High Performance Packaging of Power Electronics: 

*Role of Thermally Engineered Materials*

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### 14. Abstract
Advantages of new approaches must be demonstrated at the system, e.g., motor drive, level. Device Power Density (A/cm2 or W/cm2) System Power Density (W/m3) Lifetime Assurance of Entire System System Cost Analysis Ultimately Required

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18
Global Energy Consumption and Power Electronics

(Source: NSF Center for Power Electronic Systems: http://www.cpes.vt.edu/)

US Electrical Energy Consumption

* Output of 840 power plants

* EPRI
Defense Power Electronics Requirements Example: PEBBs

Courtesy of G. Campisi, Office of Naval Research
Power Electronic Systems

- Motor Drives
- Radar / Microwave Communications
- dc to dc Converters
- Power Supplies
- Electric Vehicle Drives
- Weapons Systems

Today’s Topic
**Drive & Motor Automation System**

Convenience AC power (fixed frequency, voltage) to AC Power (variable frequency, current, and voltage)

Enables exact control of speed (RPM) and torque of motors

Motors become *controlled electromechanical energy converters*.

**Performance Metrics:**
- Power Density
- Cost
- Reliability

Rockwell Automation - Allen Bradley 1336 Force Drive

Reliance Electric AC Motor
Basic Power Packaging Elements

- Silicon
- Ceramic Insulation
- Wirebonded Interconnections
- Soldered Interconnections
- Gel Encapsulation
- Plastic Housing
- Power Terminals
- Metal Baseplate
- Heatsink
Generic Electronic Packaging Technology Hurdles

Controlled Power Density (W/m$^3$)
High Power Requirements from Devices
High Packaging Densities
Weight Requirements

Cost ($/Function)

Reliability (MTBF)
High-Temperature Packaging of SiC Electronics

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30 May, 2001

Contract Number MDA97298C0002
Decrease in System Volume Through Utilization Of Silicon Carbide (SiC) Electronics

- **Silicon Power Density**: $10^6$ W/m$^2$
- **Baseplate Power Density**: $10^5$ W/m$^2$
- **Heatsink Power Density**: $10^3$ W/m$^2$
- **T$_{\text{fin}}$**: 55°C
- **Silicon T$_j$**: 125-150°C

- **SiC Power Density**: $10^6$ W/m$^2$
- **Baseplate Power Density**: $10^5$ W/m$^2$
- **Heatsink Power Density**: $10^4$ W/m$^2$
- **T$_{\text{fin}}$**: >200°C
- **SiC T$_j$**: 300-350°C

*Smaller, hotter heatsink feasible with SiC ($Q=hA\Delta T$)*
Thermomechatronics

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¹University of California, Los Angeles CA

30 May, 2001

Contract Number MDA97298C0002
Thermal Management of Power Electronics: Spread Power Density from Device to Heatsink

- Silicon Power Density = $10^6$ W/m$^2$
- Baseplate Power Density ~ $10^5$ W/m$^2$
- Heatsink Power Density ~ $10^3$ W/m$^2$

5 hp Motor Drive Example
Large Area Solder Joint Reliability in Power Assemblies

Examples of Buried Continuous Solder Layers

Internal view of a 1200A, 3300V IGBT module (courtesy: Eupec GmbH+ Co.)
Elastic Fracture Mechanics Energy Balance in Layered Systems

\[ G_{lc} = \frac{Z \sigma^2 h (1 - \nu^2)}{E} \]

\( \sigma = \) Stress in coating
\( h = \) Coating thickness
\( E, \nu = \) Elastic properties
\( Z \approx 0.3 \)

Driving Force for Crack Growth or Material or Interfacial Crack Growth Resistance

Cracking depends on which is larger:
Thermal Cycling of Sn - Pb (Elastic/Plastic) vs Au-Sn (Elastic) Joints

80Au20Sn on Copper

As Soldered 1 cycle 10 cycles 100 cycles 1000 cycles

0.6"

63Sn37Pb on Copper

Δα = 14.1 ppm; Elastic Solder

Δα = 14.1 ppm, Elastic / Plastic Solder

Ultrasonic Reflection Microscopy
Model of progressive crack growth in DBC/baseplate solder joint

As Soldered         1 cycle            10 cycles           100 cycles        1000 cycles

= IGBT
Thermal Equivalent Circuit

<table>
<thead>
<tr>
<th>Thermal Resistance</th>
<th>Analytic Form</th>
<th>Typical Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{JC}$</td>
<td>$\sim \rho t/A_s$</td>
<td>1.4°C/W</td>
</tr>
<tr>
<td></td>
<td>$\rho$ -&gt; thermal resistivity, $t$ -&gt; thickness</td>
<td></td>
</tr>
<tr>
<td>$\theta_{CS}$</td>
<td>$\sim \rho t/A_s$</td>
<td>$\sim 0.1-1$ °C/W</td>
</tr>
<tr>
<td>$\theta_{SA}$</td>
<td>$\sim 1/hA_s$</td>
<td>10-33°C/W (natural convection); 1-10°C/W (forced air)</td>
</tr>
<tr>
<td></td>
<td>$h$ -&gt; heat transfer coefficient</td>
<td></td>
</tr>
</tbody>
</table>
Solder Joint Fatigue Raises Package Thermal Resistance

Pristine condition - lowest thermal resistance

Thermally cycled condition - higher thermal resistance
Bipolar Transistor Performance Degradation with Repeated Power Cycling (Ref: Evans and Evans)


Experimental Results Showing Large Increase in Forward Voltage Drop, $\Delta V_{be}$, with Repeated Power Cycling, $N$
Coupled Electro-Thermal Simulation

- Nonlinear thermal circuit models
- Connect electrical to thermal circuits through unique “thermal node” (after A. Hefner of NIST)
- SPICE-like environment
Heatsource; Radius = a
Power = P

Substrate; Radius = b_o

Baseplate
Calculated Thermal Resistance, $R_{th}$, vs. Inverse Normalized Fatigue Crack Length, $b/a$.

Note the rapid increase in $R_{th}$ with penetration of the fatigue crack into the region below the device ($b/a \sim 1$).
Dependence of Junction Temperature Increase, $\Delta T_j$, on Inverse Normalized Fatigue Crack Length, $b/a$

Two different power levels and substrate thicknesses.
Strain Energy Release Rate, $G_{lc}$, Depends on $\Delta T_j$

\[
\frac{Z \sigma^2 h (1 - \nu^2)}{E} = G_{lc}
\]

Strain energy release rate is the driving force for fatigue crack growth

![Graph showing the relationship between $G$ and $b/a$ for different values of $a/w$ and $P$.]
Experimental crack growth rate data, $\frac{da}{dN}$, vs. cyclic strain energy release rate range $\Delta G$ for the Al-Al$_2$O$_3$ and Al-Al systems.
Relationship between the number of power cycles, $N$, and the crack length, $l$ for two different power levels and substrate thicknesses.

Note the highly nonlinear relationship between the crack lengths and number of power cycles.
Predicted Junction Temperature Increase, $\Delta T_j$, vs. Power Cycles, $N$

![Graph showing predicted junction temperature increase vs. number of cycles for different cases with a/w ratios of 1.25 and 5, and powers of 100 and 500.](image-url)
Thermomechatronic Analysis of coupled flow of electrical, thermal and mechanical energy
Conclusions

• Advantages of new approaches must be demonstrated at the system, e.g., motor drive, level.

  Device Power Density (A/cm² or W/cm²)
  System Power Density (W/m³)

Lifetime Assurance of Entire System
System Cost Analysis Ultimately Required

• Research Needs:

  1) Materials
     - Controllable and High Thermal Conductivity
     - Functional Integration of Electrical, Thermal, Mechanical Features
     - High Temperature Capability
     - Lightweight
     - Compatible with Solid-State Devices
     - Easily Processed

  2) Efficient, System-Based Design Methodologies
     - Mechanical, Thermal, Coupling
     - Lifetime Prediction / Reliability
     - Design Optimization / Tradeoff Capability