Selection, Metrology controls and Reliability performance of TIM in advanced 3D package designs

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Bill Ishii – Sumitomo Thermal Materials ALMT, San Diego, CA

29th Annual Components for Military & Space Electronics Conference & Exhibition, 2026, Los Angeles, CA

Christo Bojkov has over 36 years of experience in the semiconductor industry as Eng. Director and Senior Technical STAFF at multiple leading Integrated Device Manufacturers (IDM). He has managed large engineering groups in the Front End of line (FEOL) and back end of line (BEOL) Fabrication facilities with focus on heterogeneous integration of Cu interconnects, Cu-CMP, Pb-free Flip Chip, Cu-pillars with Cu-RDL, CSP Assembly and Test for high-power high-frequency GaN & GaAs mmWave products. Christo began his career as a Research Fellow at the Universities of Paris (France), Rome (Italy) and at the Max-Plank Institute (Germany). He provides leadership activities currently as active committee member at IMAPS and at IEEE/ECTC and as Adj. faculty at UT-Dallas.

Joana Catarina Mendes is a Researcher at the Institute for Telecomunications, Aveiro, Portugal. Her research focuses on integrating synthetic diamond into advanced packages for thermal management, addressing the challenges of high-power density in AI, HPC, and RF systems. Dr. Mendes has led and contributed to multiple international R&D projects, has over 60 peer-reviewed publications, and serves on the Steering Committee of the Workshop on Compound Semiconductor Devices and Integrated Circuits held in Europe (WOCSDICE). She chaired the 2023 and 2024 editions of the IEEE Signal and Power Integrity Workshop, and is a member of the Assembly & Manufacturing Technology sub-committee of the IEEE Electronic Components and Technology Conference (ECTC).

Bill Ishii is Sumitomo Electric USA (Thermal Solutions Group) Marketing and Sales manager, with over 25 years experience in electronic packaging, assembly, with focus on semiconductor thermal management components. Bill started his microelectronics career with Kyocera handling IC packaging for the high-reliability market, high-power and high-frequency applications Assembly experience includes wire bond, flip chip, die attach, and SMT. For the past 10 years with Sumitomo, his work centers on advanced thermal management materials with attention to CTE requirements. Bill is involved with IMAPS as a Symposium track chair, IEEE EPS' Assembly & Manufacturing Technology committee (AMT/ECTC), and CMSE as a session chair.

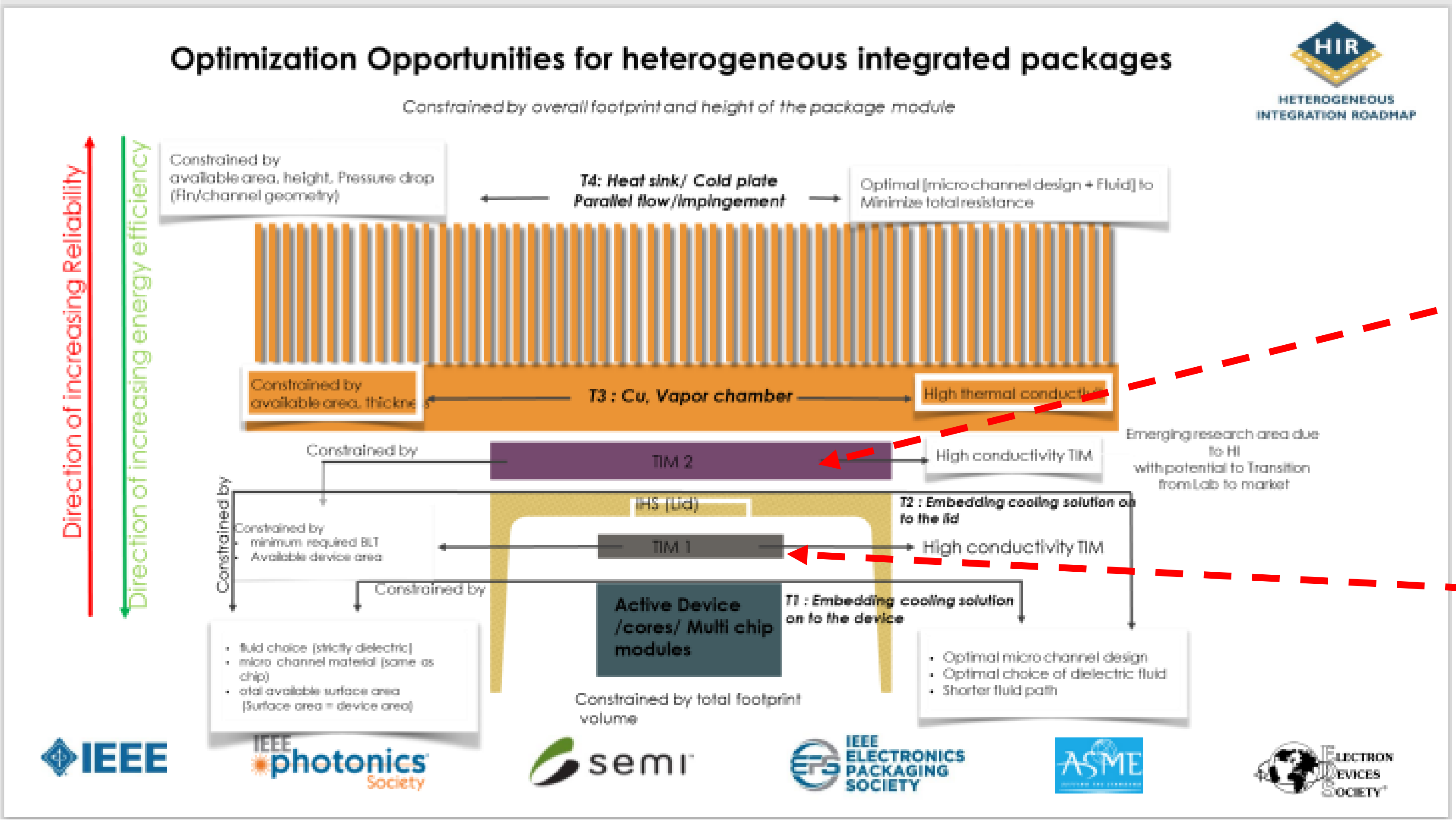
Agenda:

- **Christo Bojkov - Thermal Interface Materials Review**
  - TIM1/TIM1.5/TIM2 – materials performance vs expectations
  - Metrology and Reliability
  - Roadmaps 2025-2030

- **Joana Mendes - Diamond heat spreaders and related applications**
  - Cooling with Diamond
  - Integrating Diamond into Advanced packages
  - Challenges integrating diamond

- **Bill Ishii - Advanced composite materials for thermal management**
  - Composite Heat Spreader materials and applications
  - Microfluidics cooling and Spacers for double-side cooling
  - Siver-Diamond capabilities and roadmap

Power Dissipation is Arguably the Greatest Challenge Facing Modern Electron Devices



Optimization Opportunities for heterogeneous integrated packages

Constrained by overall footprint and height of the package module

TIM2 – Elastomers, Thermal grease, limited to 20+W/mK with most used cases closer to 5 W/m-K

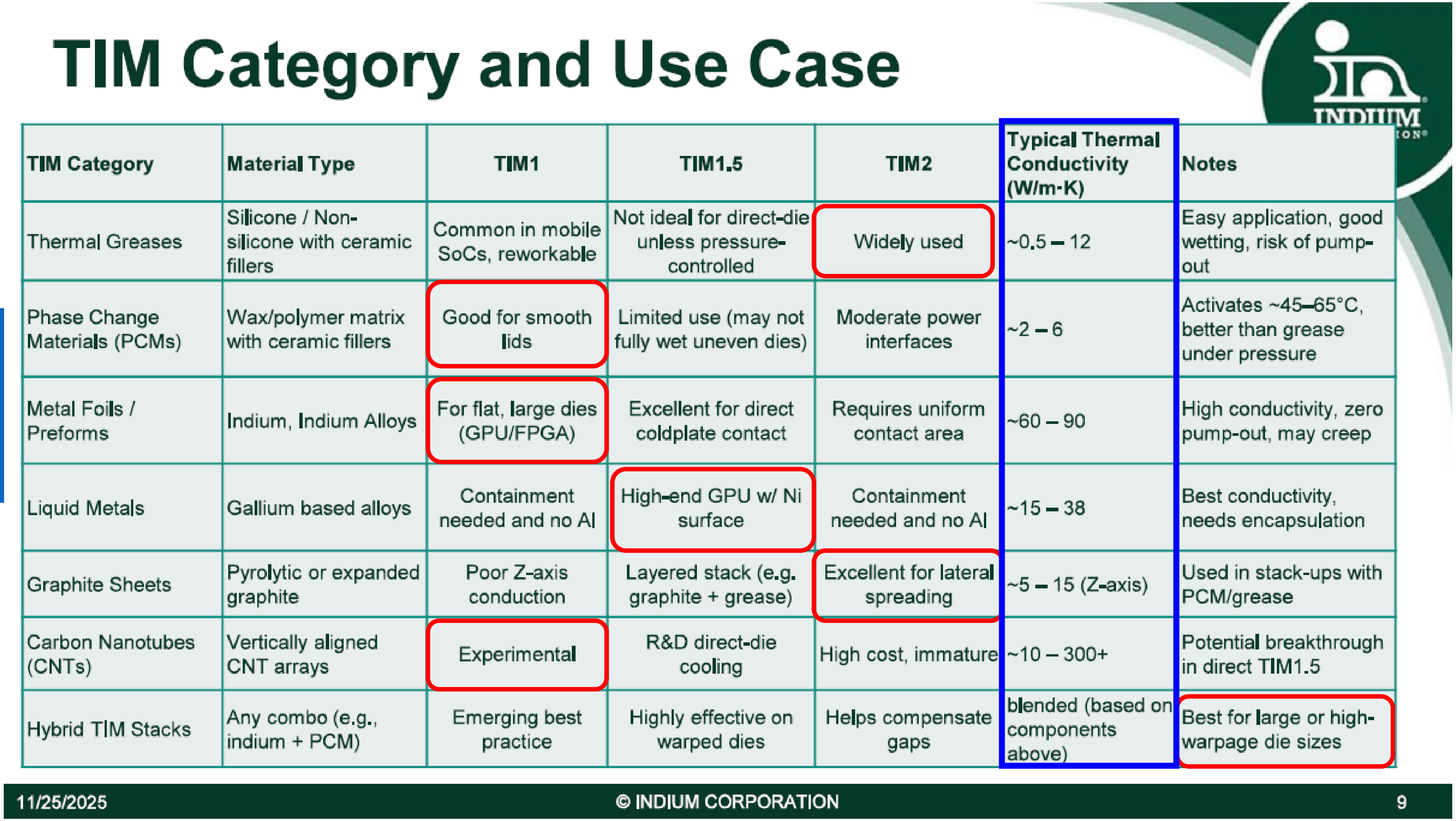
TIM 1 (TIM 1.5) - Die-attach materials (Sintered metals, LT Solders, PC materials Thermally Matched Composites ……are 60-110W/m-K

Power Dissipation is Arguably the Greatest Challenge Facing Modern Electron Devices

Cooling the Future:
TIM Strategies for High-Density AI and HPC Platforms

Dr. Jie Geng
R&D Manager – TIM Group/ Indium Corporation
INEMI Project Manager: Masahiro Tsuriya

Date of webinar: November 25, 2025



TIM Category and Use Case

TIM Category	Material Type	TIM1	TIM1.5	TIM2	Typical Thermal Conductivity (W/m-K)	Notes
Thermal Greases	Silicone / Non-silicone with ceramic fillers	Common in mobile SoCs, reworkable	Not ideal for direct-die unless pressure-controlled	Widely used	~0.5 – 12	Easy application, good wetting, risk of pump-out
Phase Change Materials (PCMs)	Wax/polymer matrix with ceramic fillers	Good for smooth lids	Limited use (may not fully wet uneven dies)	Moderate power interfaces	~2 – 6	Activates ~45–65°C, better than grease under pressure
Metal Foils / Preforms	Indium, Indium Alloys	For flat, large dies (GPU/FPGA)	Excellent for direct coldplate contact	Requires uniform contact area	~60 – 90	High conductivity, zero pump-out, may creep
Liquid Metals	Gallium based alloys	Containment needed and no Al	High-end GPU w/ Ni surface	Containment needed and no Al	~15 – 38	Best conductivity, needs encapsulation
Graphite Sheets	Pyrolytic or expanded graphite	Poor Z-axis conduction	Layered stack (e.g. graphite + grease)	Excellent for lateral spreading	~5 – 15 (Z-axis)	Used in stack-ups with PCM/grease
Carbon Nanotubes (CNTs)	Vertically aligned CNT arrays	Experimental	R&D direct-die cooling	High cost, immature	~10 – 300+	Potential breakthrough in direct TIM1.5
Hybrid TIM Stacks	Any combo (e.g., indium + PCM)	Emerging best practice	Highly effective on warped dies	Helps compensate gaps	blended (based on components above)	Best for large or high-warpage die sizes

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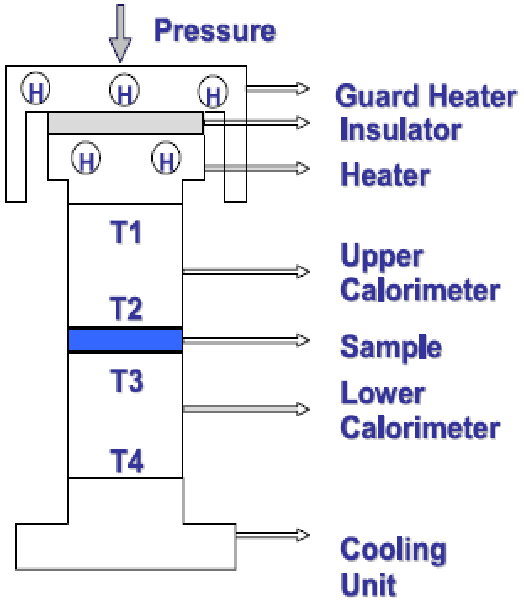
Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

Thermal Interface is the issue in most cases- thickness, roughness, Covalent bonding, modulus, CTE & elongation under stress, moisture intake…… determine total thermal impedance.

- ASTM D5470 is a convenient, standardized tool to measure and compare performance of TIMs
- Measured thermal impedance at a given pressure is determined by:
  - Bulk thermal conductivity, and
  - Bond line thickness (BLT), and
  - Contact resistance at the interfaces
- Limitations:
  - In-situ reliability measurements
  - Caution when comparing published test results from one tester to another, one lab to another …
  - … particularly for thin bond-line, very low impedance measurements
  - Caution when translating lab test results to real world applications



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March 19, 2008

Principles of Laser Flash Method

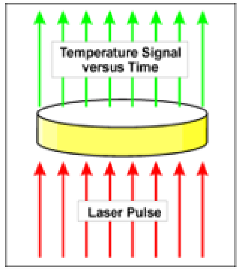
Thermal diffusivity, *α* is a measure of how quickly heat diffuses through a material.

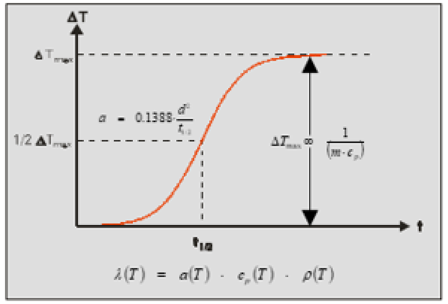
$$\alpha = \frac{k}{\rho C_p}$$

k: Thermal Conductivity; *ρ*: Mass Density; C_p: Heat Capacity.
α is a key material thermal property needed for accurate simulations and design.

In Laser Flash method, front face of a thin sample is heated by a single energy pulse from a laser source. Temperature rise on the back face is measured using an IR detector as a function of time. Comparison of the measurement with an analytical model (Parker, *et al.*, 1961) is carried out to determine thermal diffusivity.

Further, it is known that peak temperature rise in this measurement is proportional to heat capacity. Therefore, by comparison of the signal measured for a test sample with a standard sample of known heat capacity, one may determine heat capacity of the test sample. The equation above can then be used to determine thermal conductivity.





Ankur Jain
Associate Professor
Mechanical and Aerospace Engineering Department
The University of Texas at Arlington, USA

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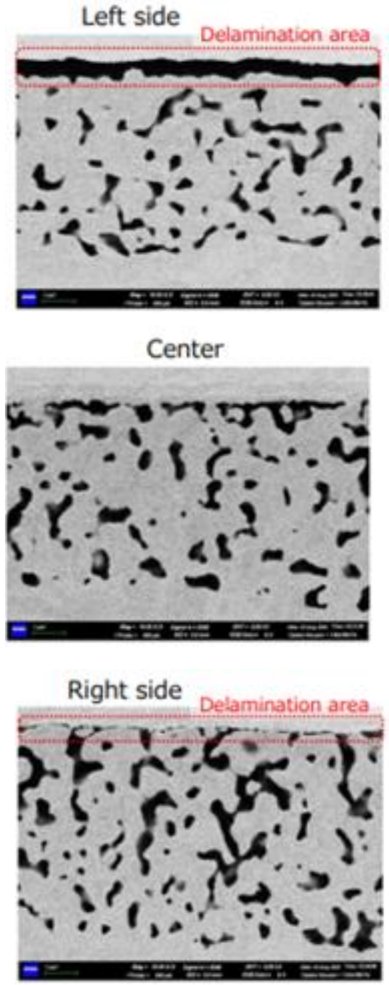
Industry Examples



Hybrid Nanocomposite Thermal Interface Materials: The Thermal Conductivity and the Packing Density

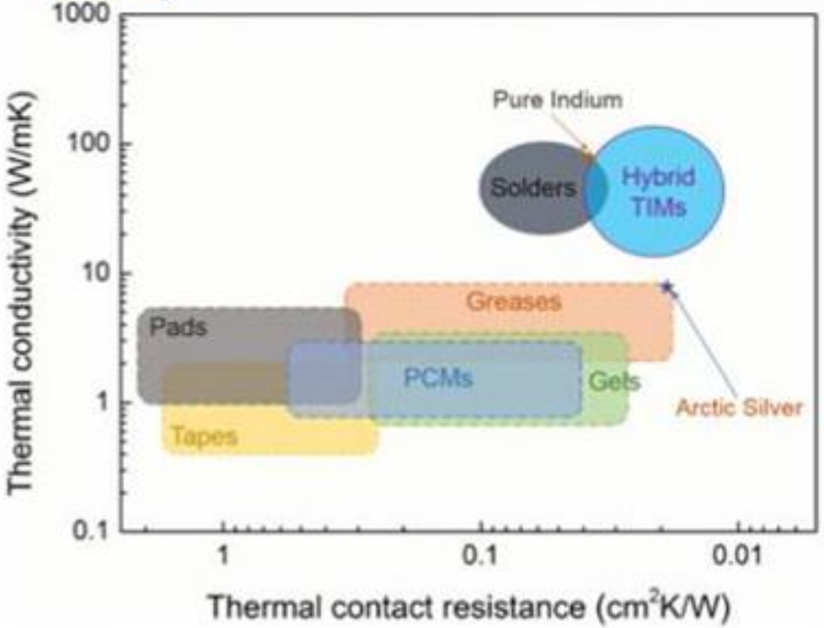


Fig. 8 Comparative mapping of thermal properties (k and R_c) of various TIMs. The novel hybrid TIMs in this study is show in the upper-right corner, with k's comparable to those of high-end solder TIMs, and R_c's as low as those of the best thermal greases.

We have investigated a novel hybrid nanocomposite thermal interface material (TIM) that consists of silver nanoparticles (AgNPs), silver nanoflakes (AgNFs), and copper microparticles (CuMPs). Continuous metallic network form while AgNPs and AgNFs fuse to join bigger CuMPs upon hot compression, resulting in superior thermal and mechanical performances. The assembly temperature is as low as 125 C due to the size effect of silver nanoparticulates. The thermal conductivity, k, of the hybrid nanocompo-site TIMs is found to be in the range of 15-140 W/mK, exceeding best-performing commercial thermal greases, while comparable to high-end solder TIMs. The dependence of k on the solid packing density and the volume fraction of voids is discussed through comparing to model predictions.

https://www.researchgate.net/publication/335882126_Hybrid_Nanocomposite_Thermal_Interface_Materials_The_Thermal_Conductivity_and_the_Packing_Density

Journal of Electronic Packaging
SEPTEMBER 2018, Vol. 140 / **031006-1**

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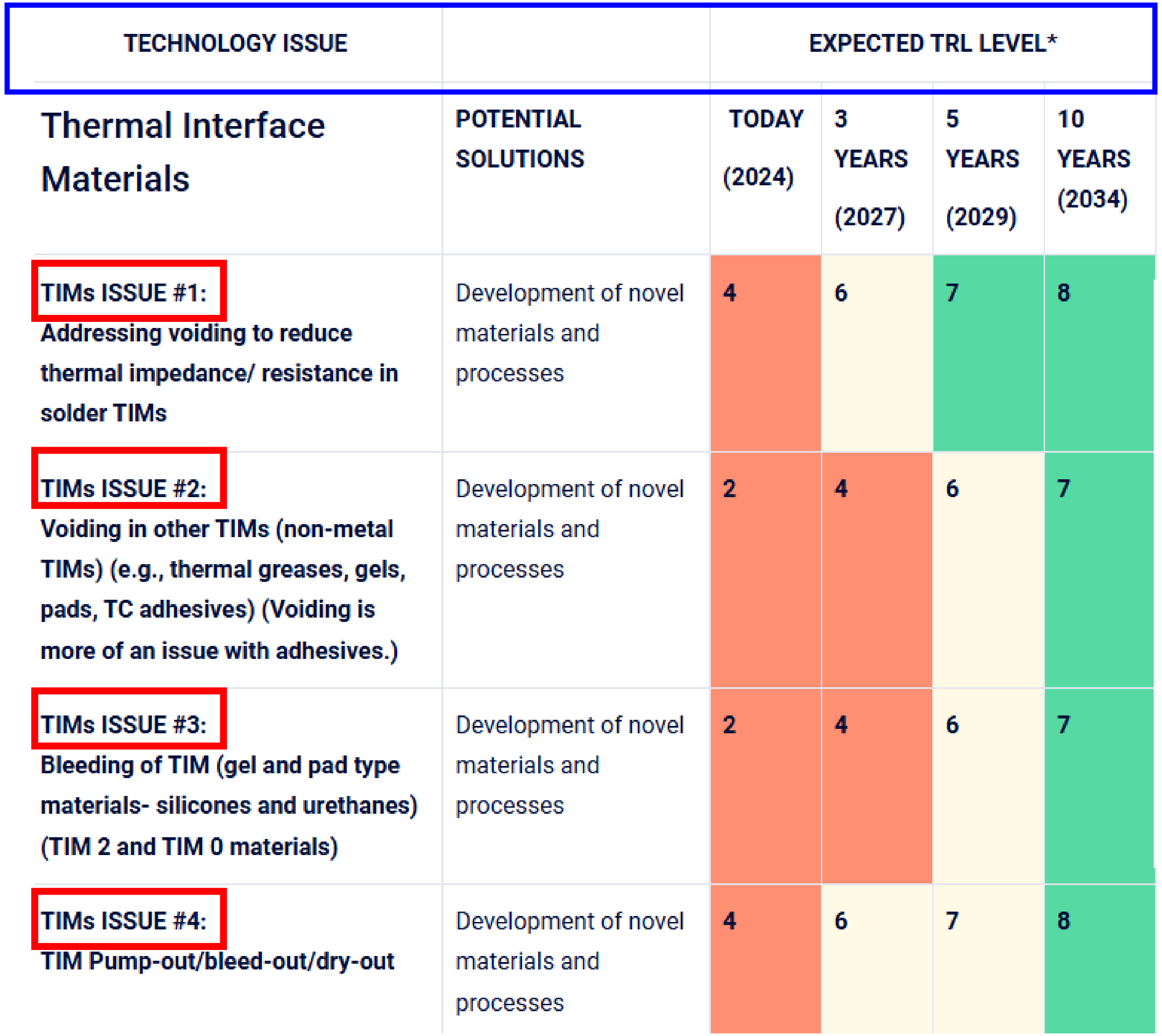

TECHNOLOGY ISSUE		EXPECTED TRL LEVEL*			
Thermal Interface Materials	**POTENTIAL SOLUTIONS**	**TODAY (2024)**	**3 YEARS (2027)**	**5 YEARS (2029)**	**10 YEARS (2034)**
TIMs ISSUE #1: Addressing voiding to reduce thermal impedance/ resistance in solder TIMs	Development of novel materials and processes	4	6	7	8
TIMs ISSUE #2: Voiding in other TIMs (non-metal TIMs) (e.g., thermal greases, gels, pads, TC adhesives) (Voiding is more of an issue with adhesives.)	Development of novel materials and processes	2	4	6	7
TIMs ISSUE #3: Bleeding of TIM (gel and pad type materials- silicones and urethanes) (TIM 2 and TIM 0 materials)	Development of novel materials and processes	2	4	6	7
TIMs ISSUE #4: TIM Pump-out/bleed-out/dry-out	Development of novel materials and processes	4	6	7	8

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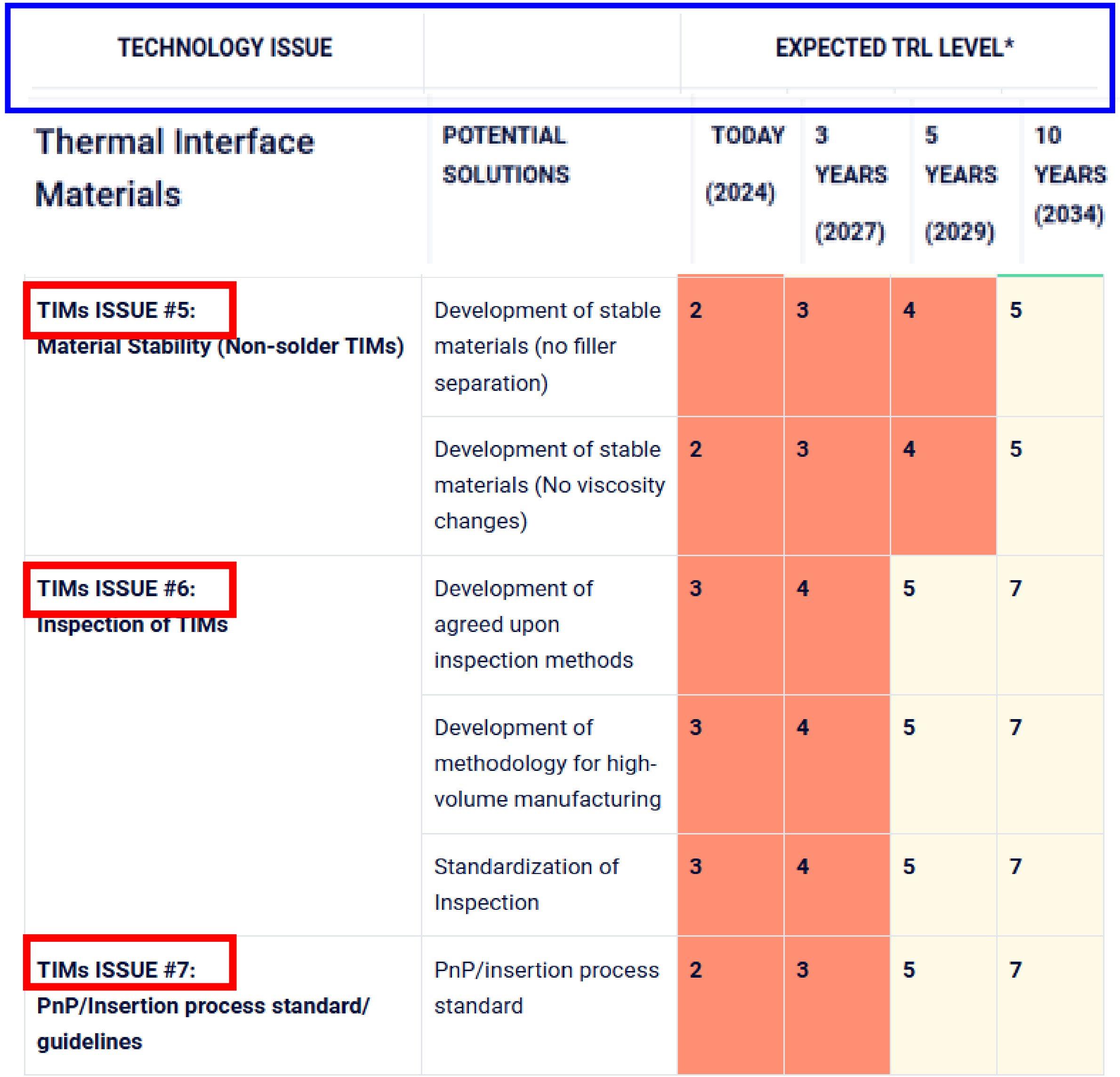
https://roadmap.inemi.org/ir/thermal-interface-materials

Approaches to address Needs, Gaps and Challenges

Table 2 considers approaches to address the above needs and challenges. The evolution of these is projected out over a 10-year timeframe using technology readiness levels (TRLs).

In-table color key ↕	Range of Technology Readiness Levels ↕	Description
2	TRL: 1 to 4	Levels involving **research**
6	TRL: 5 to 7	Levels involving **development**
9	TRL: 8 to 9	Levels involving **deployment**

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices



TECHNOLOGY ISSUE		EXPECTED TRL LEVEL*			
Thermal Interface Materials	**POTENTIAL SOLUTIONS**	**TODAY (2024)**	**3 YEARS (2027)**	**5 YEARS (2029)**	**10 YEARS (2034)**
TIMs ISSUE #5: Material Stability (Non-solder TIMs)	Development of stable materials (no filler separation)	2	3	4	5
	Development of stable materials (No viscosity changes)	2	3	4	5
TIMs ISSUE #6: Inspection of TIMs	Development of agreed upon inspection methods	3	4	5	7
	Development of methodology for high-volume manufacturing	3	4	5	7
	Standardization of Inspection	3	4	5	7
TIMs ISSUE #7: PnP/Insertion process standard/ guidelines	PnP/insertion process standard	2	3	5	7

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https://roadmap.inemi.org/ir/thermal-interface-materials

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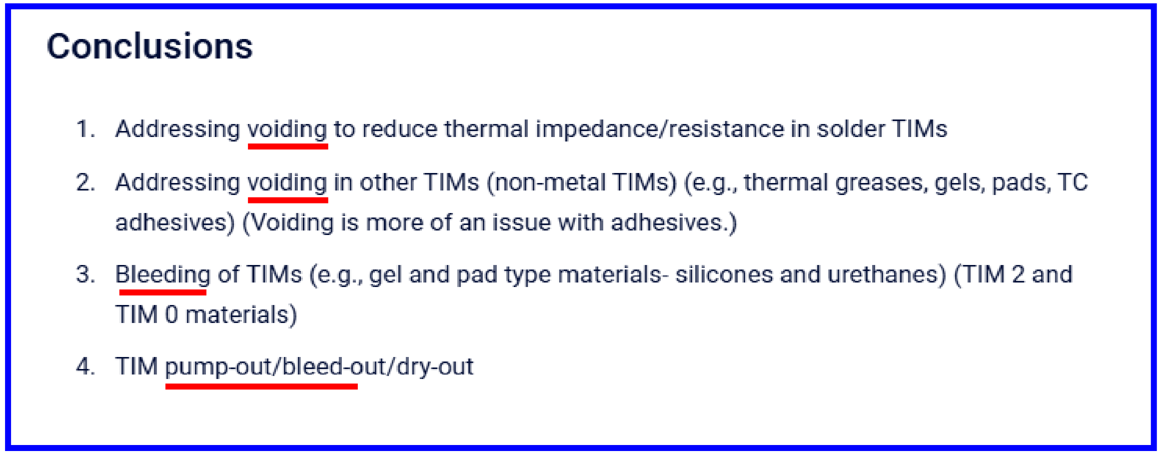

Conclusions

1. Addressing voiding to reduce thermal impedance/resistance in solder TIMs
2. Addressing voiding in other TIMs (non-metal TIMs) (e.g., thermal greases, gels, pads, TC adhesives) (Voiding is more of an issue with adhesives.)
3. Bleeding of TIMs (e.g., gel and pad type materials- silicones and urethanes) (TIM 2 and TIM 0 materials)
4. TIM pump-out/bleed-out/dry-out

Power Dissipation is Arguably the Greatest Challenge Facing Modern Electron Devices

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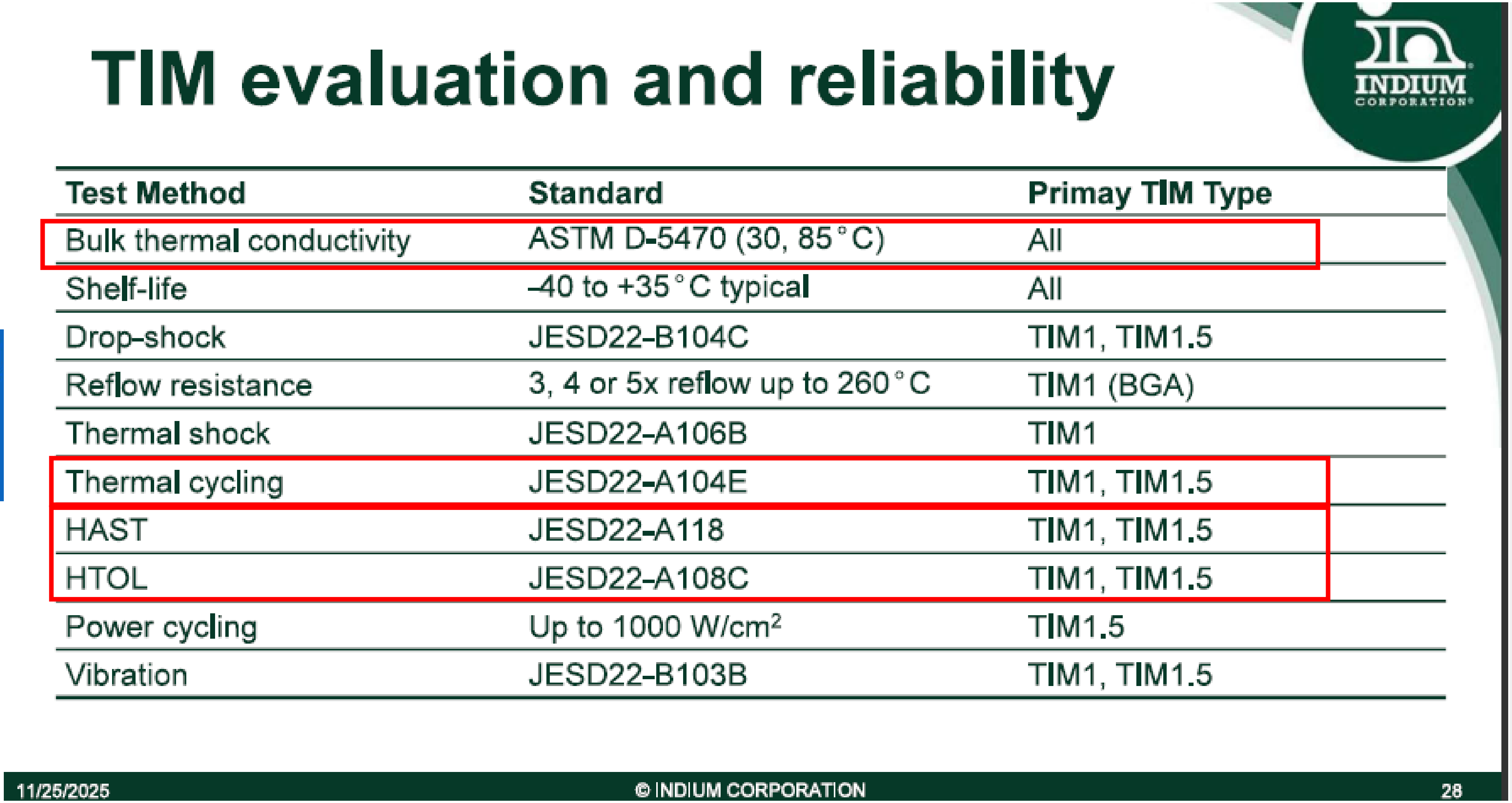
Cooling the Future:
TIM Strategies for High-Density AI and HPC Platforms

Dr. Jie Geng
R&D Manager – TIM Group/ Indium Corporation
INEMI Project Manager: Masahiro Tsuriya

Date of webinar: November 25, 2025



TIM evaluation and reliability

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Test Method	Standard	Primay TIM Type
Bulk thermal conductivity	ASTM D-5470 (30, 85 °C)	All
Shelf-life	-40 to +35 °C typical	All
Drop-shock	JESD22-B104C	TIM1, TIM1.5
Reflow resistance	3, 4 or 5x reflow up to 260 °C	TIM1 (BGA)
Thermal shock	JESD22-A106B	TIM1
Thermal cycling	JESD22-A104E	TIM1, TIM1.5
HAST	JESD22-A118	TIM1, TIM1.5
HTOL	JESD22-A108C	TIM1, TIM1.5
Power cycling	Up to 1000 W/cm^2	TIM1.5
Vibration	JESD22-B103B	TIM1, TIM1.5

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IPC/JEDEC J-STD-020E

JOINT INDUSTRY STANDARD

Moisture/Reflow Sensitivity Classification for Nonhermetic Surface Mount Devices

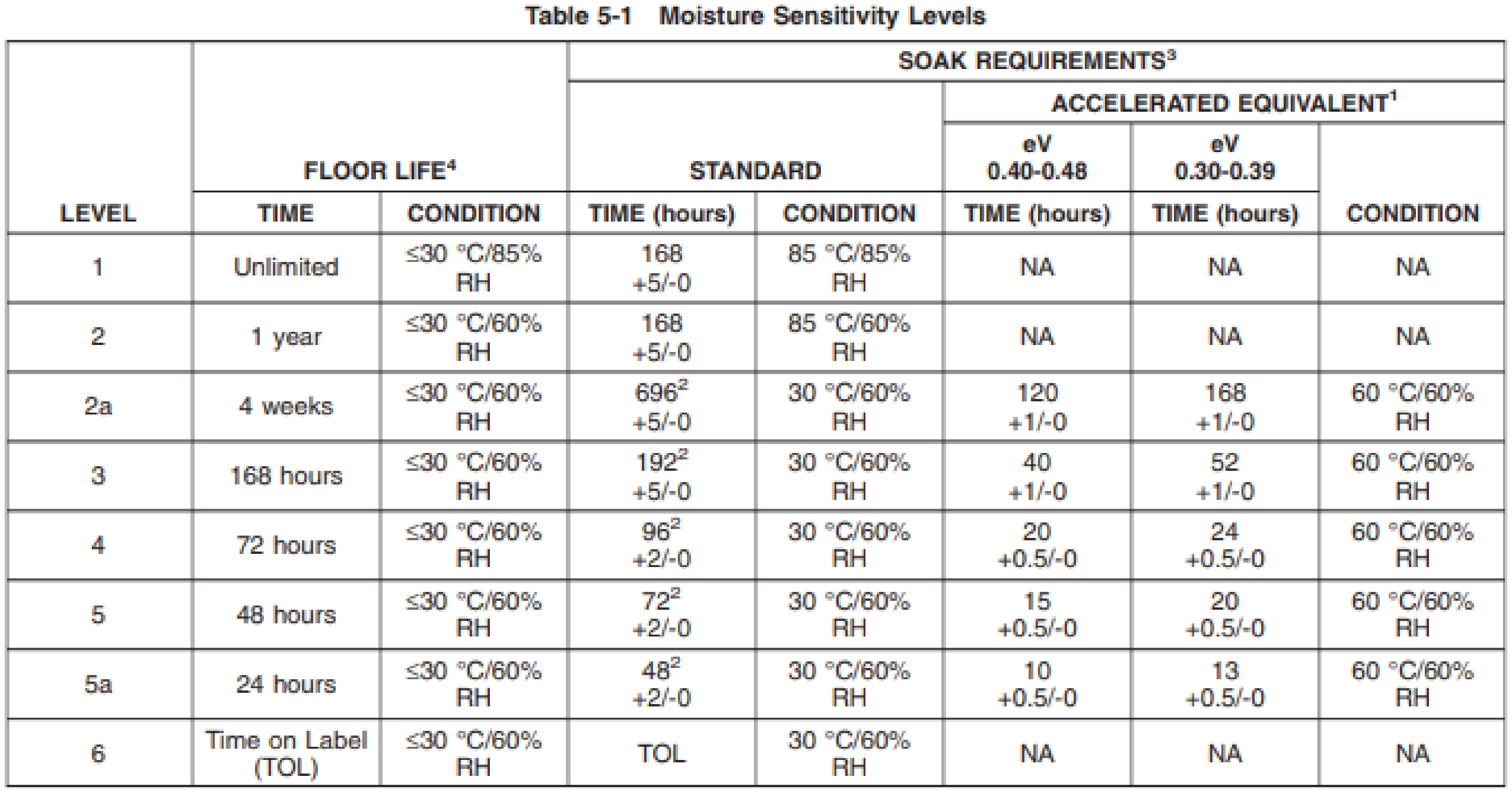


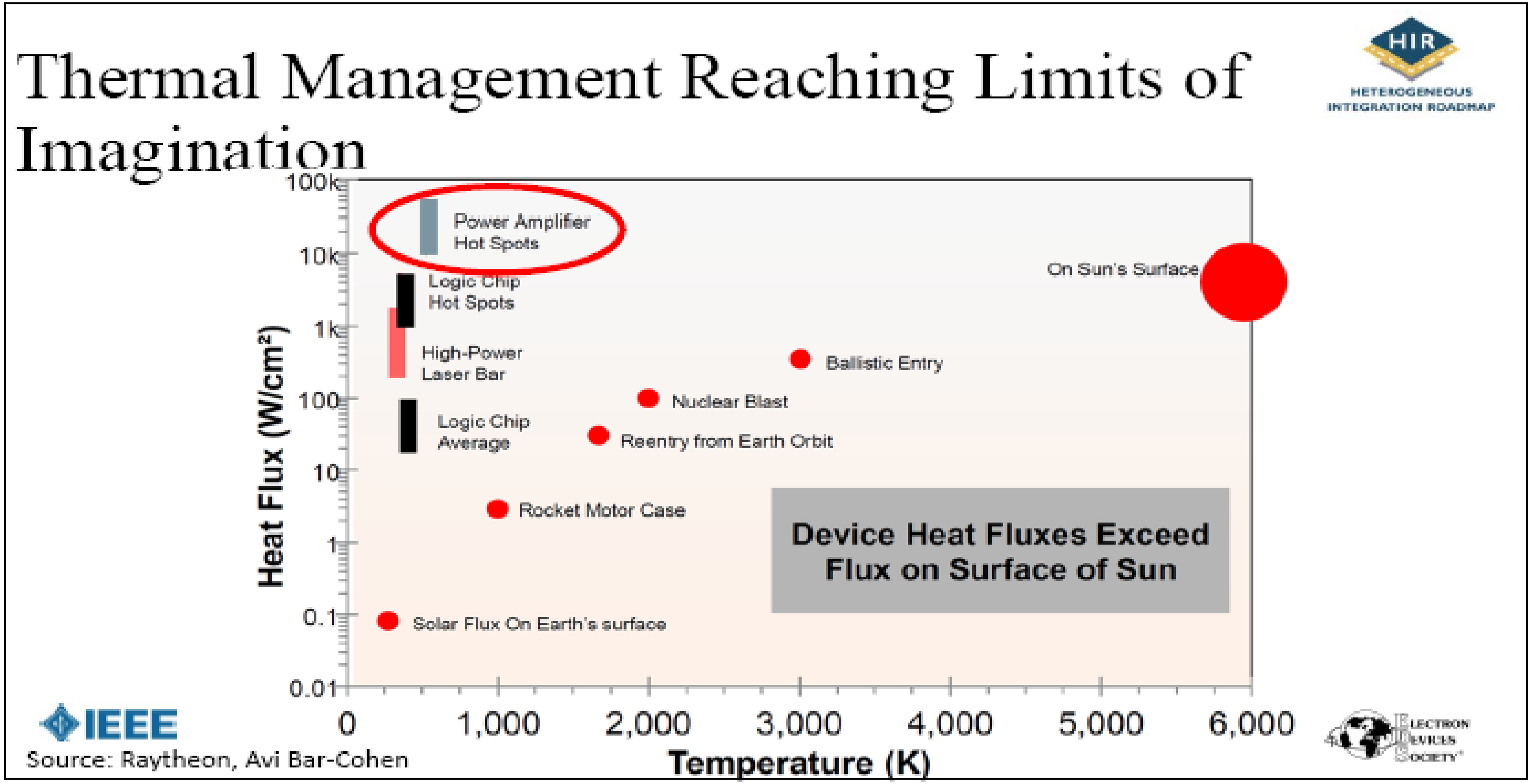
Table 5-1 Moisture Sensitivity Levels

LEVEL	FLOOR LIFE[4]		SOAK REQUIREMENTS[3]				
			STANDARD		ACCELERATED EQUIVALENT[1]		
					eV 0.40-0.48	eV 0.30-0.39	
	TIME	CONDITION	TIME (hours)	CONDITION	TIME (hours)	TIME (hours)	CONDITION
1	Unlimited	≤30 °C/85% RH	168 +5/-0	85 °C/85% RH	NA	NA	NA
2	1 year	≤30 °C/60% RH	168 +5/-0	85 °C/60% RH	NA	NA	NA
2a	4 weeks	≤30 °C/60% RH	696[2] +5/-0	30 °C/60% RH	120 +1/-0	168 +1/-0	60 °C/60% RH
3	168 hours	≤30 °C/60% RH	192[2] +5/-0	30 °C/60% RH	40 +1/-0	52 +1/-0	60 °C/60% RH
4	72 hours	≤30 °C/60% RH	96[2] +2/-0	30 °C/60% RH	20 +0.5/-0	24 +0.5/-0	60 °C/60% RH
5	48 hours	≤30 °C/60% RH	72[2] +2/-0	30 °C/60% RH	15 +0.5/-0	20 +0.5/-0	60 °C/60% RH
5a	24 hours	≤30 °C/60% RH	48[2] +2/-0	30 °C/60% RH	10 +0.5/-0	13 +0.5/-0	60 °C/60% RH
6	Time on Label (TOL)	≤30 °C/60% RH	TOL	30 °C/60% RH	NA	NA	NA

Thermal Interface is the issue in most cases- thickness, roughness, co-valent bonding, **moisture** determines total thermal impedance.

Power Dissipation is Arguably the Greatest Challenge Facing Modern Electron Devices

The thermal requirements on packaging are becoming more demanding



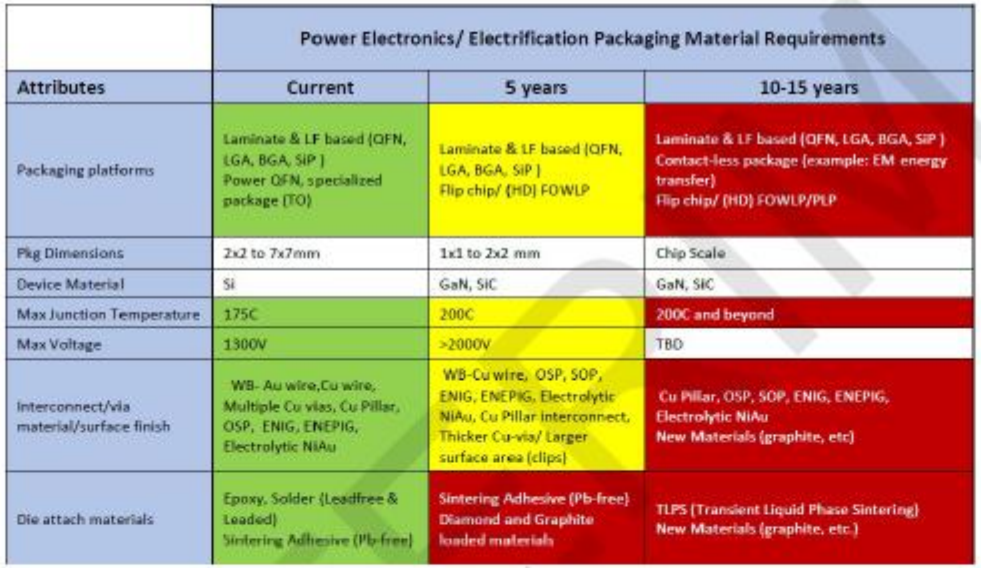
Thermal Management Reaching Limits of Imagination

Source: Raytheon, Avi Bar-Cohen

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

The thermal requirements on packaging are becoming more demanding

Material Requirements[3]



	Power Electronics/ Electrification Packaging Material Requirements		
Attributes	**Current**	**5 years**	**10-15 years**
Packaging platforms	Laminate & LF based (QFN, LGA, BGA, SiP) Power QFN, specialized package (TO)	Laminate & LF based (QFN, LGA, BGA, SiP) Flip chip/ (HD) FOWLP	Laminate & LF based (QFN, LGA, BGA, SiP) Contact-less package (example: EM energy transfer) Flip chip/ (HD) FOWLP/PLP
Pkg Dimensions	2x2 to 7x7mm	1x1 to 2x2 mm	Chip Scale
Device Material	Si	GaN, SiC	GaN, SiC
Max Junction Temperature	175C	200C	200C and beyond
Max Voltage	1300V	>2000V	TBD
Interconnect/via material/surface finish	WB- Au wire,Cu wire, Multiple Cu vias, Cu Pillar, OSP, ENIG, ENEPIG, Electrolytic NiAu	WB-Cu wire, OSP, SOP, ENIG, ENEPIG, Electrolytic NiAu, Cu Pillar interconnect, Thicker Cu-via/ Larger surface area (clips)	Cu Pillar, OSP, SOP, ENIG, ENEPIG, Electrolytic NiAu New Materials (graphite, etc)
Die attach materials	Epoxy, Solder (Leadfree & Leaded) Sintering Adhesive (Pb-free)	Sintering Adhesive (Pb-free) Diamond and Graphite loaded materials	TLPS (Transient Liquid Phase Sintering) New Materials (graphite, etc.)

Diamond and Graphite loaded materials

Thermal Requirements[3]

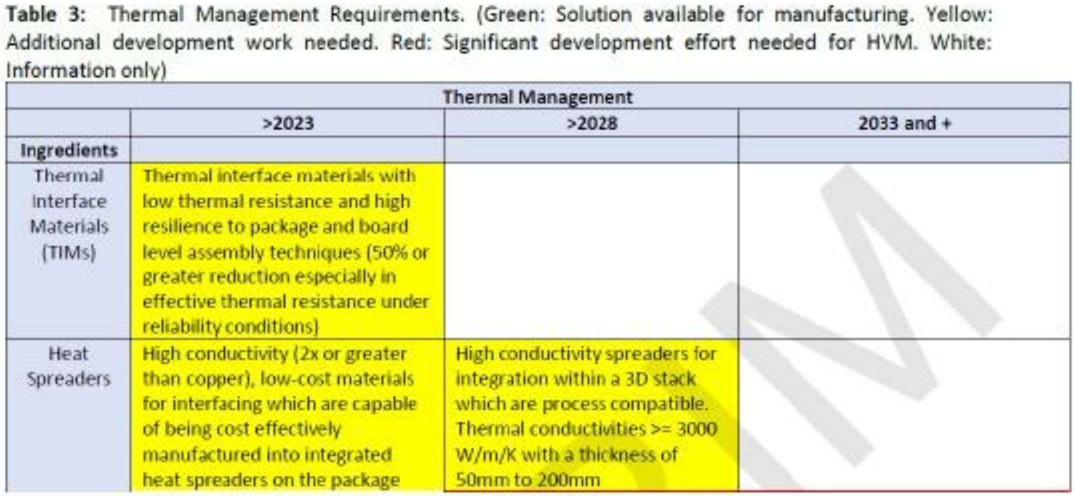


Table 3: Thermal Management Requirements. (Green: Solution available for manufacturing. Yellow: Additional development work needed. Red: Significant development effort needed for HVM. White: Information only)

Thermal Management			
	>2023	>2028	2033 and +
Ingredients			
Thermal Interface Materials (TIMs)	Thermal interface materials with low thermal resistance and high resilience to package and board level assembly techniques (50% or greater reduction especially in effective thermal resistance under reliability conditions)		
Heat Spreaders	High conductivity (2x or greater than copper), low-cost materials for interfacing which are capable of being cost effectively manufactured into integrated heat spreaders on the package	High conductivity spreaders for integration within a 3D stack which are process compatible. Thermal conductivities >= 3000 W/m/K with a thickness of 50mm to 200mm	

Thermal conductivities >= 3000 W/m/K with a thickness of 50mm to 200mm

3. National Institute of Standards and Technologies. Microelectronic and Advanced Packaging Technologies Roadmap. Interim Edition 2023.

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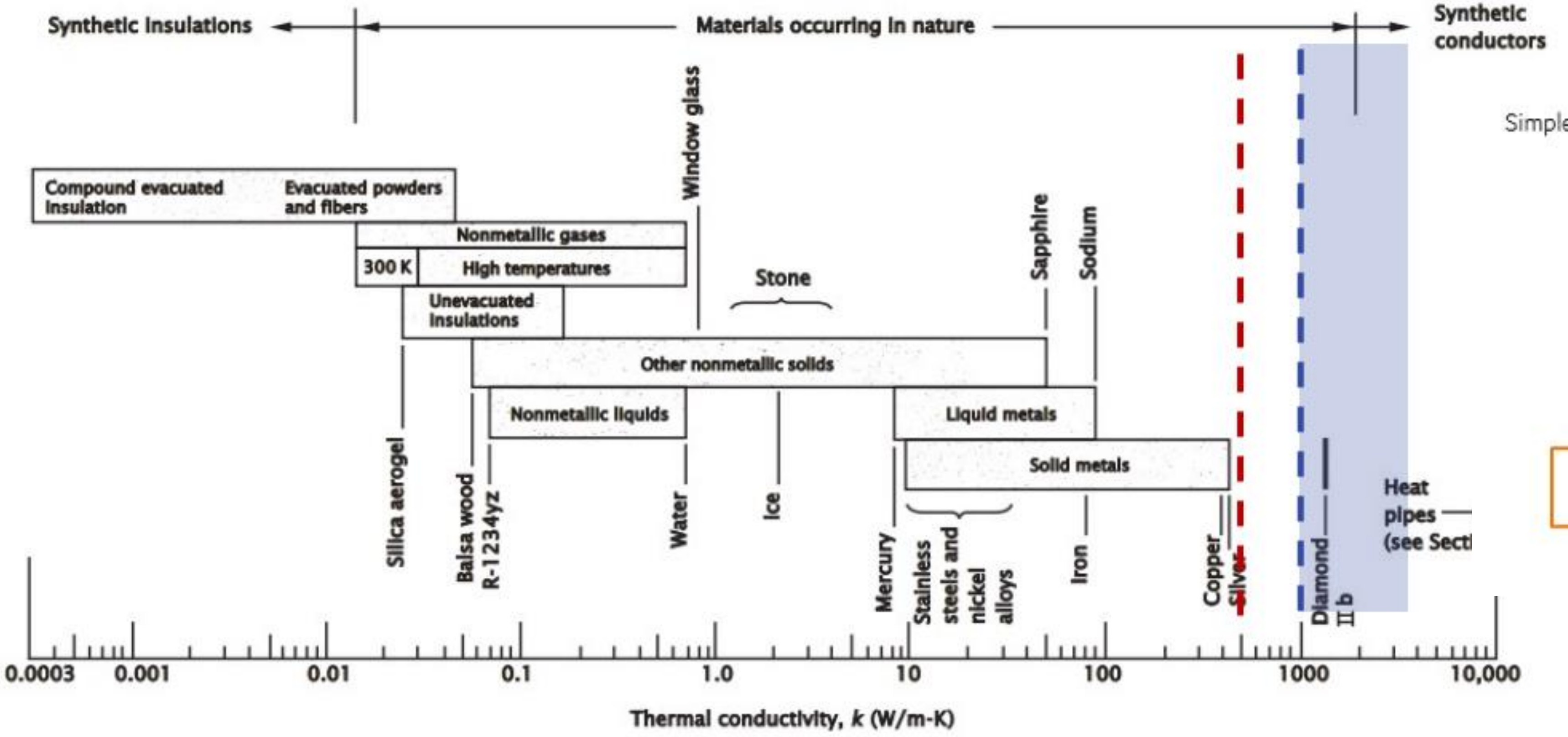
Metallic packaging is fundamentally limited to *k* ~ 10^2 W/mK and few materials can tap into the 10^3 W/mK range.



Simple Kinetic Theory of Thermal Conductivity (k)

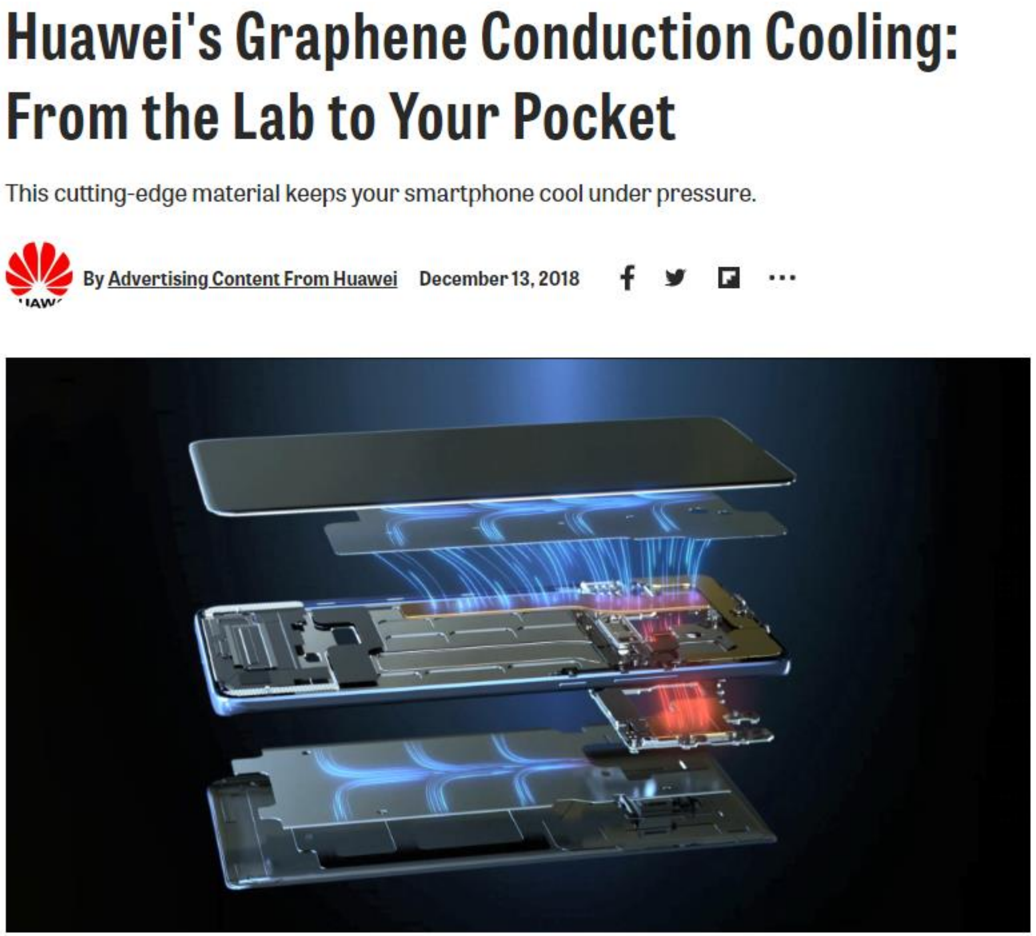
$$k = \frac{1}{3} C v \lambda$$

- C is the heat capacity
- v is the phonon group velocity
- λ is the phonon mean free path

v is directly related to the atomic mass and stiffness of the interatomic bonding

G. Chen. Nanoscale Energy Transport and Conversion. Oxford University Press 2005.

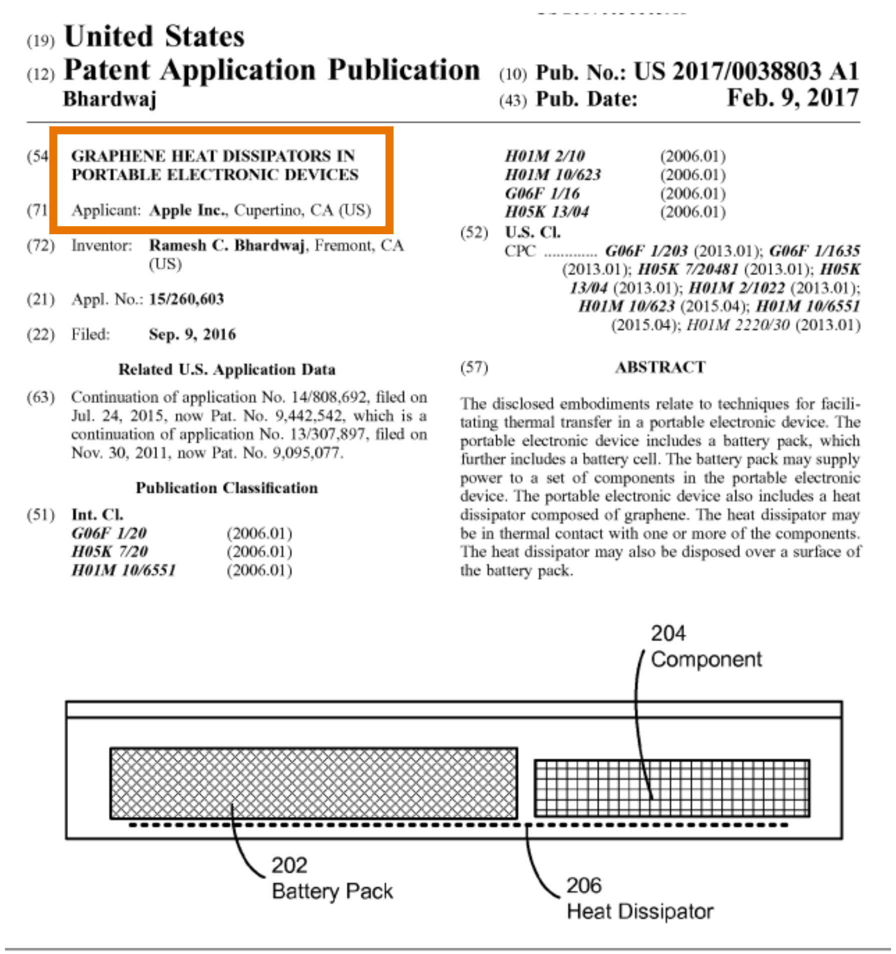
Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices



Huawei's Graphene Conduction Cooling: From the Lab to Your Pocket

This cutting-edge material keeps your smartphone cool under pressure.

By Advertising Content From Huawei December 13, 2018



(19) **United States**
(12) **Patent Application Publication**
Bhardwaj

(10) **Pub. No.: US 2017/0038803 A1**
(43) **Pub. Date: Feb. 9, 2017**

(54 **GRAPHENE HEAT DISSIPATORS IN PORTABLE ELECTRONIC DEVICES**

(71 Applicant: **Apple Inc.**, Cupertino, CA (US)

(72) Inventor: **Ramesh C. Bhardwaj**, Fremont, CA (US)

(21) Appl. No.: **15/260,603**

(22) Filed: **Sep. 9, 2016**

Related U.S. Application Data

(63) Continuation of application No. 14/808,692, filed on Jul. 24, 2015, now Pat. No. 9,442,542, which is a continuation of application No. 13/307,897, filed on Nov. 30, 2011, now Pat. No. 9,095,077.

Publication Classification

(51) **Int. Cl.**

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H01M 10/6551	(2006.01)
H01M 2/10	(2006.01)
H01M 10/623	(2006.01)
G06F 1/16	(2006.01)
H05K 13/04	(2006.01)

(52) **U.S. Cl.**
CPC ***G06F 1/203*** (2013.01); ***G06F 1/1635*** (2013.01); ***H05K 7/20481*** (2013.01); ***H05K 13/04*** (2013.01); ***H01M 2/1022*** (2013.01); ***H01M 10/623*** (2015.04); ***H01M 10/6551*** (2015.04); *H01M 2220/30* (2013.01)

(57) **ABSTRACT**

The disclosed embodiments relate to techniques for facilitating thermal transfer in a portable electronic device. The portable electronic device includes a battery pack, which further includes a battery cell. The battery pack may supply power to a set of components in the portable electronic device. The portable electronic device also includes a heat dissipator composed of graphene. The heat dissipator may be in thermal contact with one or more of the components. The heat dissipator may also be disposed over a surface of the battery pack.

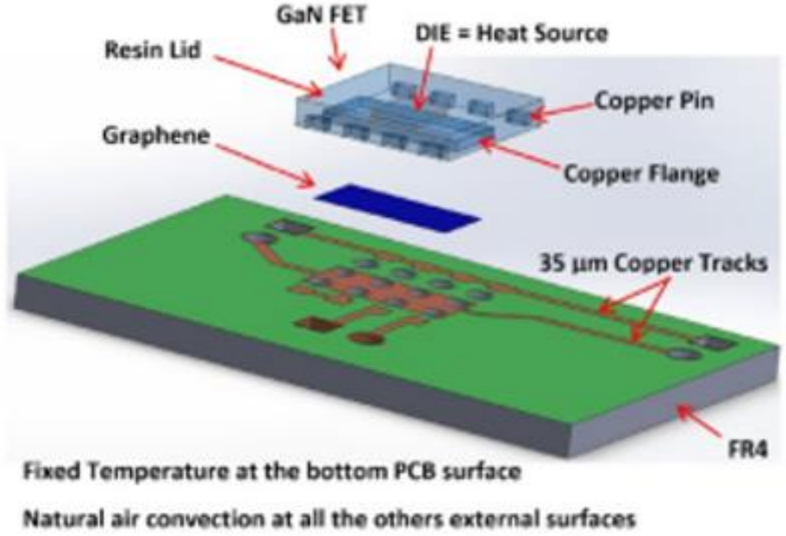
https://www.pcmag.com/news/huaweis-graphene-conduction-cooling-from-the-lab-to-your-pocket

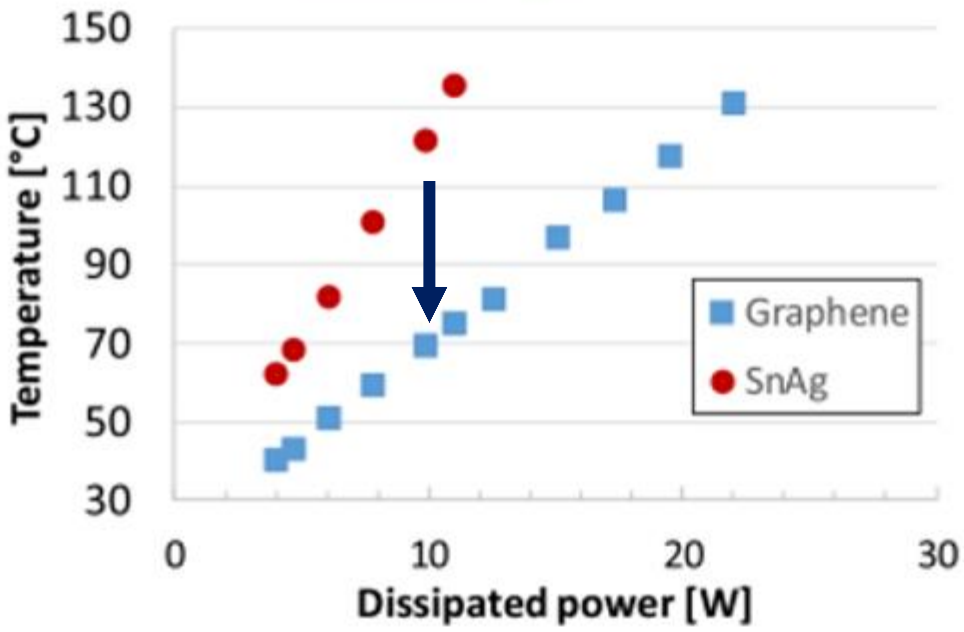
Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

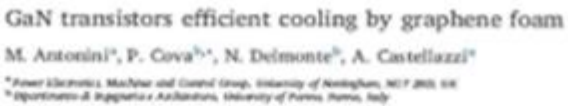
Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel







GaN transistors efficient cooling by graphene foam

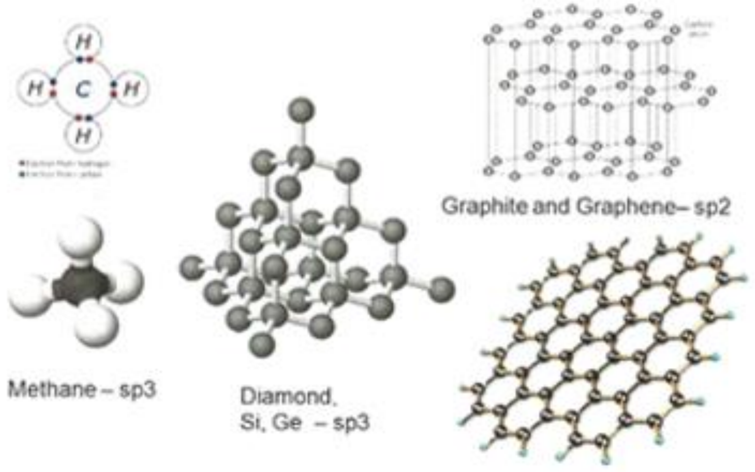
M. Antonini, P. Cova, N. Delmonte, A. Castellazzi

M. Antonini, et al. GaN transistors efficient cooling by graphene foam. Microelectronics Reliability 2018.

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

Why are carbon materials (graphene, graphite, carbon nanotubes, diamond) seemingly alone on many roadmaps for advanced passive/conductive thermal packaging?

Covalent Structures



Carbon has electrically insulating and conducting forms

$$\omega = \sqrt{\frac{k}{m}}$$

From mechanics, the vibrational frequency (ω) of a harmonic oscillator is related to the atomic mass and stiffness of the interatomic potential.

Carbon has light atoms and stiff bonds

$$k = \sum^{\text{modes}} C v \lambda$$

Heat Capacity

Phonon Mean-Free Path

From kinetic theory, the thermal conductivity is related to the group velocity ($v \propto \omega$) of the phonons.

Carbon has high thermal conductivity

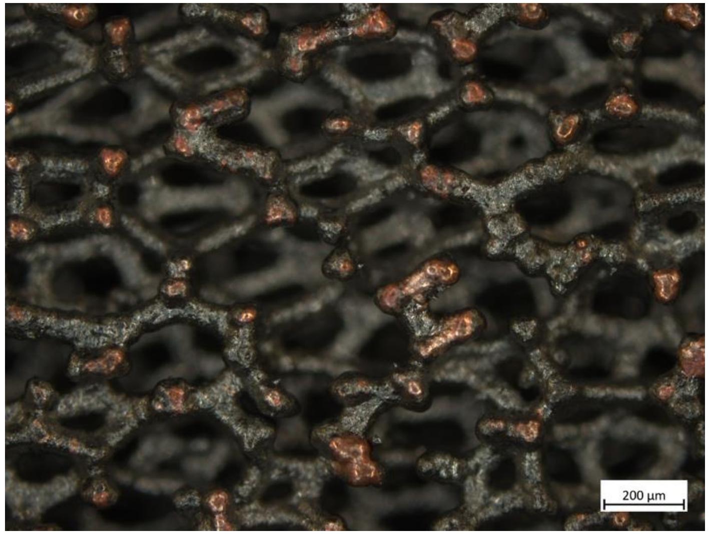
Many synthetic conductors, like heat pipes or microfluidics, may not be compatible with highly integrated systems.
For example, back-end-of-the-line compatibility for monolithic 3D integration.

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

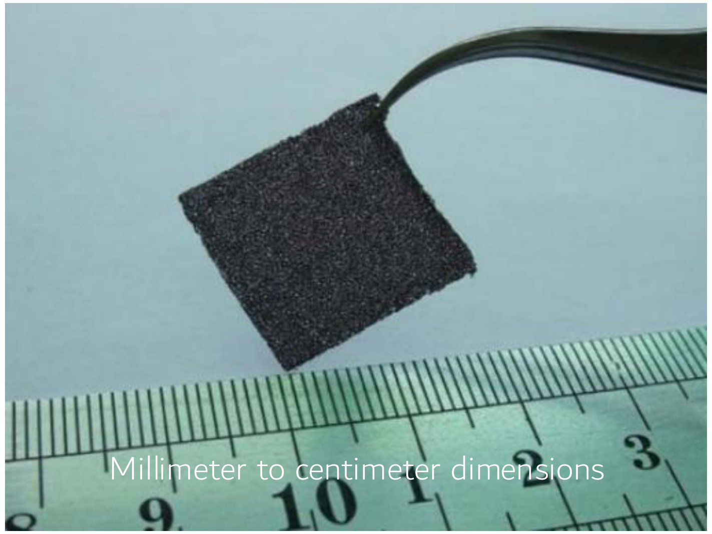
Graphene and graphite can be grown directly on 3D metal templates.

Chemical Vapor Deposition

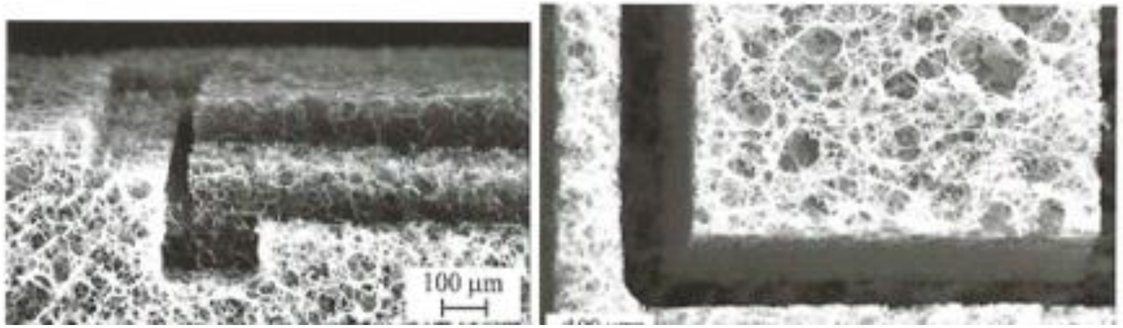
Microscopic Image



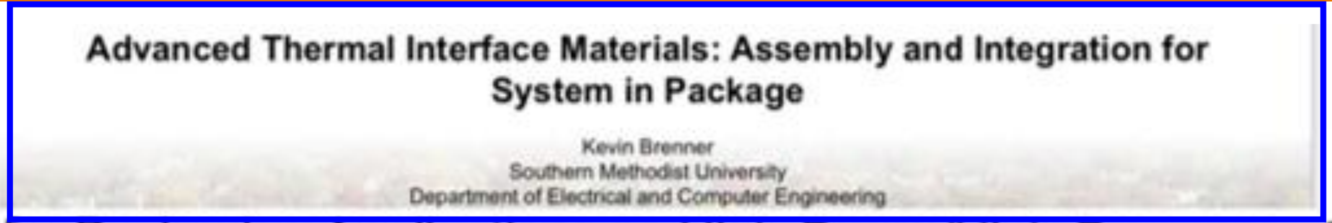
Macroscopic Image


Millimeter to centimeter dimensions

Flakes, sheets, foams



Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

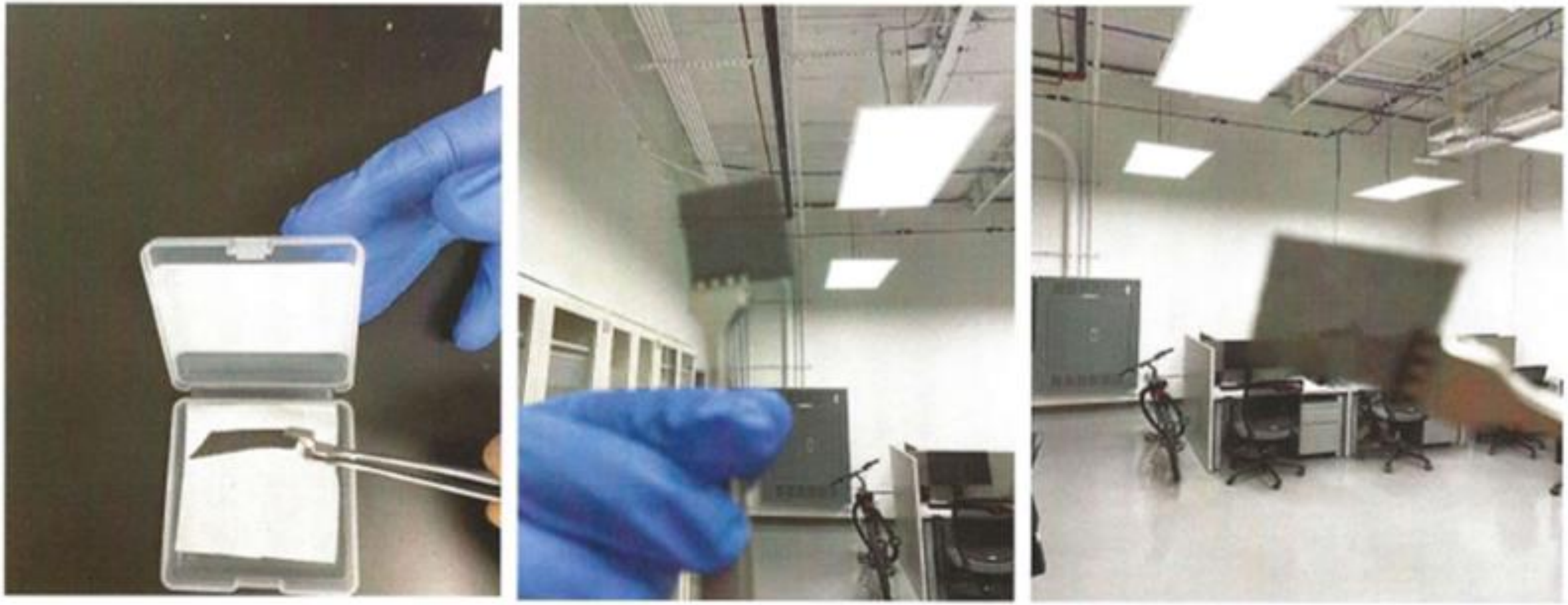


Advanced Thermal Interface Materials: Assembly and Integration for System in Package

Kevin Brenner
Southern Methodist University
Department of Electrical and Computer Engineering

Graphene for Packaging Applications on High-Power/High-Frequency Products

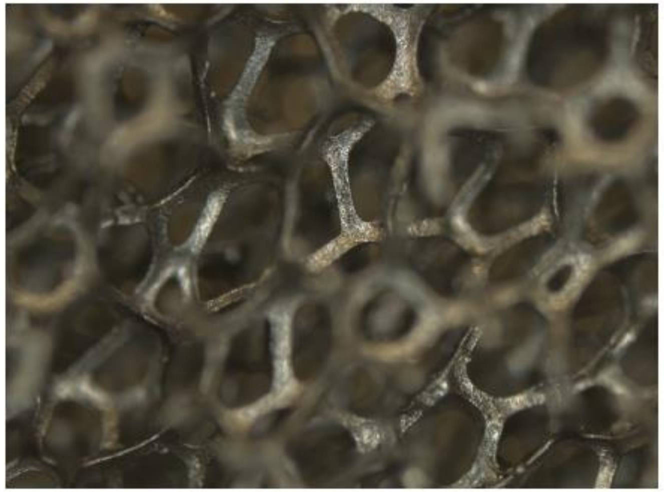
(Metallic foams coated with Graphene – no X-Y size restrictions)



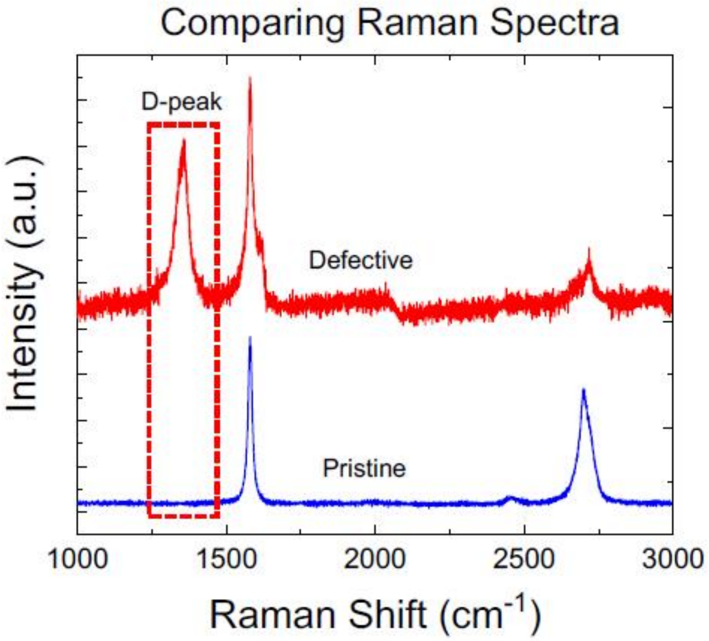
Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

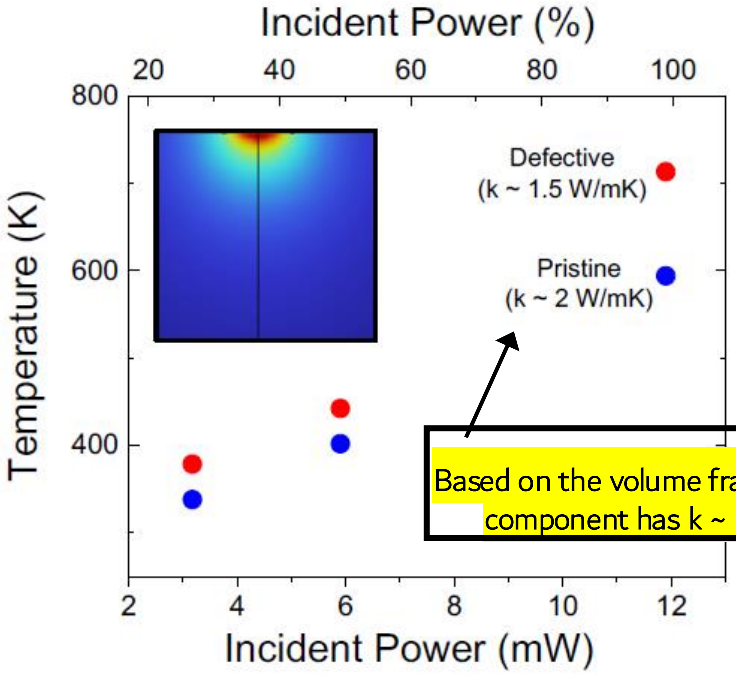
The thermal conductivity and material quality can be simultaneously characterized for carbon-based TIMs.

Graphite-Metal Composite



Comparing Raman Spectra



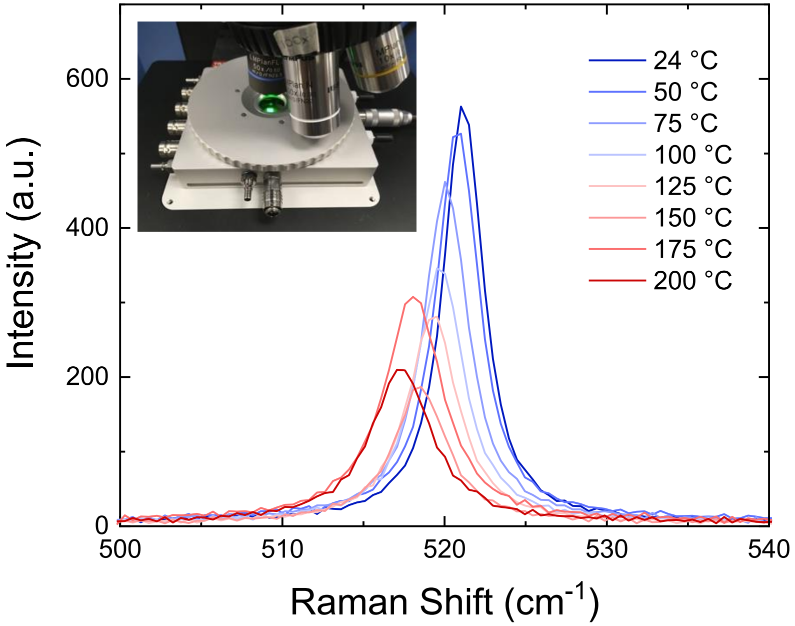


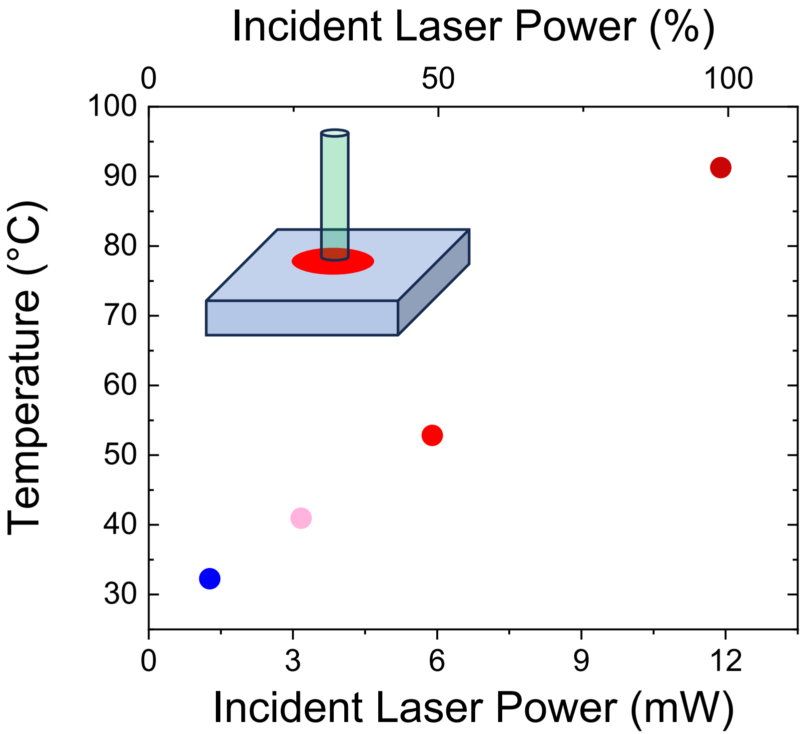
Based on the volume fraction, the solid component has k ~ 524 W/mK

Raman spectroscopy is one of the few metrologies that can uncover the underlying nature of changes in thermal conductivity. For example, correlating it with a wide range of material properties (defects, strain, etc.)

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

Raman thermometry can provide accurate temperature measurements for extracting thermal conductivity.





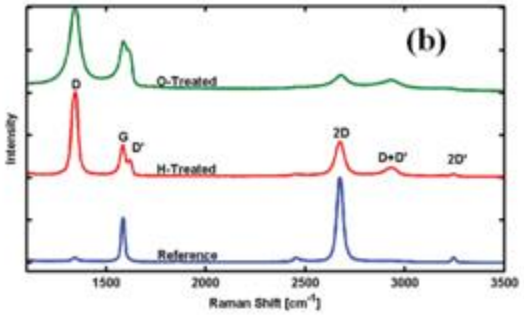
93 C at 7.3 mW heat flux gives k ~ 140 W/mK

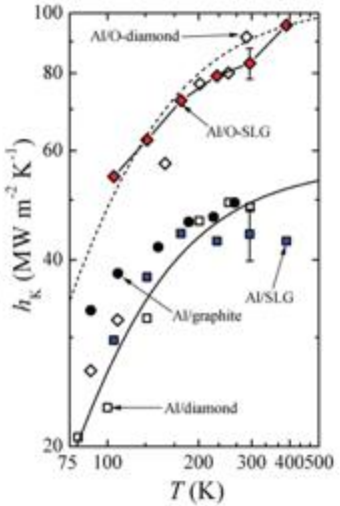
The Raman laser is now a simultaneous **heater**, **thermometer**, and **characterizer** of structural/chemical details!

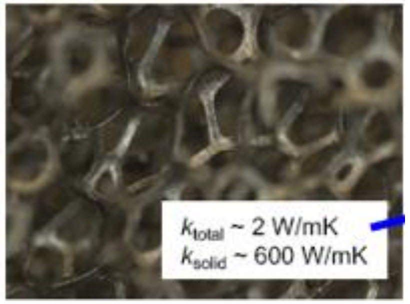
Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices

> Sound and heat can be treated similarly, and just as sound reflects at interfaces between soft and stiff materials (think echoes in open spaces with walls), so does heat. .....(Dr.Kevin. Brenner at UTD)

2× Decrease in TBR with Surface Functionalization
(graphene-metal)

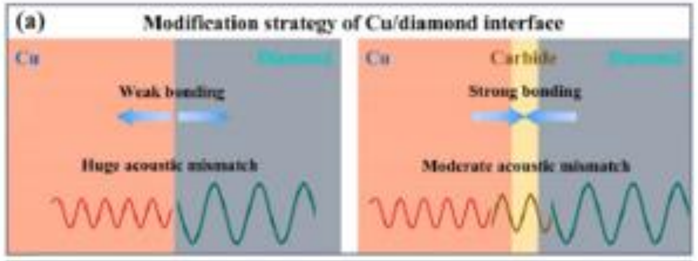


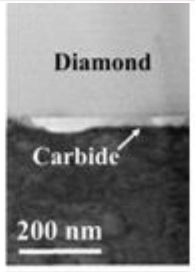


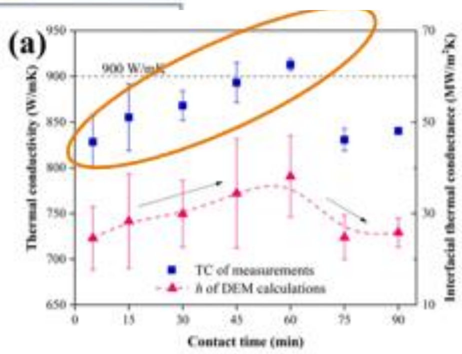


Successful Engineering of Carbon-Metal Interfaces

Interfaces can be controlled?

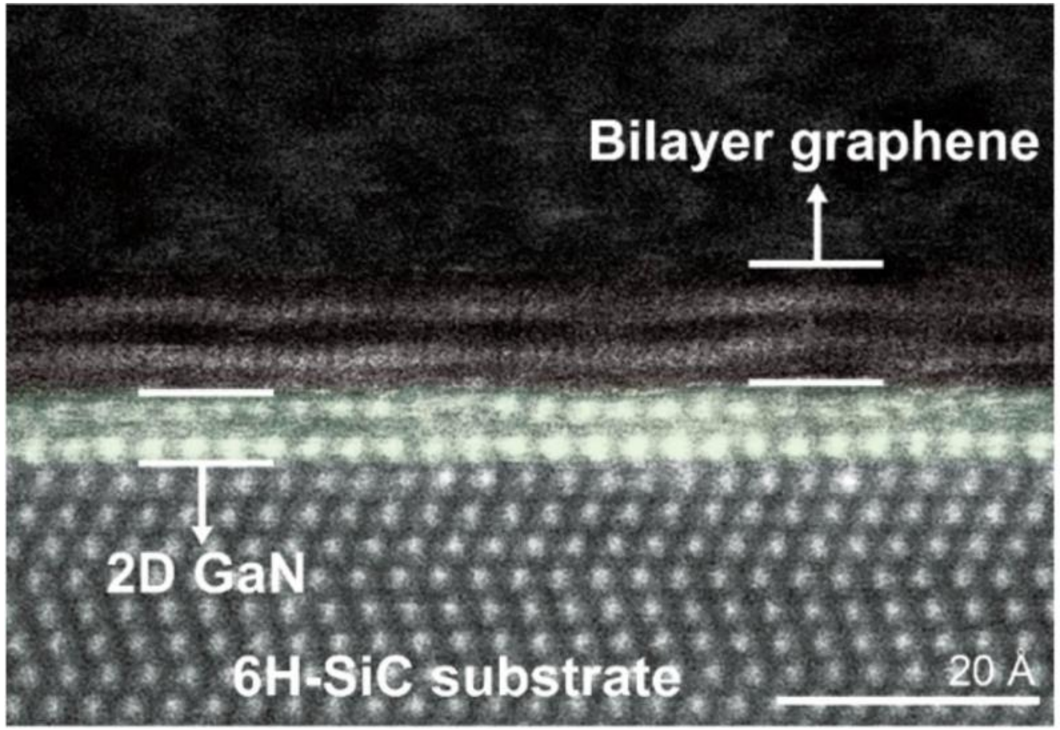




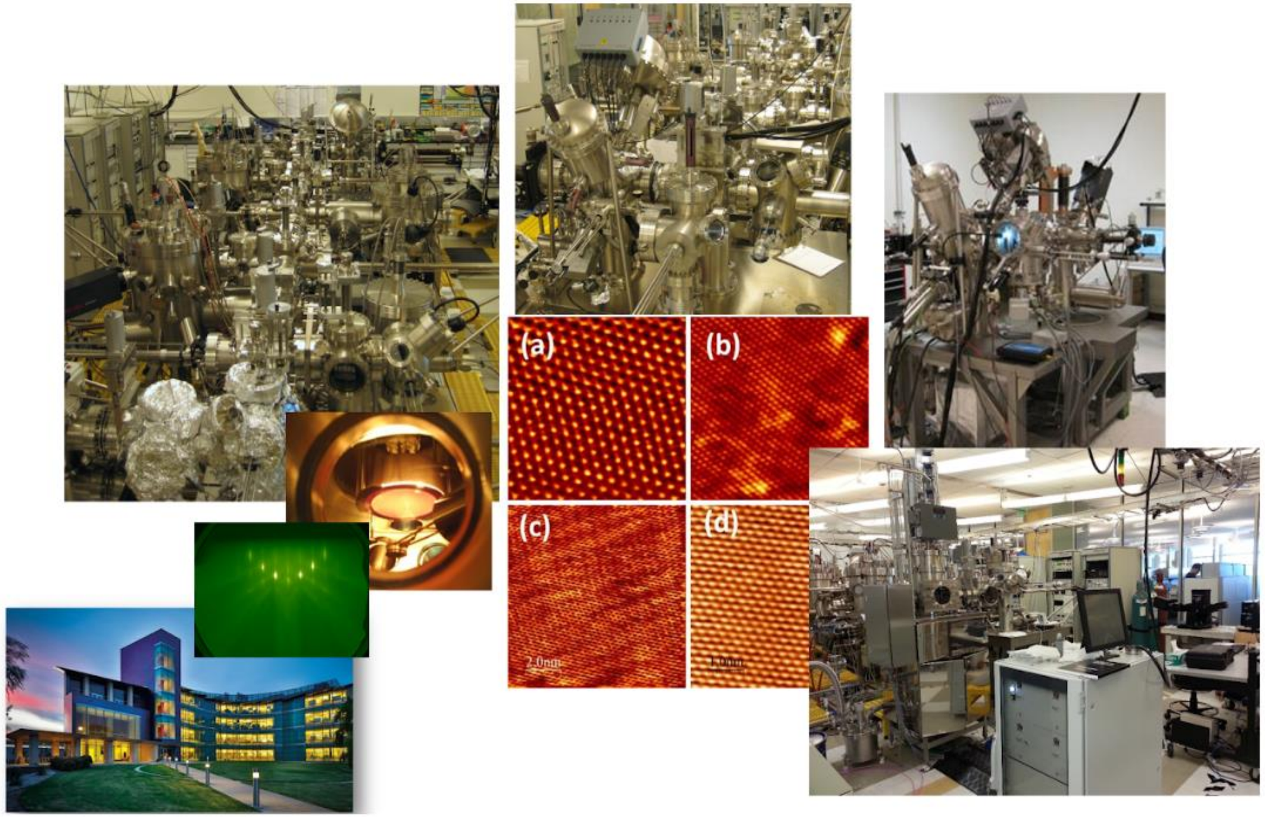


P. Hopkins, et al. Manipulating Thermal **Conductance at Metal-Graphene Contacts** via Chemical Functionalization. Nano Letters 2012.
Y. Zhang, et al. Manipulating in-situ discrete carbide interlayer to achieve high thermal conductivity in Cu-B/diamond composite. Materials Today Communication 2023.

Power Dissipation is Arguably the Greatest Challenge Facing Electron Devices



Welcome to the Addou Lab



Wallace Group

https://sites.google.com/view/robert-m-wallace/home
https://sites.google.com/view/robert-m-wallace/home/recent-research

Capabilities at UTD in Materials Science and Engineering

- **Modern CVD techniques to engineer**
  - **properties of highly thermally conductive carbon-based materials on supported (mesh)**

- **Modern spectroscopy methods to establish**
  - **atomic structures and nature of**
  - **defects affecting thermal conduction**

- **Experimental recipes to attach TIM-2 to thermal spreaders (Cu)**
  - **die attach to laminate substrates.**
  - **demonstrations of lateral cooling under multiple die for OVM & SiP designs**

- **RF testing capabilities (<100 MHz) to register cooling effects (Tj)**

- **Customer driven prototype for micro assembliey**
  - **electroless conditioning of CVD coated foams or mesh with conductive materials**
  - **PVD coating of foams or mesh for thermal improvements at the interfaces**

- **Engineering talent exchange with the customer under UTD Department of Materials Science and Engineering**

instituto de
telecomunicações

Thermal management with diamond

Joana C. Mendes

Instituto de Telecomunicações, Universidade de Aveiro, Portugal

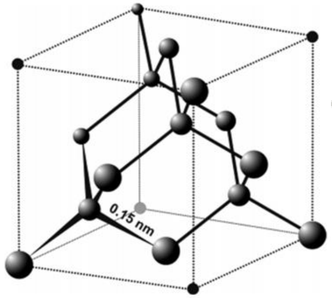
universidade
de aveiro

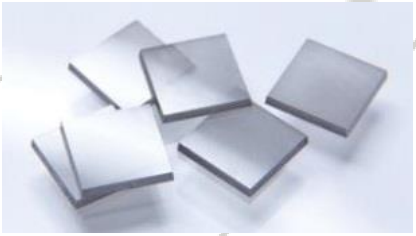
CMSE, April 29th, 2026 Los Angeles, CA

TYPES OF DIAMOND: pros and cons

Single-crystal diamond (SCD):

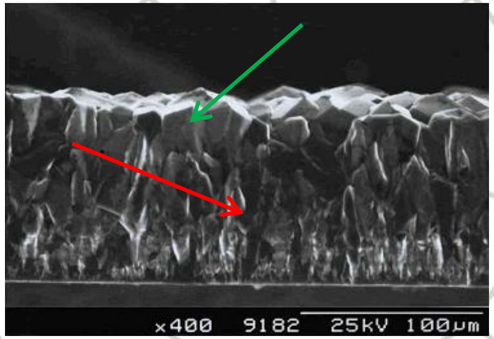
- Perfect crystalline structure.
- Thermal conductivity up to **2200 W/m-K**.
- Routinely available in sizes up to **10×10 mm²**; **2** and **4-inch** reported.

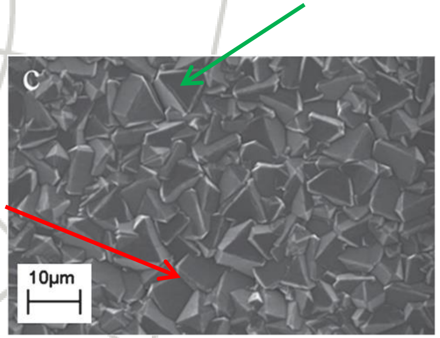




Polycrystalline diamond (PCD):

- Polycrystalline structure, with diamond grains connected via grain boundaries (graphite, amorphous carbon, etc).
- Phonons are scattered by the grain boundaries, decreasing the thermal conductivity.
- Depending on grain/grain boundaries (sp^3/non-sp^3) ratio the thermal conductivity may vary between **1000-1800 W/m-K**.
- Routinely available in **4-inch** size; **8-inch** has also been reported.





SCD and PCD is **commercially available** from different suppliers
(US, Europe, China, India, ...)

https://www.diamond-materials.com/en/products/thermal-management/heat-spreaders/; Gracio2010; Zolotukhin2012; http://www.chm.bris.ac.uk/pt

DIAMOND HEAT SPREADERS: CRITICAL MANUFACTURING STEPS

1. Polishing

- Mechanical polishing (diamond slurry + rigid plate)
- Chemical-mechanical polishing (CMP)

2. Microfabrication

- Laser micromachining (cuts, trenches, channels, vias)
- Lithography (Al, Cr, Ni, SiO_2, SiN) + RIE/ICP O_2 plasma

3. Surface cleaning

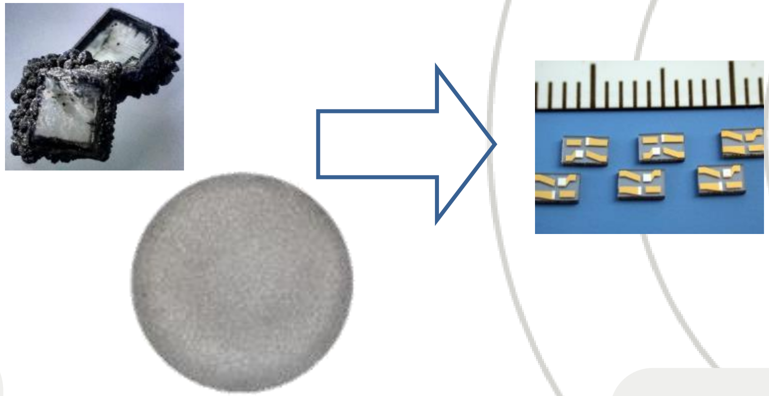
- Plasma cleaning (Ar, O_2)
- Wet cleaning (strong oxidizing/acid mixtures)

4. Metallization

- Adhesion layer (Ti/Cr)
- Diffusion barrier (Pt/Ni/W)
- Bonding layer (Au/Cu)

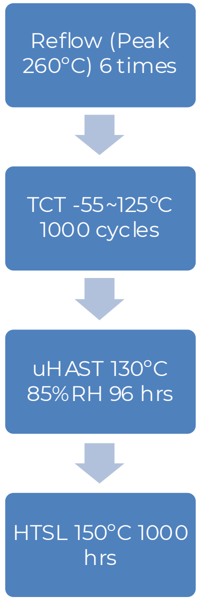
5. Bonding

- Thermocompression bonding
- Eutectic soldering
- Nano-Ag sintering
- Liquid-metal bonding



https://www.diamond-materials.com/en/products/thermal-management/heat-spreaders/; Mendes2025b

DIAMOND & Si, THERMOCOMPRESSION BONDING

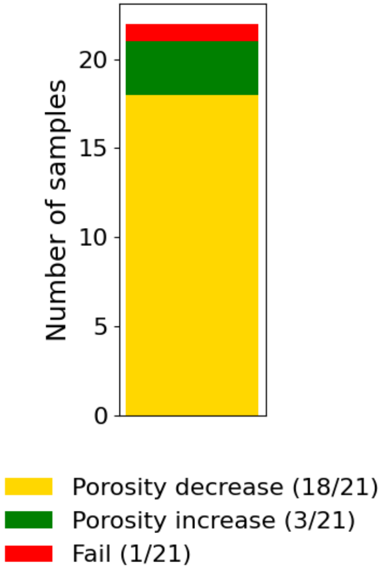


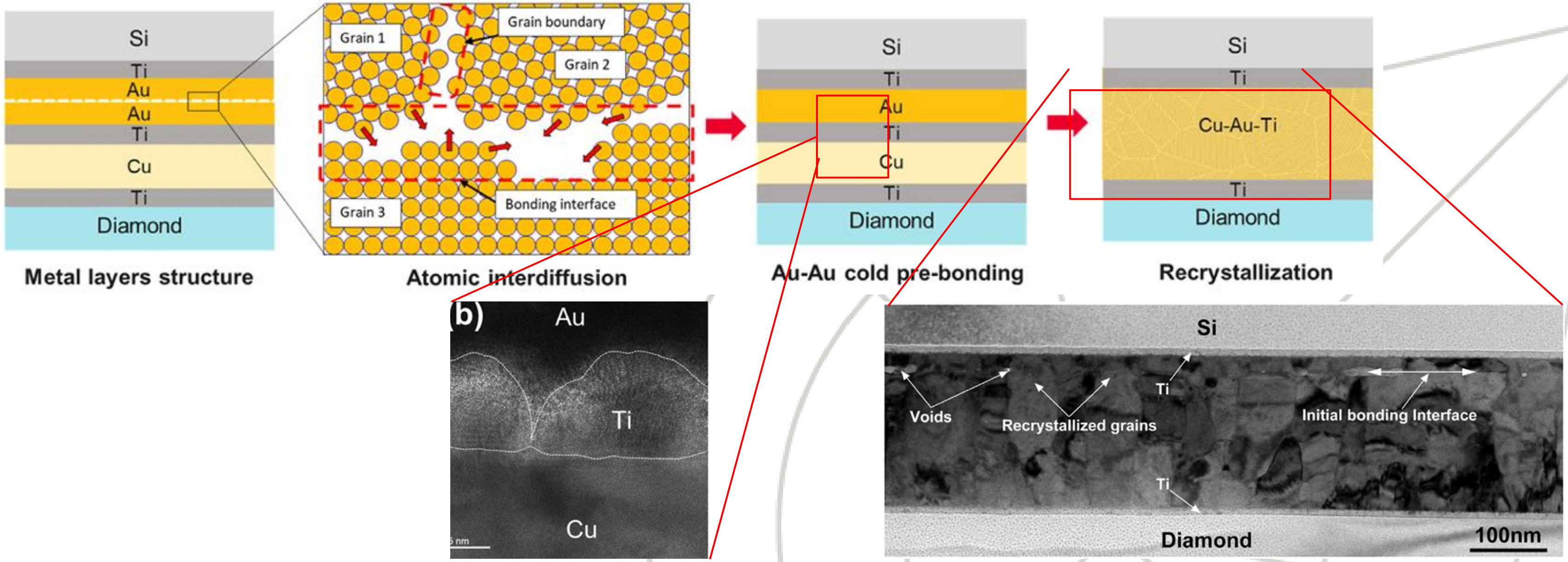
Reflow (Peak 260°C) 6 times

TCT -55~125°C 1000 cycles

uHAST 130°C 85%RH 96 hrs

HTSL 150°C 1000 hrs



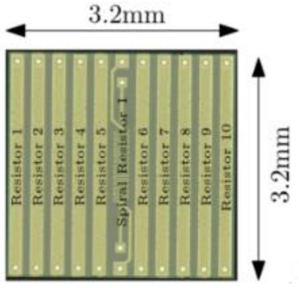


- **Heterogeneous bonding layer** with residual voids and distinct grain boundaries.
- Competing mechanisms during reliability testing:
  - In most samples **enhanced atomic diffusion** during thermal cycling reduces residual porosity (**void healing**).
  - In other samples **local stress concentrations** due to diamond-Si CTE mismatch promote **void growth** and **interfacial degradation**.

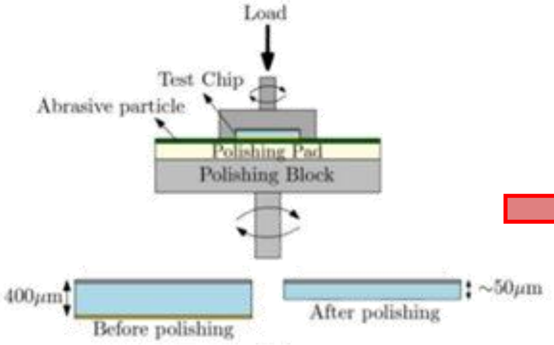
Bonding @200°C: metastable Cu-Au-Ti nanolayer interface!

Zhong2024a

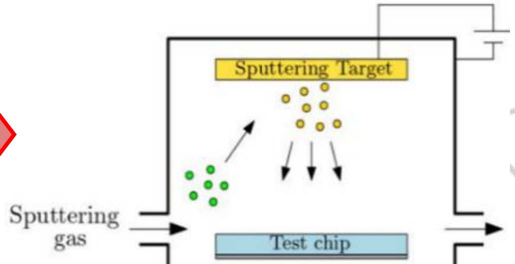
THERMALLY-ENHANCED PQFN PACKAGE (2023)



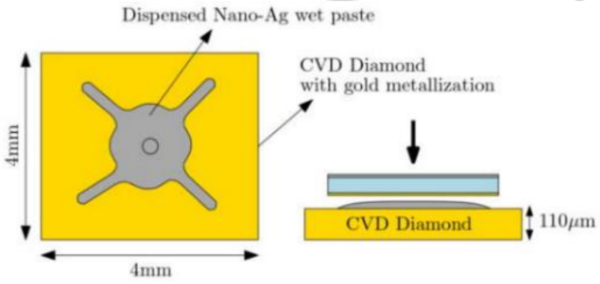
Commercial TTCs.



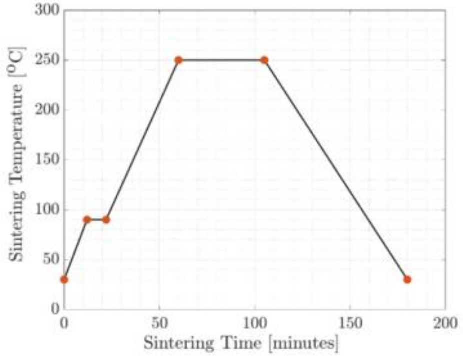
TTC thinning down.

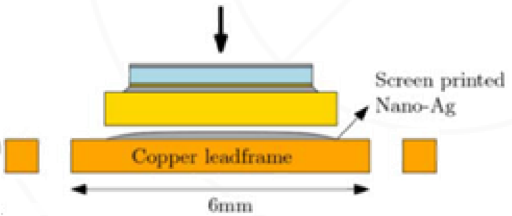


Deposition of 100/200/600 nm Ti/Pt/Au on TTC backside and 110 μm-thick diamond.

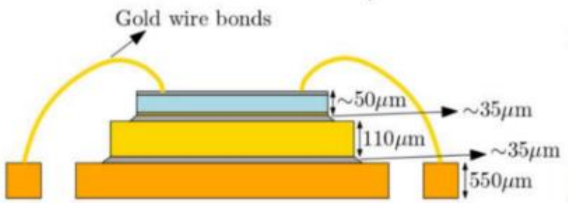


Wet/mounting of TTCs on diamond using **nano-Ag paste** + **pressureless sintering in N_2.**

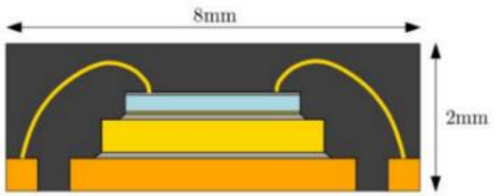




Screen printing and wet mounting of TTC-diamond stack on Cu + **pressureless sintering in N_2.**



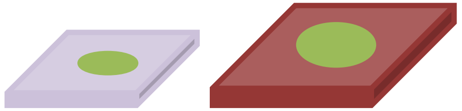
Wire-bonding.



Over-molding.

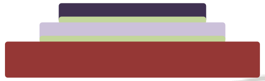
Martin2023

SYSTEM- LEVEL APPLICATION: GaN HPA MMIC (2024)

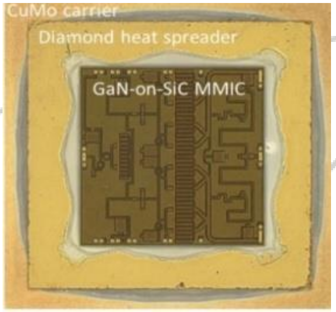


Dispensing of nano-Ag paste on Ti/Pt/Au-plated diamond heat spreaders and 25.4×25.4×3 mm³ Au-plated MoCu cold plates.

Placement of 5.25×5.4 mm² GaN-on-SiC MMIC on diamond heat spreader with a die-bonder and **pressureless sintering in N_2**.



Placement of MMIC-on-diamond on MoCu cold plate and **pressureless sintering in N_2**.

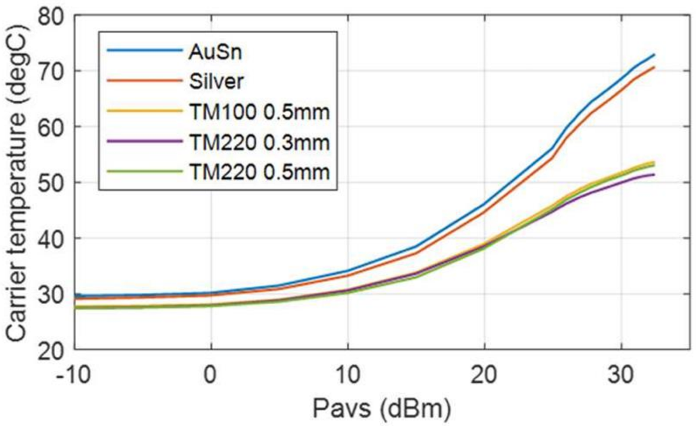


MMIC-on-diamond-on-MoCu cold plate.

DIAMOND ID	TC (W/m-K)	THICKNESS (μm)	AREA (mm²)
TM100_500	**1000**	500	8×8
TM200_300	**2200**	300	
TM200_500	2200	500	

☞ Thickness Ag layer: ≈**30 μm**.

☞ $TC_{AG\ layer}$ ≈**100 W/m-K**.

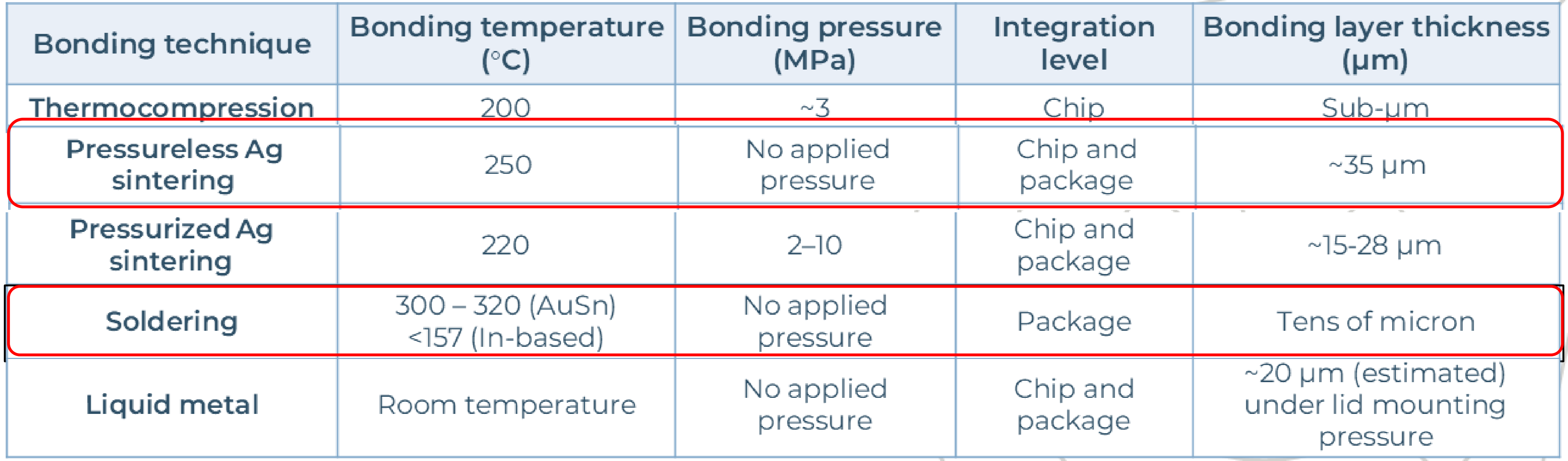


Experimental temperature values of CuMo cold plate obtained with 1 ms pulses and 10% duty cycle.

☞ Temperature of MoCu cold plate below the diamond heat spreader is almost **30% lower** than without a heat spreader.

VanHeijningen2024

COMPARISON OF DIFFERENT BONDING TECHNIQUES

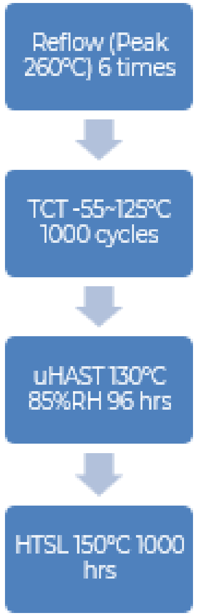


Bonding technique	Bonding temperature (°C)	Bonding pressure (MPa)	Integration level	Bonding layer thickness (µm)
Thermocompression	200	~3	Chip	Sub-µm
Pressureless Ag sintering	250	No applied pressure	Chip and package	~35 µm
Pressurized Ag sintering	220	2–10	Chip and package	~15-28 µm
Soldering	300 – 320 (AuSn) <157 (In-based)	No applied pressure	Package	Tens of micron
Liquid metal	Room temperature	No applied pressure	Chip and package	~20 µm (estimated) under lid mounting pressure

COMPARISON OF DIFFERENT BONDING TECHNIQUES

Bonding technique	Main advantages	Main limitations
Thermocompression	Ultra-thin interfaces → lowest thermal resistance; BEOL-compatible temperatures; scalable to chiplets / interposers / 3D integration	Stiff interface → higher CTE stress; requires excellent surface prep and planarity; bonding pressure may limit very thin or brittle dies
Pressureless Ag sintering	Gentle assembly; good stress relaxation; compatible with existing power / package lines; tolerant to roughness	Thick bonding layers; thickness and porosity limit ultimate TIR; not pitch-scalable for advanced packaging
Pressurized Ag sintering	Lower TIR than pressureless Ag; large-area capability; tunable via pressure; tolerant to roughness	Requires MPa-level pressure; still thick interfaces; tooling complexity
Soldering	Highly mature; strong reliability pedigree; tolerant to roughness	Low thermal conductivity; thick bonding layers; In-based solders more tolerant to CTE mismatch
Liquid metal	Best stress compliance; conformal contact; room-temperature assembly; excellent for evaluation and retrofit; tolerant to roughness	Not a structural bond; pump-out and containment risks; long-term reliability and manufacturability challenges

KNOWN TO DATE RELIABILITY CHALLENGES

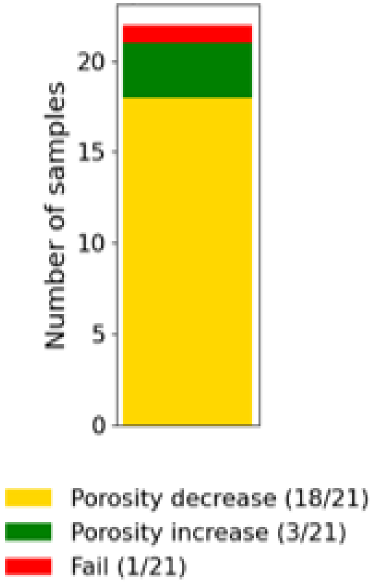


Reflow (Peak 260°C) 6 times

TCT -55~125°C 1000 cycles

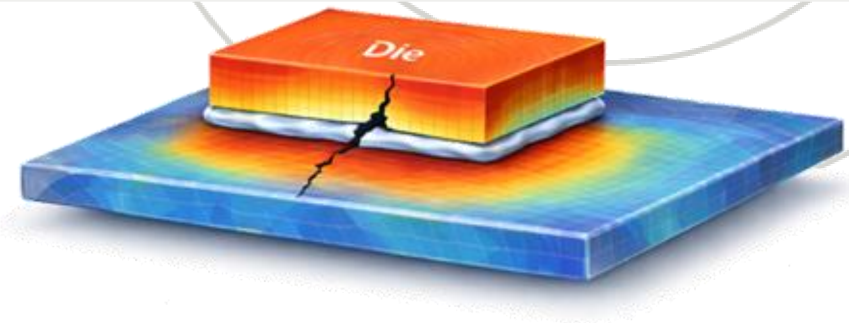
uHAST 130°C 85%RH 96 hrs

HTSL 150°C 1000 hrs



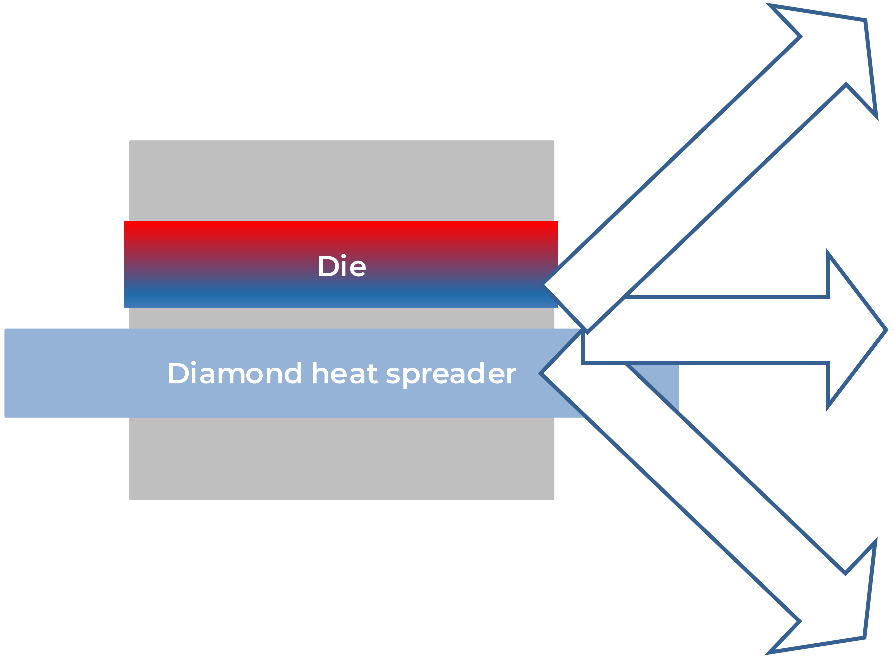
🟨 Porosity decrease (18/21)
🟩 Porosity increase (3/21)
🟥 Fail (1/21)

1. Diamond's intrinsic properties (**low CTE, high Young Modulus**) may affect assembly reliability.
2. CTE mismatch between diamond heat spreader and chip, combined with high lattice stiffness, generates **significant thermomechanical stress** during thermal cycling.
3. Thermal stresses scale with planar dimensions (length and width), so **CTE mismatch** is **especially critical for large-area chips and heat spreaders**.
4. For chips on **crystalline substrates (e.g., GaAs, InP)**, excessive tensile stress can lead to **substrate fracture** when the assembly exceeds the chip's tensile fracture load.



Mendes2025; Mendes2025a

RECOMMENDED MITIGATION STRATEGIES



Soft TIM - low-temperature solders (In, Bi alloys)

- Suitable for large chips on diamond.
- Low Young's modulus and creep behavior help relieve strain during thermal cycling.

Hard TIM - high-temperature solders (AuSn, AuGe; 280–356 °C)

- High stiffness and higher CTE (≈13–16 × 10^{-6}/K) reduce transfer of tensile load to brittle semiconductor substrates.

CTE-tailored composites

- Adjust CTE by adding Cu or Al layers to metallization stack.
- Use Cu–Invar–Cu or **Cu–Mo–Cu** stacks to tune the overall expansion of the multilayer.

Mendes2025; Mendes2025a

Thermal Management with Advanced Composite Thermal Interface Materials

Bill Ishii

Sumitomo Electric USA (Thermal Solutions Group)
A.L.M.T. Corp.

CMSE, Los Angeles, CA
April 29th, 2026

Large selection of CTE engineered Composite materials

Pure Metals

Molybdenum(Mo), Tungsten(W)

Application: Diode and Thyristor,
Power Transistor Substrate, LED Substrate

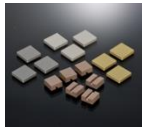
Metal Matrix Composites

Cu-W

Application: Opto Electronics, Photonics,
Wireless Communication, LED Substrate

Cu-Mo

Application: Wireless Communication,
Opto Electronics, Automobile, Green, LED,
Industrial machine



CPC™

Application: Wireless Communication,
Opto Electronics, Automotive, Green,
LED, Industrial machine

Ceramics

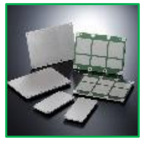
AlN

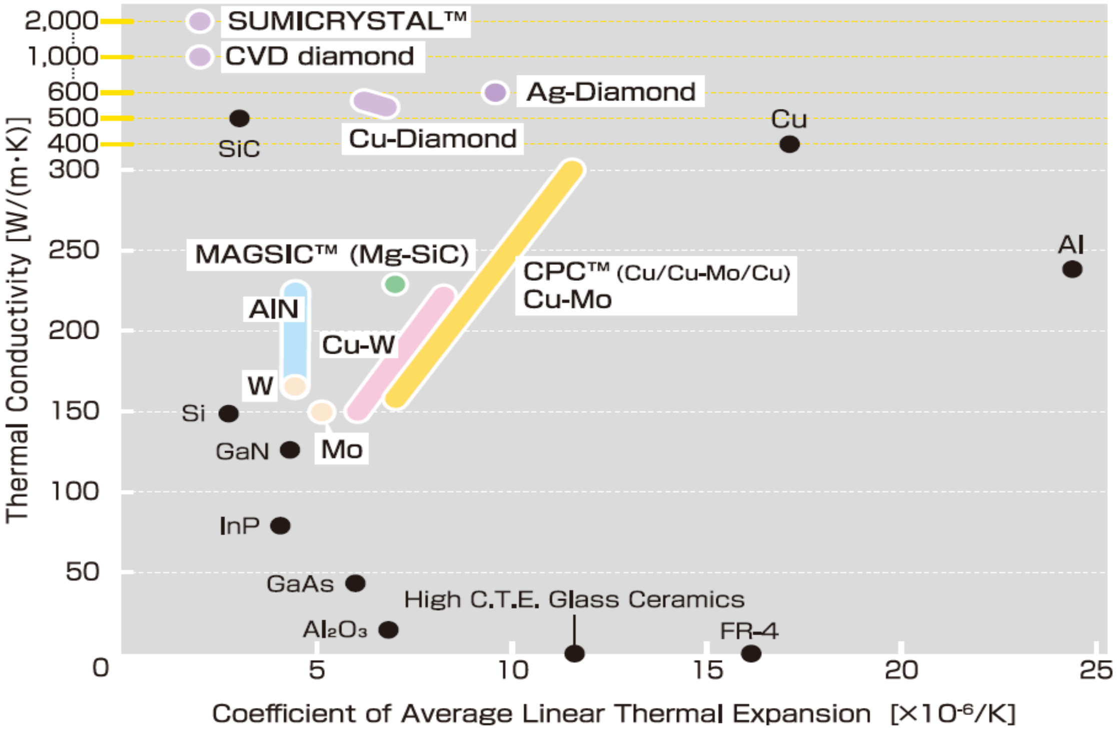
Application: Semiconductor Laser
Submount, LED Substrate

Metal Ceramics

MAGSIC™

Application: Power Module, Industrial
machinery, Automotive (HEV)

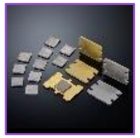




Diamond

Ag-Diamond

Application: Wireless
Communication,
Ceramic Package,
Power Transistor Substrate



Cu-Diamond

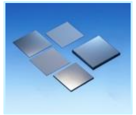
Application: Semiconductor
Laser Submount,
Power Transistor Substrate

SUMICRYSTAL™

Application: Semiconductor
Laser Submount

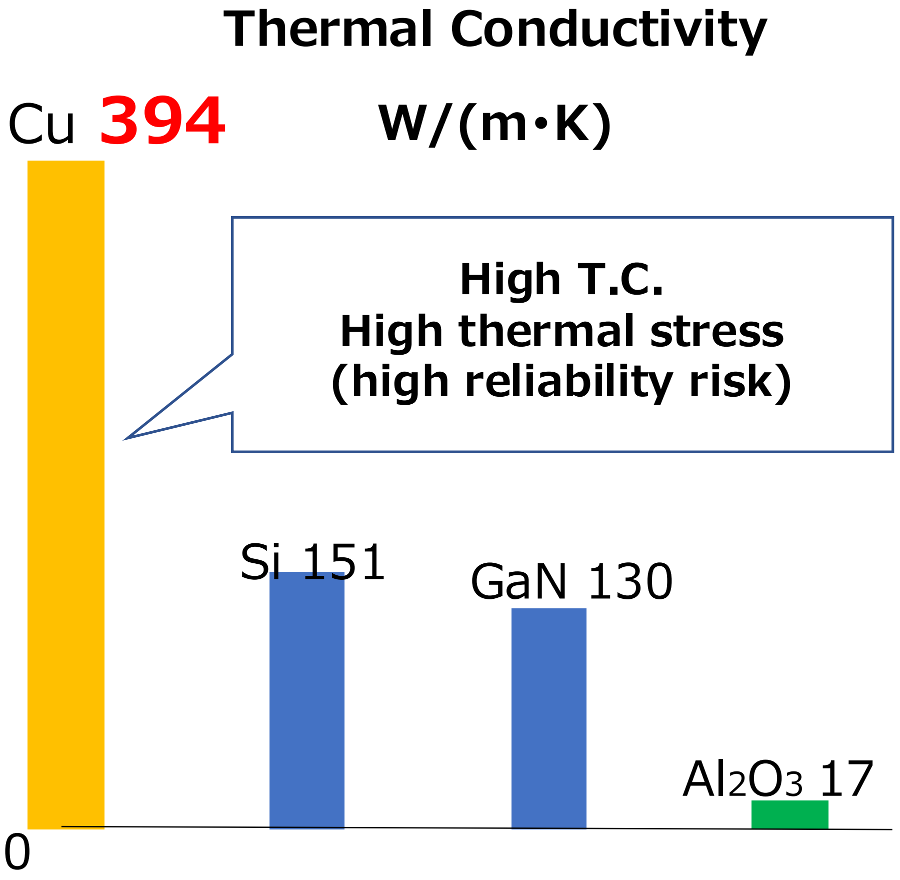
CVD diamond

Application: Semiconductor
Laser Submount,
Power Transistor Substrate

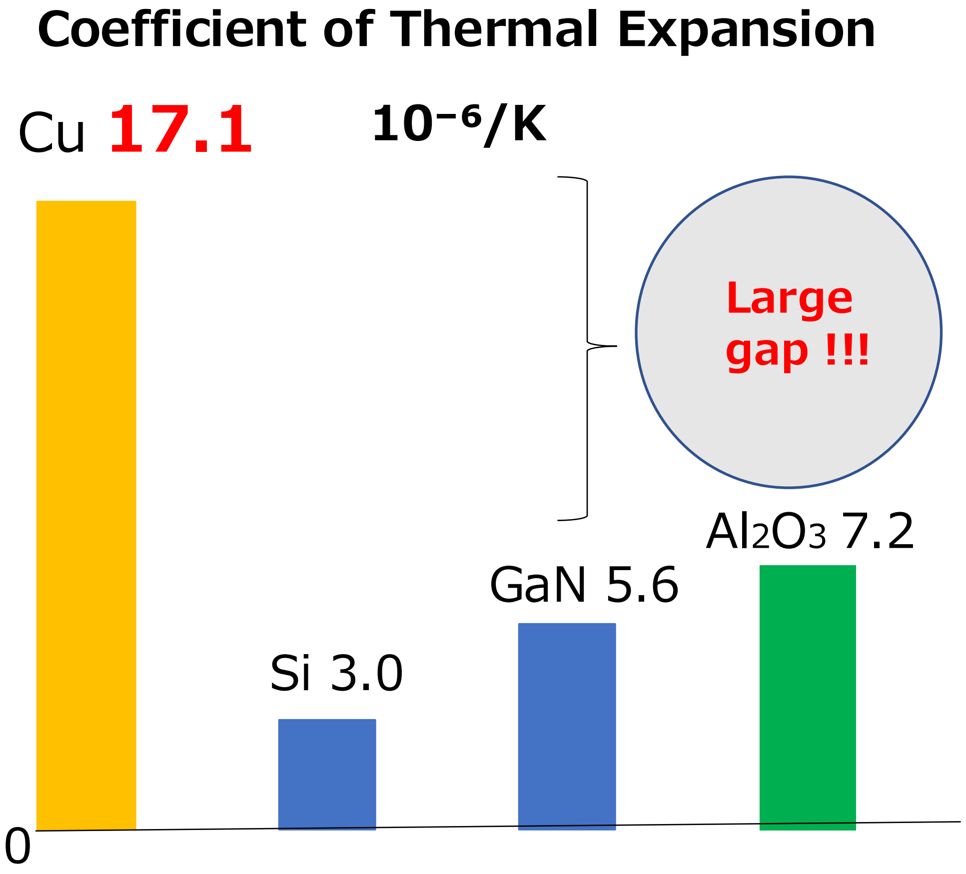


The importance for thermal management of power devices

As power devices grow in functionality, they generate higher heat and thus require advanced thermal management.

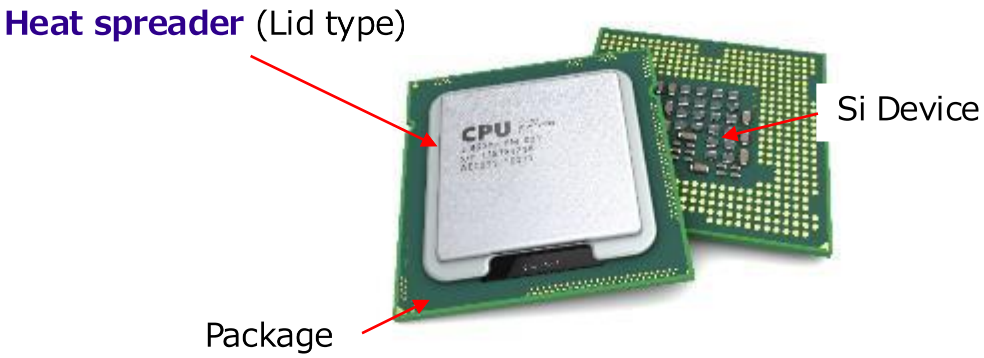


High T.C.
High thermal stress
(high reliability risk)

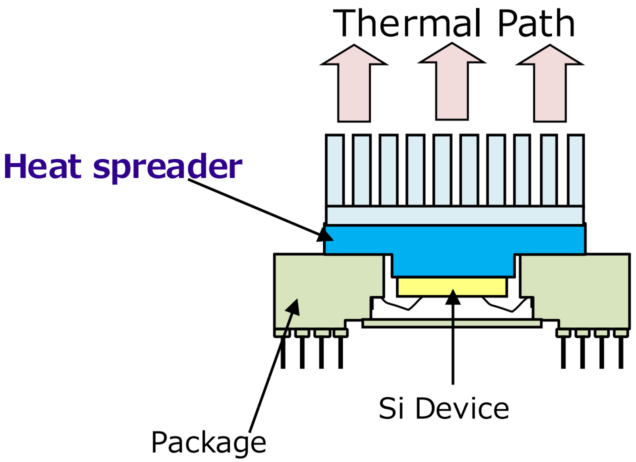


Large gap !!!

CTE engineered thermally matched interface materials

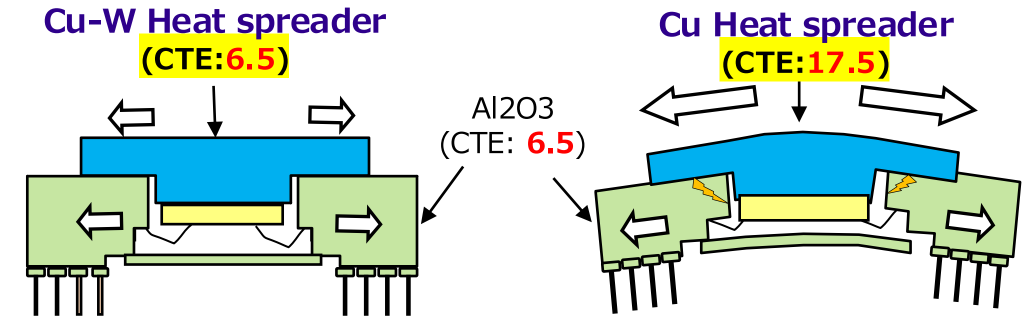


1. High Thermal Conductivity



2. Coefficient of Thermal Expansion (CTE)

Matching Attached Materials



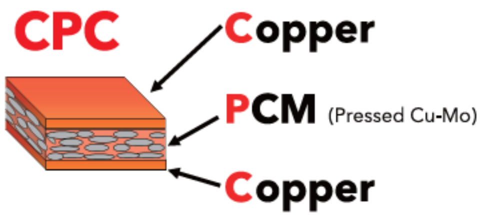
If CTE Matches with package,
→ ***NO ISSUES***

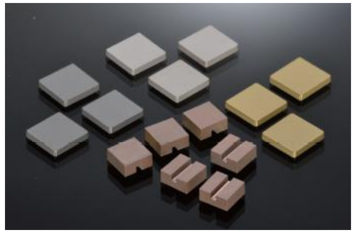
CTE mismatch with package,
→ ***CRACKS OCCUR.***

Spacers for Double Side Cooling Module

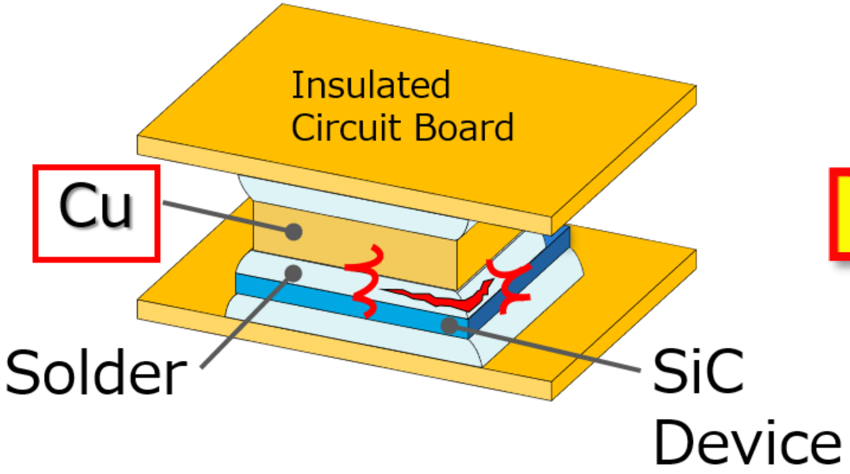
“Cu” Spacer

“CPC” Spacer

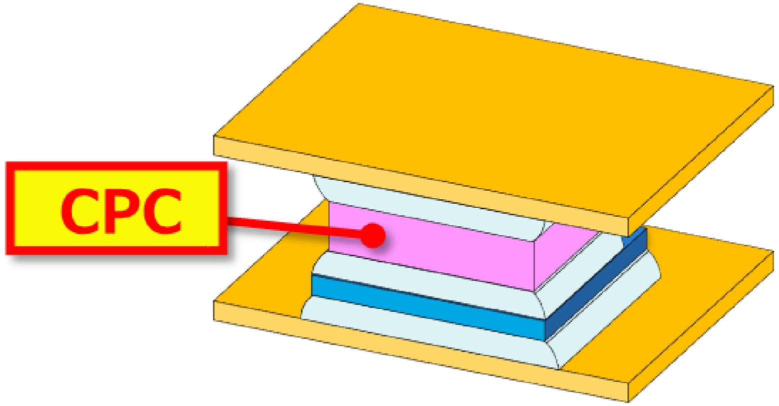




Operating temperature<200℃



Cracks occur

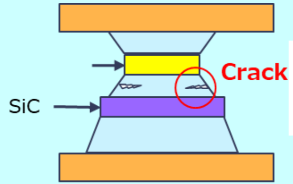


No cracks occur

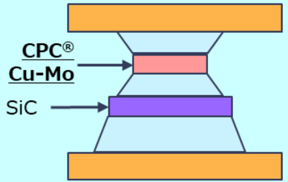
Cu-Mo

■Application

Automotive

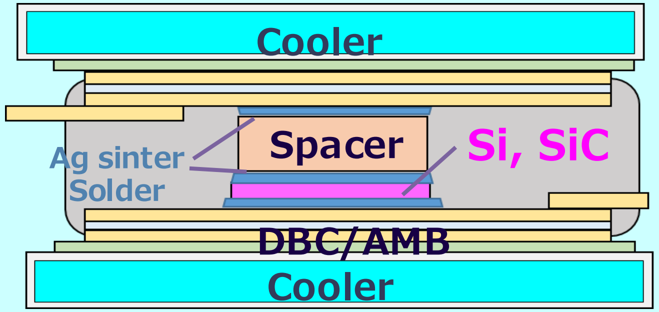


Cracks occurs.
Large CTE gap
between Cu and SiC



No Crack.
Intermediate CTE
CPC® / Cu-Mo and SiC
High reliability!

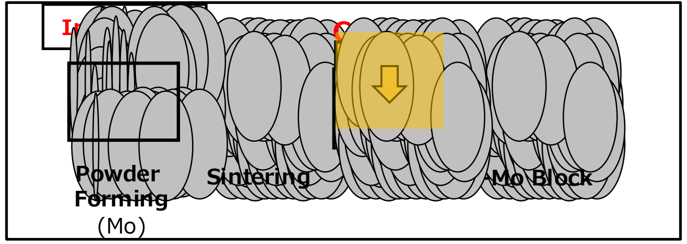
【Example】 DSC Power Modules

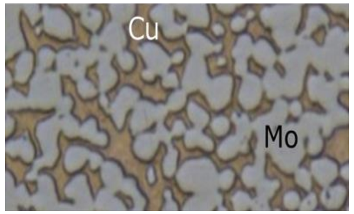


■Features

1. Integrated Production from raw material to products

・Cu-soaked Mo
*Pressed Copper Molybdenum

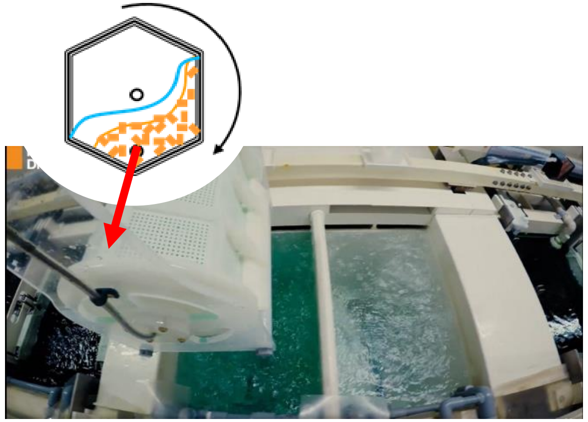




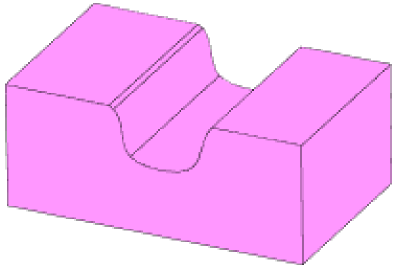
(Cross-section)

2. Common plating types

Ni, Ni-P, Au, Ag, Cu, Pd

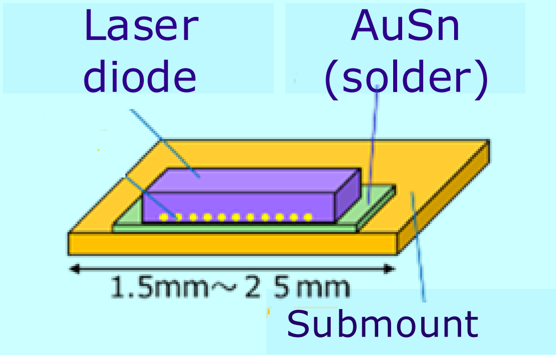


3. Stamping



Cu-Diamond composite TIM (Submount for laser diode)

■Example



■Features

1. Material

High Thermal Conductivity

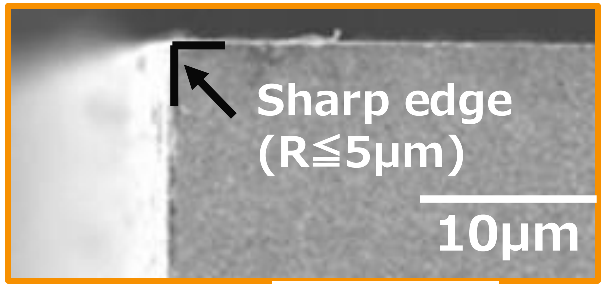
High Copper-Diamond (500W)

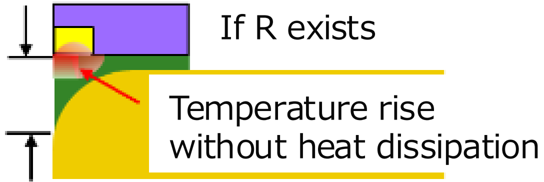
Copper-Tungsten (205W)

Low Aluminum Nitride

2.Precise Processing

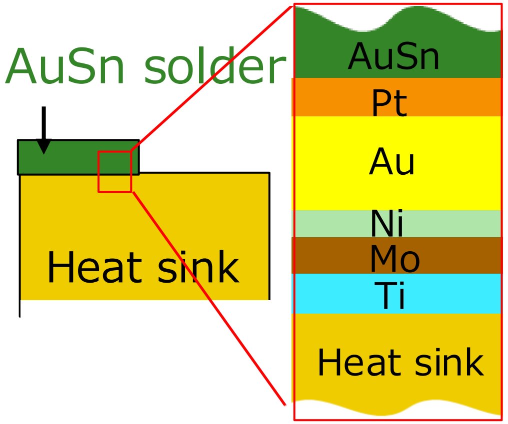
Sharp edge ⇒
Ensures thermal expansion





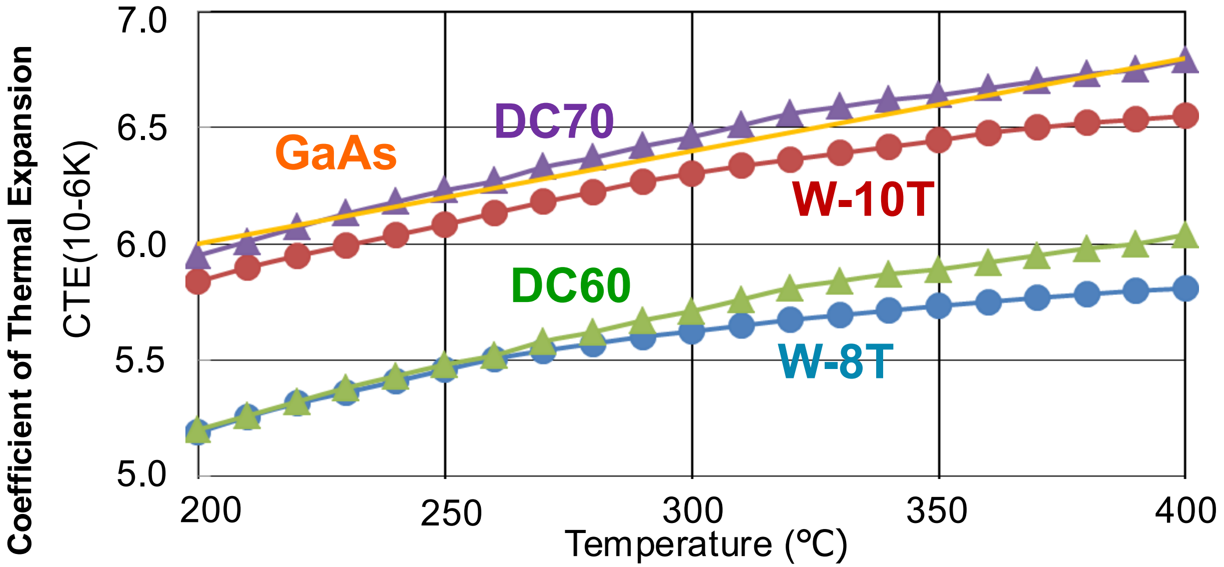
3. Metallizing

Various bonding layers can be formed



Application details for Cu-Diamond Composite Materials

Thermal Expansion close to InP and GaAs



CTE can be engineered and controlled to customer's specifications

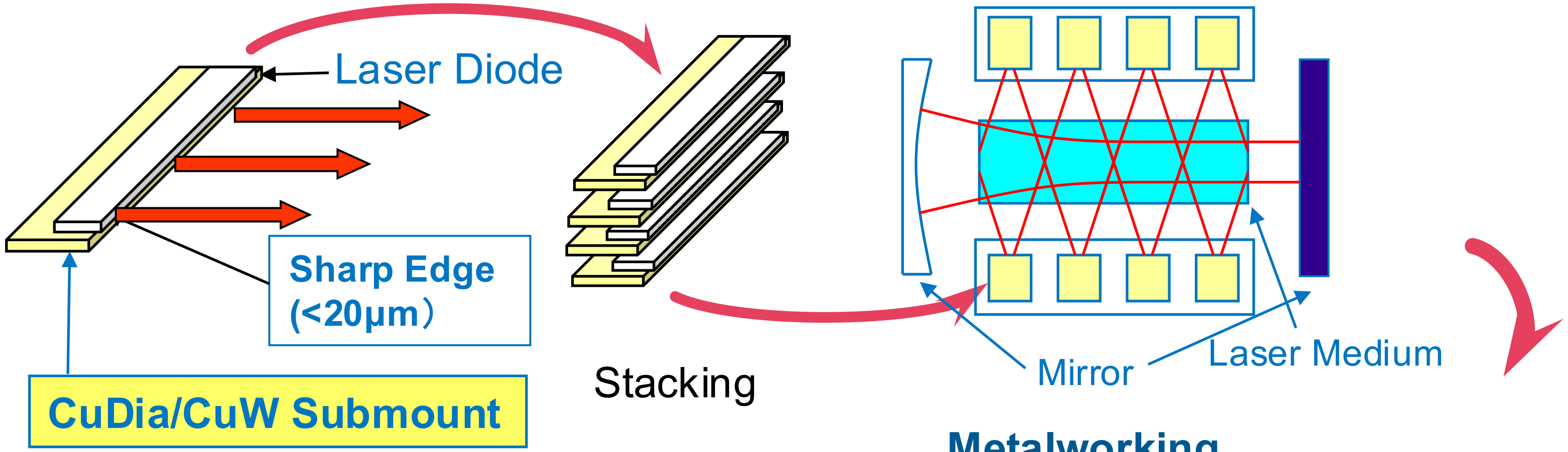
Thermal Conductivity higher than Copper

Material	Cu	**DC60**	**DC70**	**DC80**
Thermal Conductivity (W/m・K)	394	**550**	**500**	**450-500**

⇨ **Suitable for the next generation of devices such as GaN and SiC**

Application of Cu-Diamond and Cu-W Submounts

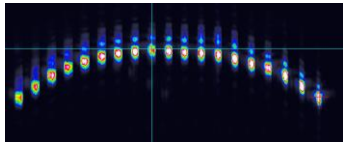
Laser Diode Stack for Industrial / Medical High Power Laser



Metalworking

1. Dissipating heat generated from Laser Diode
2. Reducing distortion of luminous point of laser diode

1~2um



Increasing focusing rate of laser beam

Industrial Laser

Cutting

Welding

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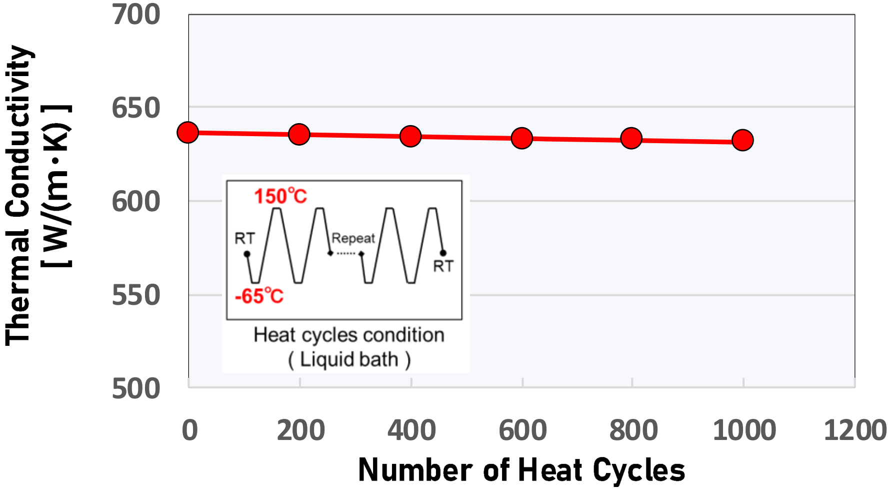
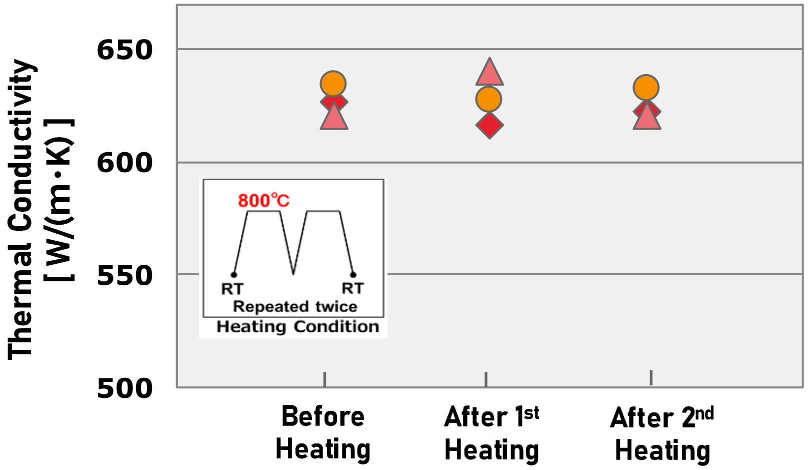
Thermal Properties of Ag-Diamond

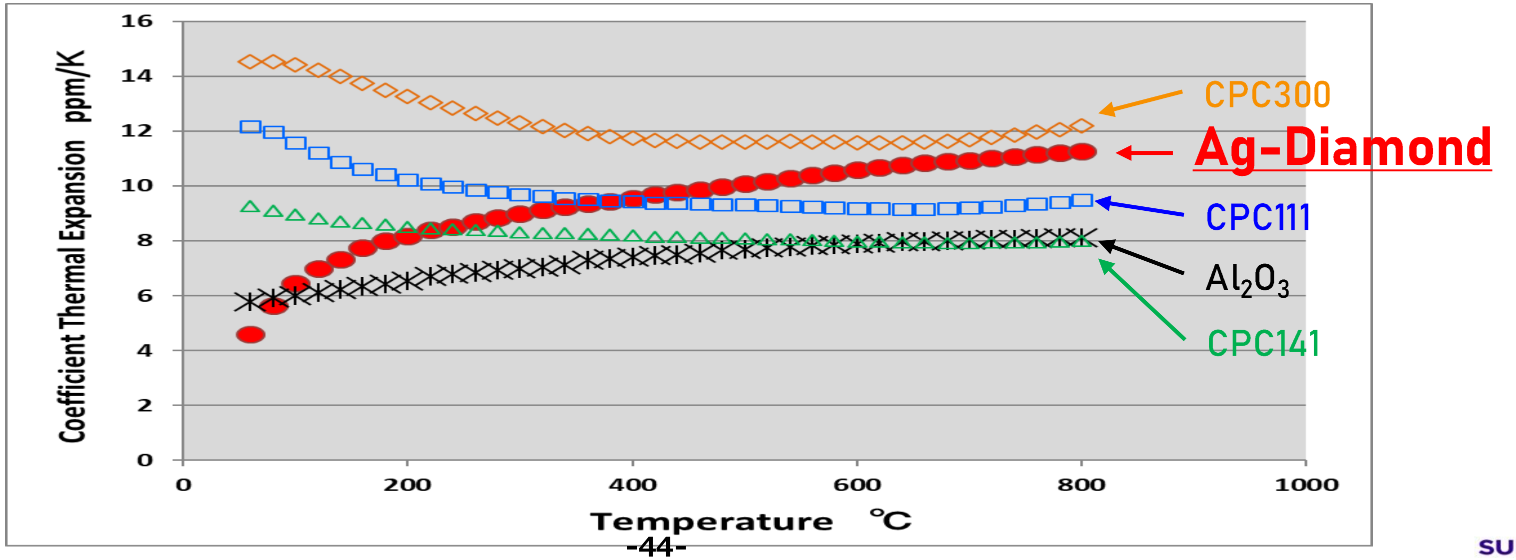
Decreasing of Thermal Conductivity



Influence of Heat Treatment (800℃)



Temperature Dependence of C.T.E.



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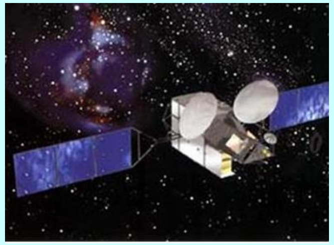
Applications of Ag-Diamond

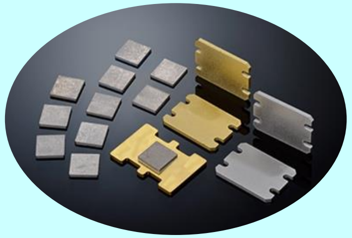
■Applications

Satcom



Airborne Radar

【Example】



■Features

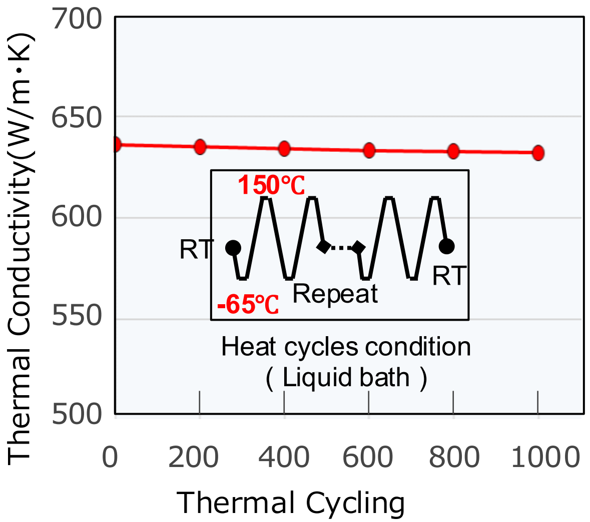
1.High Thermal Conductivity >600W/m·K

Thermal Conductivity(W/m·K)

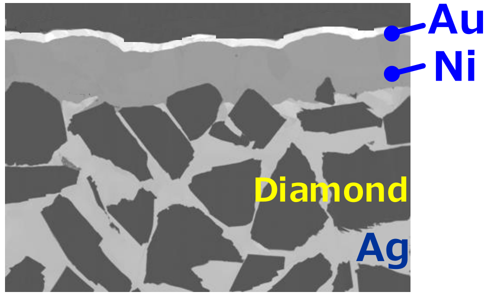
	2000	・Diamond（α=2.3)
High	**630**	**Ag-Diamond(α=9.5)**
	500	Cu-Diamond(α=6.5)
	429	Ag（α=19)
	393	Cu
Low	238	Al

(α:Coefficient Thermal Expansion ppm/℃)

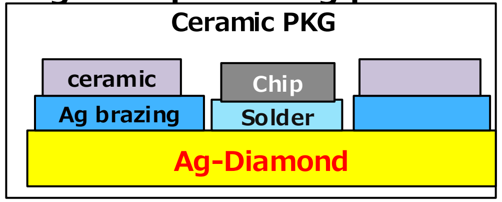
2. High Reliability Stable After Temp Shocks



3. Metallizing Ni/Ni+Au Plating

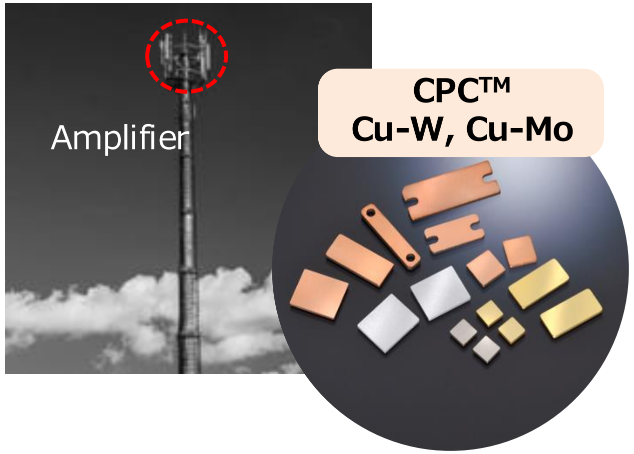


High temp. brazing possible



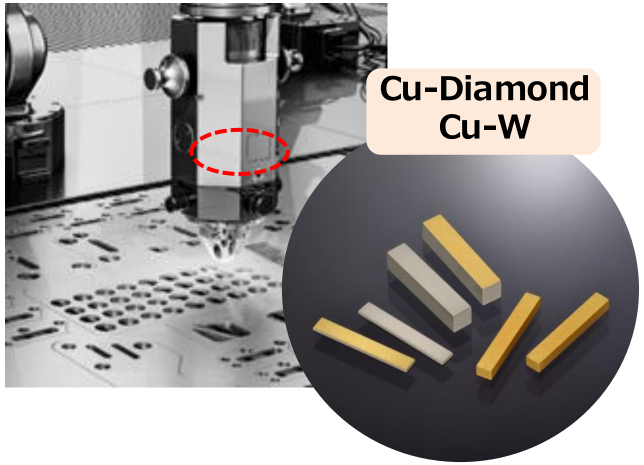
Applications for packaging and multiple product designs

Wireless Communication



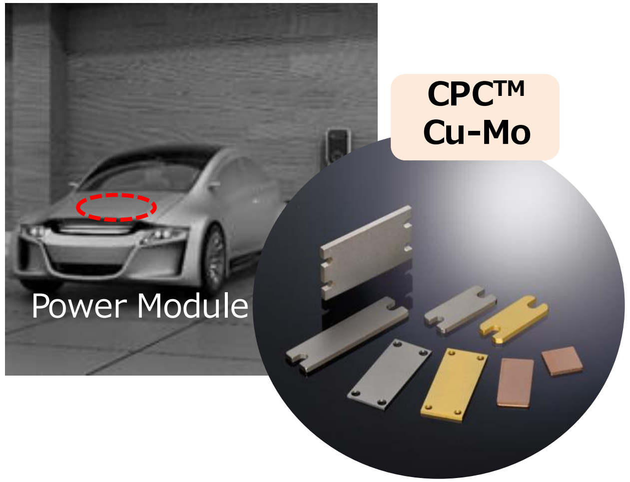
CPC™
Cu-W, Cu-Mo

Laser Diode



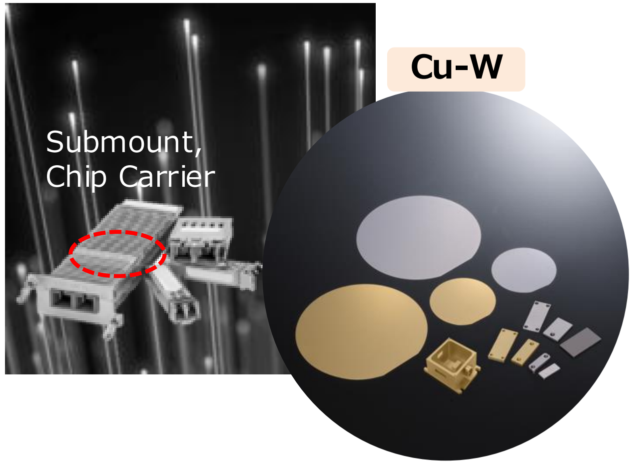
Cu-Diamond
Cu-W

Automobile



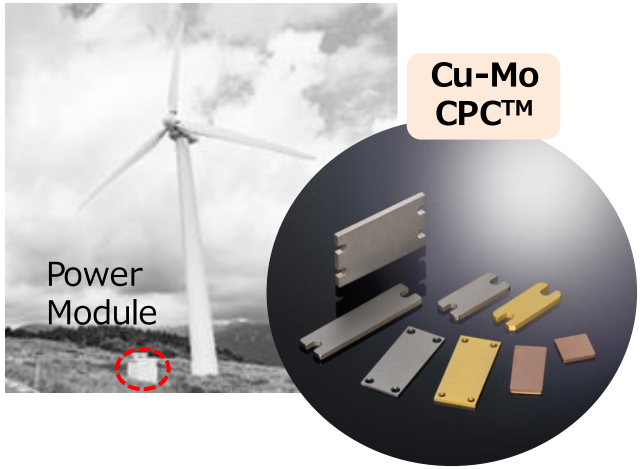
CPC™
Cu-Mo

Optical Communication



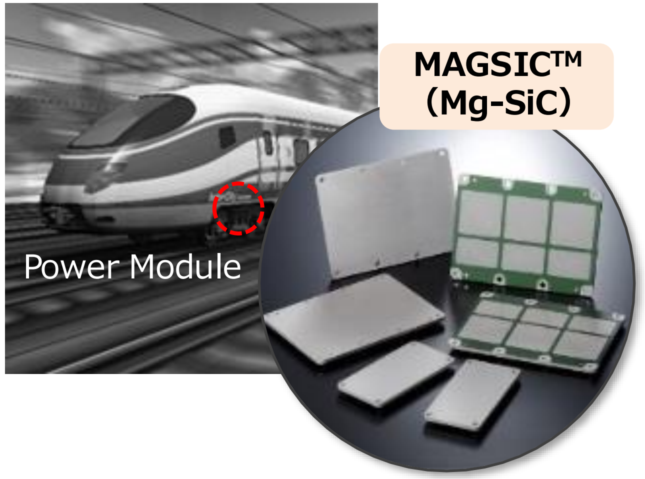
Cu-W

Wind Power Generator



Cu-Mo
CPC™

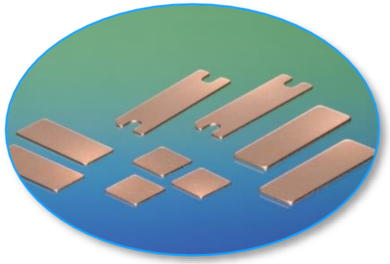
Electric Railway



MAGSIC™
(Mg-SiC)

Conclusion:

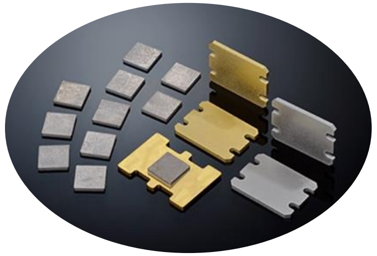
CPC™ & Cu-Mo for Spacer



-An ideal buffer plate with SiC & Cu.

-Realize higher reliability of DSC Power Modules.

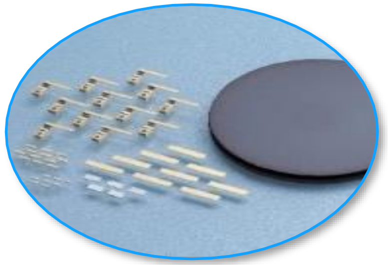
Ag-Dia, Cu-Mo, Cu-W for Chip Carrier



-Ultra-high and stable TC after thermal cycling.

-Local thermal solution for high-end application.

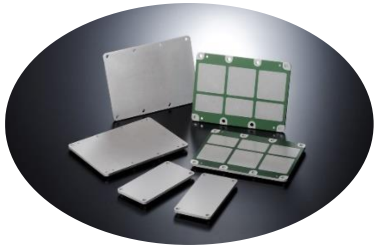
Cu-Diamond, Cu-W for laser submount



-High TC and Precision processing.

-Various bonding layers can be formed

MAGSIC™ for Baseplate



-High TC and robust shape stability.

-Decrease Thermal Resistance and grease pump-out.

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Heat spreader Materials of ALMT

Comparison of Physical and Mechanical Properties of Heat spreaders

					Coefficient of Average Linear Thermal Expansion [$\times10^{-6}$/K]					Thermal Conductivity [W/(m·K)]		Specific Heat [kJ/(kg·K)]	Density [g/cm³]	Hardness [Hv]	Transverse Rupture Strength [MPa]	Tensile Strength [MPa]	Young's Modulus [GPa]	Poisson's Ratio	Electric Resistivity [Ωm]	Dielectric Constant [at 1MHz]	Application							
	Category	Material	Name	Composition	R.T. ~100℃	R.T. ~400℃	R.T. ~800℃	R.T.~800℃ Anisotropy		R.T.	100℃										Wireless Communications	Optical Communications	Automotive	High Luminance LEDs	Lasers	Power Generators	Electric Railways	Industrial Machinery
								Rolling Direction	Transverse Direction																			
Heat spreaders	Metals	W			4.6	—	4.7	—	—	167	159	0.13	19.3	370	—	—	380	0.284	5.5×10^{-8}	—			●	●		●		●
		Mo			5.2	—	5.7	—	—	142	138	0.25	10.2	240	—	—	320	0.324	5.7×10^{-8}	—								
	Metal Composites, Alloy	CPC®	CPC141	Cu/Cu-Mo/Cu (Cu/PCM/Cu)	7.7	7.8	7.6	6.7	8.5	200	195	0.32	9.5	—	—	380	160	—	—	—	●	●	●			●		●
			CPC232		10.6	8.8	8.4	7.7	9.5	235	230	0.34	9.3	—	—	350	130	—	—	—								
			CPC111		11.6	9.5	9.8	8.0	11.2	260	—	0.35	9.2	—	—	310	125	—	—	—								
			CPC212		14.4	11.5	12.1	—	—	300	—	—	—	—	—	255	120	—	—	—								
			CPC-300		13.8	11.5	12.1	8.7	13.5	300	—	0.36	9.1	—	—	290	120	—	—	—								
		Cu-Mo	CM-15	85Mo-15Cu	6.8	7.3	7.6	—	—	148	144	0.28	10.01	150	1,200	540	280	0.42	5.3×10^{-8}	—	●	●	●	●		●		●
			CM-15K	85Mo-15Cu	7.0	7.4	8.2	—	—	173	169	0.28	10	171	1,296	551	280	0.42	4.6×10^{-8}	—								
			PCM30	70Mo-30Cu	7.7	7.6	7.5	6.8	8.6	195	190	0.29	9.8	180	—	600	230	0.315	4.0×10^{-8}	—								
			PCM35	65Mo-35Cu	8.2	8.1	7.8	7.0	9.4	210	205	0.3	9.7	175	—	560	220	—	3.5×10^{-8}	—								
			PCM40	60Mo-40Cu	8.8	8.5	8.2	7.2	9.8	220	215	0.31	9.6	170	—	530	210	0.32	3.4×10^{-8}	—								
			PCM60	40Mo-60Cu	11.5	10.8	10.5	8.2	13.5	275	268	0.33	9.4	160	—	440	170	0.33	2.7×10^{-8}	—								
		Cu-W	W-6	94W-6Cu	5.9	6.0	6.4	—	—	141	137	0.15	17.6	330	1,000	590	350	—	—	—	●	●		●	●			●
			W-10	89W-11Cu	6.5	7.1	7.9	—	—	174	167	0.16	17	300	1,100	560	330	0.295	5.3×10^{-8}	—								
			W-15[*1]	85W-15Cu	7.0	7.4	8.6	—	—	184	178	0.17	16.4	280	1,200	530	310	0.3	4.6×10^{-8}	—								
			W-20[*1]	80W-20Cu	7.9	8.6	9.8	—	—	200	197	0.18	15.65	260	1,300	490	280	0.305	4.0×10^{-8}	—								
			W-10T	89W-11Cu	6.5	7.1	7.9	—	—	205	—	0.16	17	300	1,100	560	330	—	—	—								
	Ceramics	AlN	AlN(230W)		—	4.5	—	—	—	230	—	0.72	3.27	950	320	—	300	—	10^{13}	8.5		●		●	●			
			AlN(200W)		—		—	—	—	200	—																	
			AlN(170W)		—		—	—	—	170	—																	
	Ceramics -Metal	Mg-SiC	MAGSIC®	18Mg-SiC	7.0[*2]	—	—	—	—	230	200	0.74	2.8	—	400	—	140	—	3.5×10^{-7}	—						●	●	●
	Diamond	Diamond-Metal	AD90	Ag-Diamond	—	9.5	11.2	—	—	600	—	0.34	5.9	—	—	390	340	0.24	7.3×10^{-8}	—	●							●
			DC60	Cu-Diamond	—	6.0	—	—	—	550	530	0.45	5.0	—	—	480	560	0.17	1.9×10^{-7}	—		●		●	●			
			DC70		—	6.5	—	—	—	500	480	0.44	5.5	—	—	—	—	—	1.7×10^{-7}	—								
		CVD diamond			2.3	—	—	—	—	>1,000	—	0.51	3.52	8,000~10,000	1,000	—	1,050	—	5×10^{7}	5.8		●		●	●			
		SUMICRYSTAL™			2.3	—	—	—	—	2,000	1,400	0.51	3.52	8,000~10,000	3,900	—	1,050	—	10^{14}	5.7								
Reference Data	Semiconductor		Si		3.0[*3]			—	—	151	—	0.75	2.3	—	200	—	170	—	2.3×10^{3}	11.7								
			GaAs		5.9[*3]			—	—	46	34	0.33	5.32	—	—	290	90	—	3.8×10^{6}	11.1								
			InP		4.5[*3]			—	—	70	—	0.32	4.79	—	—	—	60	—	8.2×10^{-7}	12								
			GaN		a5.6-c3.2[*3]			—	—	130	—	0.49	6.15	—	—	—	—	—	—	—								
			SiC		3.1[*3]			—	—	490	—	0.69	3.2	—	—	—	221	—	—	10								
	Ceramics		Al_2O_3		6.0	7.2	8.1	—	—	17	17	0.8	3.6	1,900	300	—	370	—	10^{12}	8.9								
			BeO		7.6[*3]			—	—	251	180	0.96	2.9	1,200	200	—	330	—	10^{13}	6.7								
			SiO_2		3.0[*3]			—	—	1.4	—	—	0.7	—	—	—	—	—	—	—								
			High C.T.E. Glass Ceramics		11.5[*3]			—	—	0.2	—	—	1	—	—	—	—	—	—	—								
	Metals		Cu		17.1	—	19.4	—	—	394	—	0.38	8.93	80	—	250	120	—	1.7×10^{-8}	—								
			Al		24.3	26.5	—	—	—	238	—	0.92	2.7	—	—	—	80	—	—	—								
			Kovar		5.3[*3]			—	—	17	17	0.44	8.36	160	—	540	140	—	4.9×10^{-7}	—								
	Organic		FR-4		x15-y17[*3]			—	—	0.2	—	—	—	—	—	—	—	—	—	—								
			Polyimide		25[*3]			—	—	0.2	—	—	—	—	—	—	—	—	—	—								

[*1] We have "T Grade", which has higher thermal conductivity. [*2] R.T.~120℃ [*3] Unknown the Temperature Range

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