Advanced Power Electronics Components

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All aerospace systems require Power Management and Distribution (PMAD) between energy source and loads. All power electronics and control circuits for PMAD systems require electrical components for switching, rectification, energy storage, voltage/current transformation, filtering, regulation, protection, and isolation. In order to increase the power density, efficiency, operating temperature, radiation resistance, and reliability of PMAD systems requires advances in power electronics materials and component technology. The primary means to develop advanced power electronics components is to develop new and/or significantly improved materials for capacitors, magnetic components (transformers and inductor), and semiconductor switches and diodes.

The specific benefits of developing advanced power electronics component technology are:

1. Higher operating frequency components give increased PMAD power density by reducing mass and volume of the passive components (transformers, inductors, and filter capacitors).
2. Higher operating temperature components give reduced cooling requirements and thus reduce complexity, size, and mass of the thermal transport system and radiators.
3. Higher efficiency components not only give reduced cooling requirements but also give reduced power generation and storage needs for a given output power.
4. Higher radiation resistant components give reduced mass and volume of shielding materials.
5. Higher voltage components give higher power systems and give reduced cable mass.

This paper will give a description and status of the Advanced Power Electronics Materials and Components Technology program being conducted by the NASA Glenn Research Center for future aerospace power applications. The focus of this research program is on the following:

1. New and/or significantly improved dielectric materials for the development of power capacitors with increased volumetric efficiency, energy density, and operating temperature. Materials being investigated include nanocrystalline and composite ceramic dielectrics and diamond-like-carbon films.
2. New and/or significantly improved high frequency, high temperature, low loss soft magnetic materials for the development of transformers/inductors with increased power/energy density, electrical efficiency, and operating temperature. Materials being investigated include nanocrystalline and nanocomposite soft magnetic materials.
3. Packaged high temperature, high power density, high voltage, and low loss SiC diodes and switches. Development of high quality 4H- and 6H- SiC atomically smooth
substrates to significantly improve device performance is a major emphasis of the SiC materials program.

4. Demonstration of high temperature (>200°C) circuits using the components developed above.
ADVANCED POWER ELECTRONICS

PRESENTATION TO
POWER SYSTEMS CONFERENCE
RENO, NEVADA

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Introduction

- Motivation for doing Advanced Electrical Materials and Component Development
  - What are the benefits?

- Rationale for selecting the magnetic, dielectric, and semiconductor materials investigated
  - What prior theoretical or experimental research justifies the selections?

- Complete technical details of some research investigations can not be given
  - Proprietary data (R&D Contracts)
  - Unpublished data (University Grants)
  - Potential flight mission data

Glenn Research Center

at Lewis Field
Introduction

- Programmatic
  - Glenn Research Center has the responsibility to develop Advanced Electrical Materials and Component Technology (AEMCT) for future aerospace power systems

- AEMCT is an element of Energetics project of NASA’s Enabling Concepts and Technology Program

- Energetics is a balanced program directed to provide critical technologies to meet the needs of NASA and the Nation
Introduction

Motivation

- All Aerospace missions (spacecraft, launch vehicles, planetary surface exploration, aircraft) require electrical Power Management and Distribution (PMAD) between energy source and load.

- Advanced electrical components needed to advance PMAD state-of-the-art
  - Semiconductor switches (MOSFETs, IGBTs, thyristors, etc.)
  - Semiconductor diodes (pn junction, Schottky)
  - Transformers and Inductors
  - Capacitors

- New and improved electrical/electronic materials needed to develop advanced electrical components
  - Magnetic
  - Dielectric
  - Insulating
  - Semiconductor
  - Solders and Contact Materials
Introduction

- **Benefits of Advanced Electrical Components**
  - Higher operating frequency components give
    - Increased PMAD power density by reducing mass/volume of transformers, inductors, and capacitors
  - Higher operating temperature components give
    - Reduced cooling requirements and thus reduce complexity, size, and mass of thermal transport system and radiators
  - Higher efficiency components give
    - Reduced cooling requirements
    - Reduced power generation and storage needs for a given output power
  - Higher radiation resistant components give
    - Reduced mass and volume of shielding materials
  - Higher voltage components give
    - Higher power systems
    - Reduced power transmission cable mass

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Introduction

- Power System Benefits
  - Increased Payload Capability
  - Decreased Spacecraft Mass/Volume/Cost
  - Increased Design Flexibility
  - Increased Reliability
SOFT MAGNETIC MATERIALS
## Soft Magnetic Materials

### Desired soft magnetic material properties

<table>
<thead>
<tr>
<th>High Power/Energy Density</th>
<th>High Temperature</th>
<th>High Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High Saturation Flux Density, $B_s$</td>
<td>• High Curie Temperature</td>
<td>• Low Coercive Force</td>
</tr>
<tr>
<td>• Flat $B_s$ vs. $T$ curve over wide temperature range</td>
<td>• High Thermal Conductivity</td>
<td>• High Permeability at Operating Flux Density</td>
</tr>
<tr>
<td></td>
<td>• Stable Characteristics under Temperature Cycling</td>
<td>• Low Core Loss at Operating Frequency and Temperature</td>
</tr>
<tr>
<td></td>
<td>• Stable Characteristics at High Temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Predictive Aging Effects</td>
<td></td>
</tr>
</tbody>
</table>
Soft Magnetic Materials

- **Core Loss Major Consideration in Power Magnetics**
  - Core loss is power dissipated in magnetic material due to hysteresis, eddy current and anomalous (excess eddy current) losses
  - Core loss is a function of
    - Material type
    - Lamination or Tape Thickness
    - Peak Operating Flux Density
    - Frequency
    - Temperature
    - Type of Excitation (Voltage or Current)
    - Excitation Waveform (Sine, Square, etc.)
Soft Magnetic Materials

- In-House Research
  - Unique core loss, static and dynamic B-H hysteresis loop measurement system developed for transformer (low Q) and inductor (high Q) magnetic materials characterization
    - Temperature Range --- -150 C to 300 C
    - Frequency Range --- DC to 1 MHz
    - Flux Density --- Up to $B_{\text{SAT}}$
    - Voltage Excitation Waveforms --- Sine and Square
  - Extensive experimental data base developed and published on B-H loop and core loss characteristics
    - Polycrystalline alloys (NiFe, CoFe, SiFe)
    - Amorphous alloys (Fe-based, Co-based)
    - Nanocrystalline (Fe-based)
    - Power Ferrites (MnZn)
DC HYSTERESIS PLOTTER

B vs. H Hysteresis Loop Instrumentation System

- H-drive signal
- B-H loop plotting controller
  - Integrates dB/dt signal to get B
  - Can hold either dB/dt or dB/dt constant
- Analog data
- B vs. H
- HP 34970A data digitizer
- B vs. H CSV file

Graphs:
- Arnold TFe635-SL
- 5-mil Superalloy
- DC loop at T=21°C

- Magnetics 55071-A2+2
- p = 60, MPR core
- TR/Slope (T=20°C)
- 2 scans/s

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Core Loss and Dynamic B-H Loop Measurement System

DATA ACQUISITION SYSTEM

 Glenn Research Center
 at Lewis Field
### Polycrystalline Alloys

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>COMPOSITION</th>
<th>FREQUENCIES (kHz)</th>
<th>TEMPERATURES (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPERMALLOY</td>
<td>79% Ni, 17% Fe, 4% Mo</td>
<td>1, 5, 10, 20, 50</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>ORTHONOL (SQ)</td>
<td>50% Ni, 50% Fe</td>
<td>1, 5, 10, 20, 50</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>48 ALLOY (RD)</td>
<td>50% Ni, 50% Fe</td>
<td>1, 5, 10, 20, 50</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>MAGNESIL</td>
<td>3% Si, 97% Fe</td>
<td>0.1, 0.4, 1, 2.5, 5, 7.5, 10</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>SUPERMENDUR</td>
<td>49% Co, 49% Fe, 2% V</td>
<td>0.1, 0.4, 1, 2.5, 5, 7.5, 10</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
</tbody>
</table>

### Amorphous Materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>COMPOSITION</th>
<th>FREQUENCIES (kHz)</th>
<th>TEMPERATURES (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>METGLAS 2605SC</td>
<td>Fe$<em>{81}$B$</em>{13.5}$Si$_{3.5}$C$_2$</td>
<td>1, 5, 10, 20, 50</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>METGLAS 2605S-3A</td>
<td>Fe$<em>{77}$B$</em>{165}$C$_{2}$</td>
<td>1, 5, 10, 20, 50</td>
<td>23, 50, 100, 150, 200, 250, 300</td>
</tr>
<tr>
<td>VACUUMSCHMELTZE 6025F</td>
<td>(CoFeMo)$<em>{73}$(SiB)$</em>{27}$</td>
<td>50, 100, 300, 400, 500</td>
<td>-150 TO +150</td>
</tr>
<tr>
<td>VACUUMSCHMELTZE 6035F</td>
<td>(CoFeMnMo)$<em>{77}$(SiB)$</em>{23}$</td>
<td>50, 100, 300, 400, 500</td>
<td>-150 TO +150</td>
</tr>
</tbody>
</table>

### Nanocrystalline Materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>COMPOSITION</th>
<th>FREQUENCIES (kHz)</th>
<th>TEMPERATURES (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VACUUMSCHMELTZE 500F</td>
<td>?</td>
<td>50, 100, 300, 400, 500</td>
<td>-150 TO +150</td>
</tr>
</tbody>
</table>

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Specific Core Loss Vs Tape Thickness and Frequency

Solid Line: Supermalloy 1, 1/2, 1/4-mil Thick Tape
Dashed line: Square Permalloy 80, 1/8-mil Thick Tape

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Dynamic B-H Loop at f=100kHz
1, 1/2, and 1/4-mil thick tapes are Supermalloy
1/8-mil Thick Tape is Square Permalloy 80

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at Lewis Field
# Soft Magnetic Materials

## Comparison of Amorphous, Nanocrystalline, Polycrystalline, and Power Ferrite Losses

<table>
<thead>
<tr>
<th>Max Flux Density</th>
<th>6025F (Amorphous)</th>
<th>500F (Nanocrystalline)</th>
<th>Supermalloy (Polycrystalline)</th>
<th>Supermalloy (Polycrystalline)</th>
<th>MN8CX (Ferrite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T)</td>
<td>(23 μm Tape)</td>
<td>(23 μm Tape)</td>
<td>(25.4 μm Tape)</td>
<td>(6.35 μm Tape)</td>
<td>(Solid)</td>
</tr>
<tr>
<td>0.1</td>
<td>2.9</td>
<td>4.0</td>
<td>14.6</td>
<td>4.1</td>
<td>4.8</td>
</tr>
<tr>
<td>0.2</td>
<td>11.7</td>
<td>15.9</td>
<td>54.4</td>
<td>17.0</td>
<td>33.7</td>
</tr>
<tr>
<td>0.3</td>
<td>27.9</td>
<td>35.7</td>
<td>119</td>
<td>37.9</td>
<td>98.0</td>
</tr>
</tbody>
</table>
# Soft Magnetic Materials

## Comparison of Amorphous, Nanocrystalline, Polycrystalline, and Power Ferrite Losses

Specific Core Loss (w/lb) @ 0.1 T and 25 C

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>6025F (Amorphous)</th>
<th>500F (Nanocrystalline)</th>
<th>Supermalloy (Polycrystalline)</th>
<th>Supermalloy (Polycrystalline)</th>
<th>MN8CX (Ferrite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.9 (23 μm Tape)</td>
<td>4.0 (23 μm Tape)</td>
<td>14.6 (25.4 μm Tape)</td>
<td>4.1 (6.35 μm Tape)</td>
<td>4.8 (Solid)</td>
</tr>
<tr>
<td>200</td>
<td>9.9</td>
<td>14.8</td>
<td>NO DATA</td>
<td>NO DATA</td>
<td>14.6</td>
</tr>
<tr>
<td>300</td>
<td>19.9</td>
<td>30.6</td>
<td>94.2</td>
<td>22.0</td>
<td>32.2</td>
</tr>
</tbody>
</table>

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Soft Magnetic Materials

- Research focused on the identification, exploration, characterization, and evaluation of soft nanocrystalline and nanocomposite magnetic materials
  - Nanocrystalline materials produced by partial re-crystallization of an amorphous alloy to give a two-phase structure
    - Crystalline grains of 10-20 nm embedded in amorphous intergranular phase
  - Nanocomposite materials fabricated by compaction of insulated magnetic nanoparticles of dimensions less than 50 nm

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Soft Magnetic Materials

- Why Nanocrystalline and Nanocomposite Magnetic Alloys?
  - Offer opportunity to develop new and improved magnetic alloys
    - High Flux Density
    - High/Wide Temperature
    - High Frequency
    - Low dc Coercivity
    - Low Loss

From: G. Herzer, Journal of Magnetism and Magnetic Materials 112 (1992), Figure 2, p. 259, North-Holland
Soft Magnetic Materials

- Nanocrystalline Vs. Nanocomposite Magnetic Alloys
  - Nanocrystalline Magnetic Alloys
    - High resistivity compared to polycrystalline alloys
    - Fabrication process starts with amorphous precursor tape and final product is a tape after partial crystallization.
      - Usage mostly restricted to tape wound cores

- Nanocrystalline grains (green)
  - 15-20 nm diameter

- Amorphous phase
  - between grains

Soft Magnetic Materials

- **Sponsored Nanocrystalline Research**
  - Collaborative effort with Carnegie Mellon University (CMU)
  - PI supported under NASA’s Graduate Student Research Program
  - Objective: Develop high temperature (>300°C), high frequency, low core loss, high saturation induction nanocrystalline alloy
  - Investigation of HITPERM compositional variants and annealing techniques primary research effort
  - HITPERM is a new class of nanocrystalline magnetic alloys recently developed by CMU
    - Composition: (FeCo)-M-B-Cu where M=Zr and Hf

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Soft Magnetic Materials

- Nanocrystalline Vs. Nanocomposite Magnetic Alloys
  - Nanocomposite Magnetic Alloys
    - Very high resistivity compared to nanocrystalline and polycrystalline alloys for well electrically insulated nanoparticles.
    - Fabrication process starts with a powder and compaction of powder into solid should permit fabrication of any size and shape of core just like for ferrites.

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Soft Magnetic Materials

- **Major Challenge to Develop Nanocomposites**
  - Consolidation of the nanocomposite powder into a solid of almost 100% packing density without destroying the nanostructure of the particles.
  - Nanocomposites with good soft magnetic properties require the magnetic moments of neighboring particles be magnetically coupled
    - Known as “Magnetic Moment Exchange Coupling”
  - Critical distance within which the magnetic moments must be exchange coupled is the exchange coupling length
    - Coupling length <50 nm---requires full densification of the particle assembly
    - Coupling length different for each alloy
DIELECTRICS & CAPACITORS
Dielectrics and Capacitors

- Desired Properties of Dielectrics for Power Capacitors
  - High Permittivity (High Dielectric Constant)
  - High Dielectric Strength
  - High Resistivity/Low Leakage Current
  - Low Dissipation Factor/Low Losses
  - Stable Characteristics under Temperature Cycling
  - Stable Characteristics at High Temperature (No Aging Effects)
  - Excellent Mechanical and Windability Properties
# Dielectrics and Capacitors

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant</th>
<th>Dielectric Strength (V/mil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.0</td>
<td>75</td>
</tr>
<tr>
<td>Kraft paper (imp.)</td>
<td>4.0</td>
<td>2,000</td>
</tr>
<tr>
<td>Polymers</td>
<td>2.5-3.0</td>
<td>5,000-9,000</td>
</tr>
<tr>
<td>Mica</td>
<td>5.4-8.7</td>
<td>1,400</td>
</tr>
<tr>
<td>Glass</td>
<td>3.0-4.5</td>
<td>500</td>
</tr>
<tr>
<td>Tantalum Pentoxide</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>7.0</td>
<td>300</td>
</tr>
<tr>
<td>Ceramics</td>
<td>12-400,000</td>
<td>200-350</td>
</tr>
</tbody>
</table>

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Dielectrics and Capacitors

- **Volumetric Efficiency Figure of Merit**
  - Volumetric Efficiency = Capacitance / Volume of Packaged Capacitor
  - For Capacitor Dielectric Only

\[
\frac{C}{(Vol)_d} = \epsilon_0 \epsilon_r / t^2
\]

- \( C \) = Capacitance (farad)
- \((Vol)_d\) = Dielectric Volume (meter\(^3\))
- \(\epsilon_0\) = Free Space Permittivity = 8.85 \times 10^{-12} \text{ farad/meter}
- \(\epsilon_r\) = Relative Permittivity (Dimensionless)
- \(t\) = Dielectric Thickness (meter)
## Dielectrics and Capacitors

### Volumetric Efficiency for Packaged Capacitors

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacitance (µF)</th>
<th>Voltage (V)</th>
<th>C/(Vol)_d µF/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Tantalum</td>
<td>120</td>
<td>100</td>
<td>62</td>
</tr>
<tr>
<td>Solid Tantalum</td>
<td>10</td>
<td>100</td>
<td>8.9</td>
</tr>
<tr>
<td>Electrolytic</td>
<td>18,000</td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td>Polyester Film-Foil</td>
<td>3</td>
<td>100</td>
<td>0.22</td>
</tr>
<tr>
<td>Polyester Film-Foil</td>
<td>3</td>
<td>200</td>
<td>0.12</td>
</tr>
<tr>
<td>Metallized Polyester</td>
<td>10</td>
<td>100</td>
<td>1.6</td>
</tr>
<tr>
<td>COG/NPO</td>
<td>12</td>
<td>100</td>
<td>0.3</td>
</tr>
<tr>
<td>X7R</td>
<td>120</td>
<td>100</td>
<td>4.5</td>
</tr>
<tr>
<td>X7R</td>
<td>120</td>
<td>200</td>
<td>3.0</td>
</tr>
<tr>
<td>Z5U</td>
<td>720</td>
<td>100</td>
<td>18</td>
</tr>
</tbody>
</table>
Dielectrics and Capacitors

- **Energy Density Figure of Merit**
  - Energy Density = $\frac{1}{2} CV^2$/Volume of Packaged Capacitor
  - For Capacitor Dielectric Only

\[
\text{Energy Density} = \varepsilon_0 \varepsilon_r (V/t)^2
\]

- $\varepsilon_0$ = Free Space Permittivity = $8.8 \times 10^{-12}$ (farad/meter)
- $\varepsilon_r$ = Relative Permittivity (Dimensionless)
- $V$ = Charging Voltage (Volts)
- $t$ = Dielectric Thickness (meter)
- $(V/t)_{\text{Max}}$ = Dielectric Strength (Volts/meter)
17 uF, 250 VDC, Florene Poly Ester (FPE) Power Filter Capacitors
Dielectrics and Capacitors

- **High Temperature Relaxor Ferroelectric Multi-Layer Ceramic Capacitors (MLCCs)**
  - A new class of relaxor ferroelectric dielectric materials based on the recently discovered BiMeO$_3$-PbTiO$_3$ (Me=Sc, Yb, Fe, etc) family of morphotropic phase boundary containing perovskites being developed under SBIR contract.

  - Phase I demonstrated MLCCs with volumetric efficiency > 1.4 uF/cm$^3$ and operating temperature to 300°C.

  - Voltage saturation measurements showed about a 2% change in capacitance over the voltage range of 0-500 V at 300°C.

  - Phase II selected for award and presently under contract with TRS Technologies.

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Dielectrics and Capacitors

• Nanocomposite Dielectric Capacitor Material
  - A new class of high performance organic/inorganic capacitor films being developed under an SBIR contract.
  - Combines the advantage of inorganic materials (high dielectric constant) and organic polymers (high dielectric strength) to give high volumetric efficiency and high energy density.
  - Phase I completed using polypropylene as the organic material.
  - Phase I demonstrated a 25% increase in dielectric constant and 30% increase in dielectric strength compared to polypropylene to give an 85% increase in energy density and 25% increase in volumetric efficiency.
  - Phase II selected for an award with emphasis on developing polypropylene with other additives and other high dielectric constant materials and also developing thinner films in order to increase the volumetric efficiency.

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- WIDE BANDGAP SEMICONDUCTOR MATERIALS & DEVICES
Wide Bandgap Semiconductor Materials

Objective
- Develop the Silicon Carbide (SiC) device material and fabrication technology (epigrowth, oxides, passivants, contacts) to enable the development of power devices which are
  - Very Reliable
  - High Temperature
  - High Off-State Voltage
  - Low On-State Voltage
  - High Current Density
  - High Frequency
  - High Radiation Resistance

Silicon Carbide Diode at 600 C
<table>
<thead>
<tr>
<th>Property</th>
<th>Advantage</th>
<th>Energy Bandgap (eV)</th>
<th>Electric Field Breakdown (V/cm)</th>
<th>Thermal Conductivity (W/cm K@RT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si*</td>
<td>Higher Temperature</td>
<td>1.12</td>
<td>2.5x10^5</td>
<td>1.5</td>
</tr>
<tr>
<td>4H-SiC*</td>
<td>High Voltage</td>
<td>3.26</td>
<td>2.2x10^6</td>
<td>3.0-3.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>TYPE</th>
<th>CURRENT (A)</th>
<th>VOLTAGE (V)</th>
<th>SPEC SHEET</th>
</tr>
</thead>
<tbody>
<tr>
<td>INFINEON (thin Q.i)</td>
<td>SCHOTTKY</td>
<td>10</td>
<td>300, 600</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>SCHOTTKY</td>
<td>4, 6, 12</td>
<td>600</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>MICROSEMI (Powermite)</td>
<td>1, 4</td>
<td>200</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>SCHOTTKY</td>
<td>1, 4, 6, 10, 20</td>
<td>400</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>SCHOTTKY</td>
<td>1, 4, 6, 10, 20</td>
<td>600</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>CREE (Zero Recovery Rectifier)</td>
<td>1, 4, 6, 10, 20</td>
<td>1200</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>SCHOTTKY</td>
<td>40</td>
<td>300</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>SCHOTTKY</td>
<td>5, 24</td>
<td>600</td>
<td>YES</td>
</tr>
</tbody>
</table>
## Silicon Carbide Schottky and Silicon PN Diodes Tested

<table>
<thead>
<tr>
<th>SiC Schottky</th>
<th></th>
<th>Silicon pn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor</td>
<td>Part #</td>
<td>Voltage (V)</td>
</tr>
<tr>
<td>Microsemi</td>
<td>UPSC 200</td>
<td>200</td>
</tr>
<tr>
<td>Infineon</td>
<td>SDT10S30</td>
<td>300</td>
</tr>
<tr>
<td>Microsemi</td>
<td>UPSC 603</td>
<td>600</td>
</tr>
<tr>
<td>Infineon</td>
<td>SDT066S60</td>
<td>600</td>
</tr>
<tr>
<td>Cree</td>
<td>CSD 10060</td>
<td>600</td>
</tr>
<tr>
<td>Cree</td>
<td>CSD 20060</td>
<td>600</td>
</tr>
<tr>
<td>Cree</td>
<td>CSD 10120</td>
<td>1200</td>
</tr>
</tbody>
</table>
Steady State Test Setup

- Forward Characteristic Curve: Apply rated current and measure forward voltage (anode to cathode)
- Reverse Characteristic Curve: Apply rated reverse voltage (cathode to anode) and measure the leakage current

Temperature of the hot plate varied from 25C to 250C

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Forward IV Characteristic Comparison

Si 300V 10A Ultra Fast pn (IXYS DSEP 8-03A)
SiC 300V 10A Schottky (Infineon SDT10S30)

- Difference between Schottky (majority, crossover) & PN (minority, no crossover)

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Reverse IV Characteristic Comparison

Si 300V 10A Ultra Fast pn (IXYS DSEP 8-03A)
SiC 300V 10A Schottky (Infineon SDT10S30)

- Si PN: Lower forward voltage drop at 200°C but no reverse voltage blocking capability
- SiC Schottky: Larger energy bandgap (Eg) allows the device to block 300V at 200°C

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**Forward IV Characteristic Comparison**

Si 150V 5A Dual Schottky (International Rectifier 10CTQ150)
SiC Schottky 200V 1A (Microsemi UPSC200)

- **SiC Schottky 200V**
- **Si Schottky 150V**

- **Si @ 25°C**
- **Si @ 100°C**
- **Si @ 200°C**
- **SiC @ 25°C**
- **SiC @ 100°C**
- **SiC @ 200°C**

- Forward voltage for SiC Schottky is higher than for Si Schottky. SiC device voltage rating is higher than 200V (600V or higher)

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Transient Current Comparison in Buck Converter, $V_{IN} = 400V$

Si 600V 8A ultrafast pn (IXYS DSEI 8-06A)
SiC Schottky 600V 6A (Infineon SDT06S60)

- Si pn diode reverse recovery current increases significantly with temperature
- SiC Schottky diode transient reverse recovery current does not change with temperature

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<table>
<thead>
<tr>
<th>VENDOR</th>
<th>TYPE</th>
<th>SPEC SHEET</th>
<th>VOLTAGE (V)</th>
<th>CURRENT (A)</th>
</tr>
</thead>
</table>

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Efficiency Comparison of Si pn-junction and SiC Schottky Diodes in Buck Converter

- Buck converter efficiency as a function of temperature and switching frequency using either the Infineon SDT06S60 (600V/6A) SiC Schottky diode or the IXYS DSEI 8-06A (600V/8A) ultra fast Si pn-junction diode.
Wide Bandgap Semiconductor Materials

- Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn
  - New growth process called “Step-Free Surface Heteroepitaxy” under development to produce atomically smooth or flat 4H- and 6H-SiC substrates
    - Mesas with dimensions up to 200 \( \mu \text{m} \) square demonstrated on commercial 4H-SiC wafers
    - Mesas with dimensions up to 50 \( \mu \text{m} \) square demonstrated on commercial 6H-SiC wafers

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Wide Bandgap Semiconductor Materials

- Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn
  - Density of screw dislocations limits scale up of size and yield of step free mesas
  - New homoepitaxial lateral "web growth" process being developed to scale up size and yield of step free mesas
  - Webbed surfaces up to $4 \times 10^{-3}$ cm$^2$ have been grown

Pre-growth optical photo of cross-shaped mesa  |  Post-growth SEM of "webbing" formed following 60-minute growth.

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Wide Bandgap Semiconductor Materials

- Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn
  - Growth of defect free 3C-SiC on 4H- and 6H-SiC has been demonstrated using the new step free growth process.

Recipe “A”
3C-SiC layer grown on 0.2 mm x 0.2 mm screw dislocation free mesa on following oxidation to reveal step free defects.

Recipe “B”

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<table>
<thead>
<tr>
<th>Component</th>
<th>Technology Improvements Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformers and Inductors</td>
<td>- High frequency, high temperature, low core loss soft magnetic materials</td>
</tr>
<tr>
<td></td>
<td>- High temperature wire insulation, interlayer insulation, and terminations</td>
</tr>
<tr>
<td>Capacitors</td>
<td>- High temperature, low loss, high dielectric constant, high dielectric strength dielectrics</td>
</tr>
<tr>
<td></td>
<td>- High temperature terminations</td>
</tr>
<tr>
<td>Switches and Diodes</td>
<td>- High quality SiC substrates, oxides, and passivants for higher voltage and current devices</td>
</tr>
<tr>
<td></td>
<td>- High temperature contacts</td>
</tr>
<tr>
<td></td>
<td>- High temperature packages</td>
</tr>
</tbody>
</table>

Long Term Temperature Aging and Stability Data Needed for All Power Electronics Components.

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