Semiconductor Industry Speaker Series

"Advanced Thermal Management Materials and Low-Expansion PCBs"

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January 27, 2021

www.meptec.org www.imaps.org

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Dr. Zweben, now an independent consultant, has directed development and application of advanced thermal management materials for over 35 years. His group at GE was the first to use Al/SiC (silicon carbide particle-reinforced aluminum) and other advanced materials in electronics and photonics thermal management. He also has developed low-CTE printed circuit boards. He was formerly Advanced Technology Manager and Division Fellow at GE Astro Space. Other affiliations have included Du Pont, Lockheed Martin and Jet Propulsion Laboratory. Dr. Zweben was the first, and one of only two winners of both the GE Astro Space One-in-a-Thousand and Engineer-of-the-Year awards. He is a Life Fellow of ASME, a Fellow of ASM and SAMPE, an Associate Fellow of AIAA, and has been a Distinguished Lecturer for AIAA and ASME. He has published widely, and consulted for many Fortune 500 companies, taught over 200 short courses and served as an expert witness.

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ADVANCED THERMAL MANAGEMENT MATERIALS AND LOW-EXPANSION PCBs

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OUTLINE

- **Introduction**
- **Traditional thermal management materials**
- **Advanced thermal management materials**
- **Applications**
- **Future directions**
- **Summary and conclusions**

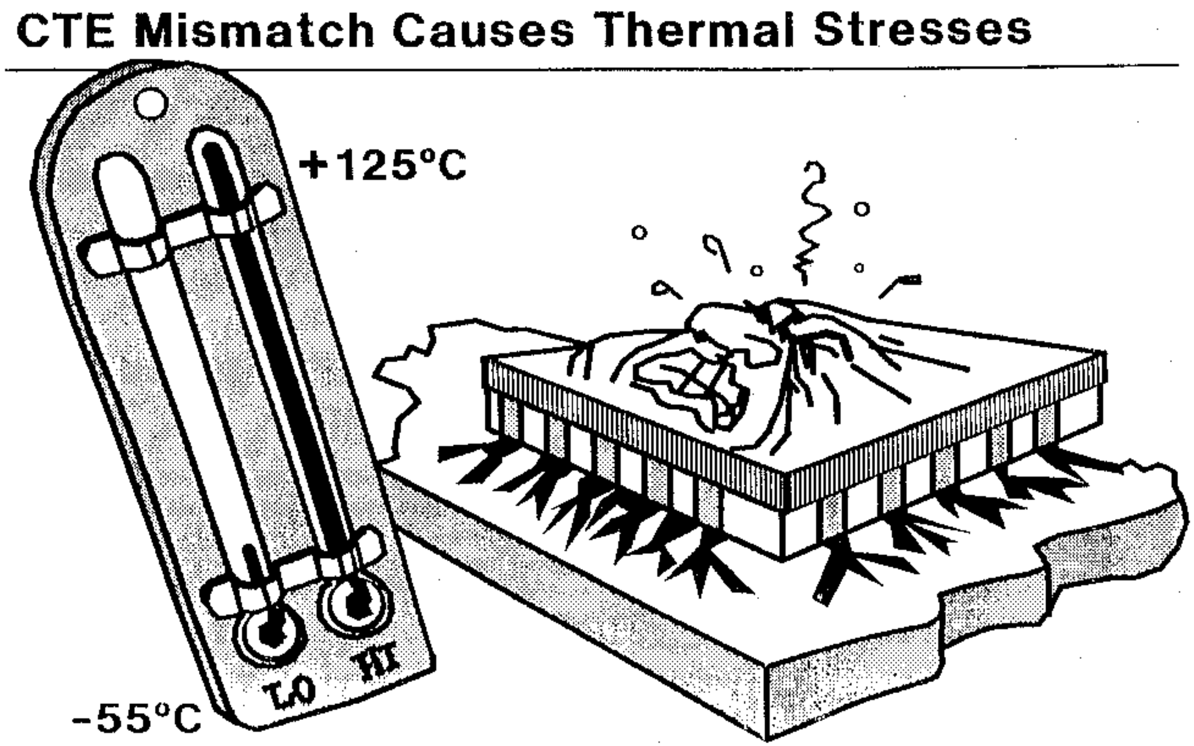
INTRODUCTION

INTRODUCTION

- **Reducing Size, Weight and Power (SWaP) key driver for many aerospace/defense and commercial applications**
- **Thermal management critical issue**
- **In addition to heat dissipation, thermal stresses are a major problem, resulting in**
  - **Warping**
  - **Fracture**
  - **Fatigue failure**
  - **Creep**
- **Deformation important for photonics**

INTRODUCTION (continued)

- **Thermal stresses caused primarily by coefficient of thermal expansion (CTE) mismatch**



Source: US Air Force

INTRODUCTION (continued)

- Weight (mass) important
  - Aerospace/defense systems
  - Portable commercial/consumer systems
  - Vibration
  - Shock/drop loads during shipping
- Cost critical

INTRODUCTION (cont)

- **Thermal problems similar for all semiconductors**
  - **Power**
  - **Microprocessors and GPUs**
  - **RF**
  - **Diode lasers**
  - **Light-emitting diodes (LEDs)**
  - **Concentrator photovoltaic (solar) cells**
  - **LCD and plasma displays**
  - **Detectors**
  - **Thermoelectric coolers**
  - **High-power laser and RF weapons**

ADVANCED THERMAL MATERIALS WIDELY USED

INTRODUCTION (cont)

- **Traditional thermal materials inadequate for many applications**
  - **Date from mid 20th century**
  - **Impose severe design limitations**
  - **Some expensive**
- **Increasing number of advanced materials**
  - **Thermal conductivities up to 1700 W/mK**
    - **>4x copper**
  - **Low CTEs**
  - **Low densities**
  - **R&D to large volume production**
  - **Some cheaper than traditional materials**

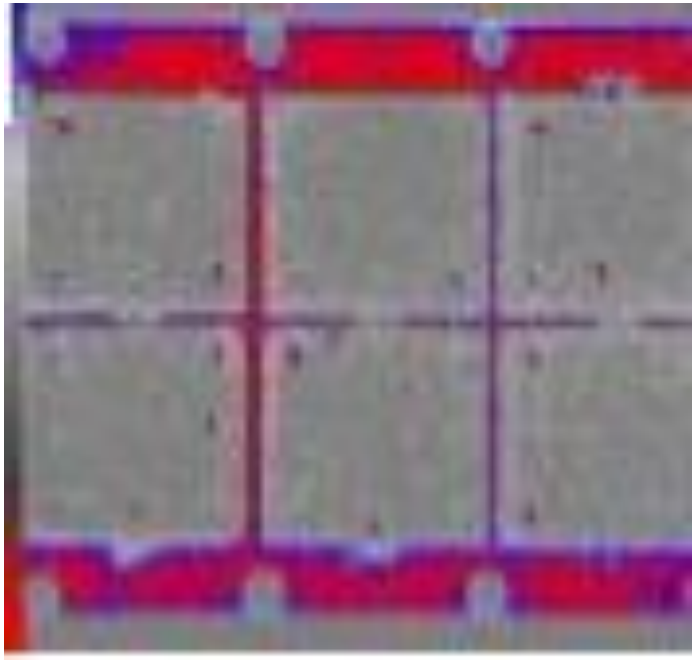
INTRODUCTION (cont)

- **Example of advanced thermal management material payoff:**
  - **Eupec/Infineon reports that replacement of IGBT module copper baseplates with Al/SiC:**
    - **Matches CTE of aluminum nitride substrate**
    - **Eliminates solder joint failure**
    - **Increases lifetime from 10 to 30 years**

Al/SiC IGBT BASEPLATES ELIMINATE SOLDER FAILURE

“The failure mechanism does not exist any longer”

COPPER BASEPLATE
<u>4,000 CYCLES</u>



Al/SiC BASEPLATE
<u>20,000 CYCLES</u>

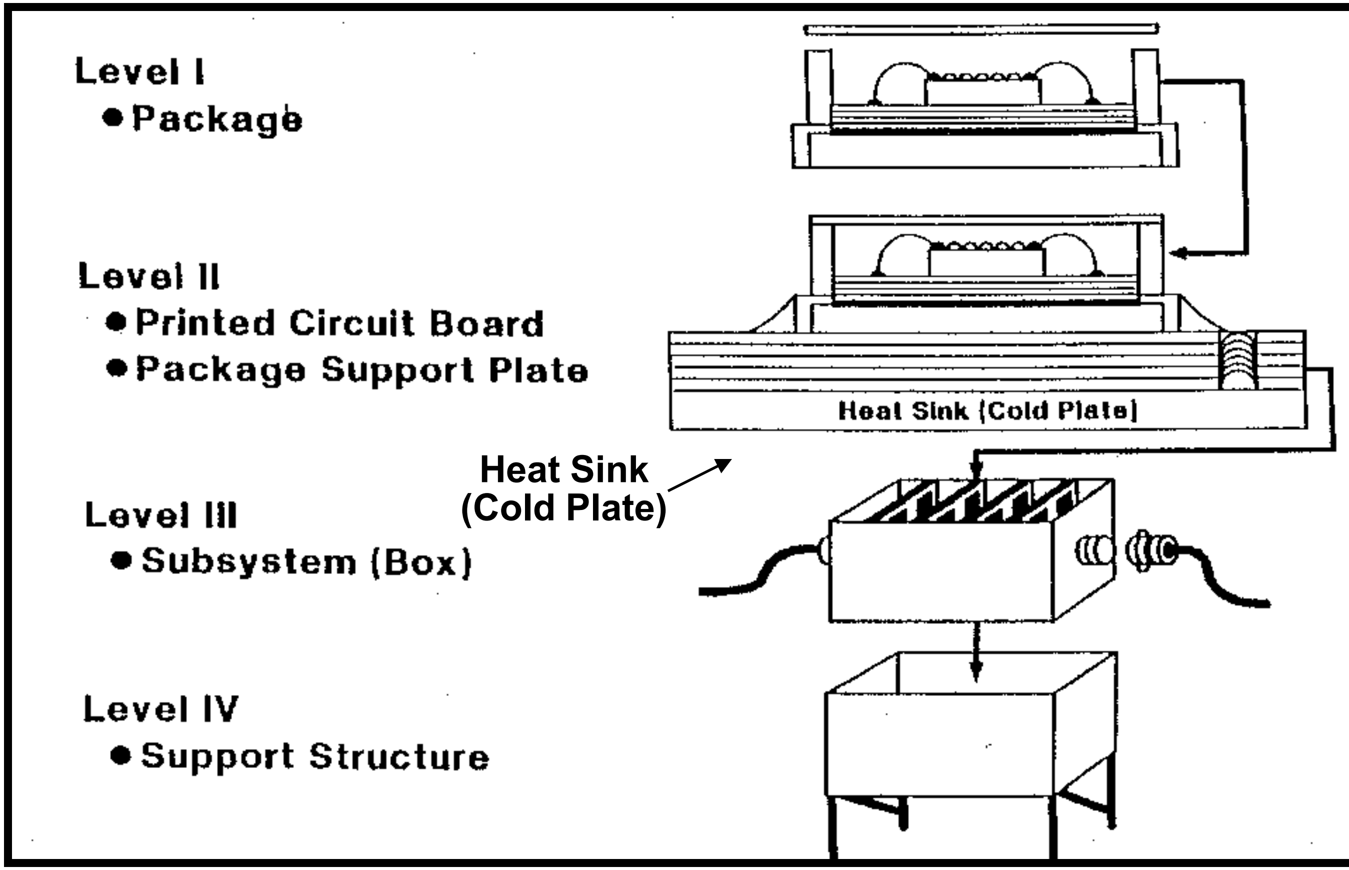
Ultrasonic Images

Source: Eupec/Infineon

INTRODUCTION (cont)

- Numerous traditional and new thermal materials
  - Many engineers only familiar with copper and aluminum
- Time constraint limits coverage of traditional and advanced materials
  - Selected materials discussed
- Seminar focus
  - Heat spreader materials used in modules, heat sinks, base plates, enclosures, etc.
  - Low-CTE printed circuit boards (PCBs)

PACKAGING LEVELS
Advanced Materials Used In All



Source: US Air Force (modified)

TRADITIONAL THERMAL MANAGEMENT MATERIALS

SEMICONDUCTOR AND CERAMIC SUBSTRATE COEFFICIENTS OF THERMAL EXPANSION (CTEs)

MATERIAL	CTE (ppm/K)
Silicon	2.5-4.1
GaAs	5.8-6.9
GaP	5.9
InP	4.5-4.8
SiC	4.2-4.9
Alumina (96%)	6.0-7.1
AlN	3.5-5.7
LTCC	4.5-7.0

CTE RANGE ~ 2 – 7 ppm/K

TRADITIONAL THERMAL AND PACKAGING MATERIALS

MATERIAL	Typical k (W/mK)	CTE (ppm/K)	Specific Gravity
Copper	400	17	8.9
Aluminum	218	23	2.7
Kovar	17	5.9	8.3
Titanium	6.7	8.6	4.4
Tungsten	164	4.2	19.3
Molybdenum	142	5.2	10.2
W/Cu (85/15)	167	6.5	17
Mo/Cu (85/15)	184	7.0	10
Cu-Invar-Cu*	164	8.4	8.4
Cu-Mo-Cu*	182	6.0	9.9
E-glass/polymer**	0.3–1.0	12-24	1.6-1.9

* Inplane (through-thickness much lower)
** Inplane

WHAT'S WRONG WITH TRADITIONAL MATERIALS?

- **E-glass/polymer PCBs**
  - **High CTE: 12–24 ppm/K**
  - **Low thermal conductivity: 0.3-1.0 W/mK**
- **Aluminum**
  - **High CTE: ~23 ppm/K**
    - **Result: thermal stresses and warping**
  - **Requires underfills and/or <u>compliant</u> thermal interface materials (TIMs): grease, polymeric, soft solders**
  - **Thermal conductivity: ~200 W/mK**
    - **Higher values desired in many applications**

WHAT'S WRONG WITH TRADITIONAL MATERIALS? (continued)

- Copper
  - High CTE: ~17 ppm/K
    - Requires underfills and/or compliant TIMs
  - Density ~ 3X aluminum (8.9 g/cc vs. 2.7)
  - Thermal conductivity: ~ 400 W/mK
    - Higher values desirable
- Greases
  - Messy to apply
  - Dry-out and pump-out
  - Silicone migration

WHAT'S WRONG WITH TRADITIONAL MATERIALS? (continued)

- Other compliant polymeric TIMs
  - Often greatest contributor to total system thermal resistance
- Compliant (soft) solders - mostly indium based
  - Poor fatigue life (low yield stress)
  - Creep, intermetallics formation, corrosion, electromigration
  - Expensive

WHAT'S WRONG WITH TRADITIONAL MATERIALS? (continued)

- **Traditional low-CTE materials all have significant deficiencies:**
  - **Kovar, Alloy 42, titanium, etc.**
    - **Very low thermal conductivities ($\leq$17 ppm/K)**
    - **High densities (except titanium)**
    - **Hard to machine**
  - **Tungsten/copper, molybdenum/copper, copper-Invar-copper, etc.**
    - **Most thermal conductivities $\leq$ aluminum**
    - **High densities**
    - **Hard to machine**
    - **Expensive**

THERMAL RESISTANCE OF COMMERCIAL TIMs

Material	Thermal Resistance $K\text{-}cm^2/W = K/(W/cm^2)$
Solder	0.05
Thermal grease	0.2-1
Elastomeric pads	1-3
Thermal tapes	1-4
Phase change materials	0.3-0.7
Gels	0.4-0.7
Conductive adhesives	0.15-1

Solders Have Lowest Thermal Resistance

Source: D. Blazej, Electronics Cooling, Nov. 2003

DIRECT ATTACH WITH HARD SOLDERS DESIRABLE: USUALLY REQUIRES CTE MATCH

TRADITIONAL LOW-CTE PCBs

- **E-glass/polymer PCBs (e.g. FR-4) have high CTEs**
  - **12-24 ppm/K**
- **Results:**
  - **High thermal stresses and warping**
  - **Failure of solder joints, ceramics, etc.**
  - **Underfills frequently required**
- **Copper-Invar-copper (C-I-C) constraining layers used for decades to reduce PCB assembly CTE**
  - **Adds thermal conductivity to PCB**
- **Advanced materials can replace C-I-C**

ADVANCED THERMAL MANAGEMENT MATERIALS

ADVANCED THERMAL MANAGEMENT MATERIALS

- **Revolutionary new materials steadily emerging**
- **Many with high thermal conductivities**
  - **Up to 1700 W/mK (> 4X copper)**
- **Low CTEs**
- **Low densities**
- **R&D to large volume production**
- **Time constraint greatly limits materials covered**

CLASSES OF ADVANCED THERMAL MATERIALS

- Monolithic carbonaceous materials
- Composite materials
  - Two or more materials bonded together
  - Some composites used for many years, e.g.
    - FR-4 glass/epoxy, copper/tungsten, etc.
- Types of composites
  - Polymer matrix composites (PMCs)
  - Metal matrix composites (MMCs)
  - Carbon matrix composites (CAMCs)
  - Ceramic matrix composites (CMCs)
- Monolithic carbons and MMCs key advanced thermal materials at this time

MONOLITHIC CARBONACEOUS MATERIALS

FLEXIBLE GRAPHITE

- **Exfoliated natural graphite and pyrolytic graphite**
- **Flexible, foil-like materials**
- **Highly anisotropic**

Inplane thermal conductivity, W/mK	**140 – 1500**
Vertical thermal conductivity, W/mK	**3 - 10**
Inplane CTE, ppm/K	**- 0.4**
Density, g/cc	**1.1-1.9**

Source: GrafTech

HIGHLY-ORIENTED PYROLYTIC GRAPHITE (HOPG)

- **Weak, brittle**
- **Highly anisotropic**
- **Typically encapsulated with metal or composite**

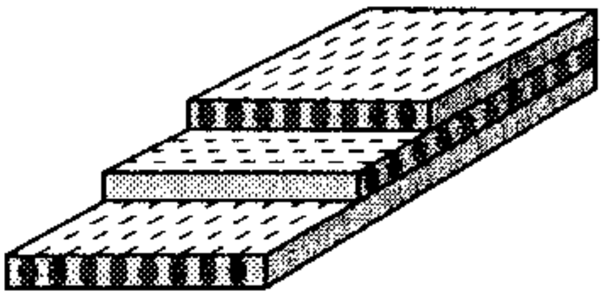
Inplane thermal cond, W/mK	**1300-1700**
Vertical thermal cond, W/mK	**~25**
Inplane CTE, ppm/K	**-1.0**
Density, g/cc	**2.26**

Source: Advanced Ceramics Corp

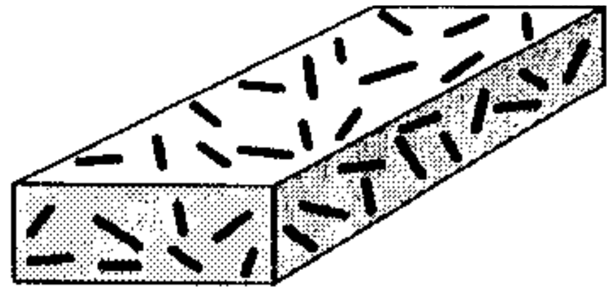
COMPOSITE MATERIALS

COMPOSITE REINFORCEMENTS

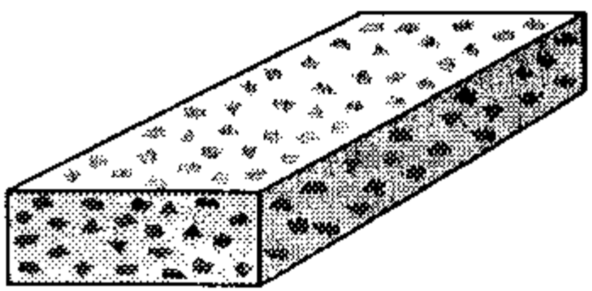
Continuous Fibers



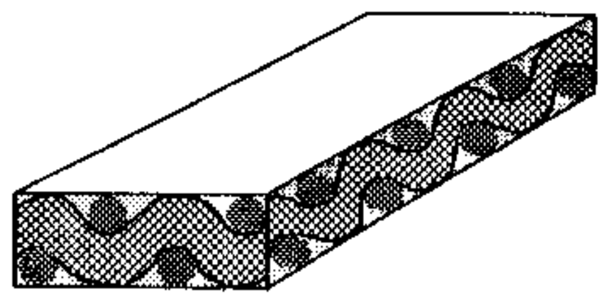
Discontinuous Fibers, Whiskers, CNTs



Particles, Platelets



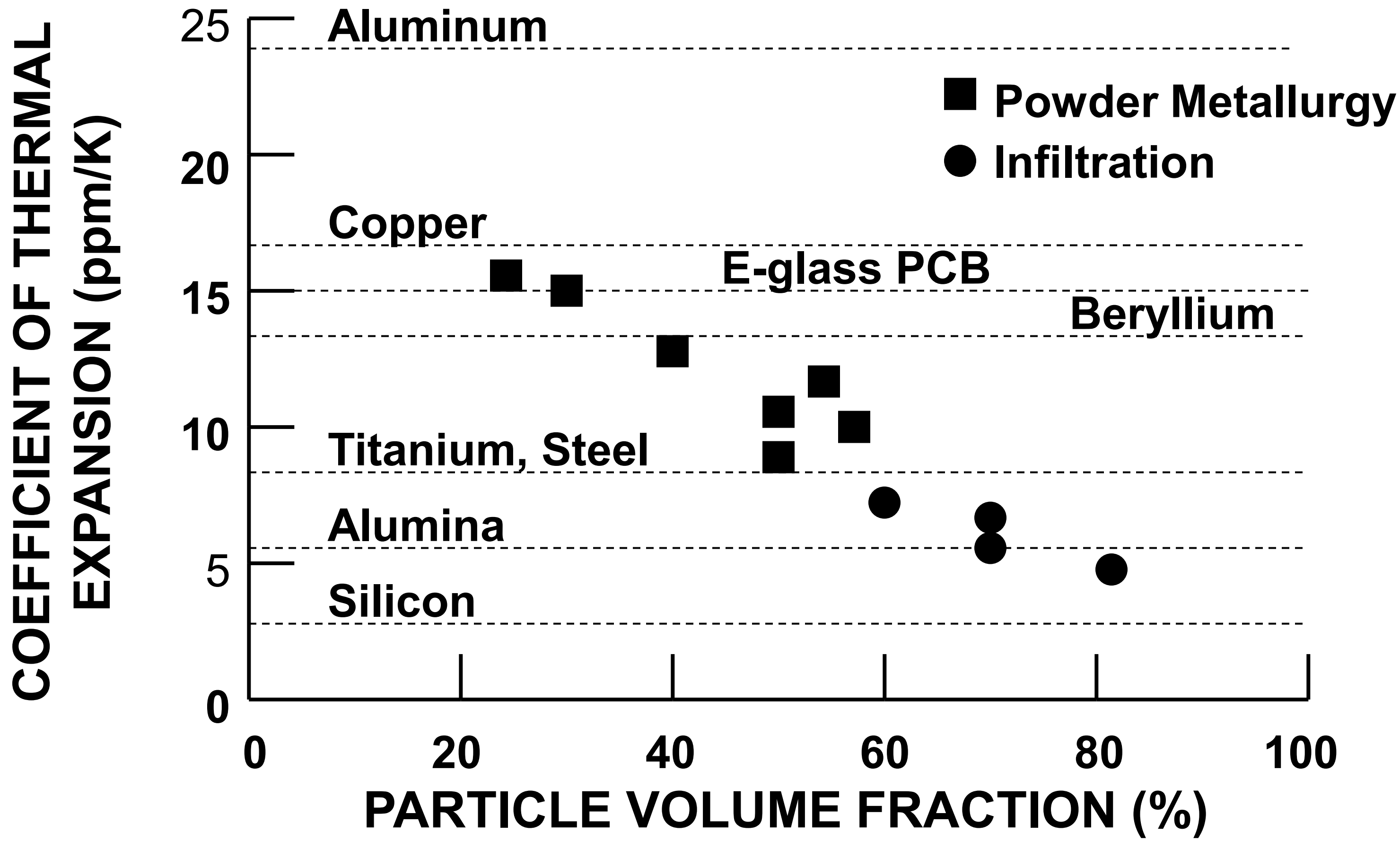
Fabrics, Braids, etc.



SILICON CARBIDE-PARTICLE/ALUMINUM (Al/SiC) MMCs

- First advanced thermal management material
  - Work started in 1980s by speaker's GE group
- Now well established in commercial and aerospace applications
- Now made by multiple processes and manufacturers
- Some processes net-shape (no machining)
- Can be cheaper than W/Cu and Mo/Cu
- One type reportedly cheaper than copper
- "Eliminates fatigue failure" in IGBT modules
  - Lifetime increased from 10 to 30 years

CTE OF SILICON CARBIDE PARTICLE-REINFORCED ALUMINUM (Al/SiC) vs PARTICLE VOLUME FRACTION



SiC-PARTICLE/ALUMINUM (Al/SiC) COMPOSITES - MMCs

- **Properties depend on composition and process**

Particle volume fraction, %	**20 - 70**
Thermal conductivity, W/mK	**132 - 255**
CTE, ppm/K	**4.8 - 16.2**
Density, g/cc	**2.6 - 3.10**
Modulus, GPa (aluminum = 70)	**100 - 250**

GRAPHITE PLATELET/ALUMINUM – MMCs

Anisotropic materials

	AlGrp 4-750	AlGrp 7-650
Thermal cond (x,y), W/mK	750	650
Thermal cond (z), W/mK	30	35
Inplane CTE, ppm/K	4	7
Density, g/cc	2.3	2.35

Source: Metal Matrix Cast Composites, Inc.

DIAMOND PARTICLE METAL MATRIX COMPOSITES USED IN INDUSTRIAL APPLICATIONS FOR DECADES

Diamond Particle/Copper Grinding Wheel Blank

Diamond Particle/Cobalt Rock Drill Bits

Sources: Kunime et al.; Element Six

DIAMOND PARTICLE-REINFORCED MMCs

- **Matrices: copper, aluminum, silver, cobalt**
- **Properties isotropic**

Thermal conductivity up to 983 W/mK

CTE, ppm/K 4–12

Density, g/cc 2.8 - 6.4

LOW-CTE PCBs

- Nonwoven aramid (e.g. Kevlar 49) fiber/polymer PCBs have low CTEs
  - 7-9 ppm/K inplane
- Copper-Invar-copper (C-I-C) constraining layers used for decades to reduce E-glass/polymer PCB CTE
- Many advanced thermal management materials are potential replacements for C-I-C
  - Carbon fiber/polymer has been used

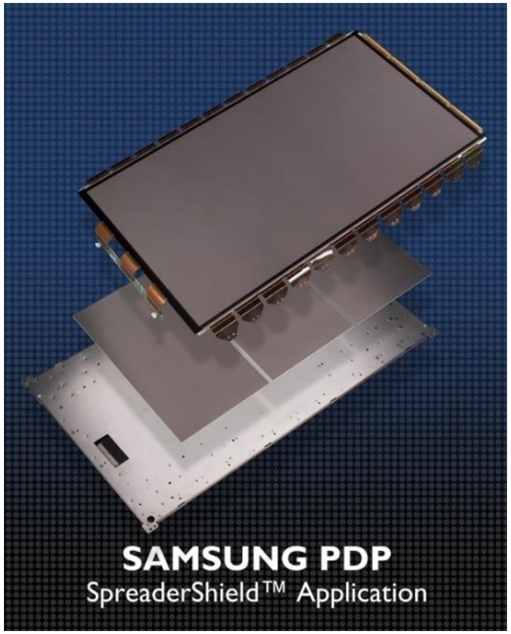
POTENTIAL PCB CONSTRAINING LAYER: ULTRAHIGH THERMAL CONDUCTIVITY CARBON/POLYMER

- **Laminate geometry: [0/90]**

Thermal conductivity, W/mK	**~ 300**
CTE, ppm/K	**- 1**
Density, g/cc (aluminum = 2.7)	**1.8**
Modulus, GPa (aluminum = 70)	**240**

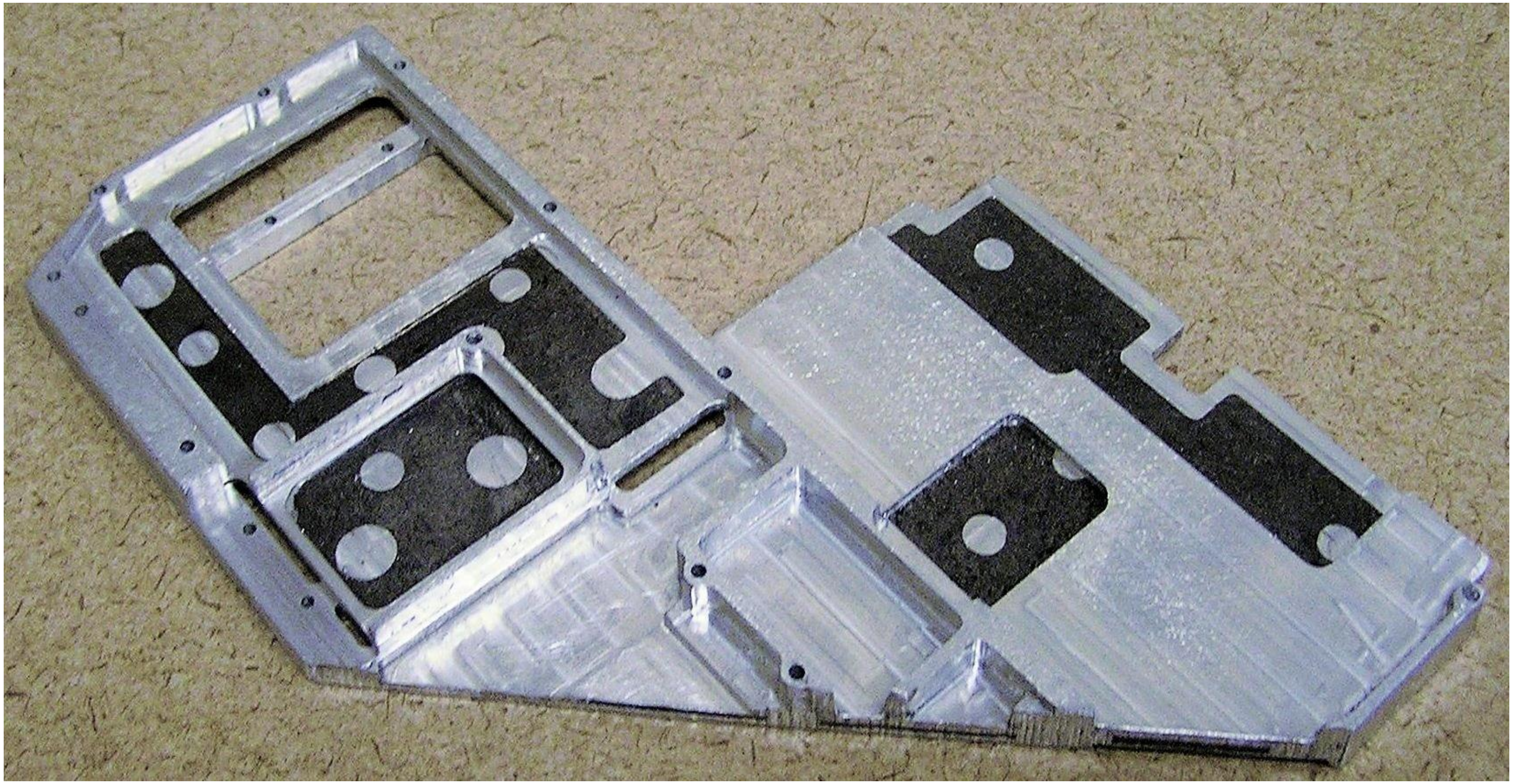
APPLICATIONS

FLEXIBLE GRAPHITE USED IN SMART PHONES, TABLETS, DISPLAYS, LED LIGHTING



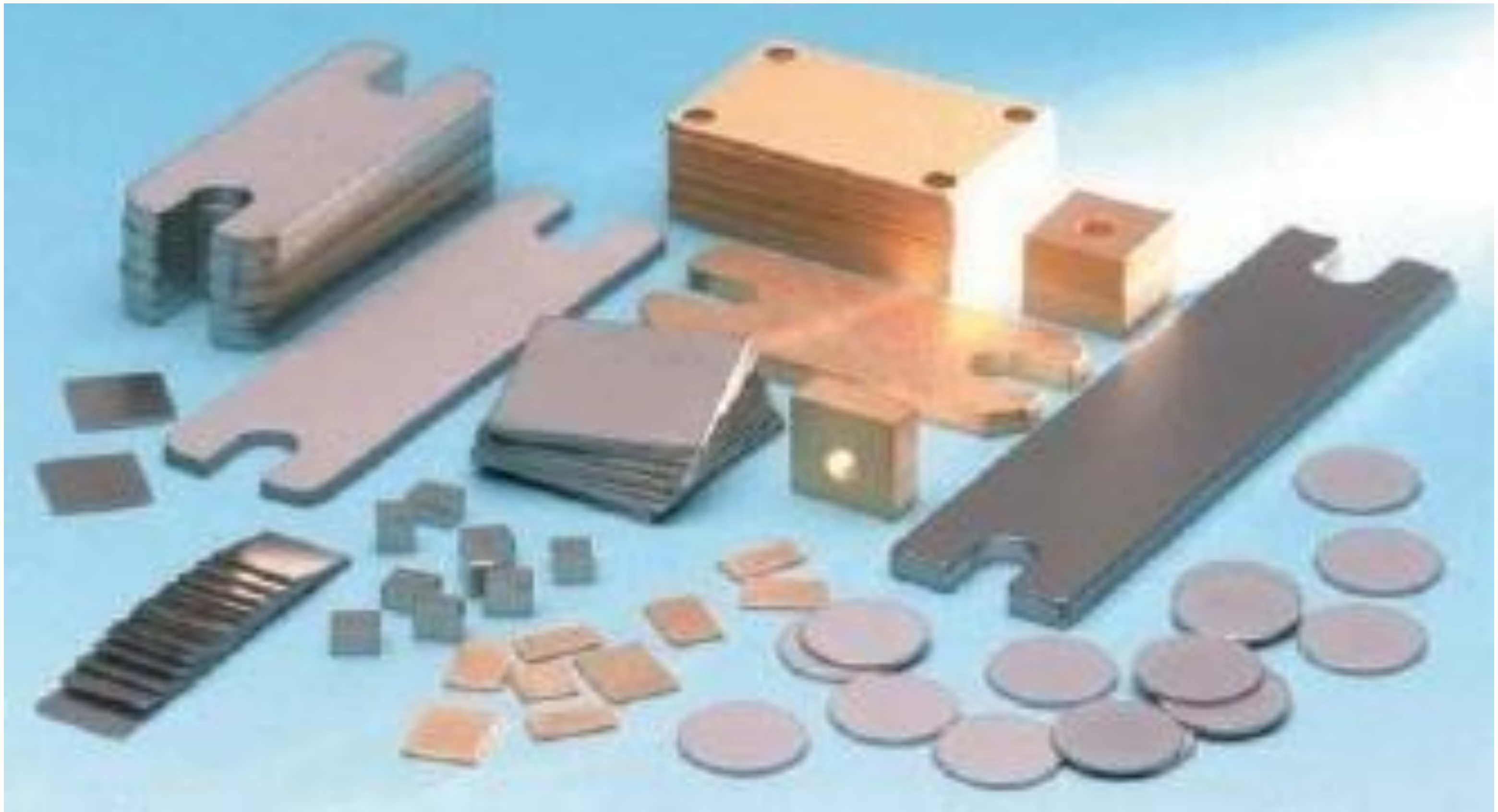
Source: GraphTech

HIGHLY-ORIENTED PYROLYTIC GRAPHITE (HOPG) INSERTS



Source: GE Advanced Materials

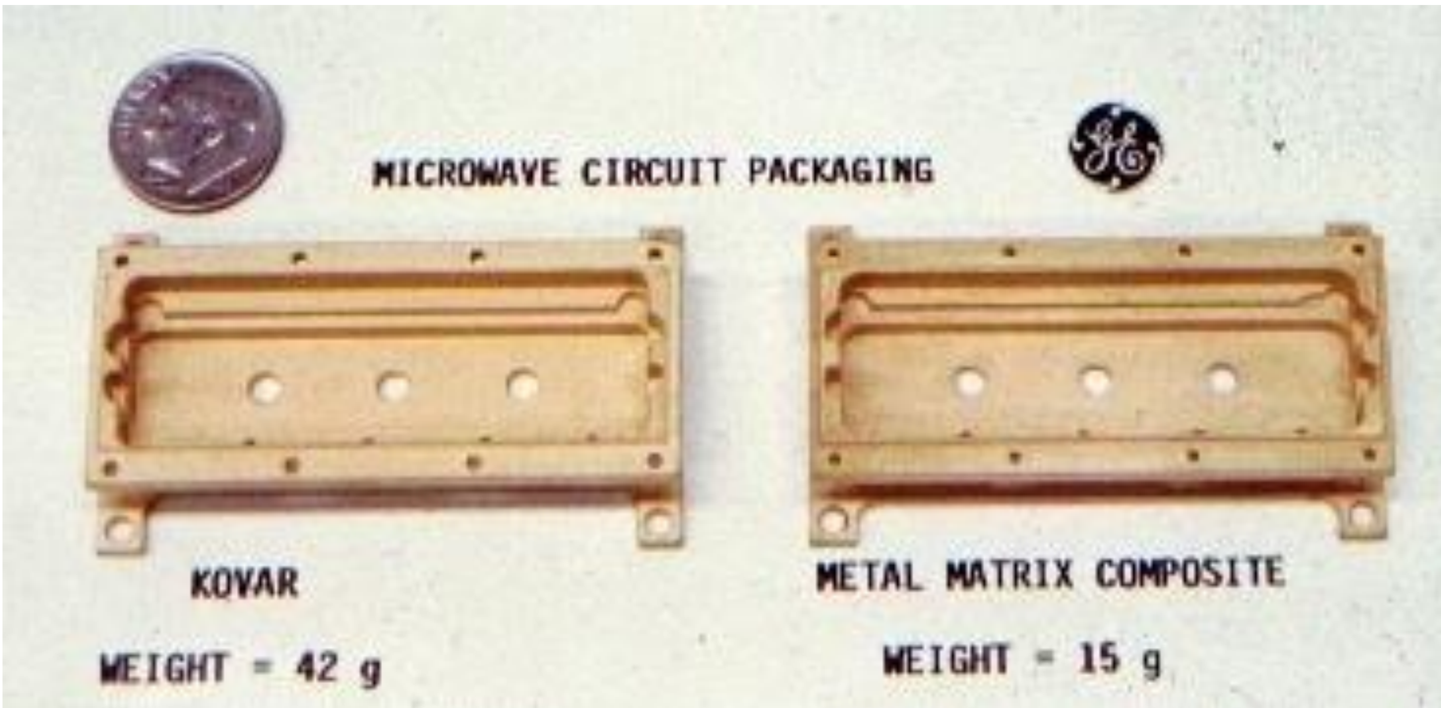
MOLYBDENUM/COPPER COMPOSITE COMPONENTS – TRADITIONAL MATERIAL



Source: Plansee

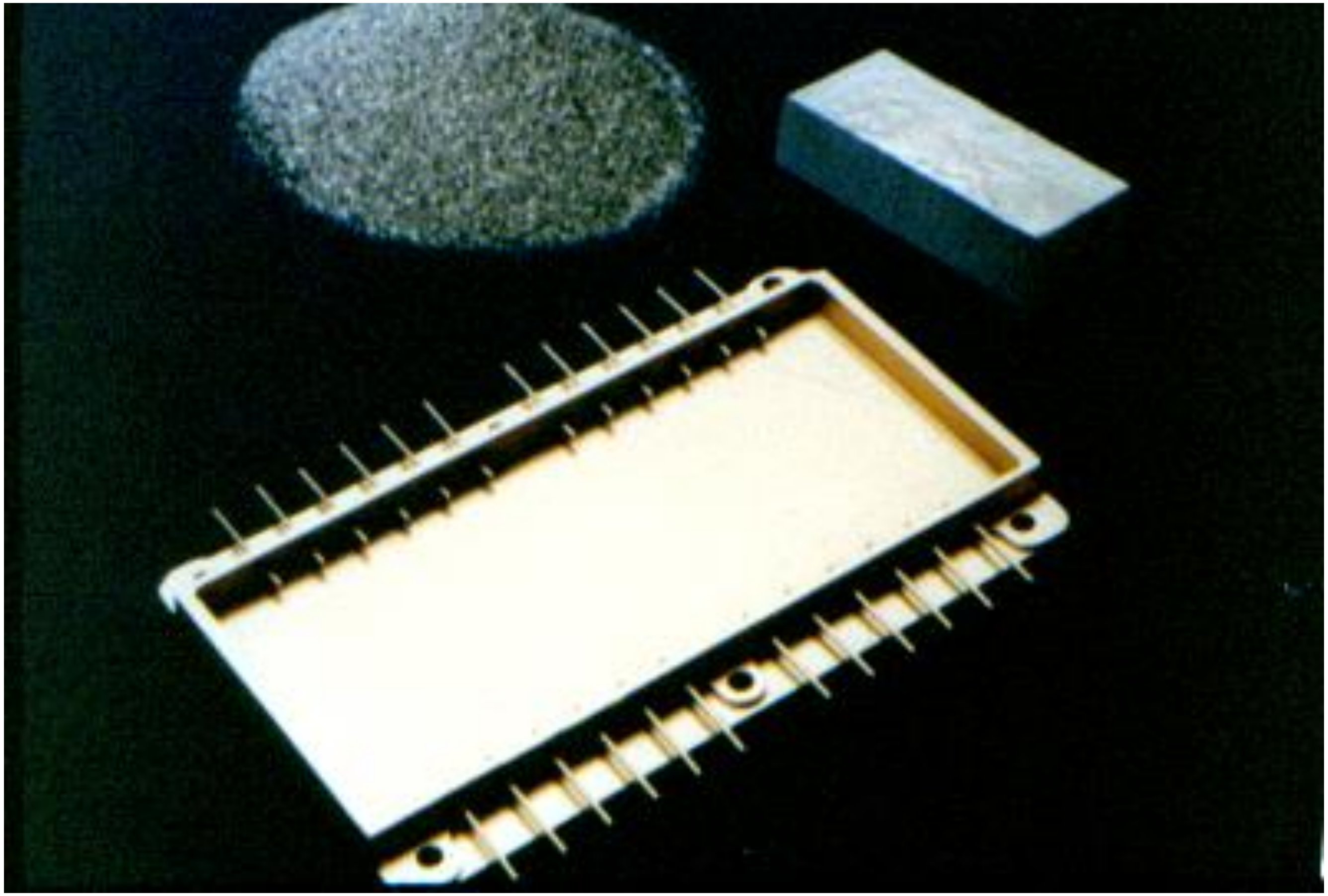
THE FIRST SILICON CARBIDE PARTICLE-REINFORCED ALUMINUM (Al/SiC) MODULE (ca 1985)

~1/3 THE WEIGHT AND 10X THE THERMAL CONDUCTIVITY OF KOVAR



Source: GE

HYBRID MODULE WITH Al/SiC BASE AND KOVAR LEAD FRAME



Source: LEC

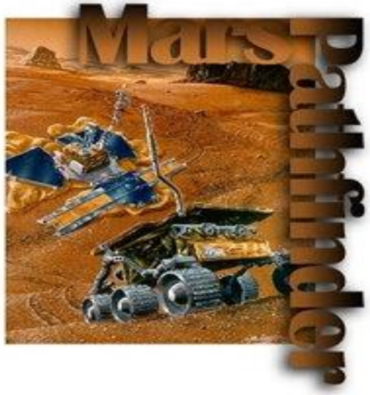
Al/SiC POWER MODULE APPLICATIONS

GM EV1

Toyota Prius

F-22 Raptor

Shinkansen 700



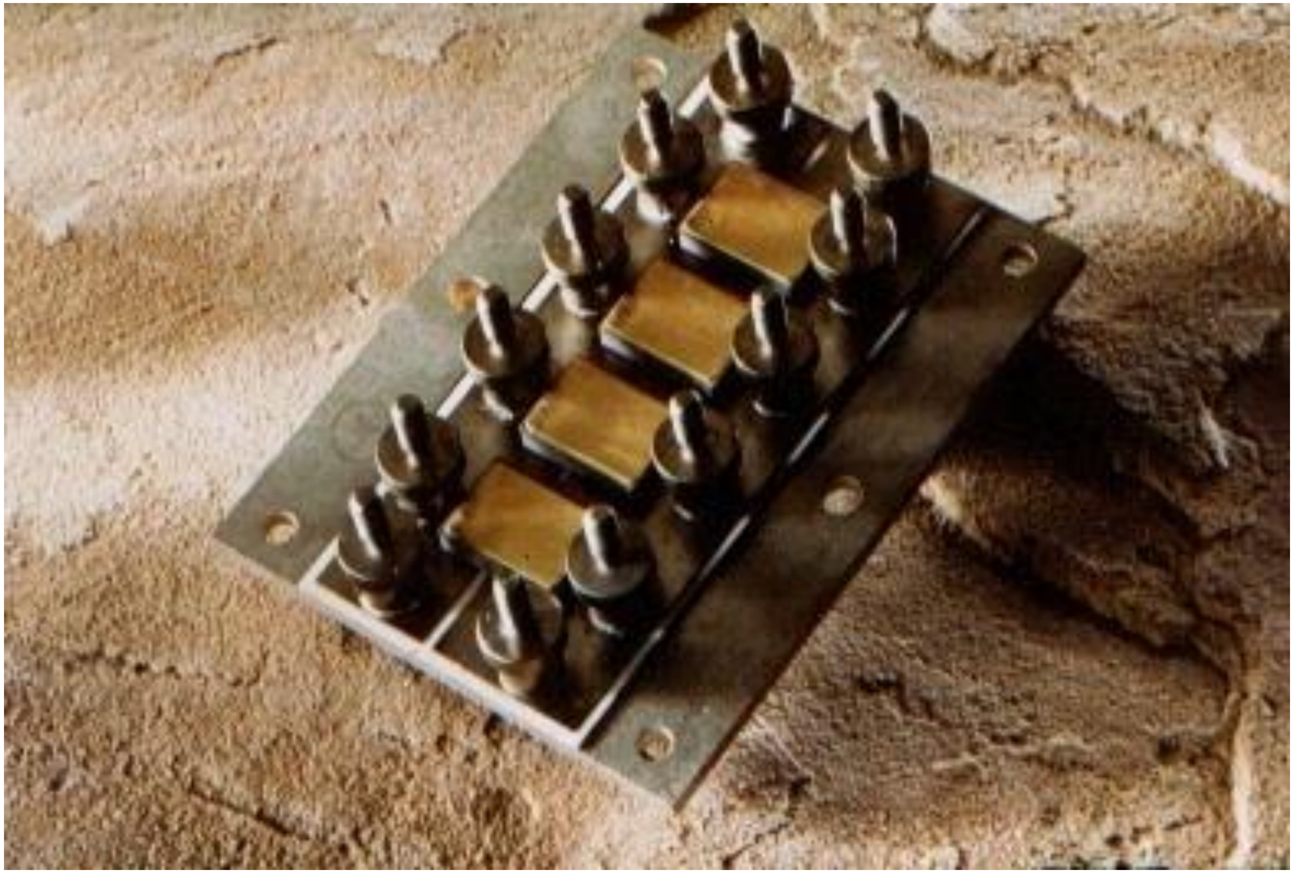
Mars Pathfinder

Source: Thermal Transfer Composites

Al/SiC MICROPROCESSOR LIDS

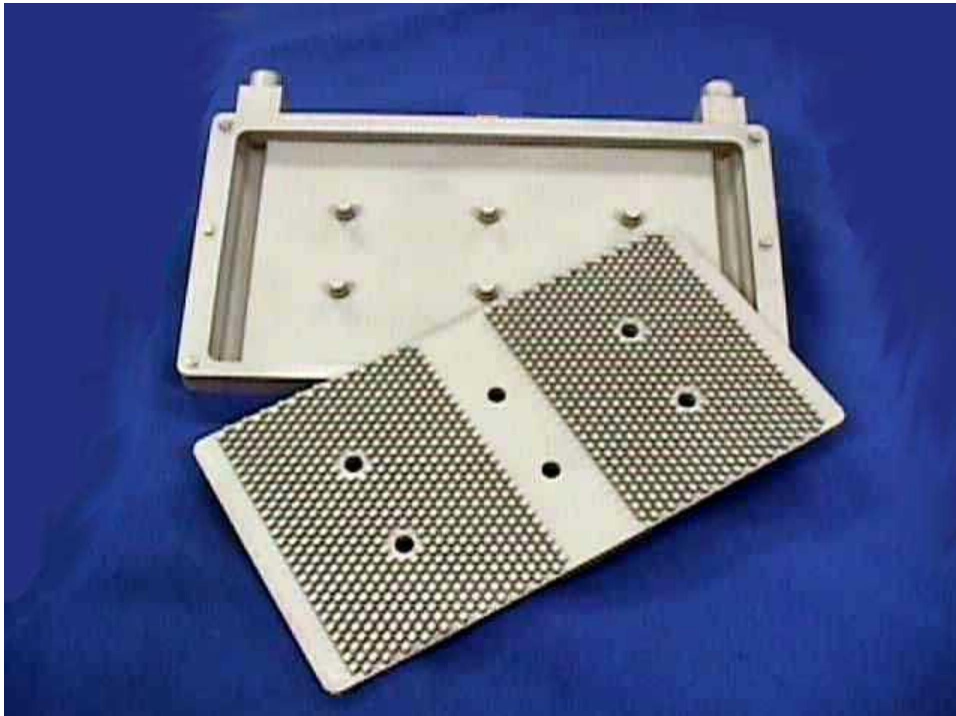
Source: CPS Technologies

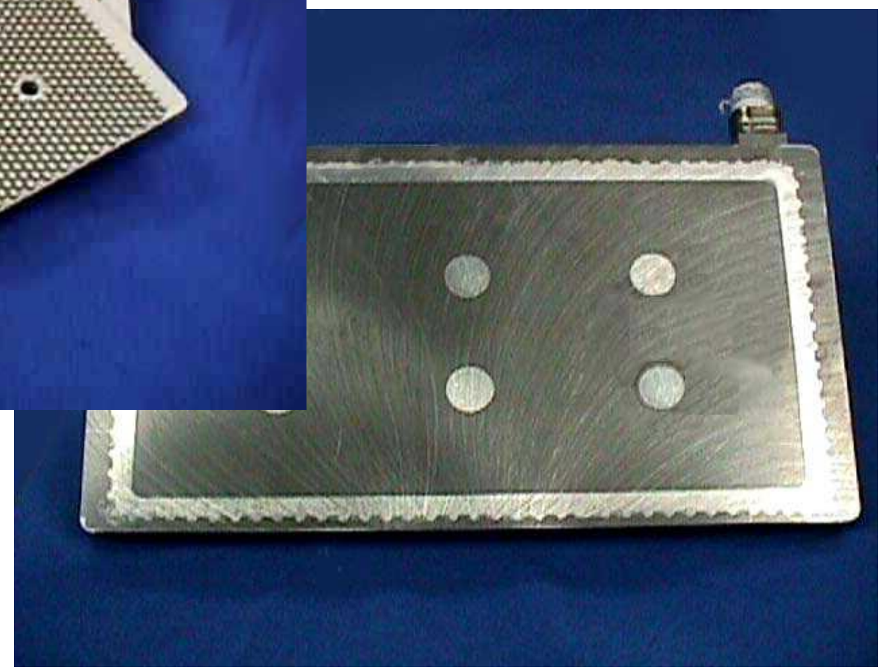
Al/SiC POWER MODULE BASEPLATE IS 85% LIGHTER THAN ORIGINAL COPPER/TUNGSTEN



Source: SSDI

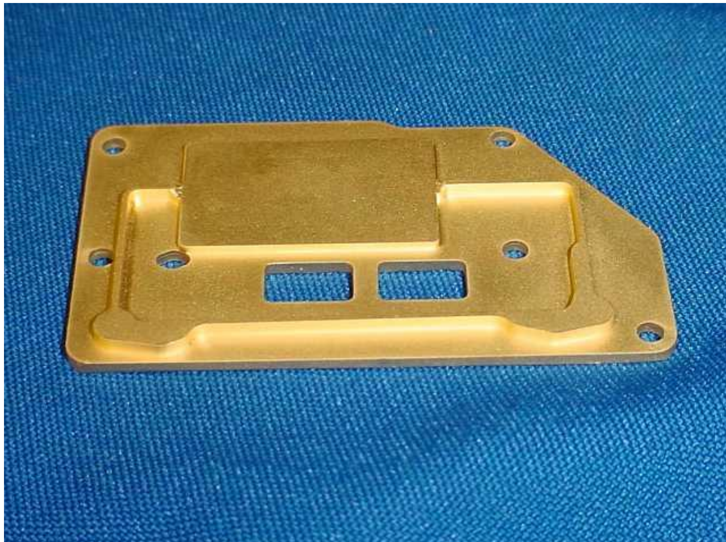
LIQUID-COOLED Al/SiC HEAT SINK

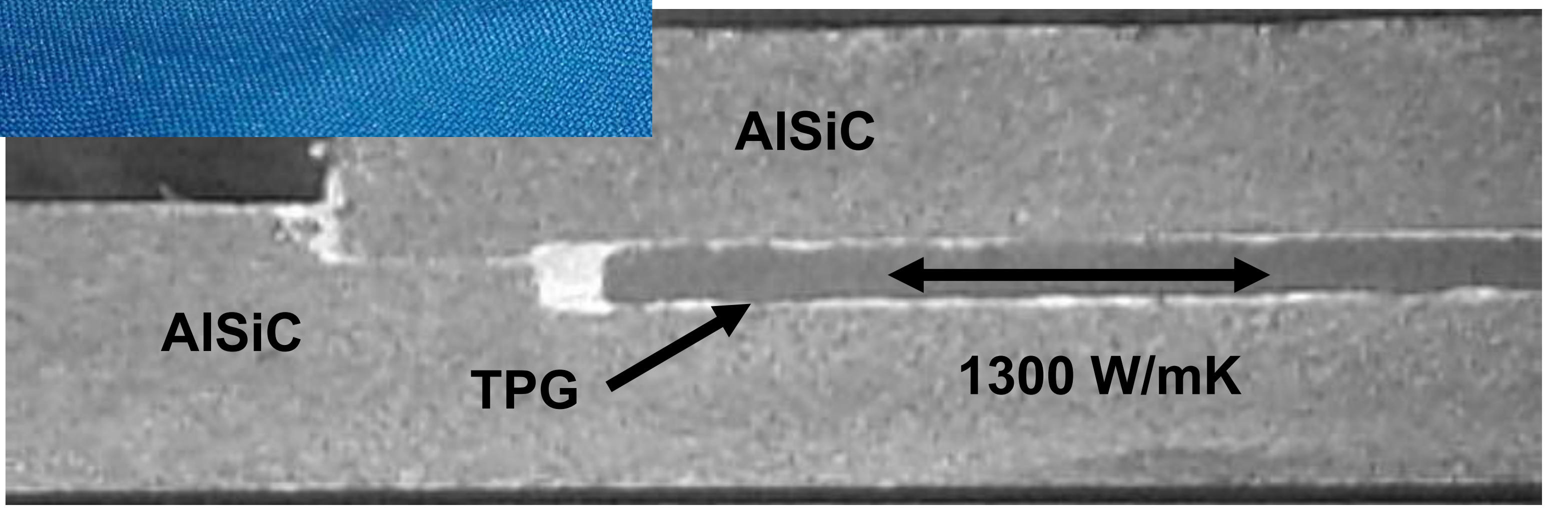




Source: CPS Technologies

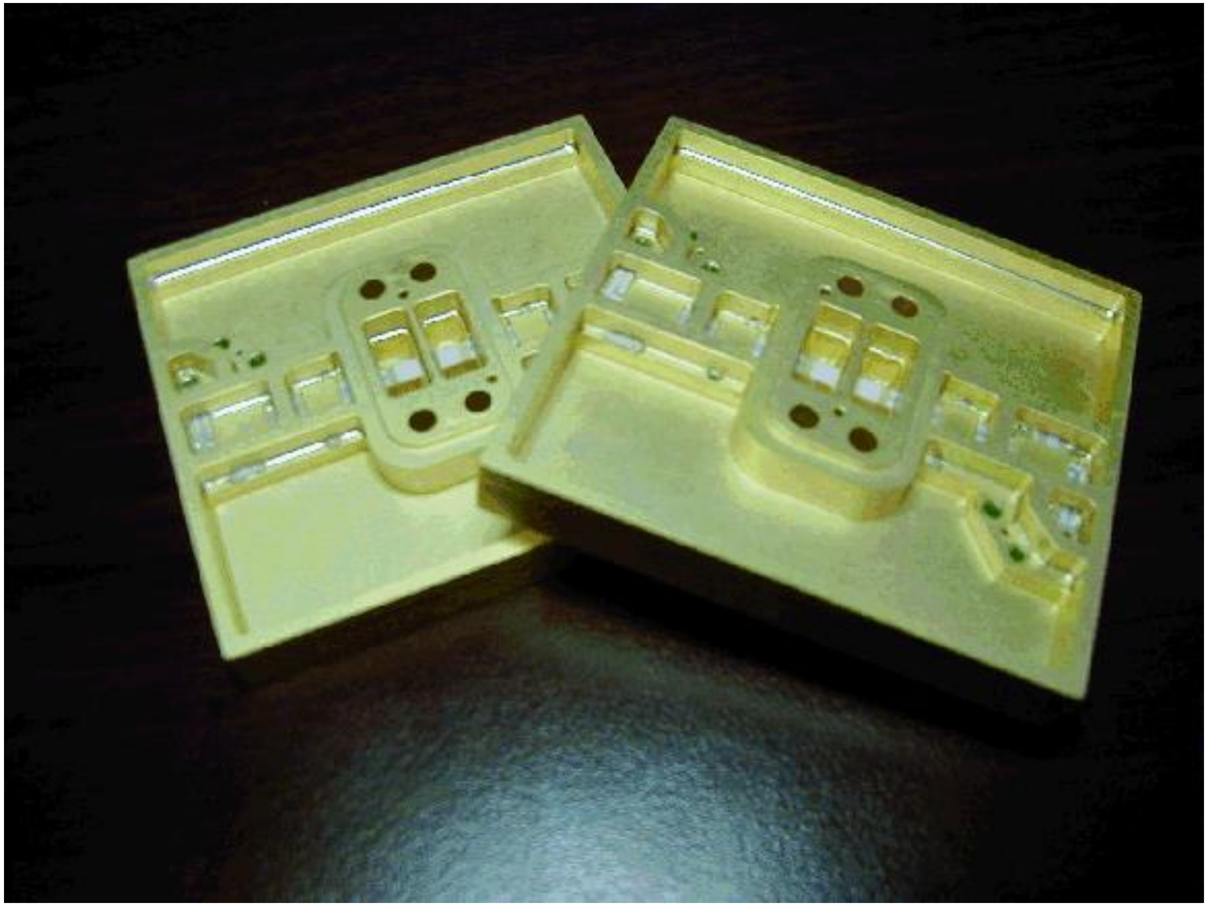
Al/SiC-HOPG HYBRID THERMOELECTRIC COOLER SUBSTRATE





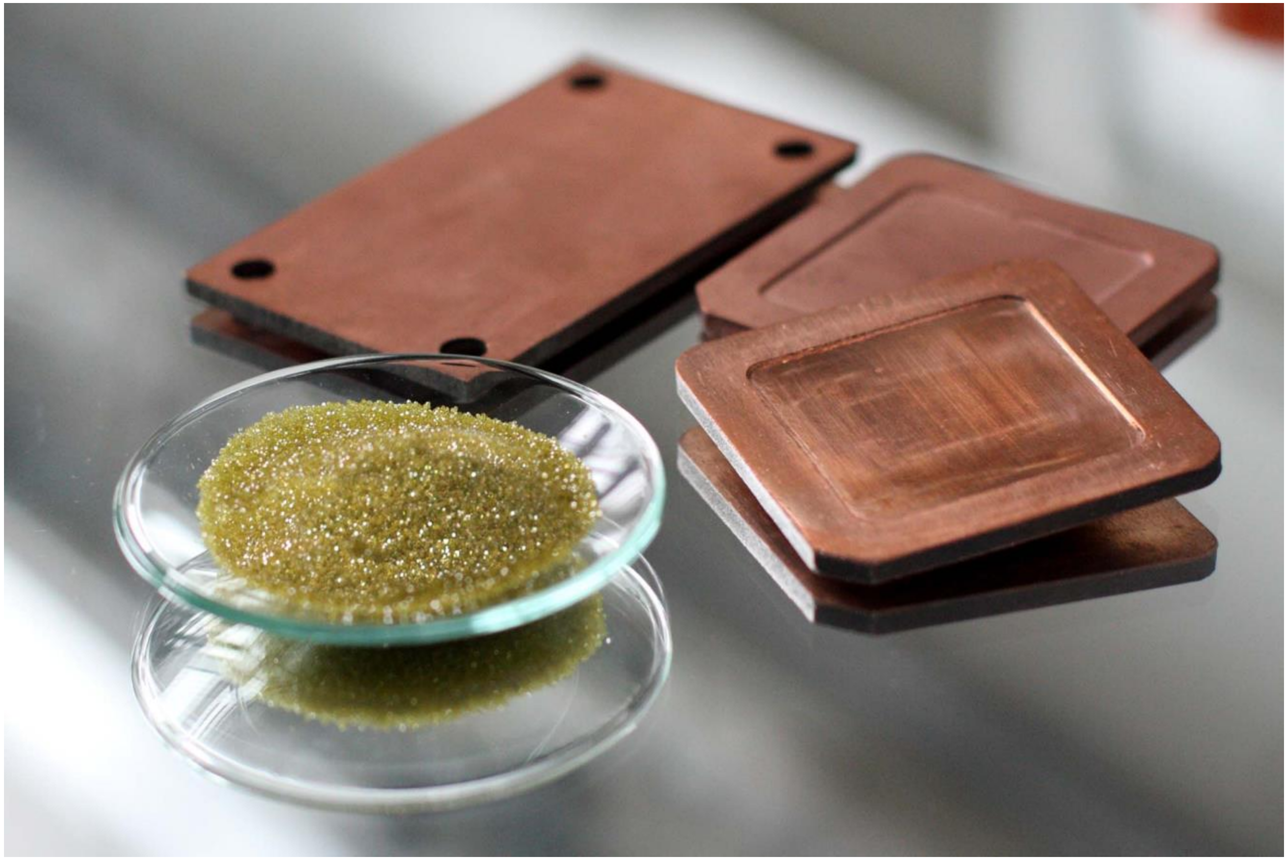
Source: CPS Technologies

CARBON FIBER-REINFORCED ALUMINUM MICROWAVE MODULES



Source: Metal Matrix Cast Composites

DIAMOND PARTICLE/COPPER LIDS



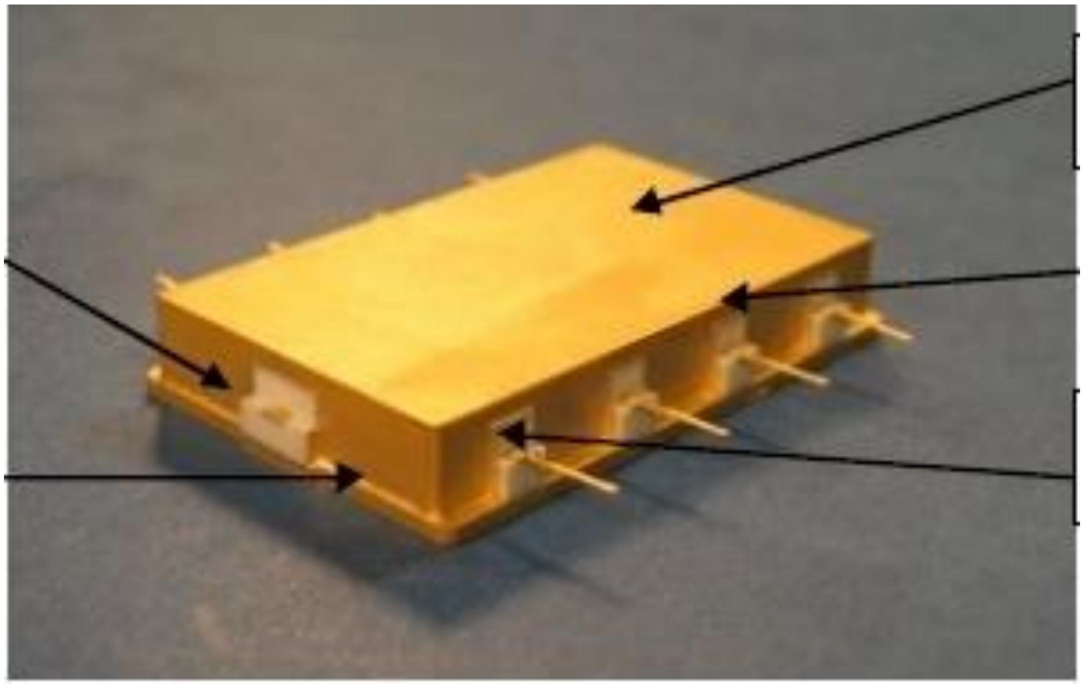
Source: Hermetic Solutions Group/RHP

TITANIUM GaN MODULE WITH DIAMOND PARTICLE/COPPER INSERTS

Source: Hermetic Solutions Group/RHP

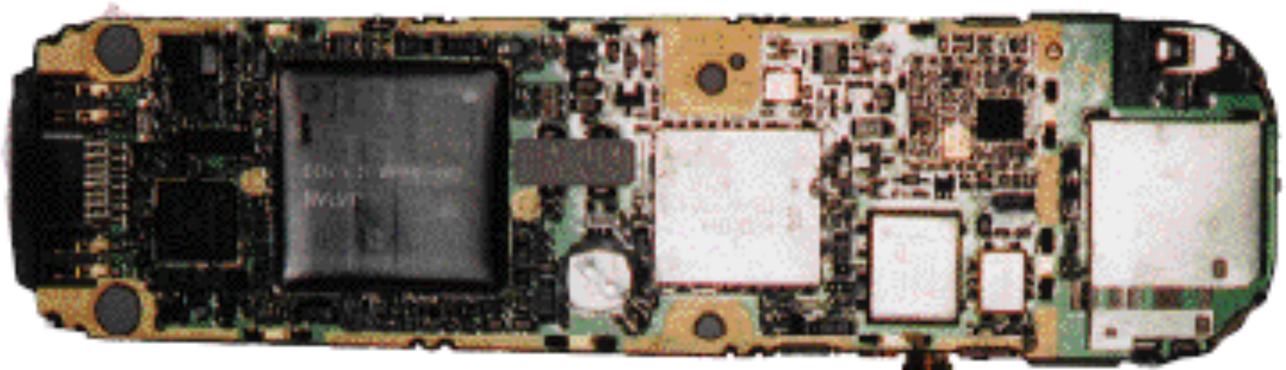
HIGH-POWER GaN SPACECRAFT PACKAGE HAS LOW-CTE DIAMOND PARTICLE/SILVER BASEPLATE

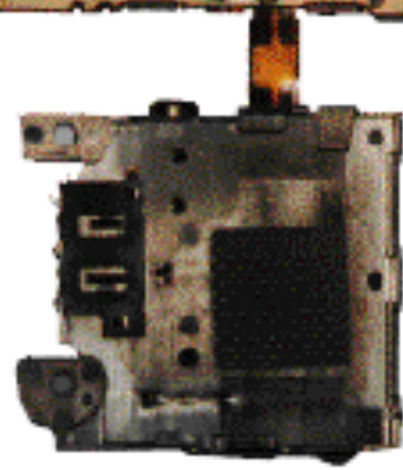
Thermal Conductivity ~ 600 W/mK



Source: Thales Alenia Space, Plansee
AGAPAC Project: Advanced GaN Package for Space

LOW-CTE ARAMID-FIBER MULTILAYER PCB





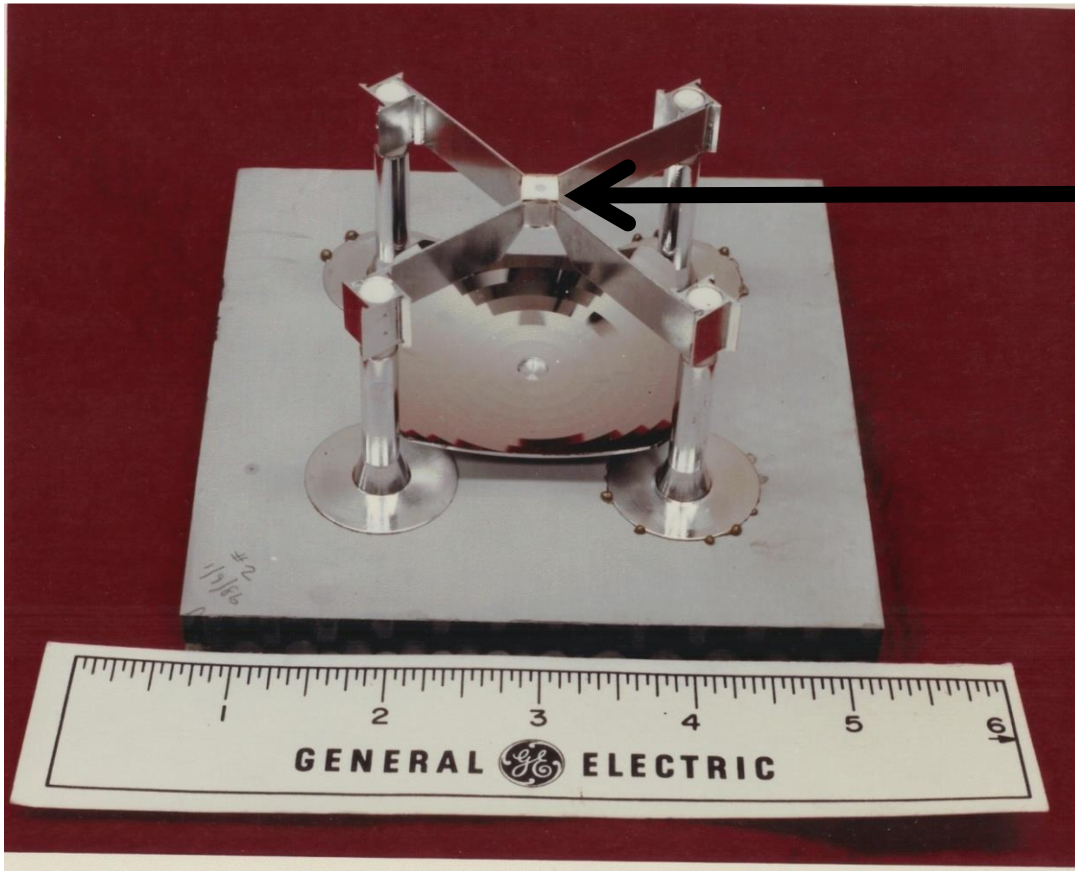
- Phone Circuit
  - Capacity 80 cc
  - Weight 83 g
  - PWB Technology ALIVH
  - Material ARAMID
  - Layers 6
  - Line width 60 μm
  - Line space 90 μm
  - Laser Hole diameter 150 μm

Source: Du Pont

E-GLASS/EPOXY PCB WITH CARBON FIBER/POLYMER CONSTRAINING LAYER

Source: Maxwell

CARBON FIBER/AL CONCENTRATOR PHOTOVOLTAIC ARRAY SPIDERS ELIMINATE SOLDER FAILURE

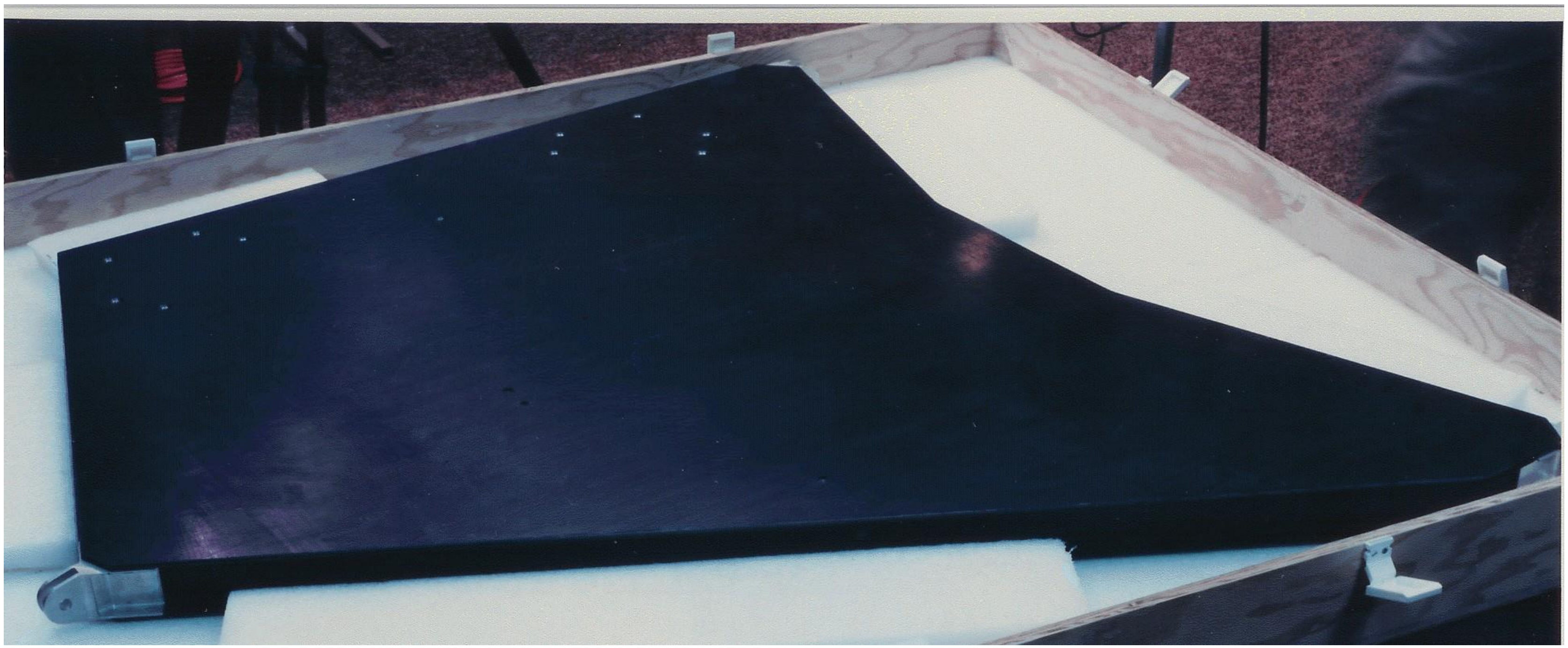


BeO Block Supporting GaAs Photovoltaic

Source: GE

LIGHTWEIGHT THERMALLY CONDUCTIVE CARBON/EPOXY COMPOSITE OPTICAL BENCH

Near-Zero CTE



Source: GE

FUTURE DIRECTIONS

FUTURE DIRECTIONS

- Thermal management will continue to be a problem in electronic and photonic packaging
- 3D architecture adds complexity
- Continuing development of new materials
  - Monolithic carbonaceous
  - Composites
- Reinforcements of interest
  - Carbon nanotubes and nanofibers (6,000 W/mK)
  - Graphite platelets (1500 W/mK)
  - Carbon fibers (900 W/mK)
  - Diamond particles (2,000 W/mK)

FUTURE DIRECTIONS (cont)

- Thermally conductive, electrically insulating composite materials
- Numerous other materials possible

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

- **Thermal management critical problem in electronic and photonic systems**
  - **Heat dissipation**
  - **Thermal stresses from CTE mismatch**
- **Size, Weight And Power important**
- **Traditional materials have significant deficiencies**
- **Increasing number of advanced materials**
  - **Thermal conductivities up to 1700 W/m-K**
  - **Low, tailorable CTEs**
  - **Low densities**
  - **Some cheaper than traditional materials**
  - **Applications increasing steadily**

WE ARE IN THE EARLY STAGES OF A THERMAL MATERIALS REVOLUTION

