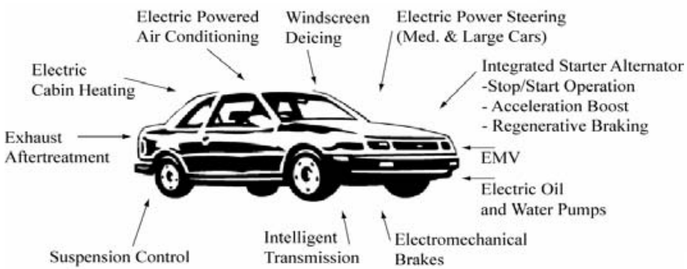


Hybrid Car

Power System Architecture

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



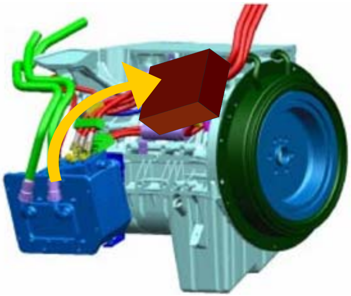


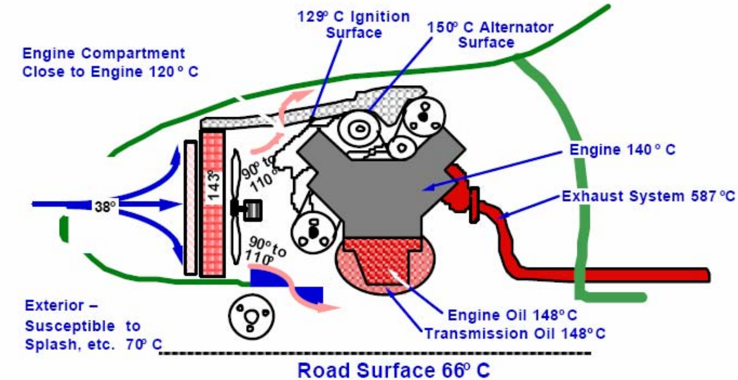
Future Motor-Integrated Power Electronics

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





FreedomCAR

Technology Gaps Power Electronics Electric Machines

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

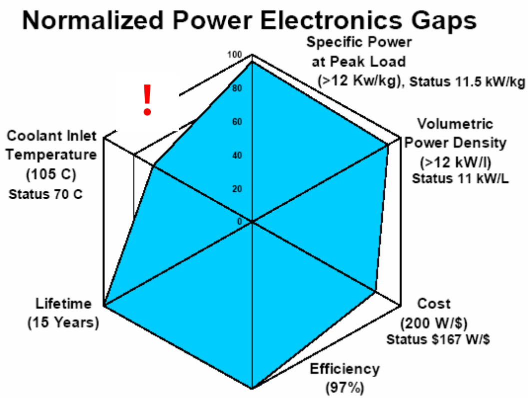
Status based on PNGV (Partnership for New Generation of Vehicles) Automotive IPEM and Automotive Electric Motor Drive Program PNGV Coolant Temp.: 70°C, Table shows Estimated Values for 105°C

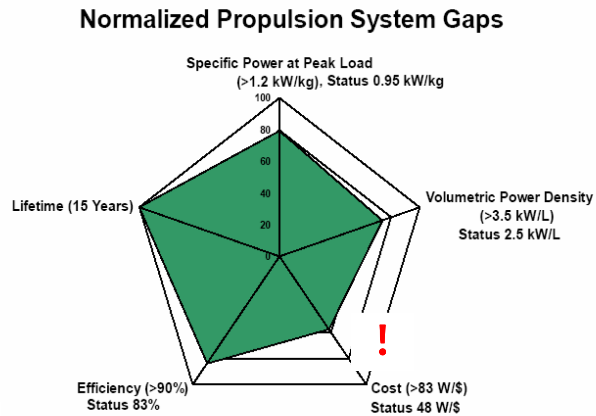
Power Electronics (inverter/controller)[a]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>12	11	1
Volumetric power density (kW/l)	>12	11.5	0.5
Cost /kW peak	<$5	$6	$1
Efficiency, %	97	97	0
Coolant inlet temperature, °C	105	70	35
Lifetime, years	15	15	0
Traction Motor[b]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>1.3	1.0	0.3
Volumetric power density (kW/l)	>5	3.5	1.5
Cost/kW peak	<$7	$15	$8
Efficiency, %	>93 at 10% to 100% max. speed	>90 at 35% to 100% max. speed	10-34% max. speed
Voltage, V	325	325	0
Maximum current, A rms	400	415	15
Peak power for 18 seconds, kW	55	55	0
Continuous power, 8.5-85 mph	30 kW	30 kW, 8.5-77 mph	77-85 mph
Propulsion System (Inverter & Motor)[c]			
	2010 Target	**2003 Status**	**Gap**
Specific power at peak load (kW/kg)	>1.2	0.95	0.25
Volumetric power density (kW/l)	>3.5	2.5	0.9
Cost /kW peak	<$12	$21	$9
Efficiency, %	>90% at 10% to 100% max. speed	90 at 35% to 100% max. speed	10-34% max. speed
Lifetime, years	15	15	0

a) 2003 status based upon recent progress report from Semikron.
b) 2003 status based upon progress review by Delphi on June 13, 2003.
c) Approximated by adding inverter plus motor.

FreedomCAR

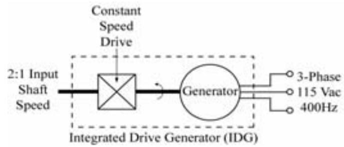
Technology Gaps for Power Electronics and Integrated Propulsion System



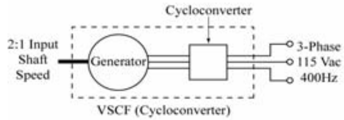


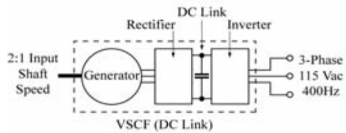
More Electric Aircraft

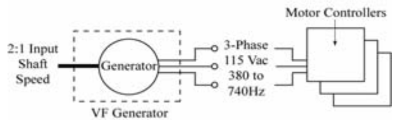
Air Traffic Growth 4.7%/a



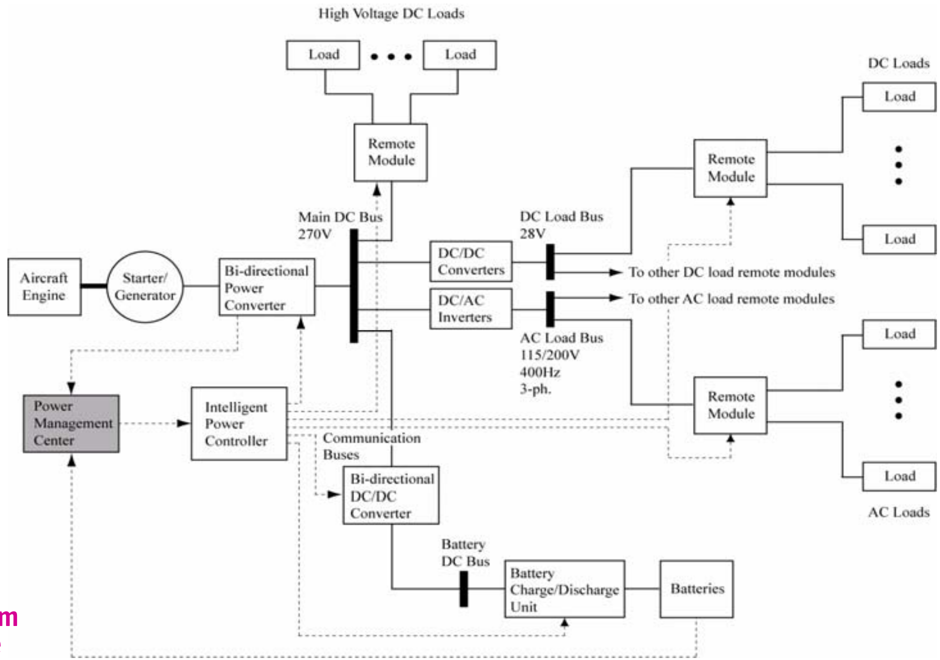
Variable Frequency Power Generation
$270V_{DC}$ Power Distribution
Replacement of Hydraulic by Electric System





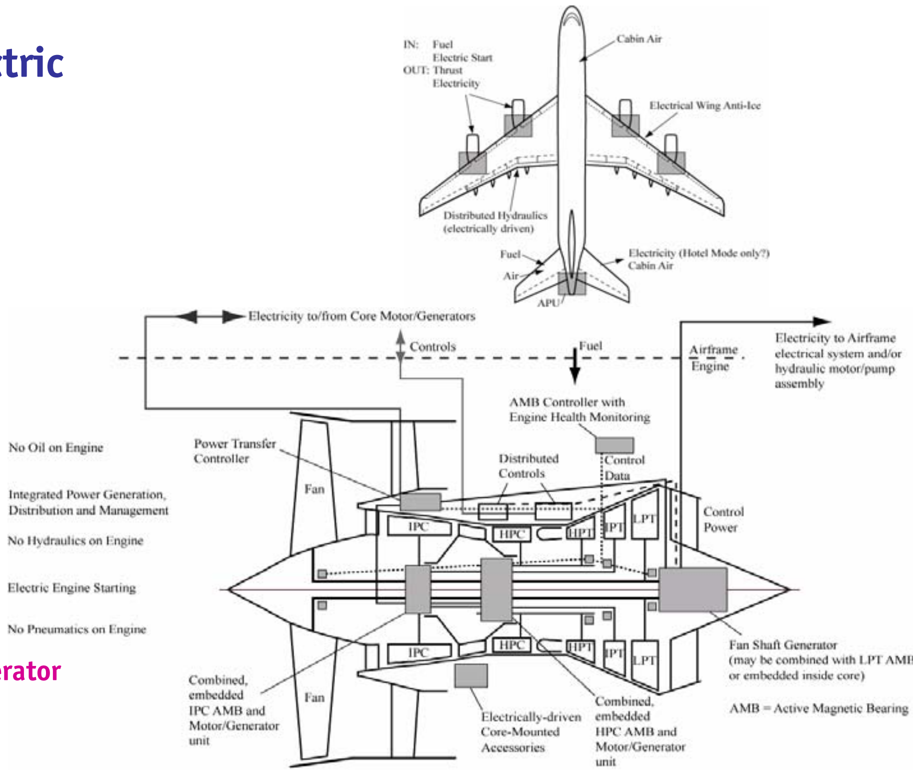


More Electric Aircraft



Power System Architecture

More Electric Aircraft



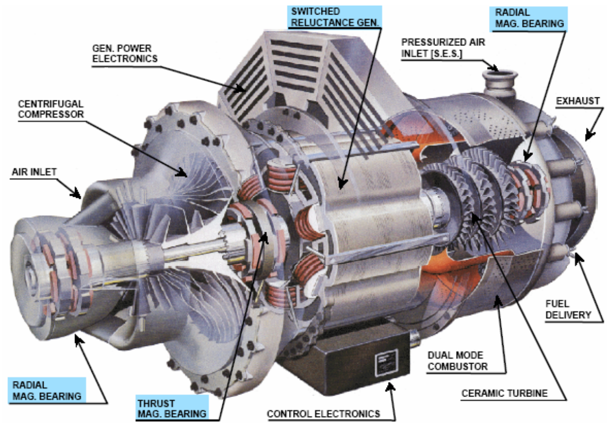
Starter / Generator System

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

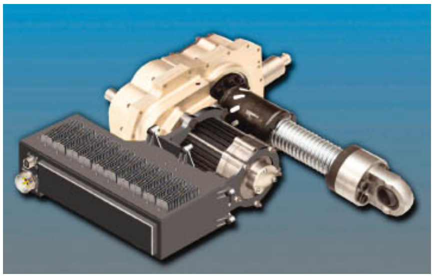


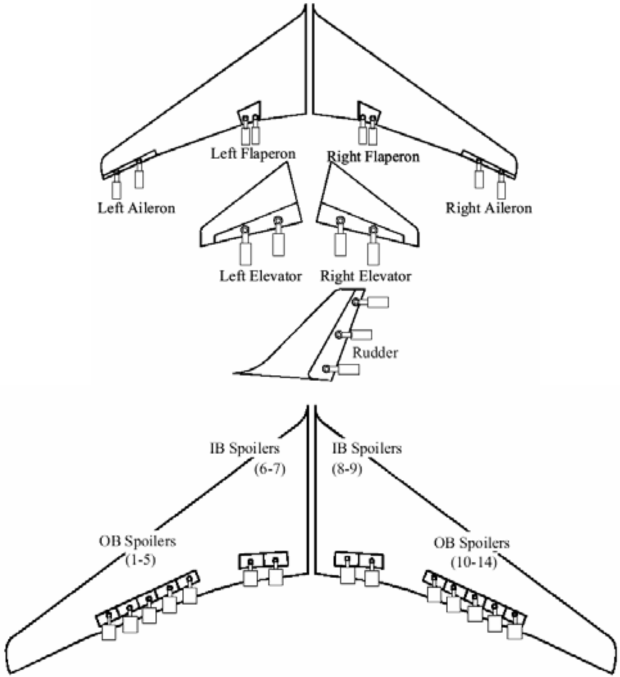
US Air Force Research Laboratory

More Electric Aircraft

Flight Control
Surface Actuation

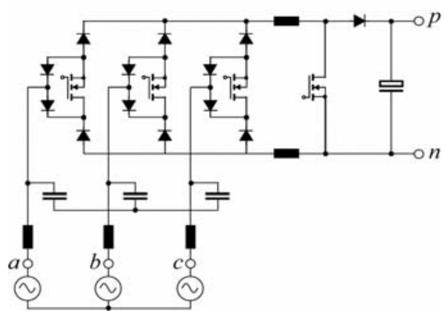
EHA Electro-Hydrostatic Actuator
EMA Electro-Mechanical Actuator



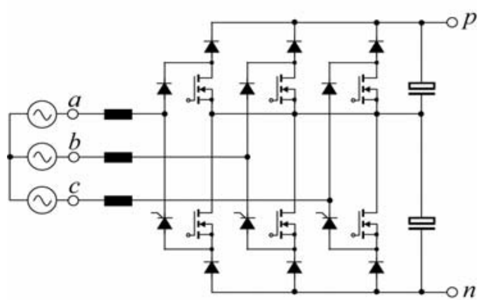


More Electric Aircraft

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



Unidirectional
Buck+Boost Converter

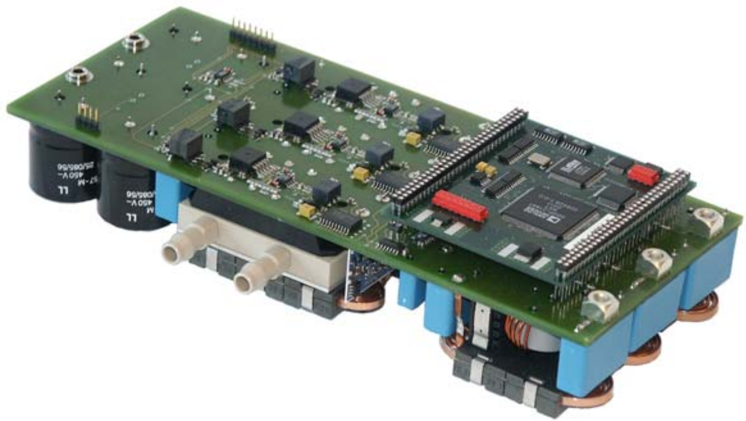


Unidirectional Three-Level
Boost Converter

Three-Phase PMW Rectifier

Specifications

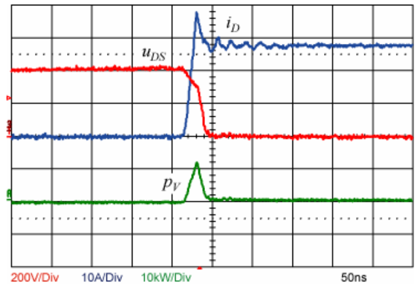
10 kW
3-Φ 480V_{AC}
800 V_{DC}
500 kHz
10 kW/dm^3



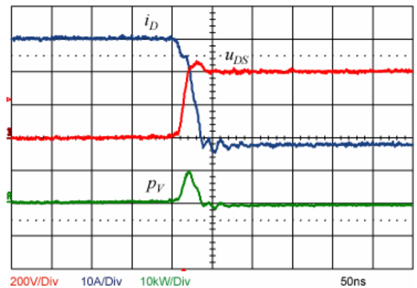
Novel Technologies

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

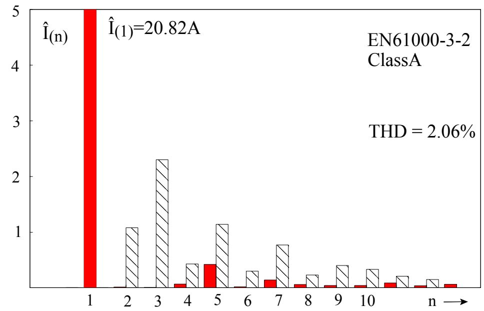
Switching Loss Measurements



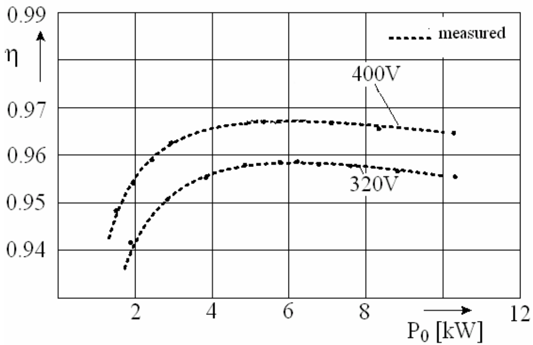
Turn-on
Turn-off

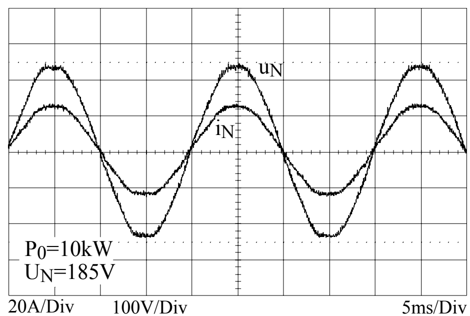


Three-Phase PMW Rectifier Performance

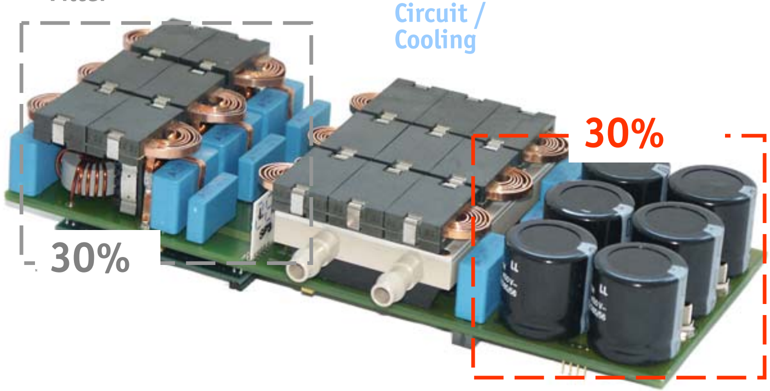


THD =2% @ P_0=10kW
η > 96%, P_0=3...10kW





Partitioning of the Converter Volume



Main Share of Passive Components

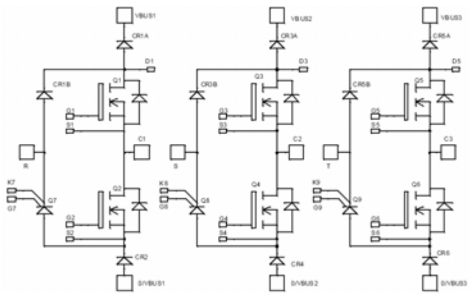
Increase of Switching Frequency

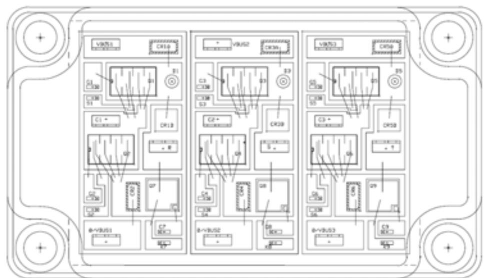
Novel Three-Phase PMW Rectifier Power Module

Specifications

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

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



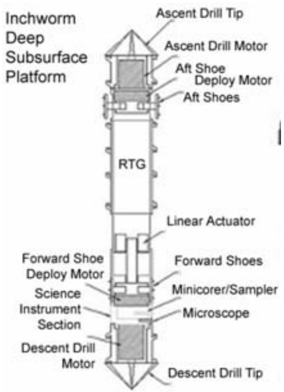


ETH Zurich
SiC Power Electronics
Research

Three-Phase 10k/l 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
$5kV_{DC}$ Power Supply
5km Maximum Supply Length
250°C Max. Operating Temp.



NASA –
Honeybee Robotics
Inchworm Deep Surface Platform

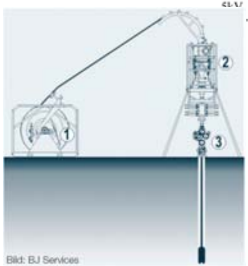
Power & Data Transmission via Highly Flexible Composite Coiled Tube

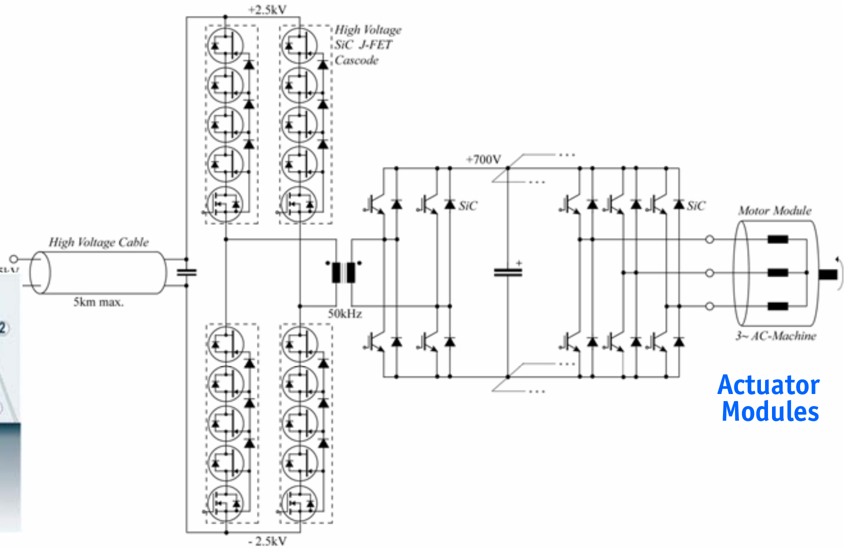
Autonomous
Deep Drilling Robot

Ultra-Compact Drilling Actuator Power Electronics

Input Stage

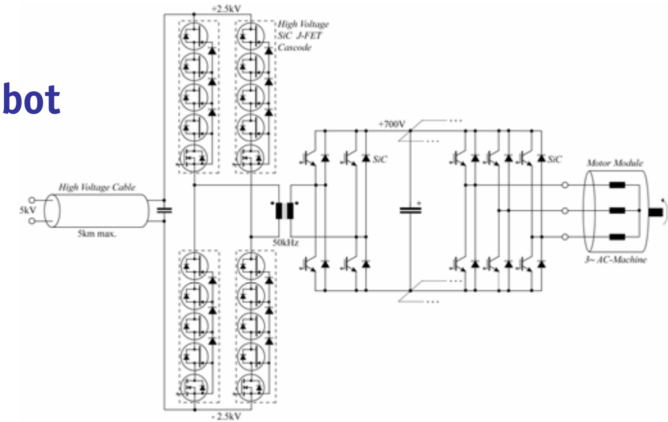
$5kV_{DC} \rightarrow 800V_{DC}$
20...50 kHz

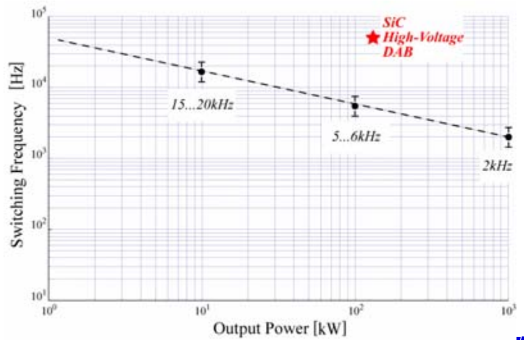




Actuator
Modules

Autonomous
Deep Drilling Robot



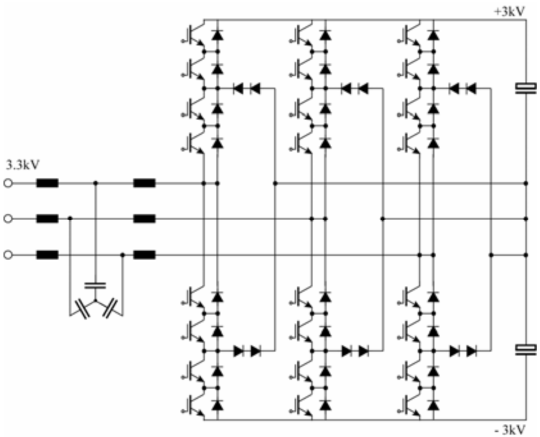


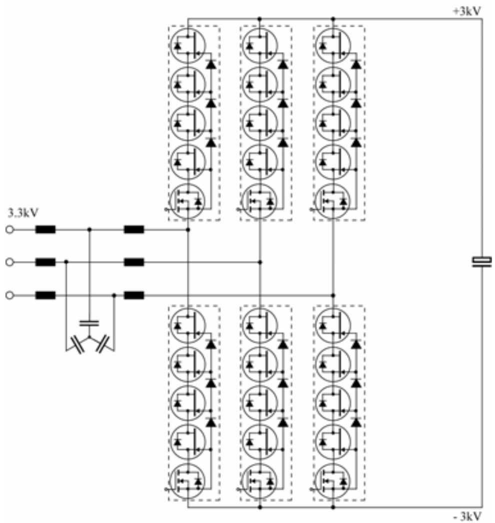
6 GHZ.VA

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

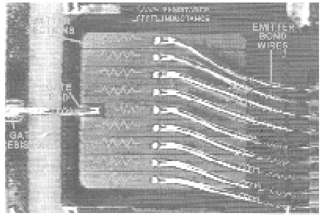
- High Temperature Packaging
- High Temperature Passives (Capacitors, Magnetics)
- High Temperature Control Circuits
- High Temperature Sensors

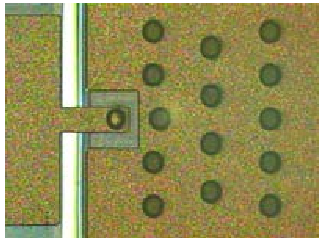
Advanced Cooling Systems

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

Planar Power Polymer Packaging (P4TM)

GE Global Research
United States - India - China - Germany





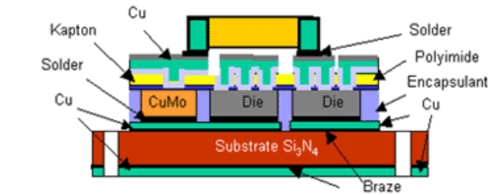
Oriented to High Power Devices
< 2400V / 100…500A
< 200W Device Dissipations

Wire-bonded Die on Ceramic Substrate Replaced with Planar Polymer-based Interconnect Structure

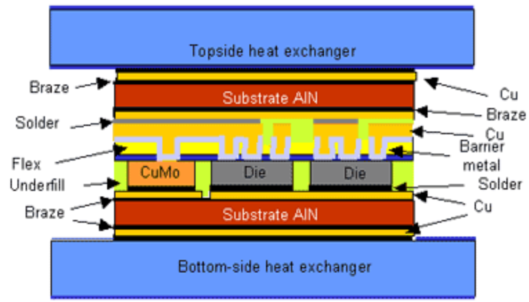
Direct High-conductivity Cooling Path

Planar Power Polymer Packaging (P4^{TM})

CROSS SECTION OF A POWER OVERLAY MODULE



DOUBLE-SIDED COOLING OF A POWER OVERLAY MODULE

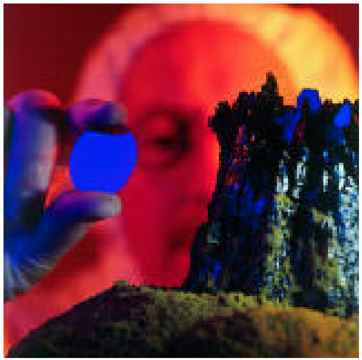


- Reduces Wire Bond Resistance by Factor 100
- Significantly Lower Switching Overvoltages
- Reduced Switching Losses
- No Ringing
- Reduces EMI Radiation
- Enables Topside Cooling
- No Mechanical Stress of Wire Boding
- Reduces CTE Wire Bond Stress of Chip Pads

Future

Higher Temperatures
Higher Powers
Higher Frequencies
Higher Efficiencies

Future



HOT
HARD
FAST