

NEW, ULTRAHIGH-THERMAL-CONDUCTIVITY PACKAGING MATERIALS

**Carl Zweben, Ph. D.
Advanced Thermal Management Materials
Consultant
62 Arlington Road
Devon, PA 19333-1538
Phone: 610-688-1772
Fax: 610-688-8340
E-mail: c.h.zweben@usa.net**

**IEEE Components, Packaging & Manufacturing
Technology Society - Santa Clara Valley Chapter
March 16, 2005
Sunnyvale, California**

ABOUT THE SPEAKER

Dr. Carl Zweben, now an independent consultant, has directed development and application of advanced packaging materials for over 30 years, and was the first to use Al/SiC. For many years, he was Advanced Technology Manager and Division Fellow at GE Astro Space. Other affiliations have included DuPont, Jet Propulsion Laboratory and the Georgia Institute of Technology NSF Packaging Research Center. Dr. Zweben was the first, and one of only two winners of both the GE One-in-a-Thousand and Engineer-of-the-Year awards. He is a Fellow of ASME, ASM and SAMPE, an Associate Fellow of AIAA, and has been a Distinguished Lecturer for AIAA and ASME. He has published and lectured widely on advanced thermal management and packaging materials.

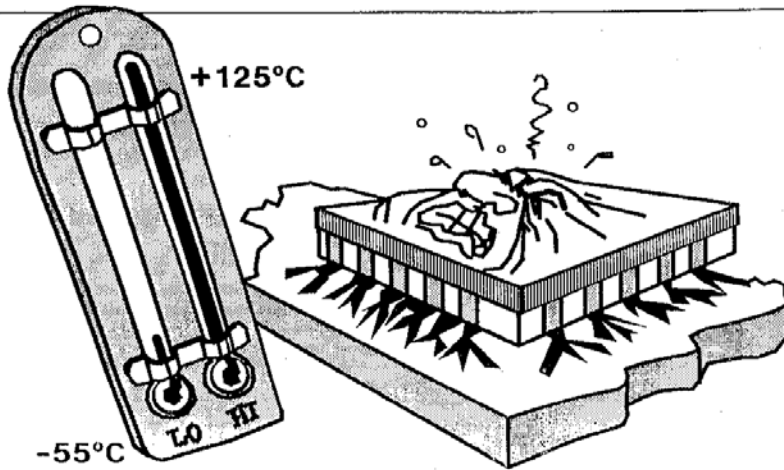
INTRODUCTION

- **Key packaging technical issues:**
 - Thermal management
 - Thermal stresses
- **Thermal stresses affect**
 - Performance
 - Reliability
- **Similar problems in packaging of**
 - Computer microprocessor units
 - Intel has “hit a thermal wall” (NYT 5/17/04)
 - Power electronics
 - High-power laser diodes
 - High-power laser and RF weapons

INTRODUCTION (cont.)

- **Traditional materials have serious deficiencies**
- **New materials continually emerging to meet user demand**
 - Monolithic carbonaceous
 - Metal matrix composites
 - Polymer matrix composites
 - Ceramic matrix composites
 - Carbon matrix composites
- **Some now low cost**
- **Others have low cost potential in high volume**

CTE Mismatch Causes Thermal Stresses



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 5

PACKAGING LEVELS

Level I

- Package

Level II

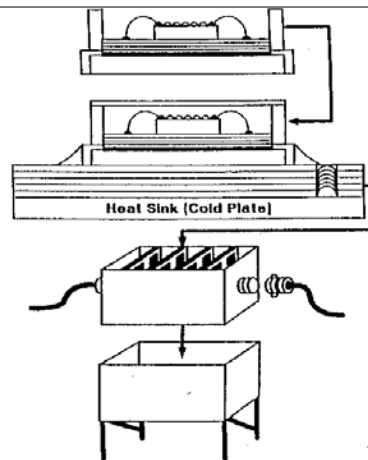
- Printed Circuit Board
- Package Support Plate

Level III

- Subsystem (Box)

Level IV

- Support Structure



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 6

WHAT'S WRONG WITH TRADITIONAL MATERIALS?

- **Copper**
 - Thermal conductivity $k = 400 \text{ W/m-K}$
 - Higher values desirable
 - High CTE
 - Thermal stresses, warping
- **Low-CTE materials have major deficiencies**
 - Thermal conductivities no better than aluminum
 - High densities

NEW MATERIALS

- **Overcome limitations of traditional materials**
- **Fifteen materials with thermal conductivities between 400 W/m-K (copper) and 1600 W/m-K**
- **Low CTEs**
 - Tailorable for some materials
- **Lower densities than copper/tungsten and copper/molybdenum**
- **Some now low cost**
- **Some have low cost potential in high volume**
- **Potential to replace heat pipes, liquid cooling, fans**

SEMICONDUCTOR AND CERAMIC PROPERTIES

<u>MATERIAL</u>	<u>k (W/m-K)</u>	<u>CTE (ppm/K)</u>	<u>Specific Gravity</u>	<u>k/S.G. (W/m-K)</u>
Silicon	150	2.5-4.1	2.3	65
GaAs	54	5.8	5.3	8
InP	68	4.5	5.9	12
Silica	1.3	0.6-0.8	2.2	0.6
Alumina	20	6.5	3.9	5
LTCC	3	5.8	3.1	1
AlN	250	4.5	3.2	78

TRADITIONAL PACKAGING MATERIAL PROPERTIES

<u>MATERIAL</u>	<u>k (W/m-K)</u>	<u>CTE (ppm/K)</u>	<u>Specific Gravity</u>	<u>k/S.G. (W/m-K)</u>
Copper	400	17	8.9	45
Aluminum	218	23	2.7	81
“Kovar”	17	5.9	8.3	2
Cu/W	209	6.5	17	12
Cu/Mo	184	6.6	10	18
Cu-Invar-Cu*	164	8.4	8.4	20
Cu-Mo-Cu*	182	6.0	9.9	18

***Inplane isotropic**

ADVANCED PACKAGING MATERIALS

- **Many advanced materials**
 - Various stages of development
 - R&D to large scale production
- **Monolithic materials**
 - Primarily carbonaceous
- **Composites**
 - Polymer matrix composites
 - Metal matrix composites
 - Carbon/carbon composites
 - Ceramic matrix composites
- **Advanced alloys (metal/metal composites)**

ADVANTAGES OF ADVANCED MATERIALS

- **Thermal conductivities up to 4X copper**
- **Tailorable CTEs: from -2 to +60 ppm/K**
- **Tailorable electrical resistivities**
 - Minimize electromagnetic emissions
- **Very high stiffnesses and strengths**
- **Low-to-moderate densities**
- **Net shape processes (some)**
- **Cost**
 - Some now low cost
 - Some have low cost potential

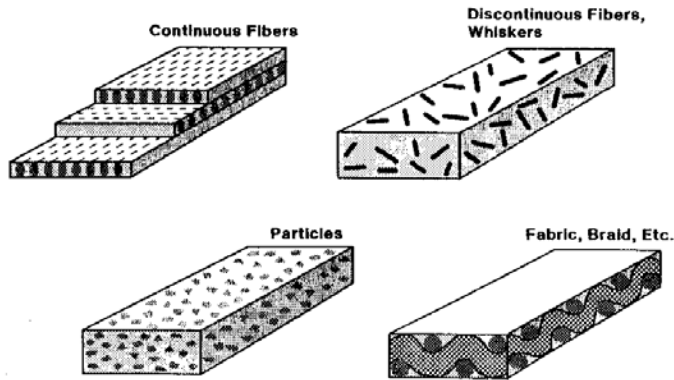
ADVANCED MATERIAL PAYOFFS

- **Higher power levels**
- **Improved performance, e.g.**
 - **Better temperature control**
 - **Reduced stresses**
 - **Improved optical alignment**
- **Simplified thermal design, e.g.**
 - **Reduce/eliminate heat pipes, fans, heaters, liquid cooling, refrigeration**
- **Increased reliability**
 - **Reduced thermal stresses and warpage**
 - **Lower junction temperatures**

ADVANCED MATERIAL PAYOFFS (continued)

- **Weight savings up to 90%**
- **Size reductions up to 65%**
- **Reduced fan noise**
- **Reduced electromagnetic emissions**
- **Increased manufacturing yield**
 - **E.g. from <5% to >99%**
- **Reduced cost potential**
 - **Component**
 - **System**

Reinforcements



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 15

ADVANCED MATERIALS EXAMPLE: Al/SiC

- History is illustrative of new materials
- First components made by author at GE
 - Starting early 1980s
 - Microwave and optoelectronic packages
 - First components machined from plates
- First papers published 1987
- Spurred industry development
 - Net shape processes developed
- Cost of early components very expensive
 - Hundreds to thousands of dollars

CPMT/SCV March 16 2005

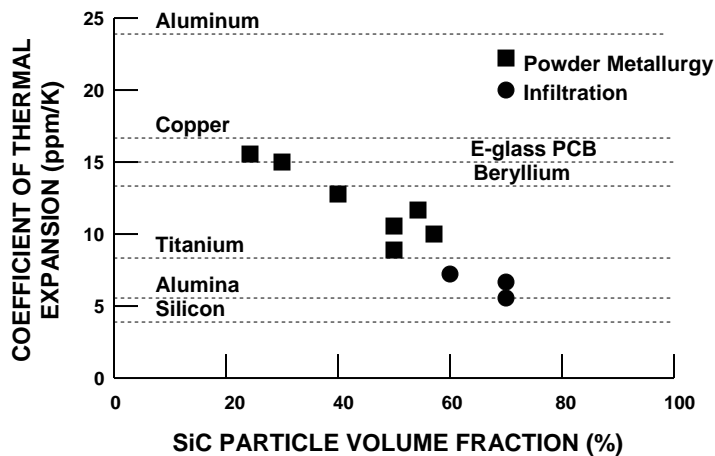
Carl Zweben, Ph. D.

Slide 16

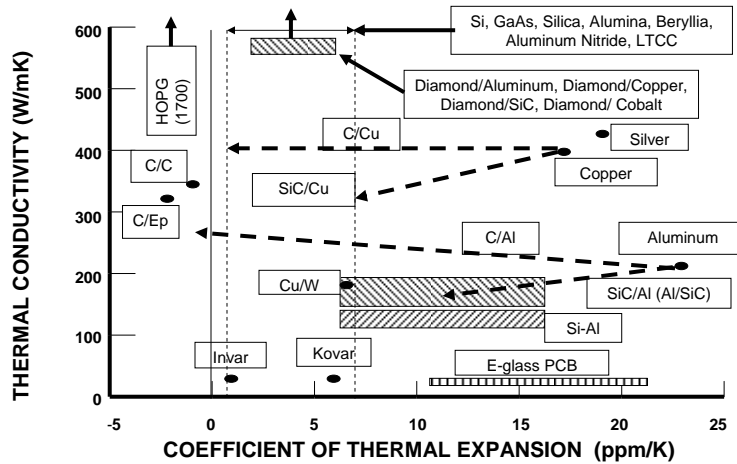
ADVANCED MATERIALS EXAMPLE: Al/SiC (continued)

- Costs dropped by orders of magnitude as technology matured and volume increased
- Microprocessor lids now \$2-5 in high volume
- Millions of parts produced annually
- Increasing number of commercial and aerospace applications
- Competition from other new materials

CTE OF Al/SiC vs. PARTICLE VOLUME FRACTION



THERMAL CONDUCTIVITY vs. CTE FOR PACKAGING MATERIALS



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 19

ULTRAHIGH-THERMAL-CONDUCTIVITY MATERIALS Part 1

<u>MATERIAL</u>	<u>k(x,y)</u> <u>(W/m-K)</u>	<u>CTE(x,y)</u> <u>(ppm/K)</u>	<u>Specific</u> <u>Gravity</u>	<u>k/S.G.</u> <u>(W/m-K)</u>
CVD Diamond	1100-1800	1-2	3.5	310-510
HOPG*	1500-1700	-1	2.3	650-740
Natural Graphite	500	-	-	-
Cont. CF/Cu*	400-420	0-16	5.3-8.2	49-79
Carbon/carbon*	400 (690)	-1.0	1.9	210 (363)
Gr Flake/Al*	400-600	4.5-5.0	2.3	174-260
"ThermalGraph"***	700-800	-0.5	1.8	390-440
*Inplane isotropic	**Axial direction			

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 20

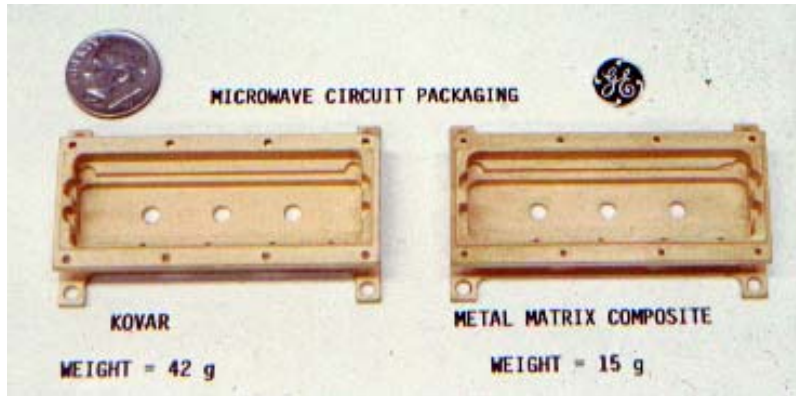
ULTRAHIGH-THERMAL-CONDUCTIVITY MATERIALS Part 2

<u>MATERIAL</u>	<u>k(x,y) (W/m-K)</u>	<u>CTE(x,y) (ppm/K)</u>	<u>Specific Gravity</u>	<u>k/S.G. (W/m-K)</u>
Diamond/Ag	400->600	5.8	5.8	69->103
Diamond/Al	550-600	7.0-7.5	3.1	177-194
Diamond+SiC/Al	575	5	-	-
Diamond/Cu	600-1200	5.8	5.9	330-670
Diamond/Mg	575	5.5	-	-
Diamond/Co	>600	3.0	4.1	>14
Diamond/SiC	600	1.8	3.3	18
Diamond/Si	525	4.5	-	-

CURRENT APPLICATIONS

- Servers
- Notebook computers
- Plasma displays
- Printed circuit boards
- PCB cold plates
- Laser diode packages

THE FIRST AL/SiC MICROWAVE PACKAGE

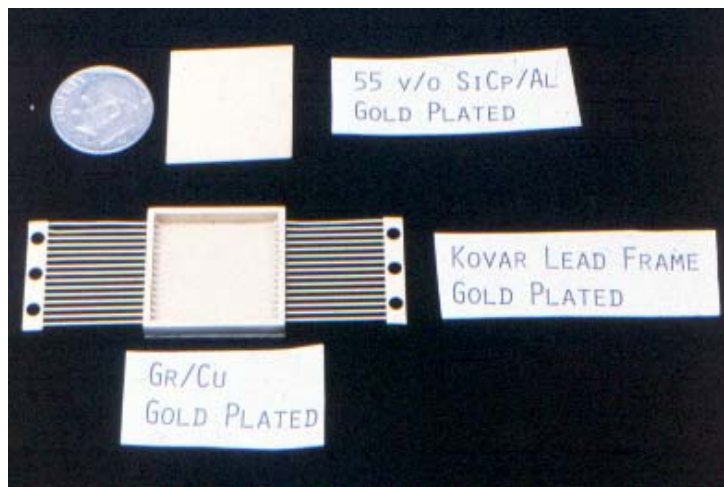


CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 23

MICROWAVE PACKAGE WITH C/Cu BASE AND Al/SiC LID



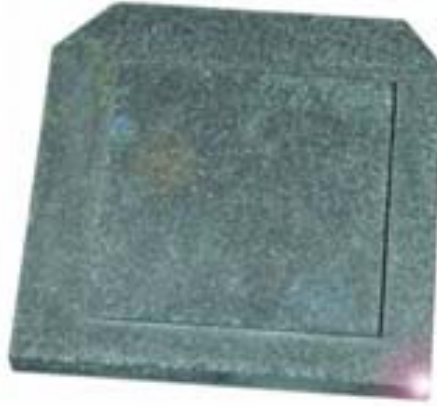
Source: GE

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 24

DIAMOND PARTICLE/SILICON CARBIDE HEAT SPREADER



Source: Skeleton Technologies

Diamond/SiC Liquid-Cooled Heat Sink

New Ceramic Heat Sink: Heat Transfer Experiments

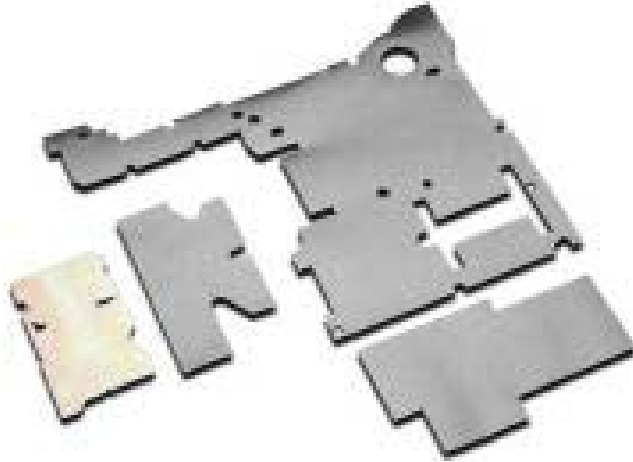


- Diamond-SiC module with straight flow channels
- Measured thermal resistance as functions of flow rate and heat flux
- Thermal resistance = $0.14 \text{ K}\cdot\text{cm}^2/\text{W}$
 - Quite low considering height & width of channels not optimized
- Translates to a cooling capacity of $\sim 280 \text{ W/cm}^2$



Source: ATEC

NATURAL-GRAPHITE/EPOXY HEAT SPREADERS



Source: GraphTech

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 27

NATURAL-GRAPHITE/EPOXY HEAT SINKS



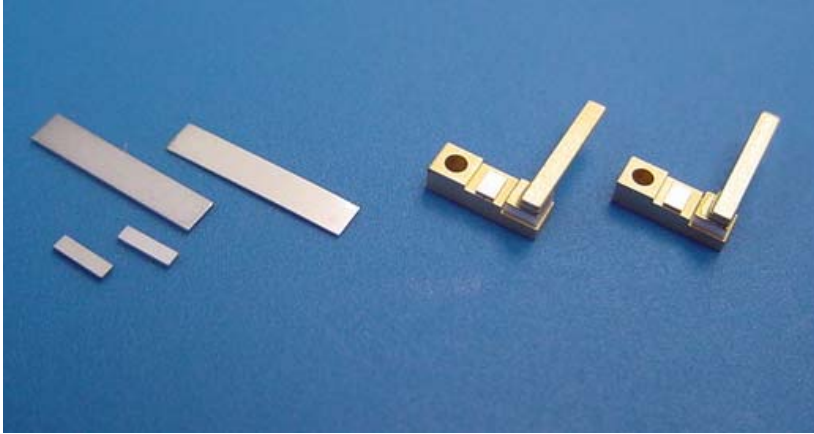
Source: GraphTech

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 28

DIAMOND-PARTICLE-REINFORCED COPPER



Source: Sumitomo

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 29

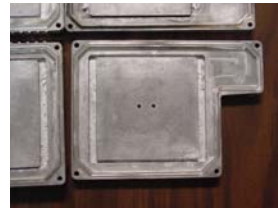
DIAMOND-PARTICLE-REINFORCED ALUMINUM



3 x 1 x 0.05" Ni/Au metallized
Diamond/Al substrate



6 x 6 x 0.5" Diamond/Al enclosure
With through holes



4 x4" Diamond/Al inserts
in heat sink case

Source: MER

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 30

Al/SiC-ENCAPSULATED HOPG TEC SUBSTRATE



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Source: CPS

Slide 31

CONDUCTION COOLED LANDSCAPE HEATSINK: "THERMALGRAPH" AND HOPG INSERTS



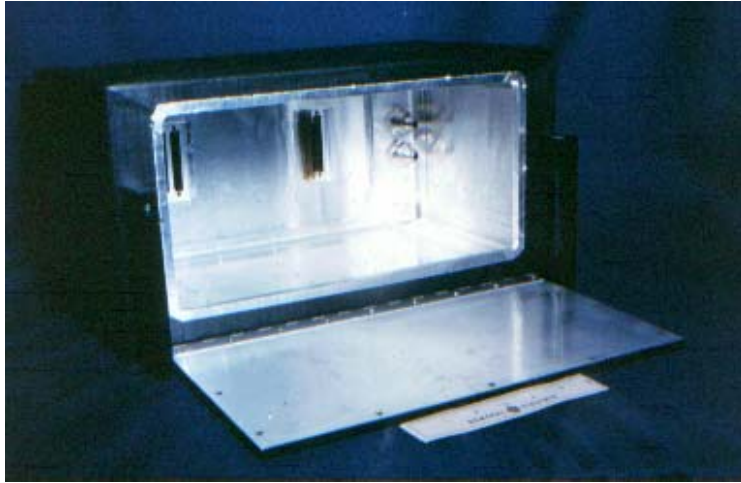
CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Source: Harris GCSD

Slide 32

CARBON/EPOXY ELECTRONICS ENCLOSURE



CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 33

REINFORCEMENT PRICES IN 1-CM CUBE VOLUME FRACTION = 50%

<u>Reinforcement</u>	<u>Price in 1-cm Cube (\$)</u>
Boron Nitride	0.21
Carbon Fibers	0.04 - 0.24
Diamond Particles	0.53 - 1.59

**POTENTIAL PREMIUM FOR IMPROVED
PERFORMANCE NOT UNREASONABLE**

CPMT/SCV March 16 2005

Carl Zweben, Ph. D.

Slide 34

FUTURE TRENDS

- **Continuing development of new materials and processes**
 - **Monolithic**
 - **Composites**
- **Lower prices as production volumes increase**
- **Significant increase in use as prices drop and awareness grows**

SUMMARY

- **Thermal management and CTE critical problems**
- **Current materials have significant deficiencies**
- **Increasing number of advanced materials**
 - **Revolutionary improvements over traditional materials**
 - **R&D to large scale production**
- **Significant payoffs**
 - **Thermal management**
 - **Performance**
- **Cost**
 - **Some low cost**
 - **Some have low cost potential**

**WE ARE IN THE EARLY STAGES OF A
THERMAL MANAGEMENT MATERIALS
REVOLUTION**