A Very High-Temperature (400 °C) Inverter for Energy Storage Applications Utilizing Silicon-on-Insulator (SOI) and Silicon Carbide (SiC) Electronics

Roberto Schupbach Jared Hornberger Alexander Lostetter

Arkansas Power Electronics International, Inc.
700 W Research Center Blvd
Fayetteville, AR 72701 USA
(479) 443-5759
marcelo@apei.net

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Outline

- **Silicon Carbide (SiC) Advantages**
  - Thermal Advantages
  - Electrical Advantages
  - Radiation Advantages
- **Multichip Power Module Design**
  - Electrical Design
  - Package Design
  - Thermal Design
- **Multichip Power Module Component Testing**
  - Power Packages and Substrates
  - Wirebonding
  - Capacitors and Magnetics
  - SiC Power Switches
- **Multichip Power Module Fabrication**
  - MCM Control Board
  - Power Substrate Board
  - Combining Control & Power
- **Multichip Power Module Testing**
  - Controller Signals
  - Gate Drive Signals
  - Deadtime
  - Vds / Ids
- **Summary**

Silicon Carbide

Thermal Advantages

- Standard Si device operating limit of 150 °C
- High temperature Si are very costly and only a handful of commercial devices are available, no high temperature Si power devices are available
- SiC device theoretical limit exceeds 600 °C

  Very high power densities can be achieved with these junction temperatures.
- SiC has a very high thermal conductivity— excellent for power devices and thermal transfer, increases power density
- Disadvantage: currently no device packaging technology exists to take full advantage of thermal capabilities. **Requires packaging advances in die attach, interconnects, and reliability.**

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Silicon Carbide

Electrical Advantages

- Very low switching losses (1/10th of Si) w/ smaller drive currents and smaller on-resistances
- Up to 10s to 100s of GHz switching range for SiC
- Very high voltage blocking

Radiation Advantages

- Strong covalent bonds
- Reduced displacement damage compared with Si & GaAs
  - By a factor of 2-3 at low radiation energies
  - By 2-3 orders of magnitude at higher energies (> 0.5 MeV)
- Rad-hard performance improves with increased temperatures

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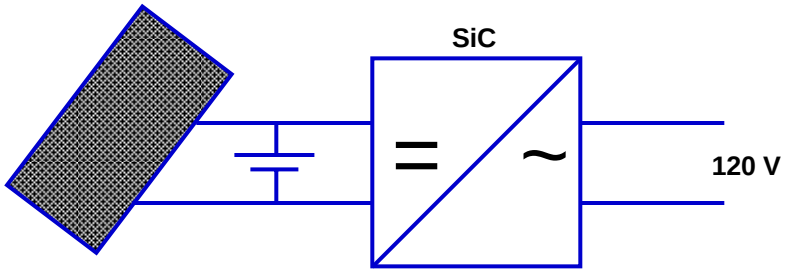
Applications

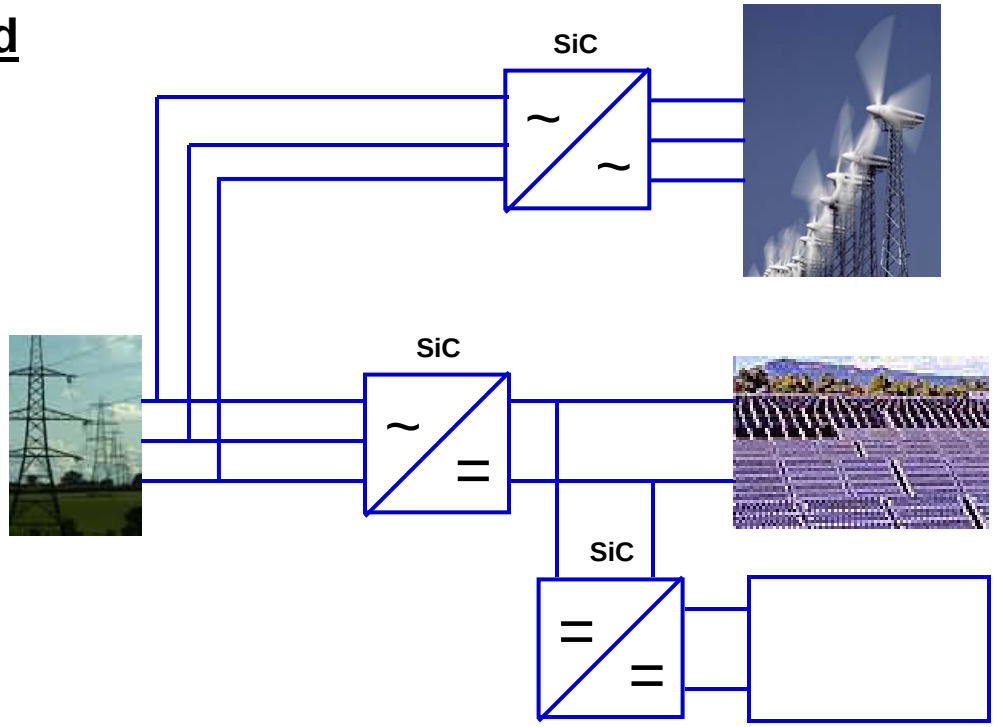
Single-Phase Inverter

- 1 k-W proof-of-concept prototype
- Stand-alone application



Three-Phase Inverters and DC/DC Converters

- High-power applications
- Renewable energy sources



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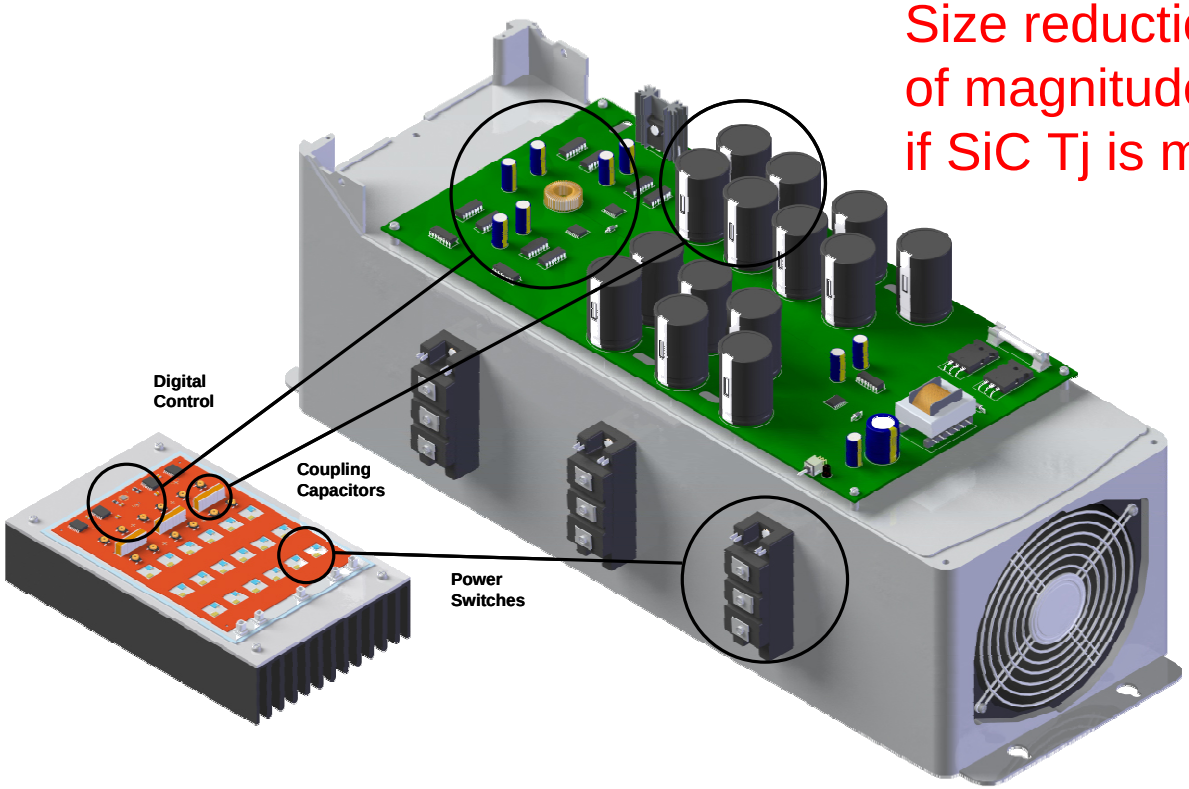
Potential Size Reduction Using SiC

Size reduction of an order of magnitude achievable if SiC Tj is maximized



30 kW APEI SiC Power Module

30 kW Standard Power Module

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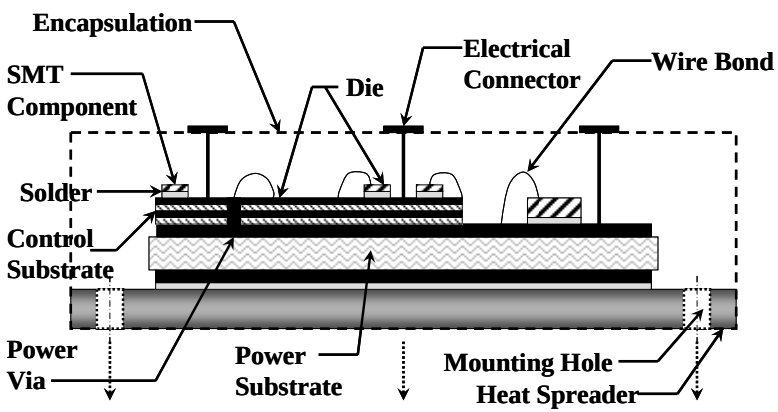
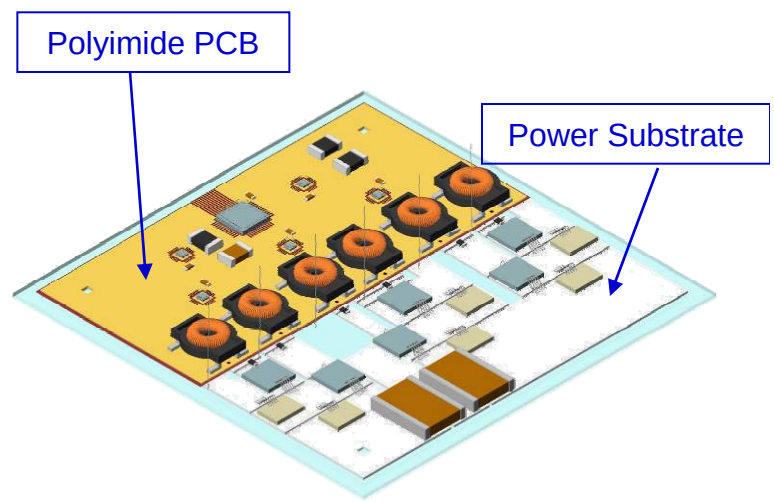
MCPM Package Design

Cross-section of the SiC MCPM design(*).



Isometric view of high-temperature MCPM.



(*) **APEI, Inc. patented technology**

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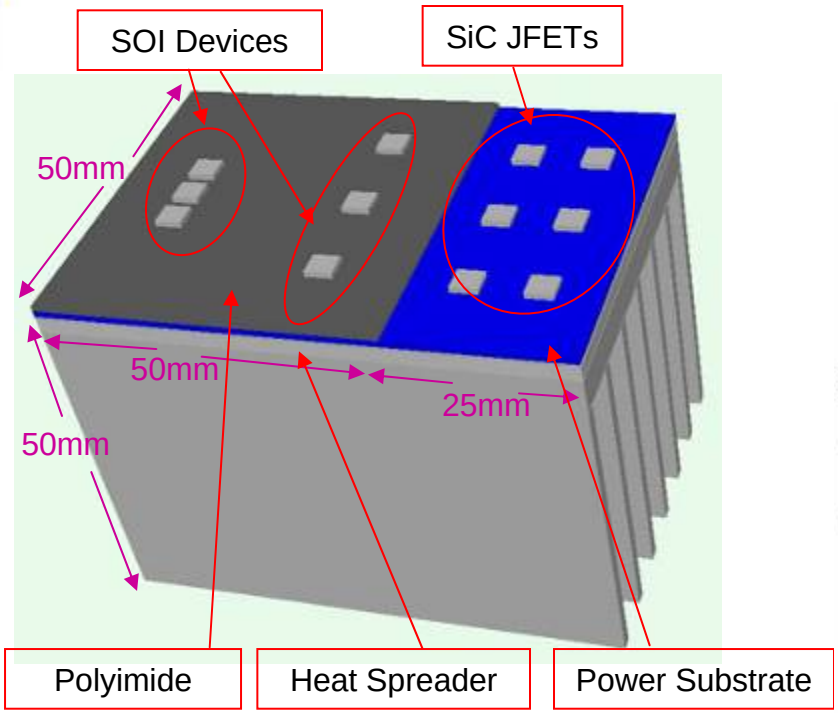
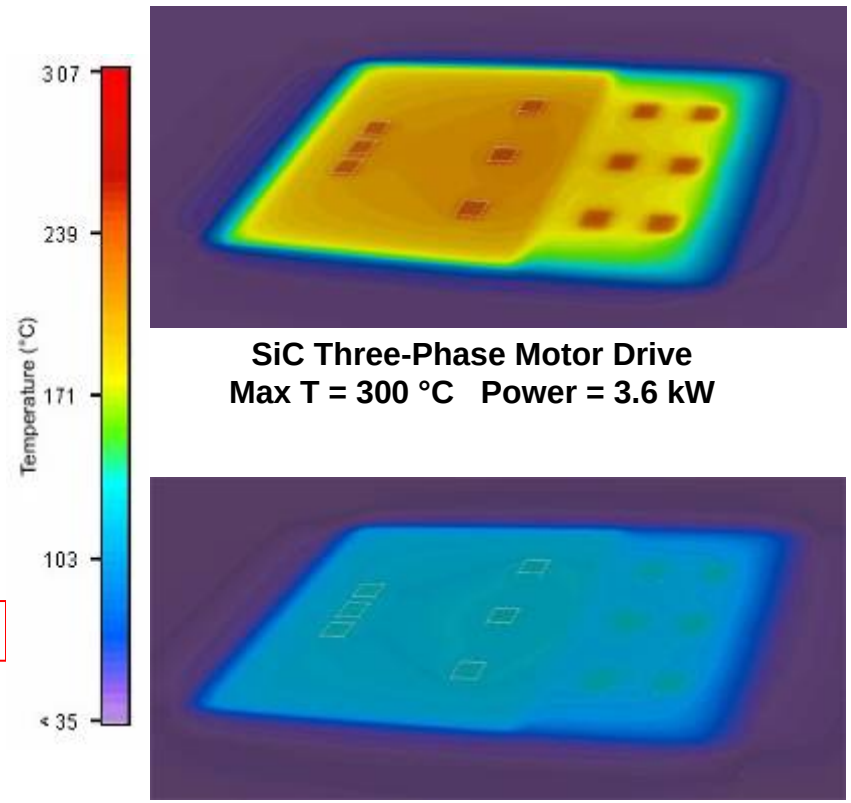
MCPM Thermal Design



Thermal Simulations



SiC Three-Phase Motor Drive
Max T = 300 °C Power = 3.6 kW

Si Three-Phase Motor Drive
Max T = 150 °C Power = 1.3 kW

- ➔ **High temperature 300 °C SiC motor drive operates at 3× the power density of Si**

or

- ➔ **SiC power modules are ~ 1/3 the mass of Si while delivering equal power**

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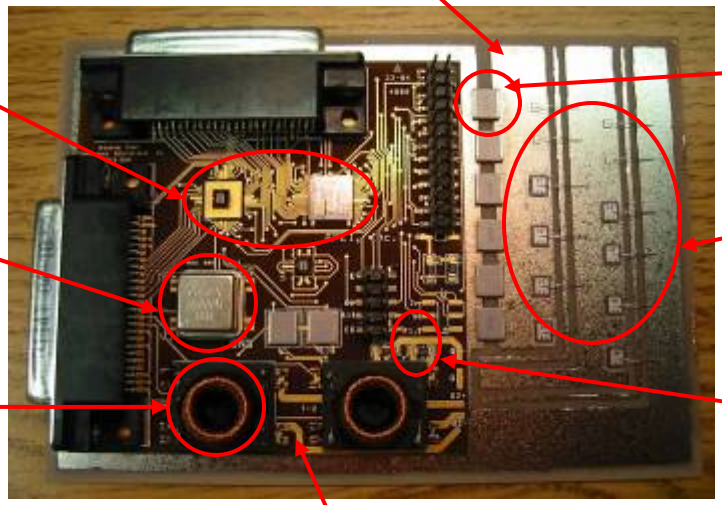
Multichip Power Module Components



Power Substrate

SOI Control Electronics (Honeywell)

High-Temp Oscillator (HEC, MF Electronics)

High-Temp Transformer (APEI, Inc.)

High-Temp Capacitors (Novacap, Kemet)

SiC Power Devices (Semisouth, Cree, SiCED, Northrop Grumman)

High-Temp Resistors (Caddock, Vishay)

High Tg Polyimide

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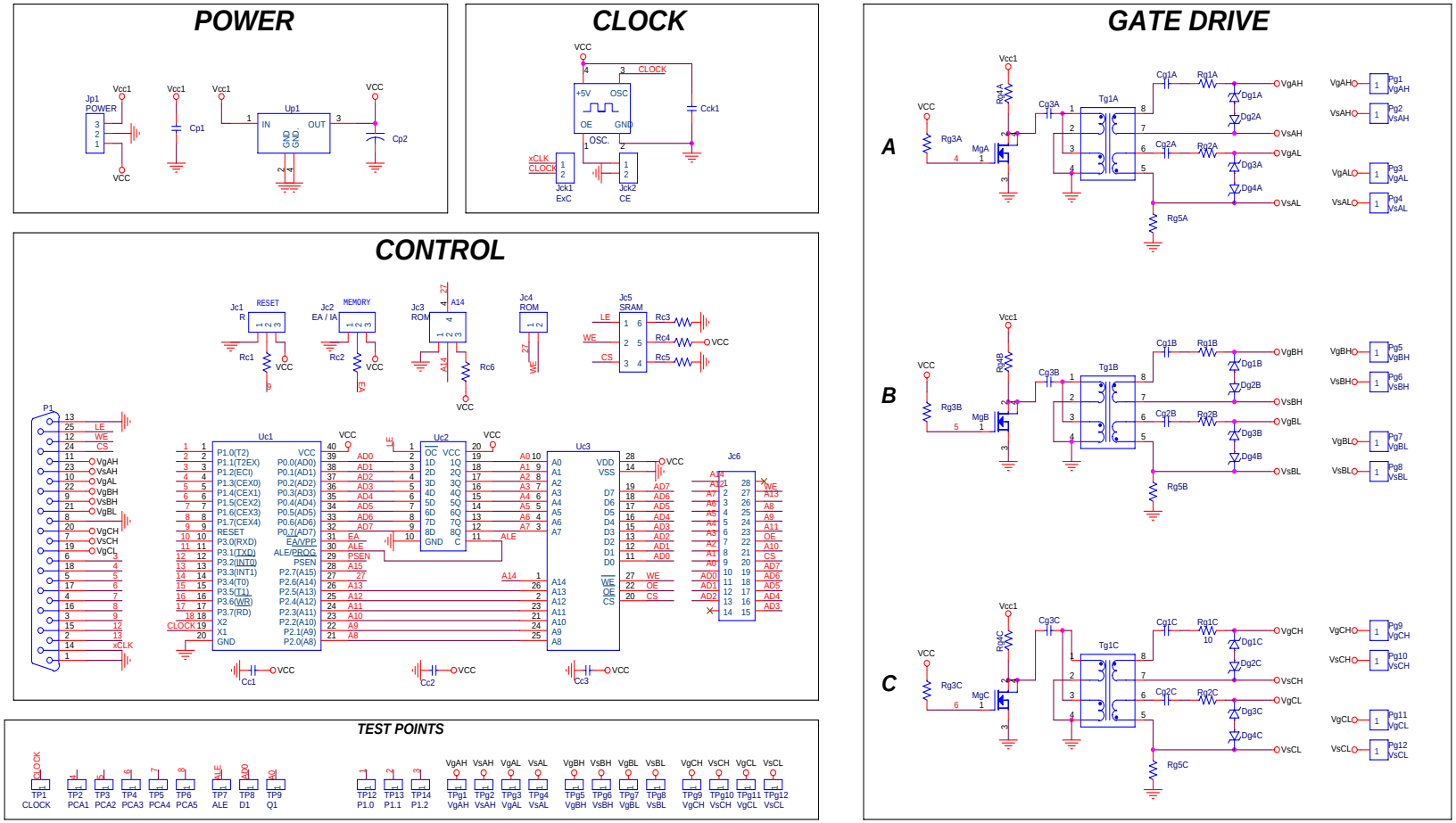
MCPM Electrical Design

MCM Control Schematic



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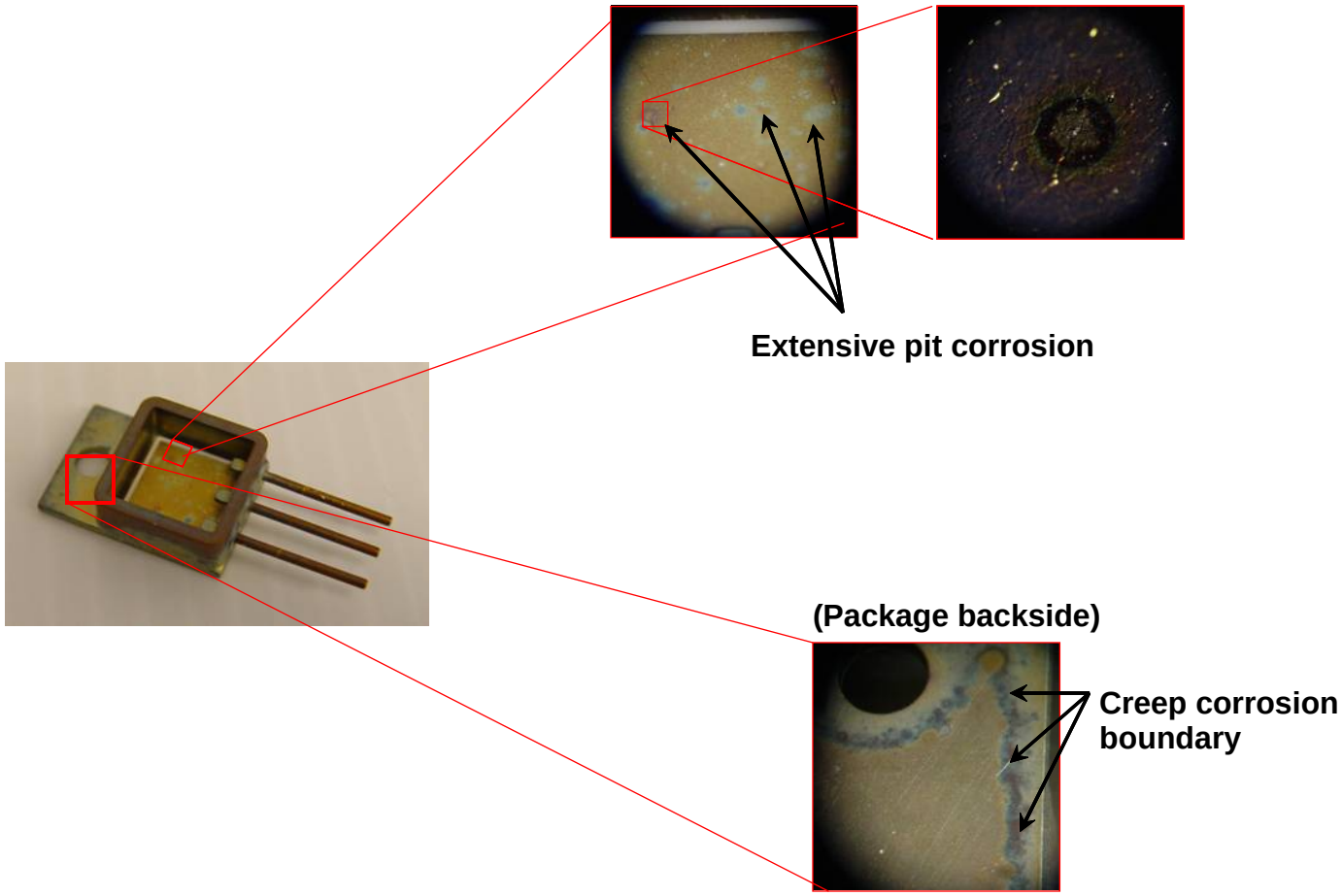
Ceramic Gold Power Package



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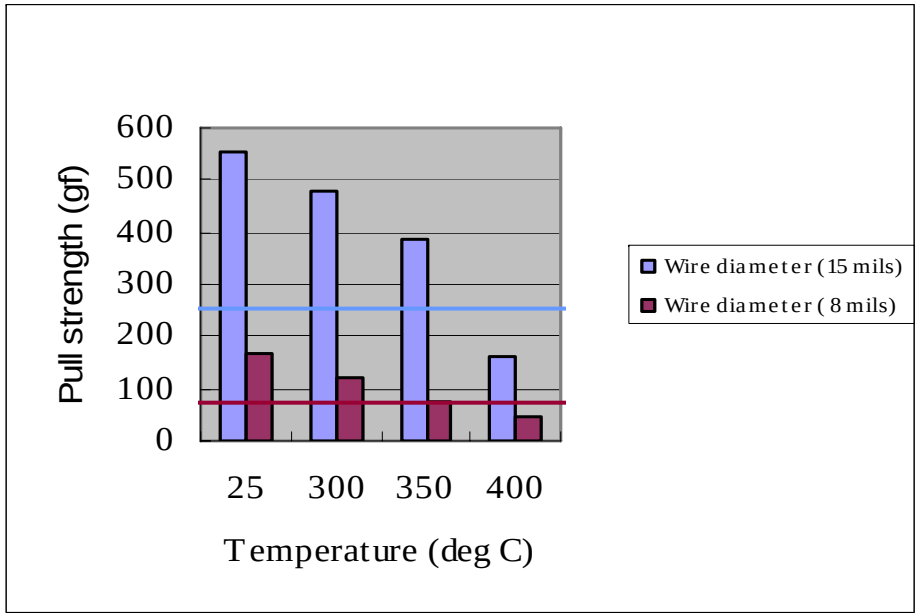
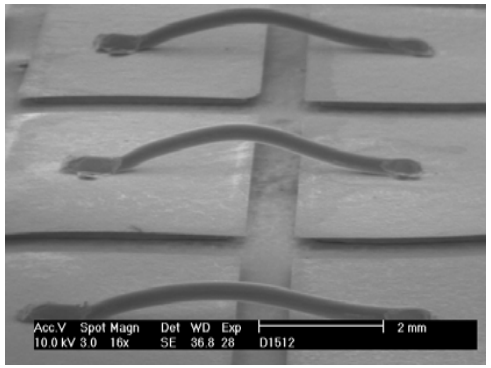
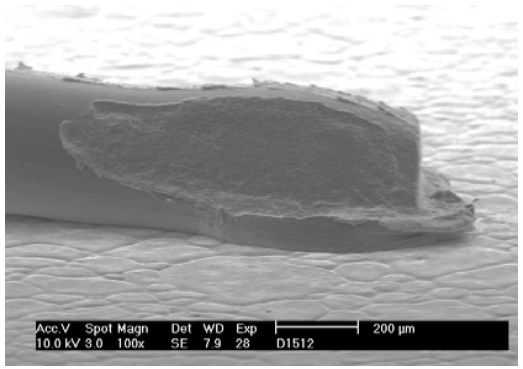
MCPM Wirebonding

Wire bonding

- Al wire to Ni pads
- Tested 640 bond pads
- Thermal cycling
  MIL-STD-883E, changed T
  -55 °C – 300, 350, or 400 °C
- 15 mils – 250 gf
  8 mils – 80 gf
- Successful up to 350 °C
- SEMs show clean interfaces after high temp cycling @ 350 °C







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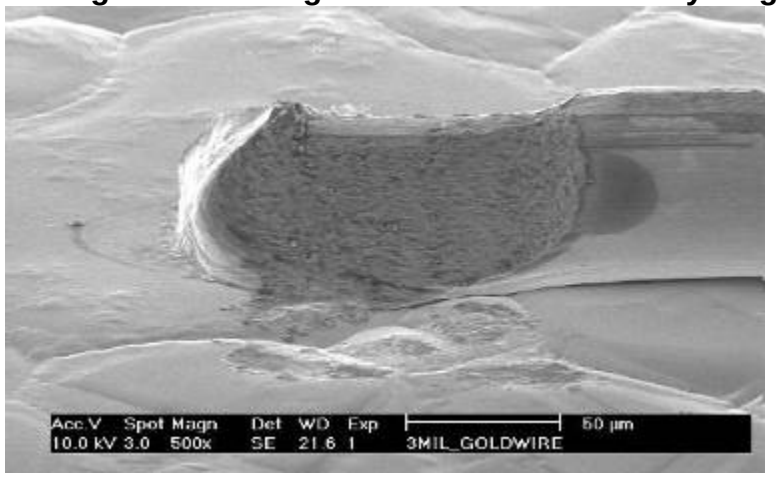
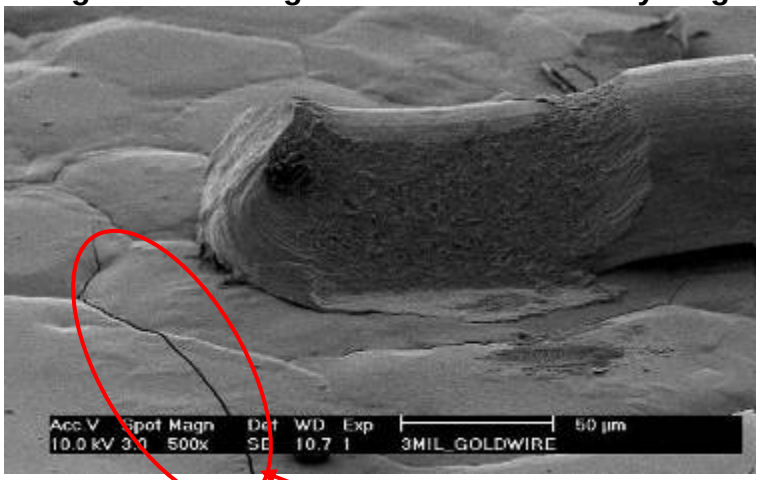
MCPM Wirebonding

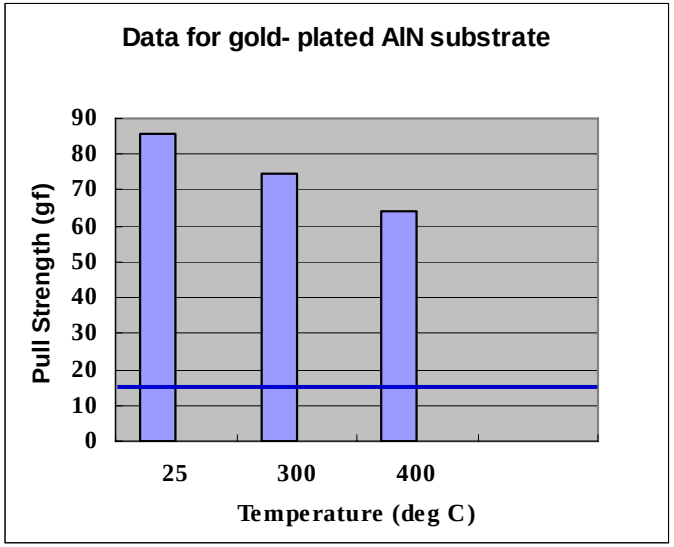
3-mil gold wire wedge bond before thermal cycling.



3 mil gold wire wedge bond after thermal cycling.



Thermal Stress Fracture



- **MIL-STD-883C, method 2011.6**
- **A minimum bond strength of 15 grams force (gf) to pass.**
- **3 electroless deposited Au/Ni on copper metallized AlN substrates.**
  1. **Control Substrate No thermal cycling**
  2. **-55 °C to 300 °C ten times at ten minutes per cycle.**
  3. **-55 °C to 400 °C ten times at ten minutes per cycle.**

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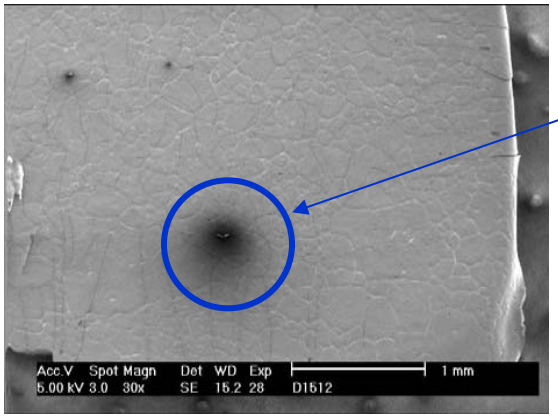
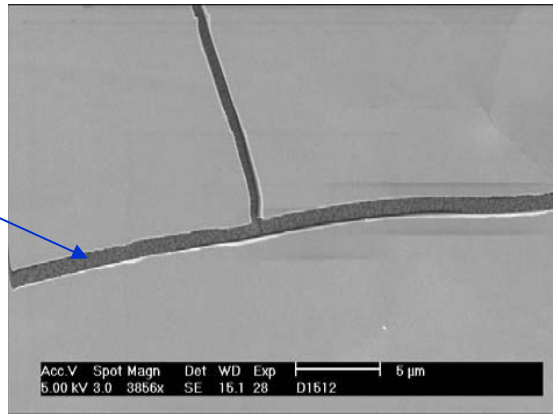
MCPM Power Substrate

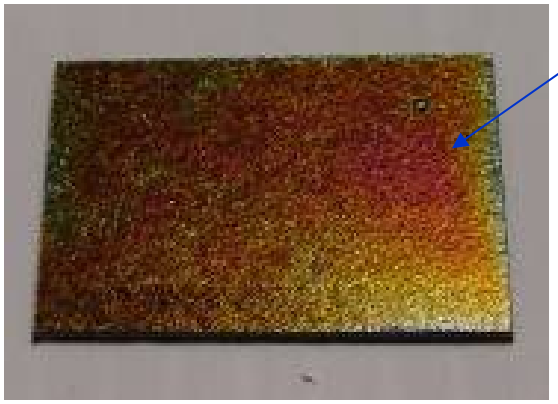
Direct Bond Copper (DBC) AlN Power Substrates



Corrosion

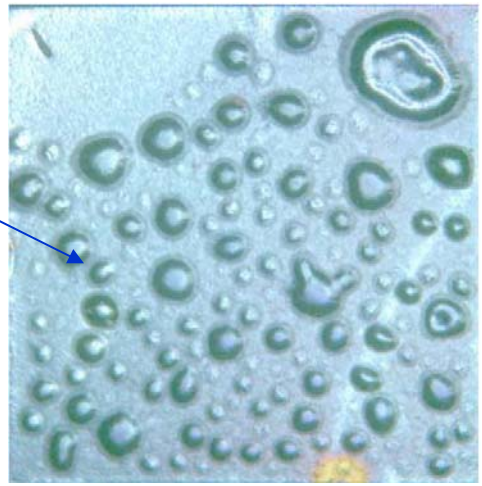
Thermal stress fractures of surface plating





P contamination (discoloration)

Blistering of copper in an AlN DBC after 100 thermal cycles from 50 °C to 350 °C *



* Results presented by Y. Liu, C. Wang, Wayne Johnson, M. Palmer at IMAPS'05

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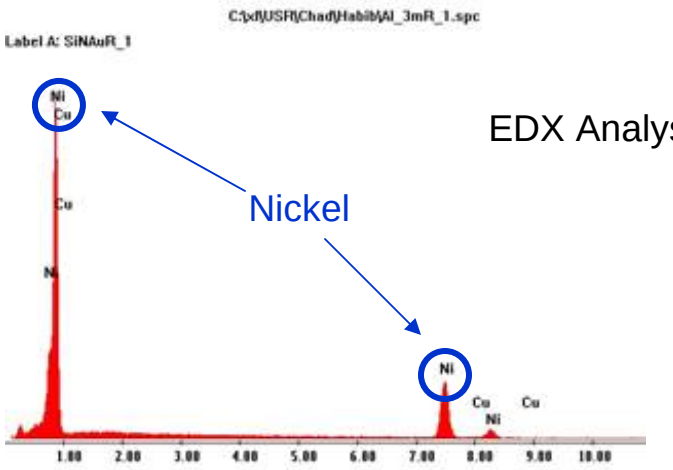
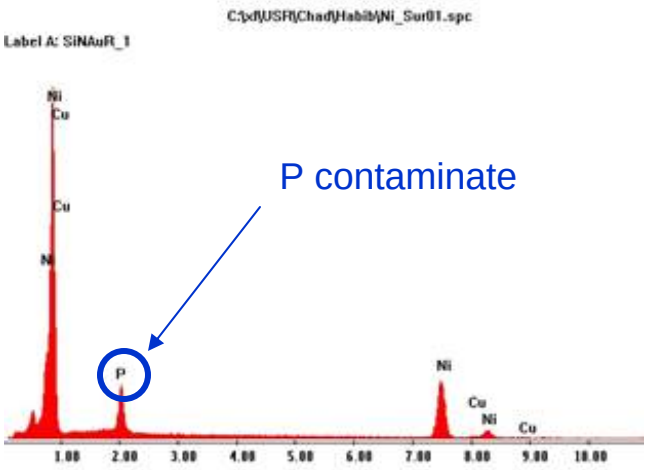
MCPM Power Substrate

Direct Bond Copper (DBC) AlN Power Substrates

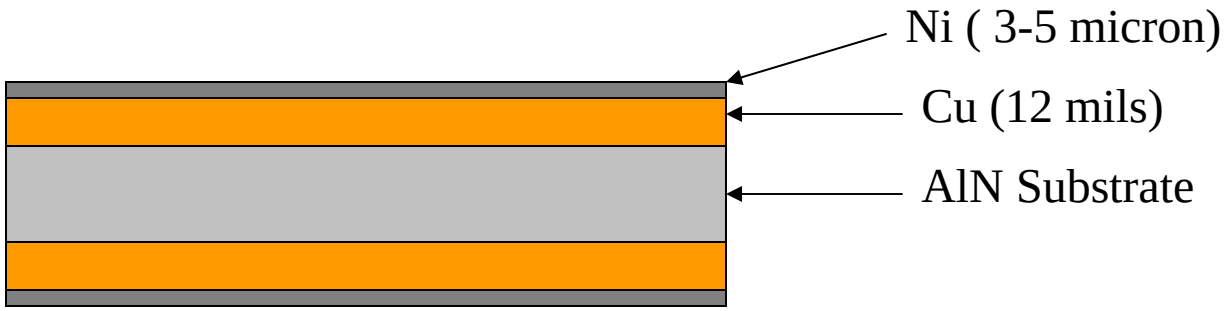


EDX Analysis



@ Room Temperature

@ 450 °C for 40 hours



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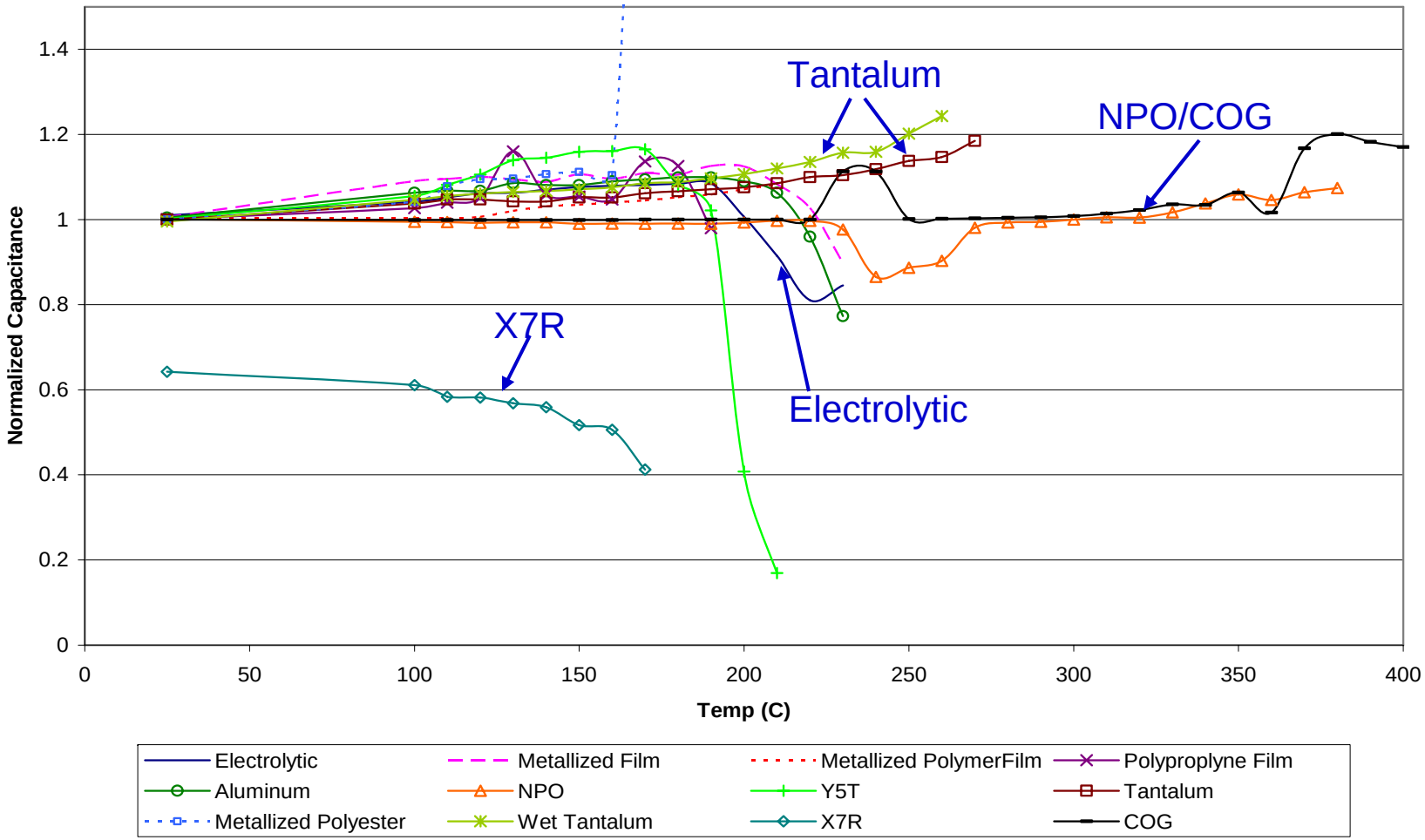
Capacitor Testing

Comparison of Capacitor Types



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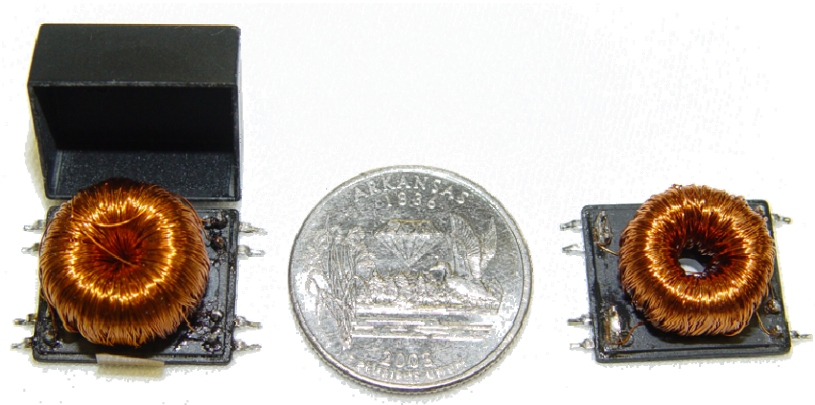
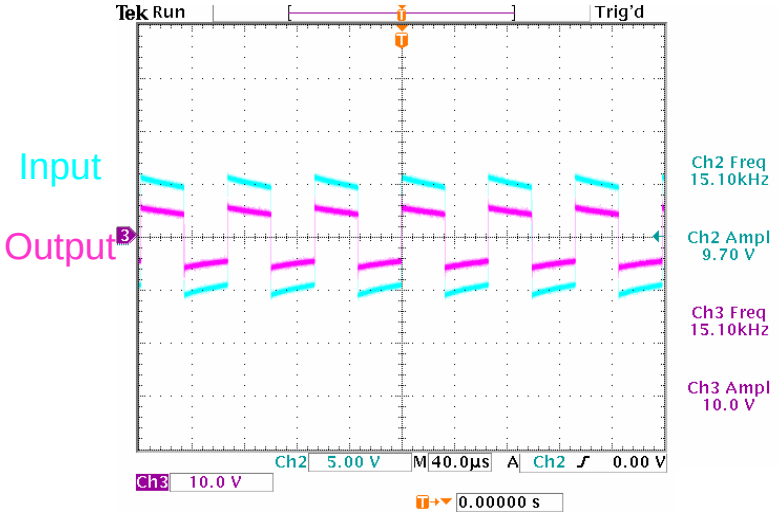
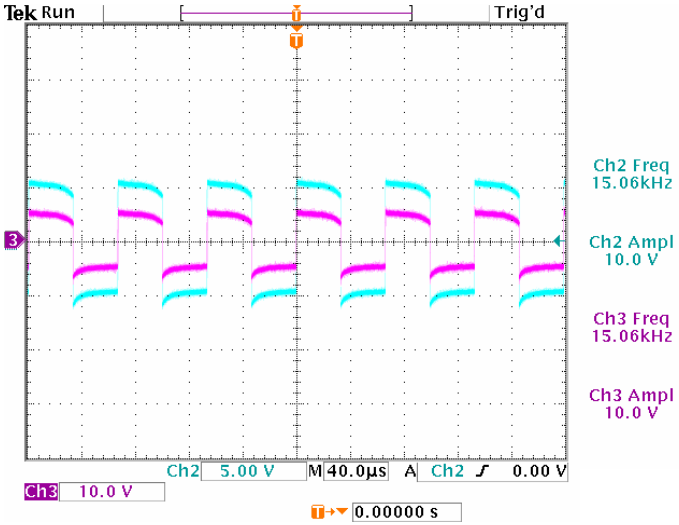
Magnetics



125 °C



400 °C



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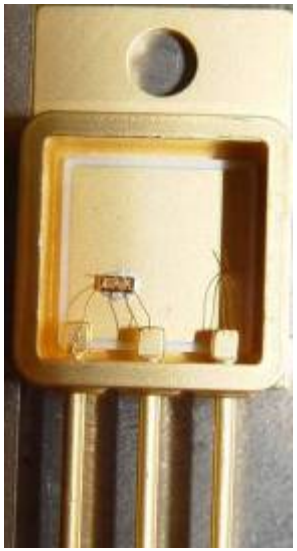
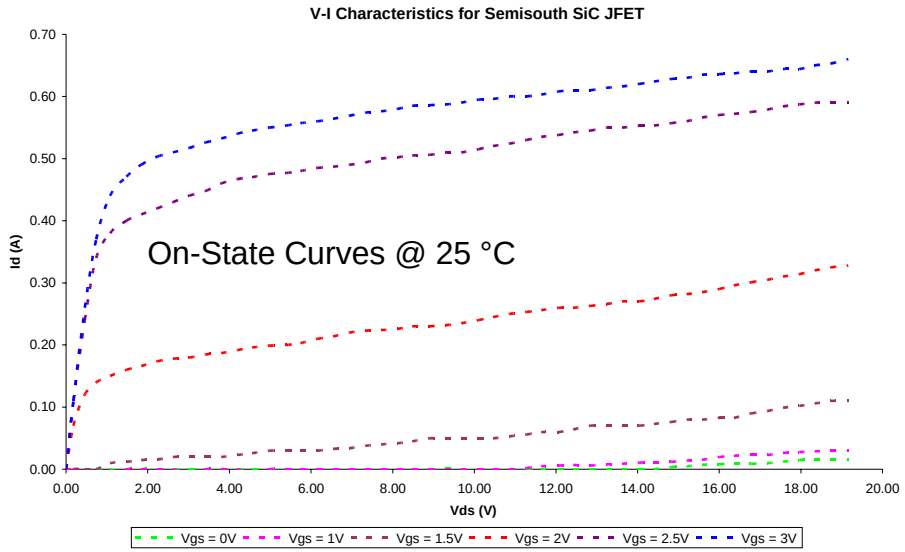
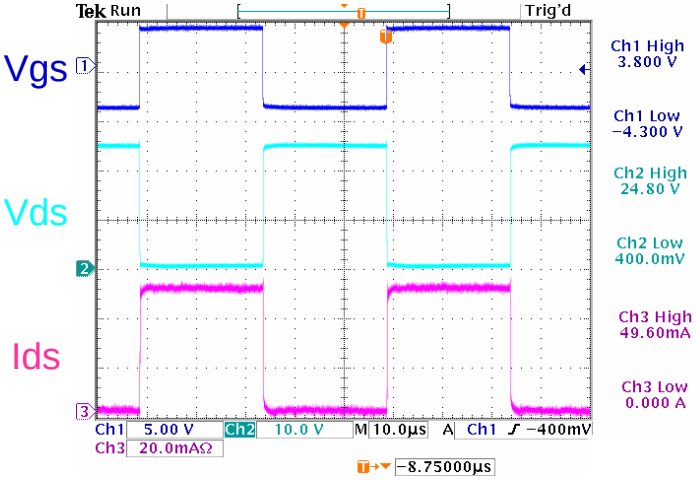
Semisouth SiC JFET



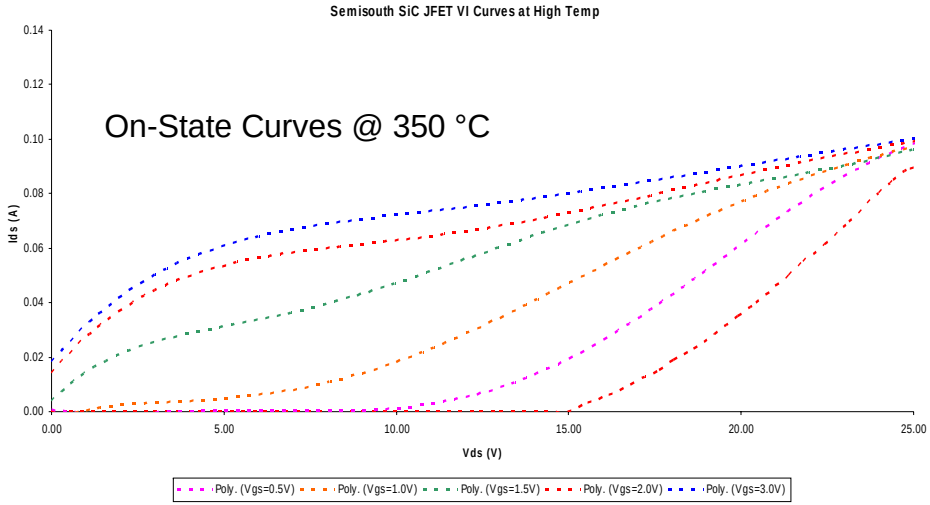
➔Semisouth SiC JFET (50 V)

➔Packaged & Tested to 500 °C





High Temp V blocking (500 °C)



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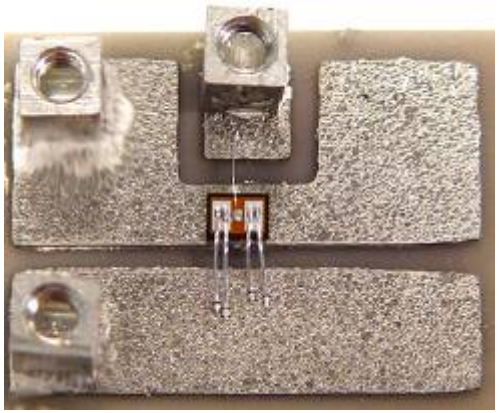
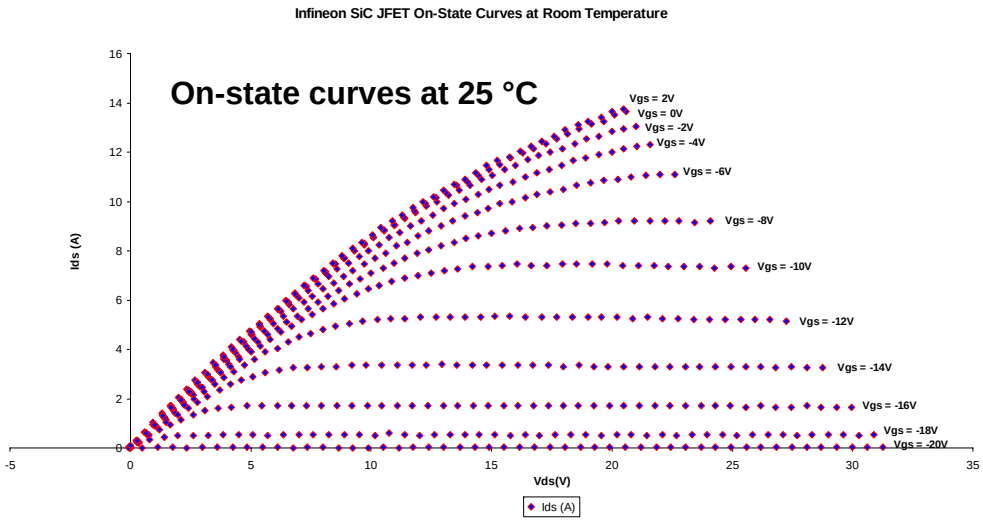
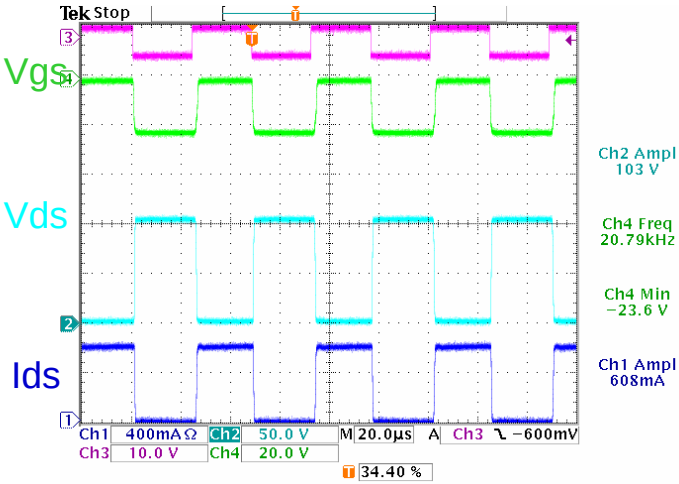
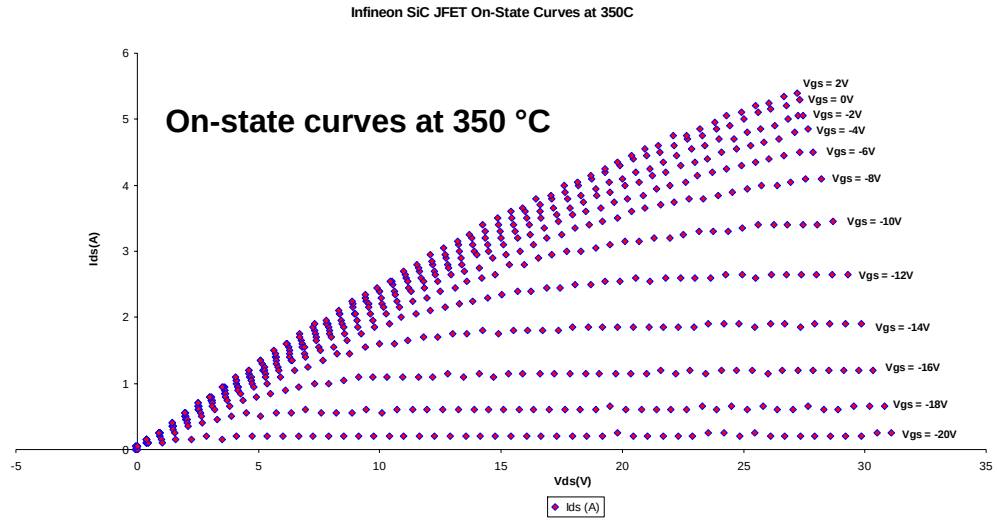
SiCED SiC JFET







Switching curves at 400 °C



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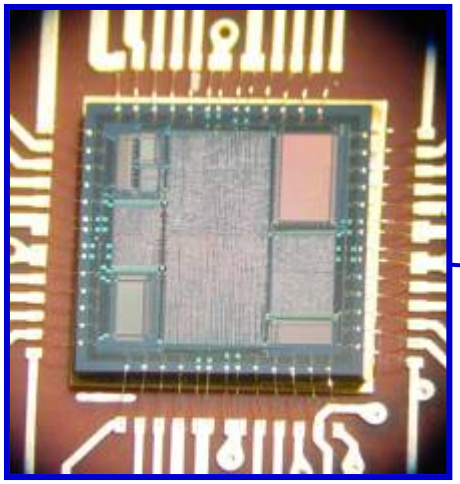
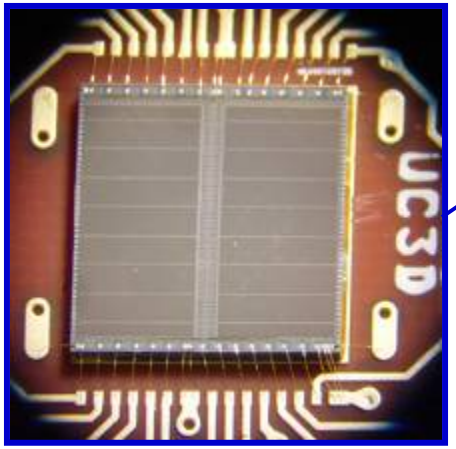
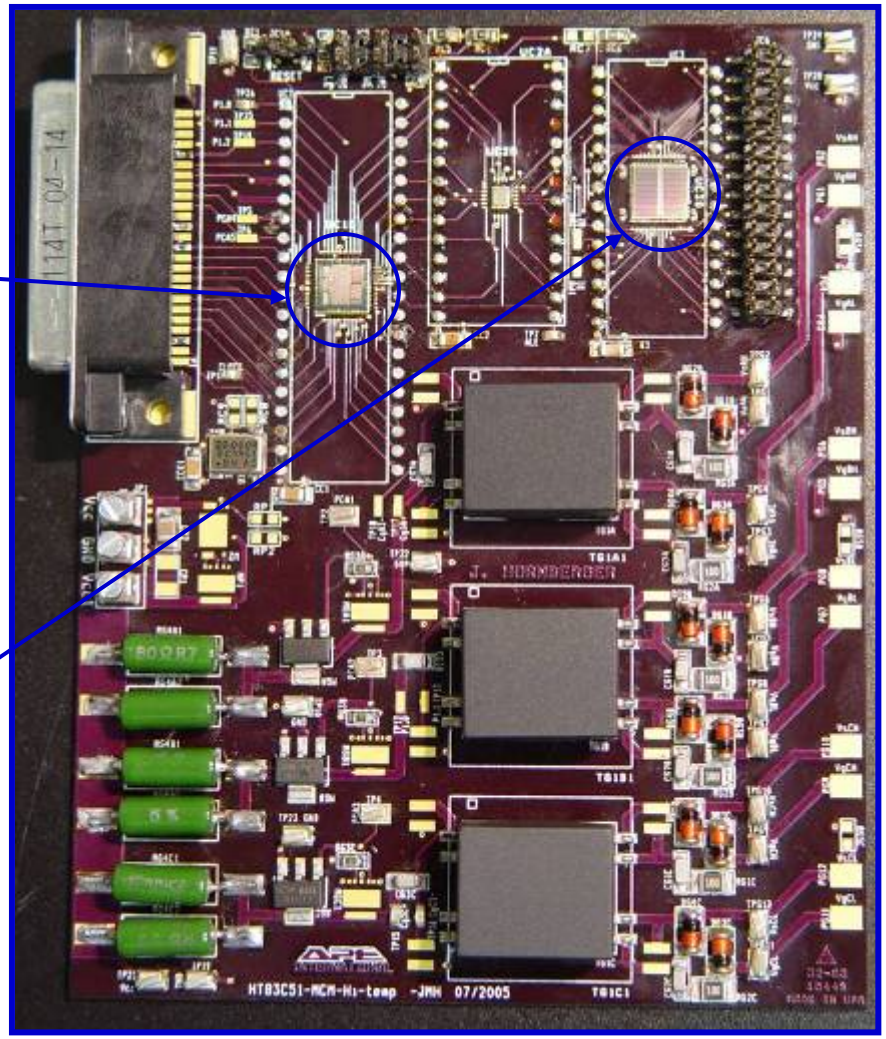
MCPM Control Board

Controller



RAM





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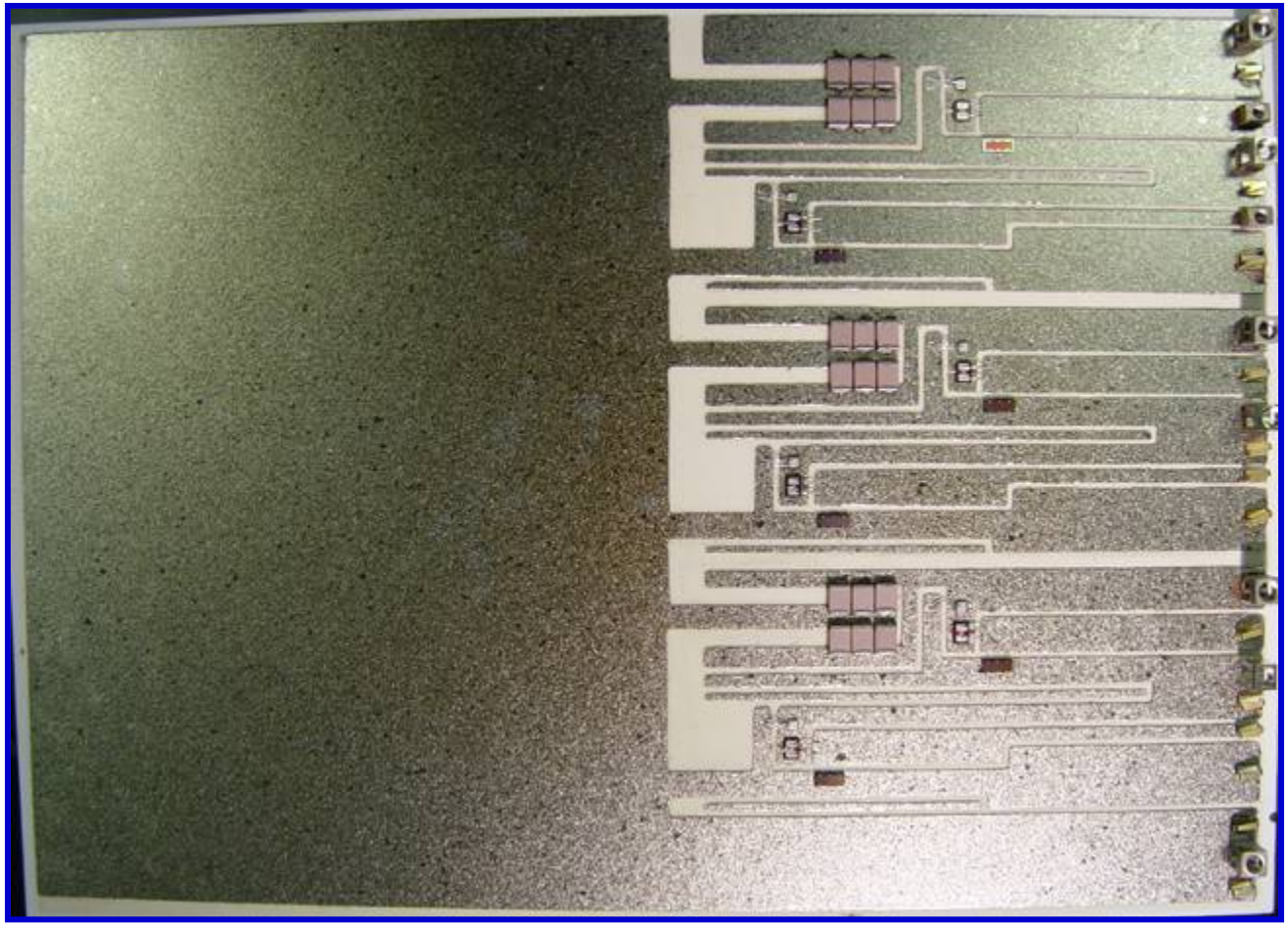
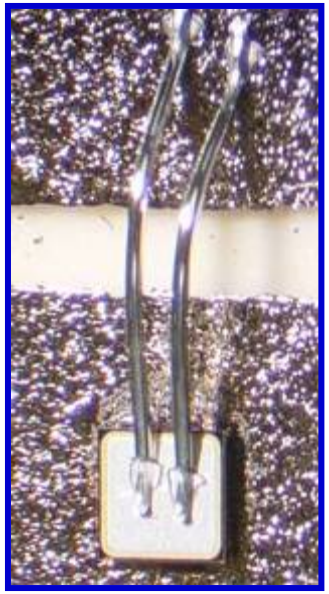
MCPM Power Substrate





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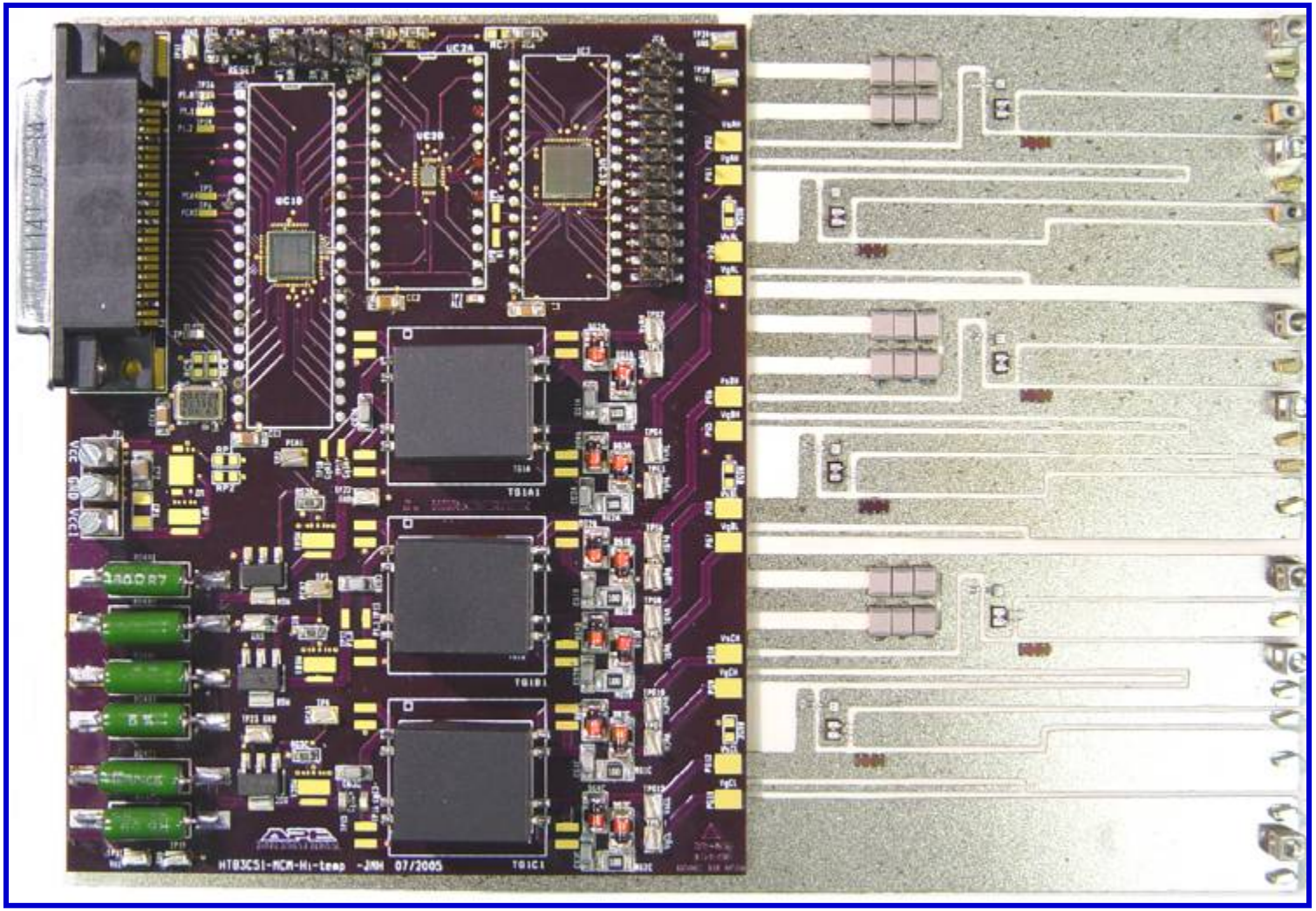
Complete MCPM



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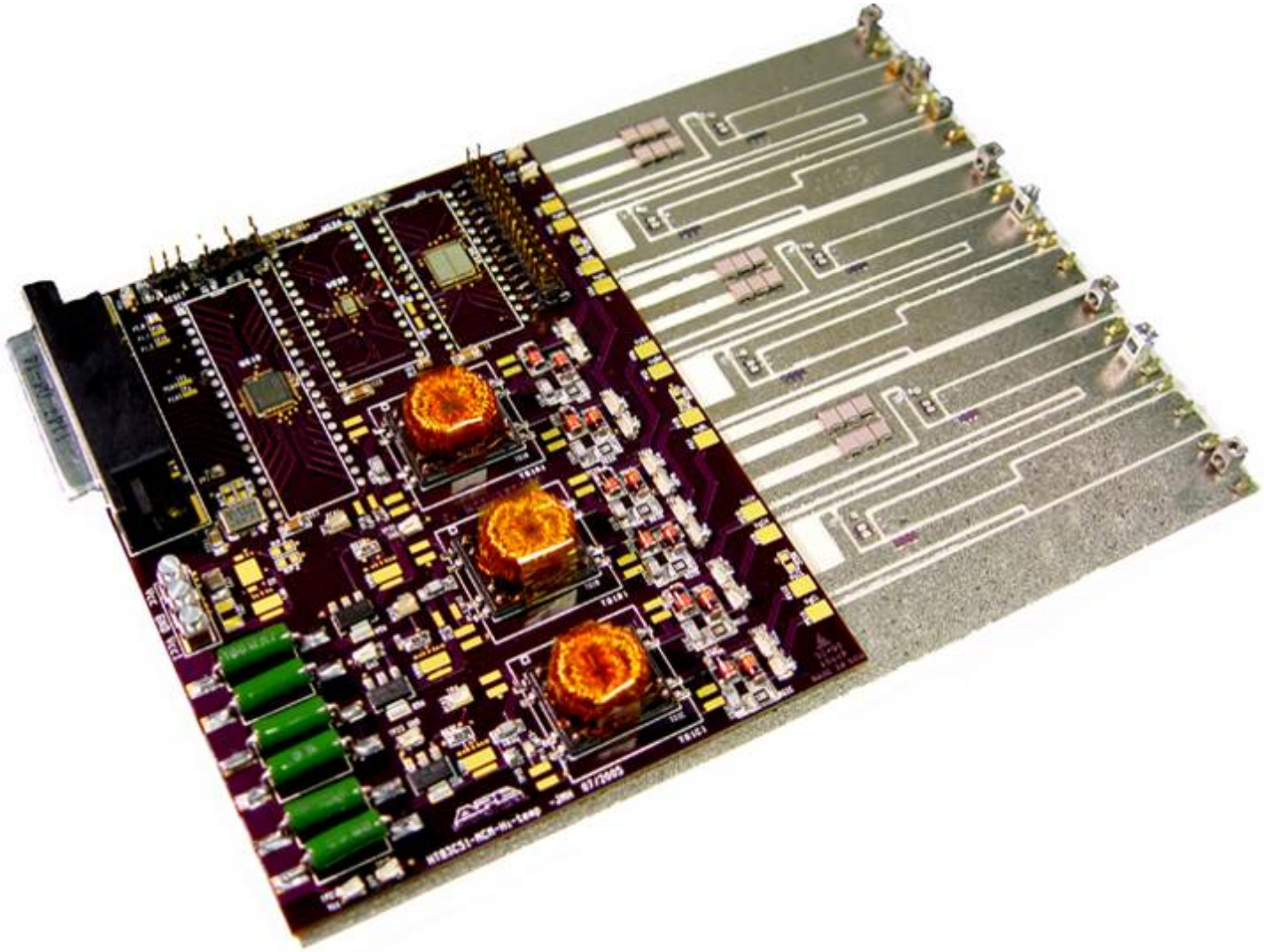
Complete MCPM



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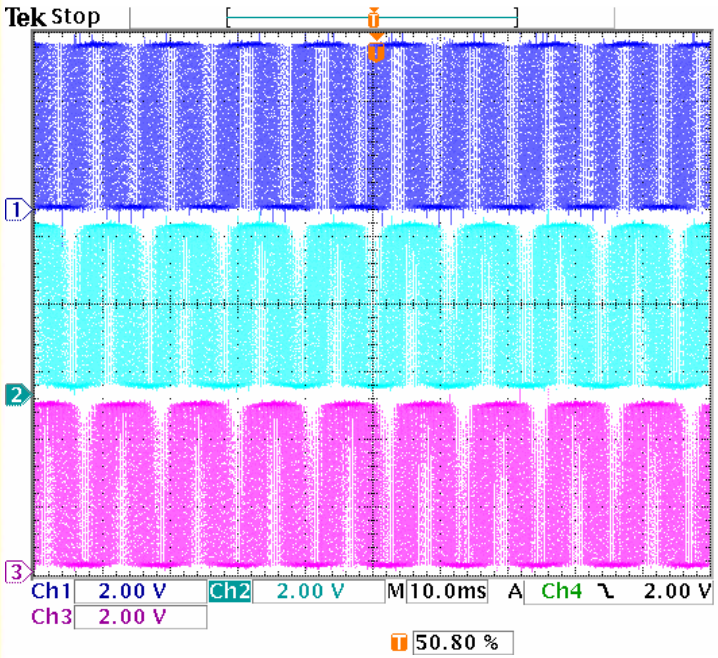
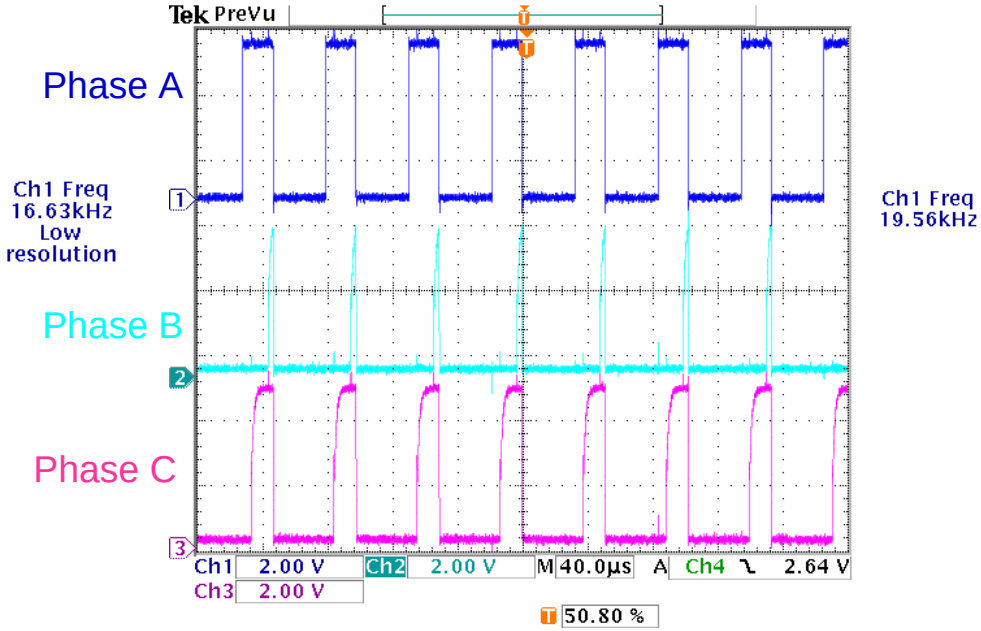
MCPM Controller Signals

Controller Command signals @ 250 °C





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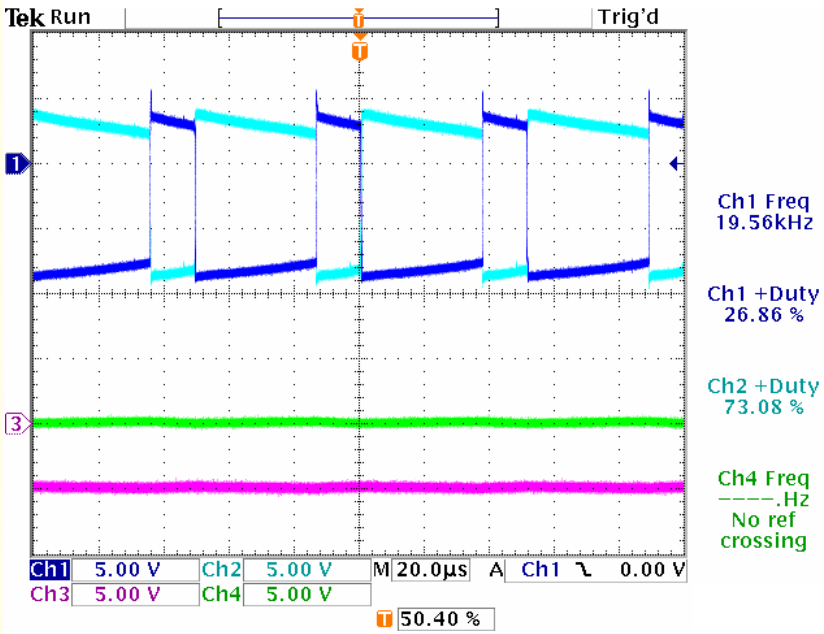
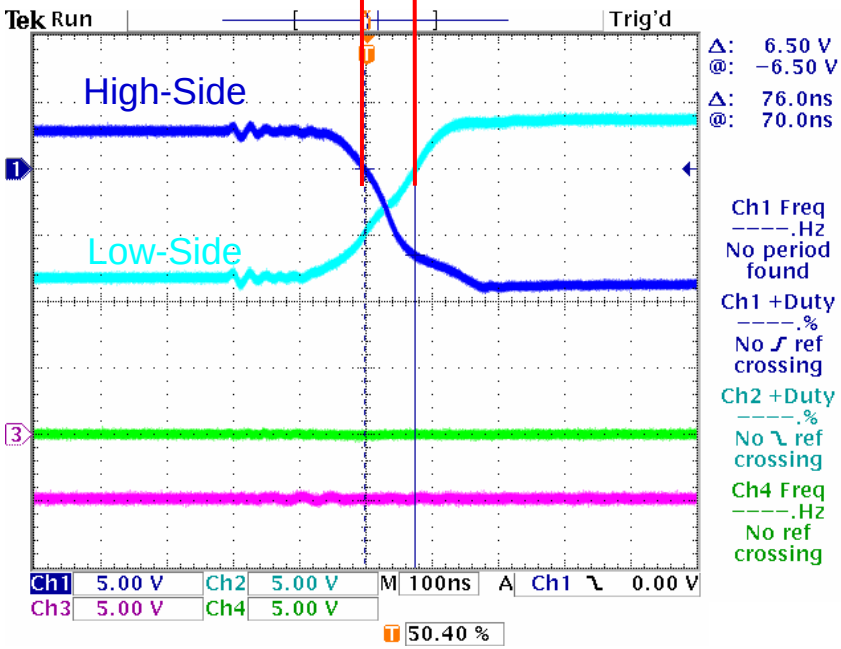
700 Research Center Blvd. Fayetteville, AR 72701 Phone: (479) 443-5759 Fax: (479) 575-7446

MCPM Gate Drive Signals

Gate Driver signals @ 250 °C





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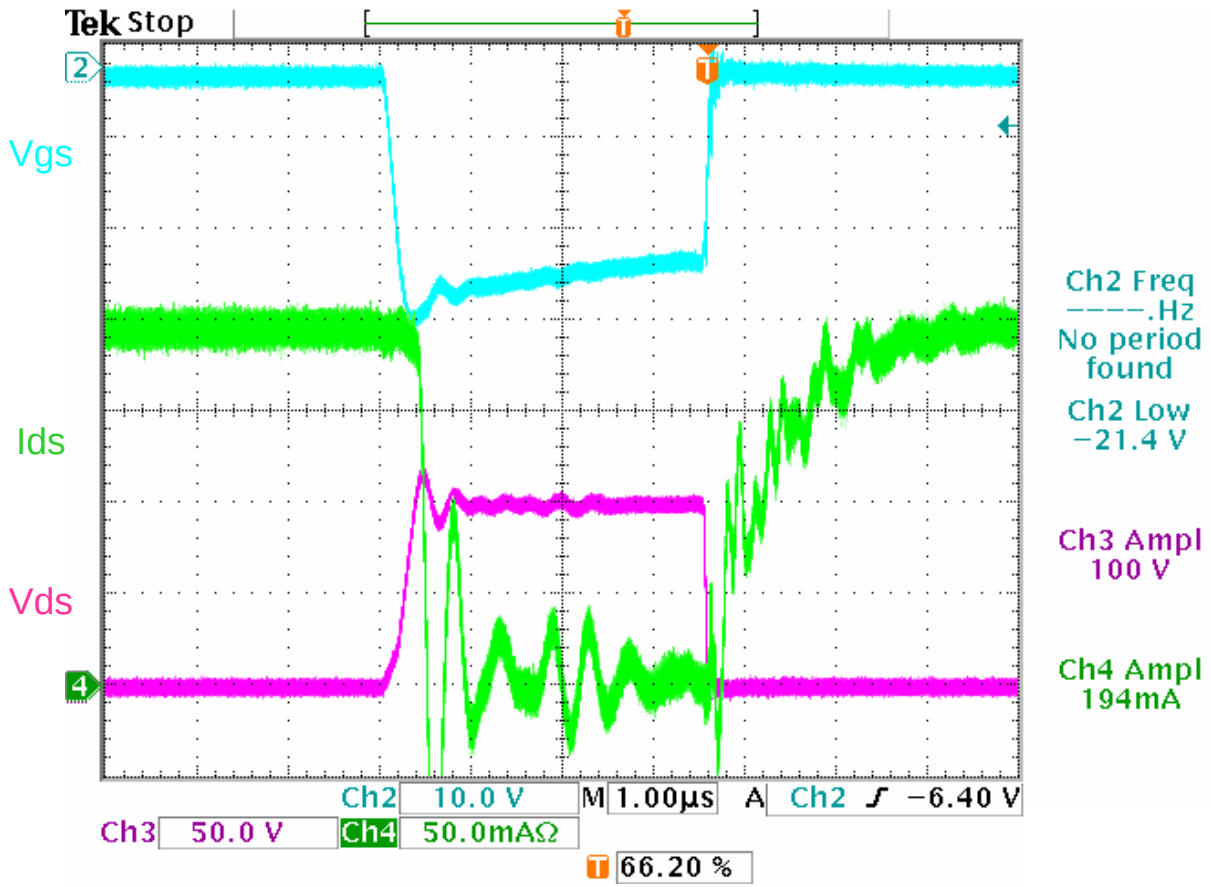
MCPM SiC Power Switch

Switching waveforms @ 250 °C



Summary

- **SiC has the potential to increase the efficiency of power electronic systems**
- **SiC has the potential to drastically reduce size of power electronic systems when combined with high-temperature operation**
- **MCPM approach combines digital control with power stage into a compact module**
- **Power packaging research is still needed to utilize the full potential of SiC**
- **Component development is still needed (i.e. capacitors, magnetics, etc.)**

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Questions?