Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
College of Engineering

The Center for Power Electronics Systems – High Density Integration Research

Dushan Boroyevich

presented at:

Packaging Review On-site Workshop

Georgia Tech, Atlanta, GA

June 7, 2016

Center for Power Electronics Systems

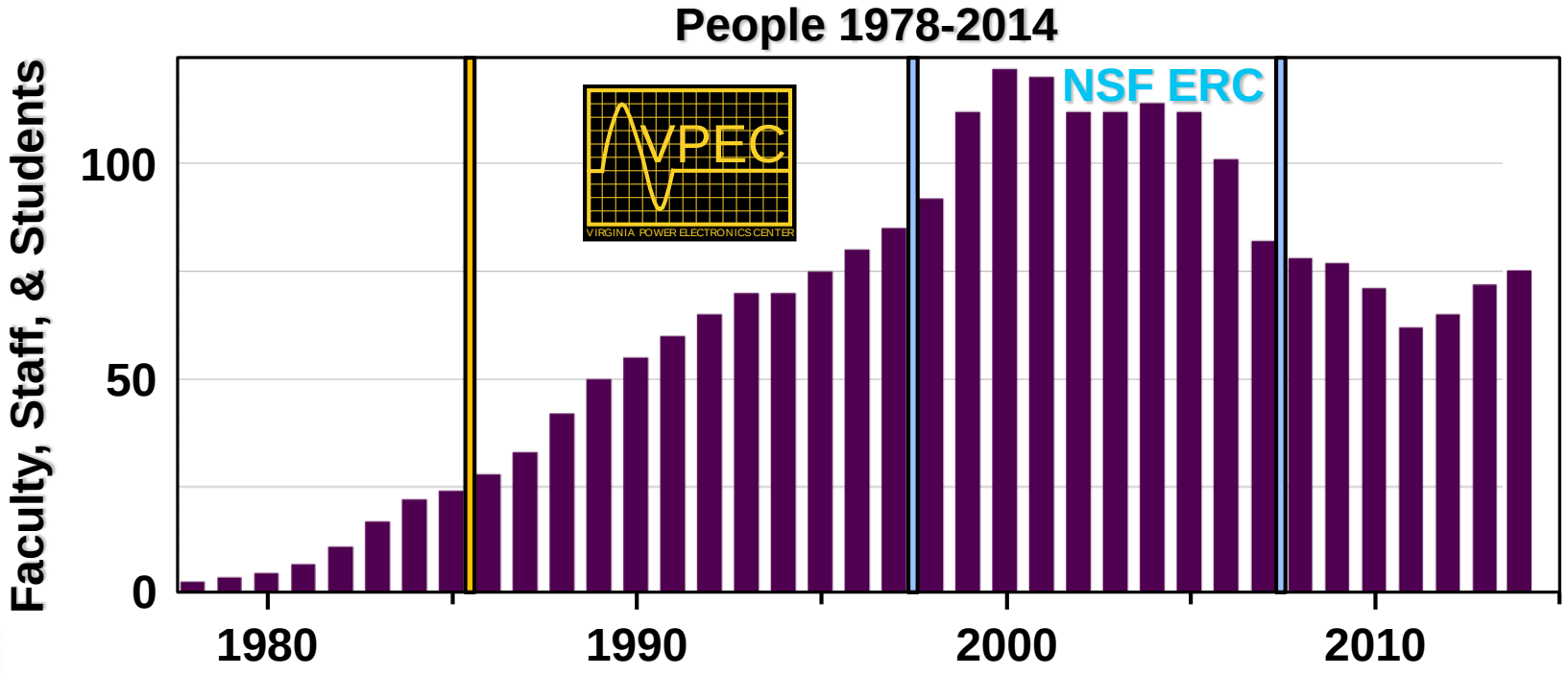
Professors:

Fred C. Lee, Director
Dushan Boroyevich, Co-Director
Khai D. T. Ngo
Rolando Burgos
Qiang Li

Annual Research Expenditures $4-5 million

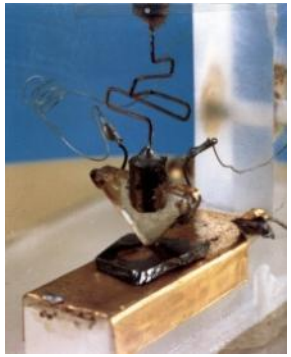
Other:

1	Adjunct/Affiliate Faculty
6	Research Associates
4	Full-time Staff
2	Part-time Staff
14	Visiting Scholars
44	**Doctoral Students**
4	**Masters Students**

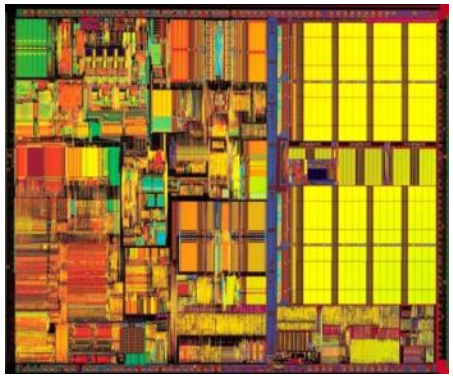


What is the Future of Power Electronics?

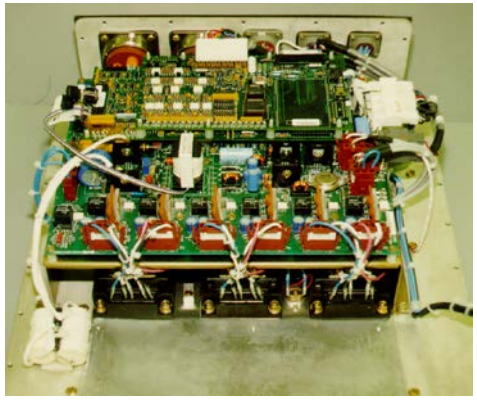
Micro-electronics



Moore's Law: "Every 1.5 years the cost of a 'bit' drops 50%."

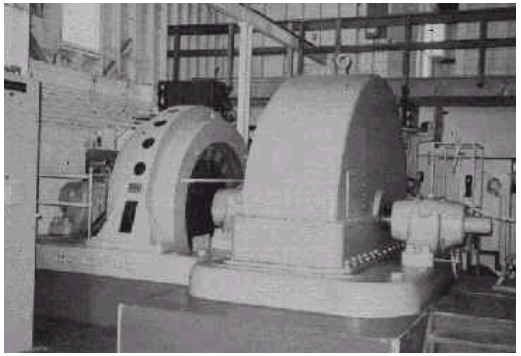


Power Electronics



?

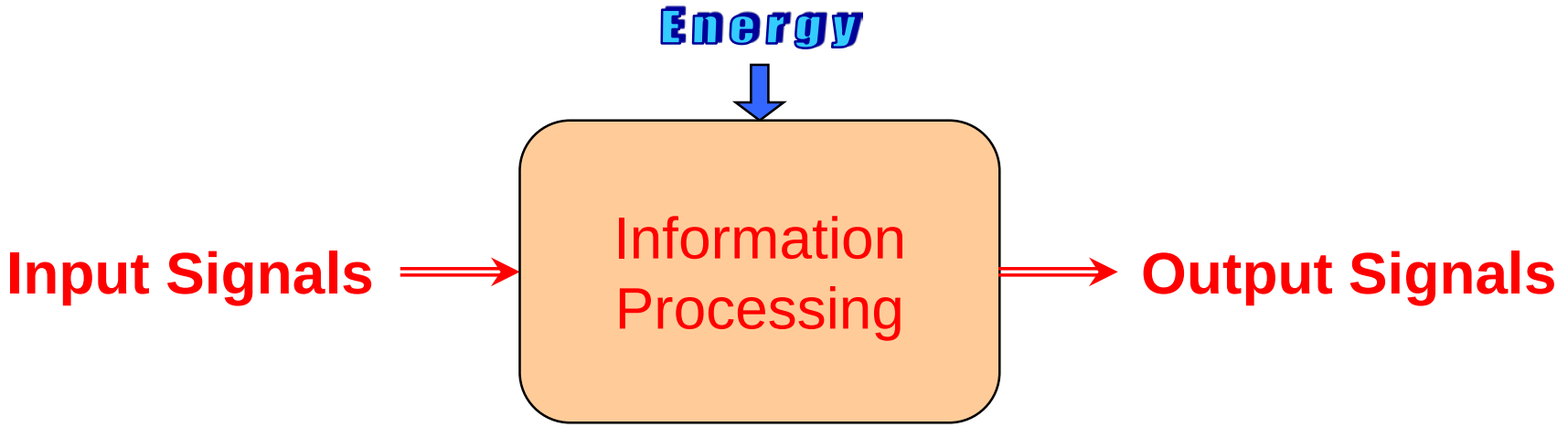
Electric Power

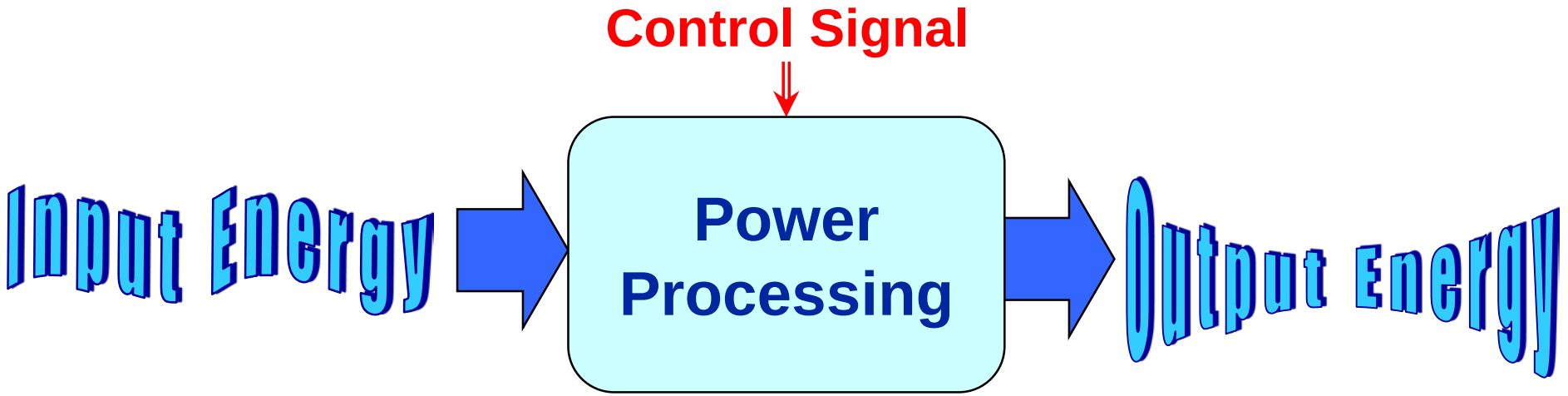


Between 1920 - 1970, every 1.5 years the cost of kWh dropped 5%.

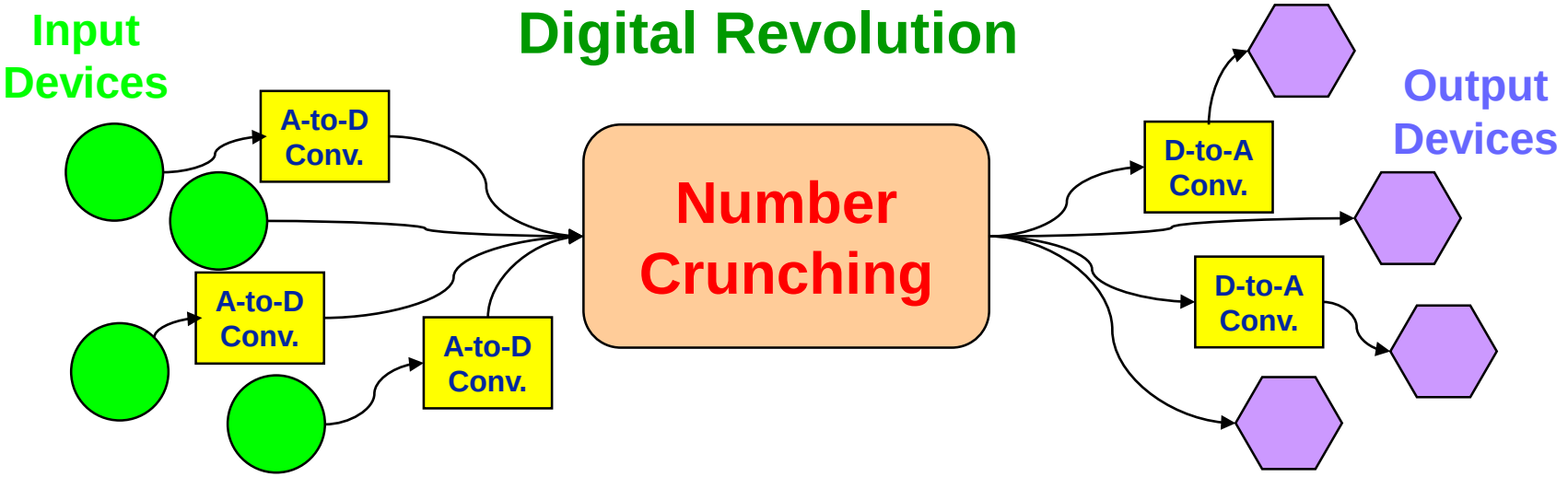
Since then it is constant.

Microelectronics *vs*. Power Electronics



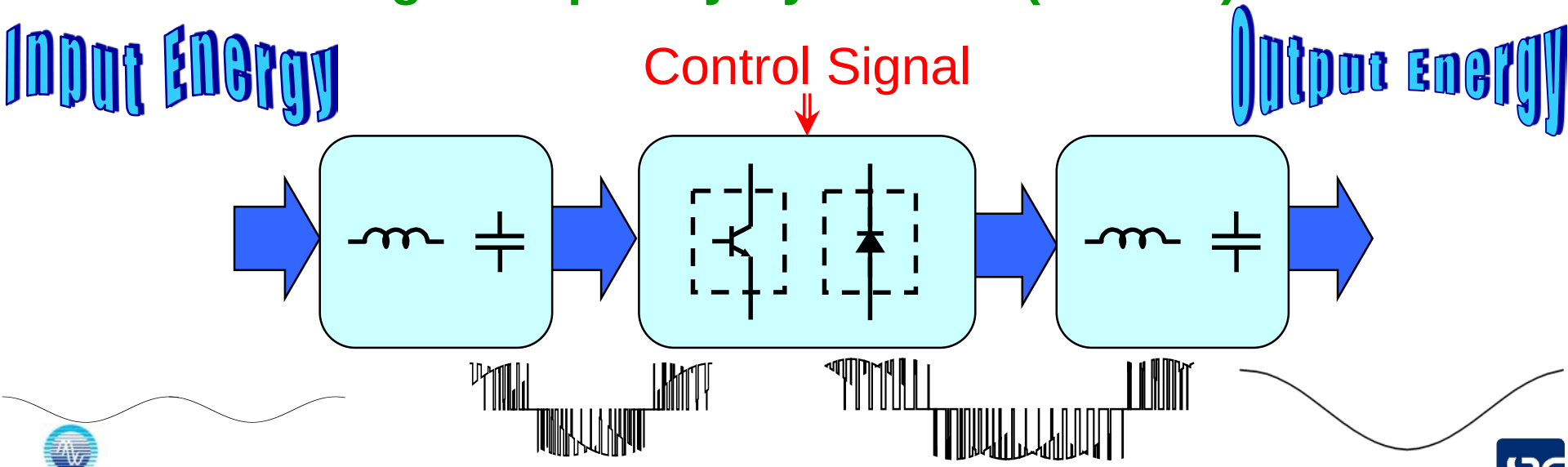


Paradigm Shift #1: **Standardization**



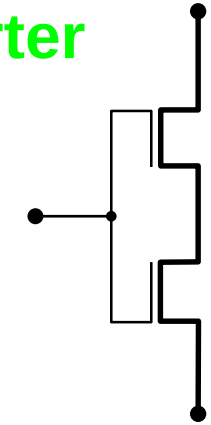
Most of Information Processing has been reduced to arithmetic and logic manipulation of binary numbers!

High Frequency Synthesis ("PWM")



Paradigm Shift #2: **Modularization**

CMOS Inverter

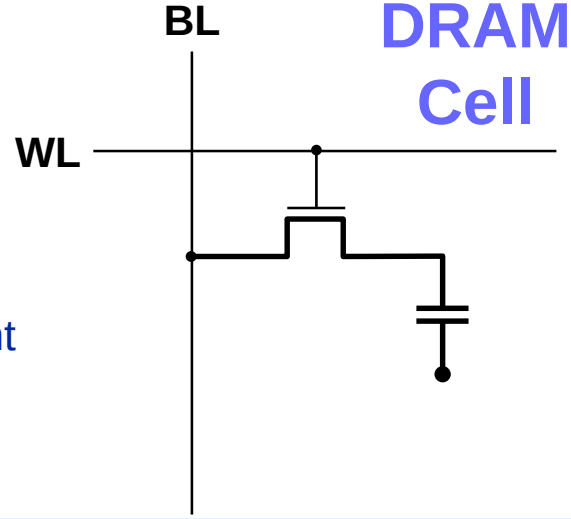


CMOS Technology

All of "number crunching" is implemented by 2 cells types

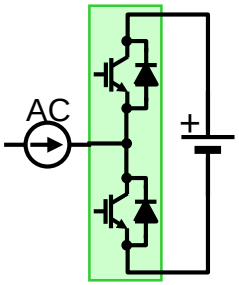
- The cell design is optimized through technology development
- System design is reduced to "combinatorics" and geometry

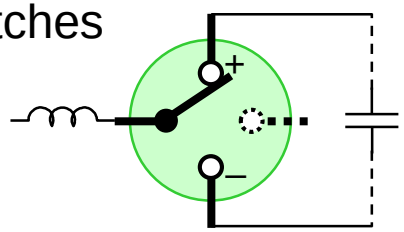
DRAM Cell



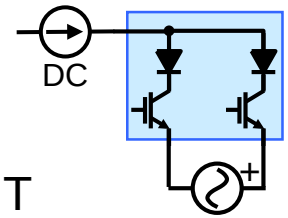
Topology Convergence?

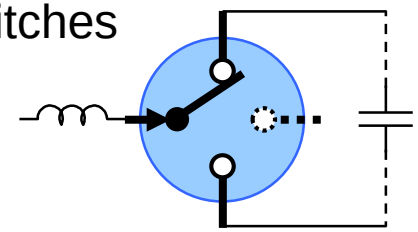
SPMT
Voltage
Unidirectional
Switches

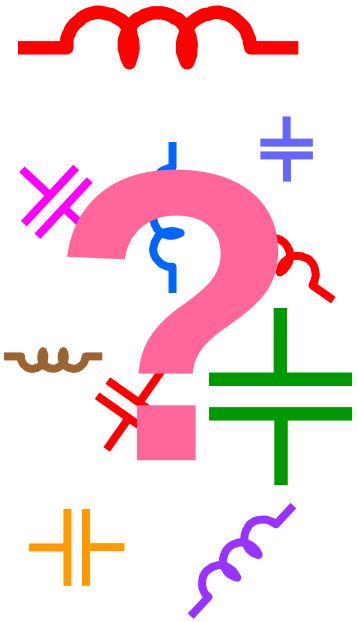




SPMT
Current
Unidirectional
Switches

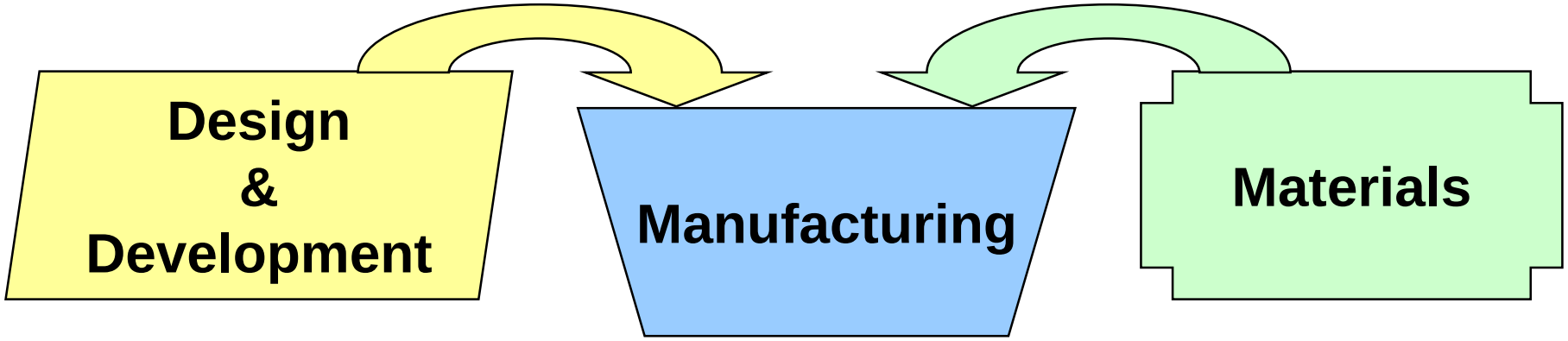






Information Processing Paradigm Shift #3: **Integration**

Product Quality, Reliability, and Cost Factors:



- **Rule-based**
- **Optimized macrocells**
- **Standard interfaces**
- **Hierarchical design**

- **Batch processing**

- **Small number of steps**

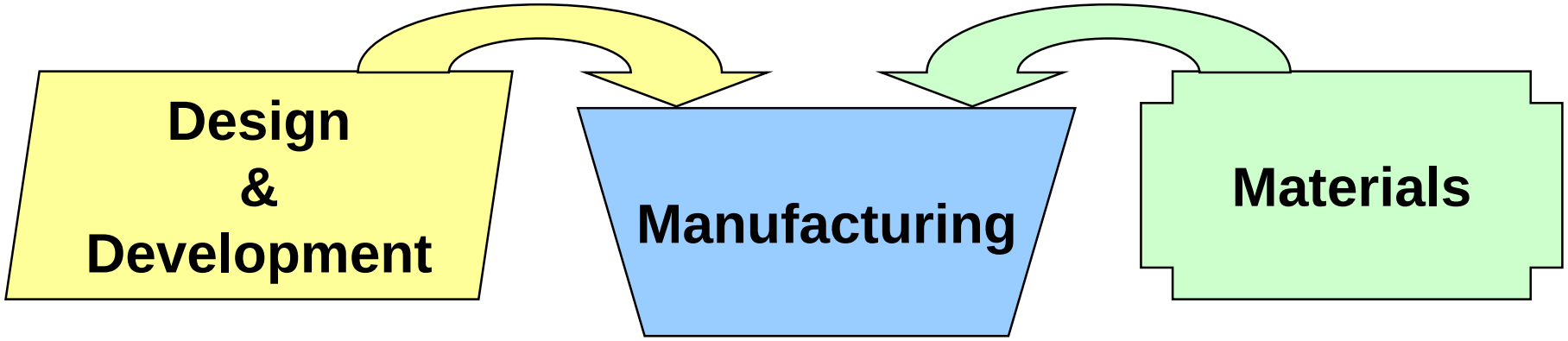
- **Small number of different materials**
- **Efficient use of materials**

Volume Production

Cost Reduction

Power Processing #3: **Integration**

Product Quality, Reliability, and Cost Factors:



- Rule-based
- Optimized macrocells
- Standard interfaces
- Hierarchical design

- Batch processing

- Small number of steps

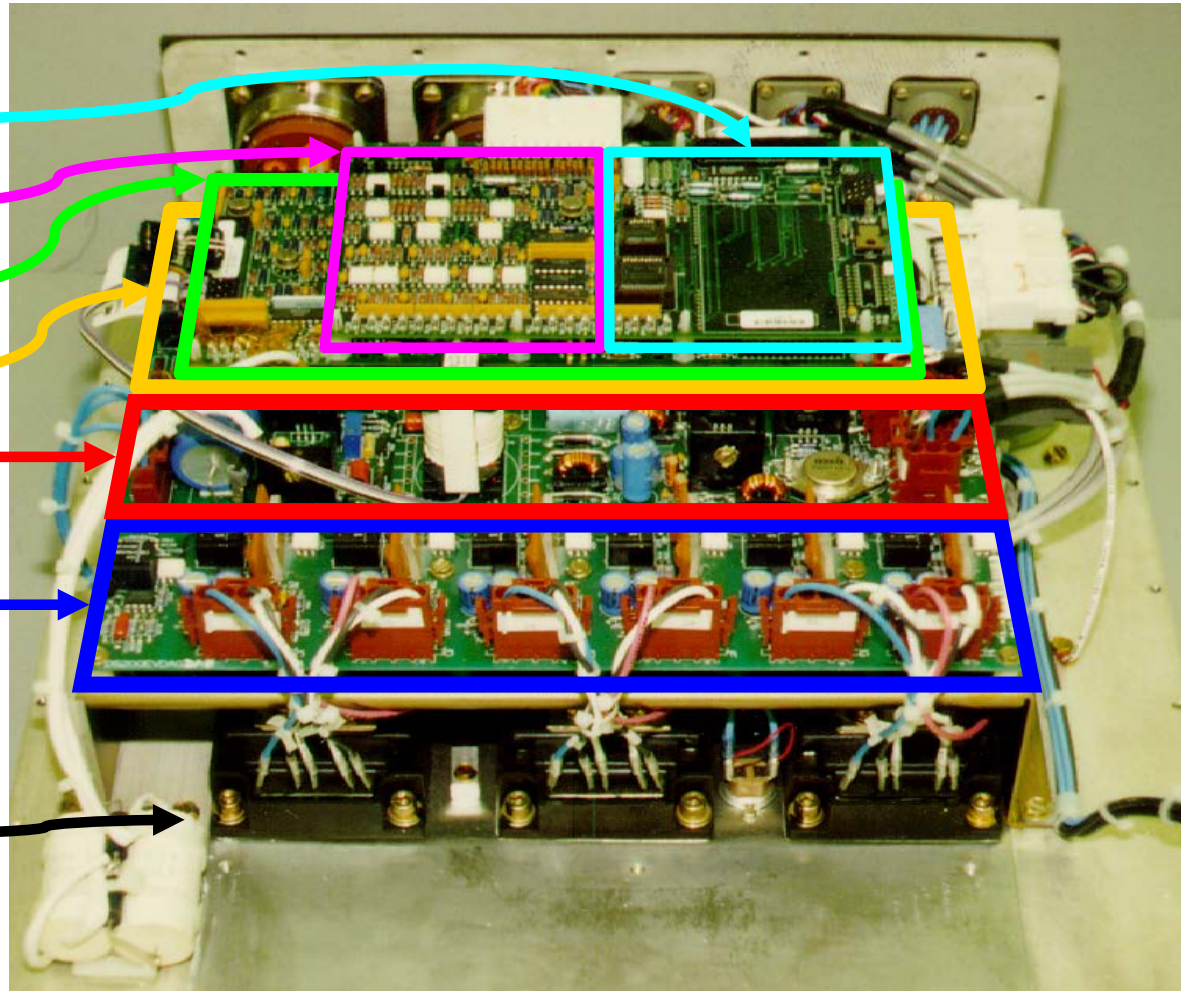
- Small number of different materials
- Efficient use of materials

Low Volume Production

High Cost

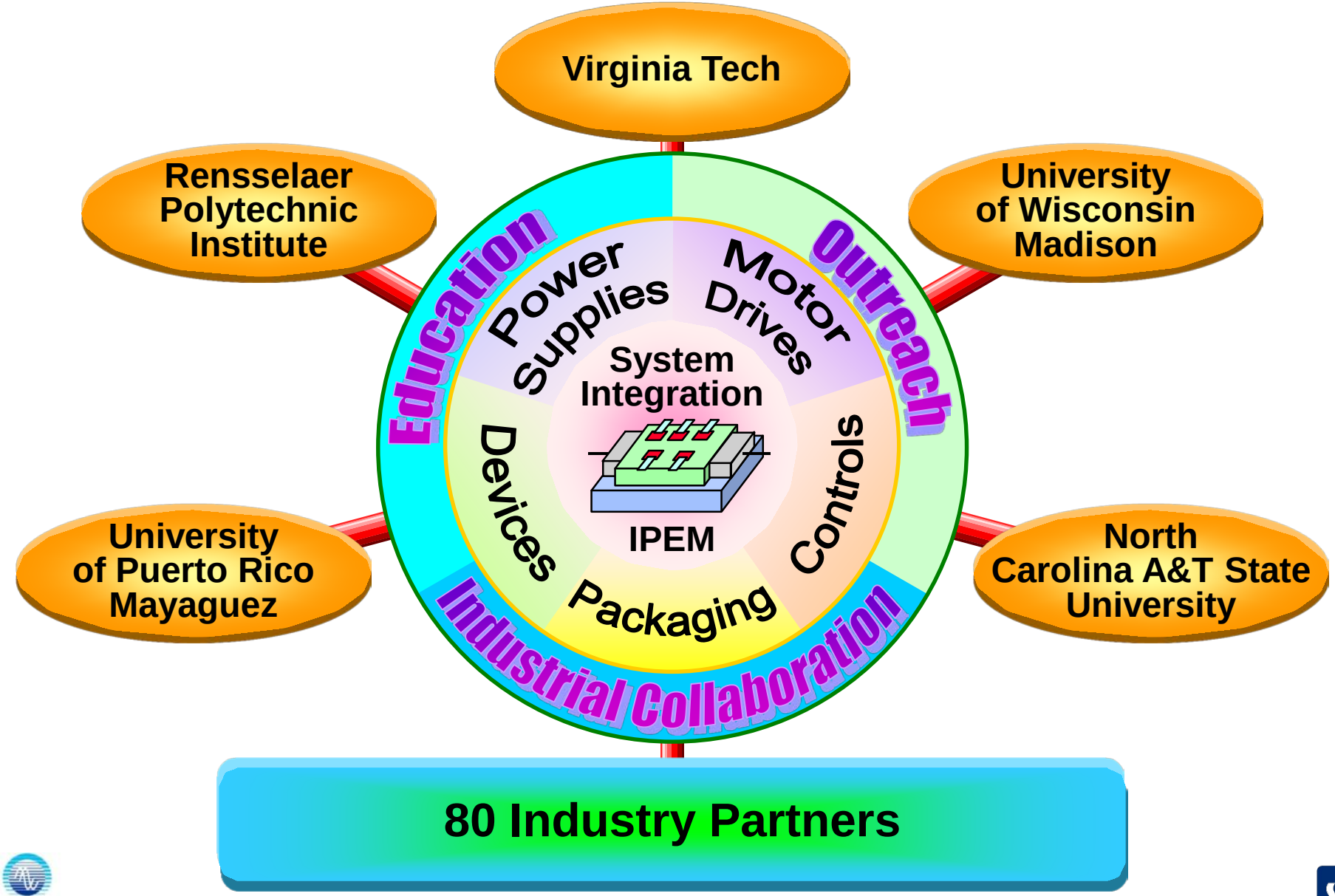
Integration in Power Processing !

Or Power Electronics Converter Design in the Last Century



Center for Power Electronics Systems

A National Science Foundation Engineering Research Center, 1998-2008

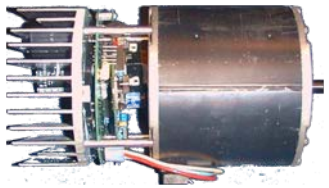


Center for Power Electronics Systems

A National Science Foundation Engineering Research Center

Datacom Power Systems and Motor Drives

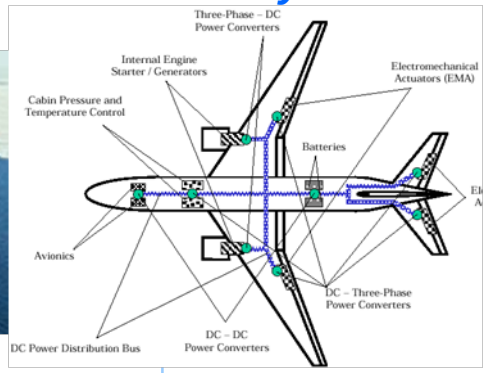
Electronic Power Distribution Systems



Integrated Motor Drive System

Front-end converter with discrete devices

Integrated front-end converter



1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008

State-of-the-Art Benchmarks

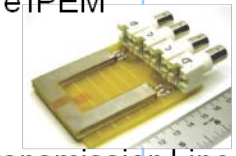
Active IPEM

IPEM with Double-sided Cooling

Passive IPEM

Integrated EMI Filter

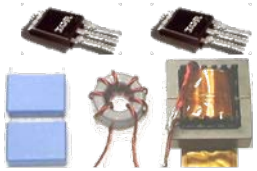
Integrated Power Supply



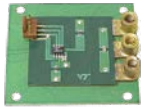
Transmission Line Filter

Integrated HID Ballast

Datacom Center Testbed

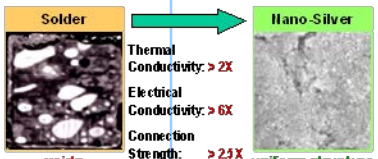


Discrete Devices

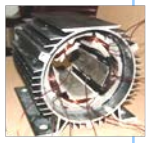


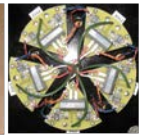
Flip-Chip on Flex

Embedded Power



Nano-Silver Die Attach



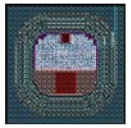


Integrated Modular Motor Drives

Si trench diode

MPS diode

SiC diode



IGBT+ MPS

GaN MOSFET

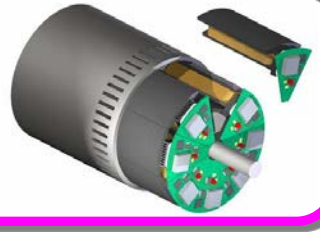
GMR Field Detector

Gen. I | Generation II | Generation III | Generation IV

Different Approaches to Integration

- **Integrated Load Converters:**
  - Low-cost, "intelligent motors"
    - motor as output filter
  - Fast power delivery to microprocessors
    - minimum distance to load

Motor and Converter Integration

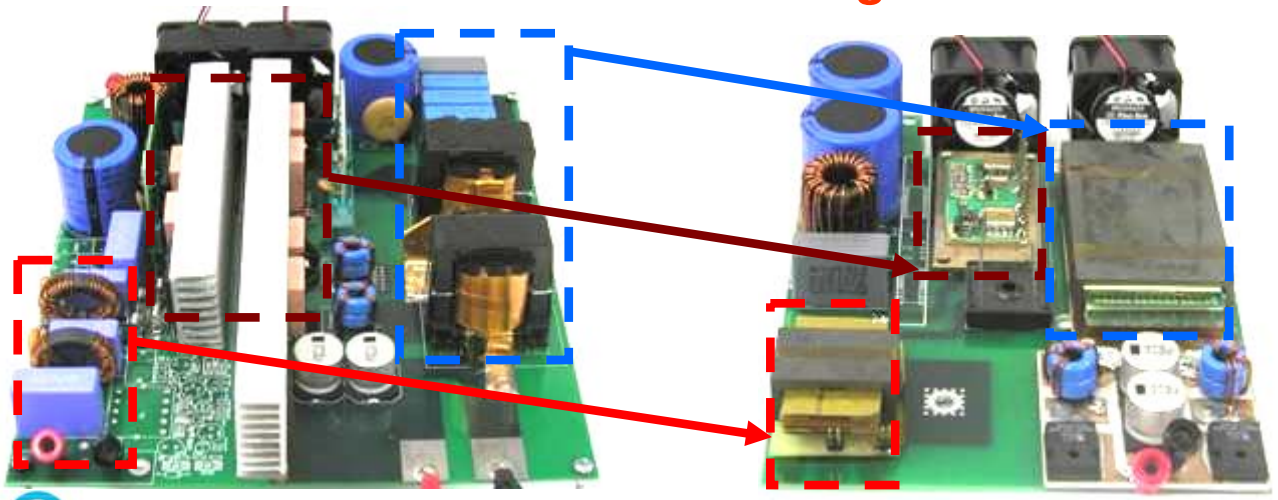


Microprocessor and Converter Integration

- **Power Distribution Converters:**

Discrete converter

Integrated converter

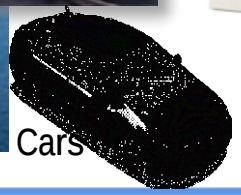


Standard-Cell IPEMs:

- Active IPEM
- Passive IPEM
- EMI Filter IPEM

Current Research Areas in CPES

Emerging Applications



Application Areas

- Vehicular Power Converter Systems
- Point-of-Load Conversion
- Power Management for Computers & Telecommunications
- Sustainable Energy Systems

Technology Areas

- Power Electronics Components
- High Density Integration
- EMI and Power Quality
- Modeling and Control
- Power Conversion Topologies and Architectures

watts to megawatts

CPES @ VT Achievement Highlights (1983 – 2014)

- **295 graduate degrees awarded (136 Ph.D., 159 M.S.)**
- **Over 3100 technical papers, theses and dissertations**
- **245 invention disclosures**
- **93 patents awarded**
- **Almost 100 government- and industry-sponsored research projects**
- **Over 175 CPES industry members**
- **97 invention disclosures reviewed by IPPF** (2002-2014)
- **65 IPPF-sponsored patent applications** (2002 – 2014)

Current year:

- 84 industry members
- $2.3M from industry consortium
- $2.2M from sponsored research
- 17 research sponsors:
  - ABB
  - ARPA-E
  - Boeing
  - Department of Energy
  - Energy Research Corporation
  - GE Appliances and Light
  - General Motors
  - Halliburton
  - Huazhong University of Science & Tech.
  - NBE Tech
  - NSF
  - Office of Naval Research
  - Panasonic
  - Safran
  - Texas Instruments
  - Toyota Motor Engineering Mfg. NA, Inc.
  - United Technologies Aerospace Systems

CPES Industry Consortium

84 Members

40 PRINCIPAL PLUS MEMBERSHIPS ($50 K/year)

- Same as Principal Member

+ Membership in a mini-consortium:
  - Guidance on research directions
  - Advance reporting of research results
  - Advance IP information

12 PRINCIPAL MEMBERS ($30 K/year)

- Preferential access to Intellectual Property
- Seat on the Industry Advisory Board

25 ASSOCIATE MEMBERS ($15 K/year)

- Free access to CPES publications, conference, and other information
- Representation on the Industry Advisory Board
- Industry residence and student internship programs
- Discount on short courses and other services

12 AFFILIATE MEMBERS (in-kind contributions or <$15 K/year)

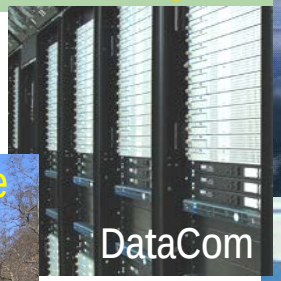
- Free access to some CPES publications and conference
- Limited discount on short courses and other services

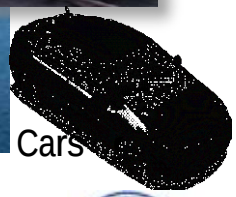
Power Management Consortium

Work Scope:

- High performance VRM/POL converters
- High efficiency power architectures for laptops, desktops and servers
- High frequency magnetics characterization and design
- Digital control
- EMI
- Solid state lighting
- Power management for PV system
- Power management for battery system
- High-efficiency and high power density power supplies with wide-band-gap power devices

Mini-Consortium for
Wide Band-Gap High-Power Converters & Systems





Work Scope:

- **DC and AC Microgrids**
  - Architectures and design
  - Grid-, battery-, PV-, and wind-interface converters
  - Power management
- **Modular Multi-level Converters**
  - Modeling, design and control
  - Grid-interface converters
- **Power Electronics for Enhanced Grid Performance and for Integration of Renewable Sources and Storage Systems**

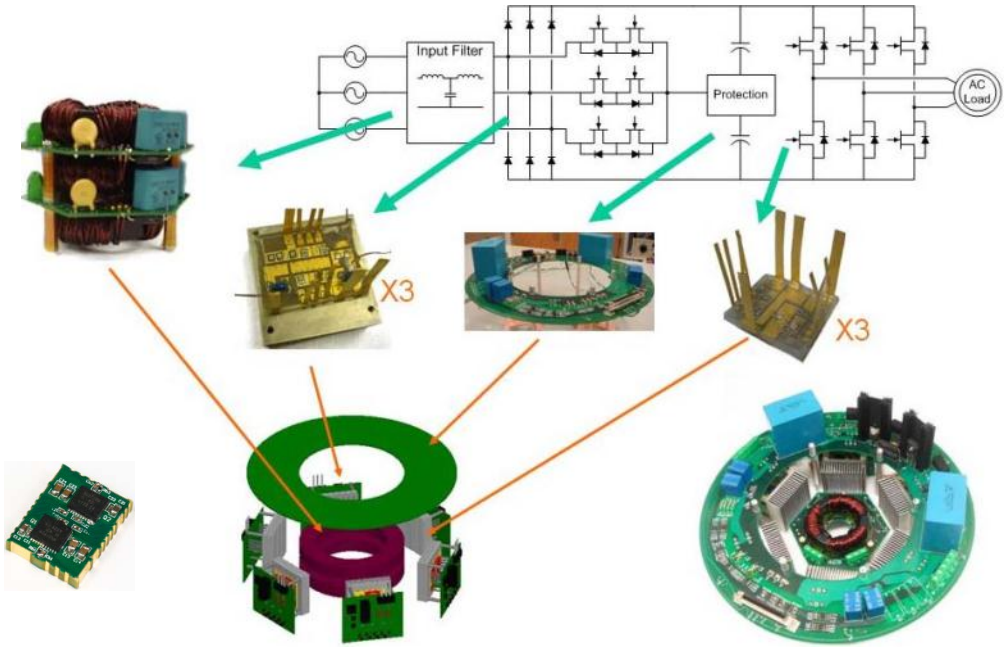
Current Principal Plus Members in this area:

SIEMENS · BOEING · DELTA · GE Energy · ABB · KEYSIGHT TECHNOLOGIES · HUAWEI

Research Sponsors:

CPES · VPT Energy Systems · NSF · NETL National Energy Technology Laboratory · Newport News Shipbuilding, A Division of Huntington Ingalls Industries · VirginiaTech · BOEING · National Instruments · Office of Naval Research · Cleanfield Energy

Mini-Consortium for
High Density Integration



Work Scope:

- Material and component characterization (interconnect, dielectrics, magnetics, SiC, GaN, ...)
- Active module integration
- Passive component integration
- Converter integration
- Wide power range (10 W - 10 MW)
- High frequency (10 MHz - 100 kHz)
- High temperature (≥ 200°C)

Principal Plus Members:

ALSTOM, CRANE AEROSPACE & ELECTRONICS, GE Global Research, NISSAN, GM, SUMITOMO ELECTRIC, ROLLS ROYCE, TEXAS INSTRUMENTS, DELTA, DOWA, ABB, SAFRAN, HUAWEI, United Technologies Research Center

Research Sponsors:

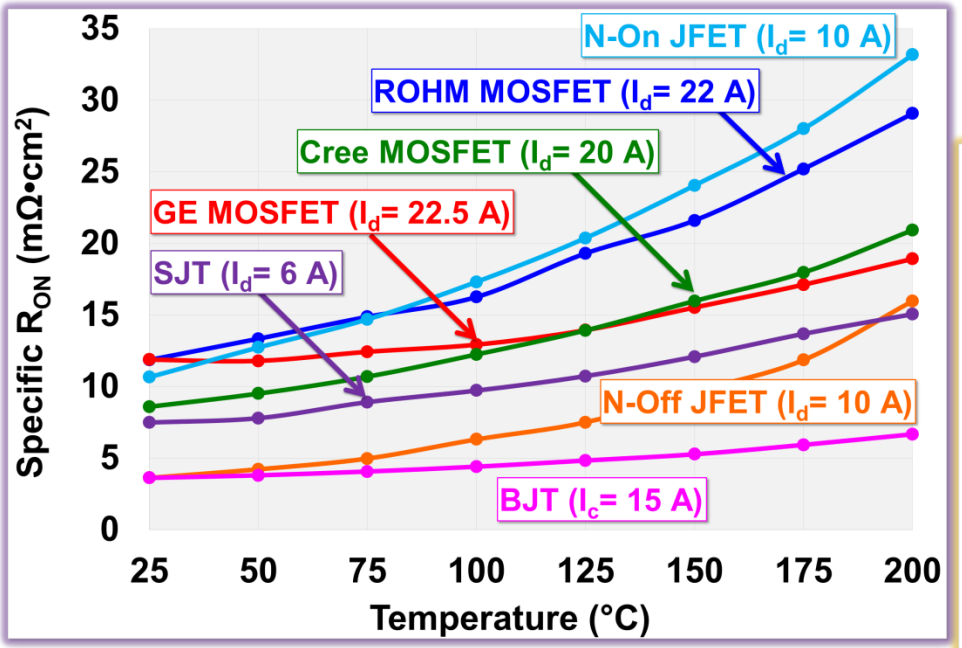
BOEING, TOYOTA, arpa·e Advanced Research Projects Agency • ENERGY, NSF, ONR Office of Naval Research, SAFRAN AEROSPACE · DEFENCE · SECURITY, ROLLS ROYCE, GE Global Research, UTC Aerospace Systems

SiC Switch Comparative Characterization

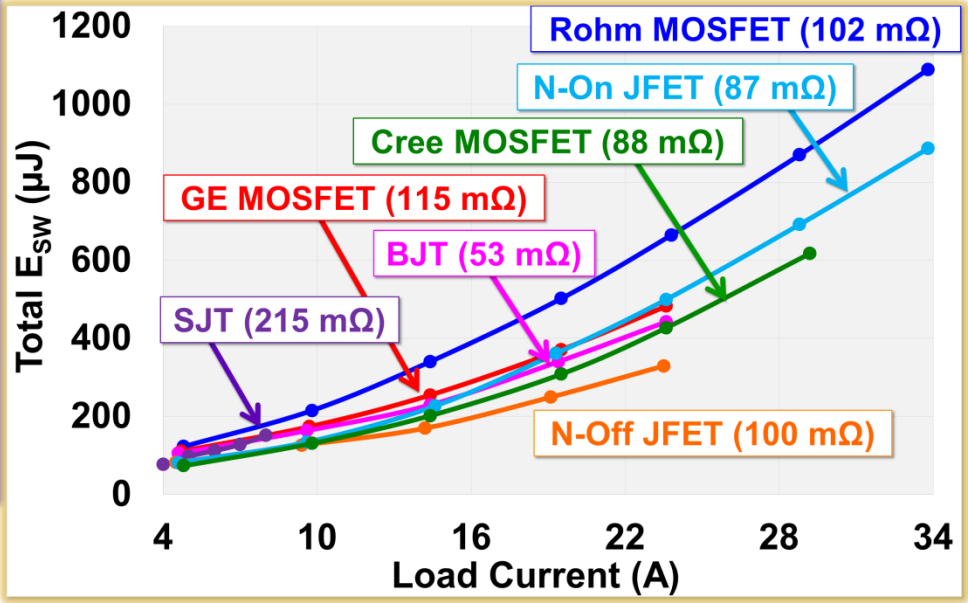
Device	Continuous Current Rating (datasheet)	T_{MAX} (datasheet)	Normalized Die Area to Cree MOSFET
Cree SiC MOSFET (C2M0080120D)	31.6 A (25 ˚C); 20 A (100 ˚C)	150 ˚C	1.00
Rohm SiC MOSFET (SCH2080KE)	35 A (25 ˚C); 22 A (100 ˚C)	150 ˚C	1.21
GE SiC MOSFET (GE12N20L)	30 A (25 ºC); 22.5 A (100 ºC)	200 ˚C	0.97
Fairchild SiC BJT (FSICBH057A120)	15 A	175 ˚C	0.64
GeneSiC SiC SJT (GA10JT12)	6 A (25 ˚C)	175 ˚C	0.33
Infineon N-On SiC JFET (IJW120R100T1)	26 A (25 ˚C); 10 A (≤ 150 ˚C)	175 ˚C	1.29
SemiSouth N-Off SiC JFET (SJEP120R100)	17 A (100 ˚C); 10 A (150 ˚C)	150 ˚C	0.43

SiC Switch Comparative Characterization

Specific On-Resistance vs. Temperature



Switching Loss vs. Load Current



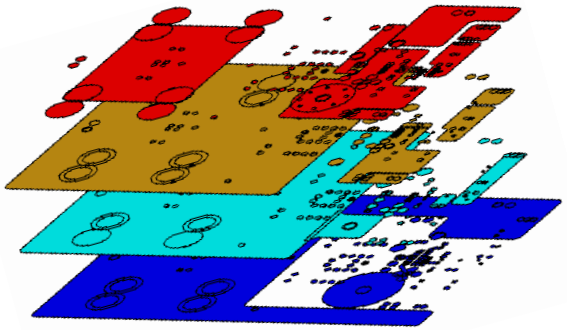
Conclusions:

- All devices have much smaller conduction loss than Si MOSFETs with similar ratings.
- All devices have much smaller switching loss than Si IGBTs with similar ratings.
- All devices operate satisfactorily at temperatures of 200 ºC and higher.

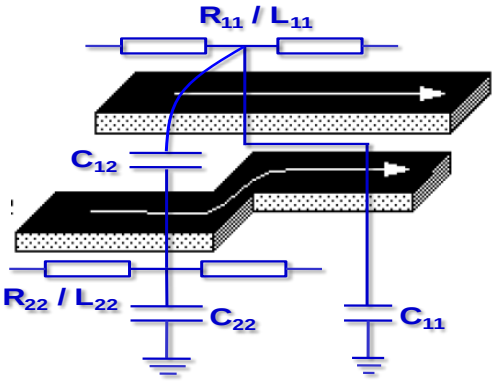
SiC Device Characterization and Modeling

Double-pulse Tester

Geometry Model

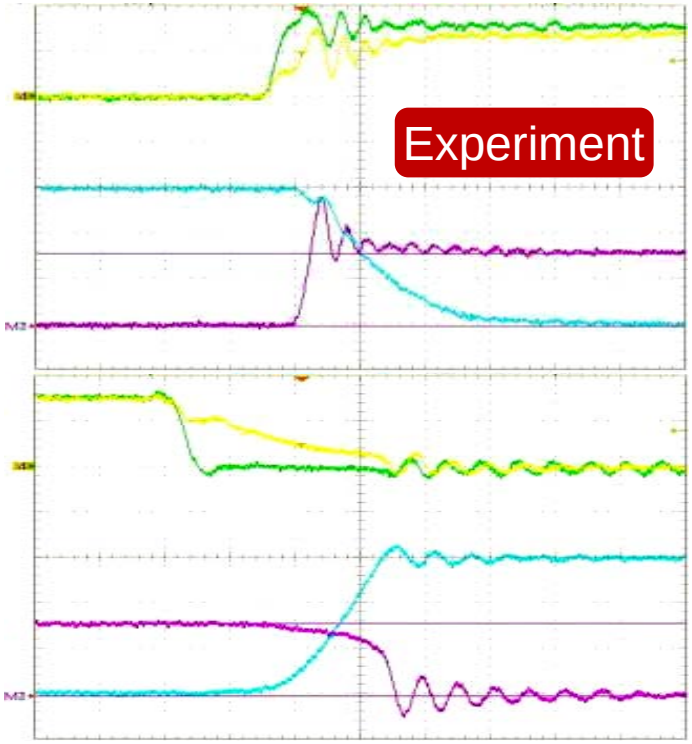


Extraction of Impedances



Turn-on

Turn-off

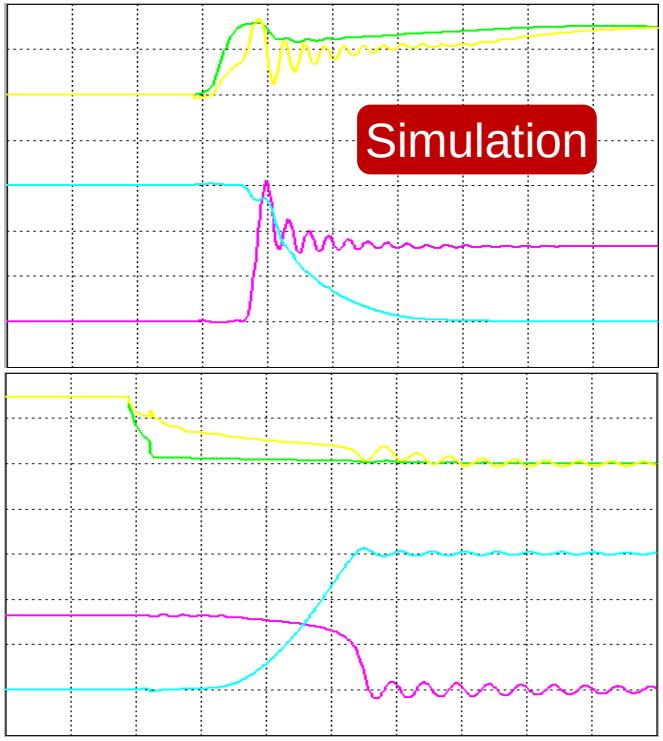


V_{drive} (10 V/div)

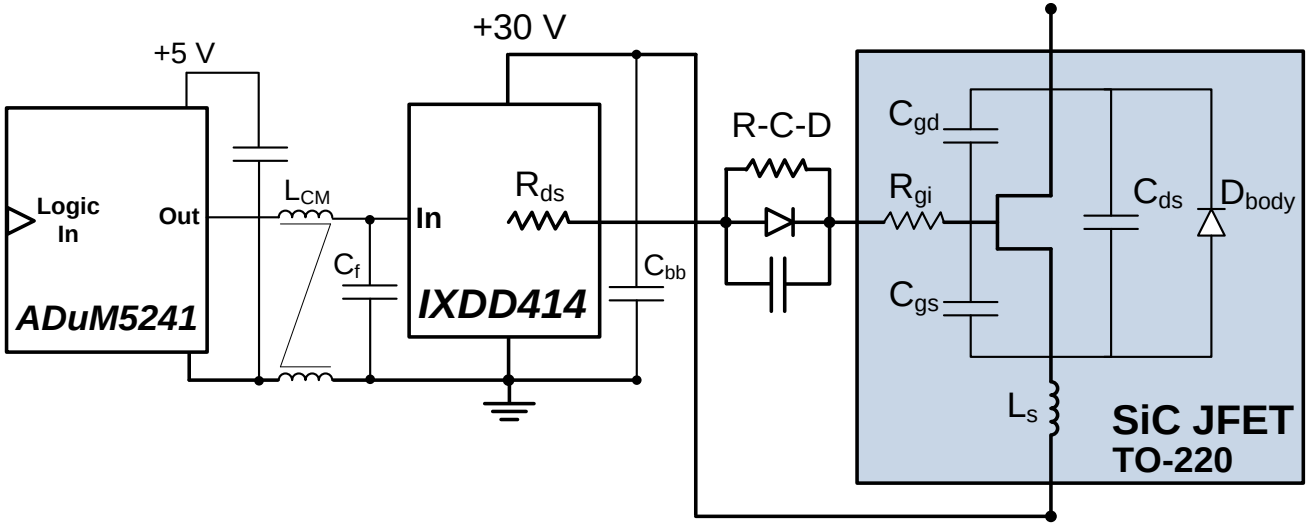
V_{gs} (10 V/div)

V_{ds} (200 V/div)

I_d (5 A/div)



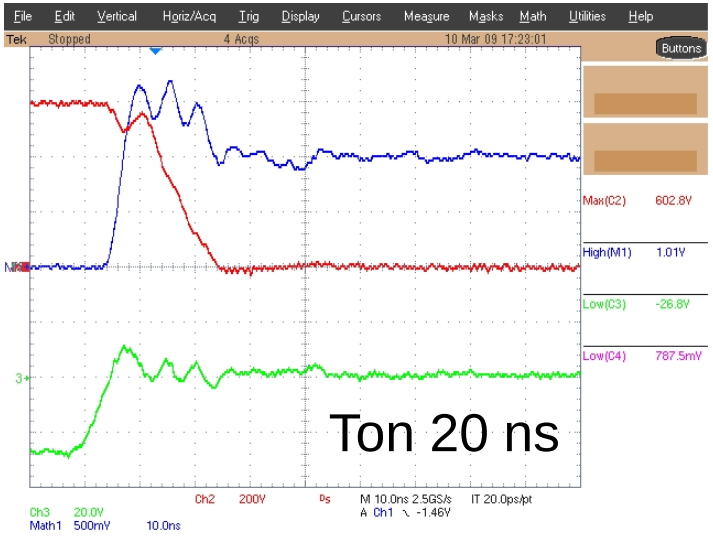
Design of a 0 Ω Gate Drive for 1.2 kV SiC JFET



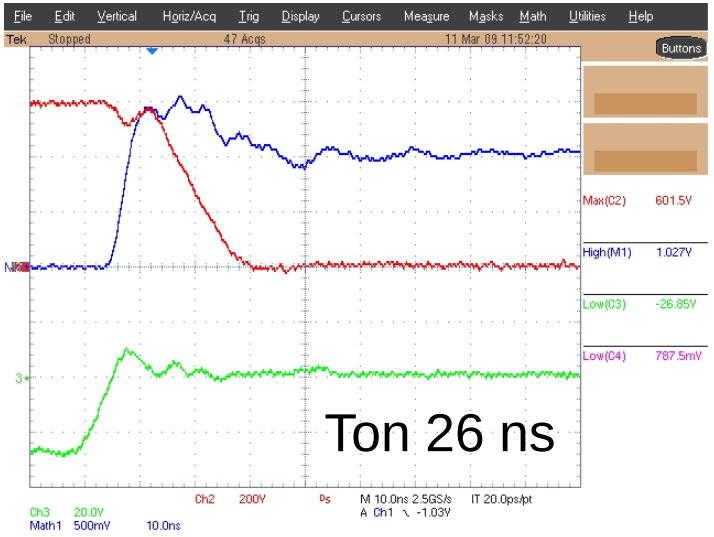
Vds: 100 x Probe, 2500 V, P5100
Vgs: 10 x Probe, 300 V, P6139A
Ids: 0.1 Ω Coaxial Shunt SDN-10

Turn-on/off at different temperatures 600 V – 10 A

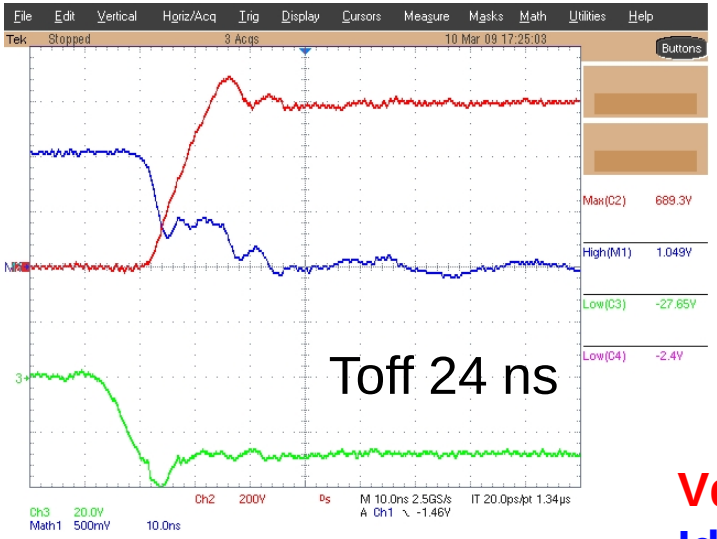
25° C

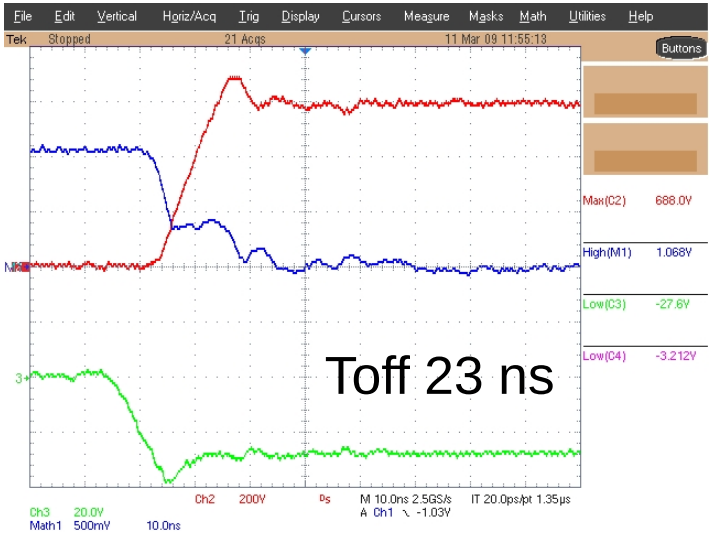


200° C



Turn ON



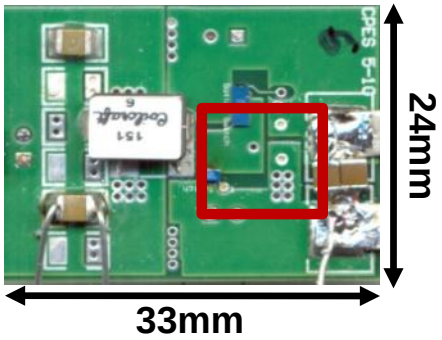


Turn OFF

Vds 200V/div
Ids 5A/div
Vgs 20V/div

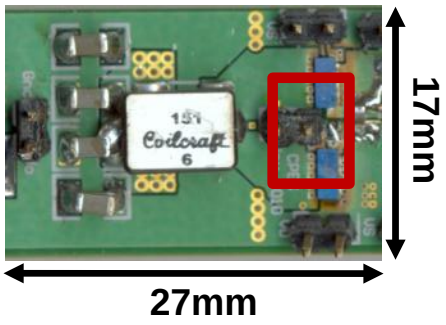
Generations of GaN POL Power Module

CPES Gen 1



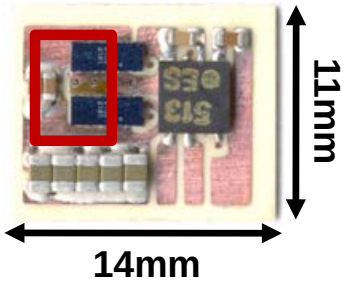
L_{Loop}=6.30nH

CPES Gen 2



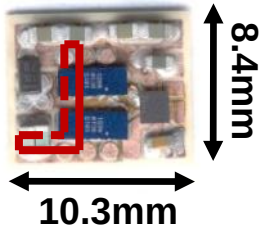
L_{Loop}=2.90nH

CPES Gen 3

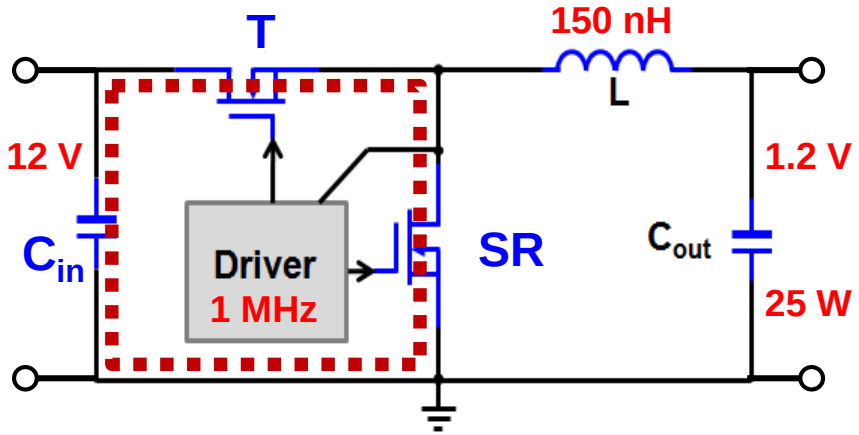


L_{Loop}=1.32nH

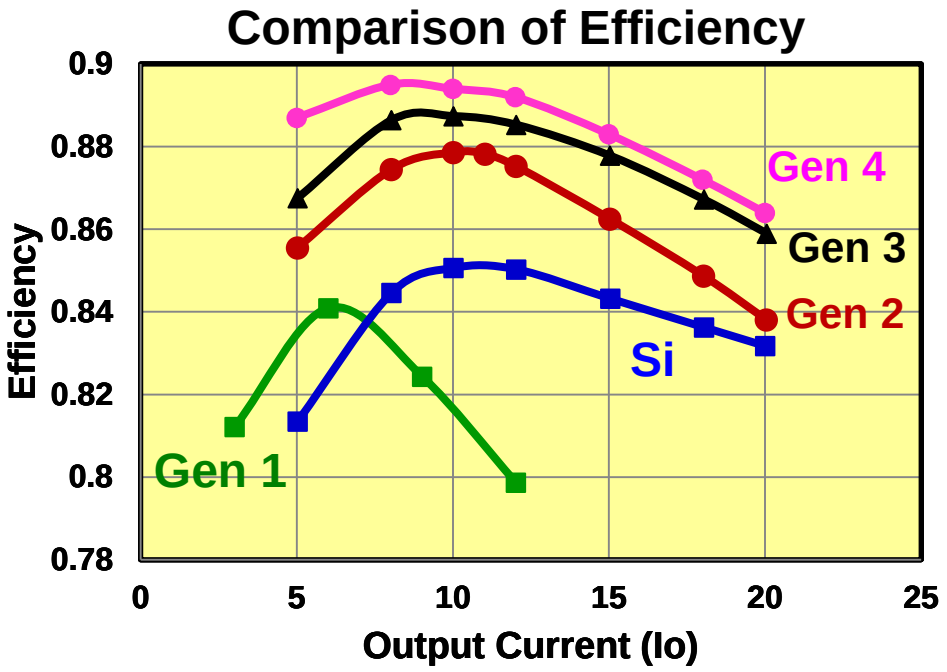
CPES Gen 4



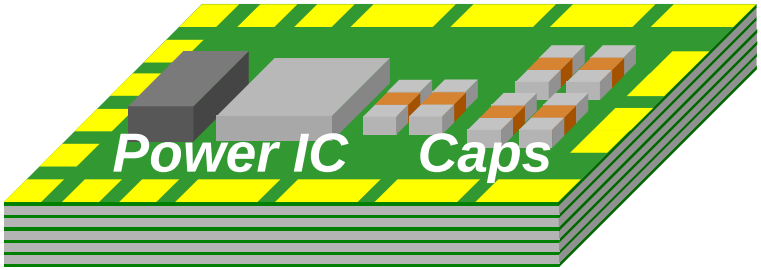
L_{Loop}=0.89nH



High frequency power loop to be minimized

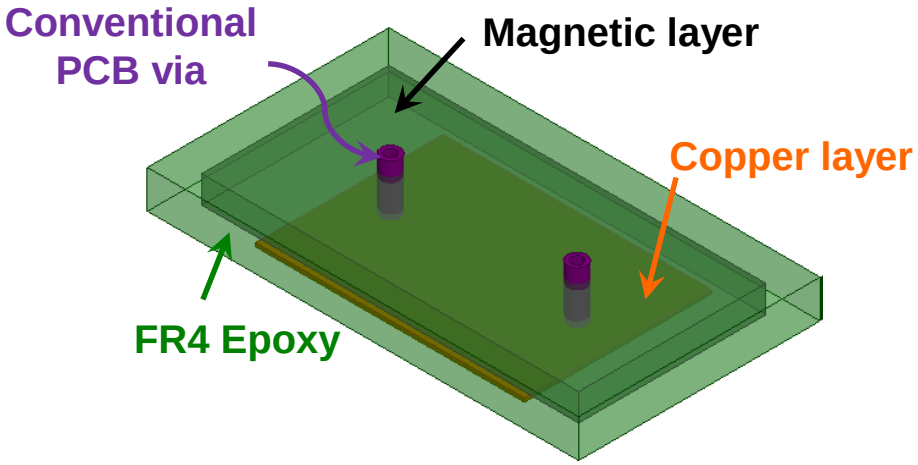


PCB Embedded Inductor Substrate
for 3D Integrated POL Module

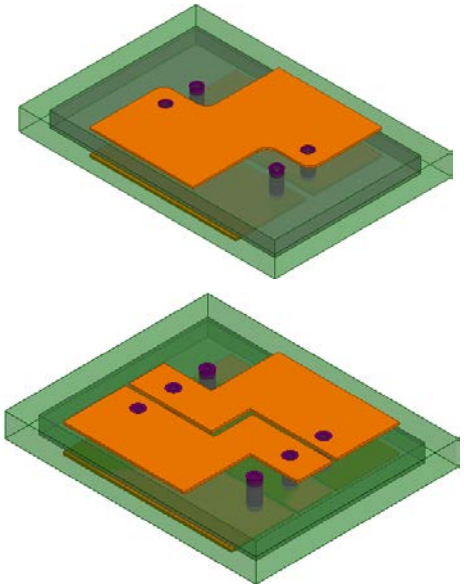


Multi-layers PCB substrate with embedded magnetic layer

f_s = 1~2 *MHz*, V_{in} = 12*V*, V_{out} = 1.2*V*, I_{out} = 20*A*



Single Turn Inductor

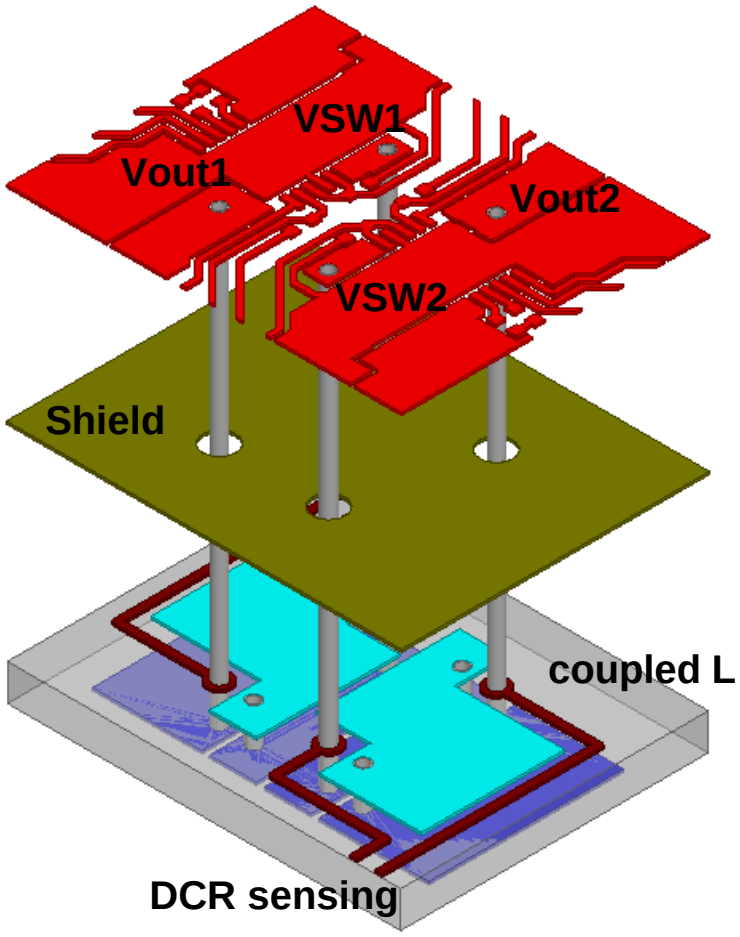


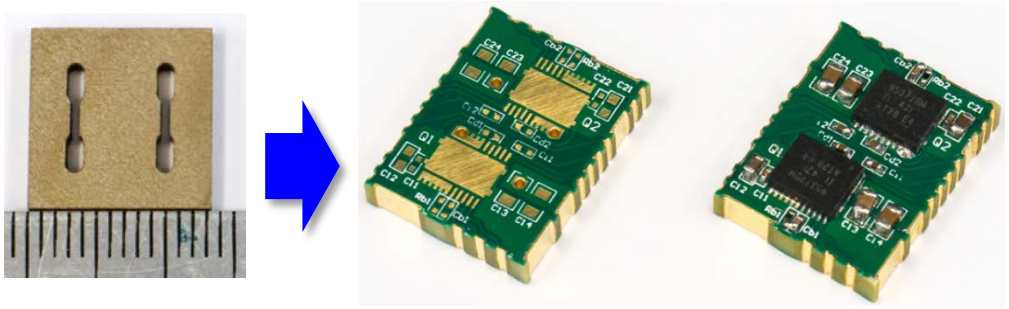
Two Turns

Three Turns

● ● ●

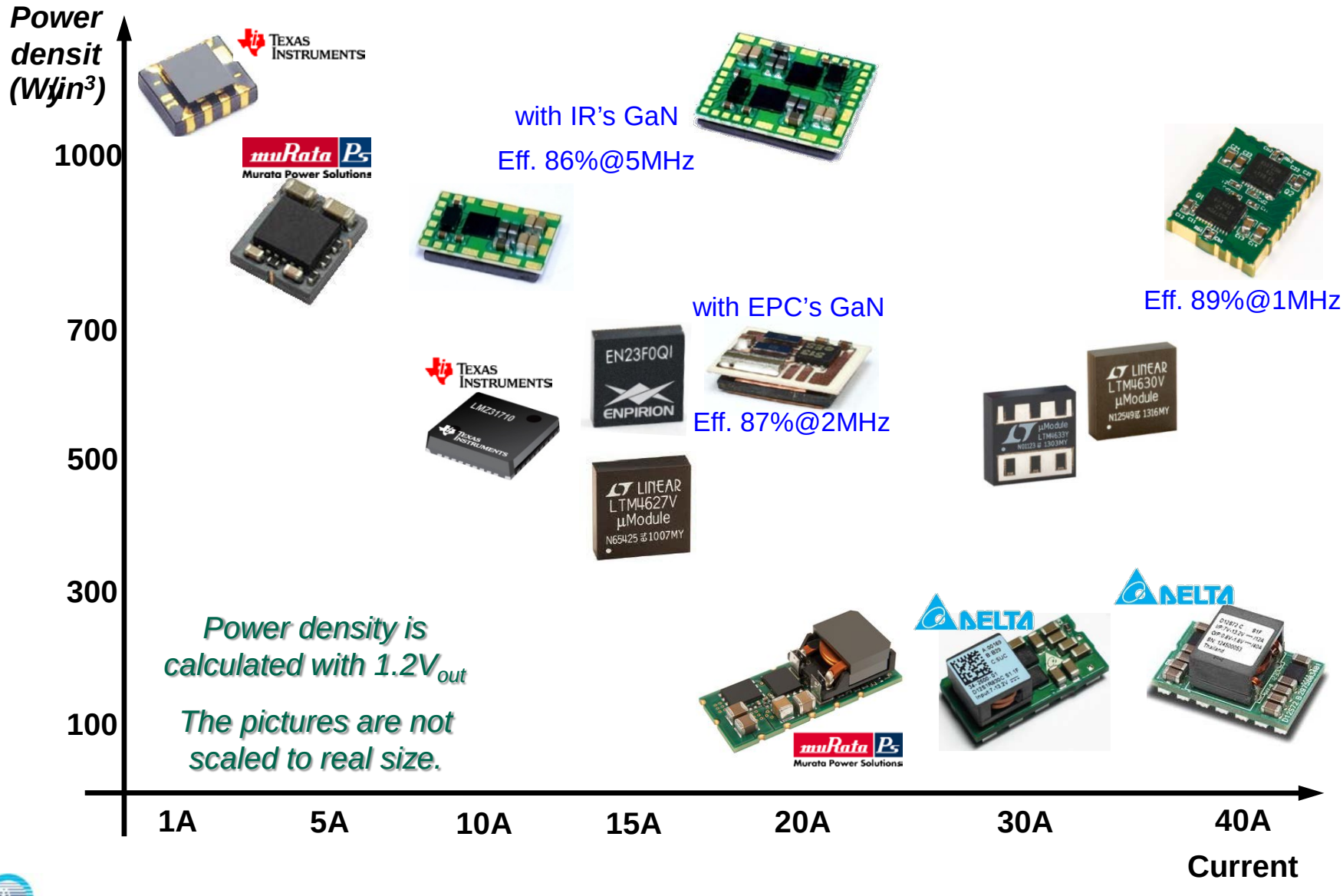
Module Design and Manufacture on 4-layer PCB





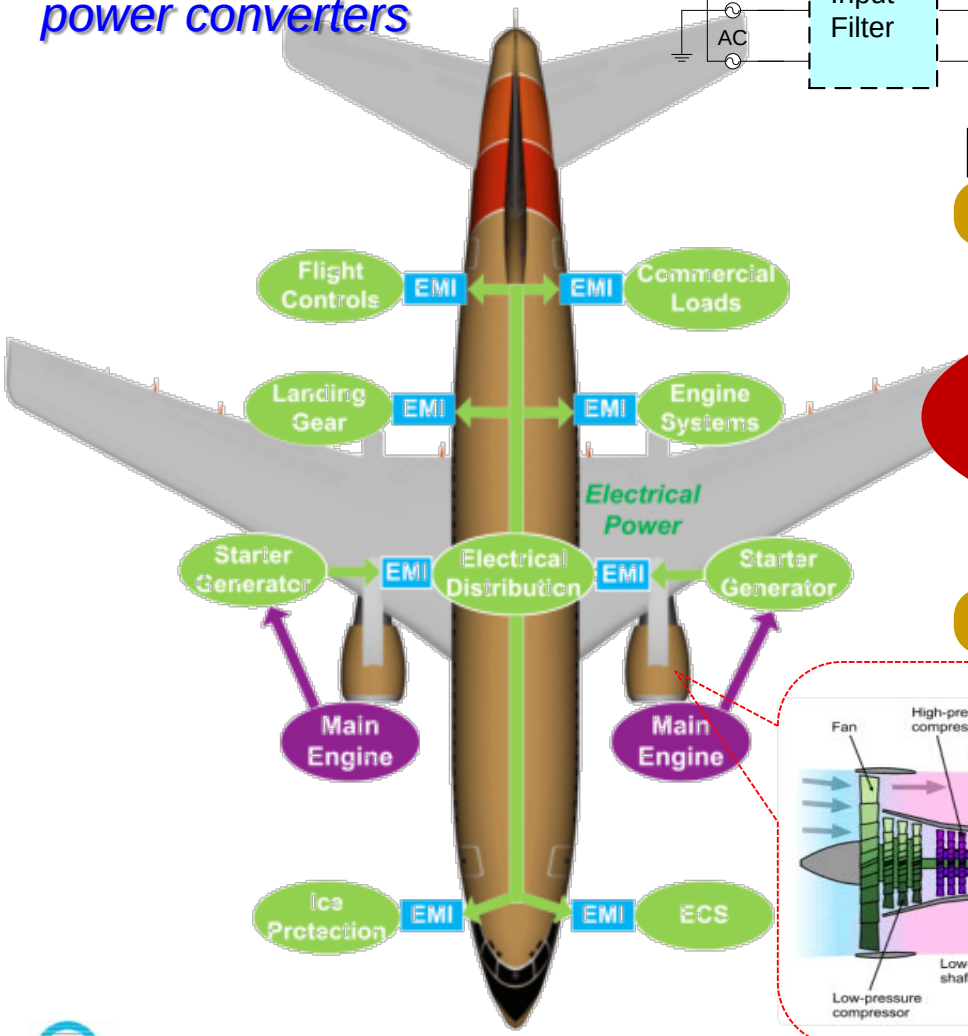
Open loop evaluation motherboard

Power Density Achievement



Demands for High-Power-Density Converters

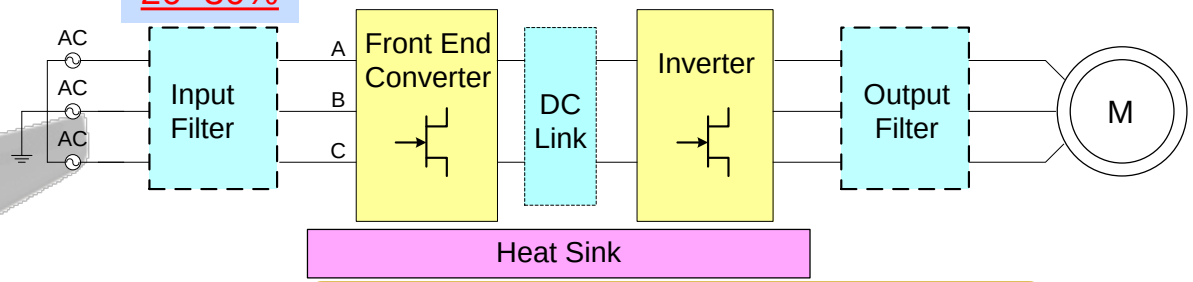
More Electric Airplanes: Limited space and more power converters



20~30%

Main Size Contributors for Motor Drive

(R. Lai, 2008)

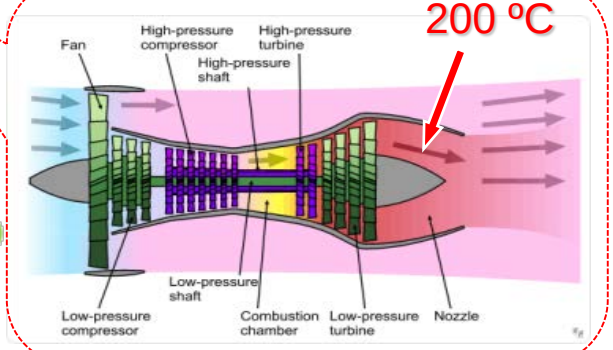


Size & weight restrictions

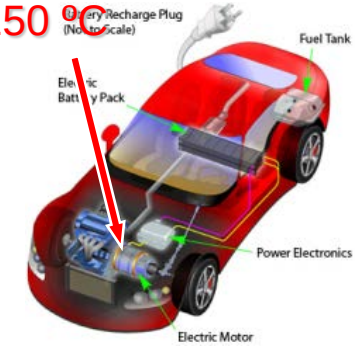
Semiconductor switches of high voltage, high frequency, and high temperature

Harsh environments

200 ºC

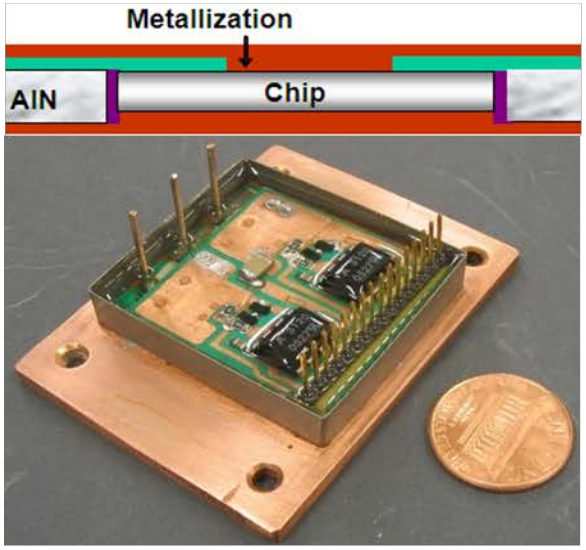


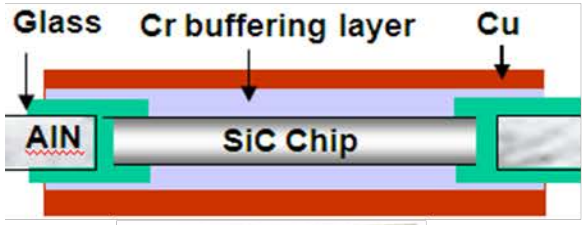
150 ºC

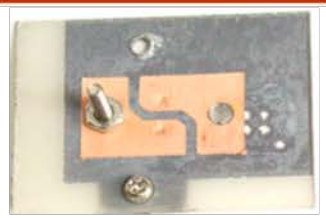


Planar Packaging

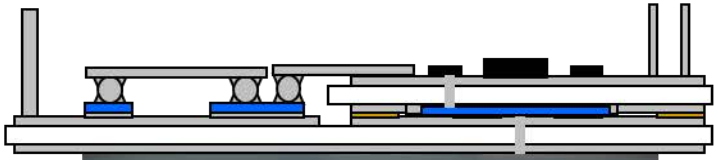
Plated Bonds

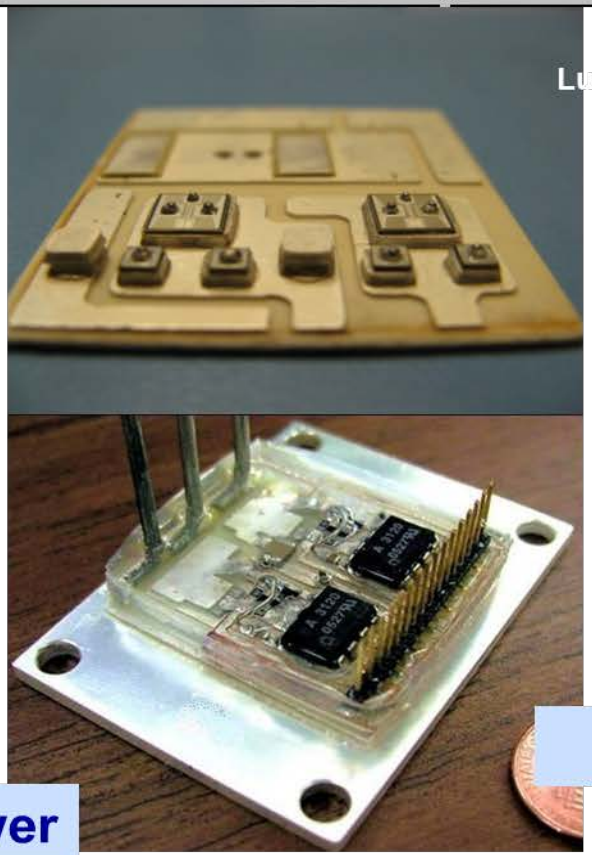






Soldered Bonds





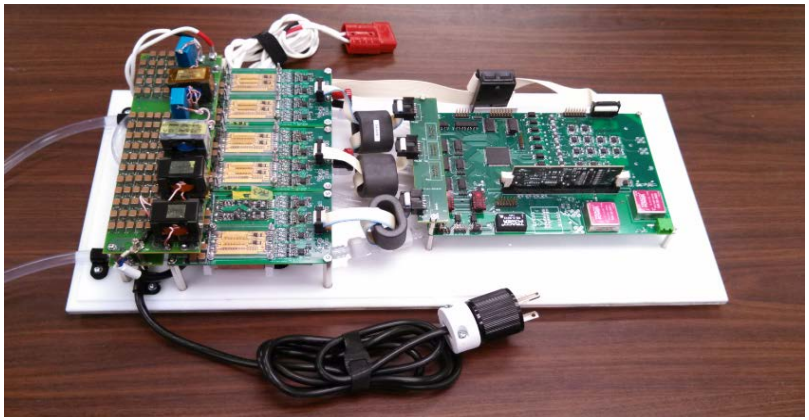
Sintered Bonds

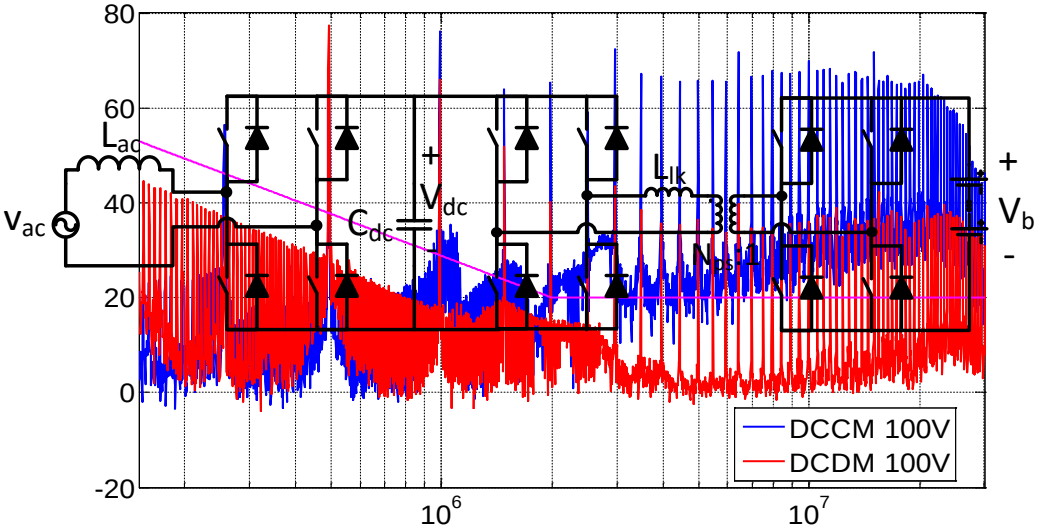
Solder-Free Package

250°C Embedded Power

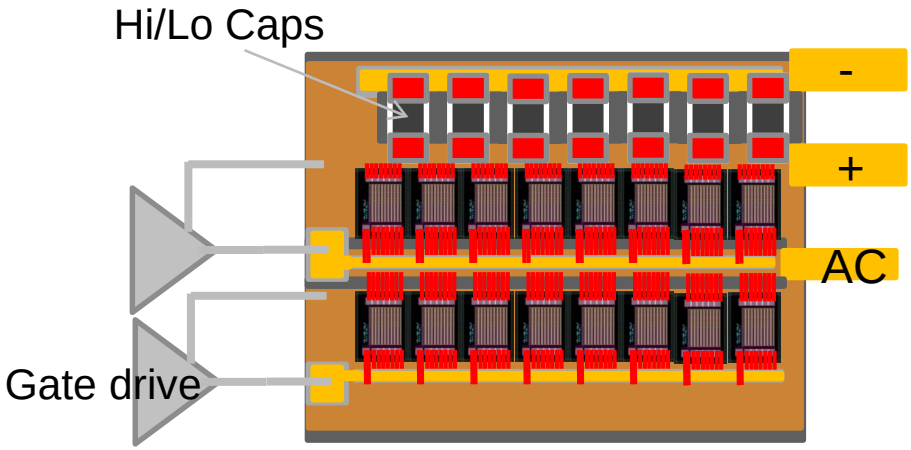
Bi-directional Battery Charger for PHEV with MHz GaN Converter

3.3 kW, 500 kHz, GaN-based, Bidirectional Battery Charger

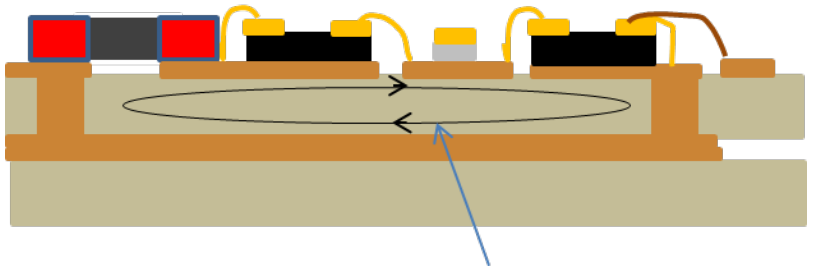




500 kHz hardware test result

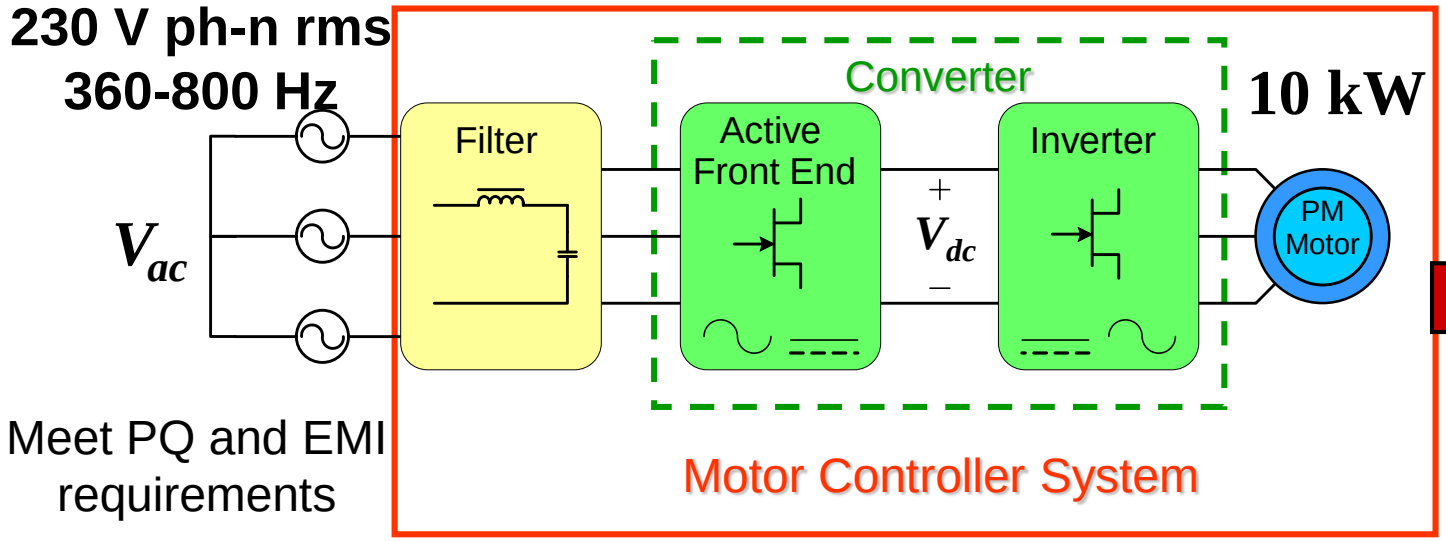


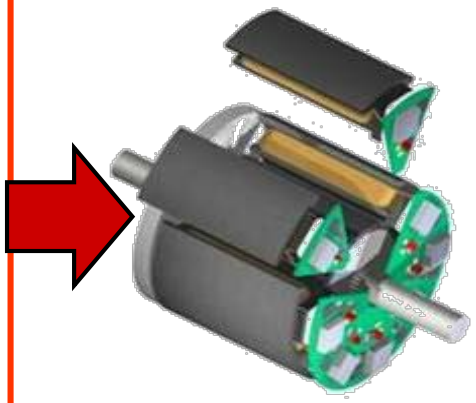
Lg = 0.9 nH



Ld = 3 nH Power loop

High-Power-Density, 10 kW Motor Drive with High-Temperature Modules





Passive cooling with air at 70°C

Objective:

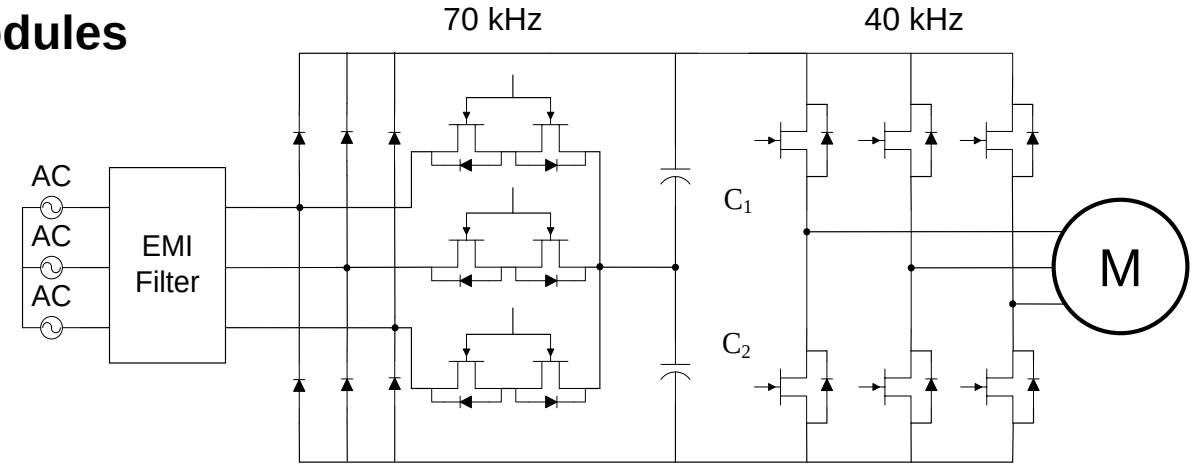
- **Reduce weight through integration and high-temperature operation**

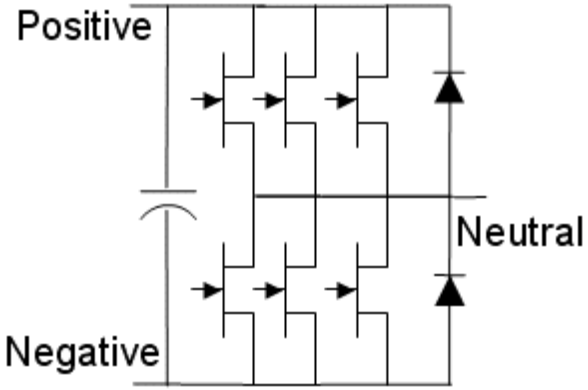
Targets & Desired Features

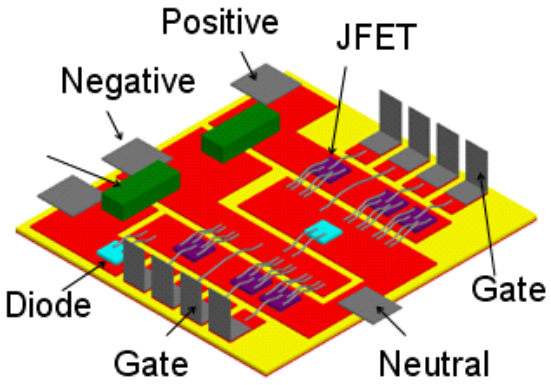
- **Specific power: > 2 kVA/lb**
- **Device junction temperature 200-300°C with SiC devices**
- **Advanced topologies**
- **Reduced filter size**

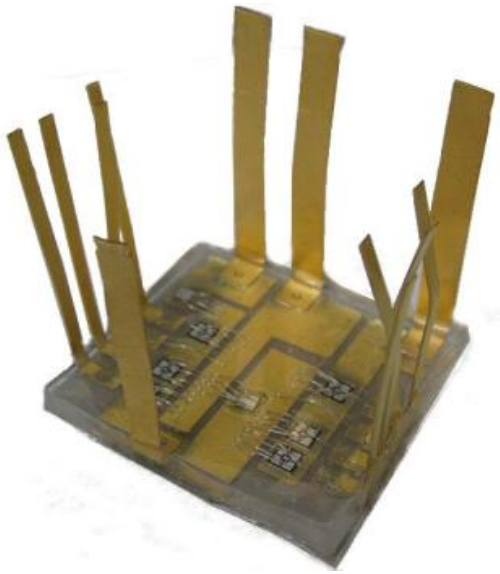
High-Power-Density, 10 kW Motor Drive with High-Temperature Modules

- **High-temperature SiC modules**
- **Sensorless control**
- **Soft start**
- **Fan load application**



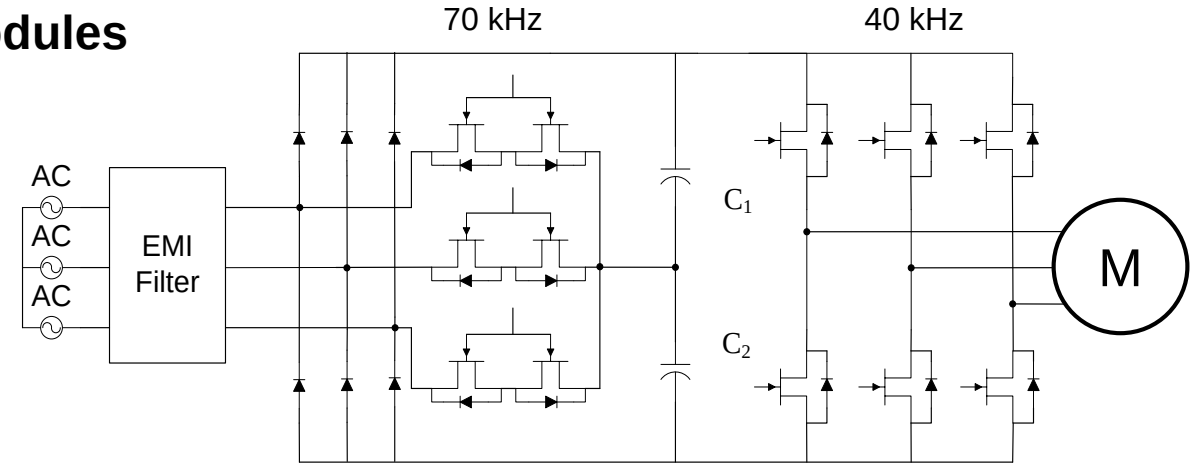




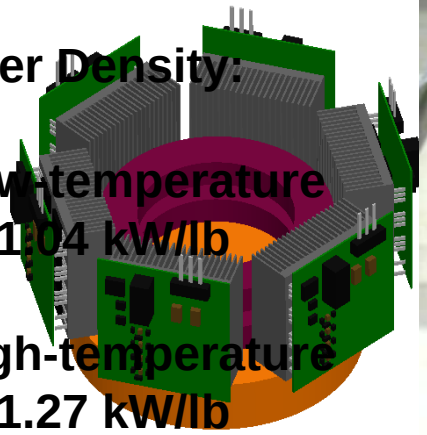


High-Power-Density, 10 kW Motor Drive with High-Temperature Modules

- High-temperature SiC modules
- Sensorless control
- Soft start
- Fan load application

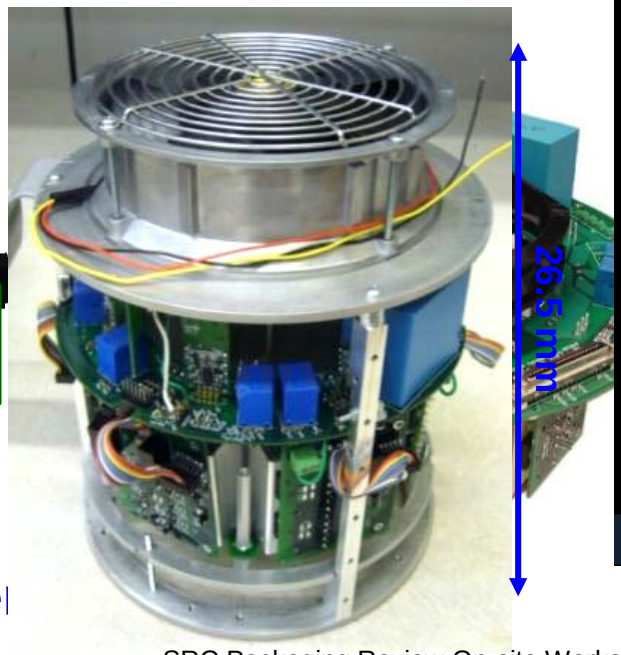


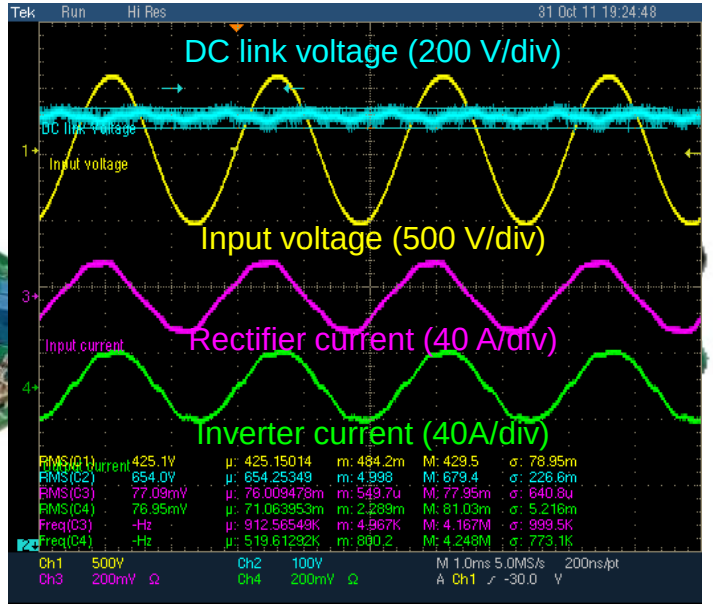
Ø = 21.5 cm



Power Density:

- Low-temperature 1.04 kW/lb
- High-temperature 1.27 kW/lb

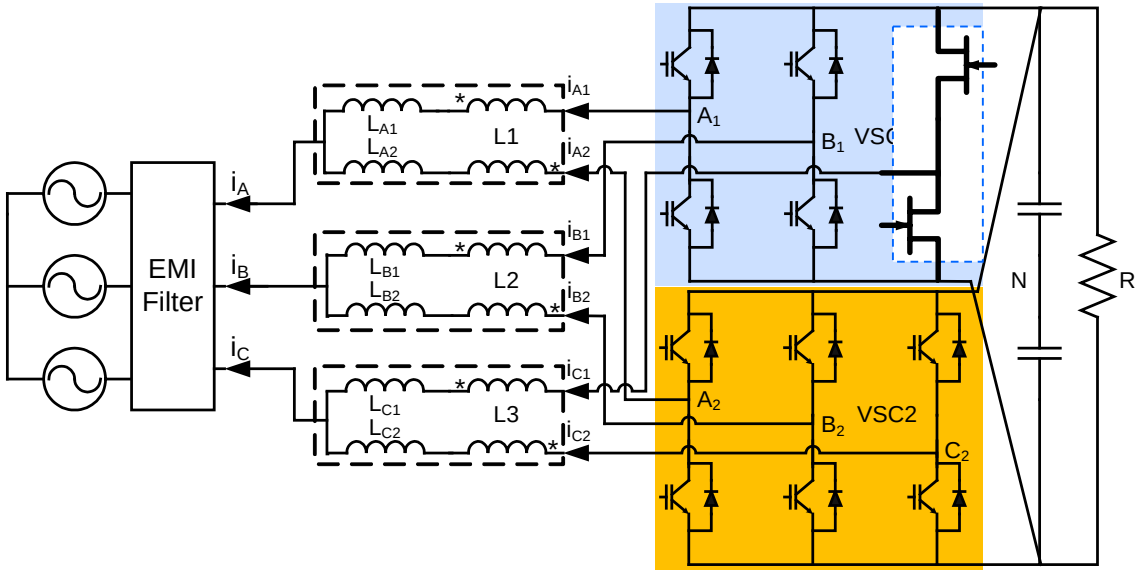




175 ºC Converter

250ºC Converter

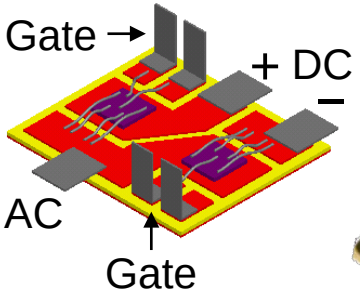
Interleaved High Power Density AFE Converter

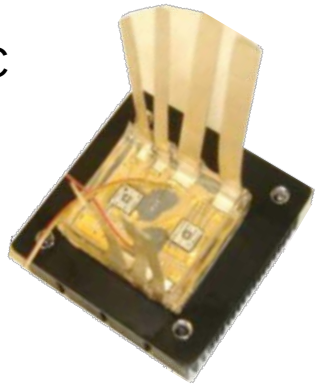


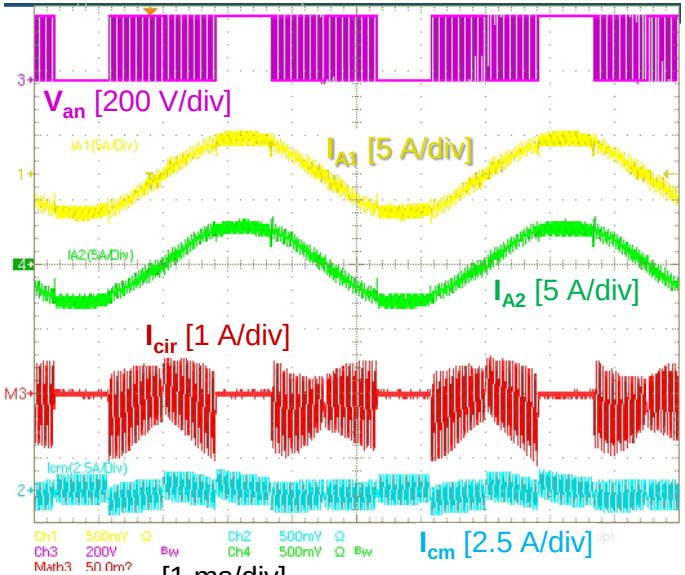
CPES High-Temp. Module

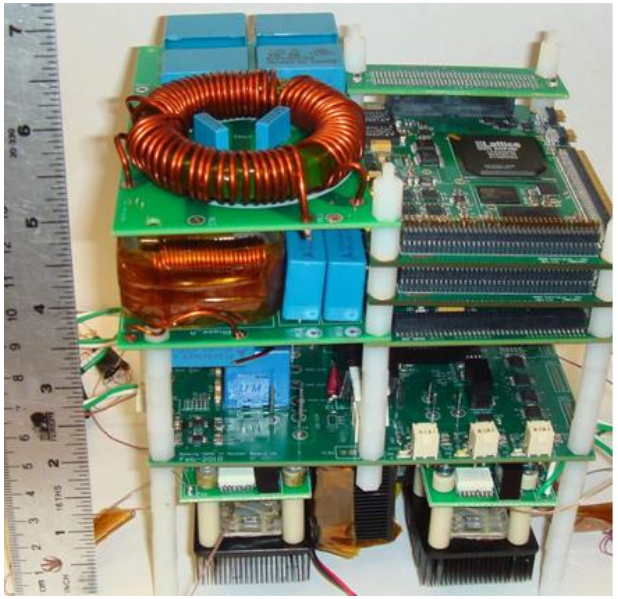
2 SiC JFETs (normally ON)

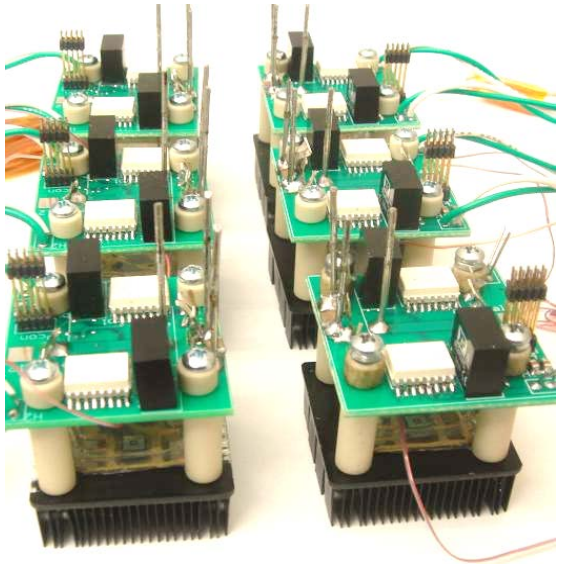
250°C, 1200 V, 20 A







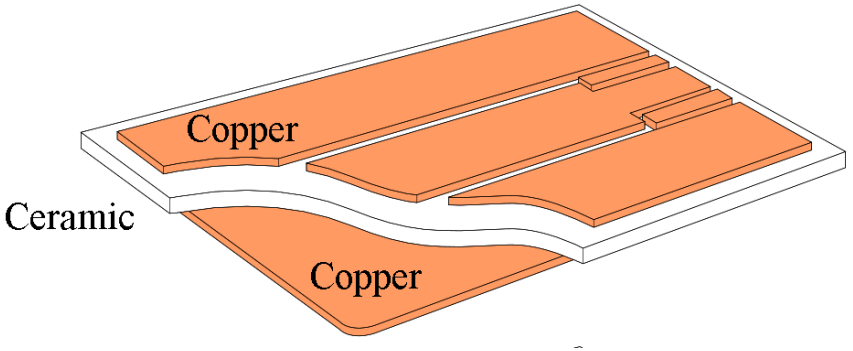


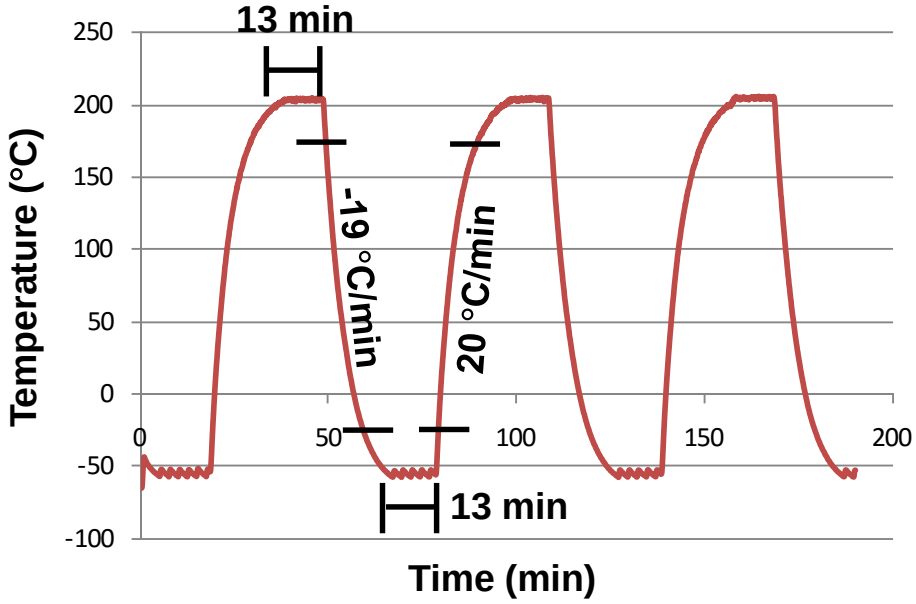


15 kW @ 6.3 kW/l

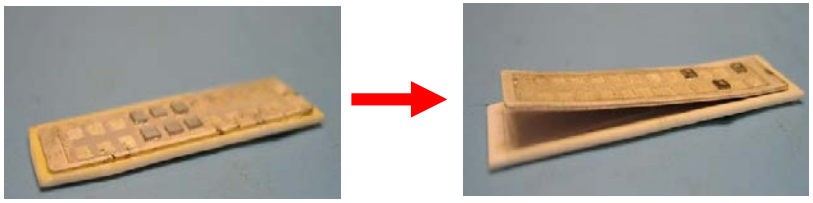
Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC



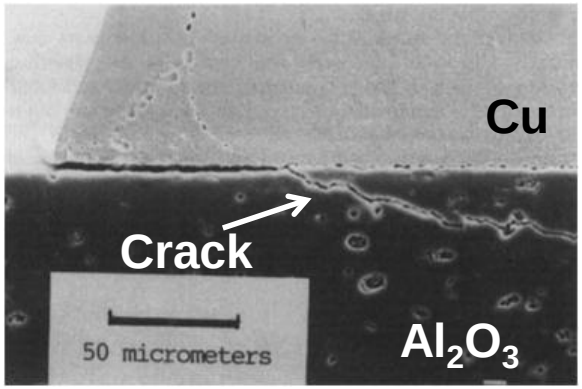


- **DBC substrate fails in** **< 20 cycles**



Before temperature cycling

After temperature cycling



Reliability of Direct-Bond-Copper (DBC) Substrate

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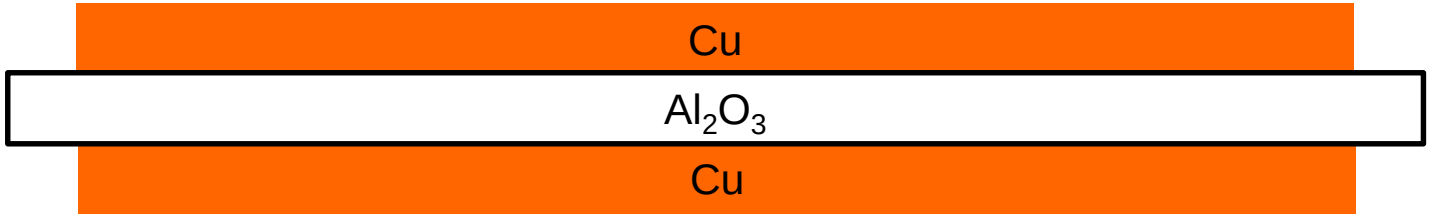
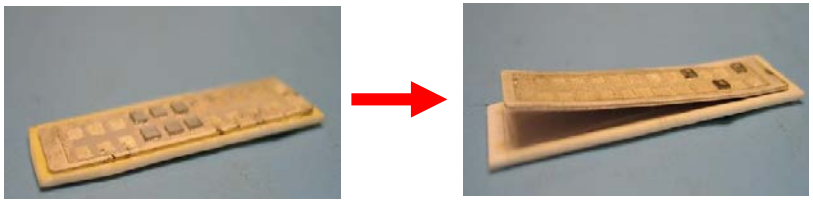


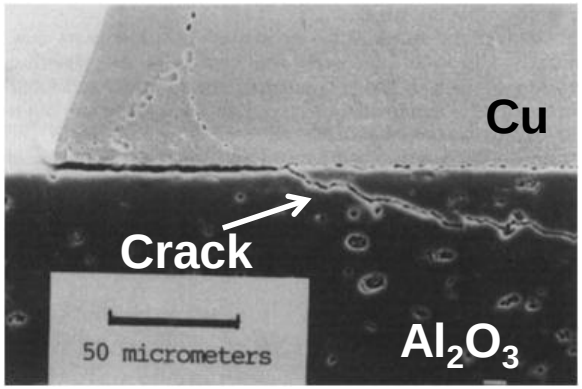
Direct-Bond-Copper Substrate

- **DBC substrate fails in** **< 20 cycles**



Before temperature cycling

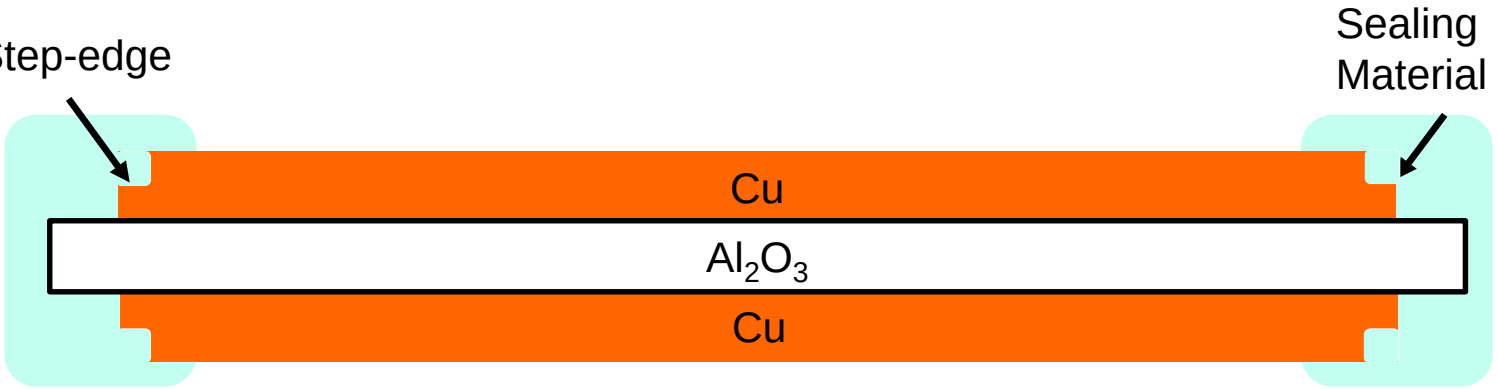
After temperature cycling



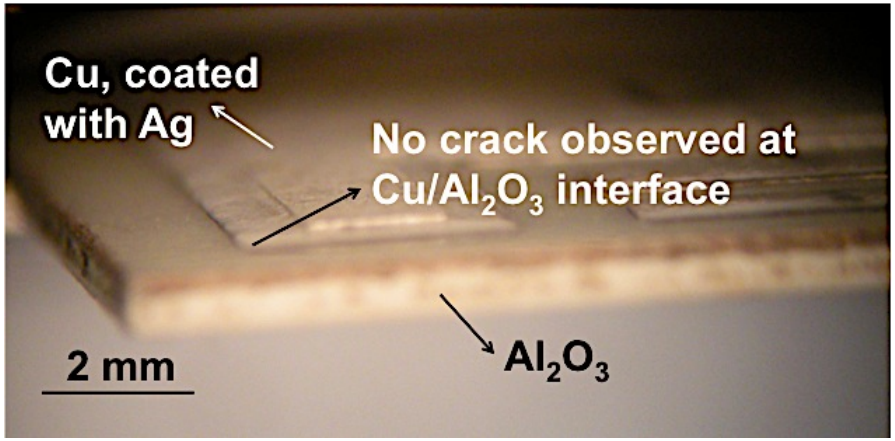
Reliability of Direct-Bond-Copper (DBC) Substrate

Reliability of DBC substrate in thermal cycling between -55ºC and 200ºC

- Creating stepped edges
- Applying sealing material



Direct-Bond-Copper Substrate

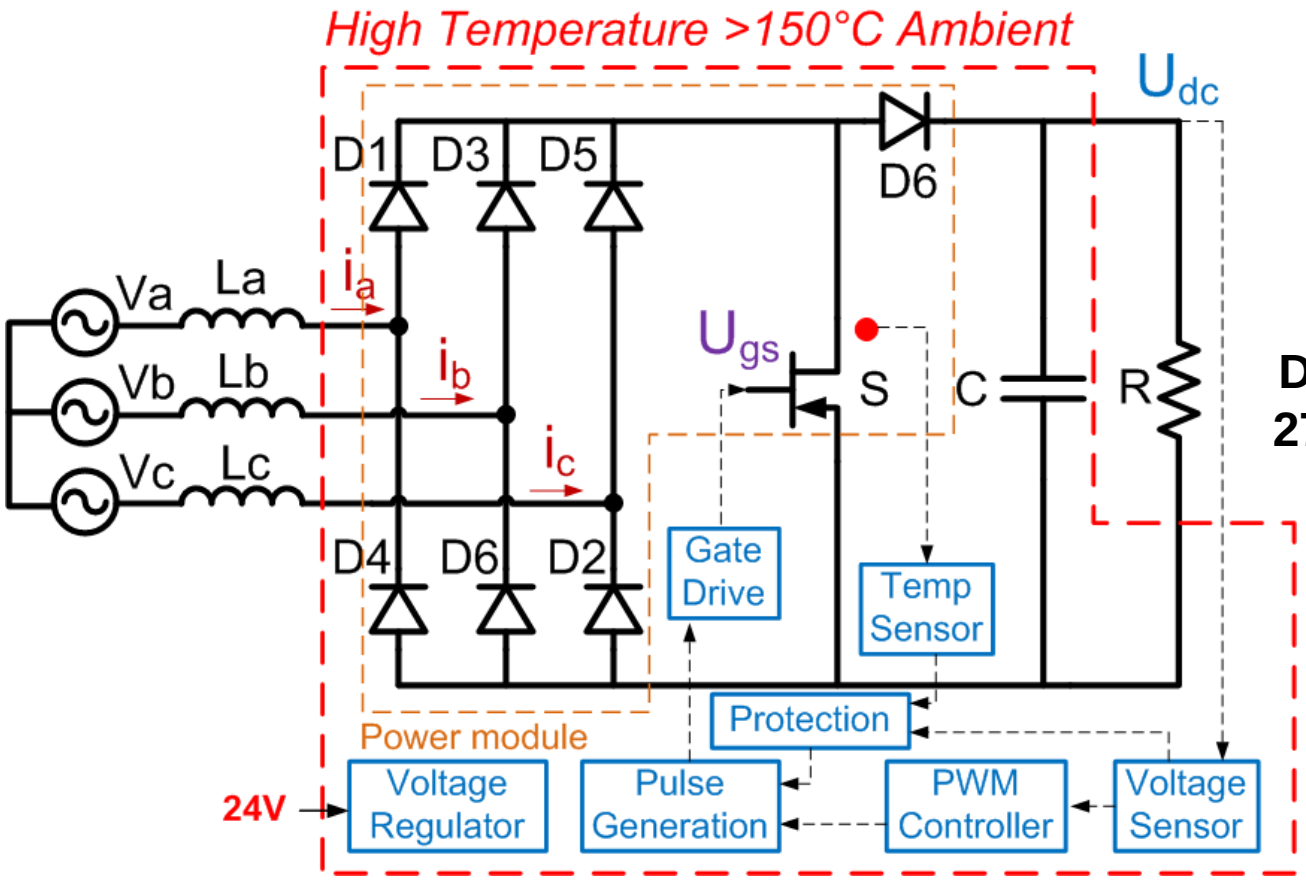


High-Temperature Single-Switch Three-Phase Rectifier

Targets:

- **Junction temperature up to 250°C.**
- **Ambient temperature over 150°C.**

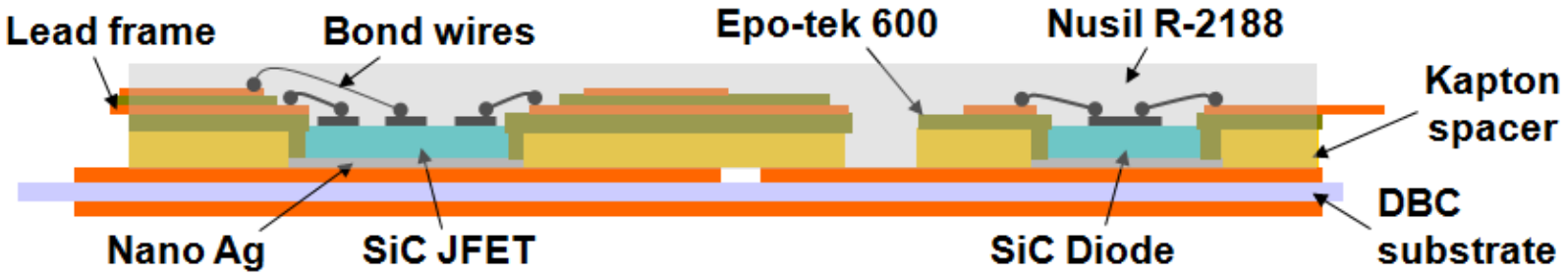
AC input:
100 V, 400 Hz

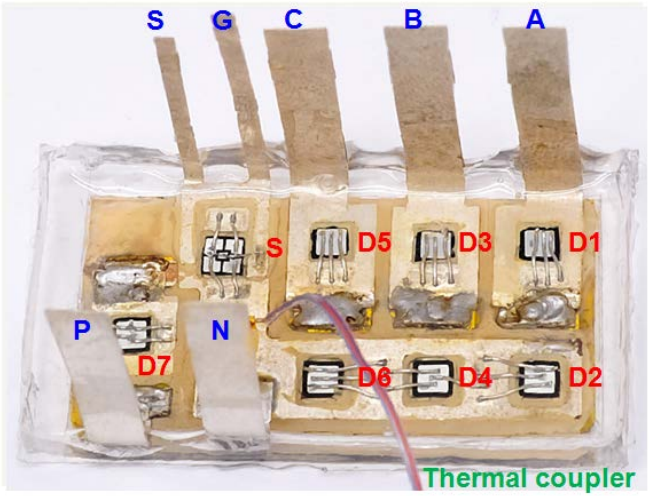


DC output:
270 V, 1 kW

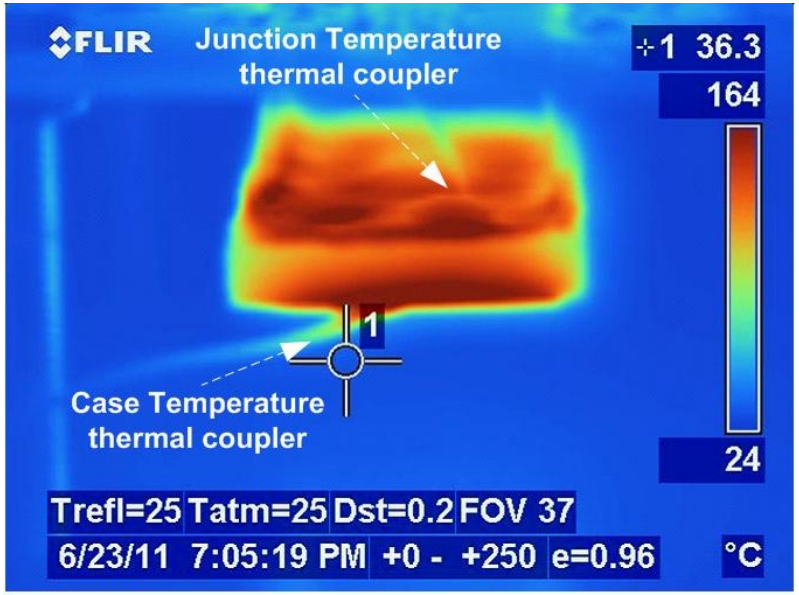
30 kHz Switching Frequency

Modified Hybrid Packaging Structure



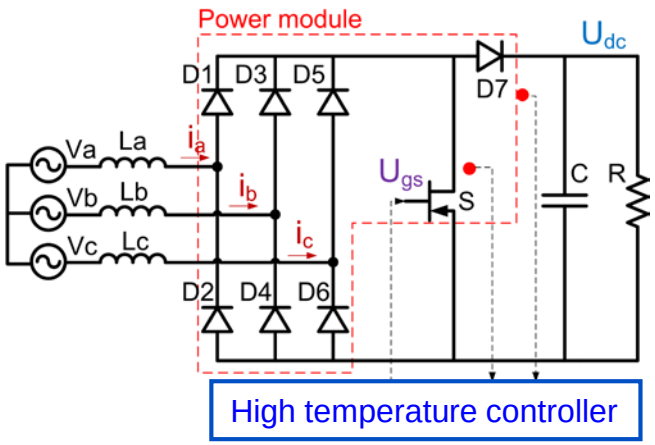


Multiple chip Hybrid Power Module

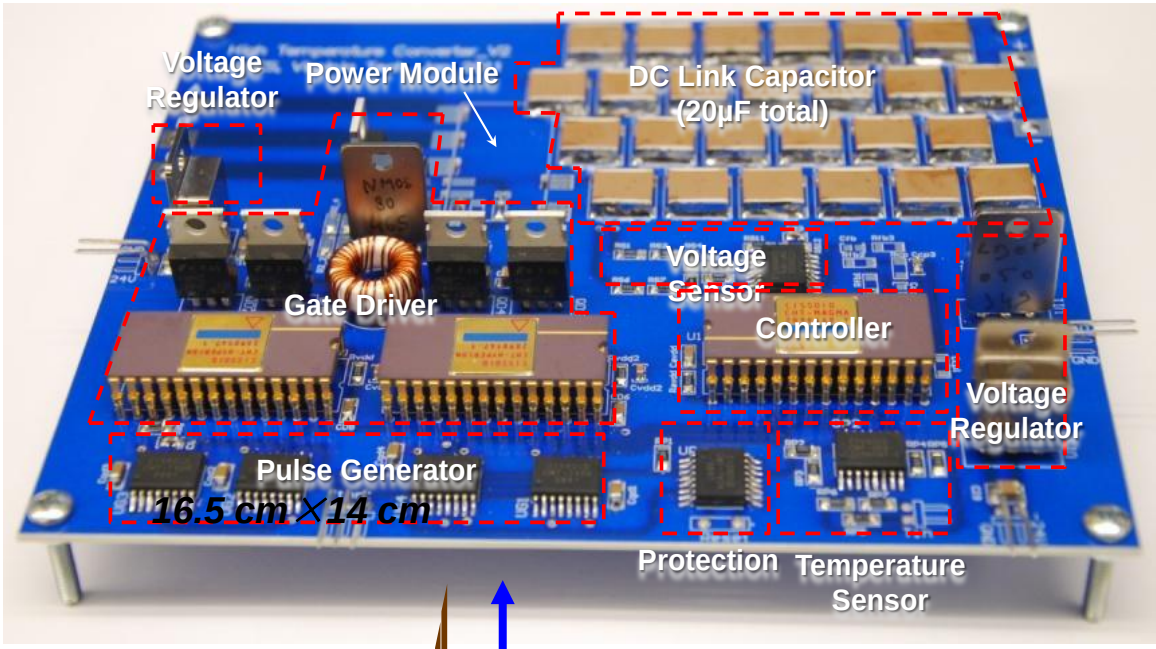


Power module thermal test

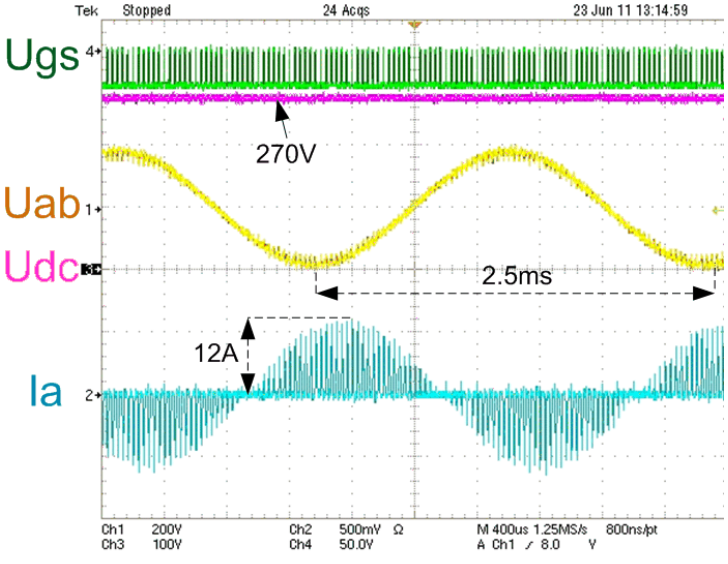
Integration of High-Temperature Three-Phase Rectifier



Mother board (driver, sensor, etc.)

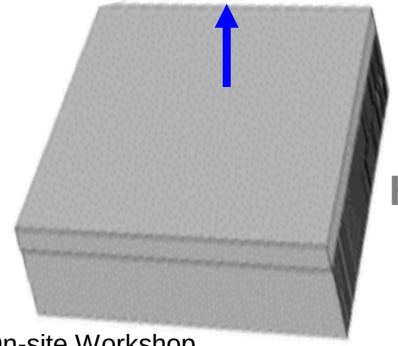


Electrical test



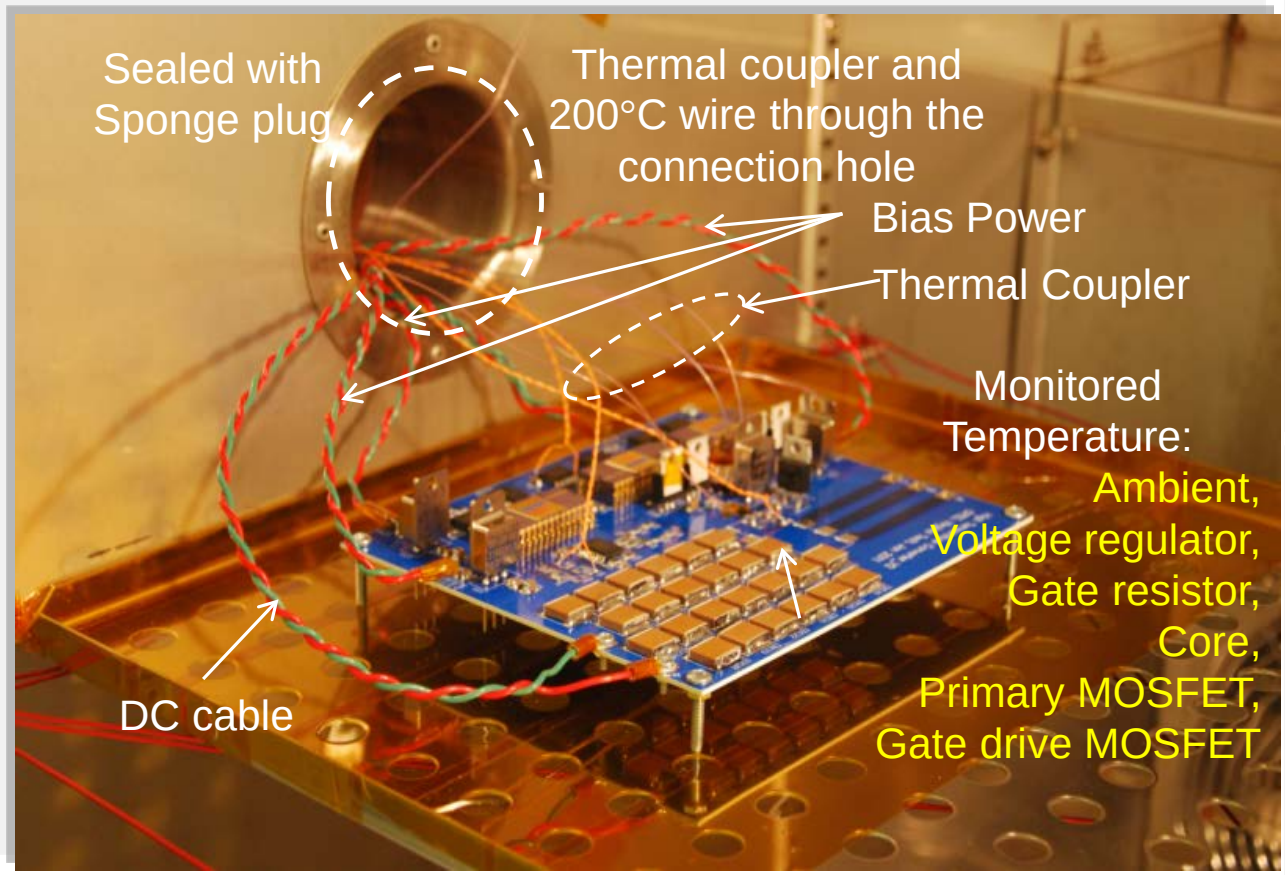
T_j = 225 ºC

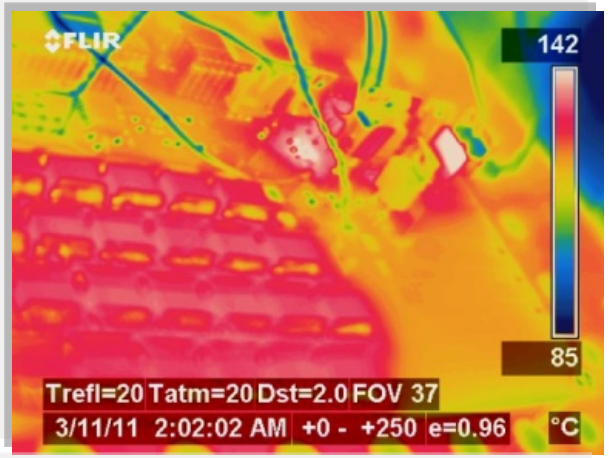
Power module



Heatsink

Converter Thermal Testing





Ambient temperature test point:

-50°C, -25°C, 0°C, 25°C, 50°C, 75°C, 100°C, 125°C, 150°C

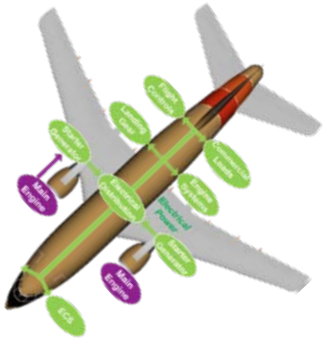
Test Picture for 150° C Ambient Temperature

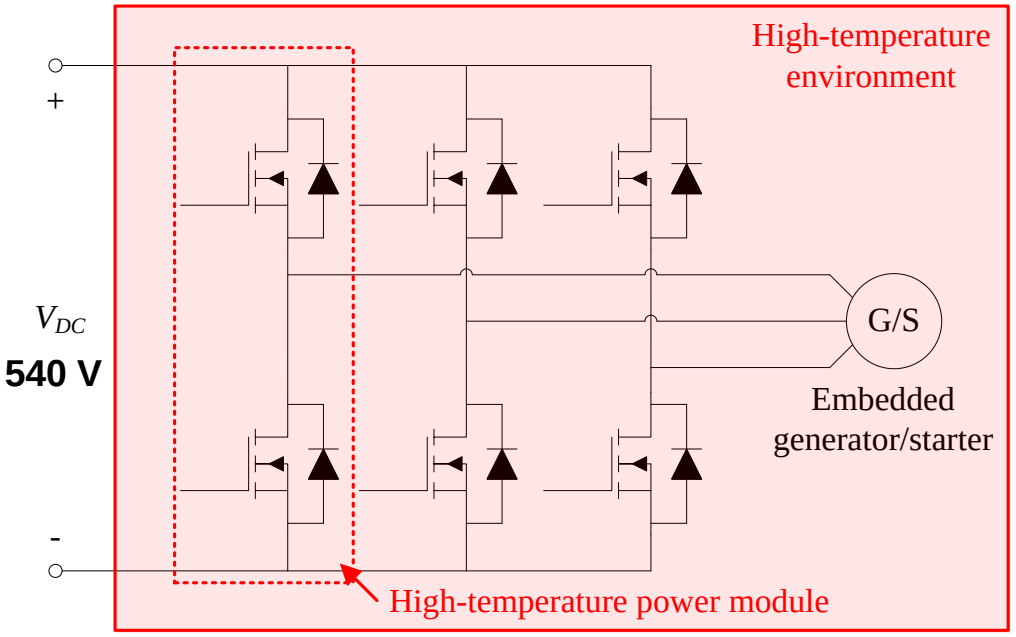
Electrical and thermal performance met design targets.
Ceramic capacitors and their attach to PCB exhibited early failures.

High-Temperature 3-Phase AC-DC Converter for Embedded Generators in MEA

Target:

- *50 kW inverter/rectifier for starter/generator*
- *High-temperature and high-power-density*
- *Ambient temperature: 200 – 250 ℃*
- *Switching frequency: 70 kHz*





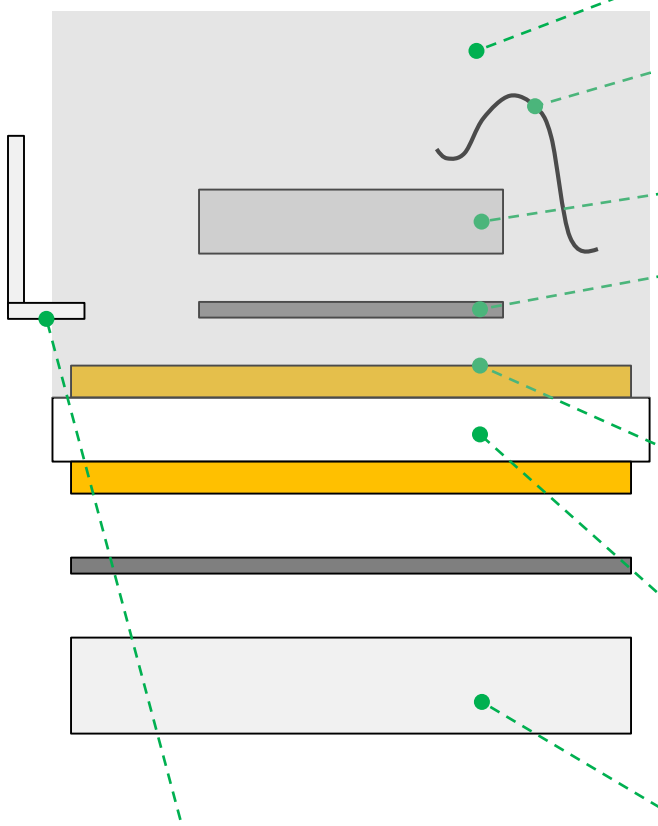
Commercial products (1200 V, 100 A)

Powerex
SiC MOSFET module (2012)
150 °C

Cree
SiC MOSFET module (2013)
125 °C

Need a power module capable of both high-temperature & high-frequency operations!

High-Temperature Packaging Materials Used



Encapsulant (*NuSil R-2188 silicone*)

Bonding wire (*Al*)

- ~15 A for a 10 mil wire

SiC MOSFET/diode

Solder (*Pb95-Sn5*)

- Liquidus point 312 °C
- Better solderability on Ni surface

Surface plating (*Electro-less Ni*)

- Works best with Al wire-bonding
- Up to 300 °C

Substrate (*AlN DBC*)

- High thermal conductivity
- Best overall performance

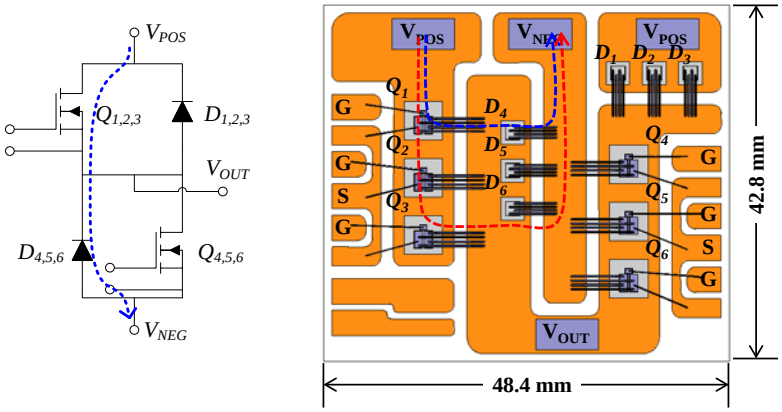
Terminals (*Ni-plated Cu*)

Baseplate (*AlSiC*)

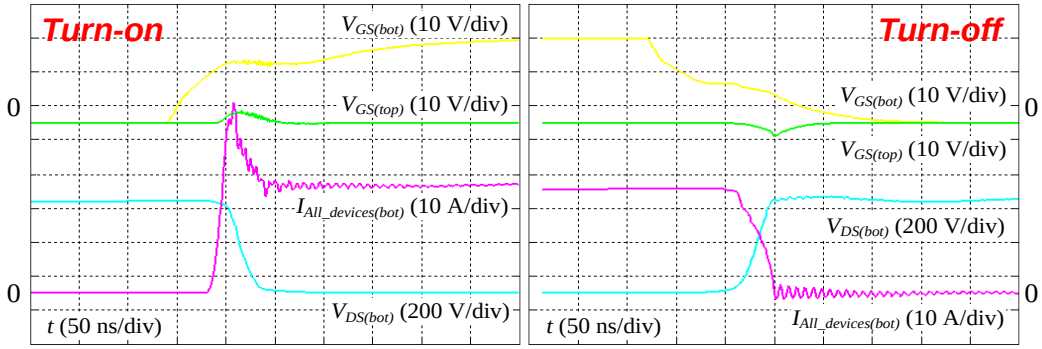
High-temperature capability of the material;
Suitable combinations of materials to achieve higher reliability

1200 V, 60 A SiC Phase-Leg Module Design

Improved substrate layout to minimize loop inductances

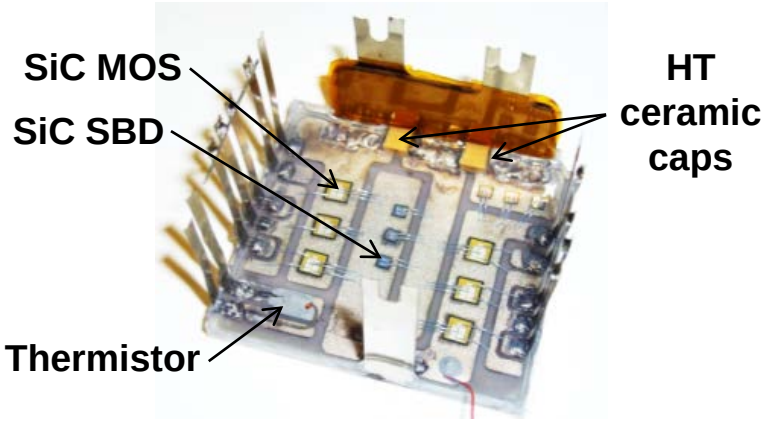


Fast & clean switching

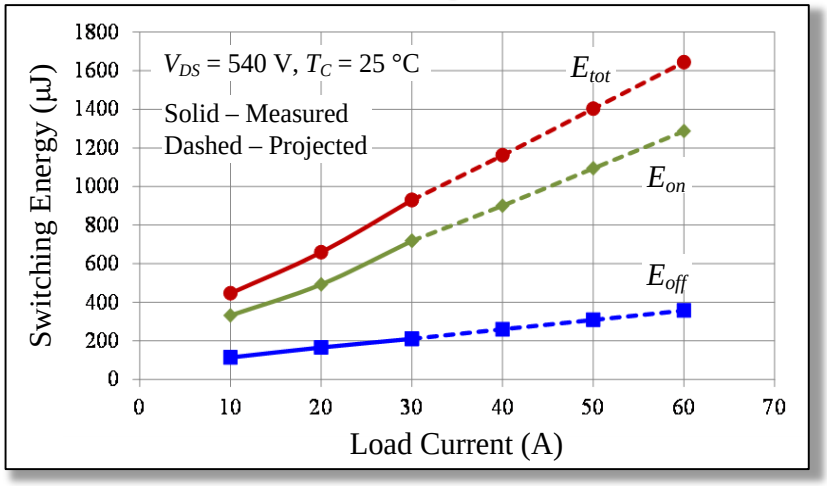


Hard switching w/ R_G = 0 Ω
Fast di/dt & dv/dt with small V_{DS} overshoot

Fabricated module with DC decoupling capacitors

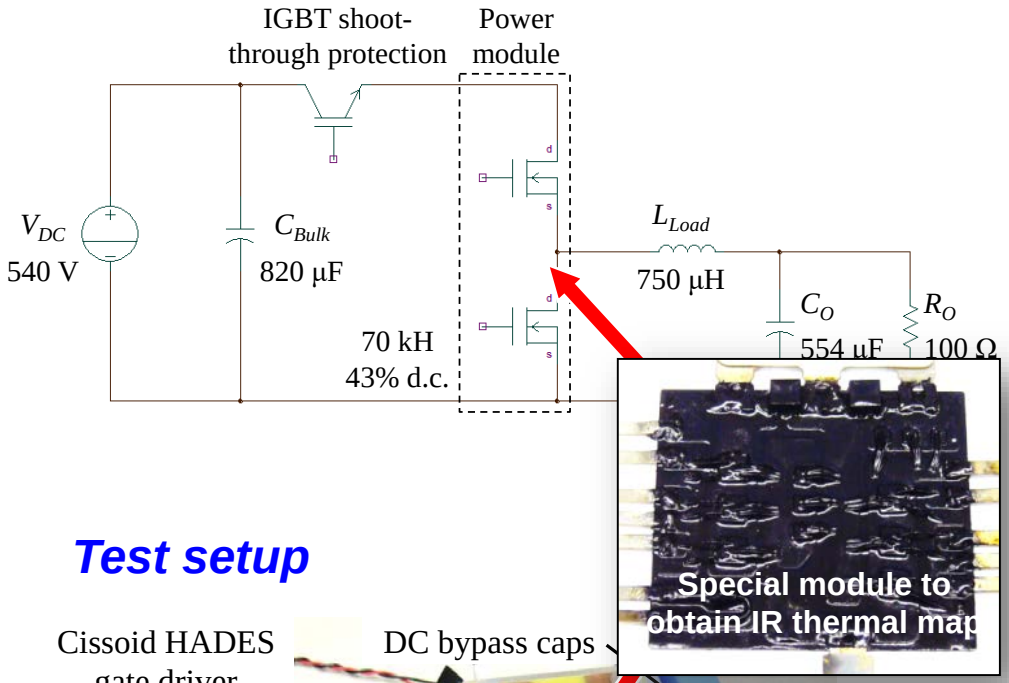


Switching Loss is 10-20% of an equivalent IGBT

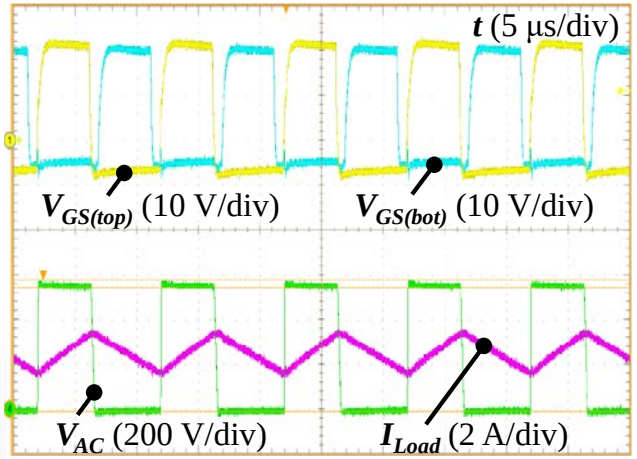


200 °C, 1200 V, 60 A SiC Phase-Leg Module: Continuous Operation at 200 °C

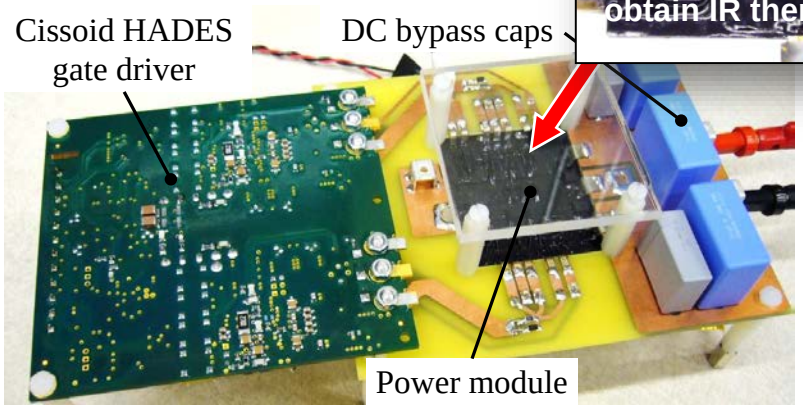
Buck-mode operation

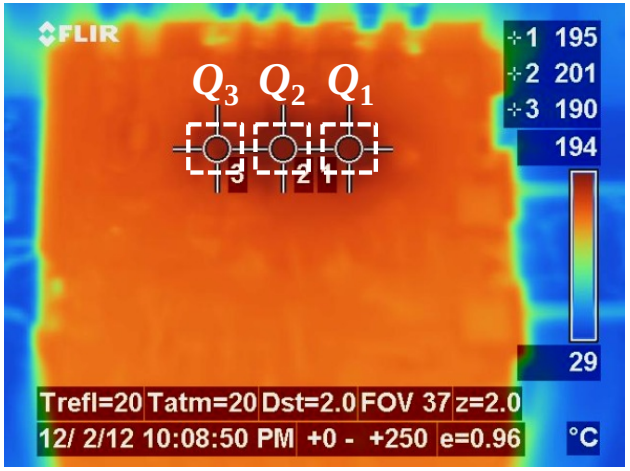


Test results at 560 V & 100 kHz



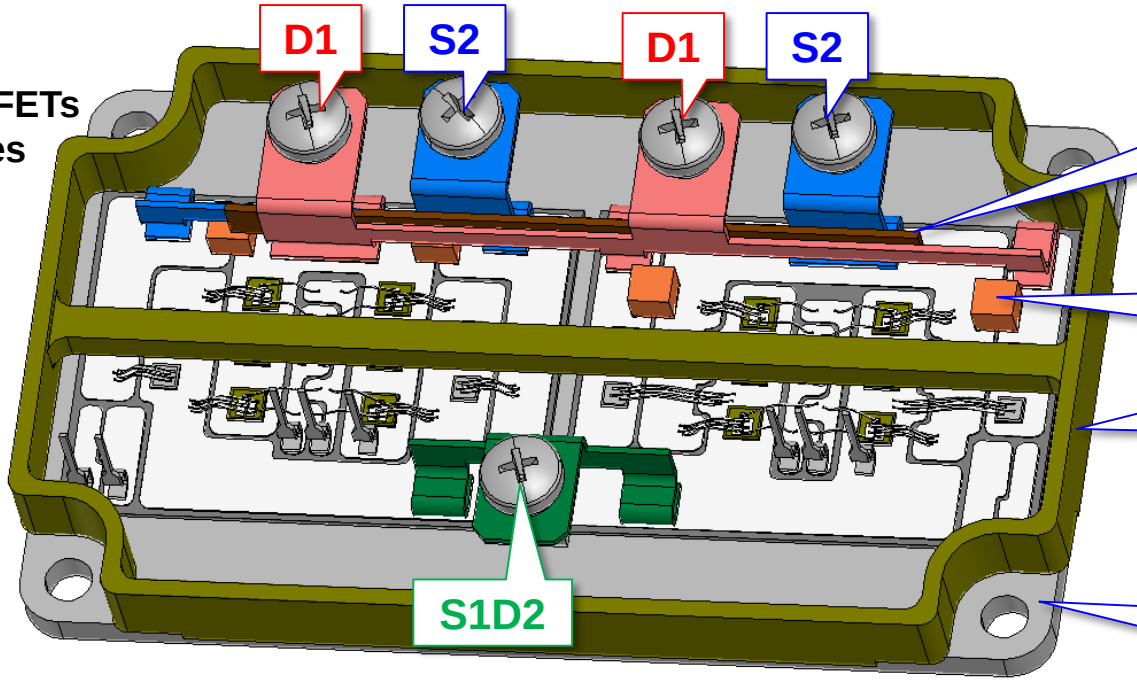
Test setup





200 °C, 1200 V, 120 A SiC Phase-Leg Module: Module Design

Each switch:
6x 20 A MOSFETs
4x 20 A diodes



Nomex HT insulation

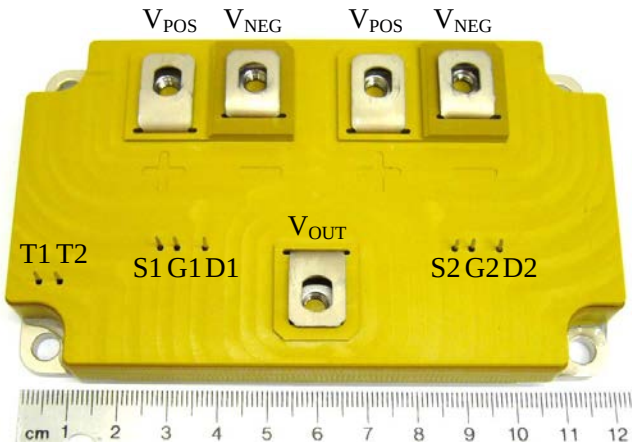
HT ceramic caps

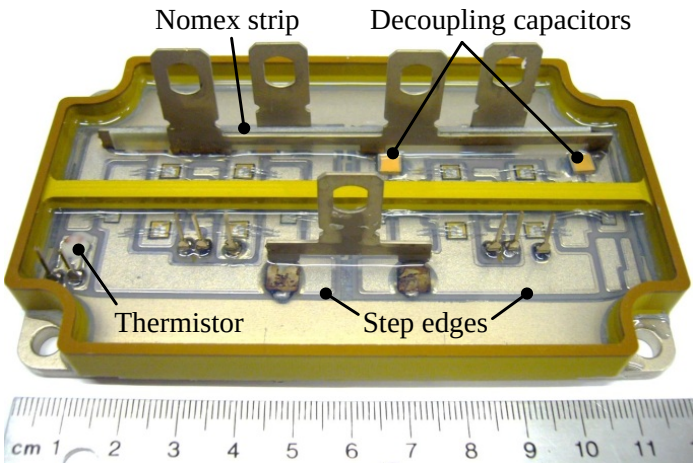
Torlon HT plastic

AlSiC baseplate

L: 119 mm
W: 69 mm
H: 19 mm

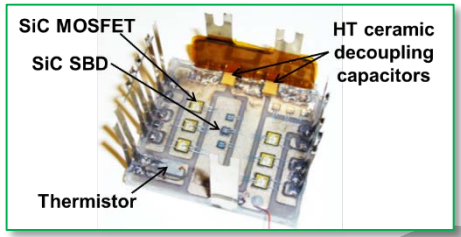
Fabricated module

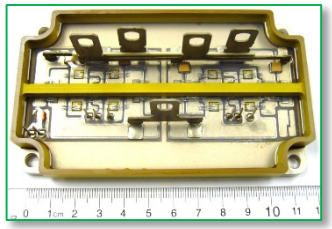




System Design

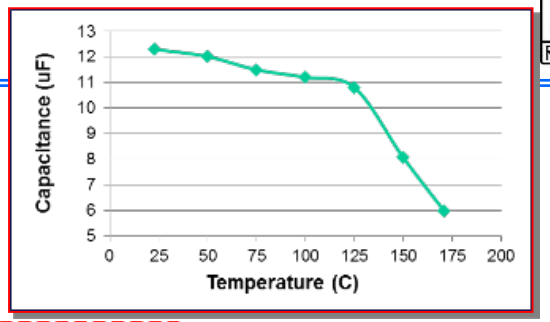
HT power module design and fabrication

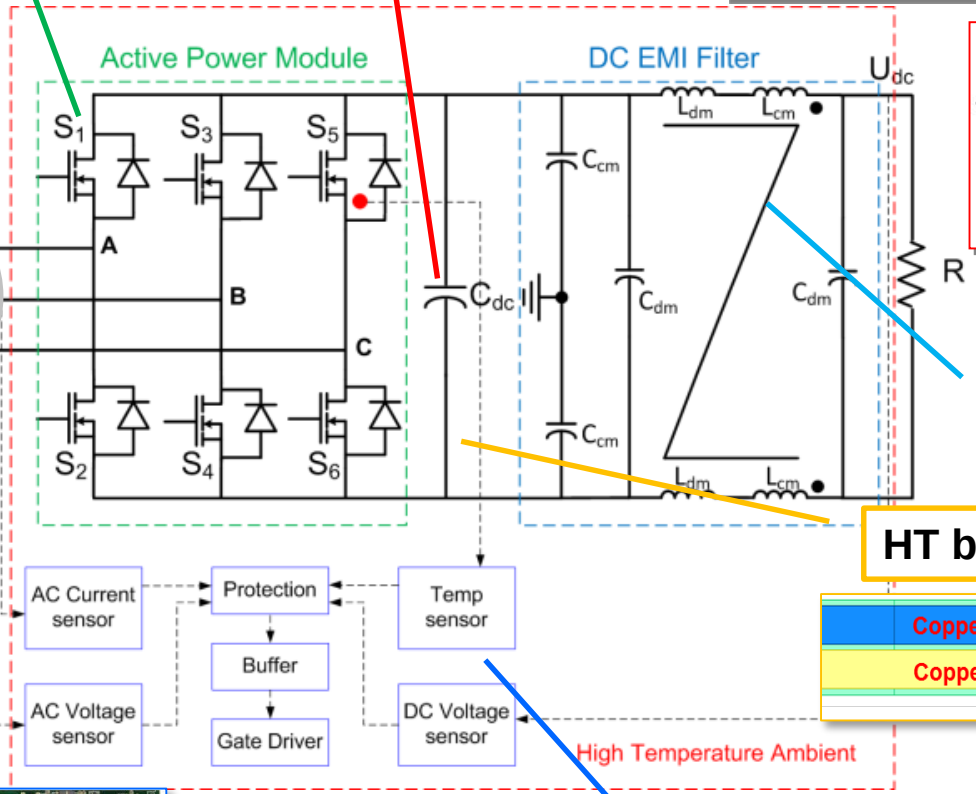


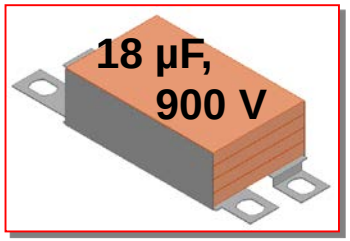


S / G

HT dc capacitor reliability testing

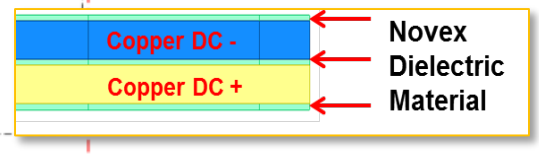




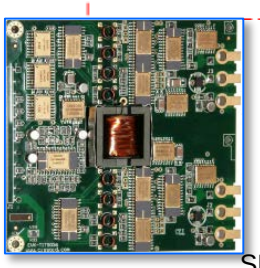


HT EMI filter survey

HT bus bar design



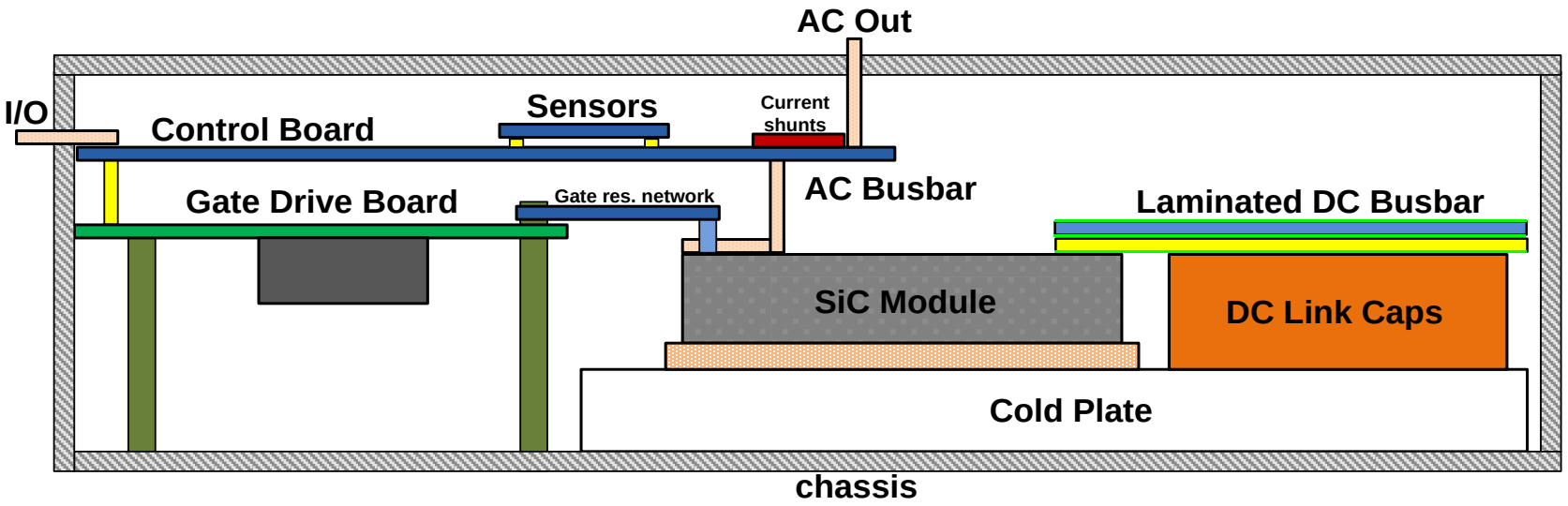
Assumed HT controller from TI could be used

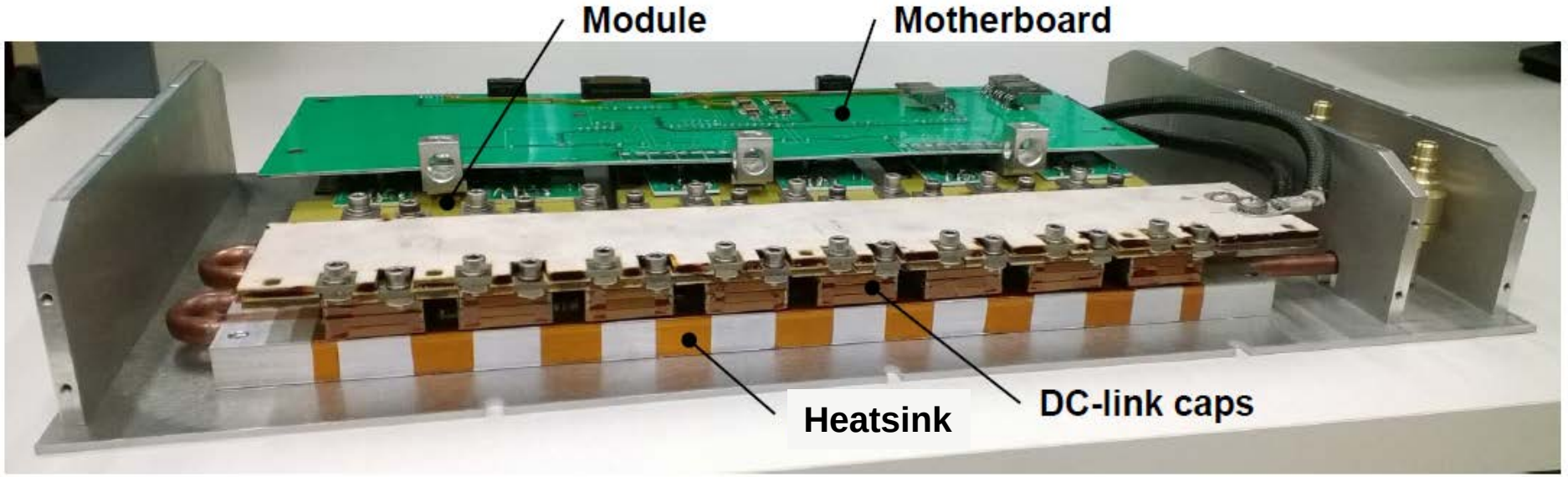


HT gate drive

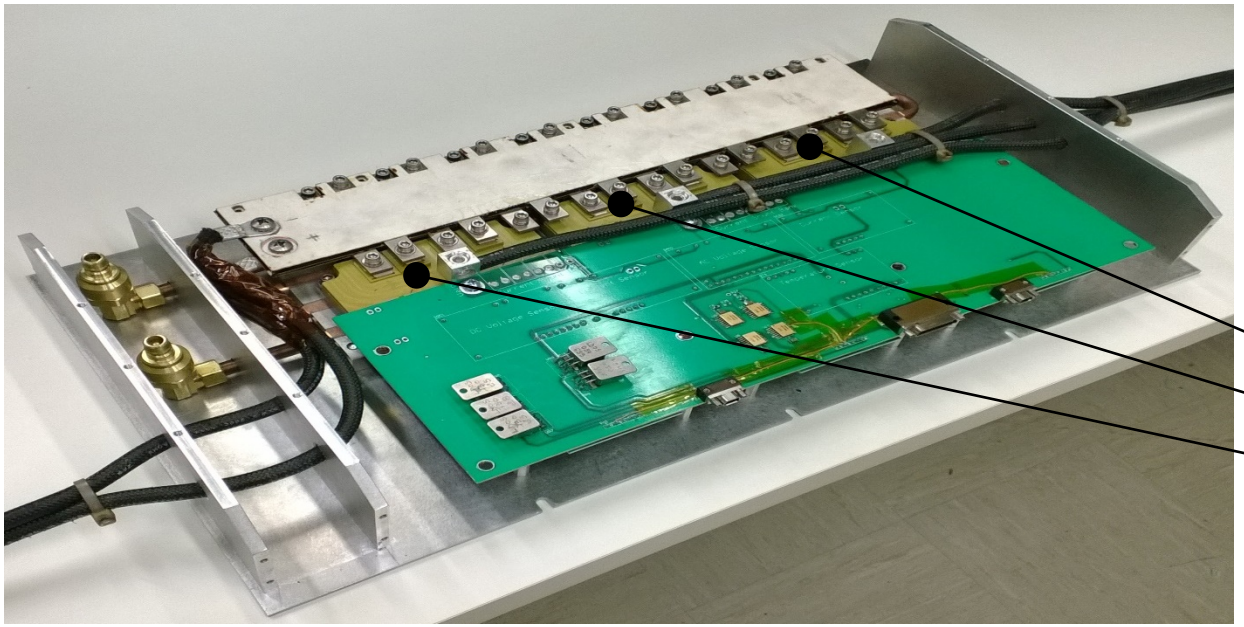
HT sensors

Converter Layout

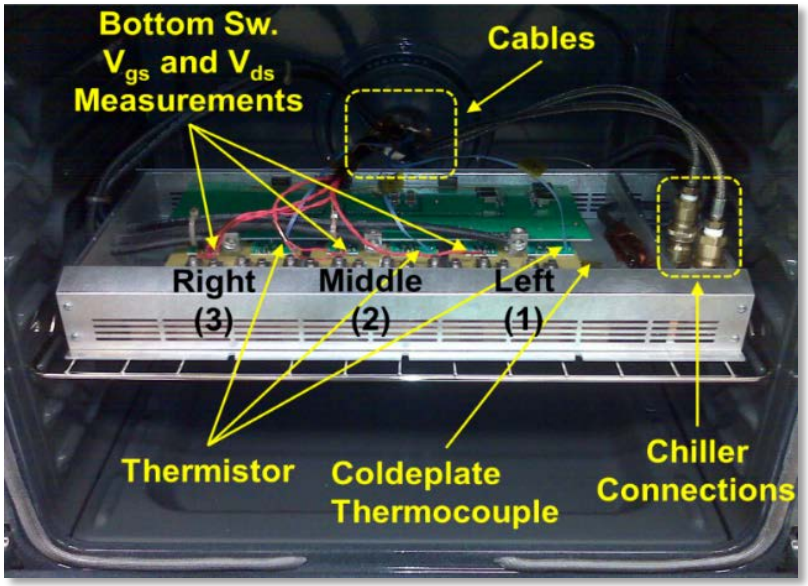




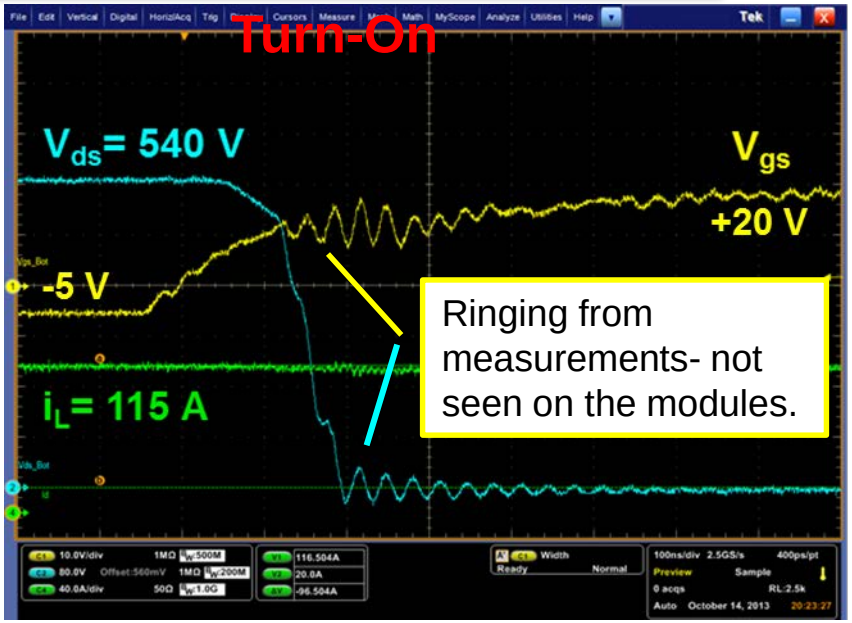
Converter Layout

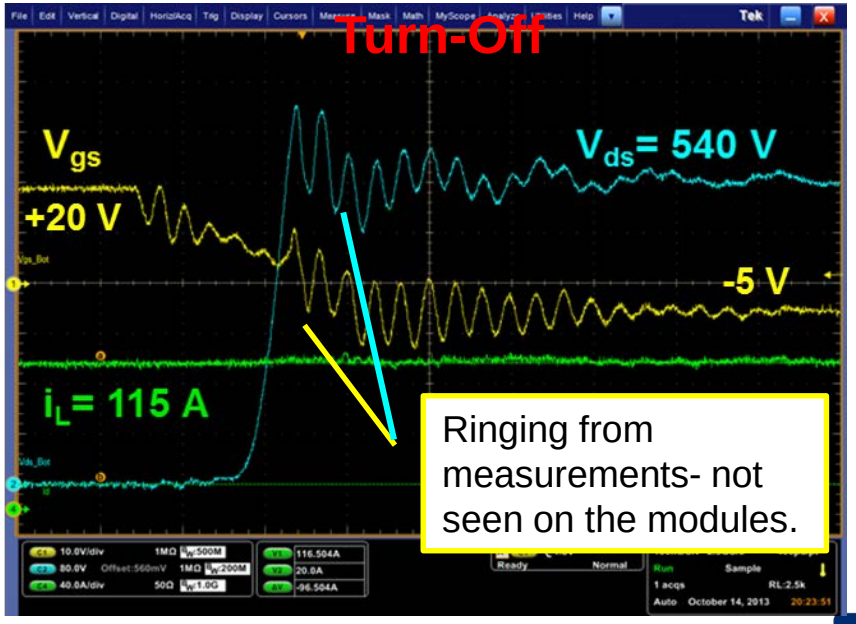


Converter Testing



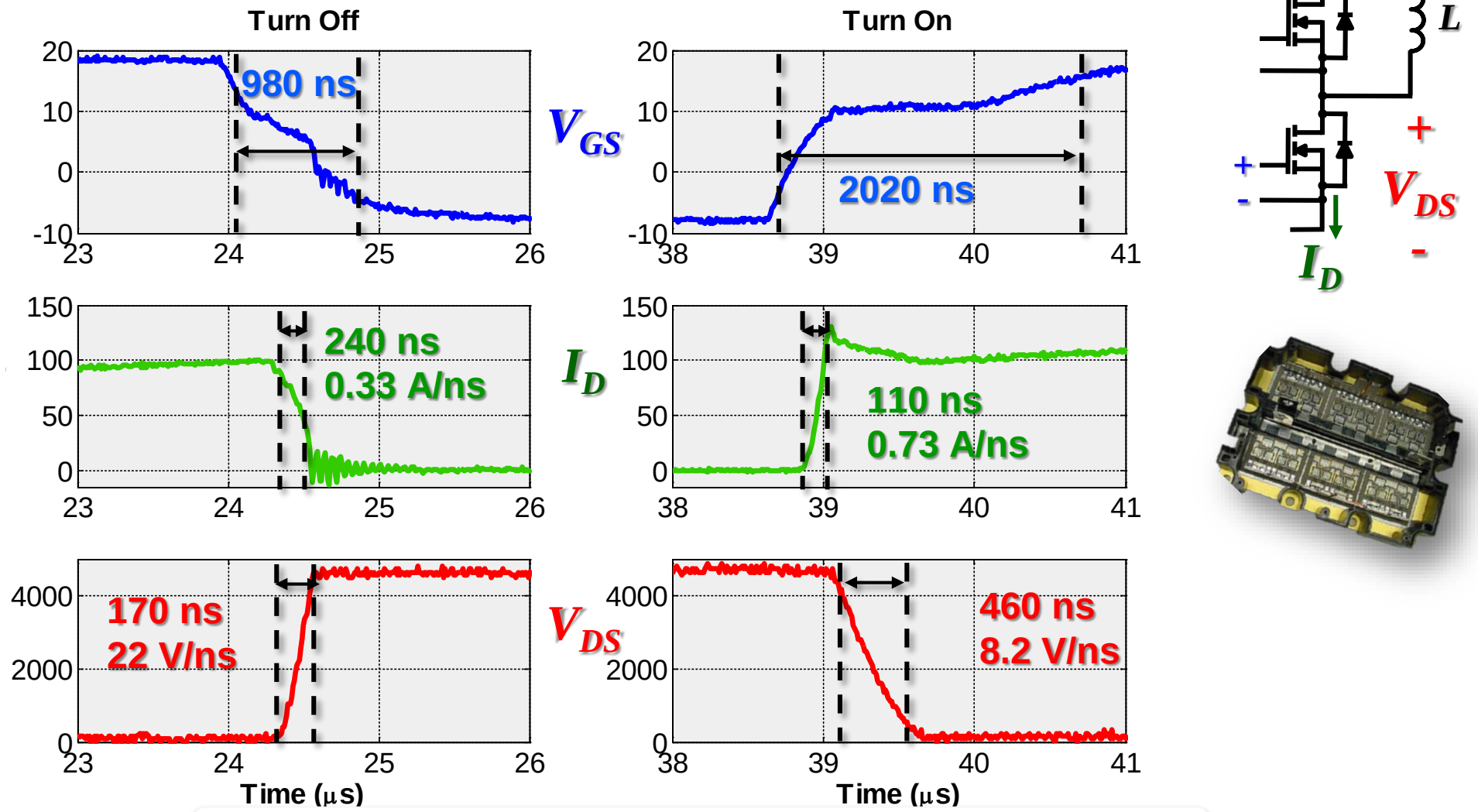
- **200 ºC ambient**
- $R_{G,on}$ and $R_{G,off}$: 3.3 Ω
- Liquid cooling temperature: 70 ºC
- Protection:
  - over-voltage
  - over-current
  - over-temperature





Utilization of 10 kV SiC Devices for Grid-scale Applications

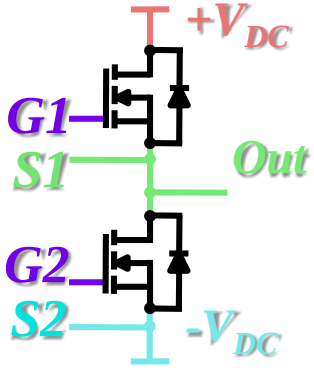
Characterization of 10 kV SiC MOSFET Modules

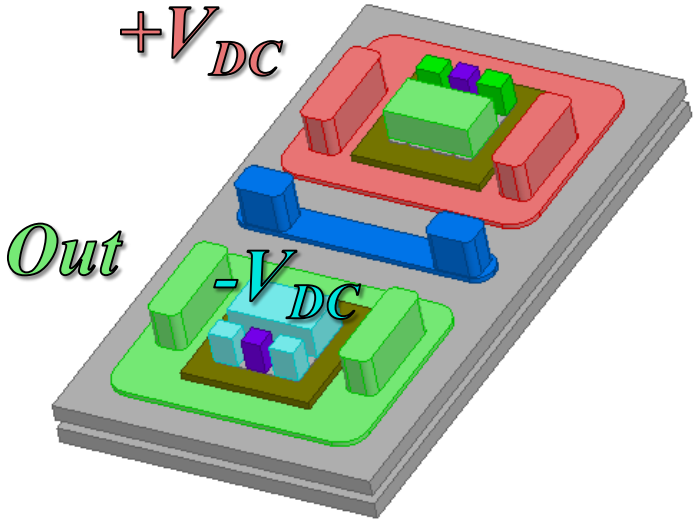


V_{DS}= 4.7 kV, I_D= 100 A, V_{GS}= +18 V to -8 V, $R_{G,ext}$= 5 Ω

Design of a high-voltage, high-density phase-leg

- Low-inductance interconnection achieved using molybdenum bumps and DBC.





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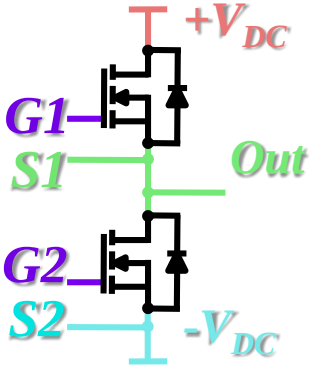
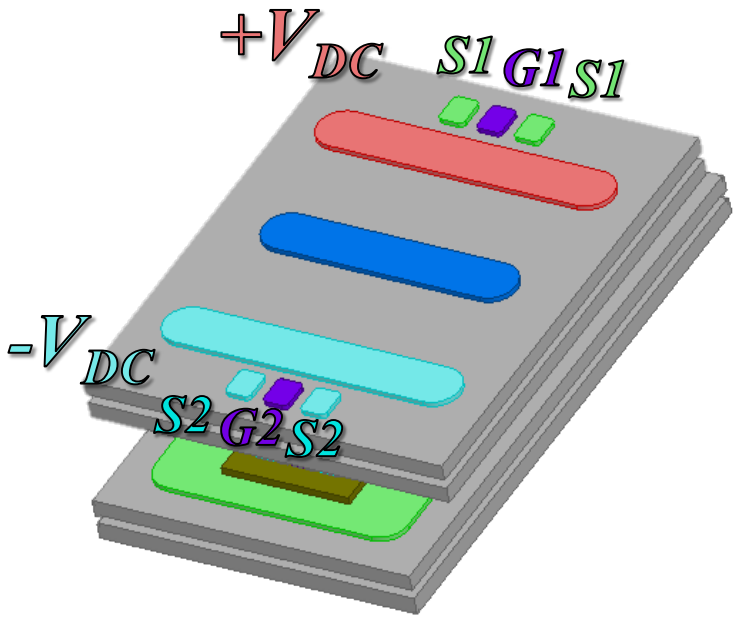
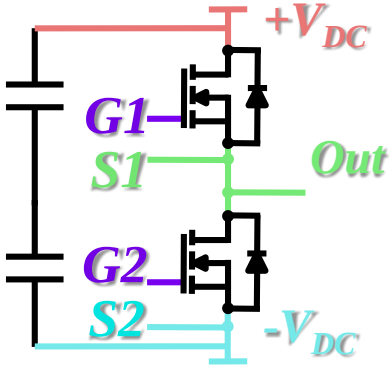
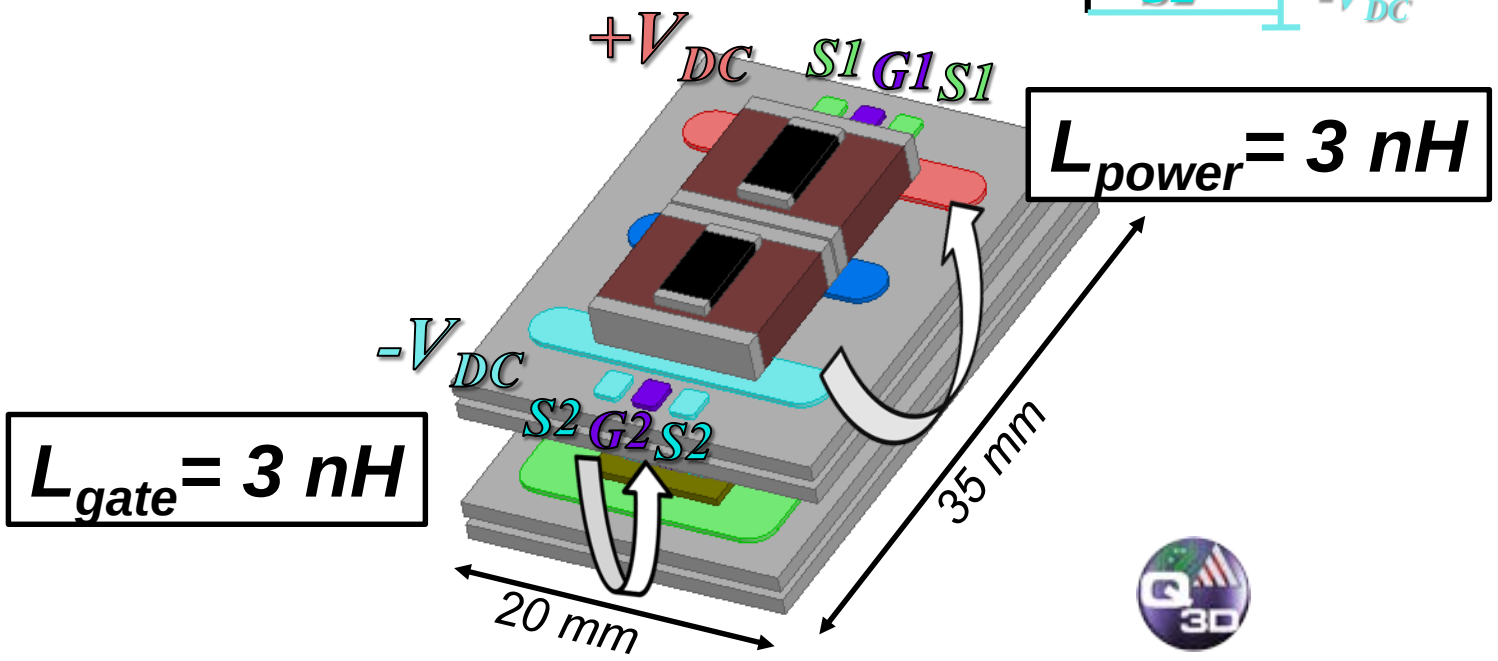




Design of a high-voltage, high-density phase-leg

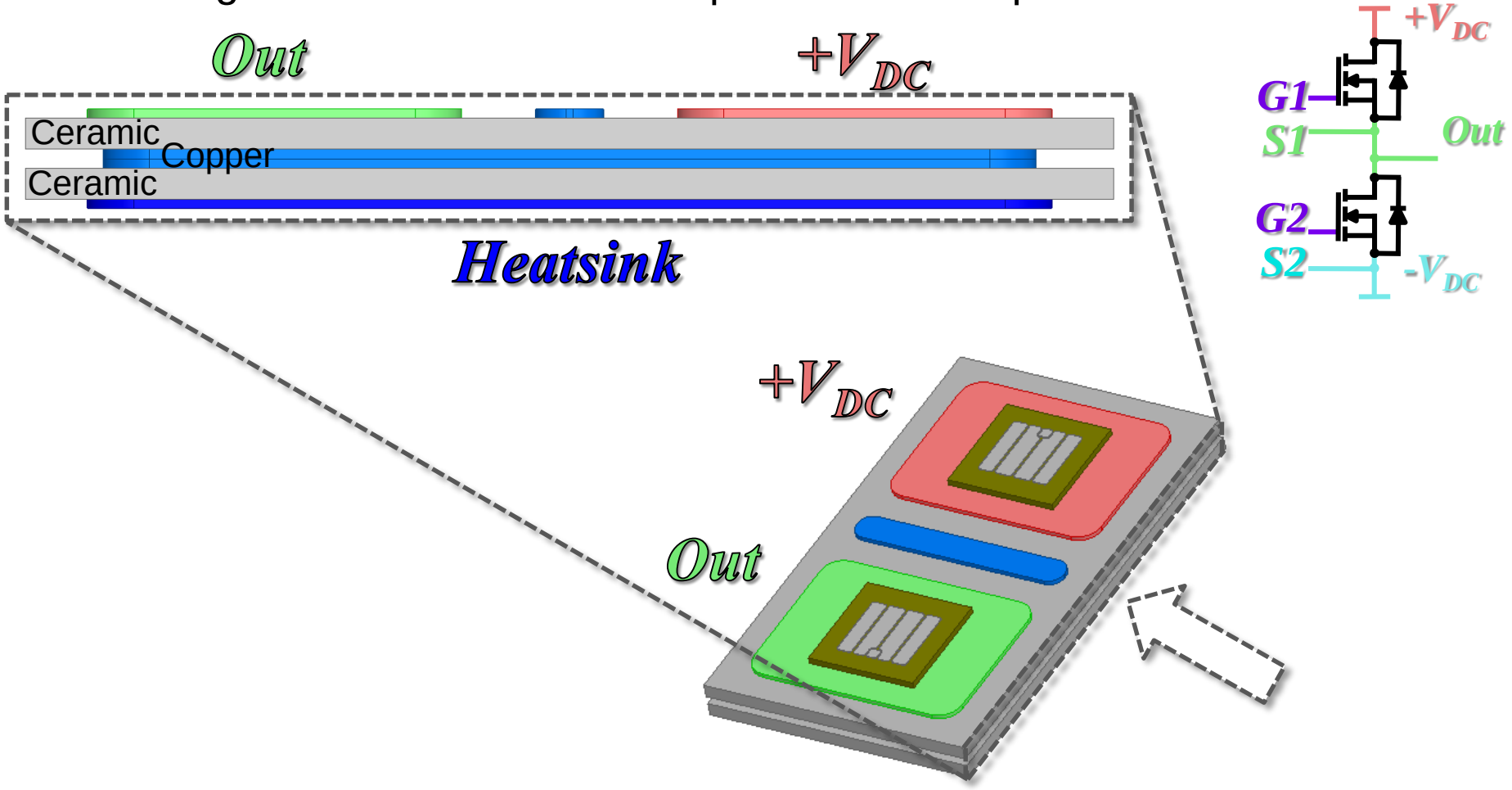
- Low-inductance interconnection achieved using molybdenum bumps and DBC.
- Embedded decoupling capacitors shorten the commutation loop.



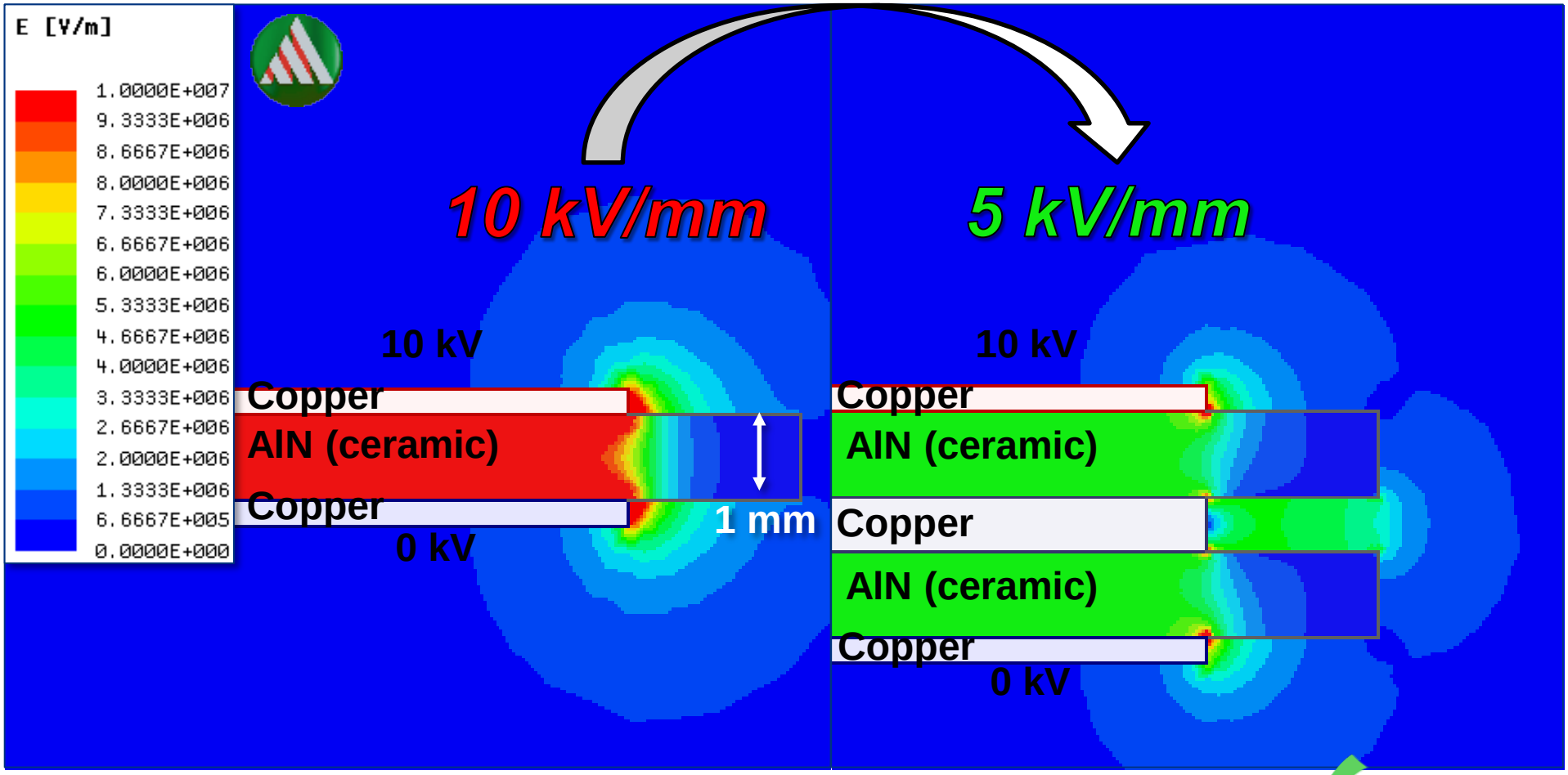


Design of a high-voltage, high-density phase-leg

- Stacking DBC substrates can help to reduce the peak electric field.



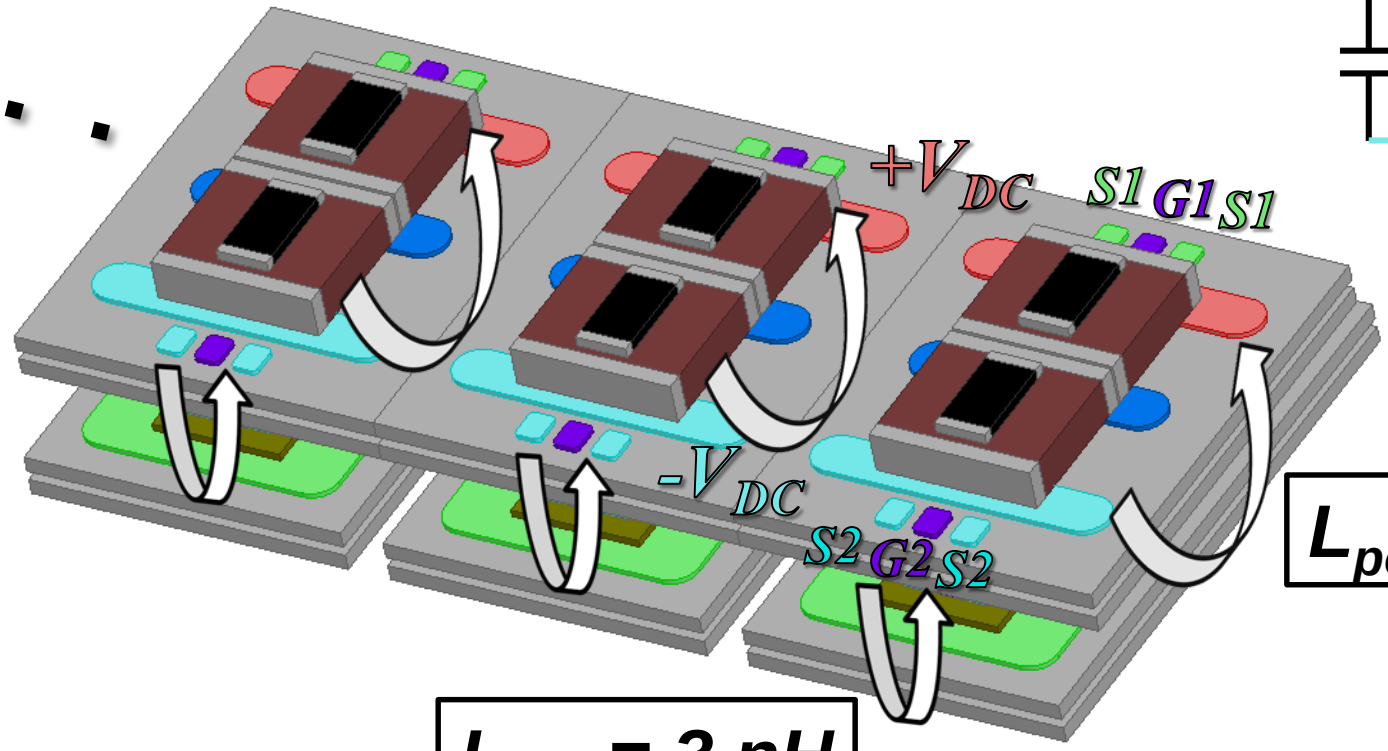
Stacking DBC substrates can help to reduce the peak electric field.

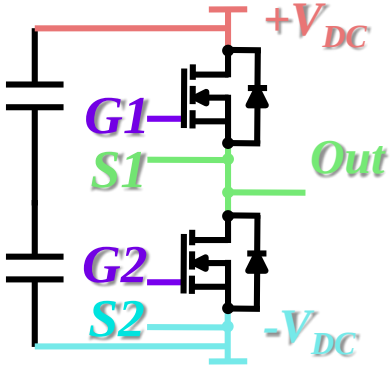


1. High-Density → Thermal & Electric Field

Each MOSFET pair has its own gate and power loops.

2. High-Power → Stress Imbalance



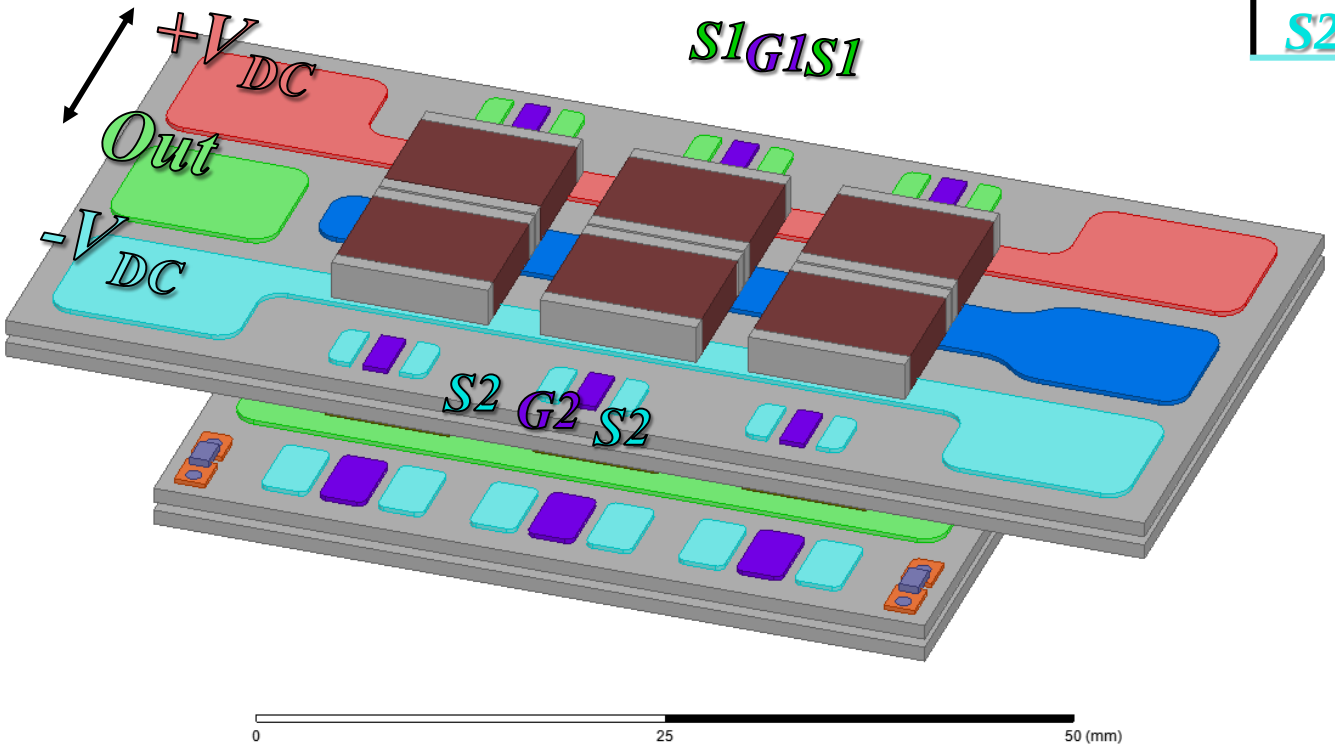


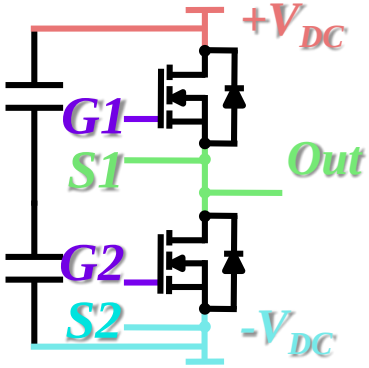
L_{power} = 3 nH

L_{gate} = 3 nH

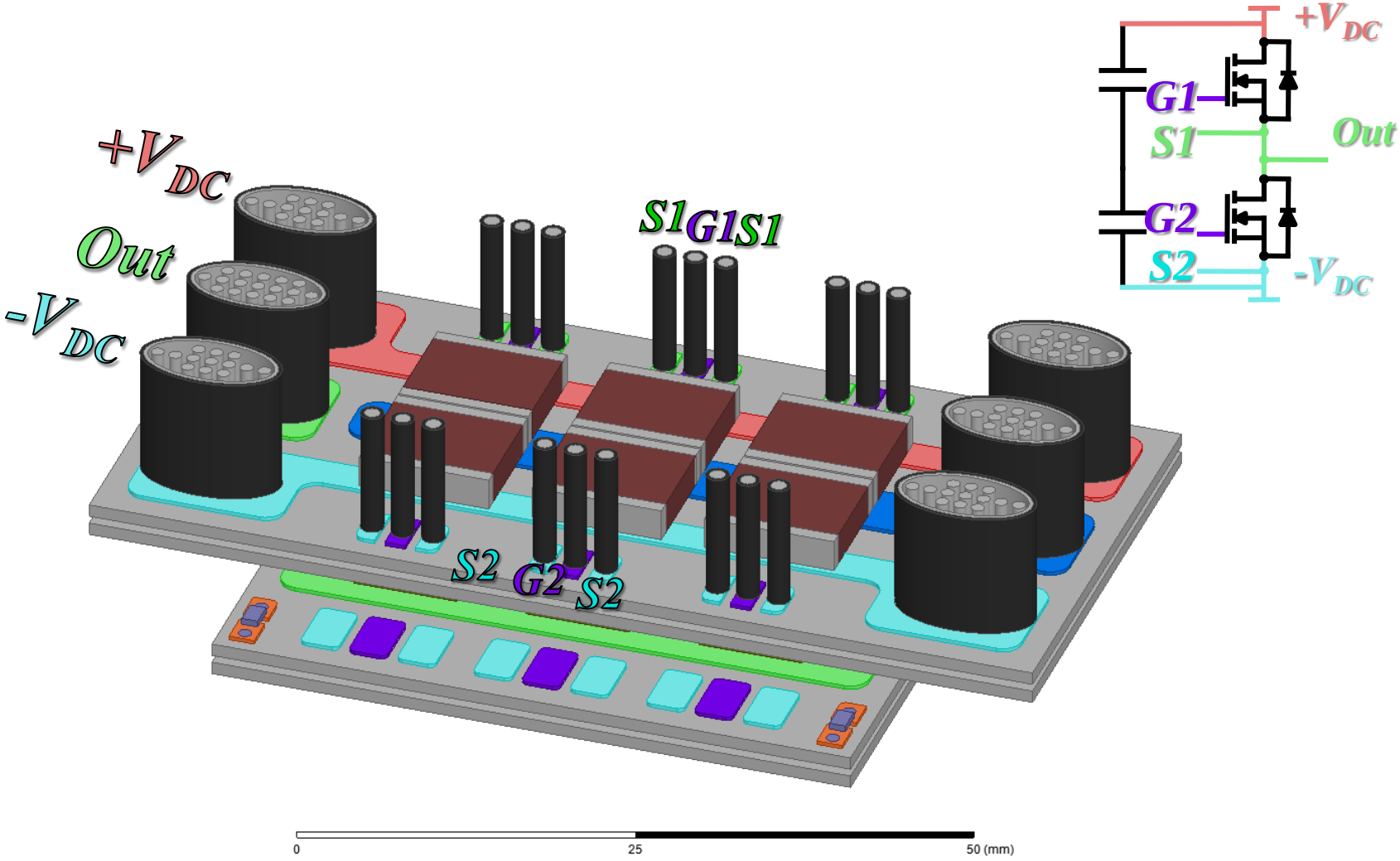
The system interface must be carefully designed to prevent partial discharge.

10 mm for 10 kV!





Surrounding pins with an elliptical conductive shield minimizes the peak electric field.



Conclusion

- **The goal of standardized "Integrated Power Circuits" that enable high-density integration has not been achieved.**

  There are too many different functions:

  - **Electrical switching,**
  - **Electrical conduction,**
  - **Thermal conduction,**
  - **Electrical insulation,**
  - **Electrostatic energy storage,**
  - **Magnetic energy storage,**

  that require too many different heterogeneous materials.

- **New semiconductor materials and devices impose new challenges on packaging:**
  - **Reduced layout and interconnect designs for reduced parasitics that enable high frequency operation;**
  - **New high temperature materials with better matched CTEs for high-temperature operation;**
  - **New high-voltage materials and designs for eliminating "air" as insulator.**