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An SiC Power Converter System –

Thermal Management and High Temperature Packaging

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Project funded through DoE STTR Project **(DE-FG02-05ER86234)**

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Supervisor: Dr. Stan Atcitty and Dr. Imre Gyuk

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Overview of Aegis Technology Inc. (ATI)

- Design, development and manufacturing capabilities
- Operation since 2002
  - President/CEO: Mr. Bob Liu
  - Chief Scientist: Dr. Timothy Lin
  - 10 employees with 5 Ph.D/M.S Scientists & Engineers
- Key technologies
  - SiC Power Electronics and Thermal Management
  - Nanocomposites and Advanced Manufacturing
- Contact information
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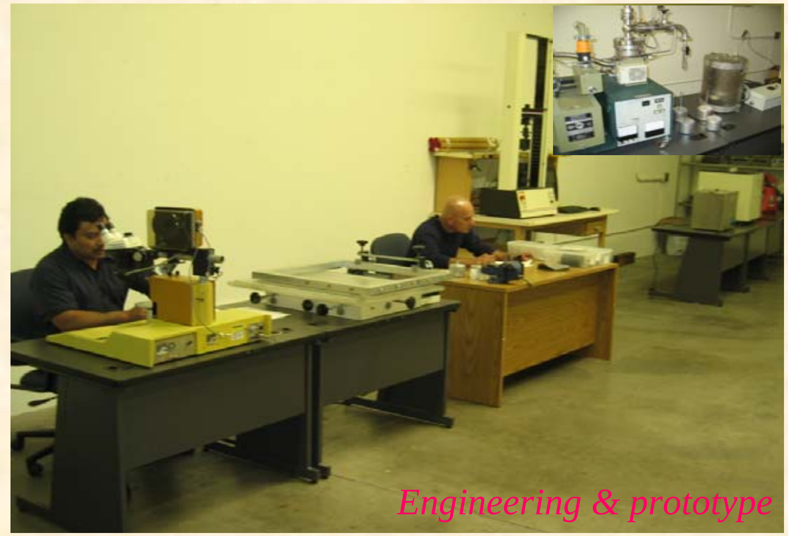
  - Main email: aegiste1400@earthlink.net
  - Tel: 714-554-5511 (Lab), 265-1238 (O); F: 714-554-9935

Capability

Assembly



Engineering & prototype

Manufacturing

Testing & inspection

Research & Development

- **Recent technology development**
  - 10 SBIR/STTR (Phase I & II) contracts since 2003
  - SiC power electronics and thermal management
    - SiC power inverters, high temperature packages and heatsink
  - Nanocomposites (ceramics, metals, semiconductors)
    - High strength and/or high thermal conductivity, low density
- **Design, modeling, processing, and prototype**
- **Strategic partners for commercialization of SBIR/STTR**
  - Powerex Inc. (Youngwood, PA) for SiC-based power electronics
  - Cercom Inc. (Vista, CA) for Nanostructured metal matrix composites
- **Technical partners**
  - University of California at Irvine
  - University of Tennessee at Knoxville

Objectives of the DoE STTR Project

- Develop an innovative power converter using high temperature, high power density SiC devices.
  - High efficiency, small size, and light weight
  - High power density, high temperature, and high frequency
  - Scalable current ratings for various motor controls
- Insert the technology for the applications in electric energy storage, motor control, and others.

Why SiC Power Devices

- **SiC power devices are superior to Si devices**
  - Operable at higher temperatures (500°C vs. 140°C of Si)
  - Higher breakdown voltages (1200 V vs. 300 V of Si)
  - Excellent reverse recovery characteristics (low switching losses)
  - Operable at higher switching frequencies (more than 100 KHz vs. less than 20 KHz for high power applications)
  - Higher thermal conductivity (4.9 W/cmK vs. 1.5 W/cmK of Si)
  - Radiation-hard

- **SiC-based power electronic systems**
  - High efficiency
  - Light weight
  - Small size (e.g. smaller heatsink, capacitor, and inductor)

Challenging Issues

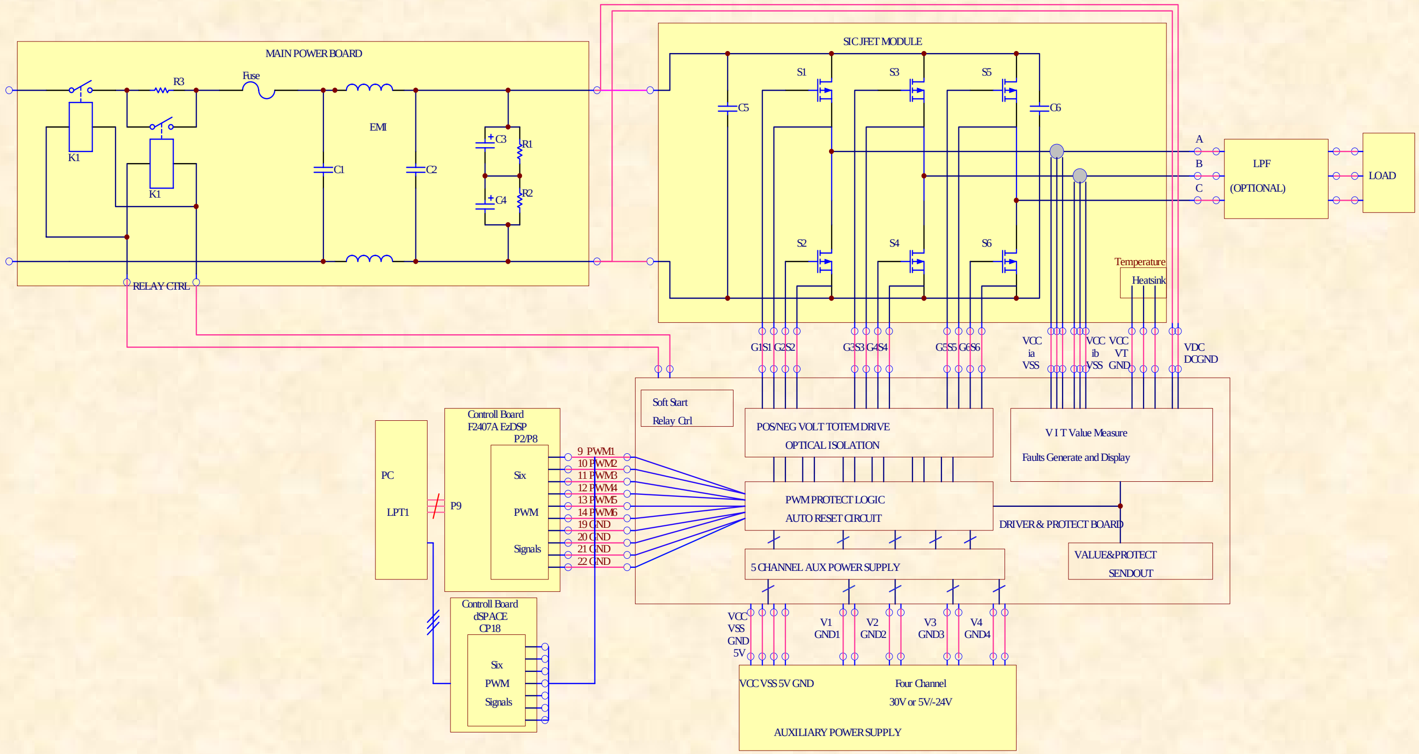
- **Limited availability (diode/JFET) and current rating of SiC power devices (diode<15 A, JFET < 7A)**
  - Paralleling of multiple devices and new layout/circuit design
- **Thermal management**
  - High temperature, high power density packaging
- **Gate drivers**
  - High temperature, high frequency capabilities
- **Passive components and system integration**
- **Technical/economical impacts**
  - High cost of SiC devices vs. Reduced power loss, heatsink and passive components

Approach

- *Device*
  - Utilize commercially available SiC devices
- *Circuit and Modeling*
  - Design suitable SiC circuit of power modules
  - Modeling and simulation
- *Package (thermal management) and gate drive*
  - Develop high temperature package, high-efficiency heatsink
  - Develop high temperature gate drive
- *System integration/demonstration/testing/applications*
  - Select high temperature auxiliary devices /components (capacitor etc.)
  - Integrate power module, gate drive/control, packaging/passive components

Converter Design

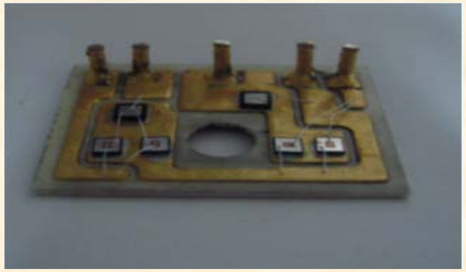
- Battery: Lead acid battery
- Converter: SiC devices (JFET, Schottky diode)

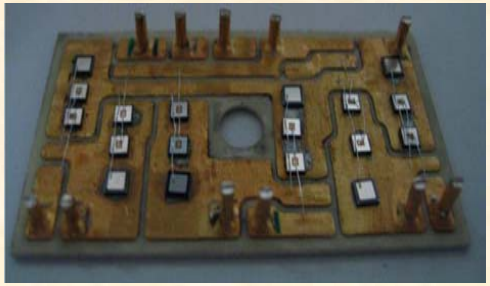


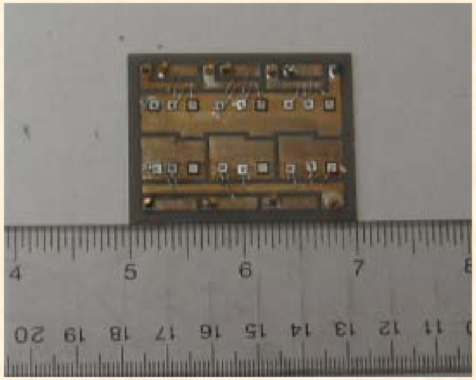
Schematics of the SiC inverter

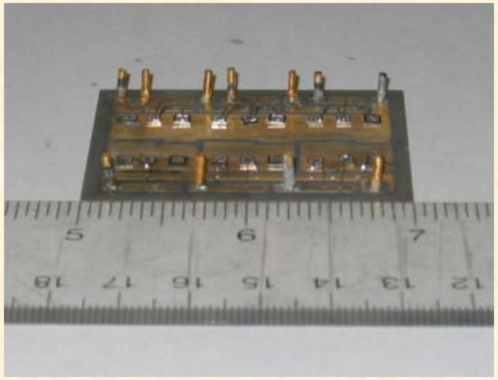
Power Module Prototype

Half-bridge and 6-packed





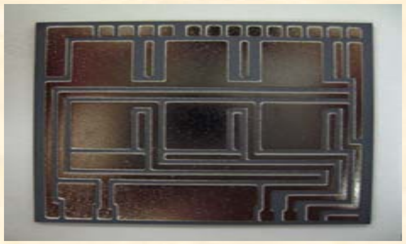


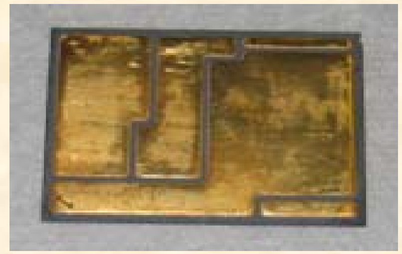


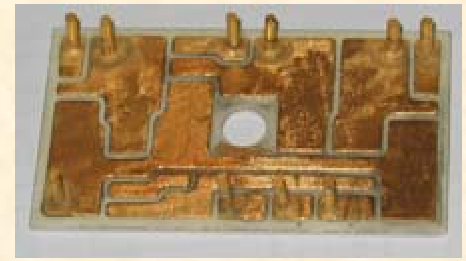
New design of Power Module layout -> Small dimension

High-temperature Packages & Thermal Management

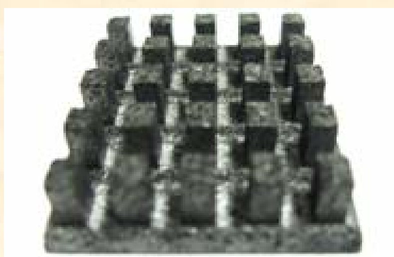
Package substrate

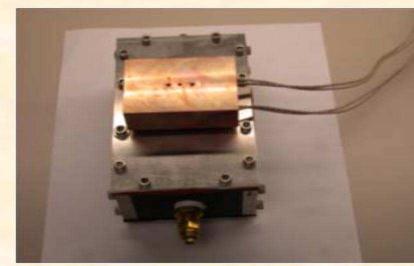




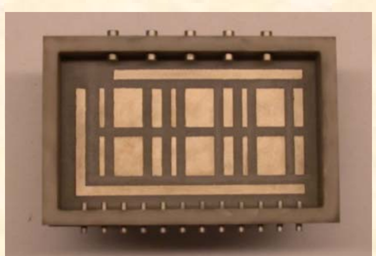


Heatsink





Package assembly



Package with Carbon foam heatsink

Test setup -> Package & heatsink

Thermal Management

High temperature, high power density package

- **High temperature AlN package**
  - **High thermal conductivity, Low CTE matchable with SiC High thermal shock resistance and insulation**
  - **High-temperature metallization for die attachment and heatsink**
- **High efficiency passive heatsink**
  - **Active cooling (e.g. networking microchannel heatsink)**
  - **A critical issue in thermal management of some applications**
    - **Space is constrained**
    - **Airflow is not available directly**

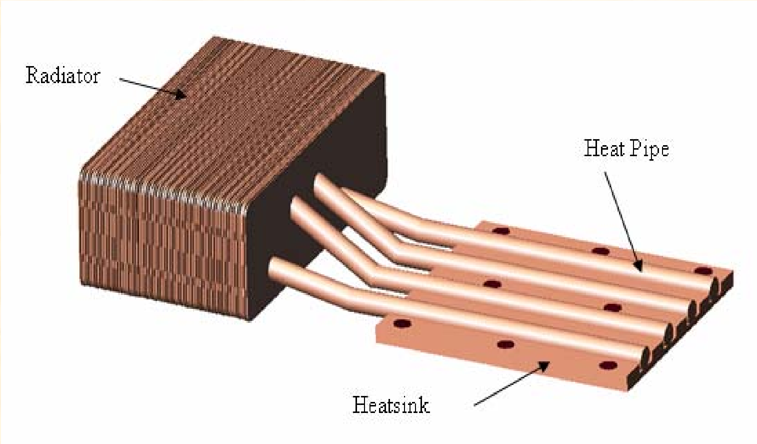
→ **Passive cooling is more attractive**

No pumping needed-> no power use, no noise, improved reliability

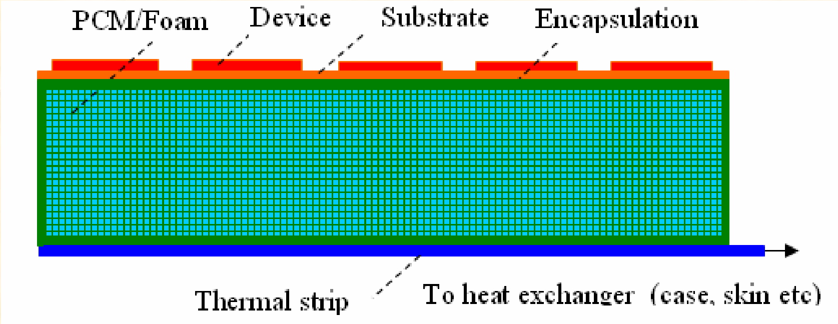
Thermal Management (cont.)

1. **A passive thermal management based on a heat pipe-enforced heatsink**
   - **Self-contained, compact, reliable**

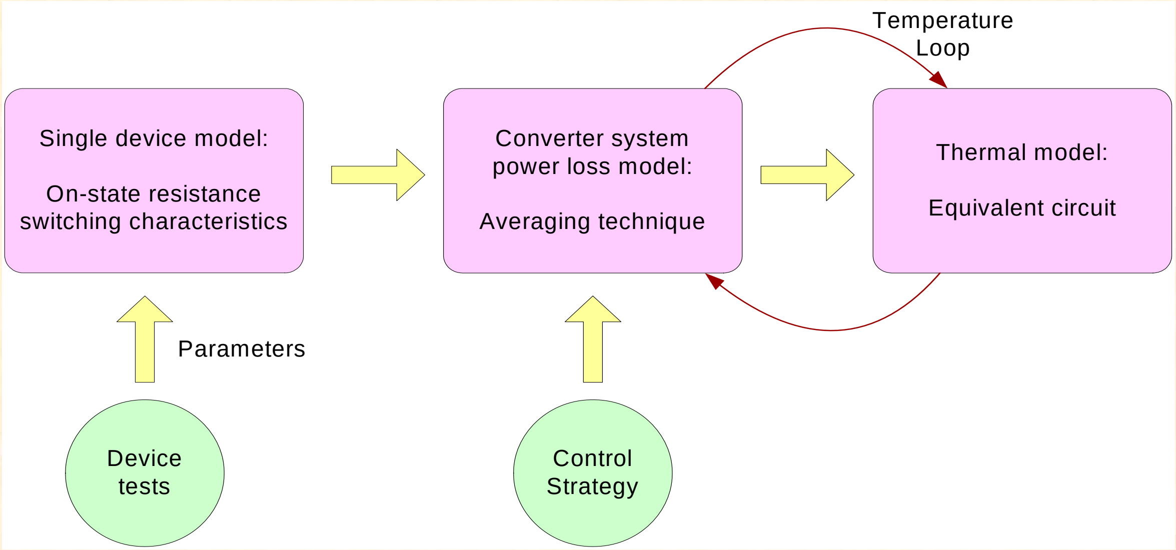
   A heat pipe-enhanced heatsink along with radiator that can also be cold end such as enclosure or case.



2. **Phase change material (PCM)/graphite foam heat exchanger (passive cooling)**
   - **High thermal conductivity, interconnected pores acting like network microchannel ->High convective heat transfer**
   - **Integrated with PCM utilizing latent heat of phase change (solid ->liquid) to absorb waste heat from chips**



Circuit Modeling & Simulation



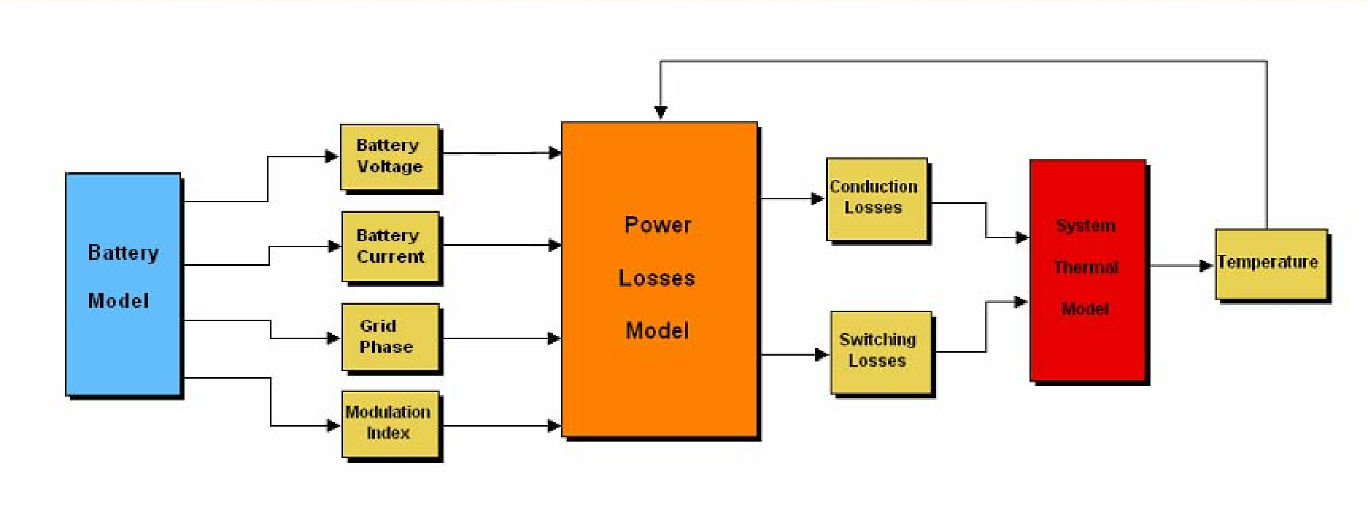
Modeling

Battery model,

Power loss model, and

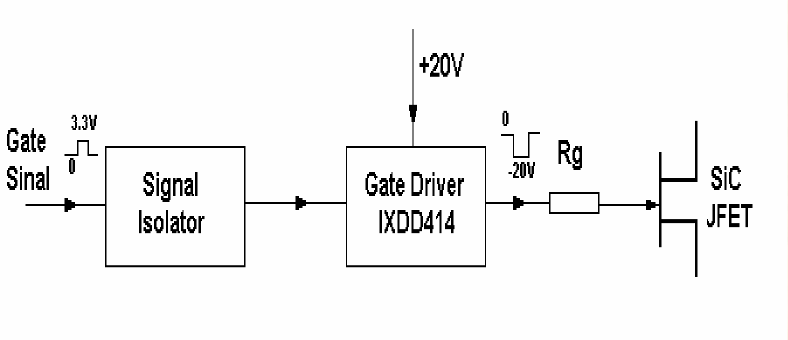
System thermal model

Simulation



Gate Drive and Control

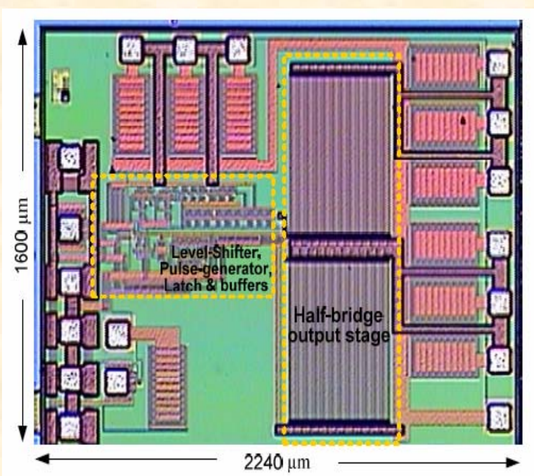
- *Challenging issues*
  - Normally-on device of JFET for high frequency operation
  - High-temperature capability
- Approach
  - Commercially available Si devices
  - High temperature SOI technology
    - Atmel's High Temperature BCD-on-SOI technology
- Phase I work
  - Commercial (IXYS IC chip IXDD414)
- Phase II work
  - A novel BCD (Bipolar-CMOS-DMOS) design based on SOI process to implement the gate driver



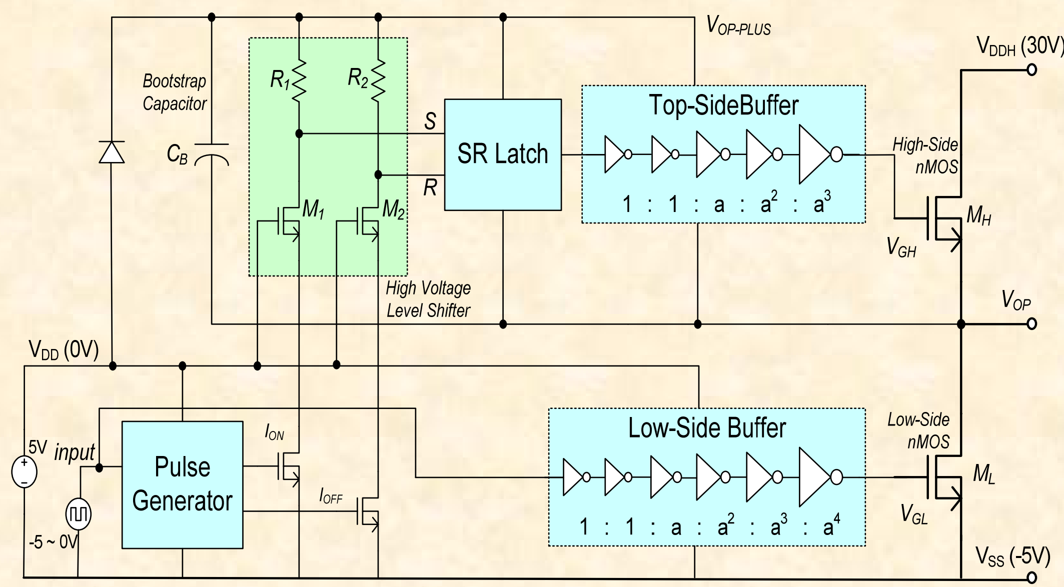
Gate drivers are necessary for driving the power switches in any power converter

SOI-based High-voltage High-temperature Gate Driver

1. Fully integrated gate drivers for high temperature applications
2. The novel BCD on SOI process offered by ATMEL corporation
3. Switching frequency: ***20 kHz,*** Output voltage: ***-5V ~ 30V,*** Load capacitance: ***10nF,*** Ambient temperature range: ***-40°C to 200°C***



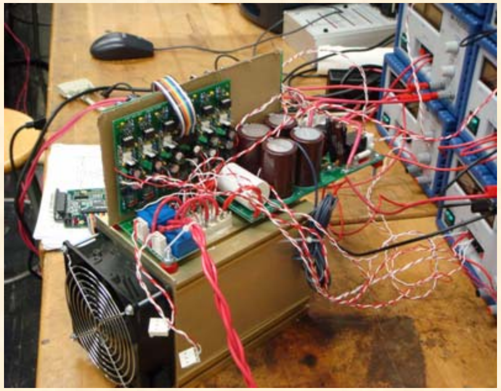
Gate drive chip

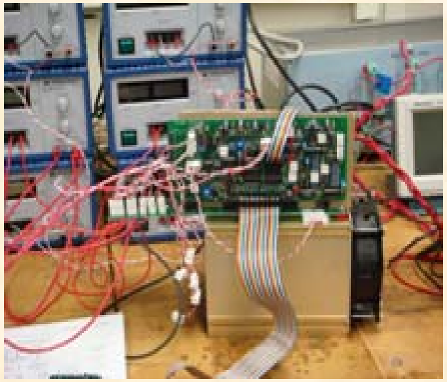


Gate driver circuit

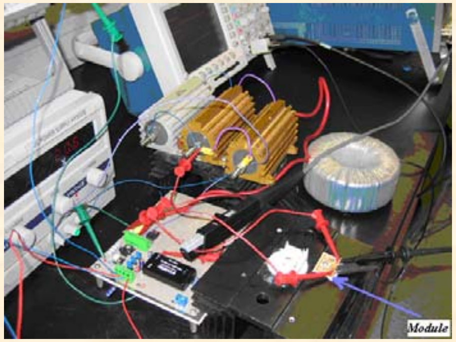
Converter Fabrication and Characterization

- Design/build SiC converter
  - **A 1200 V, 20 A all-SiC power module/inverter using JFETs and Schottky diodes**
  - **Scale up to 1200 V, 120 A**
  - **Implement high-temperature capacitors**
- Test, characterize, and converter





A preliminary prototype of a 5 kVA SiC inverter



Test setup of power module

Ongoing Work and Summary

- ***Converter fabrication and characterization***
  - Utilize technology/components currently available or demonstrated in Phase I
    - **A power module array (1200V, 120 A) by paralleling modules of 1200 V, 20 A**
    - **Gate drive (Atmel's High Temperature BCD-on-SOI technology)**
    - **High- temperature thermal packaging**
  - Fabricate, characterize and file-test the inverter
- ***Modeling and system analysis***
  - **Analyze the device/system-level impacts of the SiC inverter with similar Si inverter**
  - **Advantages of operations at high temperatures (smaller heatsink), power densities and frequencies (smaller passive component)**
  - **Technical/economical benefits in terms of efficiency, size and cost**
- ***Application and commercialization***
  - **Electric storage system (battery, capacitors)**
  - **Transportation (traction drive, hybrid electric vehicles)**
  - **Power systems (Fuel cells, micro turbine, renewable sources)**
  - **Document the benefits in terms of performance and costs for potential customers**

Through this project, a high-efficiency compact affordable SiC inverter can be anticipated