Developments in CTE-Matched Composite Thermal Materials

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Overview: A. Power Semiconductor Market Applications

This presentation is intended to provide an overview of a short list of specific types of thermal materials developments for semiconductor packaging.

Key Points for CTE-matched thermal materials:

1. Primary driver for usage for these materials is to match a specific coefficient of thermal expansion for another packaging material or a semiconductor die material.
2. Secondary requirement is for reasonable bulk thermal conductivity.
3. Primary goal is to minimize package internal stresses due to temperature.

Most significant usage is for power semiconductors of different types:

- IGBT power semiconductors for traction, electrical drives, and energy conversion
- Diode lasers
- RF devices for military/aerospace radar, communications, ECM, and similar applications
- Specialized optoelectronics, sensors, similar types of devices

Many other applications of highly-targeted nature: Examples are mirrors, backing plates for specific types of semiconductor fab end-effectors, medical imaging system drivers, others.

Power semiconductor market transition from silicon to SiC and GaN technologies is driving increases in device power dissipation, heat flux, and maximum operating temperatures.

Overview: B. Integrated Circuit Market Applications

Key Points for CTE-matched thermal materials for IC packages is the same as for power:

1. Primary driver for usage for these materials is to match a specific coefficient of thermal expansion for another packaging material or a semiconductor die material.
2. Secondary requirement is for reasonable bulk thermal conductivity.
3. Primary goal is to minimize package internal stresses due to temperature.

Most usage of CTE-matched thermal composites for IC applications has been driven by requirements for server processors and highly specialized ASICs, typically with relatively very large die:

- Silicon processor die on ceramic and organic substrates
- Single- and multi-die processor (such as System-in-Package) and ASIC modules

Applications are driven by very specific package requirements depending on a variety of factors and the CTE matching value is typically to the substrate material or in certain packages, to the die.

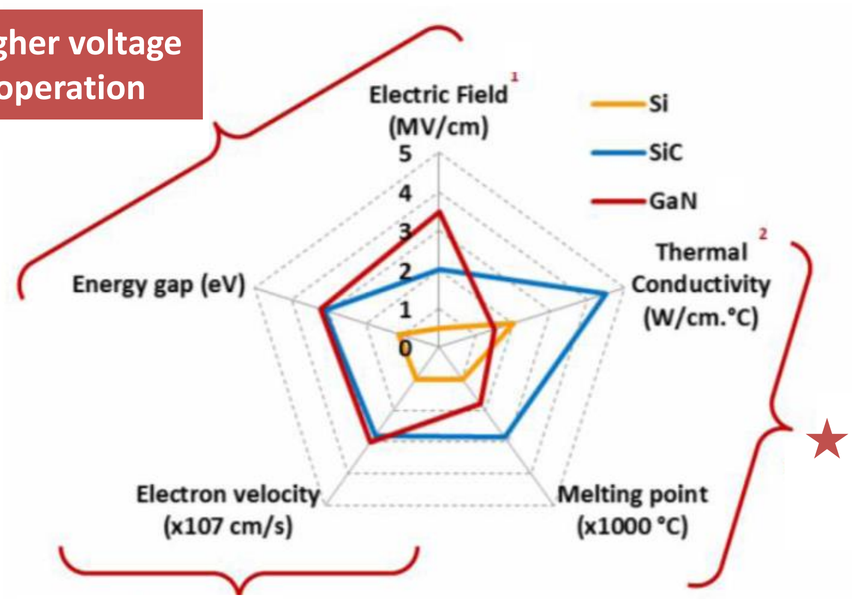
CTE-matched material developments are driven by power semiconductor industry requirements, so this presentation will focus heavily on power electronics market applications.

Drivers for Change: SiC and GaN Semiconductor Technologies:

Critical drivers for change:

- Growth of vehicle electrification: Demanding reduction in *cost, complexity, and physical volume*.
- Global drive for *energy efficiency*: Power semiconductors are the critical element.
- Transition from silicon to *wide band gap* (SiC, GaN) power semiconductor technologies:

★ **Critical factors for vehicle electrification**



★ **Higher voltage operation**

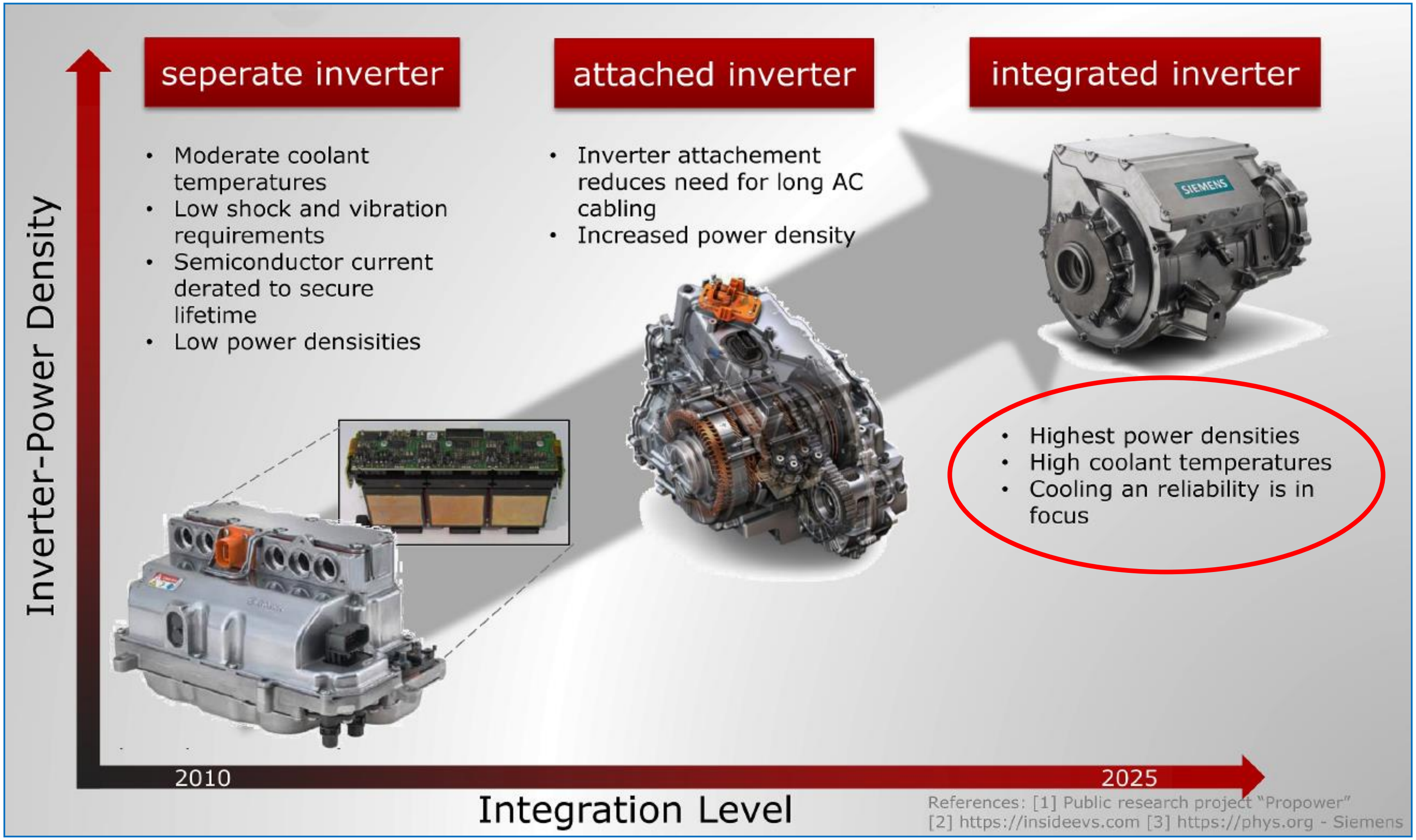
★ **High temperature capable**

★ **Higher switching frequency**

Source: Thomas Harder, ECPE. Modified with notes in red added, DS&A LLC.

EV Systems Integration: Major Driver for Change

EV industry transition to fully integrated inverter and electric machine:



seperate inverter

- Moderate coolant temperatures
- Low shock and vibration requirements
- Semiconductor current derated to secure lifetime
- Low power densisities

attached inverter

- Inverter attachement reduces need for long AC cabling
- Increased power density

integrated inverter

- Highest power densities
- High coolant temperatures
- Cooling an reliability is in focus

Inverter-Power Density

2010

2025

Integration Level

References: [1] Public research project "Propower"
[2] https://insideevs.com [3] https://phys.org - Siemens

Source: Michael Tönnes, Danfoss Silicon Power, September 2017.

Drivers for Change: SiC and GaN Semiconductor Technologies:

HEV/EV vehicle industry transition to WBG (SiC) devices is driven by these goals:

- 60+% higher output power per unit area, same lifetime
- 500+% greater lifetime per die unit area at same lifetime
- 40+% reduction in die area versus Si die (same output power, same lifetime)
- Higher temperature coolant capability

Production modules containing full SiC semiconductor devices for HEV/EV applications are beginning to enter pilot and series production:

- Limited numbers of specific device types from certain vendors
- Examples: Cree, Infineon

Complete SiC IGBT inverter modules for vehicle powertrain electrification are in lab development, testing, and pilot and early series production with several manufacturers.

Source: Andy Wereszczak, Laura Marlino, USDOE Oak Ridge National Laboratories, 2020.

Power Semiconductor Broad Package Categories

A highly generalized set of statements to categorize power semiconductor devices:

Power Semiconductor General Device Categories

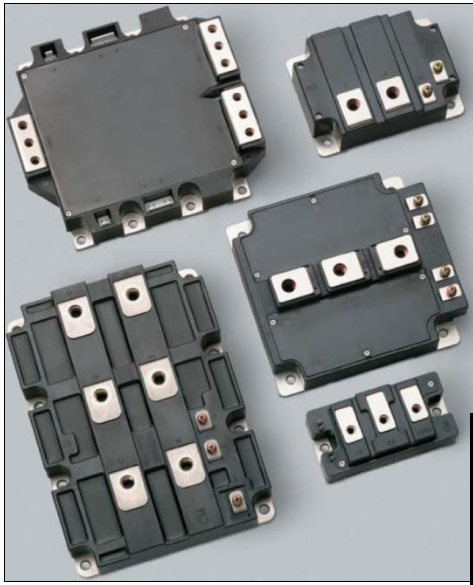
General Type	Electrical Structure	General Package Characteristic	General Package Options	Generalized Relative Global Market Unit Volumes	Generalized Thermal Characteristic Power Consumption
Discrete	Single IGBT or MOSfet Die as a Switch	Plastic Overmolded	Insulated Non-Insulated (w/exposed metal tab or backplate)	Billions of Units	<1W to ~100W
Module	Multiple die pairs (1 IGBT + 1 diode) w/logic w/o logic	**Ceramic Isolation Substrate, Baseplate, Plastic Housing**	Standard Package Custom Package w/Baseplate w/o Baseplate	Tens to Low Hundreds of Millions of Units	~75W to ~5kW
Hybrid	Multiple functions (IGBT or MOSfet + IC, RF, other die)	**Ceramic Isolation Substrate**	(Typ.) Mil/Aero Qualified	Low Millions of Units	<5W to ≥ 250W

Note: This discussion focuses on IGBT module market and packaging. Hybrids employ many packaging materials similar to and/or adapted from large high-power IGBT modules (≥ 3.3kV).

Source: DS&A LLC, 2021. Terms used are industry standard terminology, with generalized statements regarding packaging characteristics.

Standard IGBT Module Materials with Baseplates

Examples of standard IGBT module configurations:



Mitsubishi

Infineon PrimePack

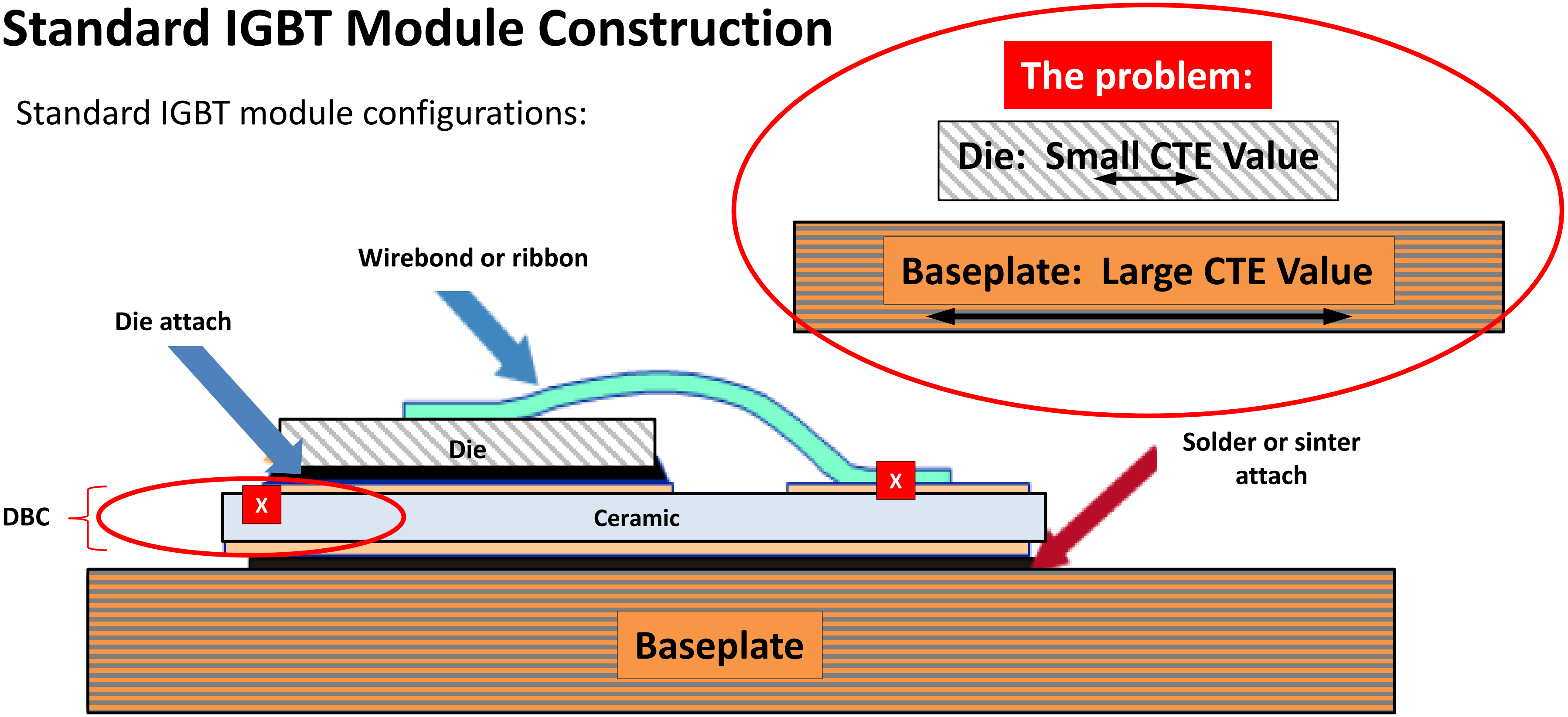
Infineon Econopack

Infineon Econopack w/pre-applied TIM2

Infineon IHV

Standard IGBT Module Construction

Standard IGBT module configurations:



DBC (Direct Bond Copper) construction:

- Critical substrate technology that provides electrical isolation for IGBT module;
- Copper bonded to ceramic isolation layer provides solderable/sinterable surfaces;
- Multiple DBC substrates may be used in a single module construction;
- Typically the highest cost component within a large IGBT module.

Baseplate provides critical mechanical support and (as required) internal stress reduction via CTE matching with a *CTE-matched alternative material to copper.*

Standard IGBT Module Construction

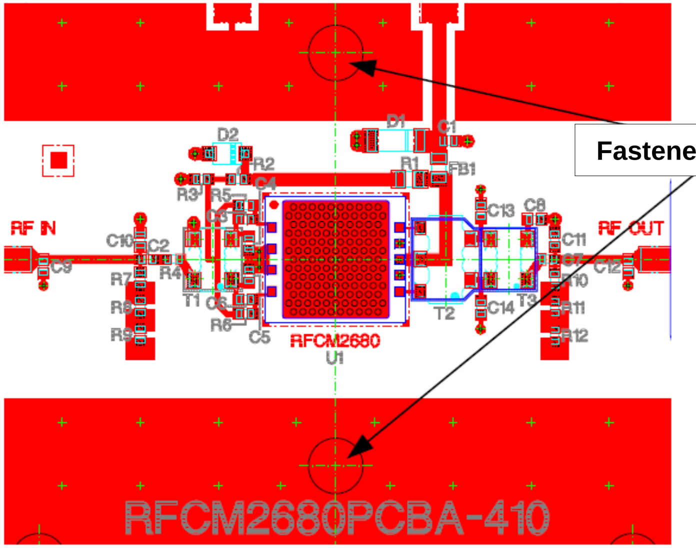
IGBT Material Stack – Component, Function, Material, and Thermal Conductivity				
Component	**Function**	**Material**	**Thickness (Typ., mm)**	**Bulk Thermal Conductivity (Typ., W/mK)**
Die	Electronic Switch	Silicon Carbide (4H-SiC)	0.4	270
Solder	Die Attach	Solder Alloy (Classical) Sintered Ag Paste (Advanced)	0.05 0.05	35 200
Metallized Isolation Substrate	Interconnection, Isolation, and Heat Transfer Path	Cu AlN Cu	0.3 0.635 0.3	400 150 400
Solder	Substrate Attach	Solder Alloy	0.1	35
Baseplate	**Mechanical Support, Heat Transfer Path**	**Copper or CTE-Matched Composite**	**4**	**200**
TIM	Heat Transfer	(As Selected)	≤ 2	(As Selected)

Note: Only copper baseplate conductivity value shown. CTE-matched thermal composites provide the development path for alternatives to copper baseplates.
Source: DS&A LLC, 2021, with modifications from original source: Reynes, H., Maneiro, J., Buttay, C., Dworakowski, P., "Optimization of a 5MW Power Electronic Converter", IMAPS France 12th Thermal Management and Micropackaging Workshop, La Rochelle, France, 1-2 February 2017.

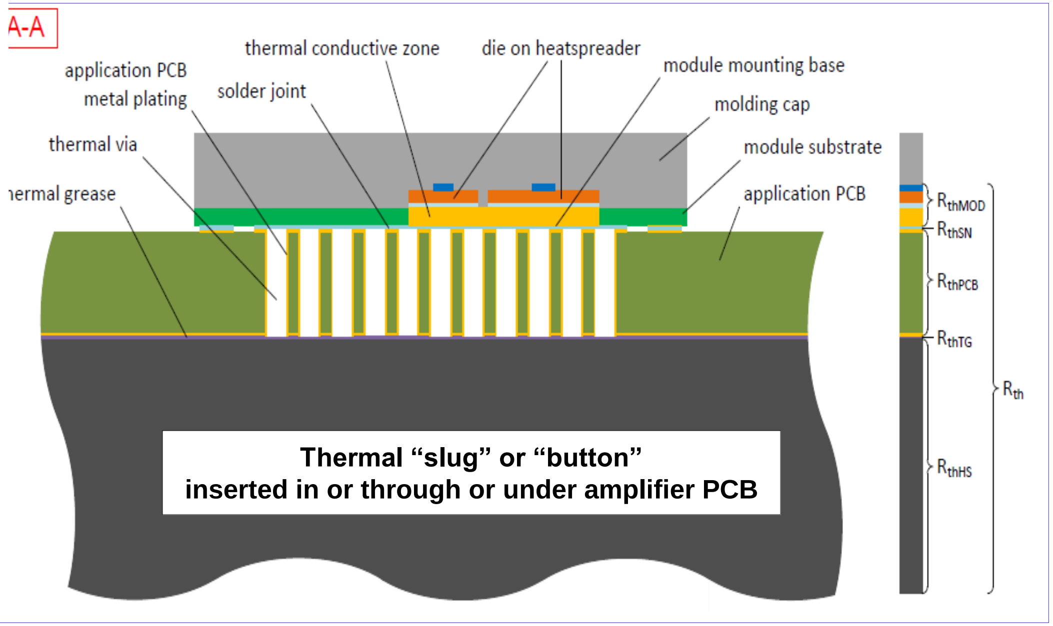
CTE-Matched Baseplates for GaN RF Devices

Thermal challenges for PCBs with multiple flange-mount and soldered RF devices:

- Application of a “button” or “slug” as a copper, CuW, Mo, or CuMo slug captured within the RF PCB or under the PCB is a common solution in commercial telcom amplifiers.
- “Button” or heat sink or slug material is determined by the system OEM and assembled during final system manufacturing or is incorporated into the RF system PCB by the PCB manufacturer.



Fasteners thru PCB to heat sink



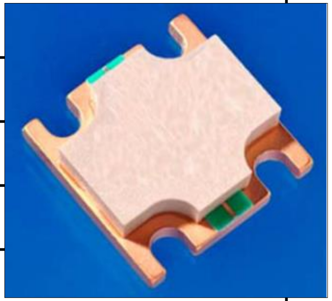
**Thermal “slug” or “button”
inserted in or through or under amplifier PCB**

Source, figures: RFMD RFCM2680 applications note, PCB thermal requirements.

Developments in CTE-Matched Composites for GaN RF

Industry goals for phased array radar and other aerospace applications:

Major Goal	Solution Target
Increased Power Output	Transition to GaN-on-SiC RF semiconductor technology
	Optimize device design
	Implement advanced circuit design and modeling
	Implement advanced thermal management technologies
Reduced Module Weight	Implement advanced semiconductor technology
	Move to higher semiconductor integration levels
	Multilayer materials technology
	Implement advanced packaging technologies
	MMIC/module coatings
Reduced Module Cost	Transition to advanced RF semiconductor technology
	Move to higher semiconductor integration levels
	Implement automated manufacturing technologies
	Implement encapsulation technology



Source: R. Borkowski, Raytheon IDS, USA (non-confidential, previously published data.)

Standard IGBT Module Materials: Baseplates

Baseplates for IGBT modules for HEV/EV inverters are manufactured in several formats:

- Flat plate (top and bottom surfaces)
- Round, oval, diamond, and square pin fins (shape dependent upon process)
- Skivved fin or pin* structure
- Infineon ribbon**

Cost pressures for commodity high volume IGBT modules result in use of copper or aluminum baseplates. (Coefficient of expansion values for aluminum alloys create excessive potential for DBC ceramic fracturing, so typically aluminum is used only on the smallest modules.)

Module Baseplate Heat Spreader Material Choices			
Component Type	**Manufacturing Process**	**Material**	**Bulk Thermal Conductivity (Typ., W/mK)**
AlSiC baseplate, CTE matched***	Net-shape casting	AlSiC	190
Copper pin fin baseplate (3mm)	Machined or skivved* pin array	Cu	360 - 385
Copper baseplate (flat, 3mm)	Coined/stamped plate	Cu	360 - 385

*Notes: *Skivved fin designs are manufactured with a traveling tool bit to turn a thin integral section of copper or aluminum to a vertical or other angle from the base. **Ribbon processes have been manufactured by Infineon Technologies as aproduction process.   *** MMCC manufacturers use different manufacturing processes and care must be taken in selecting appropriate vendors.*

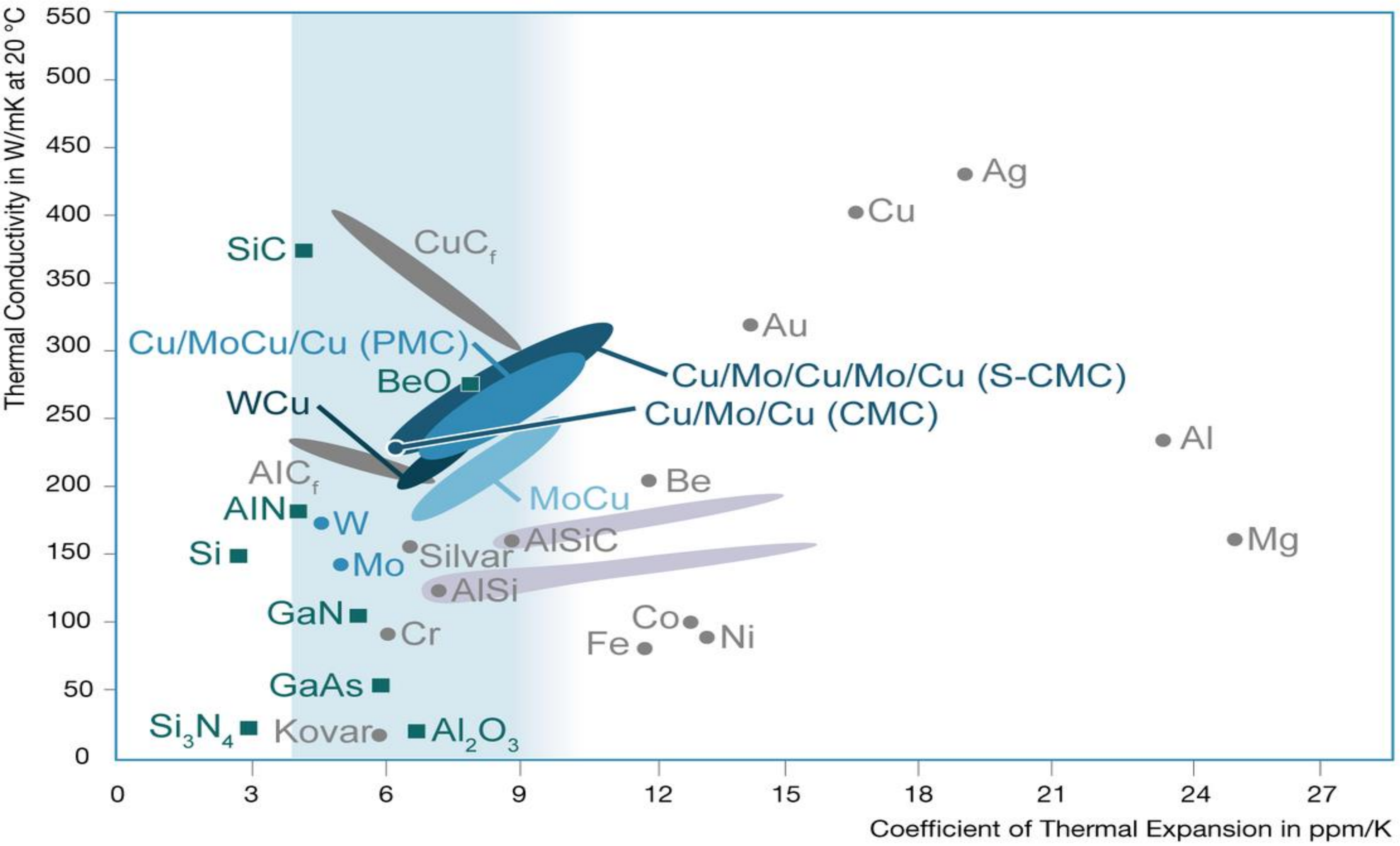
IGBT and RF CTE-Matched Thermal Materials: Physical Properties

Physical Properties (Typical, R.T.):   Ranked by CTE

Material Type	Coefficient of Thermal Expansion (ppm/°C)		Bulk Thermal Conductivity (W/mK)		Density (g/cc)	Young's Modulus (Gpa)	Data Source
	In-Plane (X-Y)	Through-Plane (Z)	In-Plane (X-Y)	Through-Plane (Z)			
Molybdenum	5.0		140	142	10.2	330	1
Cu-Mo-Cu (CMC)	6.0		170-182	170-182	9.9 – 10.0	280	1
85Mo/15Cu	6.2		160		9.8 – 10.2	230	2
Mo-Graphite	2.4	14.7	650	45	2.57	69.7*	3
20Cu/60Invar/20Cu	6.0	7.7	164	22	8.5	135	4
Cu-Diamond	7.0	8.0	450		5.4	NA	5
Cu/Mo70Cu/Cu (CPC)	7.2 – 9.0		340	300	9.5	N/A	6
Cu-Graphite	7.0	16	325	225	6.1	76	7
AlSiC-9 (37Al/63SiC)	7.4		190		3.0	188	8
Al-Diamond (Al/57Dia)	7.5		450		3.2	340	9
25Cu/50Mo/25Cu	7.9		268	N/A	9.6	220	4
Cu	16.4		385		9.0	110	10
Al-6061-T4	23.4		154		2.7	69	10

*Notes: * In-plane value. Data Sources: (1) Collins Aerospace; (2) H. C. Starck; (3) Nanoker Research, 2021 (average CTE of MoGr is 6.5 ppm/°C); (4) Pecht, M., Agarwal, R., McCluskey, F.P., Dishongh, T.J., Javadpour, S., Mahajan, R., Electronic Packaging Materials and Their Properties, CRC Press (1998) ISBN 0-8493-9625-5; (5) RHP-Technology GmbH & Co., KG; (6) Quantum Leap Packaging; (7) Parker Hannifin, 2019; (8) CPS Technologies, 2021; (9) Denka, Japan; (10) Matweb, 2021. All values stated at room temperature. Newer, highest bulk thermal conductivity relative to copper shown in grey.*

CTE-Matched Thermal Materials: CTE vs. Thermal Conductivity



Source: Plansee 2017.

CTE-Matched Thermal Materials: Manufacturing Process

Module Baseplate CTE-Matched Heat Spreader Material Choices				*© DS&A LLC 2021*
Material Type	Manufacturing Process	Material	CTE [Typ., ppm/°C(R.T.)]	Bulk Thermal Conductivity (Typ., W/mK)
Diamond	Synthetic	Diamond, hexagonal MBD6	**1**	1,000 – 1,200
Al-graphite	Net-shape casting/machined	Al/graphite composite, anisotropic	**4**	230
AgD	Infiltration-hot pressing/machined	Silver diamond composite	**5.8 – 6.4**	550
W-Cu	Sintering/machined	90W10Cu composite	**6.2**	201
Silicon-aluminum	Ingot/machined	Si/aluminum	**6.5**	125
CuD	Infiltration-hot pressing/machined	Cu/diamond composite	**6.7**	470
W-Mo	Sintering/machined	85Mo15Cu	**6.9**	154
Cu-graphite	Net-shape casting/machined	Cu/graphite composite, near-isotropic	**7**	285
CuD	Net-shape casting	Copper diamond composite, Cu skin	**7**	500

Notes: Typical values are shown. Specific values will be determined by selection of vendor and manufacturing process.

CTE-Matched Thermal Materials: Manufacturing Process

Module Baseplate CTE-Matched Heat Spreader Material Choices (Continued) *© DS&A LLC 2021*

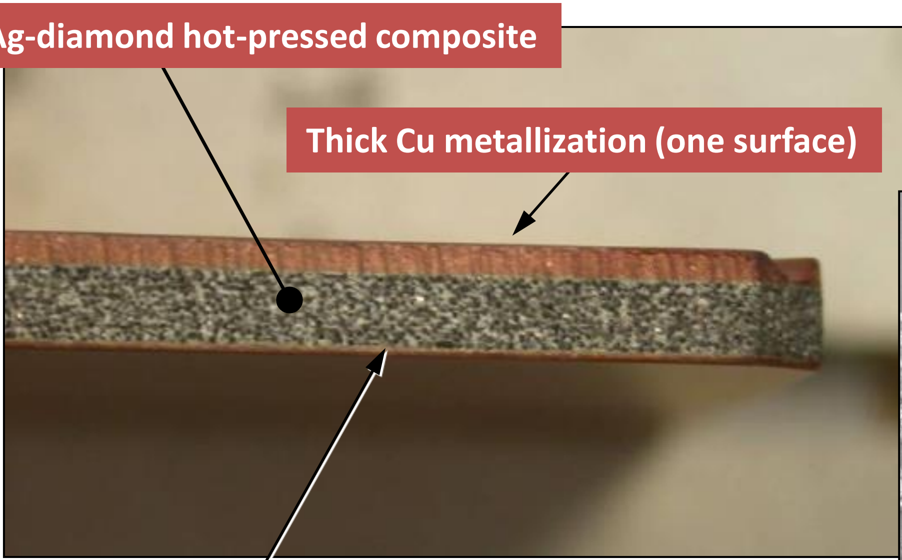
Material Type	Manufacturing Process	Material	CTE [Typ., ppm/°C (R.T.)]	Bulk Thermal Conductivity (Typ., W/mK)
AlD	Infiltration-hot pressing/machined	Al/diamond composite	**7.0 – 9.0**	440-530
AlSiC	Net-shape casting/infiltration	AlSiC, Al skin	**8**	200
CuD	Casting/machined	Cu/diamond	**11-12**	400
AlSiC	Net-shape casting/infiltration	AlSiC composite, isotropic	**12**	200
CuD	Hot pressing	Cu/40%D composite	**12**	475
Cu (Reference)	--	Copper (non-OFHC)	**17**	360

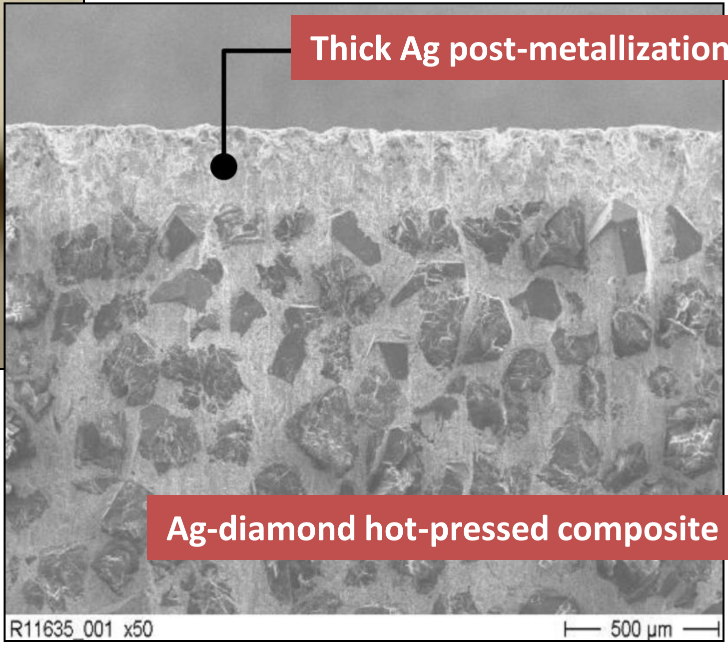
Notes: Typical values are shown. Specific values will be determined by selection of vendor and manufacturing process.

IGBT Module Materials: Baseplates

Examples of hot-pressed diamond composite baseplate structures:

- A Copper metallization on AgD composite lid
- B Ag metallization on AgD composite baseplate





Source: Sven Knippscheer, Tecnisco Europe GmbH (09-24-2019).

CTE-Matched Thermal Materials: Metallization

CTE-Matched Thermal Composites: Common Component Standard Metallizations

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Process	Specification	Comment	Replaced
Electroless Nickel (Ni-P)	ASTM B733	MIL-C-26074E continues to be widely specified globally in existing component drawings and remains widely available from multiple plating firms globally. Replaced by ASTM B733, AMS2404.	MIL-C-26074E
	SAE AMS2404J-2018		
Electroless Gold	ASTM B488-18	Typically, Class III, Type 2 Specified	MIL-DTL-45204D
	SAE AMS2422F	Electrodeposited gold	--
	ISO 4527-2003	Widely specified international standard, replaces 4227-1987.	--
ENIG	IPC 4522 Rev A	Rev B pending.	--

Notes: General statements are given above.   Specific values will be determined by component specification, specific composite material to be plated, and applicable standard, and selection of vendor and vendor process capabilities. Replacement specifications for older MIL-specs include common requirements, with additional or changed call-outs for thickness, alloy, and test methods.

Notes: SAE AMS 2404J supersedes AMS-MIL-C-26074 which employs Grade designations to convey thickness requirements.   Complete cross reference documents are available from certain plating vendors, giving changes from AMS-MIL-C-26074 callouts to the technically identical provisions within specification AMS 2404,in order to comply with the purchase order requirements.

ASTM B733-04 is markedly updated from ASTM B733-90 and previous, in that the coating Type specifies the phosphorous content of the coating. (ASTM B733-90 does not make this distinction.) Typical references are: Low- (3-4%), Mid- (6-9%), and High- (11-12%) Phosphorus content of the NiP alloy.

Qualified vendors provide coatings that conform to the requirements of ELV Directive 2000/53/EC, WEEE 2002/96/EC and RoHS 2002/95/EC, and are FDA approved and RoHS compliant.

CTE-Matched Thermal Materials: Rth Impact

3.3kV IGBT Module Thermal Resistance Empirical Comparison CTE-Matched vs. Copper IGBT Module Baseplate			
Baseplate Material Type	**CTE [Typ., ppm/°C (R.T.)]**	**Thermal Conductivity (W/mK)**	**Rth_{JA} (°C/W)**
Copper (Non-OFHC)	17	360	**0.0283**
AlSiC	8.7	200	**0.0317**
Cu-diamond	6.7	470	**0.0268**
Al-diamond	9.0	520	**0.0248**

Thermal performance value of alternative baseplate material selection:

- Module dissipating 2kW: Al-D baseplate vs. AlSiC baseplate = ~ 14°C reduction
- Module dissipating 2kW: Cu baseplate vs. Al-D baseplate = ~ 7°C reduction

➡ *Significantly higher cost differential for an Al-D baseplate vs. AlSiC baseplate must be considered.*

Note: IGBT module, 3.3kV, 800A, (187mm x 137mm baseplate footprint).   Source data: Bollina, R., "Thermal Management and Packaging with Diamond Composites", IMAPS Advanced Technology Workshop on Advanced Substrates, Baltimore MD, May 1-2, 2008.

Printed Circuit Board Thermal Core Materials: CTE Matching

Example PCB Materials, CTE Relationships

Material Type	CTE [ppm/°C, Room Temperature (typ.)]	Thermal Conductivity (W/mK)
Epoxy-coated E-glass[1]	**4-6**	**0.4**
Stablcor® ST-325[1]	**4-6**	**X-Y: 175** **Z: 1**
20Cu-60Invar-20Cu[2]	**X-Y: 6.0** **Z: 7.7**	**X-Y: 164** **Z: 22**
Parker Hannifin Cu-MetGraf™ 7-300[3]	**7**	**X-Y: 287** **Z: 225**
25Cu/50Mo/25Cu[2]	**7.9**	**X-Y: 268** **Z: N/A**
DuPont (Arlon) Thermount™ woven/nonwoven aramid with thermoset resins[1]	**8-10**	**0.3**
Typical multilayer PCB[1]	**15-17**	**0.5**
Copper[4]	**17**	**385**
Aluminum[4]	**25**	**150 - 160**

Data sources:

1. *J. Vesce, TTM Technologies, Inc., USA.*
2. *Pecht, M., Agarwal, R., McCluskey, F.P., Dishongh, T.J., Javadpour, S., Mahajan, R., Electronic Packaging Materials and Their Properties, CRC Press, 1998.*
3. *Pergande, A., Rock, J., "Advances in Passive PCB Thermal Control," Proceedings of the 2011 IEEE Aerospace Conference, Big Sky MT USA, March 2011.*
4. *Collins Aerospace, Inc., USA.*

Developments in Thermal Materials: Implications and Summary

Specialized needs for thermal materials continue to develop as module packaging technologies, higher power dissipation and heat flux, and higher operating temperatures develop.

IGBT power semiconductor module market continuing development requirements demand:

- Improved lifetime and reliability, critical in traction, energy infrastructure, aerospace, and electrical drives markets.
- Accelerating demand for higher-performance, reduced form factor, lower cost, and higher-temperature-capable EV powertrain modules and inverters.
- Continued cost pressures for all materials associated with IGBT module manufacturing.

A continuing critical need for improvements in thermal materials is driven by transition from silicon to SiC and GaN semiconductor devices with higher power density and $T_{J\,MAX}$ capabilities.

Developments continue in a range of CTE-matched thermal composites and structures that better address requirements for improved lifetime and reliability.

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Focus is on thermal management and packaging developments for power semiconductors, power electronics, and energy storage:

- **Power semiconductor device packaging**
- **Power electronics packaging**
- **Thermal materials, components, and systems**
- **Joining materials and systems for power semiconductors**
- **Energy storage packaging**
- **Thermal solutions and temperature control for energy storage**
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Dave Saums, General Chair
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Information will be available in May 2021 at: www.semi-therm.org