Too Hot To Test

February 9 - 11, 2021

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Thermal Management Materials and Technologies
Semiconductor Test

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Short Course

MEPTEC *Too Hot To Test*
Virtual Workshop
February 9-11, 2021

Overview

Emphasis is given in this presentation to an overview of thermal management technologies, especially for semiconductor test and recognizing rapid increases in semiconductor power dissipation.

Topics included:

- Thermal interface materials (TIMs)
- Thermal materials: CTE-matched composites and heat spreader materials
- Thermal component types (heat pipes, vapor chambers, thermosyphons, and similar)
- System-level thermal technologies (single- and two-phase liquid cooling, liquid immersion)

These materials and technologies apply generally to all forms of electronic components and systems:

- Integrated circuits
- Power semiconductors and LEDs
- Modules and systems of all types across electronics industry

Overview – Thermal Management Objectives

Thermal management objectives for electronic systems:

- *Dissipate heat* from components and systems to an “ultimate heat sink” (typically ambient air);
- *Reduce temperature-generated stress* internal to semiconductor devices;
- Maintain *temperature control* of sensitive components and internal system operating temperature:
  - Typically, maintain semiconductor device operating junction temperatures below specified maximum values;
  - As required, maintain minimum temperature above specified values (e.g., outdoor electronic systems).

Thermal management design must abide with the *laws of physics*:

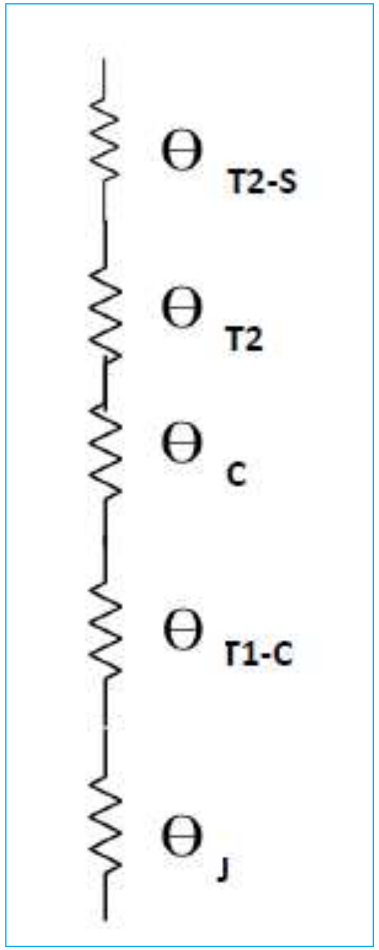
- Limited number of useful natural materials with required thermal conductivity values, physical properties
- *Engineered* materials, fluids, and composites can expand available materials within limits of physical laws
- Heat is a dominant factor as an electronic system failure mechanism

Cardinal rules for semiconductor and electronic system thermal design:

1. *Minimize the number* of thermal interfaces
2. Minimize *interfacial thermal resistance* for any required interface

Overview – Thermal Management Objectives

Thermal management from die junction to the ultimate heat sink constitutes a series of packaging and thermal materials , each with a specific thermal resistance value. *Goal overall is to reduce the sum of the thermal resistances:*



Heat sink: Inherent bulk material property – typically aluminum or copper

TIM2: Specific to material selected (bulk value) and contact resistances

Case (or lid): Inherent bulk material property – typically copper or aluminum

TIM1: Specific to material selected (bulk value) and contact resistances

Semiconductor die: inherent bulk material property (Si, SiC, GaN, GaAs)

Thermal Terminology and Purpose

Thermal Interface Material Terminology

Term	Generally Accepted Definition	Value (Typ.)
Thermal Resistance (Bulk)	Barrier to the flow of heat from a heat source through a material or component	°C/W
Thermal Resistance (Interfacial)	Barrier to the flow of heat at the surface of a component	°C/W
Thermal Resistance (Contact)	Alternative term for interfacial thermal resistance (per above)	°C/W
Thermal Resistance (per unit area)*	Barrier to the flow of heat through a material, per unit area (most useful value for selecting a TIM)	°C-in^2/W (or) °C-cm^2/W
Thermal Impedance	Alternative term for thermal resistance per unit area	°C-in^2/W (or) °C-cm^2/W
Heat Flux (Heat Density)	Power dissipated per unit area (e.g., from a point on the surface of a processor die or GaN RF device)	W/in^2 (or) W/cm^2

*Note: *The above terminology may be used casually and identifying the most useful term is important when selecting a TIM to characterize for a given application. The most important term for determining performance of a TIM is thermal resistance per unit area. Heat flux is the principal driver for the need for a specific TIM and thermal solution.*

Industry Practice – Thermal Management Design

Thermal management materials include a wide range of different types of materials that are used as thermal solutions or in combination with other thermal management hardware components:

- Thermal interface materials (TIMs)
- Thermally-conductive plastics
- Thermal management composites, graphite films: Specific CTE values and various bulk thermal conductivity values.

Thermal management hardware technologies include a range of hardware components and systems used in natural (passive) convection, forced (air) convection, and liquid cooling systems, including:

- Extruded, stamped, and cast aluminum heat sinks and similar components
- Heat pipes and heat pipe assemblies
- Vapor chambers
- Thermosyphons and other types of passive two-phase (pumpless) heat transport mechanisms
- Liquid cold plates (typically aluminum or copper), single-phase and two-phase
- Liquid-to-air heat exchangers and other types (e.g., liquid-to-liquid, condensers, similar)
- Single- and two-phase pumped liquid cooling systems
- Vapor compression cycle (VCC) systems – refrigeration, incorporating a compressor
- Air-moving devices (AMD)
- Thermoelectric modules (TEC), also referred to as Peltier effect modules and solid state refrigerators
- Liquid immersion fluids and systems, single- and two-phase

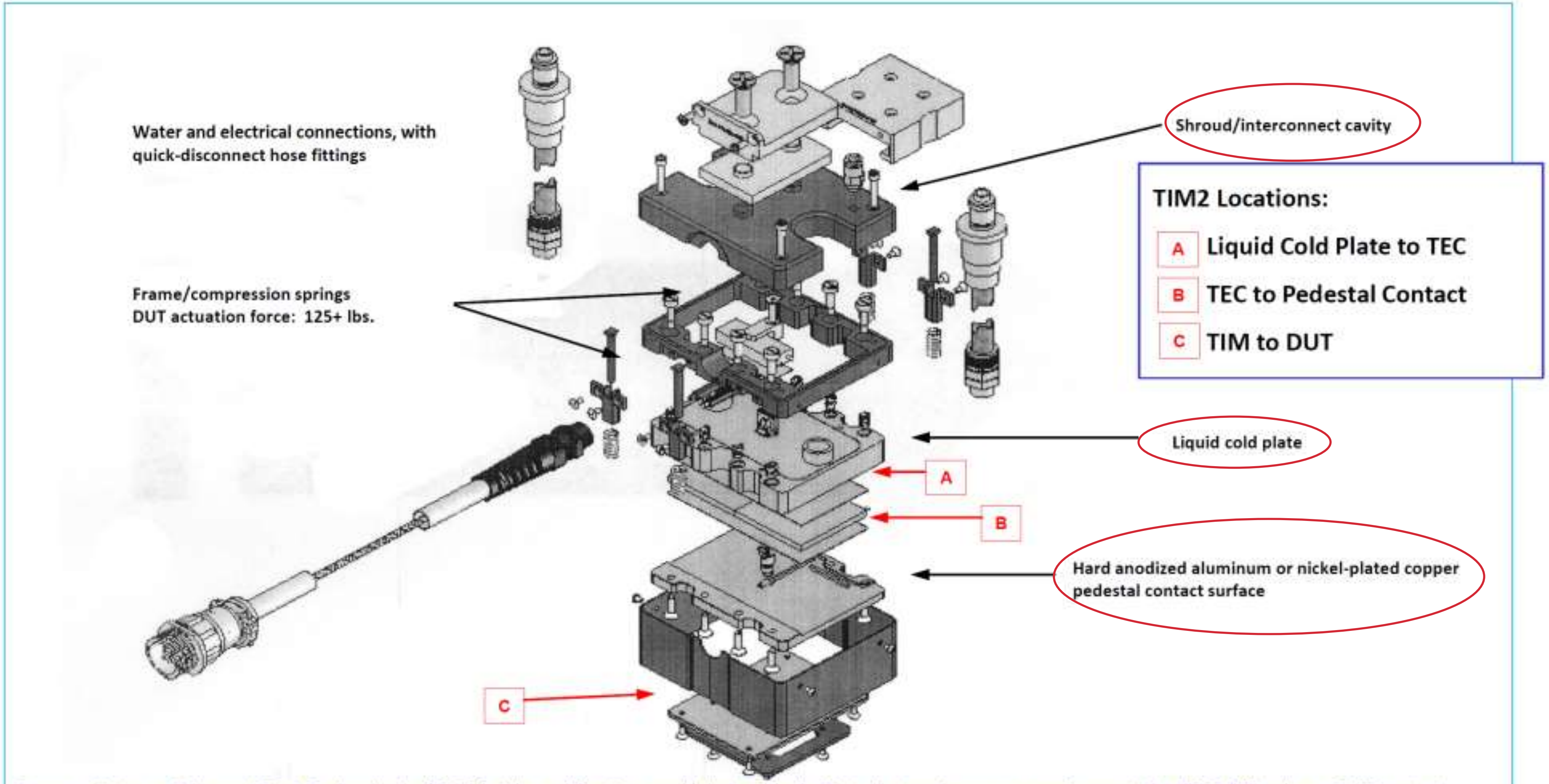
Semiconductor Test Industry Practice – Thermal Management Design

Semiconductor Burn-In/Test System Thermal Management Technologies							
Thermal Management Technology	**Accuracy and Stability**	**Temperature Range Capability**	**Thermal Efficiency**	**Heat Flux Range (W/cm^2)**	**Dynamic Response**	**Cost**	**Environmental and Ergonomic**
Refrigeration	Very High	Wide (Cooling)	Very High	(Very High)	Very Fast	Very High	Use of low-GWP refrigerants
TEC + Liquid Cooling	High	Wide (Cooling and Heating)	Moderate to High	<250	Fast	Moderate	Condensation (requires insulation)
Liquid Immersion	High	Wide	High	<250	Slow	Moderate	None
Liquid Cooling	Low	Wide (Above Ambient Temperatures)	High	<150	Slow	Low	Condensation (Requires insulation)
Fan + Heat Sink	Low	Narrow (Cooling)	Moderate	<50	Slow	Very Low	Fan Noise , Vibration
Heat Sink	Low	Narrow (Cooling)	Low	<10	Slow	Very Low	None

Source: DS&A LLC, modified from Kulicke & Soffa (USA).

Semiconductor Test Head Construction

Examples of complex test head design and components:



Water and electrical connections, with quick-disconnect hose fittings

Frame/compression springs
DUT actuation force: 125+ lbs.

Shroud/interconnect cavity

TIM2 Locations:

- A Liquid Cold Plate to TEC
- B TEC to Pedestal Contact
- C TIM to DUT

Liquid cold plate

Hard anodized aluminum or nickel-plated copper pedestal contact surface

Source: Antares Advanced Test Technologies (USA) (with modifications and labels added). Note that performance requirements for TIM2 "C" only are DUT contact.

Note: Thermal components and materials are identified in red notations in this exploded test head illustration.

Semiconductor Industry Trends

Critical at die level

Overall significant market drivers:

- Increase in heat flux at die level, increasing performance requirements for thermal technologies, materials
- Doubling to 800+W/die by 2024 for high-performance AI accelerators, processors, graphics processors, ASICs
- Higher semiconductor switching frequency
- Increased semiconductor maximum operating temperatures
- Reduction in semiconductor losses and increases in efficiency
- Reduction in electronic system physical volumes

Broad industry issues:

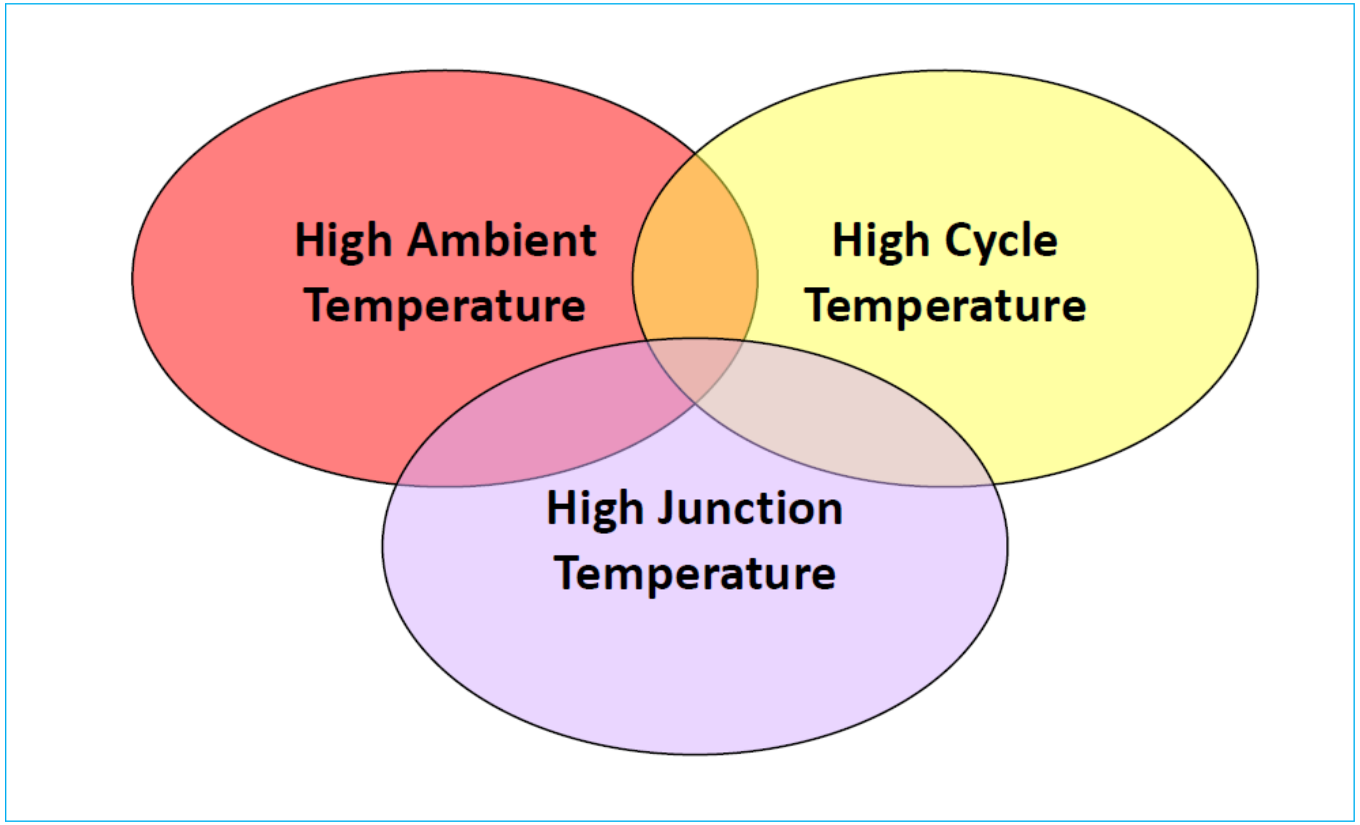
- These system-level technology changes are driving greater rates of change for thermal management system technologies and implementation, including semiconductor test.
- Statements also apply to power semiconductor devices and industry transition to wide band gap (WBG) semiconductor technologies (SiC, GaN).
- We all operate in our own “silo” – very disconnected from other disciplines and other industry segments.
  - This is a critical issue for design, manufacturing, and test engineering at all levels.

➡ Significant industry thermal material and liquid cooling experience resides in the power semiconductor and power electronics market over fifty-year history. This is a valuable resource for the integrated circuit design community.

Industry Trends: High Temperature Electronics Applications

Definitions for what is meant by "high temperature" are relative:

- Three general modes for temperature:

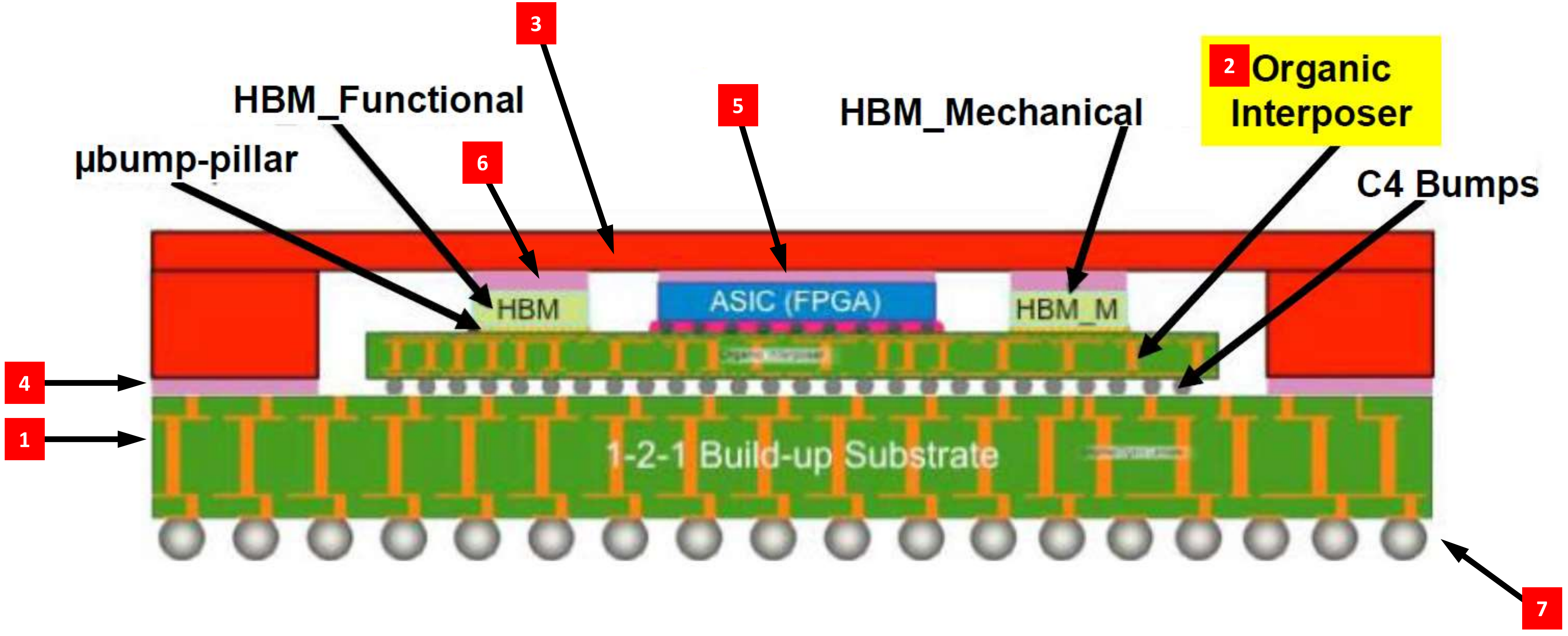


Source: ElcoScint, J. Postle, Microsemi UK, "The Future of High Temperature Interconnect" (September 17, 2015). "Junction temperature" indicating operating temperature at semiconductor die surface.

Heterogeneous Integration: Thermal Challenges

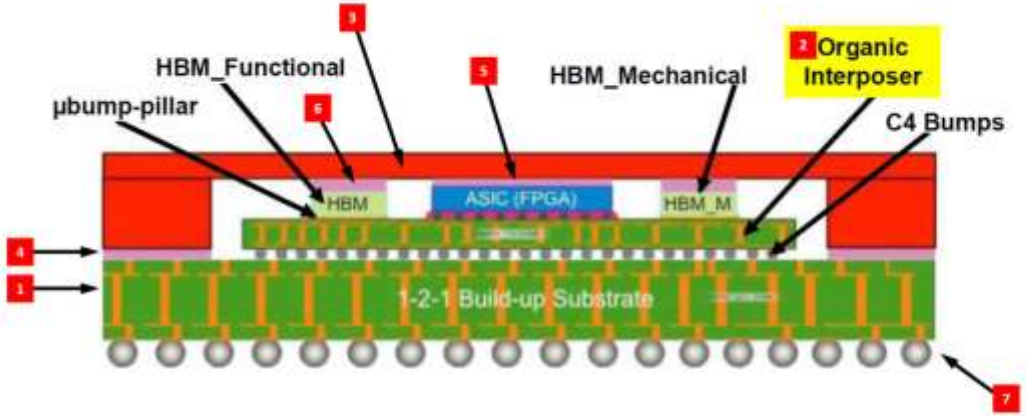
Major components within a highly integrated IC module with multiple device types:

1 Numbered references added by DS&A LLC for clarity.



Source: J. Lau, Unimicron Technology Corporation, "Recent Advances and Outlook in Heterogeneous Integration, IEEE EPS Silicon Valley Chapter Meeting, February 28, 2020; Li, L.; Chia, P.; Ton, P.; Nagar, M.; Patil, S.; Xue, Jie, "3D SiP with Organic Interposer for ASIC and Memory Integration," Proceedings, 66th Electronic Components and Technology Conference, June 2016; L. Li, P. Ton, M. Nagar, P. Chia, Cisco Systems, Inc., "Reliability Challenges in 2.5D and 3D IC Integration," Proceedings, 67th IEEE Electronic Components Technology Conference, May 2017.

Heterogeneous Integration: Thermal Challenges



SiP/SoC/HI/Processor Module Thermal-Mechanical Components and Materials

	Component or Material	Thermal/Mechanical Function	Primary Thermal Requirements
1	Package Substrate	Carrier and mechanical support	Minimum CTE mismatch*
2	Interposer	Carrier and mechanical support	Minimum CTE mismatch*
3	Lid	Die physical protection	Thermal conductivity, flatness, finish
4	Edge-seal Adhesive	Lid attachment	Minimum CTE mismatch*
5	ASIC/Processor TIM1 (Thickness A)	Principal heat transfer path	Minimum ϴ, stability, specific CTE*
6	HBM/Other TIM1 (Thickness B)	Secondary heat transfer path	Minimum ϴ, stability, specific CTE*
7	Solder bumps/pads/balls	Minor heat transfer path	Thermal conductivity, stability, CTE*

Source: DS&A LLC.   Notes: (*) CTE value relative to other package components and materials. All statements are highly generalized.   ϴ: Thermal resistance (see definition).

Thermal Interface Materials

Overview – Thermal Interface Materials

Cardinal rules for semiconductor and electronic system thermal design:

1. *Minimize the number* of thermal interfaces.
2. Minimize *interfacial thermal resistance* for any required interface.

What purpose does a TIM serve?

1. Material used to transfer heat from one component mounting surface to a mating surface, eliminating voids and air gaps.
2. Reduce potential for fracture or separation due to differing CTE values.

What constitutes a TIM?

- A compound, gel, pad, film, foil, graphite sheet, or composite requiring mechanical fasteners;
- An adhesive, thermally-conductive, not requiring fasteners;
- A combination of an adhesive with a pad, film, foil, or graphite sheet, and other combinations of materials.

Overview – Major Factors:

1. Heat is identified as a major contributor to electronic system failure.
2. The transfer of heat away from semiconductors and other components is a critical function:
   - *TIMs are a minor cost* item on the bill of materials for any electronic assembly
   - *Performance and long-term reliability improvements* for TIMs are a continuing need
3. Improved understanding of TIM performance, testing, and reliability is now critical.

TIM Terminology and Purpose

Thermal Interface Material Terminology		
Package Level	Generally Accepted Definition	TIM Terminology
1	Semiconductor die to heat sink (external, bare die package)	TIM0*
1	Semiconductor die to package lid (internal, lidded package)	TIM1
2	Semiconductor lid, case, or baseplate: external to the package, conducting heat to a heat sink, liquid cold plate, or metal component	TIM2
3	PCB or PCB-mounted components or enclosure sheet metal: conducting heat from the PCB or components mounted on the PCB to a large heat sink or metal component (the primary use for gap-filler TIMs). Thickness (typ.) > 0.10” (250µ)	Gap-filler
4	Platform or subassembly level, conducting heat from the case of an IC or power device, with a large gap. Thickness (typ.) > 0.10” (250µ)	Gap-filler

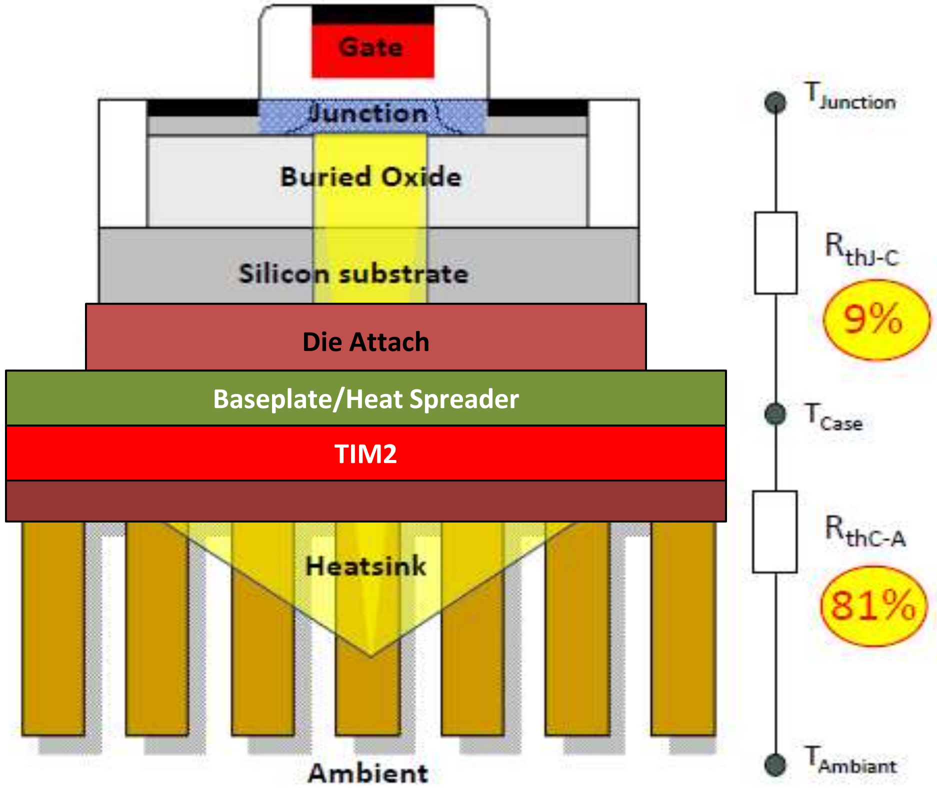
*Note: * Both the term “TIM 0” and “TIM 1.5” are used to denote the same terminology level within integrated circuit packages and are interchangeable. “TIM 0” is more common today.*

TIM Terminology and Purpose

Heat Flow Path and Relevant TIM Placement: Common Discrete Power Semiconductor Applications

TO-220 Package

Layer	BLT [µm]	A [mm^2]	λ [W/mK]	Rth [K/W]	%	% total
Si Die	100	25	150	0,027	50%	5%
Die Attach	20	25	50	0,016	30%	3%
Cu Heat spreader	200	50	380	0,011	20%	2%
			Rth_J-C	0,053	100%	9%
TIM 2	100	50	5	0,400	88%	71%
Al heat sink	2000	200	180	0,056	12%	10%
			Rth_C-A	0,456	100%	81%
			Rth_J-A	0,562		100%
			TIM total	0,416		74%



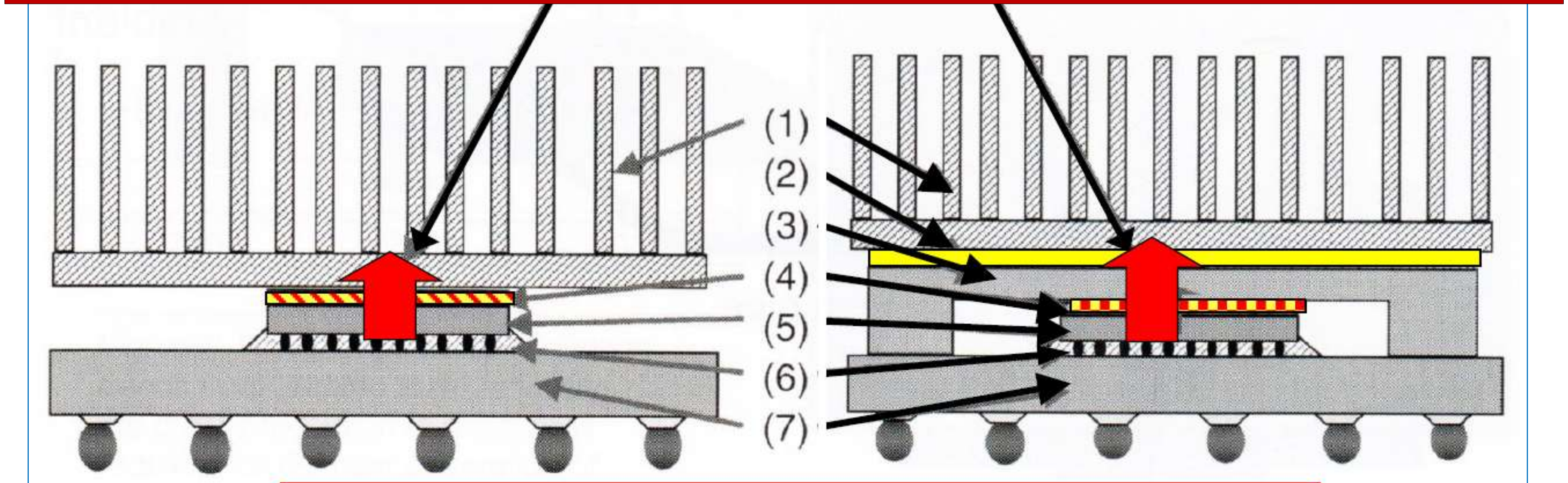
TIM2 and the die attach material are responsible for approximately 74% of the thermal budget through this discrete power semiconductor package (if considering die attach as an equivalent for TIM1)

Source: Mohamed Abo Ras, Berliner Nanotest und Design GmbH. Used with permission.

TIM Terminology and Purpose

Heat Flow Path and Relevant TIM Placement: Common Integrated Circuit Applications

Primary heat transfer path is from semiconductor die through TIM/heat sink/ambient air or liquid



Key:

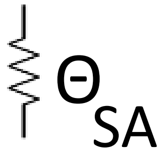
(1) Thermal Solution (Heat Sink)
(2) TIM2 🟨
(3) Package Lid
(4) TIM:
  A. Bare die package: TIM0 ▨
  B. Lidded package: TIM1 ▦
(5) Semiconductor die
(6) Interconnect and Underfill
(7) Package Substrate

Note: The terms "TIM 0" and "TIM 1.5" are interchangeable and apply to the same level within integrated circuit packages. "TIM 0" is more common. TIM 0 and TIM 1 are both in direct contact with the die.

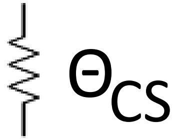
TIM Terminology and TIM Purpose

In practice, we need to simplify the set of thermal resistances for a stack:

- Thermal resistance is stated as a value determined as the increase measured in temperature (°C) for each watt dissipated:
  - Values are stated as °C/W;
  - Thermal resistance from the base (contact surface) of a heat sink to the ambient air is expressed as a value "sink-to-air":



  - Thermal resistance for a TIM from the surface of the lid of an IC to the base of a heat sink is expressed as a value "case-to-sink":



Contact Interfacial Resistance

A note on contact (interfacial) resistance and material behaviors:

- Contact (interfacial) resistances are hardest to measure and model.
- In materials and devices with submicron layers, interfacial resistances (and not bulk conductivity) have the greatest impact on heat flow.
- Understanding boundary thermal resistance between dissimilar materials remains a challenging problem despite 60 years of research.
- A breakthrough in testing capability and developments in this area, to allow simulation and prediction of heat flow in non-homogeneous materials, is a current need.

Reference: Mark D. Losego, David G. Cahill, “Breaking Through Barriers”, *Nature Materials,* Vol. 12, May 2013, pp. 382-384.

TIM Categories

Purpose:

- Identify differences between TIM types
- Distinguish differences in material thickness, dispensability, carriers
- Separate important categories of solid preforms, pastes, gels, compounds
- Separate adhesives vs. TIM categories requiring mechanical fasteners
- Identify dielectric versus non-dielectric materials
- Develop selection procedure

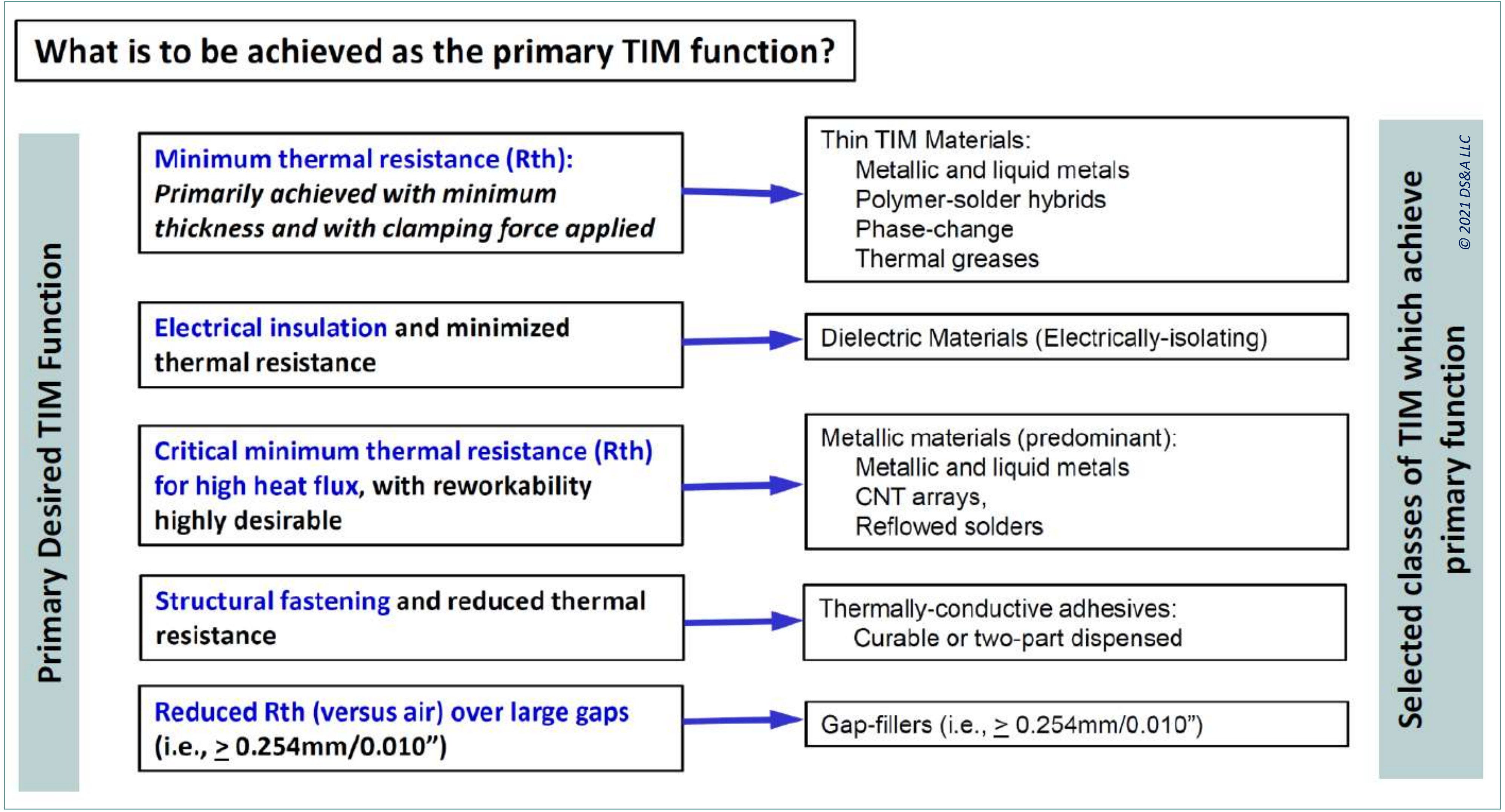
TIM Categories

General Categories of Thermal Interface Materials
Thermally-conductive adhesives (TCA)
Die-attach adhesives (DA) – Used as TIM1
Gap-fillers
Graphite sheets and films (as heat spreaders and TIMs)
Elastomeric sheets
Electrically-isolating die-cut preforms
Thermal greases (Compounds, dispensed) and gels (dispensed)
Phase-change compound (dispensed) and die-cut preforms
Metallic die-cut pre-forms
Liquid metals, solid/liquid metallic hybrids, reflowed solders (as TIM1)
Vertically-aligned carbon fibers (VA-CNF)
Vertically-aligned carbon nanotubes (VA-CNT)
Vertically-aligned graphite

TIM Selection Methodology

Primary TIM Function: Functional Requirements Definitions

What is to be achieved as the primary TIM function?



Primary Desired TIM Function

Selected classes of TIM which achieve primary function

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Primary Desired TIM Function	Selected classes of TIM which achieve primary function
Minimum thermal resistance (Rth): ***Primarily achieved with minimum thickness and with clamping force applied***	Thin TIM Materials: Metallic and liquid metals Polymer-solder hybrids Phase-change Thermal greases
Electrical insulation and minimized thermal resistance	Dielectric Materials (Electrically-isolating)
Critical minimum thermal resistance (Rth) for high heat flux, with reworkability highly desirable	Metallic materials (predominant): Metallic and liquid metals CNT arrays, Reflowed solders
Structural fastening and reduced thermal resistance	Thermally-conductive adhesives: Curable or two-part dispensed
Reduced Rth (versus air) over large gaps (i.e., ≥ 0.254mm/0.010”)	Gap-fillers (i.e., ≥ 0.254mm/0.010”)

TIM Selection Methodology

Selecting an appropriate thermal interface material:

- *Interfacial thermal resistances dominate* over TIM bulk thermal resistance for most TIM types that are thin by design;
- Gap-fillers are by definition designed to be *thick* materials. *Bulk thermal resistance will dominate* over contact thermal resistances, due to the extremes of thickness;
- TIM0-1-2: Maximized surface wetting achieved is critical to overall performance, to *minimize contact thermal resistance at each of two contact surfaces*.
- TIM2: Mechanical fastening and applied force is required to achieve the thinnest TIM for best performance value.

A *critically important design factor selecting a TIM0 or TIM1* for an IC package is determining how warpage is to be controlled and what thickness and placement of TIM is required for *adequate die coverage with expected warpage* due to temperature-induced package stresses.

TIM Testing Methods

Property Category	Property Parameter	Method/Value
Thermal Resistance	Through-plane (primary) bulk + contact	ASTM D 5470-17 (°C-mm^2/W) JEDEC JESD 51-14 (Transient) Thermal Test Vehicle (TTV)
Thermal Conductivity	Homogeneous, bulk (isotropic)	ASTM D5470-17 (Steady-state) JEDEC JESD 51-14 (Transient) Laser flash 3Ω Characterization
	Non-homogeneous, bulk (through-plane)	ASTM D5470-17 (Steady-state) JEDEC JESD 51-14 (Transient) 3Ω Characterization
	Non-homogeneous, bulk (in-plane)	Nanotest LaTIMA (Steady-state) Scanning pulsed laser

Note: Not all test methods are suitable for testing certain categories of TIMs such as anisotropic and/or non-homogeneous structures (examples are compounds coated on a dielectric carrier or multilayer TIMs.)

TIM Testing Methods – Other Characteristics

Material Attribute	Value or Type
Automated Placement/Dispensing Formats	Vacuum Roll format Liquid dispensed
Flammability Rating	UL 94 V0
Working Life	X Hours @ X°C
High Temperature Storage (Completed Assembly)	Y Hours @ Y°C
High Temperature Storage (as supplied)	Z Hours @ Z°C
Transit/Storage Temperature	Maximum
Low Temperature Transit/Storage	Minimum
Material Stability	% loss of tack permissible; Dimensionally stable; No moisture sensitivity during processing
Outgassing	% Permissible/Zero Permissible

TIM Testing Methods

Major test methods for bulk thermal conductivity and thermal resistances:

Steady State

ASTM D 5470-17

- Data is generated under controlled, known unidirectional flow conditions
- Known: Power, pressure, surfaces, heat flow
- Application-dependent variabilities removed
- Generate data sheet values under known conditions – *vital for TIM manufacturers*
- Data is used for *down selection* to determine materials to test and evaluate.

Transient Techniques

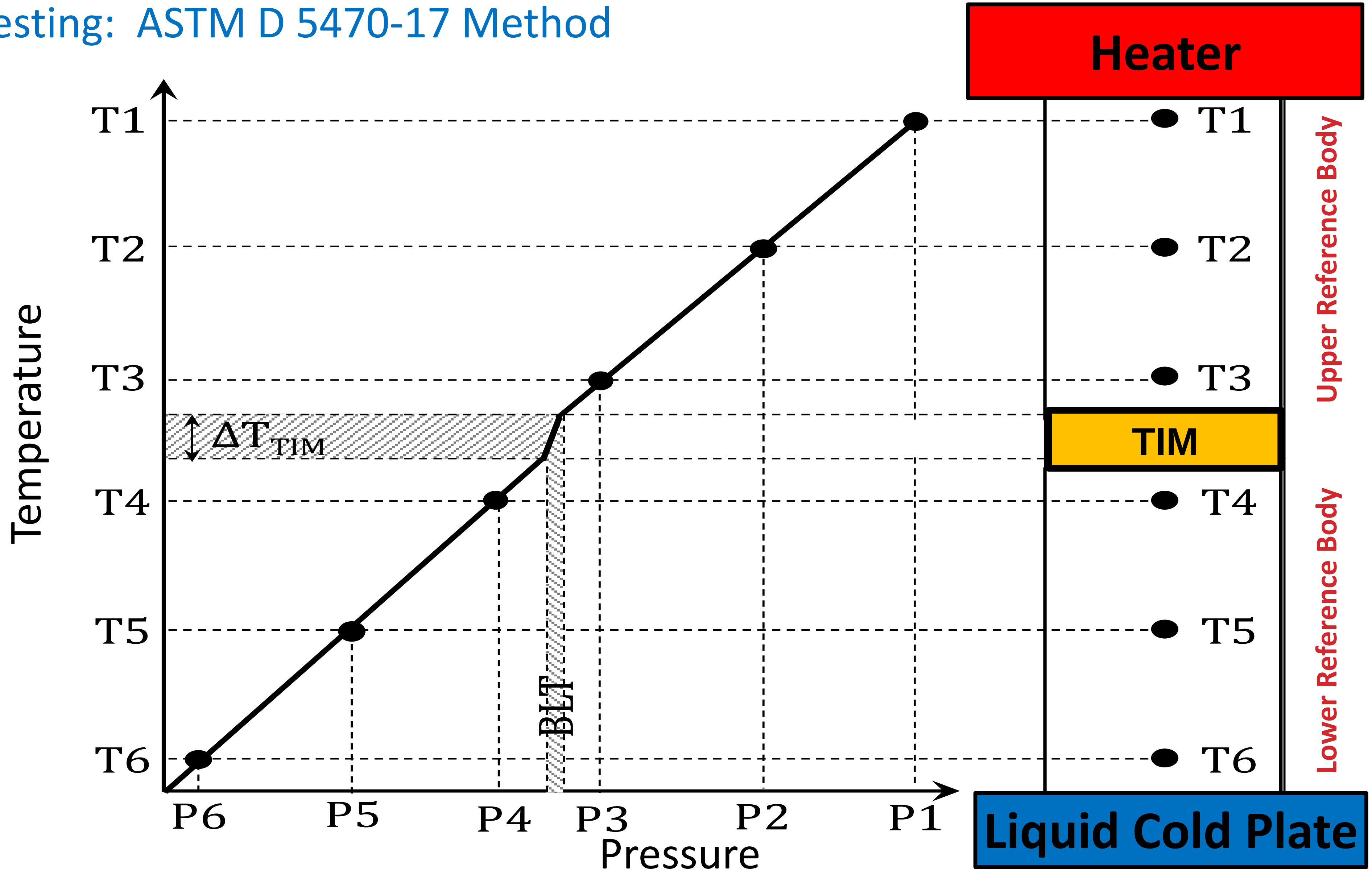
JEDEC JESD 51-14

- Data is generated under application-specific ("in-situ") conditions
- Results will *not* necessarily correspond to ASTM D 5470-17 data – *by definition*
- Results will be tightly aligned and only relevant to a specific package
- Results can be imported to CFD models for that specific package and set of conditions.

★ These two methods are complementary: *one does not replace the other*.

★ The majority of users of TIMs do not have in-house TIM test capability.

TIM Testing: ASTM D 5470-17 Method



Note: ASTM D 5470-17 methodology may be purchased for a nominal fee from ASTM International. Information can be found at www.astm.org

TIM Testing: ASTM D 5470-17 Method

Commercial TIM test stand:

- Designed per ASTM D 5470-17, the industry-standard TIM test methodology for comparative material testing;
- System measures force applied, power (heat), temperature, thickness – precise, uniform heat flow.
- Measures thermal conductivity and provides calculated thermal resistance values.
- Servo control allows many different types of reliability and ageing characterization, including for adhesives.

Example shown: Servo-controlled ASTM D 5470-17 test stand, TIMA5.

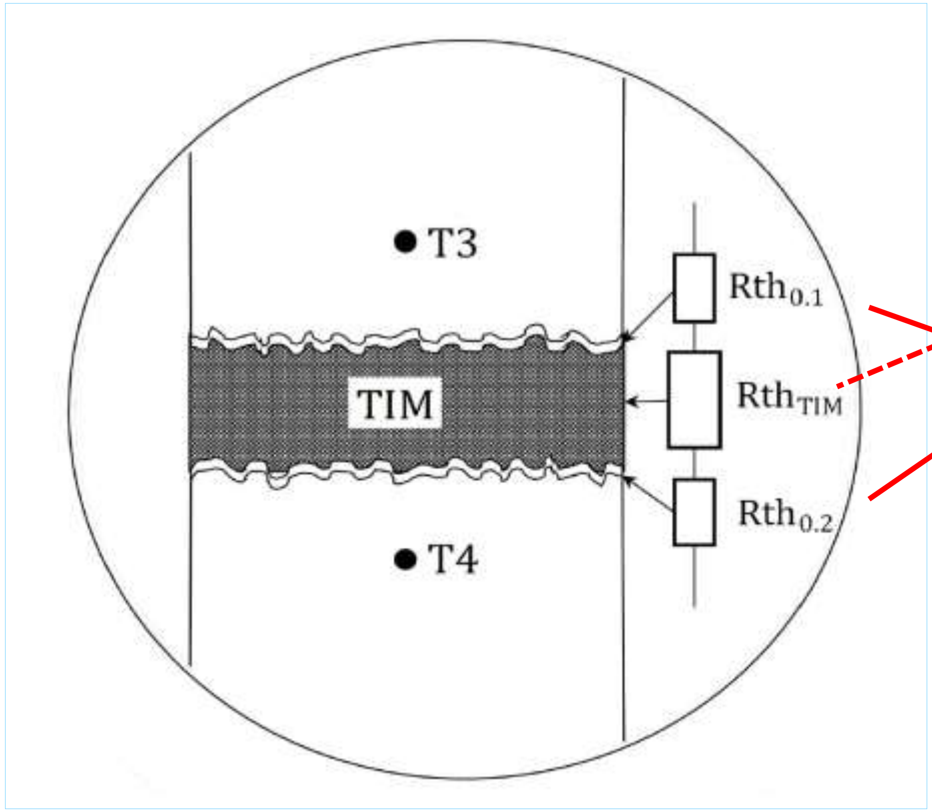
An addendum is attached with additional information regarding TIM testing methods and equipment, including TTVs.

Photograph: Courtesy, Berliner Nanotest und Design GmbH.

TIM Testing: ASTM D 5470-17 Method

ASTM D 5470-17 describes a methodology to provide measurement of a thermal resistance value that is the sum of three constituent values:

- The TIM thermal resistance *total* (R_{th}) is the important value, in practice.



TIM Bulk Resistance

+

(2) Interfacial Contact Resistances (Calculated)

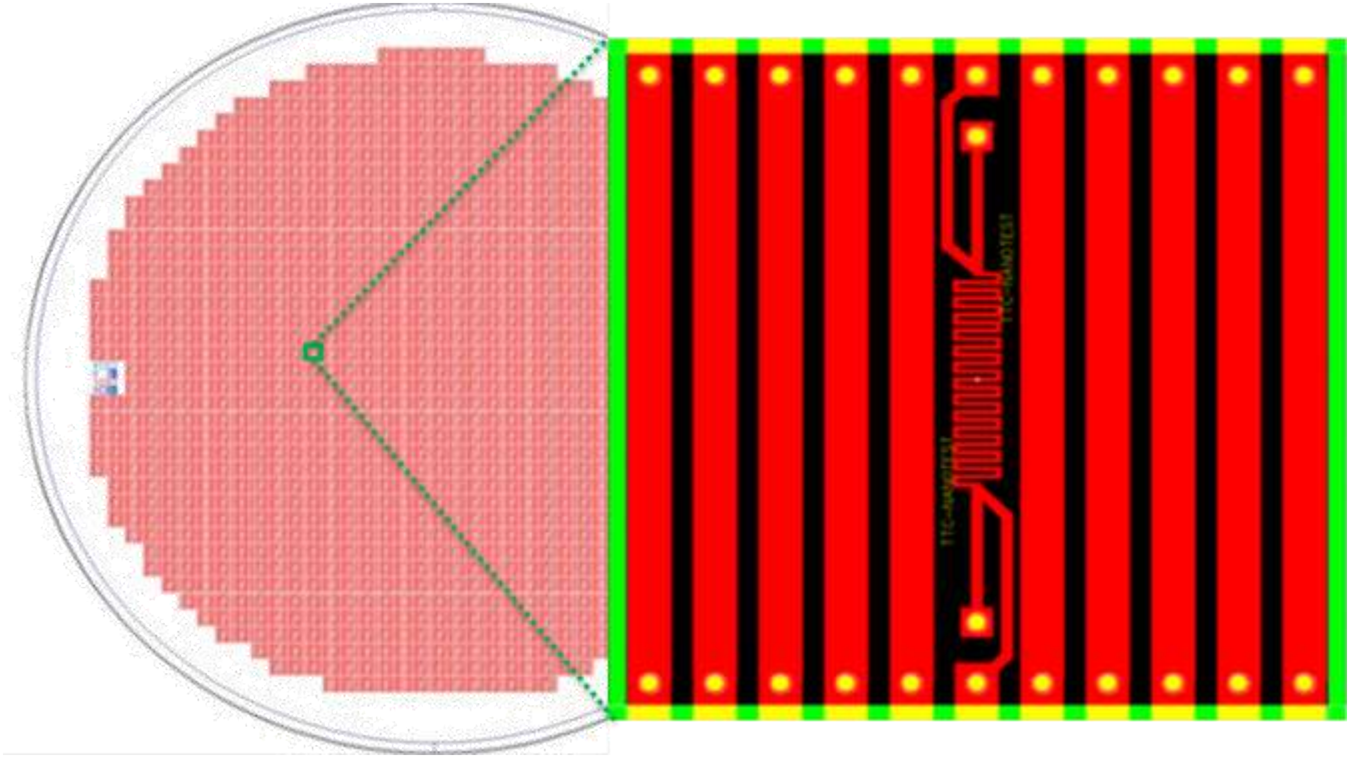
=

R_{th} (or Θ_{TH}) TIM Thermal Resistance (Total)

TIM Testing: Thermal Test Vehicles

Thermal test wafer (example, Nanotest):

- Standard 150mm Si wafer
- 1200 cells (3.2mm x 3.2mm) per wafer
- Thermal test die:
- Test cell (10 resistors, 1 sensor) x 9/die
- Heat dissipation up to 1W/mm^2

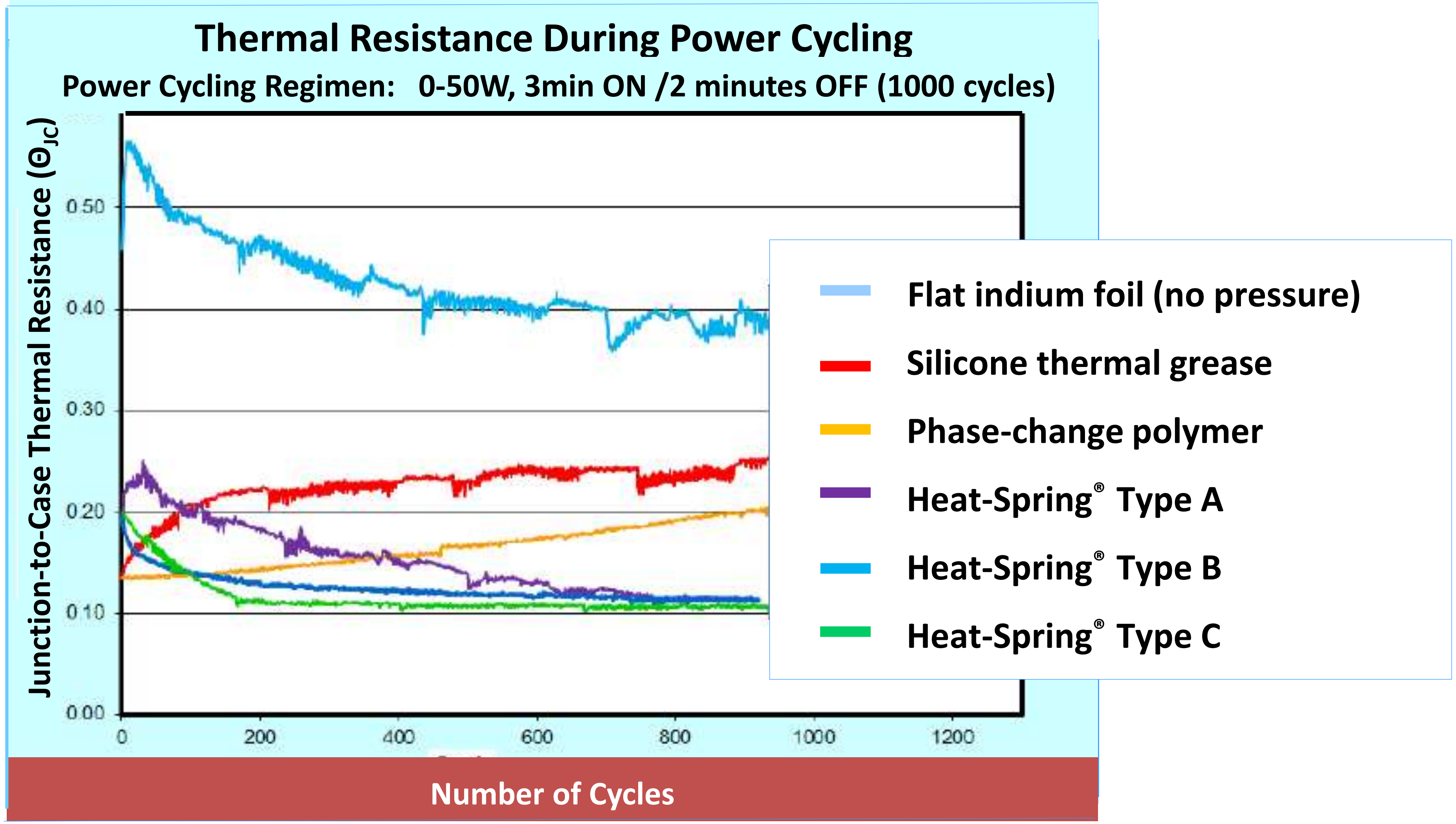


TTCs are an important tool for thermal characterization and qualification of materials and packages in electronics.

- Available in different configurations from:
    - Berliner Nanotest und Design GmbH (Berlin) – Flip chip and wirebond designs
    - IMEC (Belgium)
    - Thermal Engineering Associates (US).

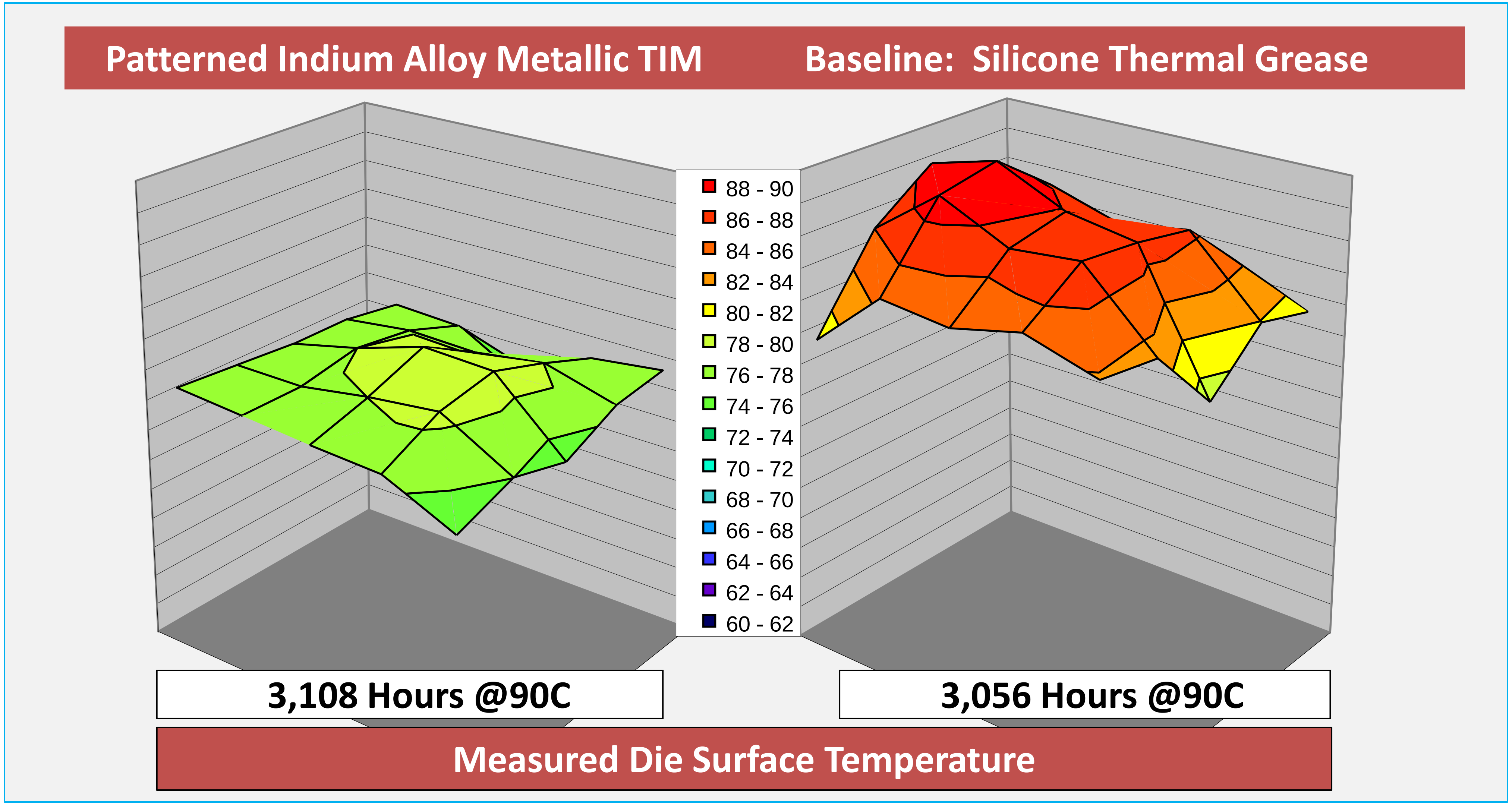
Illustration: Courtesy, Berliner Nanotest und Design GmbH, Berlin.

Comparative Thermal Resistances: Power Cycling



Source: Indium Corporation

Comparative Thermal Resistances: Bake Testing



Patterned Indium Alloy Metallic TIM

Baseline: Silicone Thermal Grease

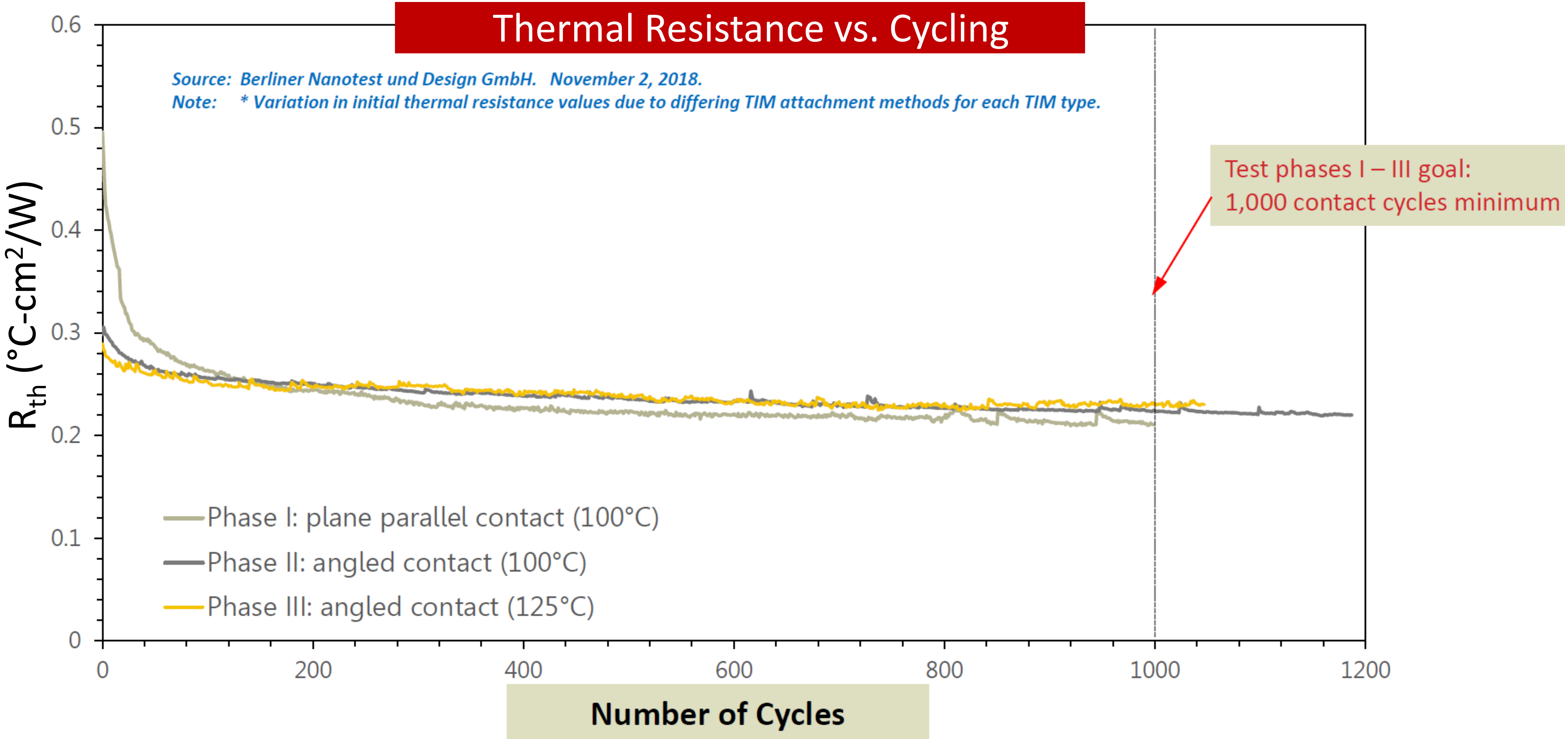
3,108 Hours @90C

3,056 Hours @90C

Measured Die Surface Temperature

Note: Measured die surface temperature at time zero was shown to be approximately equivalent. Above test data taken after 3,000-hour bake test. Increased die surface temperature for Figure B reflects increased thermal resistance due to dry-out of silicone oil in the tested premium silicone-based thermal grease. Data source: Indium Corporation.   Thermal test vehicles provided by Intel Corporation.

Cycling Reliability Testing: Contact Cycling for Semiconductor Test/Burn-In



Source: Berliner Nanotest und Design GmbH. March 19, 2019.

TIM Development Parameters

Semiconductor Test/Burn-in: High Performance TIM Material Target Specification *© 2021 DS&A LLC*

Product Attribute	Goal
Material Stability	No staining, no residue on contact surfaces. Dimensionally stable*; no moisture sensitivity during processing.
Silicone Stability	No silicone content; no dry-out, no silicone oil separation*; zero measurable separation by weight (TGA)*
Outgassing	No permissible outgassing per NASA, aerospace applications; no outgassing for medical, optical, optoelectronic applications and systems
Conformability	Same TIM conforms to different die sizes, lid sizes without damage or change in performance
Particulates	No permissible loss of particulates, fibers
Cost	Product market leading, target and stretch goals met

*Note: * Generalized statement.*

Developments: Graphite Sheet Materials – *TIMs*

Graphite Sheet Thermal Interface Materials

Material Type	Vendor	Product Designation	Thickness (µm)	Bulk Thermal Conductivity (W/mK)	
				X-Y axis	Z-axis
TIM	Dexerials (J)	EX20200XX Gap-filler	100-200	N/A	15-20
	Graftech (US)	Grafoil® GTA-005, GTA-030[(1)]	130-760	140	5.5-7.0
	Hitachi (J)	TC-001	150-500	N/A	40-90

Examples – Similar products available

Note: (1) Included as an example of a very traditional graphite sheet TIM, commercially available for decades. Data sources: Vendor data sheets for the respective suppliers.

Developments: Liquid Metal Alloys and Composites

Solid-liquid hybrids using indium/gallium combinations, dispensed:

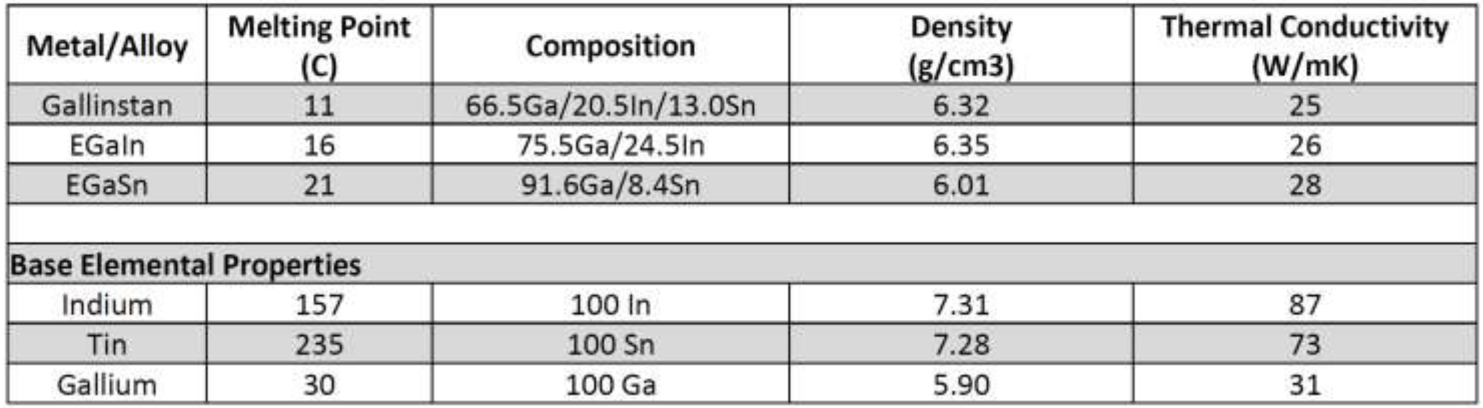
Metallic TIM Types: Current and Development			
Metallic TIM Type	**Primary Application Suitability**	**Advantages**	**Disadvantages**
Compressible	TIM0, TIM2	Long life and reliability, incl. cryogenics and immersion Pump-out resistant Range of alloys available	Requires mechanical fastening Relatively high thickness
Solder	TIM1	High performance Mechanical joining	Requires metallization (BSM, lid) Require flux and reflow process temperatures
Liquid	TIM0, TIM1	Low interfacial resistance Excellent surface wetting	Subject to pump-out Thermal cycling degradation
Solid/Liquid Hybrid	TIM0, TIM1	Improved performance over liquid Excellent surface wetting	Thermal cycling challenges HVM challenges: process development
Amalgam	TIM0, TIM1	Final structure is a solid Some mechanical adhesion due to expansion	Requires phase change Solid interface can be brittle

Note: Modifications by DS&A: Shading indicates development materials. Source documents: 1. Jensen, T., "Metal TIM Innovations for High Performance Computing Applications: IMAPS UK-IEEE EPS Joint Thermal Management Workshop (Virtual), November 25, 2020; 2. Jensen, T., "Liquid Metal Innovations for High Performance TIMs", Semitherm Symposium 35, March 2019.

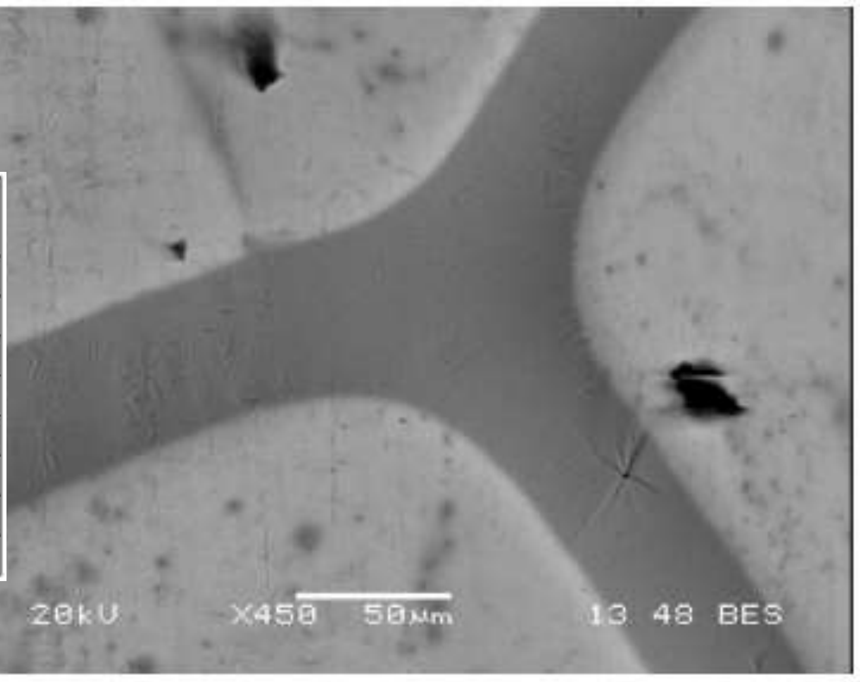
Developments: Liquid Metal Alloys and Composites

Solid-liquid hybrids using indium/gallium combinations, dispensed:

- Primary development target: TIM1, TIM1.5 for use within semiconductor modules
- Combining a metal alloy that is liquid at RT with a metal alloy that is solid at RT
  - Liquid alloy provides very high surface wetting and low thermal resistance
  - Solid alloy creates a structure to minimize pump-out
  - Solid alloy selected must have limited solubility in the liquid alloy
- Dispensable liquid/solid slurry adapted to high-speed dispensing
- Solid creates sponge structure
- Current development programs: Indium Corporation (US).



Metal/Alloy	Melting Point (C)	Composition	Density (g/cm3)	Thermal Conductivity (W/mK)
Gallinstan	11	66.5Ga/20.5In/13.0Sn	6.32	25
EGaIn	16	75.5Ga/24.5In	6.35	26
EGaSn	21	91.6Ga/8.4Sn	6.01	28
Base Elemental Properties				
Indium	157	100 In	7.31	87
Tin	235	100 Sn	7.28	73
Gallium	30	100 Ga	5.90	31



Source: Jensen, T., "Liquid Metal Innovations for High Performance TIMs", Semitherm Symposium 35, March 2019.

Summary – Thermal Interface Materials

TIMs are a small cost but a *critical element in heat transfer* for semiconductors and heat dissipating components:

- Categorizing TIMs by type is important in understanding down selecting materials for characterization – and understanding data sheet values is critical.
- Significant technical improvements for increased accuracy and reproducibility for commercial TIM test stands are now available per ASTM D 5470-17 and TOCS methodologies.
- Specialized TIM materials must be measured against multiple requirements for critical applications.
- This is an era of *increasingly specialized high-performance TIMs* to meet specific needs.
- Metallic TIMs in different forms offer the best overall performance and assembly potential.
- Critical goal: *Meet assembly and thermal interface requirements*, <u>not</u> solely the maximum theoretical thermal conductivity or minimum thermal resistance.

CTE-Matched Thermal Composites and Laminates

CTE-Matched Thermal Composites and Laminates

CTE-matched thermal materials have been utilized for decades, beginning with RF devices for telcom and wireless applications. The traditional materials are molybdenum, Mo-Cu, and W-Cu.

Newer metal matrix composites have been developed since 1998, for IGBT baseplates and similar applications. Examples of some materials are shown in the two following tables:

- These materials are selected only when a CTE matching issue is encountered in packaging materials.
- Bulk thermal conductivity value is secondary.

CTE-Matched Thermal Composites and Laminates

New CTE-matching composite development programs: New alternatives to copper and old materials such as CuW:

CTE-Matched Composite and Laminate Heat Spreader Materials
Table 1 - Physical Properties (Typical, R.T.): *Rank by CTE Value*

Material Type	Data Source	Coefficient of Thermal Expansion (CTE) (ppm/°C)		Bulk Thermal Conductivity (W/mK)		Density (g/cc)	Young's Modulus (Gpa)
		In-Plane (X-Y)	Through-Plane (Z)	In-Plane	Through-Plane		
Molybdenum	1	**5.0**		140	142	10.2	330
Cu-Mo-Cu (CMC)	1	**6.0**		170-182	170-182	9.9 – 10.0	280
20Cu/60Invar/20Cu	2	**6.0**	**7.7**	164	22	8.5	135
MoGr	3	**6.5**		650	45	2.57	69.7**
Cu-MetGraf 7-300	4	**7.0**		287	225	6.1	76
25Cu/50Mo/25Cu	2	**7.9**		268	N/A	9.6	220
Cu (Non-OFHC)	2	**17**		360-385		8.9	120-130

*Notes: * In-plane value: 2.4; Through-plane: 14.7. ** In-plane value. Data Sources: (1) Collins Aerospace; (2) 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; (3) Nanoker Research; (4) Parker Hannifin. Volumetric CTE of MoGr is 6.5 ppm/°C. All values at room temperature (20°C).*

CTE-Matched Thermal Composites and Laminates

New CTE-matching composite development programs: New alternatives to copper and old materials such as CuW:

CTE-Matched Composite and Laminate Heat Spreader Materials (Continued)
Table 2 - Physical Properties (Typical, R.T.) and Manufacturing Process: *Rank by Bulk Thermal Conductivity Value*

Material Type	Material	Manufacturing Process	CTE [Typ., ppm/°C (R.T.)]	Bulk Thermal Conductivity (Typ., W/mK)
MoGr	Molybdenum-Ti-Graphite	Infiltration/machined	6.5*	**650/45**
AlD	Al/diamond composite	Infiltration-hot pressing/machined	7.0 – 9.0	**440-530**
CuD (Vendor A)	Cu/40%D composite	Hot pressing	12	**475**
CuD (Vendor B)	Cu/diamond	Casting/machined	11-12	**400**
Cu (Reference)	Copper (non-OFHC)	--	17	**360**
AlSiC	AlSiC, cast w/Al skin	Net-shape casting/infiltration	8	**200**
AlSiC	AlSiC, cast w/Al skin	Net-shape casting/infiltration	12	**200**

Notes: * Volumetric CTE value. All values at room temperature (20°C).
Data sources: Respective vendors.

Heat Pipes, Vapor Chambers, Thermosyphons

Passive and Active Liquid Cooling Technologies for Electronic Systems

A variety of liquid cooling technologies are available for removing heat in power electronic systems. In broad terms, these are:

Passive systems (no electrical or mechanical energy input required):

- Heat pipe and vapor chamber assemblies
- Thermosyphons and loop heat pipe (LHP) systems

Active systems (i.e., mechanically pumped):

- Capillary pumped-loop (CPL)
- Single-phase liquid cooling, passive and pumped, primarily using deionized water/glycol
- Two-phase liquid cooling systems, pumped, using several fluids
- Liquid immersion using dielectric liquids
- Refrigeration systems -- Vapor cycle compression (VCC)

Heat Pipes and Vapor Chambers

Heat pipes as a broadly defined hardware technology are *sealed and passive (i.e., no pump) devices* which incorporate a liquid within the sealed chamber as the working fluid for heat transport from source to dissipation location.

A generalized categorization of heat pipes includes these differentiated component types:

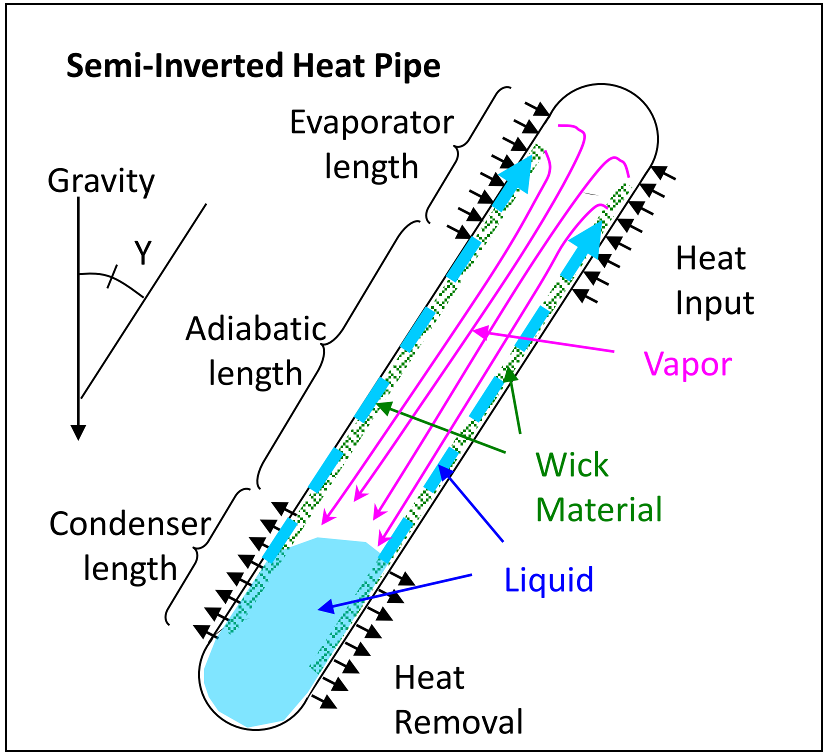
- Conventional heat pipes – Extremely common in PCs, tablets, high-end smart phones. Frequently found in multiples in large heat sink assemblies for stationary electrical drives.
- Thermosyphons – Uncommon in North America; used principally for stationary electrical drives in Japan. Used in some traction applications in Japan, European Union. Does not work against gravity.
- Loop heat pipes (and capillary loop heat pipes, CPL, separate liquid return) – Uncommon, limited use
- Pulsating and oscillating heat pipes – Uncommon, typically in satellites and other applications
- Liquid piston pumped heat pipe – Research concept
- Vapor chambers – Flat, rectangular components containing a small amount of liquid and designed with a large *integral* contact area at the heat source as compared to heat pipe assemblies. Typically found in server processor modules and similar specialized applications.

Source: DS&A LLC.

Heat Pipes and Vapor Chambers

Initially developed in 1964, considered to be an esoteric satellite cooling technology until 1995.

- First high unit volume application in computing in notebook PCs in 1995, for processor cooling, brought heat pipes into mainstream electronics thermal management.



- Hundreds of millions of small diameter heat pipes are manufactured today and the heat pipe is considered to be a common component for heat sink assembly design.

Functional description:

- Low pressure liquid (typically water) boils at heat source location;
- Vapor moves to other end, condenses, and returns via wick or wall structure
- Cycle repeats

General description for terrestrial applications:

- Copper tube construction with an internal wick structure
- Water as the liquid (<1cc in the majority of small-diameter applications, in the 3-7mm diameter range).

Source: Ross Wilcoxon PhD, Advanced Technology Center, Collins Aerospace (2018).

Thermosyphons

Thermosyphons in comparison to heat pipes:

- By definition, a thermosyphon has no wick structure.
- By definition, a thermosyphon will not operate ("pump") when approaching "flat" orientation (0 degrees).
- Lack of wick structure increases the total available vapor space.
- Higher total Q_{MAX} capability for a given diameter and length.

Significant drawbacks for thermosyphon application:

- Gravity dependent
- Will not function in an inverted installation
- Fluid selection and fluid fill percentage must be considered for any applications subject to freezing.

Primary distinction between a heat pipe and a thermosyphon:

- Heat pipe: Capillary effect, utilizing internal wick structure
- Thermosyphon: Gravity flow

Primary applications in vehicle systems for thermosyphons are in rail traction market: heavy haul freight locomotives and transit and rail passenger power units.

Thermoelectric Modules

Thermoelectric Modules

Thermoelectric modules were first introduced in the early 1960s:

- Referred to as a “solid state refrigerator” for providing cooling (or heating);
- Also known as Peltier-effect devices;
- Requires electrical power input to generate sub-ambient cooling on a module surface;
- May also be reversed to generate heat, so highly useful for incorporation into semiconductor test head designs;
- Also currently being investigated as the primary component utilized for energy harvesting, typically from the catalytic converter or manifold of an ICE engine.

Well known, well characterized in abundant industry literature:

- Many vendors, globally, for high unit volume production and specialized designs;
- Typically always used in combination with an air-cooled heat sink or liquid cold plate for continuous operation.

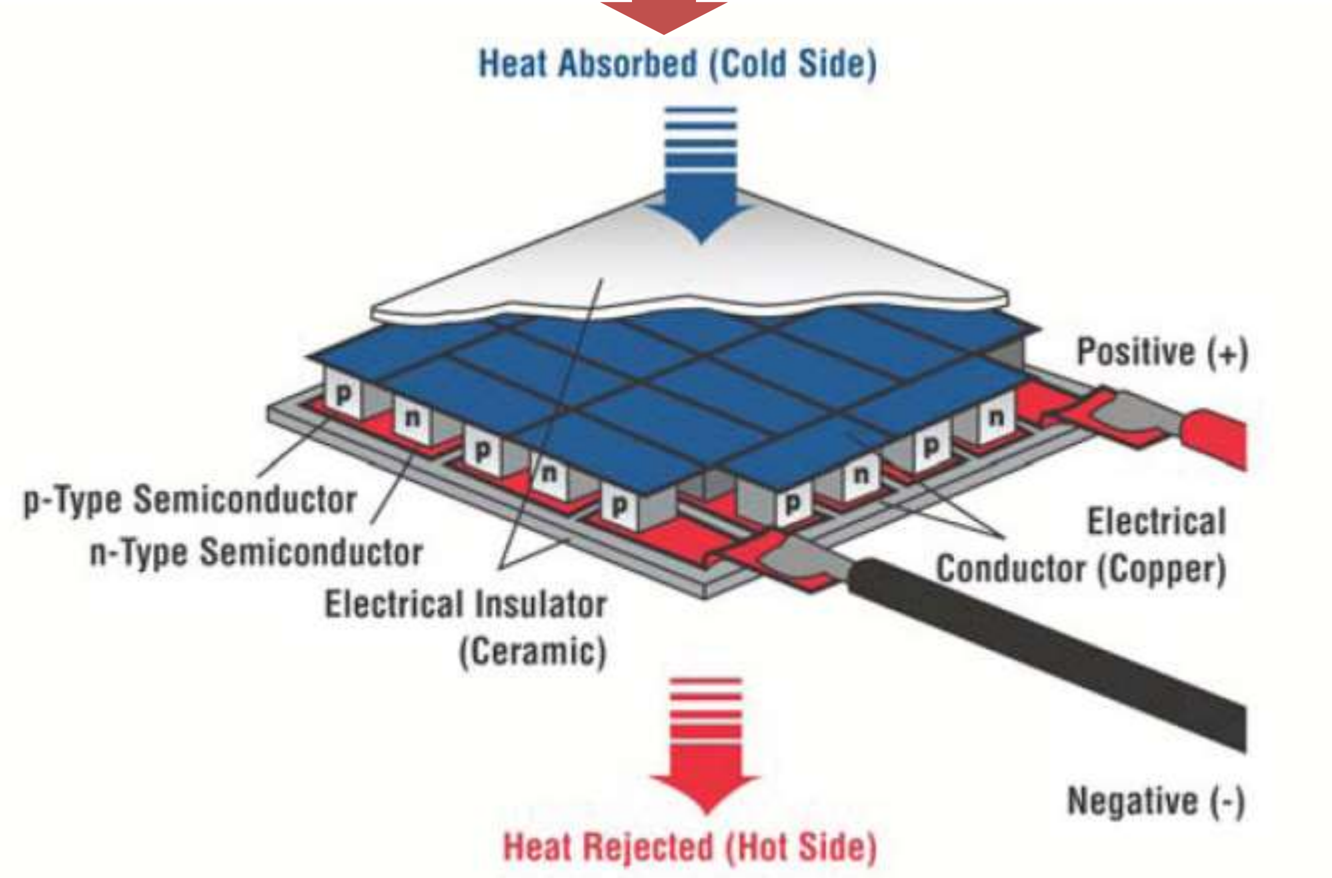
Currently utilized in complex semiconductor test heads, typically in combination with a miniature liquid cold plate sized correctly to remove heat loads for the required thermal management performance need.

Source: DS&A LLC.

Thermoelectric Modules

Basic concept of TEC implementation:

Device Under Test – Heat Source



Heat Sink or Liquid Cold Plate – Heat Removal Mechanism

Source: Laird Thermal Systems "Thermoelectric Handbook", November 2020.

Thermoelectric Modules

Basics of thermoelectric modules (TECs):

- Functions as a miniature heat pump, without moving parts or fluids;
- TECs are utilized where there is a specific need to handle a heat load in a small physical volume, to very precisely control a surface temperature, to reduce weight, or with certain environmental conditions such as high ambient;
  - Maximum temperature change effected in a minimum device volume is a common design requirement.
  - TECs can be ganged in different implementation configurations (for example, to handle multiple spot heat sources).
  - Typical TEC cold side surface contact areas available range from 5mm to 60mm on a side.
- Major advantage that is unique is the temperature control precision that may be designed into a test head, applying cooling or heat instantaneously, as needed, with sensors and control circuits;
- Major advantage is the ability to drive to sub-ambient temperatures without requiring a compressor and refrigeration system.
- Major disadvantage is the relative module electrical inefficiency, requiring significant electrical power input.
- Primary device selection is based on three basic application parameters:

T_C – Cold surface temperature required

T_h – Hot surface temperature required

Q_c – Cold surface heat load to be absorbed

Source: DS&A LLC.

Liquid Cooling Systems (Active)

Overview: Liquid Cooling Fluids for Electronic Systems

Fluids available for liquid cooling systems (including thermosyphons):

- Water or deionized water
- Ethylene glycol/water (EGW) and polyethylene glycol/water (PGW) mixtures
- Common refrigerants (R134a, R-1234yf, R-1234zf, R245fa, others)
- Polyalphaolefin (PAO) :
  - Typically, only specified for military airborne platforms
  - Currently under evaluation for single-phase liquid immersion cooling for computing systems
  - Light oils available from multiple vendors, typically used as a lubricant
- Silicate esters: Monsanto Coolanol™ – Not practical, given high boiling point, generally no longer used
- Perfluorinated fluorocarbons:
  - 3M Company Fluorinert™ and Novec™
  - Solvay Solexis Galden™

Liquids as Electronic Coolants

Liquid immersion cooling for servers and enterprise servers containing high power dissipation processors and other ICs can be effectively cooled with liquid immersion, achieving these goals:

- Reduce the temperature differential between high-power, high heat flux processors, memory, and coolant inlet temperature
- Reduce device operating temperatures
- Reduce electricity consumption by eliminating fans
- Enable higher coolant operating temperature at the inlet
  - Reduce total energy consumption required for chilled water
  - In turn, enable heat recovery and reuse for other purposes, such as building heating
- Potentially lower overall system complexity, eliminating:
  - Large numbers of rack fans
  - server cabinet exhaust blowers
  - Data center/server room CRAC/CRAH units
  - Large volumes of underfloor pumped chilled water.

Source: DS&A LLC.

Two-phase Passive and Pumped Liquid Cooling Systems

Primary reason for evaluating a two-phase system:

- Two-phase passive* systems (heat pipes, vapor chambers, thermosyphons) with *boiling occurring in a permanently-sealed system, without requiring any external energy source for pumping*.
- Two-phase pumped liquid system *can move 2-4X heat per fluid mass*:
  - Taking advantage of the *heat of vaporization*.

Benefits for use:

- High temperature stability across system: <1% variation across hundreds of liquid cold plates;
- Ability to more *precisely control* temperature: cold plates in series or parallel;
- Ability to *adapt to rapid change in total heat load* due to cycling, surge, or other effects;
- Significantly *smaller tubing diameters*, given 100X – 1,000X higher cooling capability on a volumetric basis;
- Smaller volume of fluid;
- Lower total system mass.

First commercial AI server utilizing two-phase pumped dielectric liquid cooling from a major OEM introduced in November 2020 – a significant step.

*Notes: * By definition, not requiring an external energy source for mechanical pumping.*
Source: DS&A LLC.

Two-phase Pumped Liquid Cooling Systems

Selected examples of current development for pumped* two-phase dielectric liquid cooling system technologies:

Company	Coolant	Status
ACT Inc. (US)	R-134a/R-1234yf	Continuing development
Alcatel-Lucent (US)	R-134a	R&D project completed
Fujitsu (Japan)	R-134a	Production
IBM Research (US)	R-1234ze	Continuing development
NEC System Research Laboratories (Japan)	3M Novec™ HFE-7100	Continuing development
USDOE Oak Ridge National Laboratory (US)	R-134a/R-1234yf	Continuing development
Parker Hannifin* Precision Cooling Business Unit (US)	R-134a/R-1234yf	Business unit closed
Durbin Group/Thermal Form & Function Inc. (US)** (1)	R-134a/R-1234yf	Continuing development

Notes: (1) Originator, Pumped Liquid Multiphase Cooling concept utilizing pumped refrigerant for computing and power electronics cooling.

** Utilizing a refrigerant pump to pump liquid refrigerant through a system, with boiling occurring in the liquid cold plate and vapor-to-liquid phase change for recirculation.*

*** See Durbin Group/Thermal Form & Function Inc.*

Source: DS&A LLC.

Liquid Immersion: Single-Phase Heat Removal

Liquid immersion server development systems:

Single Phase Bath Immersion

1. Heat Sinks pulled

2. CPUs removed

3. Previously installed indium foil removed & heat sinks reinstalled, bare chip to heat sink contact

Indium foil TIM2

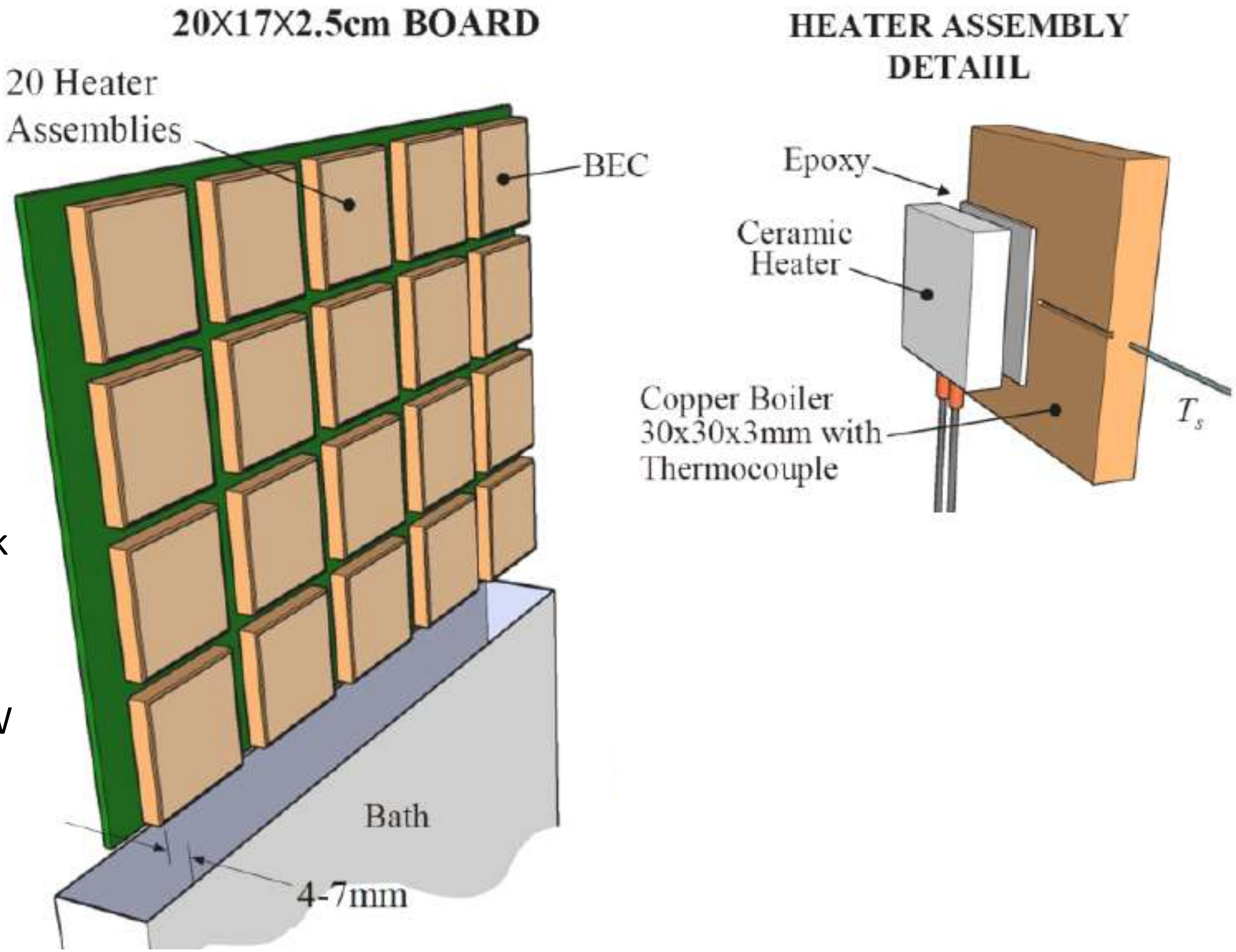
SEMI-THERM TTW
Thermal Technologies Workshop

Source: H. Alissa, Microsoft, "Liquid Cooling in the Cloud," SEMI-THERM Thermal Technologies Workshop 2020 (Virtual), November 10-12, 2020.

Liquid Immersion: Two-Phase Heat Removal

Liquid immersion demonstration:

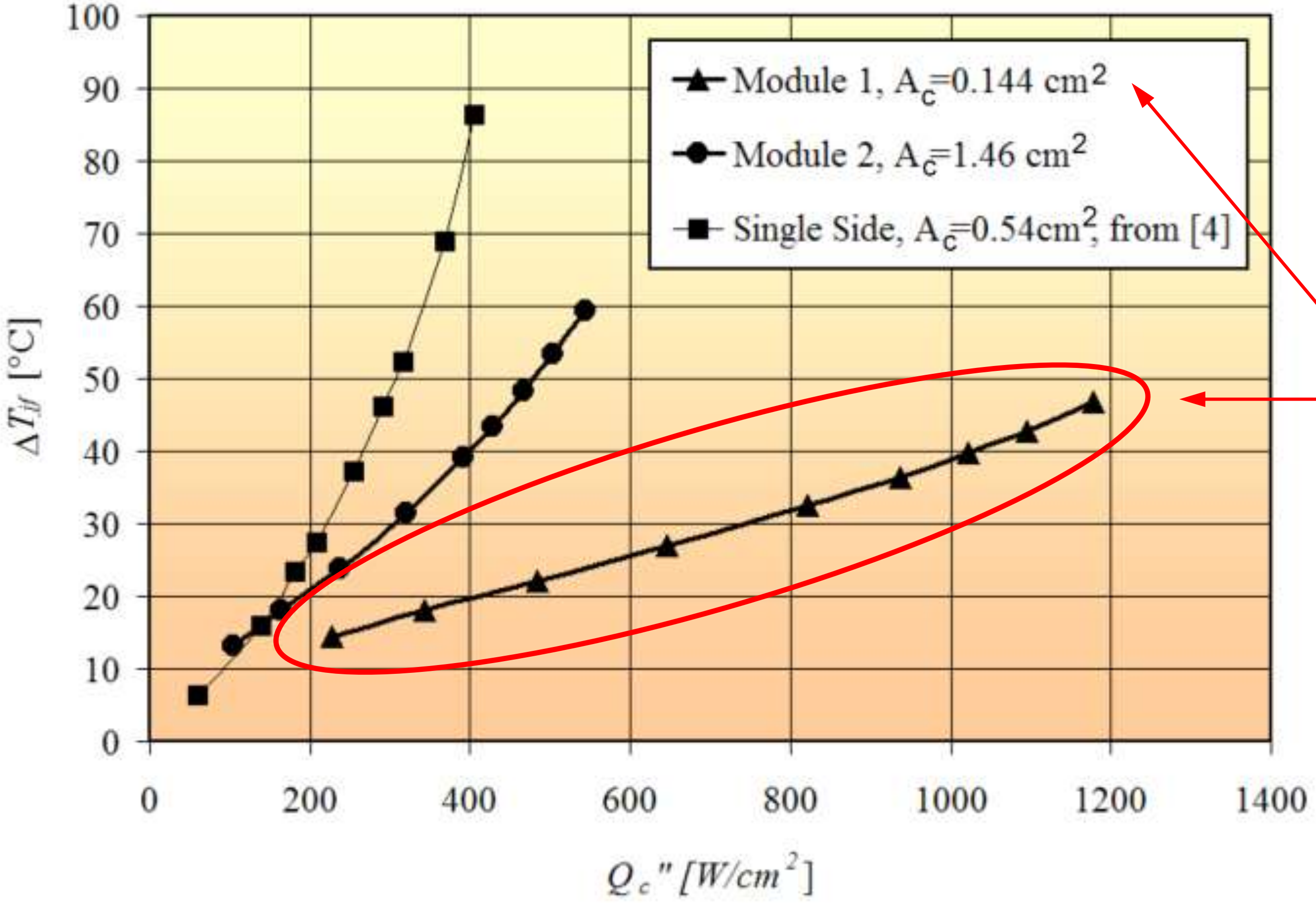
- Mock-up of system board with 20 semiconductor devices
- 20x17cm system board
- Each simulated semiconductor device bonded to copper boiler
- (20) 200W sources, each with 30x30mm boiler surface area
- Immersion in two-phase HFE dielectric fluid within a metal wall tank
- Total tank volume: 1 liter
- Fluid: <200cm^3
- Total power dissipation achieved: 4kW



Notes: Demonstration system designed and constructed at 3M Company EMSD Liquids Laboratory, St. Paul MN USA. Fluid: 3M Novec Hydrofluoroether (HFE).
Reference: Tuma, P.E., "Two-Phase Immersion Cooling of IGBTs", SEMI-THERM Thermal Technologies Workshop 2020 (Virtual), November 10-12, 2020.

Liquid Immersion: Two-Phase Heat Removal

Liquid immersion tested performance:



38x38mm die

Notes: Demonstration system designed and constructed at 3M Company EMSD Liquids Laboratory, St. Paul MN USA. Fluid: 3M Novec Hydrofluoroether (HFE).
Reference: Tuma, P.E., "Two-Phase Immersion Cooling of IGBTs", SEMI-THERM Thermal Technologies Workshop 2020 (Virtual), November 10-12, 2020.

Liquids as Electronic Coolants

Single-Phase Liquid Cooling vs. Air Cooling	
Advantages of Single-Phase Water Cooling	Disadvantages of Single-Phase Water Cooling
Order of magnitude lower unit thermal resistance	Added hardware and complexity
3500X volumetric heat-carrying capacity	Added cost (but not necessarily cost/performance)
Total control of flow	Water freezes at 0°C
Lower temperature • Higher clock frequencies • Less power (leakage current) • Better reliability	Perceptions of water cooling
Less power consumption in the data center • "Chiller-less" operation ⟹ Warm water cooling • Far less or no computer room air handlers (CRAC) • Less heat to transfer to outside ambient	

Notes: (1) Advantages of single-phase liquid cooling with water and additives versus forced convection air cooling.

Source: Ellsworth, M., "Liquid Cooling Today's High Performance Computers," Keynote, IMAPS Advanced Technology Workshop on Thermal Management 2016, Los Gatos CA USA, October 25-27, 2016.

Liquids as Electronic Coolants

Two-Phase Dielectric Liquid Cooling vs. Single-Phase Water Cooling	
Advantages of Two-Phase Dielectric Liquid Cooling	**Disadvantages of Two-Phase Dielectric Liquid Cooling**
Higher heat transfer coefficients achieved (4X)	Greater operational complexity
Phase change leads to lower fluid volume required	Questions regarding dielectric liquids and potential environmental issues
Aluminum can be used (for lower cost components)	Some coolants will require degassing prior to use
Dielectric coolants will not freeze to -40C	Coolants more expensive than water
Ship to field full; no need to fill, test, and drain (prior to shipment due to potential for freeze damage)	
Leaks will not damage electronics	
Direct contact liquid cooling potential (to die)	

Notes: (1) Advantages of two-phase dielectric liquid cooling compared to use of single-phase water (with necessary additives).
Source: Ellsworth, M., "Liquid Cooling Today's High Performance Computers," Keynote, IMAPS Advanced Technology Workshop on Thermal Management 2016, Los Gatos CA USA, October 25-27, 2016.

Liquids as Electronic Coolants

General Types of Coolants		
Coolant Type	**Example of Typical Coolant**	**Comments** © DS&A LLC 2017-2021
Solvents	Water	Most common, deionized water, with antifreeze and other additives
	Ammonia	Typically, heat pipes only
	Methanol	Flammable, unstable
Aliphatic Hydrocarbons	Polyalphaolefin (PAO)	Typically, military airborne systems applications (preferred USAF fluid)
Alcohols	Ethanol, Methanol, Isopropanol	Flammable, typically for aerospace and specialty passive two-phase (heat pipe, vapor chamber, thermosyphon) applications
Fluorocarbons, Fluoroketones	3M Novec™ (FK), 3M Fluorinert™ Solvay Solexis Galden® D02TS, D03	Very common dielectrics for semiconductor testing and liquid immersion systems
Glycol Solutions	Ethylene Glycol/Water (EGW)	Traditional commercial coolant
	Propylene Glycol/Water (PGW)	Traditional military/aero coolant
Refrigerants	R-134a, R-1234yf, R-1234ze, R-245fa	Common refrigerants, available globally
Silicate Esters	Coolanol®	(Formerly) common for military/aero applications
Liquid Metals*	Indium-Gallium Alloy	Use only in very specialized local cooling system applications

*Notes: Fluorinert and Novec are trademarks of 3M Company; Galden is a registered mark of Solvay; Coolanol is a registered mark of Monsanto Chemicals. * Liquid metals are very specialized electronics systems and are not widely utilized. Research and development activities continue, especially recently, given the specific requirements of specialized potential application requirements within integrated circuit packaging and airborne and computing systems applications. Source: DS&A LLC.*

Liquids as Electronic Coolants

Coolant	Thermal Conductivity (W/m-K)	Thermal Expansion Coefficient (K^{-1})	Specific Heat (J/kg-K)	Boiling Point (°C)	Freezing Point (°C)	Reference Temperature (°C)
Water*	0.600	0.0003	**4279**	**100**	**0**	25
PGW - Propylene Glycol/Water (50%)	0.382	0.0023	**3640**	**222**	**-28**	25
3M Novec 649 Fluoroketone	0.059	0.0018	**1103**	**49**	**<-100**	25
3M Fluorinert FC-72 (PFC)	0.057	0.0016	**1100**	**56**	**-90**	25
PAO - Polyalphaolefin (2cSt)	0.142	0.0008	**2219**	**55**	**-73**	26.67
Coolanol-20	0.120	0.0005	**1907**	**232**	**<-73**	26.67
R-134a	0.0824/0.0145 Liquid/vapor[1]	N/A	**1400**	**-26.1**[2]	**-103**	25

Notes: Fluorinert and Novec are trademarks of 3M Company; Galden is a registered mark of Solvay; Coolanol is a registered mark of Monsanto Chemicals.

** Without dilution and without performance reduction through addition of antifreeze, biologic growth containment inhibitor, anti-contaminant, or other additive types.*

1. Vapor at 1 atm (101.3kPa), 25°C.

2: Boiling point at 1 atm, 25°C.

Source: DS&A LLC.

Liquids as Electronic Coolants

Coolant *© DS&A LLC 2017-2021*	GWP (GWP)	Flashpoint (°C)	Vapor Pressure (kPa)	Dielectric Constant (@1kHz)	Prandtl Number	Liquid Density (kg/m^3)	Reference Temperature (°C)
Water*	0	None	3.2	78.5	6.2	997	25
PGW - Propylene Glycol/Water (50%)	Low	99.1	N/A	N/A	46	1034	25
3M Novec™ 649 (FK)	1	None	40	1.8	N/A	1600	25
3M Fluorinert™ FC-72	>6000	None	30	1.8	14	1680	25
PAO – Polyalphaolefin 2cSt)	N/A	163	<1	N/A	88	787	26.67
Coolanol®-20	N/A	>230	5.3[1]	2.1	31	887	26.67
R-134a	1300	None 750[2]	661.9[3]	9.5	N/A	1210	25

Notes: Fluorinert and Novec are trademarks of 3M Company; Galden is a registered mark of Solvay; Coolanol is a registered mark of Monsanto Chemicals.
** Without dilution and performance reduction with addition of any antifreeze, biologic anti-contaminant, or other additive.*
*1: @150°C**
2: Autoignition temperature; Flash point: None.
3: Vapor pressure, saturated liquid.

Source: DS&A LLC.

Liquid Cooling Technologies: Performance

What performance improvements can be gained with different thermal management solutions?

Type of IGBT Packaging and Thermal Management Technology	Average Heat Flux Achieved (W/cm^2 of Silicon)
Standard IGBT Module/Natural Convection (Air)	11
Standard IGBT Module/Forced Convection (Air)	33
Press-Pack GTO/Pool Boiling	25
Standard IGBT Module/Heat Pipe	32
Standard IGBT Module/Oil cooling	60
Standard IGBT Module/EGW* Cooling	83
Direct Cooling/Minichannel EGW* Cooling	120
Direct Cooling/Minichannel Double Sided EGW* Cooling	180
3D Silicon/Microchannel/EGW* Cooling	400 ALSTOM

*Note: * Ethylene Glycol/Water (EGW) mixture.*

Source: Adapted from M. Mermet-Guyennet, Alstom Transport, "An Overview on Thermal Management for Power Chips", IMAPS France ATW Thermal 2006, La Rochelle, France, February 1-2, 2006.

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Market assessment and product strategy development for electronics thermal management: Advanced thermal materials, thermal composites, thermal component concepts, and two-phase pumped liquid cooling systems.

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Addendum

Industry Practice – Thermal Management Design

Designing for adequate heat dissipation requires these basic steps:

1. Identify and understand the operating temperature and operating characteristics (maximum power dissipation, allowable temperature differential at junction, case, internal ambient, external ambient) at the module and system level
2. Determine all relevant materials and maximum allowable temperature at each level in the "thermal stack":
   - Semiconductor(s)
   - Thermal and packaging materials (TIM0 or TIM1, solder bumps/balls, interposers, internal heat spreaders)
   - Module lid
   - Additional thermal interface material (multiple levels)
   - Heat sink or liquid cold plate (aluminum, copper)
   - Air or liquid
   - Housing or enclosure
   - "Ultimate heat sink" (where the system operating heat load is to be dissipated externally in the data center)
3. Calculate a thermal resistance values for each level and material within the thermal stack
4. Adapt an initial overall thermal design concept (forced air, single- or two-phase closed liquid, or liquid immersion) as required to meet specified system design parameters
5. Develop a thermal model of a proposed thermal solution to allow repeated model iteration with improvements
6. Working with a thermal solution supplier, develop a manufacturable heat sink or cold plate design
7. Build prototypes for validation and test; modify, iterate.

Source: DS&A LLC.

TIM Evaluation

Narrowly-defined thermal performance is not the only criteria for selection of a TIM:

- A *holistic view* is needed of *multiple application factors*:

➡ The single *lowest thermal resistance* TIM or the TIM having the *highest bulk thermal conductivity* may not necessarily be selected.

➡ A ‘well-performing’ TIM within a *range of application factors* must be selected.

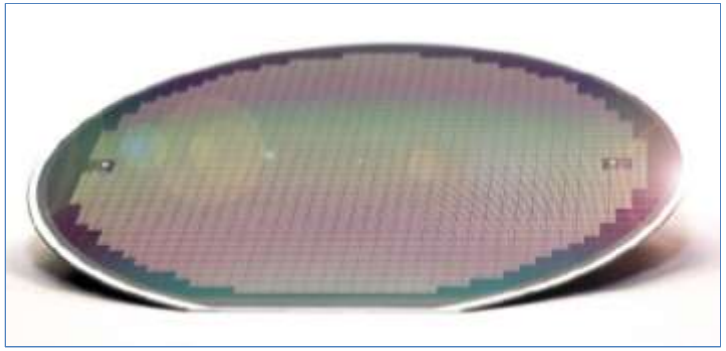
It is important to recognize that only a small percentage of electronics assembly facilities and design staffs, globally, have access to TIM testing/characterization capabilities. *Data sheet values are the primary selection tool.*

TIM Evaluation

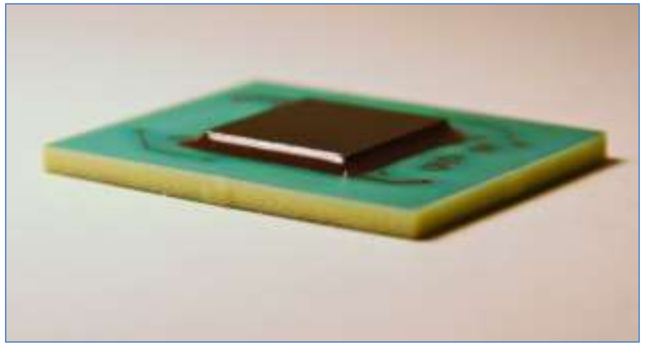
Specialized TIMs can be characterized as “well-performing”:

- Measured successfully against specific requirements of an application;
  - ✓ Required thermal resistance value;
  - ✓ Suitable per applicable surface flatness, roughness, clamping force;
  - ✓ Suitable per anticipated operating environment;
  - ✓ *No* compound run-out due to temperature
  - ✓ *No* compound pump-out due to mechanical stress
  - ✓ *No* silicone bleed, outgassing, redeposition on critical optical elements.
  - ✓ Required product life and reliability;
  - ✓ Suitable cost and delivery format;
  - ✓ Appropriate assembly process and handling and storage.

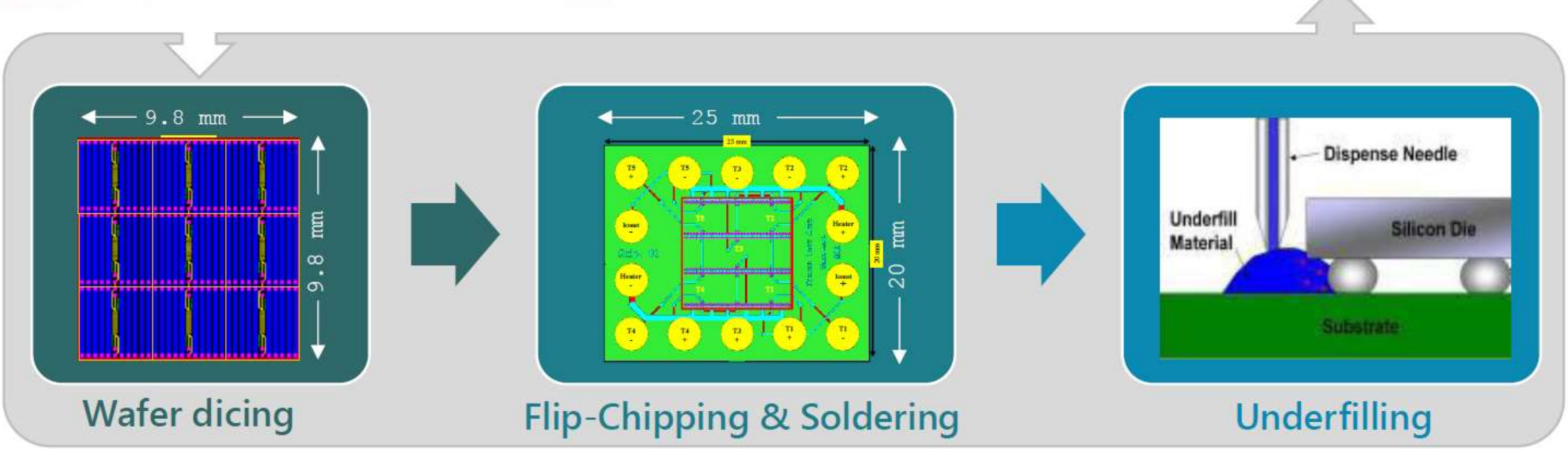
TIM Testing: Thermal Test Vehicles



Wafer



Thermal Test Vehicle:
Flip Chip or Wire Bond Variants



Wafer dicing

Flip-Chipping & Soldering

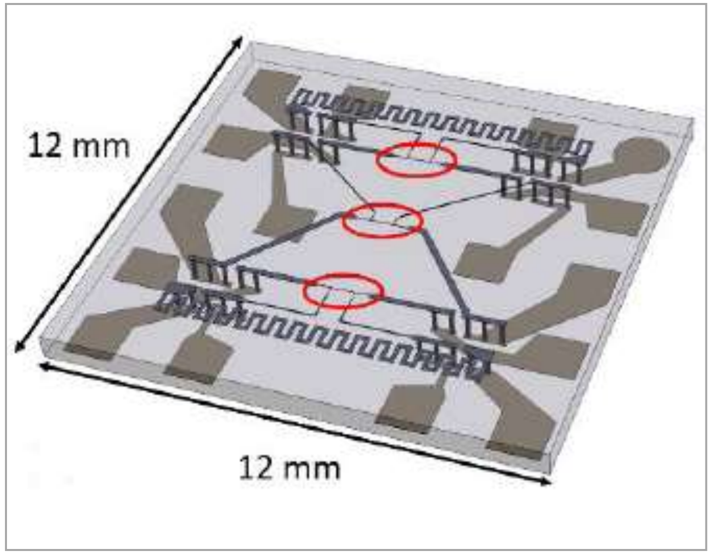
Underfilling

Source: Berllner Nanotest und Design GmbH (Berlin).

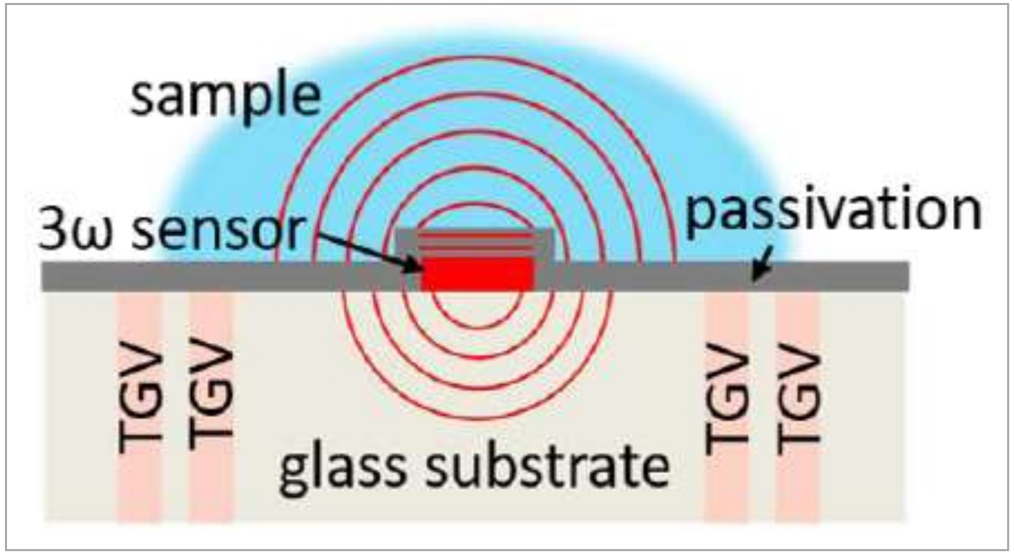
TIM Testing: 3Ω Characterization

Thermal characterization may be accomplished with a rapid *bi-directional* 3Ω system that is particularly useful for liquids, gels, and pastes:

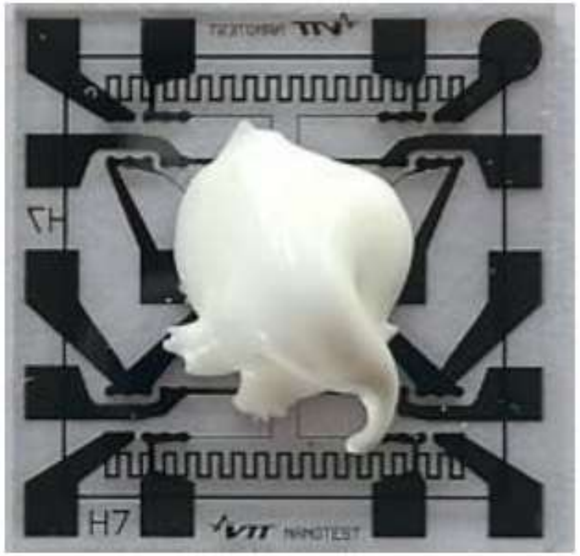
- Tests may be conducted in minutes for thermal conductivity, diffusivity;
- Bidirectional 3Ω method utilizes a sample placed on a die with through-glass vias (TGVs) connecting a sensor to the backside of the die:



TOCS glass die dimensions



Concept

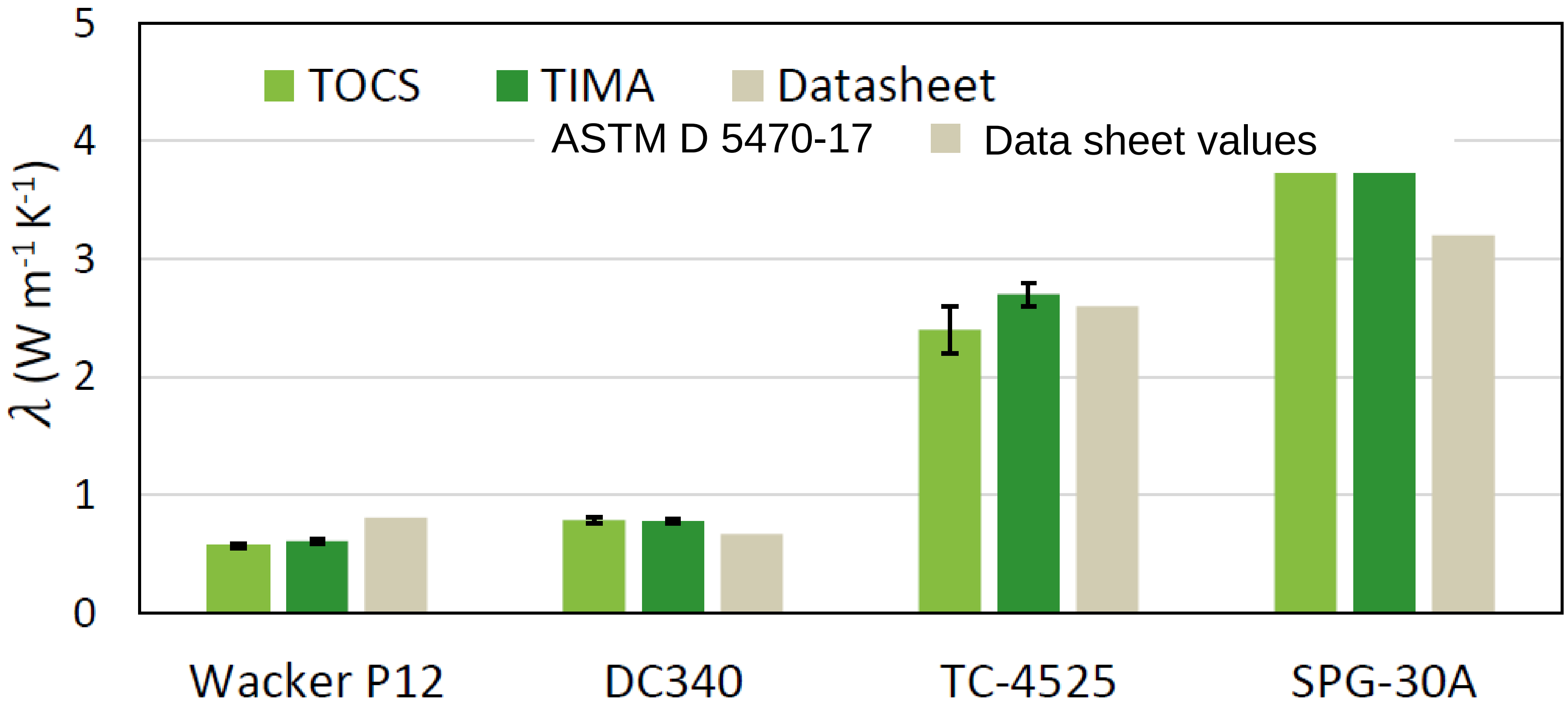


Photograph, TOCS glass die with epoxy sample

Source, Photographs and Illustrations: Berllner Nanotest und Design GmbH (Berlin). Ref: [1] Lubner, S.D. et al., Rev. Sci. Instrumentation 86, 014905 (2015); [2] Grosse, C., et al., Sensors and Actuators A 278, 33-42 (2018), DOI: 10.1016/ j.sna. 2018.05.030.

TIM Testing: 3Ω Characterization

Excellent correlation of test results with ASTM D 5470-17 and data sheet values – note error bars:



Source: Berllner Nanotest und Design GmbH (Berlin).

TIM Test Equipment Manufacturers

Selected TIM Test Equipment Manufacturers	
Company	**Test Stand General Type**
Berliner Nanotest und Design GmbH Berlin, Germany	TIMA®5 ASTM D 5470-17
	TOCS® 3-Ω Liquid Bulk Thermal Conductivity Test System
	LaTIMA In-Plane Bulk Thermal (X-Y) Conductivity Test System
	Thermal Test Die, Thermal Test Wafers, Thermal Test Vehicles (TTVs)
Siemens/Mentor Graphic Mechanical Analysis Division	“T3Ster” Structure Function Transient Test Stand; DynTIM™ Test Head JEDEC JESD 51-14
Thermal Engineering Associates, Inc. Santa Clara CA USA	ASTM D 5470-17 (Modified), Thermal Test Die

Source: DS&A LLC . Selected vendors only shown.

Development Categories – Current New Materials

A wide range of development efforts is constantly underway in industry.

Current new development examples by material type:

- High-temperature-capable materials (e.g., 175 – 400°C)
- Mixed modality fillers
- Development of new carrier alternatives to silicone and silicone oils
- Improved thixotropicity of polymeric compounds
- Oriented fiber graphite sheet materials as heat spreaders and TIMs
- Potential for the use of graphene coatings for fillers
- Potential for the use of vertically-aligned CNT and CNF arrays
- Potential for the use of BNNT fillers
- Metallic materials: Liquid metals, liquid metal hybrids

Comparative Thermal Resistances: Accelerated Reliability Testing

Impact of power cycling and bake testing on TIM types (following slides):

- *Demonstrating the importance of comparative thermal resistance testing beyond time zero*, for material reliability evaluation:

✓ Power cycling
  - Increasing thermal resistance values indicates decay in performance over time.
  - Declining thermal resistance values indicate TIM performance is *improving* over time.

✓ Bake cycling
  - Declining thermal resistance indicates bake-out of silicone oil carrier from thermal grease.
  - Example following, 90°C

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