High Performance Pyrolytic Graphite Heat Spreaders: Near Isotropic Structures and Metallization

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Agenda

Background
Metallization
Case Study – Two Dimensional Laser Diode Application
Case Study - Three Dimensional Heat Spreader Applications
  • T/R Module
  • CTE Analysis
Conclusions
Who Are We?

GLOBAL RESOURCE AND TECHNOLOGY BASED GROWTH COMPANY THAT DEVELOPS, PRODUCES AND MARKETS, SPECIALTY MINERALS, SYNTHETIC MINERAL PRODUCTS, SYSTEMS AND SERVICES.

$1.1B 2007 Sales
MTX NYSE

Refractory Products – One of the World's Leading Developers and Marketers of Mineral-Based Monolithic Refractory and Ceramic materials

Pyrogenics Mission:

*Provide engineered carbon based products for key industries requiring innovative material solutions*

Largest single source producer of pyrolytic graphite, thin films, and specialty carbon composites
Markets – Aerospace, Semiconductor/ Electronics, Medical Imaging, Isothermal Forge, Glass

Leading manufacture of high quality piezoelectric, alumina and specialized thermal management components/systems for thermally constrained circuitry for military applications, as well as alternative energy systems
An Effective Thermal Management Solution is Key to Continued Growth

Widespread growth of smaller packages forcing increased power density for applications found in:

Defense/Military
Commercial Industry

Need performance thermal management solutions for:

• Laser Diodes
• T/R Radar Modules
• LED Lighting
• OLED/COLED
• All High Power Devices
MINTEQ International’s Pyrographics Group has Decades of Experience Perfecting the Chemical Vapor Deposition Processing of Pyrolytic Graphite

- High purity > 99.999%
- Single crystalline structure
- Thermal Conductivity
  - 1700 W/mK matching CVD diamond
  - Anisotropic (“Engineered” 2 plane orientation)
- Density: 2.25 g/cc (only 25% of Copper)
- Plate and wafer production
  - > 30 cm wide x 3 meter long
  - Tailored thickness up to 2.5 cm
  - Easily cut, diced and lapped to mirror finish
  - High production, pick/place, capable of integration to volume packaging requirements
PYROID® HT Conductivity (20° C)

X-Y Plane  1,700 W/mK
Z Plane    7 W/mK

Standard Pyrolytic Graphite

X-Y Plane  440 W/mK
Z Plane    1.7 W/mK

PYROID HT

4X Thermal Conductivity of Copper
25% Weight of Copper

↑↑↑ Performance/Cost Over Diamond or Copper
Metallization to PYROID® HT Pyrolytic Graphite must insure an acceptable bond strength

Sebastian Pull Test (semiconductor coating strength measurement)

✓ Industrial standard test of adhesion strength
✓ Epoxy coated 2.69 mm metal stud bonded to sample
✓ Constant strain rate “pull” perpendicular to bonding plane
✓ 3 metallization compositions
✓ Compatible tested with solder types (Pb-Sn, Au-Sn, Indium, etc.)

Shear test using MIL STD 883
Key Enabler for Use - Metallization Development

Summary of Sebastian pull test results for three metallization types.

<table>
<thead>
<tr>
<th>Metallization type</th>
<th>Avg. fracture stress (Mpa)</th>
<th>Avg. shear failure load (Kg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti -1000 Å NiCr-1000 Å Au-3000 Å</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td>Ti -1000 Å Ni-1000 Å Au-3000 Å</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>Ti-1000 Å Pt-1000 Å Au-3000 Å</td>
<td>28</td>
<td>21</td>
</tr>
</tbody>
</table>

Failures in the material
Not in the metallization interface
Conclusion:

**PYROID® HT metallization bond strength meets or exceeds semiconductor standards**

Compatibility and wettability of selected solder types with metallization

- Au Sn (80Au/20 Sn) Hi temperature
- Ag Sn
- In Sn
- SAC 305
- traditional Sn Pb

Typical Au Sn solder wire
Attachment
Case Study - Two Dimensional Laser Diode

Two dimensional PYROID® HT Heat Spreaders vs. Copper Laser Diode Application Experiments

Objective:

Measure laser diode temperature and match to 3D Omega Piezo Technologies’ finite control volume thermal conduction program

Materials tested and modeled

1. Copper-Molybdenum (industry accepted for CTE)
2. Copper
3. Pyroid® HT Pyrolytic Graphite
Case Study - Two Dimensional Laser Diode

Finite control volume computational grid with laser diode attached to the heat spreader end

- Two dimensional heat spreader configuration
- Low conductivity plane across diode
- High conductivity plane
- Constant heat flux 200 W/cm²
- Copper heat sink temperature 30 °C
Case Study - Two Dimensional Laser Diode

Resultant temperature Contours for CuMo vs PYROID® HT Pyrolytic Graphite heat spreaders for a heat flux of 200 W/cm$^2$
Case Study - Two Dimensional Laser Diode

RESULTS: 70 °C REDUCTION in $T_{\text{junction}}$

Laser Diode Application Experimental Results

Application:
Laser Diode
Power Input
200 W/cm$^2$ flux

Resulting interface Temperature reduction
Delta $T_{\text{junction}} = 70^{\circ} \text{C}$
Case Study - Two Dimensional Laser Diode

RESULTS: > 50% INCREASE IN POWER OUTPUT

Interface temperature for three heat spreader configurations

- Cu Spreader, $k = 400 \text{ W/mK}$
- Pyroid HT Pyrolytic Graphite, $k = 1700, 10$
- CuMo Spreader, $k = 160$

*For constant $T_{\text{junction}} = 100^\circ \text{C}$, power output INCREASES > 50% over CuMo*
Case Study - Radar Transmit/Receive (T/R) Module

PYROID HT® Heat Spreaders
What is the optimum near isotropic 3D spreader?

- Case G02
- Pyrolytic Graphite Spreader (5 bars)
- 12,010 control volumes
- 95,200 iterations
- Spreader thickness = 0.080 in (2.032 mm)
- Conductivity, \( k = 1700 \text{ & } 10 \text{ W/mK} \)
- \( T_{sink} = 30 \text{ C} \)
- \( T_{interface \ max} = 83.6 \text{ C} \)

Measure die/spreader interface temperature

Grid & temperature contours
five bar Pyroid HT® T/R Module
3D PYROID HT® Heat Spreaders
Resultant $K = 1350 \text{ W/mK}$ isotropic bulk conductivity

Optimum spreader:
- 2.0 mm first layer
- 0.5 mm second layer
- 2.5 µm Au/Sn solder

RESULTS: 30° C REDUCTION IN TEMPERATURE

![Graph showing temperature reduction with different spreader thicknesses and conductivities.]

- 0.050 in (1.27 mm) thick
- 0.080 in (2.032 mm) thick
- CuMo
- Pyroid HT Pyrolytic Graphite

Max temperature:
- $T_{max} = 73° C$ for 2.03 mm thick spreader
- $T_{max} = 103° C$ for 1.27 mm thick spreader

Temperature difference:
- $\Delta T = 30° C$
Consider two materials:

Low CTE material in restrained state creates:
• compression in high CTE material

High CTE in restrained state creates:
• tension in low CTE material

Resultant Modulus of Elasticity of material is as important as is CTE
Simplified Model for Thermal Stress

High CTE material in restrained state creates:
• compression in High CTE material
Low CTE in restrained state creates:
• tension in Low CTE material

Assume materials are joined along surface with normal stresses transferred by shear (zero at joint center and along free surfaces)

Resultant governing system equation:

\[ \sigma = \frac{(\alpha_A - \alpha_B) \Delta T E_A E_B}{(E_A + E_B)} \]
Case Study - Three Dimensional CTE Stress Analysis

Properties of die and spreader materials

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE (1/°C)</th>
<th>E, modulus of elasticity, (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>4.68 x 10^-6</td>
<td>110.3</td>
</tr>
<tr>
<td>PYROID® HT Pyrolytic Graphite</td>
<td>0.5 x 10^-6 (\parallel) 25 x 10^-6 (\perp)</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Diamond</td>
<td>1.18 x 10^-6</td>
<td>700 - 1200</td>
</tr>
<tr>
<td>Copper</td>
<td>16.5 x 10^-6</td>
<td>110.3</td>
</tr>
</tbody>
</table>

For 200° C temperature excursion thermal stresses for various die/spreader materials

Resultant governing system equation:

\[
\sigma = \frac{(\alpha_A - \alpha_B)\Delta T}{E_A + E_B} \frac{E_A E_B}{E_A + E_B}
\]
For 200°C temperature excursion thermal stresses for various die/spreader materials

<table>
<thead>
<tr>
<th>Die/spreader Materials</th>
<th>Stress, MPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon/Diamond</td>
<td>-71 (-10,260) (die compression)</td>
</tr>
<tr>
<td>Silicon/Copper</td>
<td>130 (18,900) (die tension)</td>
</tr>
<tr>
<td>Silicon/PYROID HT® Pyrolytic Graphite</td>
<td></td>
</tr>
<tr>
<td>Silicon/PYROID HT® Pyrolytic Graphite ⊥</td>
<td>-11 (-1600) (die compression)</td>
</tr>
</tbody>
</table>

Order magnitude lower than diamond or copper.

No damage after numerous thermal cycling RT to 150°C.
Pyroid HT® Pyrolytic Graphite Options

- Metallization or Non Metallized Graphite Base
- Metallization overlay on Pyroid HT Pyrolytic Graphite
  - Ti/NiCr/Au  Ti/Ni/Au  Ti/Pt/Au base  other material
    - Forms a reliable and sealing overlay to allow solder process
    - Amenable solders Pb/Sn, SAC 305, In/Sn, Au/Sn, other
- Mounting options
  - As is
  - Metal reinforcing backings
  - Epoxy/fiberglass reinforcement
- Amenable Pick/Place
Portfolio Graphite Heat Spreader Architectures

PYROID® HT Laser diode spreader

Machined HT billet

Three dimensional bonded HT graphite composite

Metallized substrates

Copper clad, solder bonded HT graphite sandwiches

HT sandwich layer

4” x 4” x 0.013” plate radiator
Conclusions

- Intrinsic anisotropy and strength limitations addressed through “engineered” orientation and fabrication approaches.

- Optimization tools/models available for layered PYROID® HT Pyrolytic Graphite heat spreader designs and performance analysis.

- Elastic Modulus is just as important as CTE to mechanical compatibility between spreader and die materials.

- PYROID® HT Pyrolytic Graphite Heat Spreaders are cost effective alternatives to expensive diamond and heavier, low performing copper spreaders.
PYROID® HT heat spreader material for

- Wide band gap
- RF and MW
- Insulated Gate Bipolar Transistors (IGBT)
- Power amplifiers
- High-brightness LEDs
- Laser diodes
- Processors, ASICs, other
- Light weight applications
- Confined enclosures
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