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Testing and Selecting Thermal Interface Materials for Semiconductor Test and Burn-in Applications

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Purpose and Outline:

This tutorial describes the following:

- Electronics thermal management:
  - Terminology for components
  - Terminology for thermal performance metrics
- Thermal interface materials:
  - Importance of material types
  - Definitions of material types
  - Testing methodologies
  - New thermal materials developments for applications in semiconductor test and burn-in
  - Test equipment manufacturers

Electronics Thermal Management

Electronics Thermal Management

Electronics modules and systems are different in many ways, including:

- Intended function
- Processing, data storage, and communications capabilities
- Physical size, volume, weight
- Degree of criticality of function – such as a medical implant or vehicle braking control module
- Operating environment: ambient temperature, extremes, vibration, acoustics, duty cycle, other factors
- Corresponding reliability requirements
- Package type

Electronics Thermal Management

Virtually all semiconductors and many other electronic components generate heat, from very small to very large values:

- Operating efficiency of a semiconductor or device determines how much input power is lost as heat, dissipated through the package:
  - A diode laser may operate at 55% efficiency – meaning that 45% of input power must be dissipated as heat.
  - A large IGBT power semiconductor module is typically 93.5 – 95.5% efficient but may dissipate nearly 1kW, in operation (depending on duty cycle).

Electronics Thermal Management Terminology

Thermal Management Component Terminology		
Term	**Generally Accepted Definition**	**Cooling Method**
Heat Sink	Metal component or assembly designed to remove heat: May be a formed plate, stamped, extruded, or cast assembly with fins.	NC, FC, L
Heat Pipe	Copper tube containing a wick structure and a small amount (<1cc, typ.) of water or other fluid; an evaporator section at one end and a condenser section at the opposite end, used to move heat from a source to a finned area or other heat dissipation component.	NC, FC
Vapor Chamber	Flat, wide heat pipe, used as a heat spreader or baseplate for a finned heat sink assembly to move heat load in X-Y plane.	NC, FC
Heat Spreader	Flat, thin device to move heat in X-Y planes, spreading heat load from focused source. May be an isometric material.	NC, FC, L
Lid	Package cover to protect a semiconductor die. Typically copper.	NC, FC, L

Note: NC = Natural convection (air); FC = Forced convection (air); L = liquid cooling; these are terms in general use. In an academic sense, all of the above component types perform a heat exchange function and therefore may be termed a "heat exchanger" – but this is not useful in practice..

Electronics Thermal Management Terminology

Thermal Management Component Terminology		
Term	Generally Accepted Definition	Cooling Method
Fan/Heat Sink	Finned heat sink assembly with an integral fan attached; fan/heat sink assemblies are primarily used with microprocessors in desktop/notebook PCs; may include heat pipes.	NC, FC
Heat Exchanger	A liquid-to-air finned assembly that transfers heat from a liquid to ambient air. A liquid-to-liquid heat exchanger is used to move heat from one liquid coolant circuit to a second.	L
Liquid Cold Plate	A flat plate (aluminum or copper) containing either machined liquid channels or a tubing circuit (typ., copper). Heat sources such as IGBT modules are mounted on the flat surface.	L

Note: NC = Natural convection (air); FC = Forced convection (air); L = liquid cooling; these are terms in general use. In an academic sense, all of the above component types perform a heat exchange function and therefore may be termed a "heat exchanger" – but this is not useful in practice..

TIM Terminology, Purpose, and Evaluation

Terminology and TIM Purpose

Adequate thermal management is a critical factor in function and reliability of semiconductor-based systems.

- Junction temperature is affected by current and device efficiency and duty cycle, heat removal mechanism efficacy, and ambient temperature.
- Each interface between two package components can require a TIM;
- System thermal resistance consists of a series of thermal resistance values through packaging layers and TIMs (or materials “stack”).

Terminology and TIM Purpose

What constitutes a TIM?

- A paste, gel, pad, film, foil, graphite sheet, or composite requiring mechanical fasteners;
- An adhesive, ideally thermally-conductive, not requiring fasteners;
- A combination of an adhesive with a pad, film, foil, or graphite sheet, not requiring fasteners.

Purpose of the TIM is to eliminate air voids between two surfaces, improving heat transfer capability from a heat source to a heat-dissipating component:

- Semiconductor die
- Package lid or heat-dissipating component (typ., metal)

Terminology and TIM Purpose

What purpose does a TIM serve?

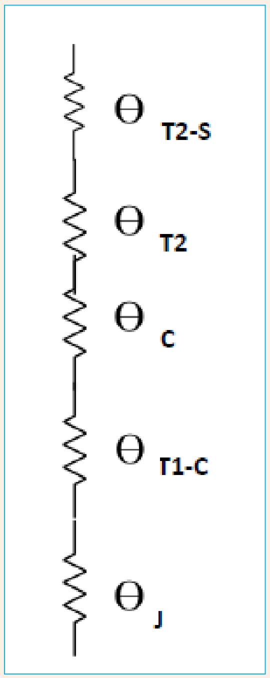
1. Transfer heat from one surface to a second component surface.
2. Reduce potential for fracture or separation due to differing CTE values.

Temperature-driven failure modes can include failure of the semiconductor or the package, or both:

- Due to inadequate temperature control of the die;
- Due to the inability to remove sufficient heat from the system, leading to failure of a solder joint or other material due to differing CTE values.

Terminology and TIM Purpose

System thermal management is the sum of a series of 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)

Terminology and TIM Purpose

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

- Thermal resistance is stated as a value determined as the increase measured in temperature (°C) for every watt (W) 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":

    Θ_{SA}

  - 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":

    Θ_{CS}

Terminology and TIM Purpose

The primary performance value for a thermal interface material is thermal resistance per unit area (sometimes referred to as thermal impedance):

$°C\text{-}in^2/W$ or $°C\text{-}cm^2/W$ (also commonly used, $°C\text{-}mm^2/W$)

- Value is expressed as thermal resistance for per clamping force applied.
- In a performance graph, thermal resistance appears on the Y-axis versus clamping force on the X-axis.
- Increased clamping force has a large impact on thinning a TIM and improving (*lowering*) the thermal resistance value.
  - Values are asymptotic.

Terminology and TIM 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-in²/W (or) °C-cm²/W
Thermal Impedance	Alternative term for thermal resistance per unit area	°C-in²/W (or) °C-cm²/W
Heat Flux (Heat Density)*	Amount of power dissipated per unit area (e.g., from a point on the surface of a processor die or across the baseplate of a GaN RF device)	W/in² (or) W/cm²

Note: The above terminology may be used casually and identifying the most useful term is important for selecting a TIM to propose for a given application. The most important term for determining performance of a TIM is thermal resistance per unit area, marked above with an asterisk (*).

Terminology and TIM Purpose

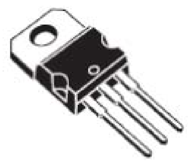
Thermal Interface Material Terminology		
Package Level	Generally Accepted Definition	TIM Terminology
1	Semiconductor die to heat sink (external, bare die package)	TIM0
1	Semiconductor die to package lid (internal, lidded package)	TIM1
2	Semiconductor lid, case, or baseplate: external to the package, 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 > 0.10" (typ.)	Gap-filler
4	Platform or subassembly level, conducting heat from the case of a power supply or other large module, large heat sink, metal component	Gap-filler

Note: Terms such as "TIM0" (and alternatives, such as "TIM1.5") may also be found, but are not in common usage beyond specific minority applications.

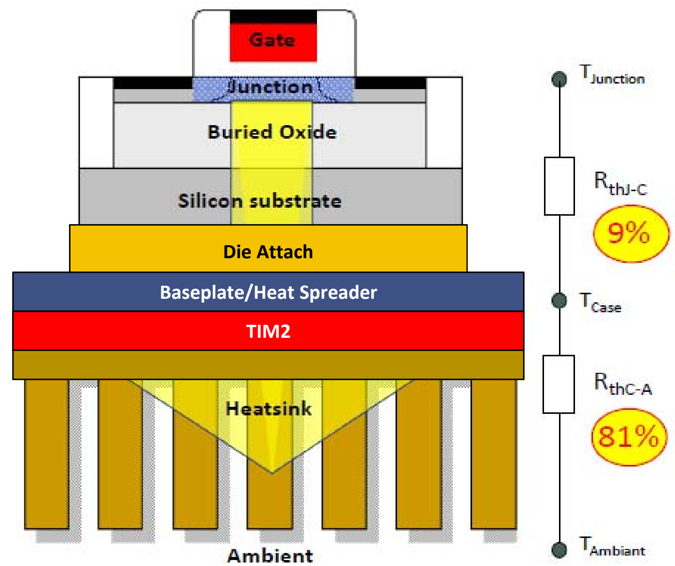
Thermal Interface Materials: Terminology

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

TO-220 Package



Layer	BLT [µm]	A [mm²]	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%



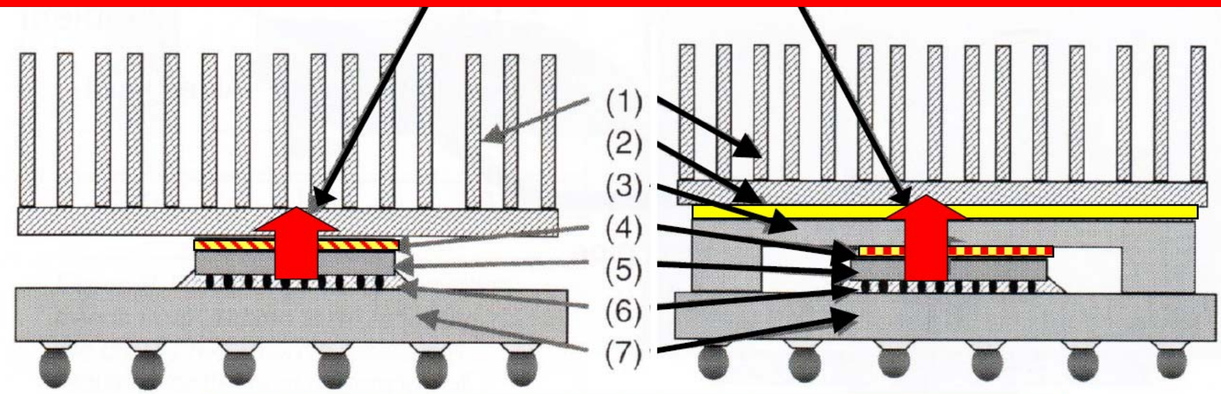
TIM2 and the die attach material are responsible for approximately 74% of the thermal budget through this discrete power semiconductor package (considering solder die attach as an equivalent for TIM1)

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

Thermal Interface Materials: Terminology

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

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



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

TIM Evaluation

Impact of TIM selection on device operating temperature:

- Thermal interface materials (TIM) are integral for adequate heat transfer from a semiconductor source to an external environment.
  - Significant differentiation in application requirements has driven the need for development of many different types of TIM materials
  - Categorizing materials is important for guiding material selection to meet application requirements.
  - Testing and evaluation of TIMs is critical to understanding and selecting a single material for a specific application.

TIM Evaluation

Thermal performance is not the only criteria for selection of a TIM.

- A *holistic application view* frequently will result in an application process or a specific reliability requirement influencing selection;
- As a result, the single *lowest thermal resistance* material or the material having the *highest bulk thermal conductivity* may not be selected.

TIM Evaluation

A large number of criteria must be established for developing a TIM:

- Important to be aware of the number of criteria and how these individually affect performance of a given TIM;
- The following table is a snapshot of these development parameters, which constitute a complex science.
- Certain of these factors (such as filler percentage by volume) can impact the ability of a TIM to move and not suffer “run-out” (highly thixotropic), affecting relative *thermal performance* and *reliability over time*.
- Selection of a TIM for an application will require certain of these development criteria, but not all.

TIM Evaluation

TIM Typical Development Parameters	
Thermal Impedance	Dielectric Strength**
Bond Line Thickness Post-Assembly	Cut-Through Resistance**
Thermal Conductivity	Thermal Cycling
Clamping Force Applied	Power Cycling
Wettability	Humidity and Bake
Thixotropicity	HAST
Dispensing/Placement Process Automation	Shock and Vibration
Cure Schedule*	Flammability
Adhesion, Peel Test*	Working Life
Contaminants	Storage/Transit Temperature Range (As Supplied)
Modulus of Elasticity	Shipment/Storage Temp Range (Complete Assembly)
Material Stability	Removability and Rework Process
Silicone Stability	Environmental and Recycling Process
Flammability	Cost

*Notes: *Applies only to adhesive TIMs. **Applies only to dielectric TIMs.*

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;
- ✓ Required product life and reliability;
- ✓ Suitable cost and delivery format;
- ✓ Suitable assembly process, handling, storage.

TIM Evaluation

What is meant by a "well-performing" TIM?

- ✓ *No* compound run-out due to temperature
- ✓ *No* dry-out of a carrier compound due to temperature
- ✓ *No* compound pump-out due to mechanical stress
- ✓ *No* silicone bleed, outgassing, or redeposition on critical system elements.

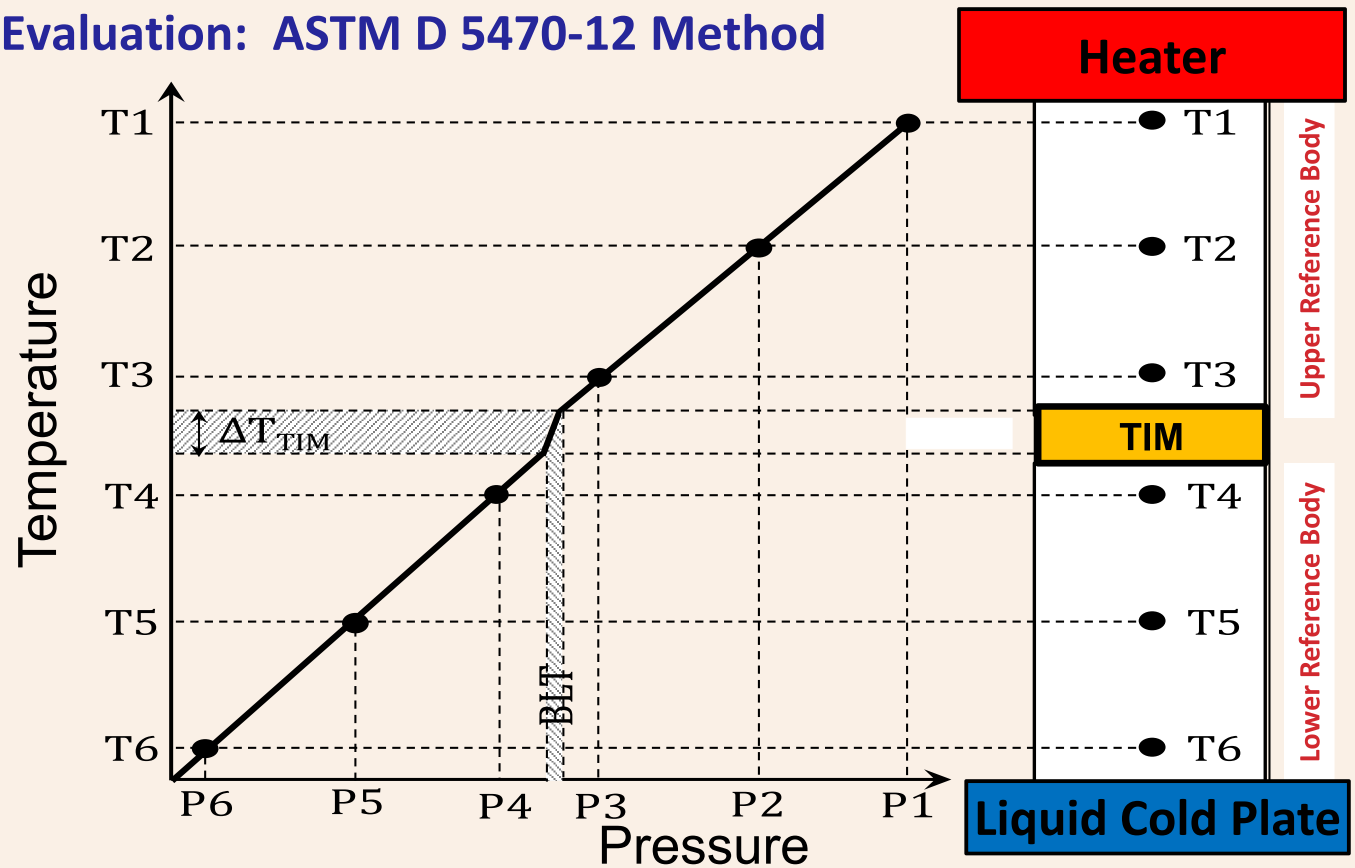
TIM Evaluation

What is meant by a "well-performing" TIM?

1. An application for a thermal interface material in a given high-performance design must be assessed against a defined list of specialized criteria in addition to bulk thermal conductivity alone.
2. These specialized requirements may include, for example:
   - Minimum thermal resistance (100% surface wetting)
   - Higher operating temperature range
   - Higher dielectric properties with improved thermal resistance (if a dielectric is required)
   - Durability to resist cycling

Any one of these these factors may be more important than bulk thermal conductivity

TIM Evaluation: ASTM D 5470-12 Method



Note: ASTM D 5470-12 methodology may be purchased for a nominal fee from ASTM International. Information can be found at www.astm.org

TIM Evaluation: ASTM D 5470-12 Method

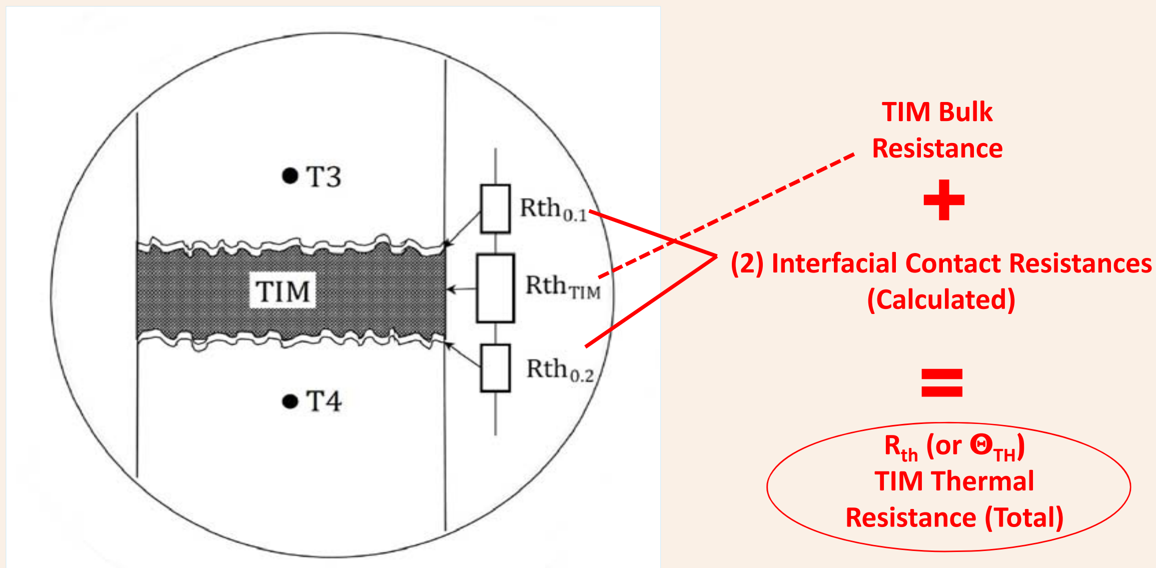
Berliner NanoTest und design GmbH commercial TIM test stand:

- Designed per ASTM D 5470-12, the industry-standard TIM test methodology for comparative material testing;
- System measures force applied, power (heat), temperature, thickness – with precise and uniform heat flow.
- Measures thermal conductivity and provides calculated thermal resistance values.
- Many additional capabilities.

TIM Evaluation: ASTM D 5470-12 Method

ASTM D 5470-12 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.



Comparative Thermal Resistances

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

- Demonstrating importance of comparative thermal resistance testing beyond time zero, for material evaluation

✓ Power cycling:

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

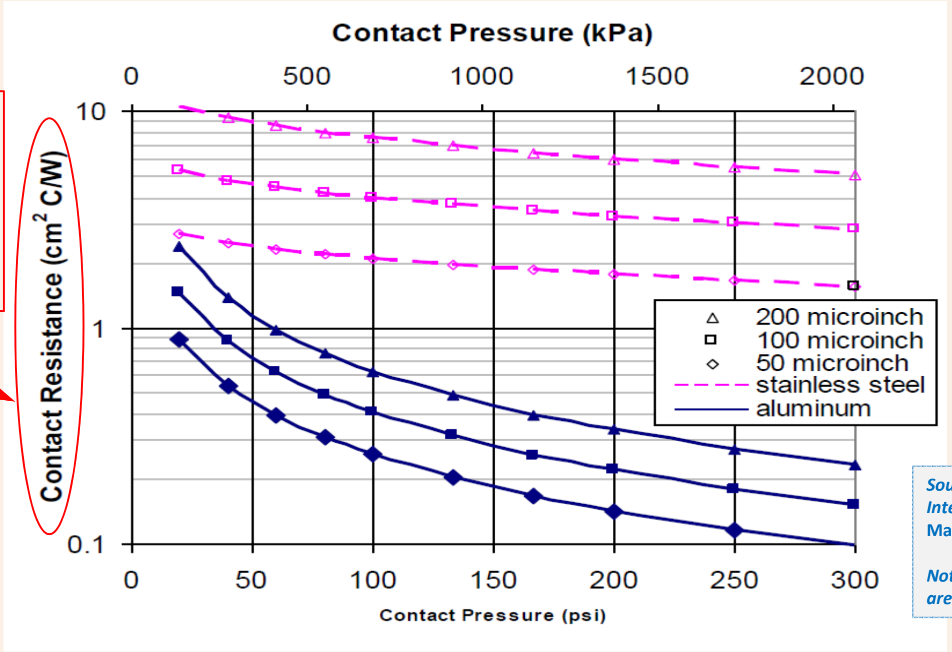
✓ Bake cycling (90°C):

  - Declining thermal resistance indicates bake-out of silicone oil carrier from thermal grease.

Comparative Thermal Resistances

Metal-to-metal surface contact resistance – comparison of two metals, three surface finishes (roughness), under load:

The primary function of a TIM is to minimize thermal contact resistance between two mating surfaces



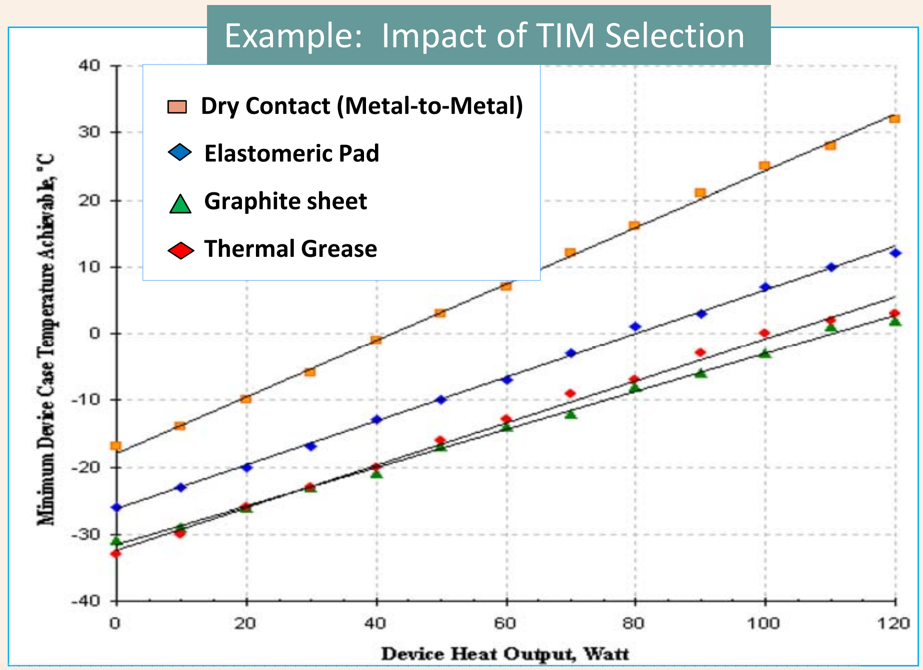
Source: M. Yovanovich, et al., "Calculating Interface Resistance", Electronics Cooling Magazine, May 1997, Vol. 3, No. 2.

Note: 100 microinch = 2.54 microns. Values are RMS values.

Comparative Thermal Resistances

Impact of a TIM versus dry contact on device operating temperature:

- Three different classes of TIM applied to a semiconductor test system test head, showing impact of different TIM types (versus dry contact):



Source: K. Moody, R&D Manager, Kulicke & Soffa (USA). Note: All other conditions held equal.

Comparative Thermal Resistances

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 evaluation

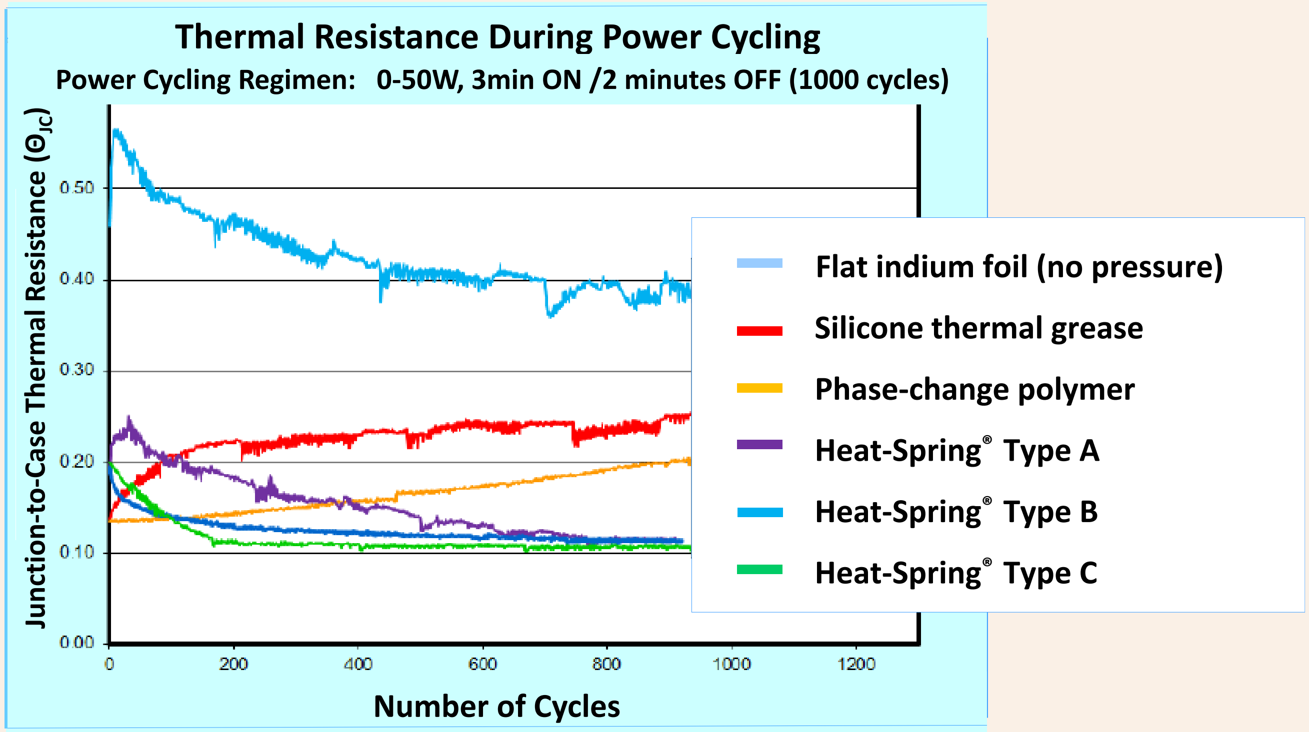
✓ Power cycling

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

✓ Bake cycling (90C)

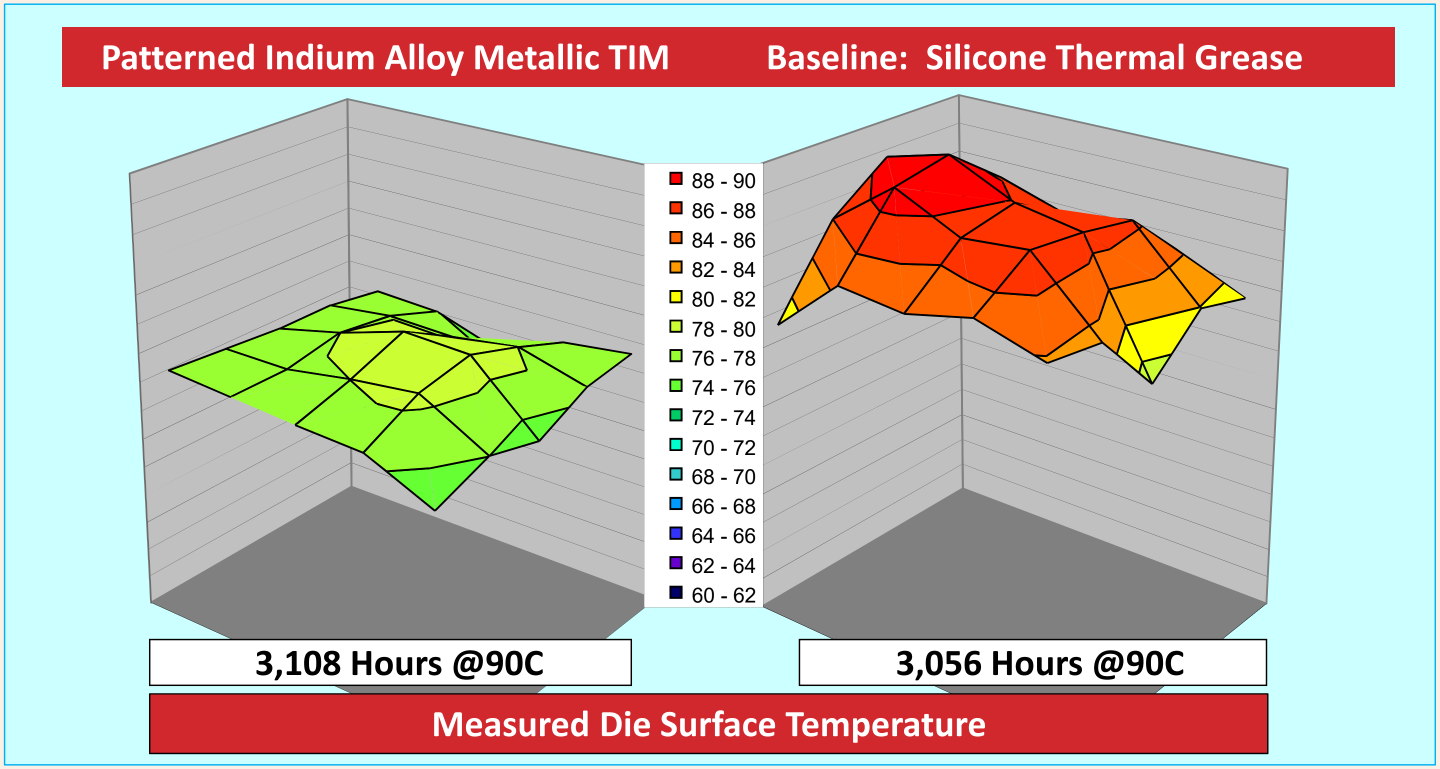
  - Declining thermal resistance indicates bake-out of silicone oil carrier from thermal grease.

Comparative Thermal Resistances: Power Cycling



Source: Indium Corporation

Comparative Thermal Resistances: Bake Testing



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 9B reflects increased thermal resistance due to dry-out of silicone oil in the tested premium silicone-based thermal grease. Data source: Indium Corporation. Die thermal test vehicles provided by Intel Corporation.

TIM Categorization and Material Selection

TIM Categorization System

Purpose:

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

TIM Categorization System

General Functions and Categories of Thermal Interface Materials *Adhesive Types*		
Primary Function	**Material Category**	**General Statements**
Adhesive TIM attachment Component (heat sink) fastening Reduced thermal resistance Shock dampening	**Thermally-conductive adhesives***: Pressure sensitive preforms Curable or two-part dispensed	▪ Generally very poor thermal performance ▪ Providing adhesive attachment of a heat sink or other component ▪ No mechanical fasteners required
Minimum Rth, heat spreading, with CTE control; adhesive	**TIM1 Materials:** Die-Attach Adhesives used as TIM1	▪ Relatively high bulk thermal conductivity and low thermal resistance ▪ Applied between die and heat spreader

TIM Categorization System

General Functions and Categories of Thermal Interface Materials *Poor Rth Thermal Performance**		
Primary Function	**Material Category**	**General Statements**
Reduce thermal resistance (Θ_{CS} or Rth) versus air over large gaps (i.e., $\geq$ 0.254mm/0.010")	**Gap-fillers**	▪ Very thick for large air gaps ▪ Relatively low thermal performance due to moderate bulk thermal conductivity and significant thickness
Large-area heat dissipation, temperature control, temperature modulation	**Graphite, Elastomeric Sheets**	▪ Wide range of materials ▪ Wide range of thermal performance, cost
Electrical insulation w/minimized thermal resistance	**Electrically-Isolating**	▪ Less common, higher cost ▪ Lower thermal performance due to dielectric layer

TIM Categorization System

General Functions and Categories of Thermal Interface Materials ***Better Rth Performance***		
Primary Function	**Material Category**	**General Statements**
Minimum thermal resistance (Rth) *Primarily achieved with minimum thickness and with clamping force applied*	**Thin TIM1/TIM2 Materials**: Thermal greases Phase-change Polymer-solder hybrids, solders	▪ Low thermal resistance ▪ Use requires mechanical fasteners to apply consistent, constant pressure.
Minimum Rth, heat spreading, with CTE control	**TIM1 Materials**: Gels, Phase-change, thermal greases, solders, VA-CNT#	▪ Relatively low Rth and high bulk thermal conductivity ▪ Between die, heat spreader ▪ Multiple material types available for TIM1 evaluation

TIM Categorization System

General Functions and Categories of Thermal Interface Materials ***Best Rth Performance***		
Primary Function	**Material Category**	**General Statements**
Critical minimum Rth for high heat flux; reworkability highly desirable	**Carbon-Based Arrays:** Carbon Fiber-based Arrays: Vertically-aligned Carbon Fiber Arrays (VA-CNF)	• Lowest (best) Rth commercially available currently • Higher cost • Require mechanical fastening
	Carbon Nanotube-based Arrays: Vertically-Aligned CNT (VA-CNT)#	• Lowest (best) Rth projected, as commercial products (future) • Significantly higher cost • Require mechanical fastening

TIM Categorization System

General Functions and Categories of Thermal Interface Materials ***Best Rth Performance***		
Primary Function	**Material Category**	**General Statements**
Critical minimum Rth for high heat flux; reworkability highly desirable, with CTE control	**Metallic Preforms** **Reflowed Solders, Liquid Metals (as TIM1)**	• Lowest (best) Rth commercially available currently • Variety of metal alloys and patterns available • Higher cost • Require mechanical fastening

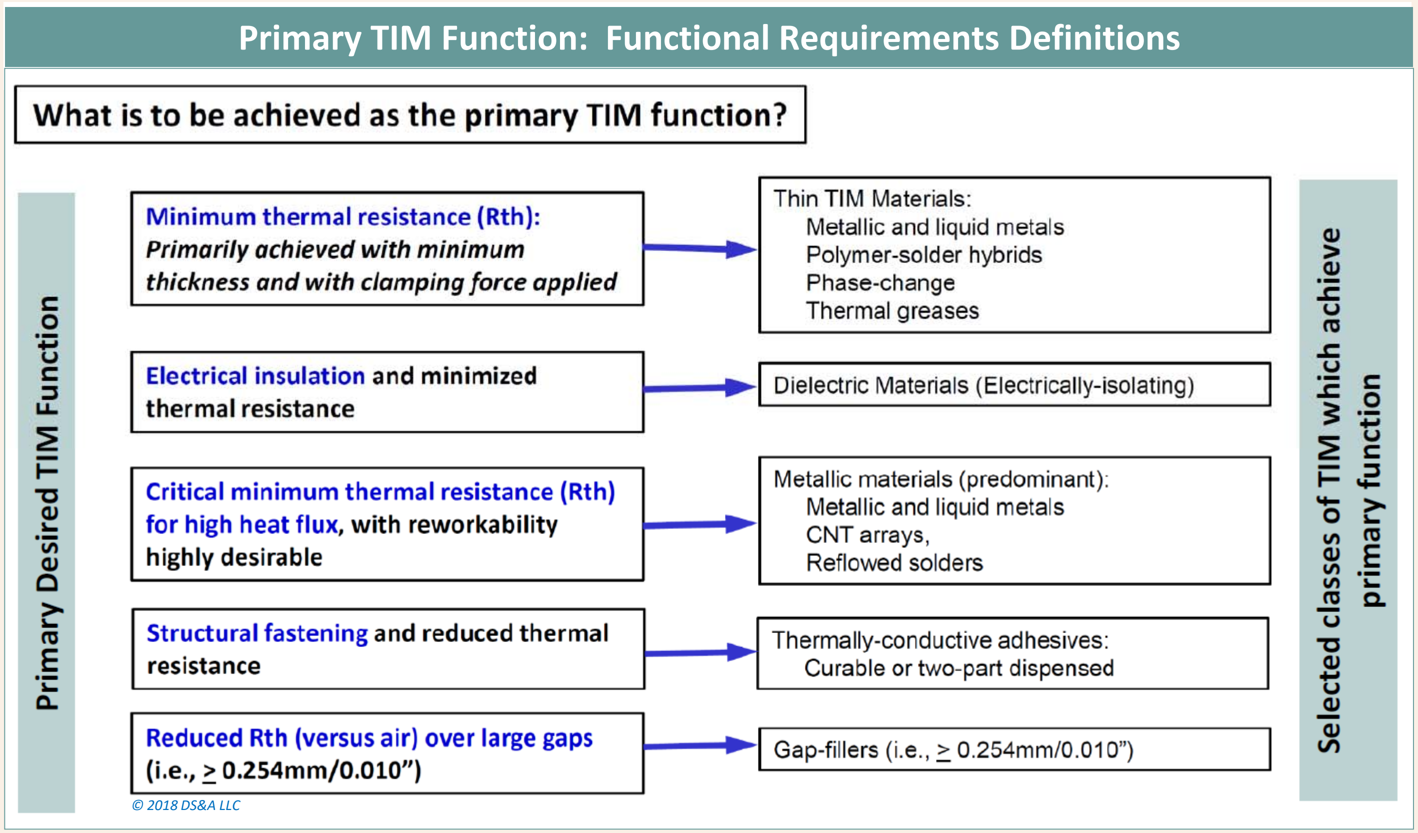
TIM Category Selection Methodology

Selecting from thousands of TIM products for a single application can be an arduous and time-consuming task.

The following slides illustrates a logical selection process.

1. Identify primary function(s) necessary for a TIM application, in order to begin separating out applicable types.
   a. A requirement to avoid mechanical fastening hardware will indicate an adhesive;
   b. An electrical insulation requirement will preclude numerous types of greases and compounds;
2. Select a secondary TIM function, if any;
3. Select from appropriate TIM categories.

TIM Selection Methododology



TIM Selection Methodology

Selecting an appropriate thermal interface material:

- *Degree of surface wetting* achieved is critical to overall performance, to minimize contact thermal resistance at each of two contact surfaces.
  - Contact thermal resistance dominates overall TIM resistance for most materials that are thin by design;
  - Exception: For gap-fillers, bulk thermal resistance will dominate over contact thermal resistance, due to extreme thickness;
  - Driving to *highest wetting* and *thinnest clamped* thickness is *critical to successful TIM selection* in traditional TIM applications.

TIM Selection Methodology

Clamping force (uniformly applied) is intended to achieve:

- Maximized surface wetting;
- Thinnest possible TIM thickness (to minimize influence of bulk thermal conductivity, which is normally low);
- Metal-to-metal contact for surfaces.

Relatively good bulk thermal conductivity is most important when surface wetting is not possible:

- Semiconductor test applications are an example where surface wetting is not desirable, due to need to avoid residue and/or DUT marking.
- Above statements are intended to apply for applications where low or lowest thermal resistance is required.
- These are generalized statements, applied as a rule for most materials.

TIM Categorization System

Thermal Interface Material Classification Selection and Evaluation

Prioritized TIM Requirements	Property	Typical Value		Alternative/Opposing Value	
1. Electrical	Dielectric Properties	Electrically Conductive		Electrically Non-Conductive	
2. Mechanical	Fastening	Mechanical Fasteners	Adhesive	Mechanical Fasteners	Adhesive
	Thickness	Minimum	Maximum	Minimum	Maximum
	Surface Roughness, Flatness	Minimum	Maximum	Minimum	Maximum
3. Application Process	Dispensing/Placement	Automated	Manual	Semi-Auto	Manual
4. Thermal	Thermal Resistance	Minimum	Maximum	Minimum	Maximum
	Operating Temperature Range	Minimum	Maximum	Minimum	Maximum
	UL Flammability Rating	UL V-0	UL V-0	--	--
5. Cost	Material only/application process/total cost	Material only	Application process only	--	--
6. Environmental/ Health/Safety	Constituent analysis: silicones, toxicity, environmental, H&HS	Government, industry, company regulations			

TIM Selection and Testing/Evaluation Methodologies

Property Category	Property Parameter	Method/Value
Thermal Resistance (Impedance)	Through-plane (primary) bulk + contact	ASTM D 5470-12 (°C-mm^2/W) JEDEC 51-14 (Transient)
Thermal Conductivity	Homogeneous, bulk (isotropic)	ASTM D5470-12 (Steady-state) JEDEC 51-14 (Transient) Laser flash
	Non-homogeneous, bulk (through-plane)	ASTM D5470-12 (Steady-state) JEDEC 51-14 (Transient)
	Non-homogeneous, bulk (in-plane)	Scanning pulsed laser

TIM Selection and Testing/Evaluation Methodologies

Property Category	Property Parameter	Method/Value
Testing Conditions for Thermal Impedance Data Collection	Test methodology	ASTM D5470-12 (Steady-state) JEDEC 51-14 (Transient) Laser flash TTV (in-situ)
	Test coupon area	mm^2/in^2
	Surface flatness	mm/mm (“/”)
	Surface roughness	Ra, Rs (μ-in)
	Clamping force applied	Bar/PSI
	Input power applied	W
	Ambient (chamber) temperature	°C
	Thickness	mm (”)

TIM Selection and Testing/Evaluation Methodologies

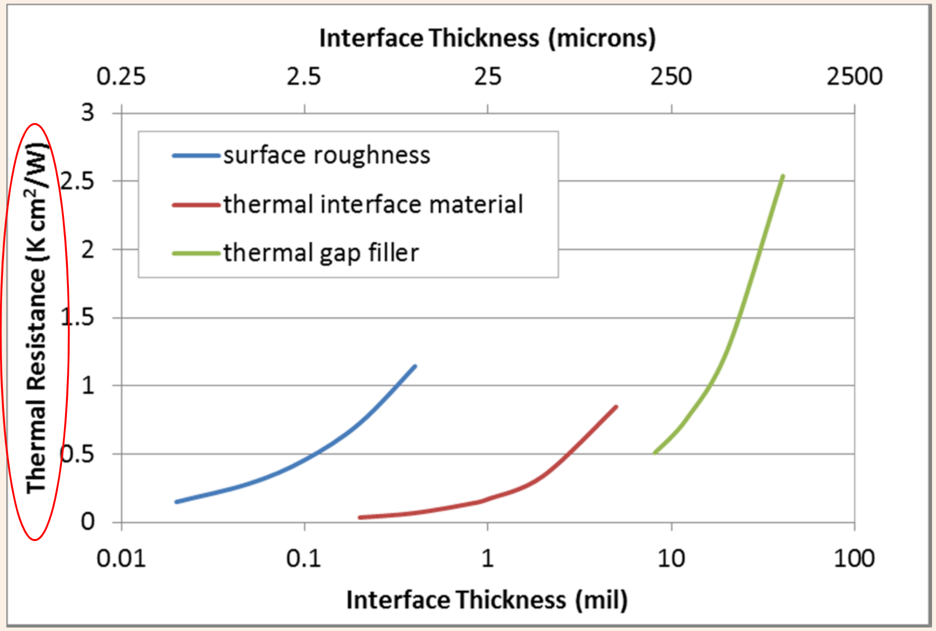
Material Attribute	Value or Type
Automated Placement/Dispensing Formats	Vacuum Roll format Liquid dispensed
Flammability Rating	UL 94 V0
Working Life	X Hours @ X°C
High Temperature Storage (Completed Final Assembly)	Y Hours @ Y°C
High Temperature Storage (as supplied)	Z Hours @ Z°C
Transit Temperature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

TIM Major Categories for Test/Burn-In

Gap-Fillers: Where Are These Needed?

Comparison of surface roughness and relative interface thicknesses, to define a *general* application range for TIMs versus gap-fillers, under load:

The primary function of a TIM is to minimize the thermal contact resistance between two mating surfaces



These are rough estimates *and values will vary with material properties and contact pressure (clamping force) applied.*

Source: Ross Wilcoxon PhD, Advanced Technology Center, Rockwell Collins, Inc., Cedar Rapids IA USA. Unpublished; used with permission.

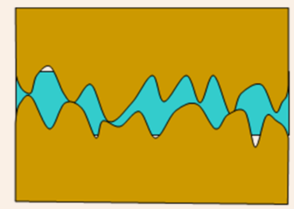
Note: 100 microinch = 2.54 microns. Values are RMS values.

Gap-Fillers: Where Are These Needed?

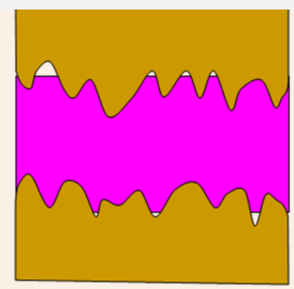
One general definition for TIMs versus gap-fillers, used in the aerospace industry:

- Thermal Interface Materials: Replace air in an interface that would otherwise be there due to surface roughness;
- Thermal Gap-fillers: Replace air in an interface that would otherwise be there due to tolerance stack-up.

Note that these are very generalized definitions.



Thermal Interface Material (TIM)

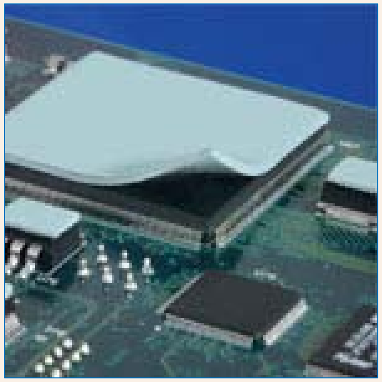


Gap-filler

Source: Ross Wilcoxon PhD, Advanced Technology Center, Rockwell Collins, Inc., Cedar Rapids IA USA. Unpublished; used with permission.

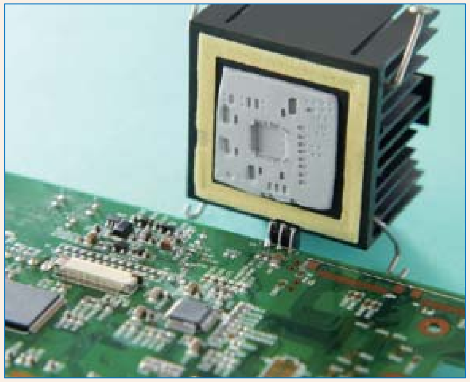
Gap-Fillers: Examples

Gap-filler examples in typical electronics industry applications:



Die-cut preform GF

Die-cut preform GF



Dispensed liquid GF*

*Note: * May also be referred to as a gap-filler "putty". Terms and definitions are imprecise given the very wide range of applications for these types of materials across industry.*

Gap-Fillers: Attributes

General statements about each main type of gap-filler follow.

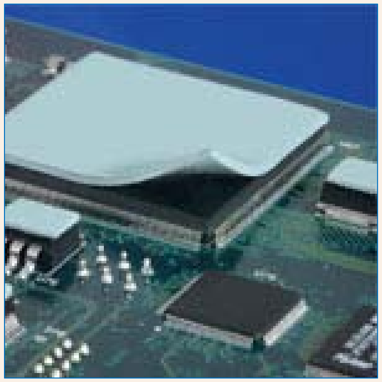
- Broad characterizations to assist with understanding differences in materials types and relative thermal performance characteristics;
- Characterizations of material physical performance and trade-offs in development of materials

Note: Statements and definitions are imprecise given the very wide range of applications for these types of materials across industry.

Gap-Fillers: Attributes

Die-cut preform Gap-fillers:

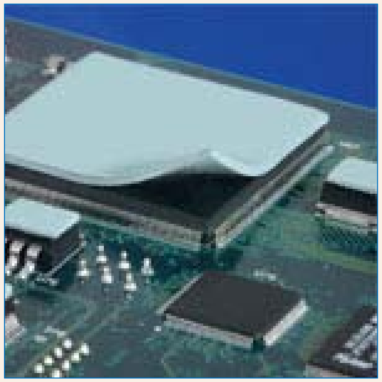
- Generally, higher bulk thermal conductivity than dispensed GF products;
- Higher bulk thermal conductivity is generally achieved with higher loading of fillers;
- Higher filler loading will increase relative stiffness.



Note: Statements and definitions are imprecise given the very wide range of applications for these types of materials across industry.

Gap-Fillers: Attributes

Die-cut preform Gap-fillers (continued):

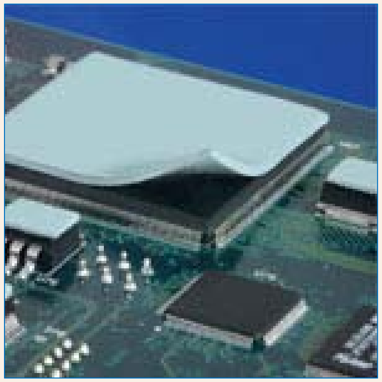


- Generally, compression below 50% of initial thickness is not possible or recommended:
  - *Induced failure risk* to solder balls, underfill, or interconnect or package, from excessive force applied to achieve compression;
  - High compression will generally force out carrier fluids, such as silicone oil;
  - Silicone oil is not desirable in electronic systems;
  - Silicone oil may outgas and redeposit on electrical contacts, impacting solder processing operations and system interconnect performance.

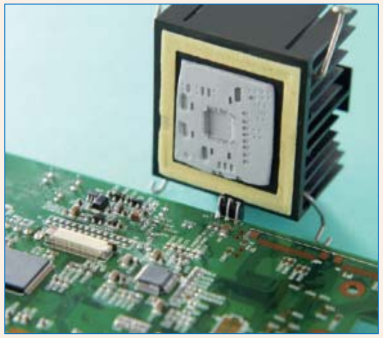
Gap-Fillers: Attributes

Die-cut preform Gap-fillers (continued):

- Silicone oil-containing materials are frequently banned from optical systems:
  - Outgassing of silicone oil will result in redeposition on lens elements, other optical components;
  - Deposition can disrupt collimated light beams for diode lasers and other optical devices;
- Increased surface wetting for gap-fillers can be easily attained by increasing percentage by weight of silicone oil:
  - Improvement in thermal performance with poorly-designed gap-fillers can therefore negatively impact optical system performance.



Gap-Fillers: Attributes



Die-cut preform Gap-fillers:

- Generally, lower bulk thermal conductivity than dispensed GF products;
- May be compressed further more than 50%;
- Challenging for operations environment:
  - Dispensing equipment complexity and cost
  - Set-up time, dispensing inconsistency, curing time (if required)
  - Generally not preferred in manufacturing for low-volume assembly
  - Clean-up and post-processing residue may be problematic.

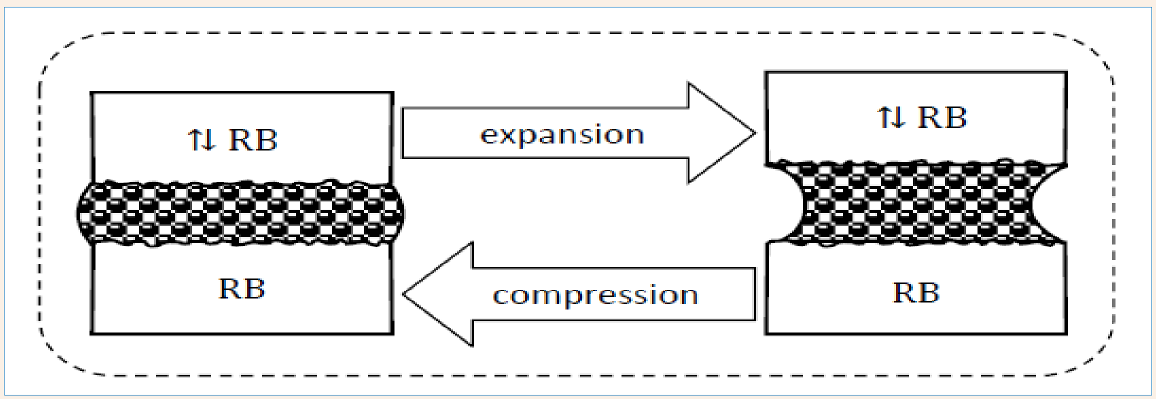
Gap-Fillers: Cycling Reliability Testing

- Mechanical cycling and other types of reliability testing over time can demonstrate useful results for evaluating TIMs.
- Previous reliability testing has been undertaken by Berliner Nanotest of "gap-filler" TIMs, examining cyclic compression and relaxation
- Certain of such TIMs may also be useful for test/burn-in – with different reliability testing requirements.
  - An example is the use of so-called "gap-filler" TIMs for testing with PCBs and other substrates.
  - The same test equipment described can be adapted for reliability testing of metallic TIMs with contact/dwell/release cycling.

Gap-Fillers: Cycling Reliability Testing

Mechanical cycling and other types of reliability testing over time can be used to examine long-term thermal and mechanical performance of TIMs.

- Example: Mechanical compression/relaxation cycling of gap-fillers:

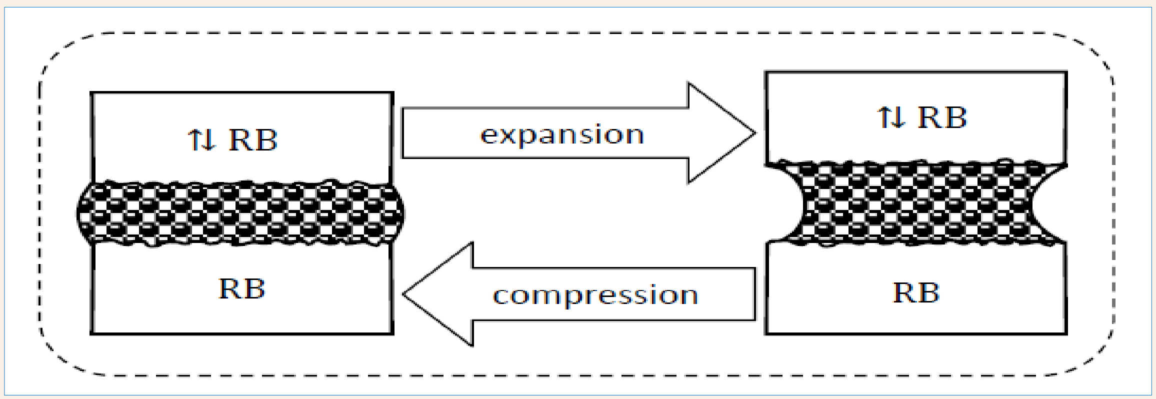


Source: Berliner Nanotest und Design GmbH. February 16, 2018.

Gap-Fillers: Cycling Reliability Testing

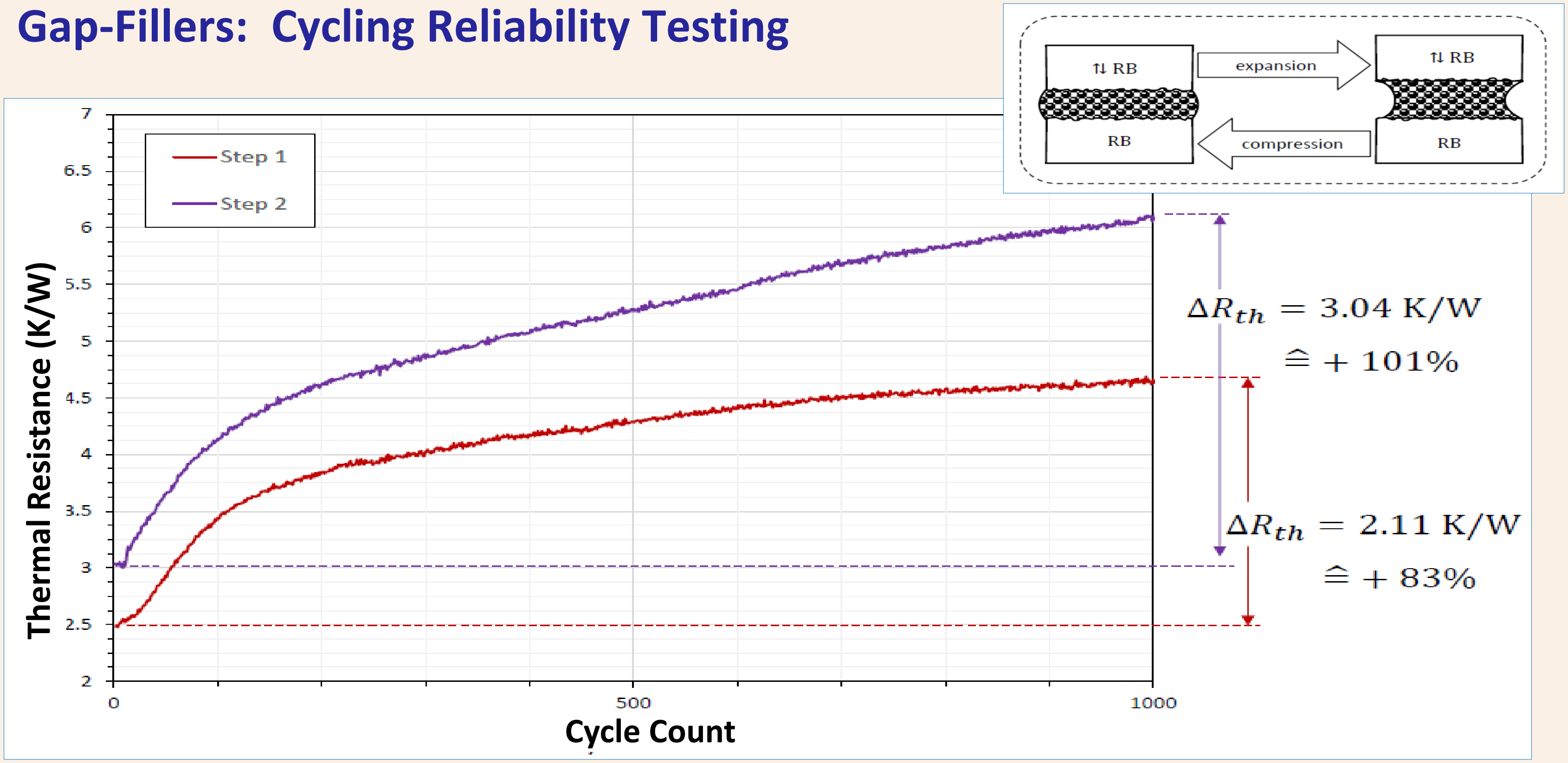
Data analysis indicates increasing thermal resistance over time and cycling:

- Examining time zero thermal resistance values alone is not adequate
- *Increasing thermal resistance over time* and cycling indicates a potential failure mechanism as junction temperature increases.



Source: Berliner Nanotest und Design GmbH. February 16, 2018.

Gap-Fillers: Cycling Reliability Testing



Source: Berliner Nanotest und Design GmbH. February 16, 2018.

Graphite Sheets and Elastomeric Preforms

Materials that are manufactured in viscoelastic sheet forms:

- Polymers having both viscosity and elasticity properties
- Low Young's modulus and high failure strain
- Wide range of softness (measured as Shore A value)
- Typically, referred to as "silicone rubber" (incorrect), manufactured from silicones.

Hundreds of such products are manufactured in many thicknesses, with varying types and volume percentage of fillers:

- Typically, die-cut to required shapes and features (through-holes, etc.)
- Fillers provide bulk thermal conductivity, typically isometric
- Contact resistances are typically relatively high.

Graphite Sheets

Graphite sheet forms are manufactured by a wide range of vendors, with:

- Wide range of bulk thermal conductivity values
- Typically extremely anisotropic
- Available in different formats for encapsulation, lamination:
  - PET and other plastic laminates for electrical isolation
  - Adhesive coating (single- or double-sided) for simplified application process
- Technically, these are *heat spreaders*, not thermal interface materials.

New developments will be covered in a later section on high-performance graphite sheet materials for both in-plane (X-Y axes) and through-plane (Z-axis) applications.

High Performance TIMs: Patterned Metal Alloy Foils

Indium foil has been used as a TIM for decades, for very specific applications and therefore no well-known:

- Flange-mount RF discrete power amplifiers and modules (telcom, radar, radio communications, satellite communications);
- Reflowed indium solder has been used as a high-volume TIM1 for server processors and desktop processors for major processor families.
- Semiconductor test and burn-in.

Properties of indium metal are exceptional for test applications:

- Usable for multiple thousands of high-speed contact cycles;
- Little or no residue on contact surface;
- No compound run-out, pump-out, residue, or outgassing;
- Flexible, adaptable formats for easy test head/socket attachment.

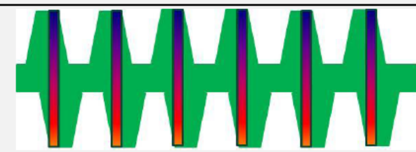
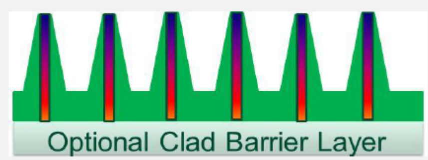
High Performance TIMs: Patterned Metal Alloy Foils

Recent developments with indium and metal alloy foils as TIMs include:

- Application of patterning to improve gap-filling and uneven surface thermal performance;
- Laminated aluminum foil (5µ thickness, typ.) to eliminate “tackiness” and/or residue upon contact cycling;
- Expansion of range of metal alloys available with above enhancements;
- Evaluation for challenging semiconductor test gimbaled heads, higher temperature testing.

High Performance TIMs: Patterned Metal Alloy Foils

Three examples of patterning applied to metallic TIMs:

Available Patterns for Indium Heat-Spring® Metallic TIMs	
Pattern Type	**Configuration**
Pattern 1: Designed for interfaces with tight surface control for roughness and parallelism.	
Pattern 2: Design as a high-profile variant for surfaces with lack of parallelism or greater warpage, with 2X compressibility.	
Pattern 3: Single-sided pattern designed for clad multiple insertion applications and for selected large surface area applications.	

Data Source: G. Wilson, Indium Corporation. US Patent 7,593,228-B2 "Heat-Spring" is a registered mark of Indium Corporation.

High Performance TIMs: Patterned Metal Alloy Foils

Selection of metal alloys currently available:

"Heat-Spring" Patterned Metallic TIM Alloy Selection by Thermal Conductivity	
Alloy	**Bulk Thermal Conductivity (W/mK)**
Indalloy 1E	34
100 Pb	35
80 In/20 Sn	53
In/Al Clad	-
100 Sn	73
100 In	86
100 Cu	395

High Performance TIMs: Patterned Metal Alloy Foils

Suggested maximum operating temperature for metallic TIMs:

- Table shows *suggested* values for selected metals and alloys
- Application specifics of interface surfaces may affect maximum temperature.

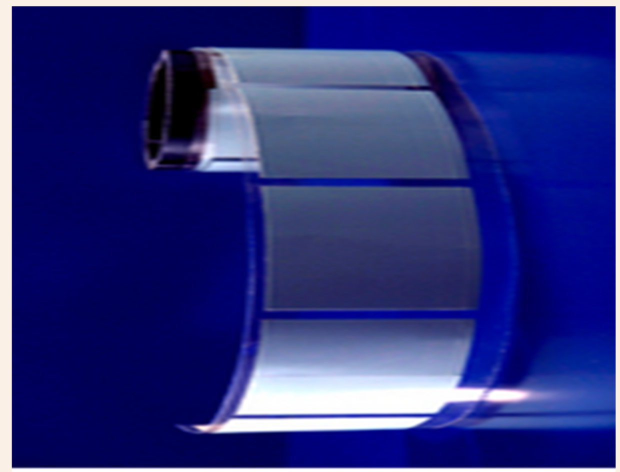
Maximum Suggested Operating Temperature for Metallic TIMs	
Metallic TIM Composition*	**Suggested Maximum Operating Temperature (°C)**
52In/48Sn Indalloy 1E	100
80 In/20 Sn	110
100 In	125
In/Al Clad	125
Sn, “Sn+”	200
HSMF, HSMF-OS	200
100 Pb	250
100 Cu	750

** “Indalloy”, “Sn+”, “HSMF”, and “HSMF-OS” are Indium Corporation products. Data source: Indium Corporation.*

High Performance TIMs: HSMF-OS

Indium Corporation HSMF-OS is supplied in die-cut form on release liner for ease of application:

- Aluminum foil (0.002” thickness)
- Non-silicone thermal compound is applied to one side only
- Bare aluminum foil surface is applied to face DUT, ensuring no residue will remain after test
- Thermal compound ensures sufficient surface contact with test head.
- Developed specifically for semiconductor test and burn-in applications.



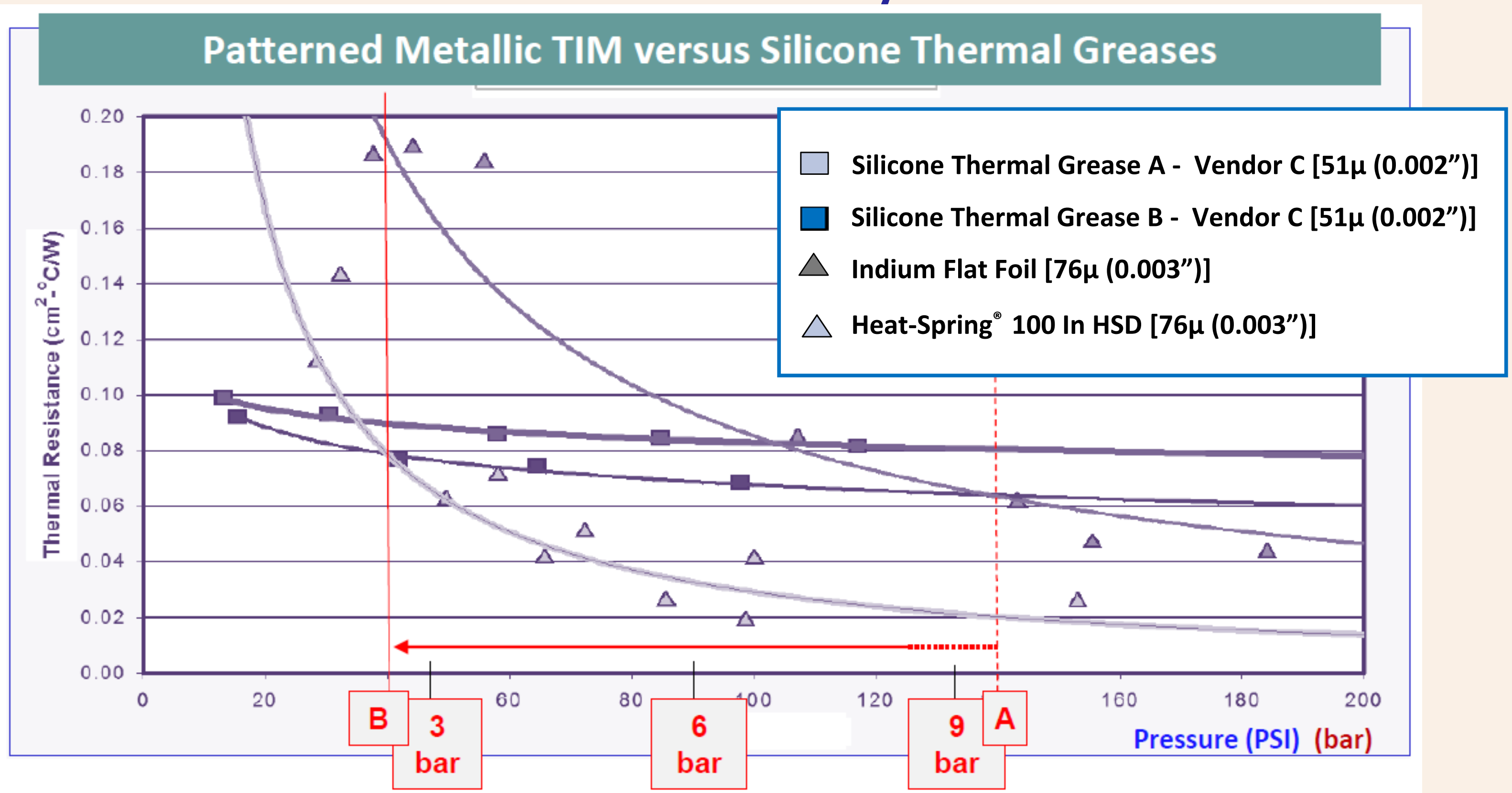
High Performance TIMs: Patterned Metal Alloy Foils

Comparative test data for indium flat foils versus patterned indium foil and two high-performance silicone-based thermal greases:

- Patterned metallic foils outperform thermal greases at clamping pressures >40 PSI.
- Tested improvement value of patterning versus flat foils and greases seen in force reduction (Points A to B).
- Thermal greases tested contain silicone oil carrier.
- See following graph.

Data Source: Indium Corporation. DS&A LLC Model 101 ASTM D5470-12 Test Stand. "Heat-Spring" is a registered mark of Indium Corporation.

High Performance TIMs: Patterned Metal Alloy Foils



Data Source: Indium Corporation. DS&A LLC Model 101 ASTM D5470-12 Test Stand. "Heat-Spring" is a registered mark of Indium Corporation.

High Performance: Graphite Sheet Heat Spreaders

Graphite Sheet Heat Spreader Materials				
Vendor	Product Designation	Thickness (µm)	Bulk Thermal Conductivity	
			X-Y axis W/mK	Z-axis W/mK
DSN (China)	DSN5017	17	1600-1900	15-20
TTCL (China)	TGS-17	17	1700	15
Panasonic (Japan)	PGS EYG-S-25	25	1600	N/A
NeoGraf (US)	eGraf® SpreaderShield Flexible Graphite SS1500	17	1500	3.4
Panasonic (Japan)	PGS EYG-S-100	100	700	N/A
NeoGraf (US)	eGraf® SpreaderShield Flexible Graphite SS600	127	600	3.5
NeoGraf (US)	eGraf® HiTHERM™ 700	127	240	6

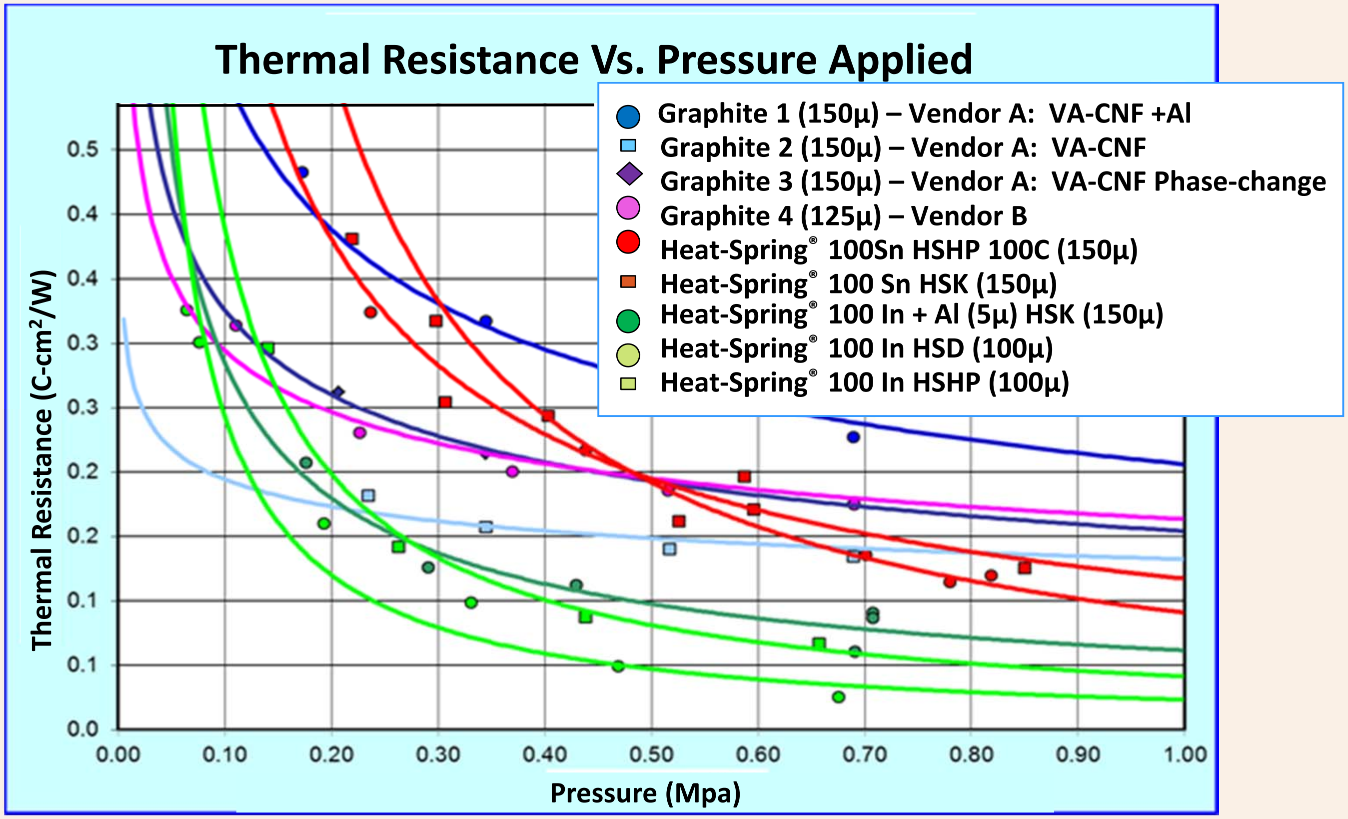
Data Source: DS&A LLC.

High Performance: Vertically-Aligned Carbon Fiber (VA-CNF) TIMs

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

Data Source: DS&A LLC.

High Performance: Metal Alloy TIMs vs. VA-CNF



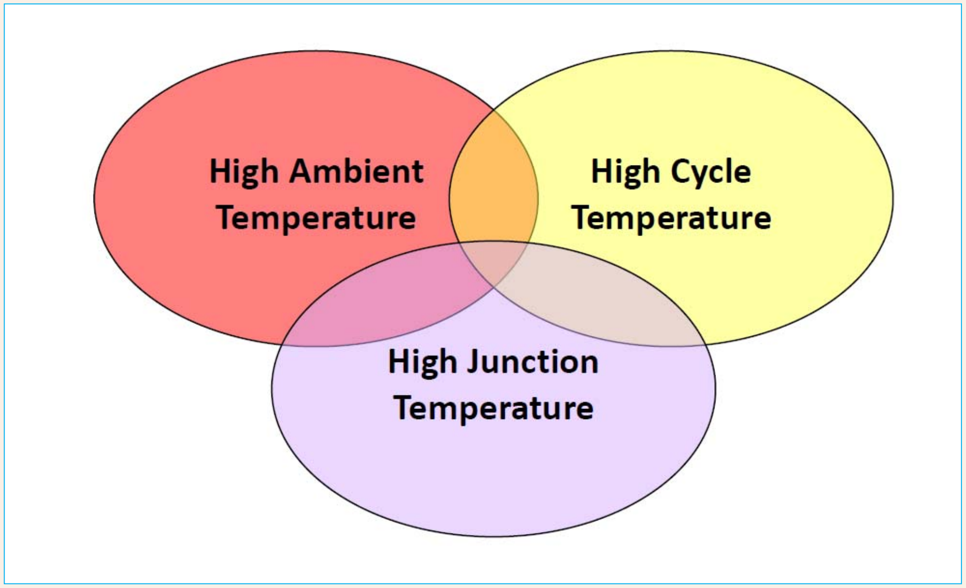
Data Source: Indium Corporation. DS&A LLC Model 101 ASTM D5470-12 Test Stand.

High Temperature and Test/Burn-In Cycling and Reliability

High Temperature Applications

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

- Three modes for high temperature



Source: ElcoScint, J. Postle, Microsemi UK, "The Future of High Temperature Interconnect" (September 17, 2015)

High Temperature Applications

Definitions for what is meant by “high temperature” are relative:

Typical Operating Temperature Range by Market Sector	
Market Sector	**Temperature Range, Operating (°C)**
Consumer	0 to +40
Computing	+10 to +40
Telcom	- 40 to + 85
Power (General)	- 40 to + 95
Power (Traction)	- 55 to + 95
Power (Aircraft)	- 55 to + 95
Ground Vehicle	- 60 to + 105
Semiconductor Test/Burn-In	-40 to + 155
Geothermal	-60 to + 275 (+225 minimum, typ.)

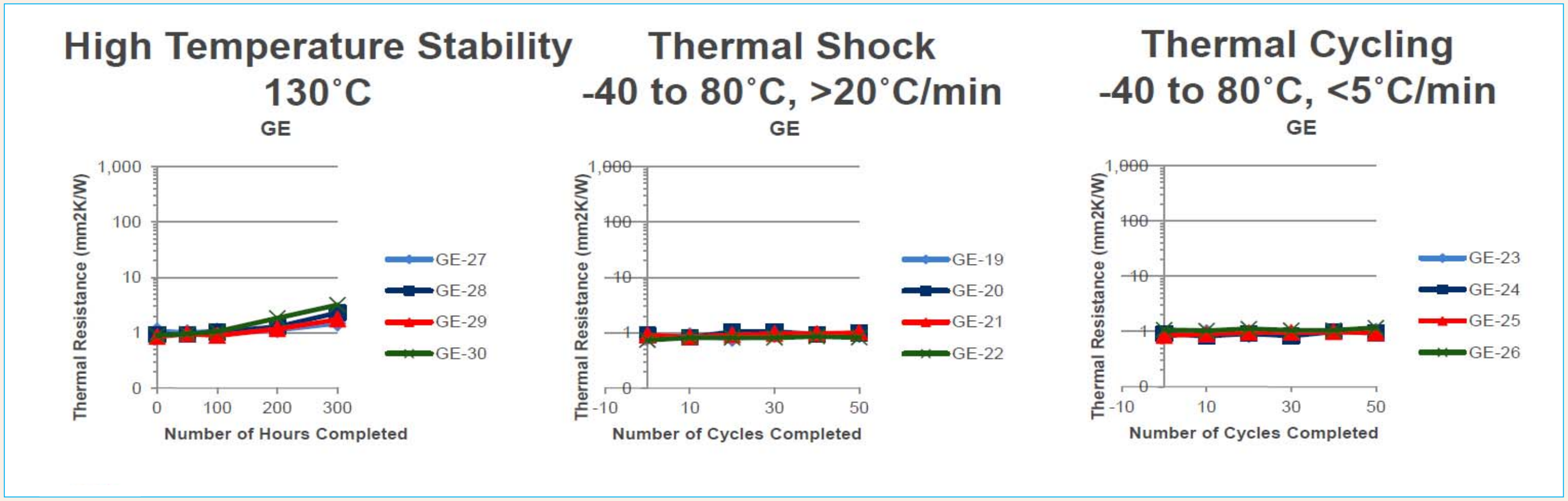
High Temperature Applications

Higher operating temperature can severely restrict available thermal solutions:

- May lead to increased focus on TIM *performance,* if the available thermal operating range is reduced *;*
- Requires selection of *high-temperature-capable TIMs* matched to specific expected application operating temperatures;
- Higher ambient temperature = higher device junction temperature;
- Ambient and junction temperature requirements will dictate TIM *processing temperature* range.

High Temperature Applications

Examples of TIM testing at NREL for "high temperature" for GE Global Research:



- Moderately high temperature range, for stability testing at 130C.

Source: David Shaddock, Brian Rush, GE Global Research, "Thermal Management Technologies", IMAPS ATW Thermal 2014, Los Gatos CA USA.

High Temperature Applications: Pressure-Sensitive Adhesives

A key component of many TIMs used for electronics applications is the addition of a pressure-sensitive adhesive. Definition of a PSA:

- Adhesion is achieved when stress is applied (i.e., the application of pressure):
  - Aggressive and permanent tack
  - Adheres with no more than finger pressure
  - Requires no activation energy to adhere
  - Has sufficient ability to hold an adherend
  - Has enough cohesion to hold an adherend

Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA.

High Temperature Applications: Pressure-Sensitive Adhesives

Cohesion and shear strength:

- Cohesion is an internal force:
  - An attractive force within a PSA
  - Resistance to separation
- Shear strength measurements
  - Static: ASTM D3654D
    - Weight constant, measured with time to failure
  - Dynamic: ASTM D1002
    - Force increases at rate
  - Shear adhesion failure temperature (SAFT) per ASTM D4498

Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA.

High Temperature Applications: Pressure-Sensitive Adhesives

Two major PSA categories:

- Acrylic-based
  - Co-polymeric
  - Cross-linked
    - Example: polyacrylic acid and hydroxypropyl acrylate
    - *Temperature use: < 125°C*
- Silicone-based
  - Co-polymeric
  - Cross linked
  - *Temperature use: > 125°C*

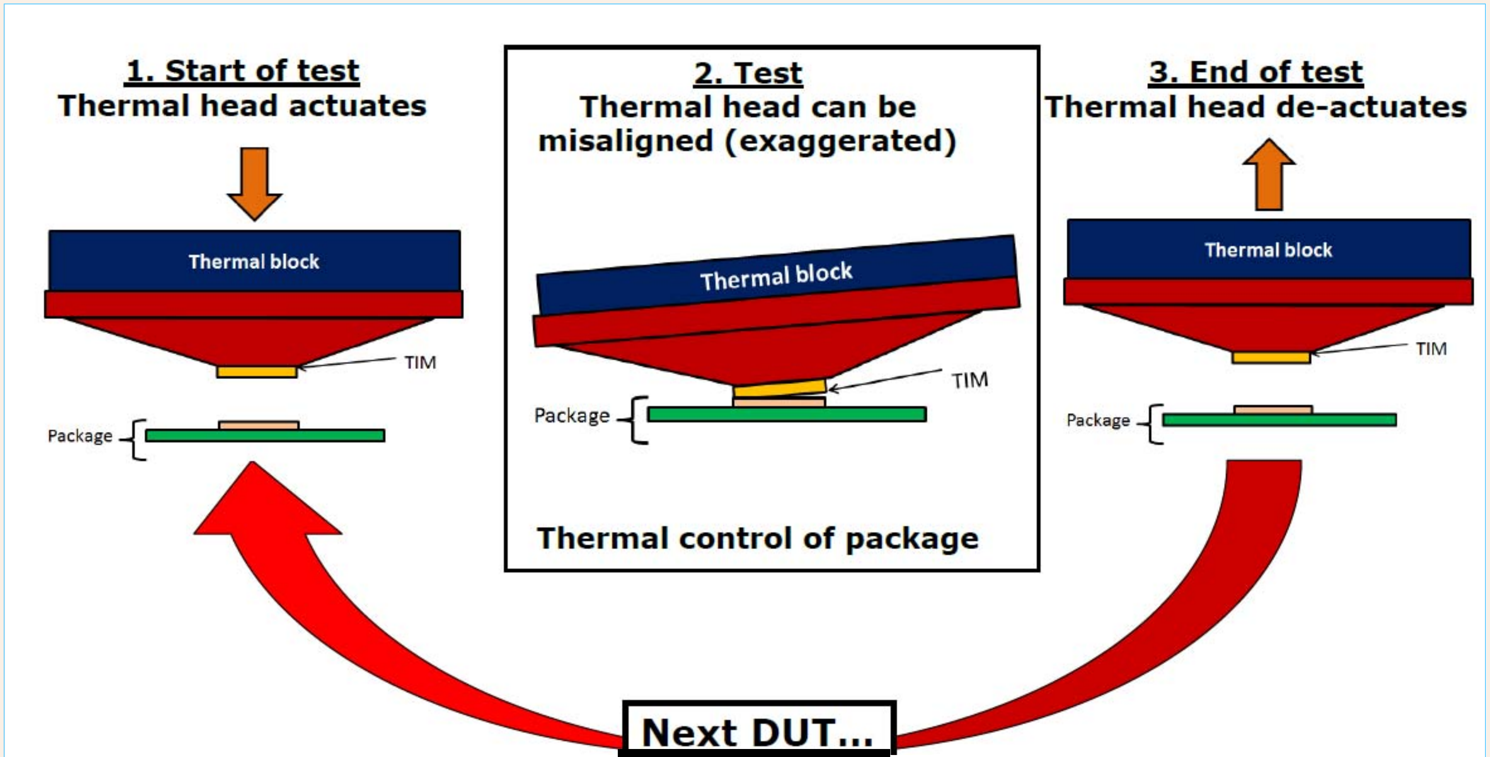
Source: Tom Rogers, Technical Director, Polyonics Inc., Westmoreland NH USA.

TIM Development - Specific to Semiconductor Test

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/ 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 Cooling	Low	Narrow (Cooling)	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

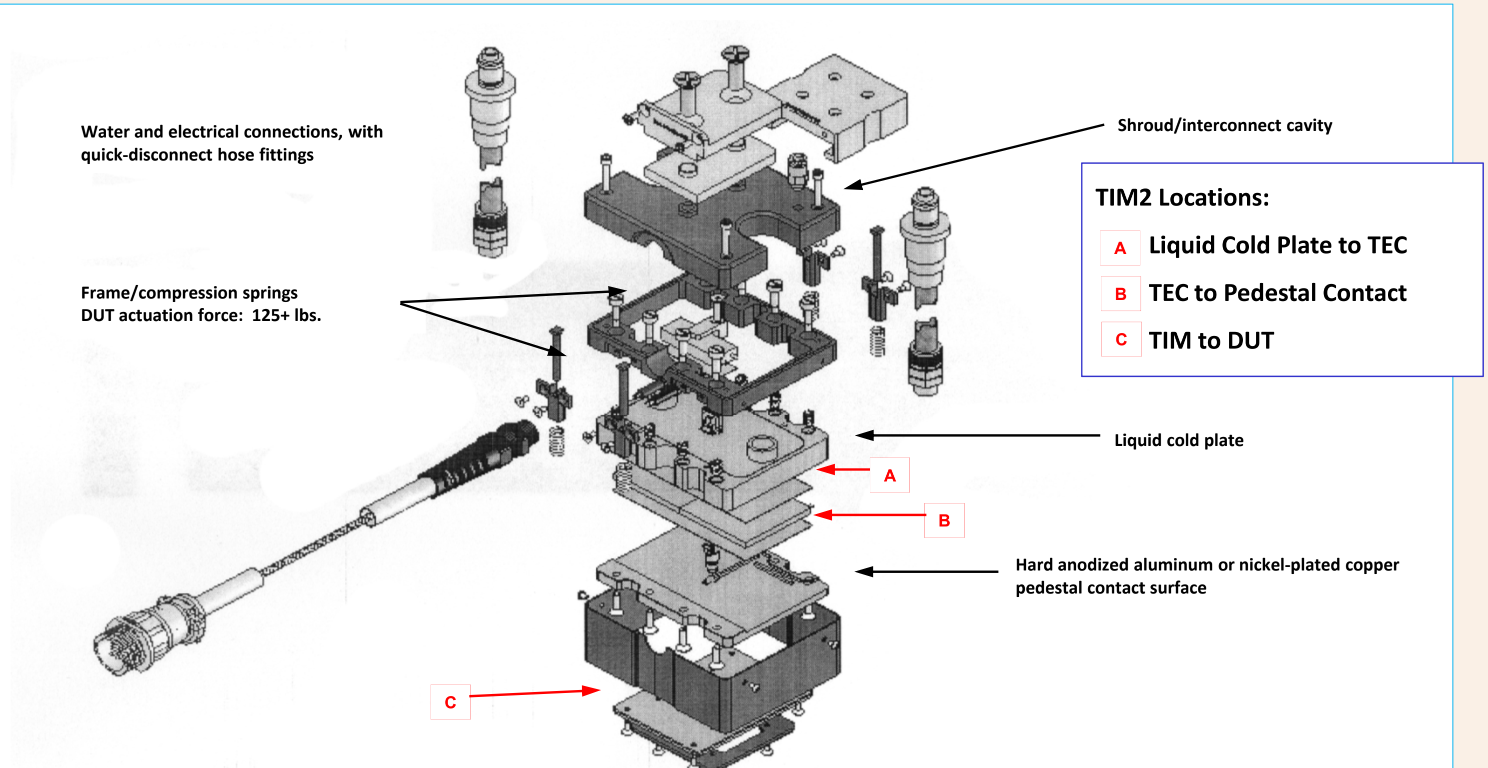
Source: DS&A LLC, modified from Kulicke & Soffa (USA) .

TIM Development - Specific to Semiconductor Test: Gimbaled Test Head



Source: J. Sanchez, Intel ATTD, Chandler AZ USA

TIM Development - Specific to Semiconductor Test: Gimbaled Test Head



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

TIM Development - Specific to Semiconductor Test

High Performance Commercial TIM Material Target Specification: Test/Burn-In	
Product Attribute	**Goal***
Thermal Resistance	Target: < 0.35°C-cm^2/W @ Minimum clamping force applied Stretch: < 0.15°C-cm^2/W @ 60PSI clamping force applied
Contact, Non-Coplanar Surfaces	Target: 1,000 – 5,000 Cycles Stretch: 5,000 – 15,000
Thermal Conductivity	30W/m-K ■ (Minimum) >100W/m-K ▲ (Ideal)
Operating Temperature	-15°C to 120°C ■ (Minimum) -40°C to 200°C ▲ (Ideal)

*Key to symbols: ▲ Market leading product. ■ Market improvement w/equivalent or better pricing. * Generalized statements.*

Source: DS&A LLC.

TIM Development - Specific to Semiconductor Test

High Performance Commercial TIM Material Target Specification: Test/Burn-In	
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 for 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

*Key to symbols: ▲ Market leading product w/premium pricing ■ Market improvement w/equivalent or better pricing * Generalized statement*

Source: DS&A LLC.

TIM Development - Specific to Semiconductor Test

Examples of TIM2 Developments					
Thermal Material General Type	**Thermal Resistance**	**Temperature Range Capability**	**Suppliers**	**Cost**	**Development Status**
VA-CNT*	Very Low	Wide	Limited	Very High	Development, Early Prototyping
VA-CNF**	Very Low	Wide	Limited	Moderate	Development, Early Prototyping
Graphite Heat Spreaders	High	Very Wide+	Many	Moderate	Production
Al Foils+Compound (Non-Silicone)	Low	Wide	Limited	Low	Production
Patterned Metallic Foils	Very Low	Wide	Limited	Moderate	Production

Source: DS&A LLC . Key: VA-CNT: Vertically-aligned carbon nanotube array in carrier. VA-CNF: Vertically-aligned carbon fiber or graphite particulates in carrier.
+ Graphite heat spreaders are highly anisotropic and are not TIMs; temperature tolerance to 400+ °C.

TIM Contact Cycle Reliability Testing for Semiconductor Test

An example of a test program follows in three phases for TIM contact cycling and reliability testing specific to semiconductor test and burn-in:

Thermal /Mechanical Cycling Test Program Design				
Program Phase	Purpose	Test Head Configuration*	Operating Temperature (°C)	Data Output
I	Baseline Values	Parallel	70 – 95	R_{th}**, Thickness Change,** * Cycle Count
II	Strike Angle	Upper Body: Strike Angle	70 – 95	R_{th}**, Cycle Count
III	Strike Angle/Elevated Temperature	Upper Body: Strike Angle at Elevated Temperature	125	R_{th}**, Cycle Count

Notes: * *Test head configuration and test system design per ASTM D 5470-12 thermal interface material testing methodology. Use of this test system and method is intended to provide industry-standard baseline thermal performance values.*

** *Thermal resistance value is the principal thermal performance value for a TIM and uniform, stabilized values indicate an appropriately stable testing system.*

*** *Thickness change data is intended to provide indication of a stable test cycling process for baseline data.*

TIM Contact Cycle Reliability Testing for Semiconductor Test

Semiconductor test engineers were surveyed to determine test parameters:

Thermal /Mechanical Cycling Test Parameters			
Organization	**Test Pressure Reported (PSI)**	**Test Temperature Range Reported (°C)**	**Dwell (Seconds)**
Company A	170	25**/100	60
	170	100	60
Company B	100	-	60
Company C	-	120	-
Company D	-	100	-
Company E	-	80	60
Company F	60/100*	105**/125	-
	100*	105**/125	-

*Notes: * Pressure applied dependent upon die or package contact area. ** Initial value. Source: DS&A LLC.*

TIM Contact Cycle Reliability Testing for Semiconductor Test

Testing utilized a commercial ASTM D 5470-12 (modified) test stand:

Thermal /Mechanical Cycling System Design	
Property	**Value**
System	Berliner Nanotest TIMA6
Upper Reference Body (Heater Bar)	125°C
Lower Reference Body (Liquid Cold Plate)	75°C
Sample Temperature	95°C
Clamping Force Method	Servo Automated
Clamping Force Applied	500kPa (72PSI)
Temperature Measurement	In situ
Thickness Measurement Under Force Applied	In situ

Note: Uniform single clamping force applied for all materials. Source: Berliner Nanotest und Design GmbH.

TIM Contact Cycle Reliability Testing for Semiconductor Test

Reliability test data:

- The first phase of this test program is intended to establish a baseline of mechanical data with three types of TIMs
- *Parallel* test heads
- TIM (material under test) temperature: 95°C
- Phase I testing includes three commercial TIM products designed to meet semiconductor test and burn-in market requirements.
- Success of Phase I program will determine if other TIM products will subsequently be tested.

TIM Contact Cycle Reliability Testing for Semiconductor Test

Test heads were adapted for this mechanical cycling test program to fit an existing test stand. Test head values are shown:

Thermal /Mechanical Cycling Test Head Design	
Property	**Value**
Material	Aluminum Alloy (AlMgSi1)
Contact Area	17.5mm x 17.5mm (306mm^2)
Contact Surface Roughness	Rz $\leq$ 1µm
Sample Temperature	95°C
Upper Reference Body (Heater Bar)	125°C
Lower Reference Body (Liquid Cold Plate)	75°C
Temperature Measurement	In situ
Thickness Measurement Under Force Applied	In situ @ 72PSI

Note: Uniform single clamping force and temperature applied for all materials.

TIM Contact Cycle Reliability Testing for Semiconductor Test

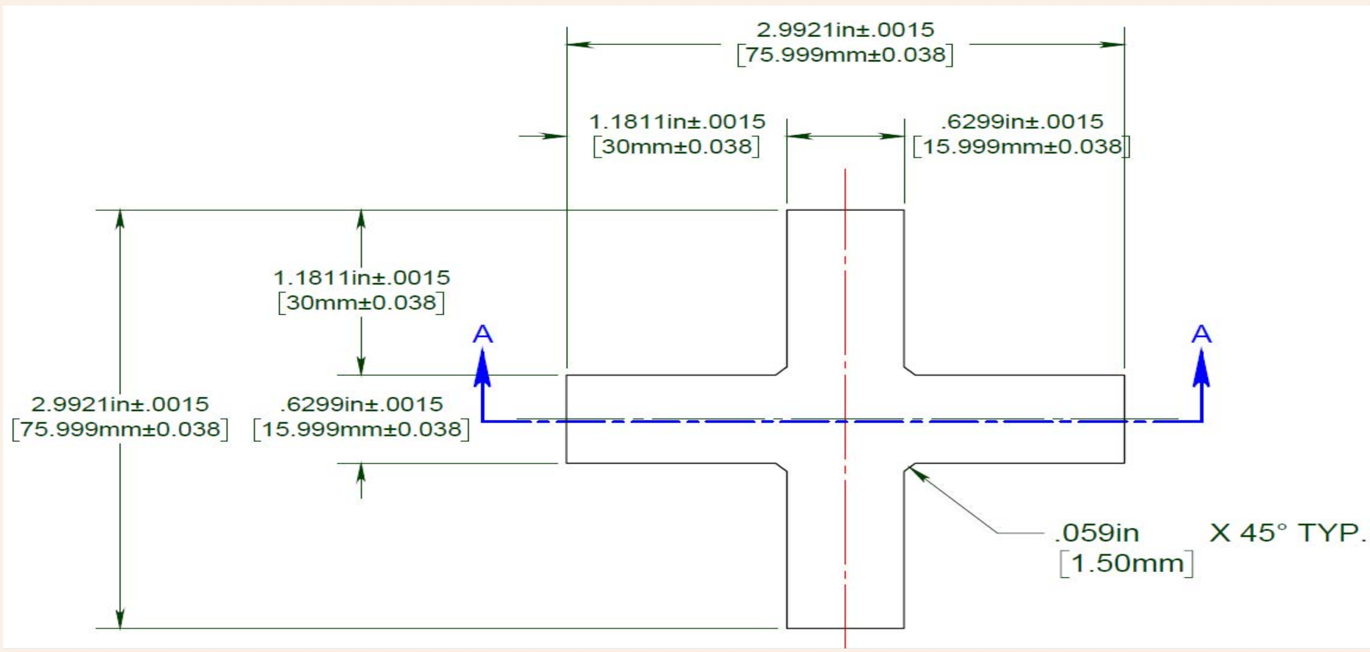
TIM commercial products developed for semiconductor test requirements, included in Phase I test program:

Thermal Interface Materials Tested	
Graph Key	**Description**
CLAD	Indium (99.99%) flat foil, clad one side (0.0005”) aluminum
CLAD HSK	Indium (99.99% foil, clad one side (0.0005”) aluminum, HSK pattern applied*
HSMF-OS	Aluminum foil (0.002”), coated one side with dry thermal compound**

*Note: * Indium Corporation Heat-Spring® HSK. ** Indium Corporation HSMF-OS.*

TIM Contact Cycle Reliability Testing for Semiconductor Test

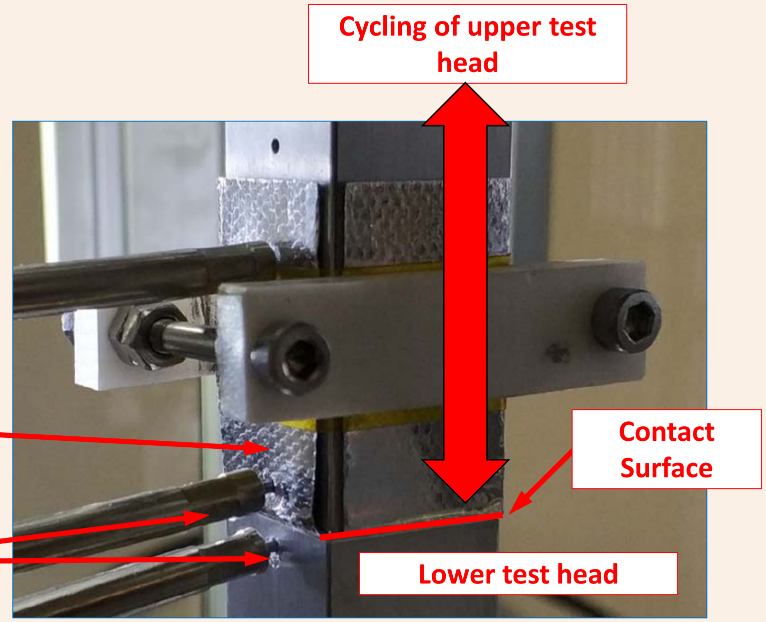
"Red Cross" test material designed for head attachment:



TIM Contact Cycle Reliability Testing for Semiconductor Test

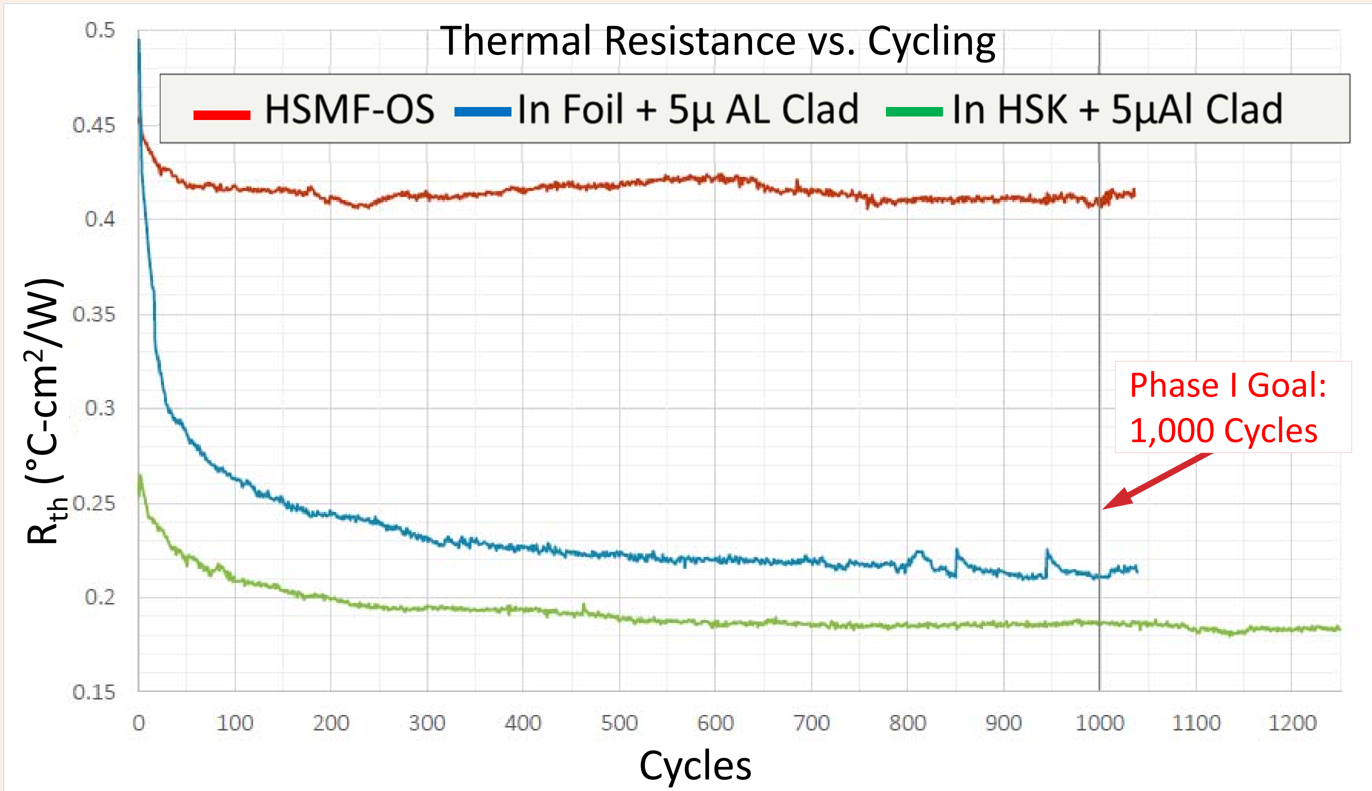
Test heads were adapted for this mechanical cycling test program to fit an existing test stand.

- Test assembly shown with TIM under test applied
- Heat-Spring® HSK aluminum-clad patterned indium alloy TIM applied to upper test head



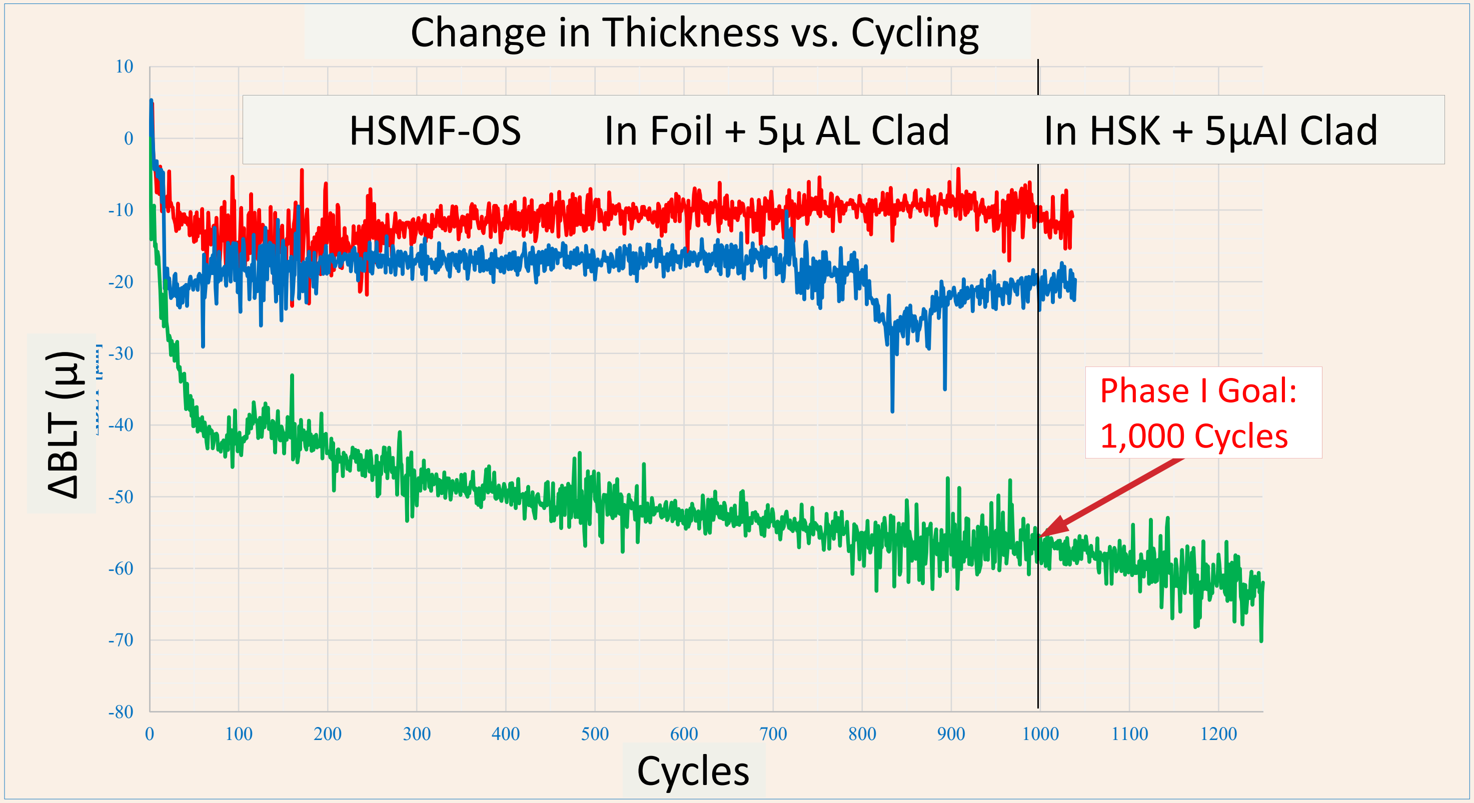
Note: Uniform single clamping force and temperature applied for all materials.

TIM Contact Cycle Reliability Testing for Semiconductor Test



Source: Berliner Nanotest und Design GmbH. February 16, 2018.

TIM Contact Cycle Reliability Testing for Semiconductor Test

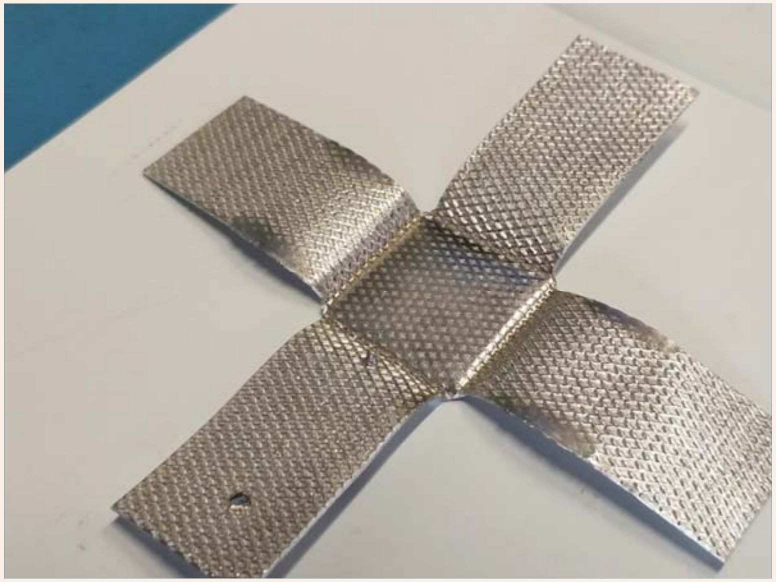


Source: Berliner Nanotest und Design GmbH. February 16, 2018. Observed variation (>800 cycles) for indium flat foil with aluminum cladding was caused by an error with hot water supply for the liquid cold plate and the temperature-related error correction algorithm of thickness measurement. Testing concluded at 1,000 cycles (with exception of patterned In HSK +5µ Al cladding).

TIM Contact Cycle Reliability Testing for Semiconductor Test

Test heads with aluminum-clad flat indium foil TIM applied.

Appearance of HSK-patterned indium foil with aluminum cladding, after conclusion of >1,000 cycles in testing.



Source: Berliner Nanotest und Design GmbH. February 16, 2018.

TIM Contact Cycle Reliability Testing: Data Analysis

Phase I testing of all three TIM types successfully passed 1,300 cycles:

- HSMF-OS: 0.004” (0.102mm)-thick aluminum foil, coated one side only with non-silicone thermal compound. Applied with Al surface facing DUT.
- 99.99% flat indium foil [0.012” (0.30mm) thickness, including clad one side only with 0.0005” (0.0001mm) aluminum]. Applied with Al surface facing DUT.
- Indium Corporation Heat-Spring® HSK patterned 99.99% indium foil, clad one side only with 0.0005” (0.0001mm) aluminum . Total thickness: 0.0220” (0.559mm). Applied with bare Al surface facing DUT.

TIM Contact Cycle Reliability Testing: Data Analysis

Phase I testing has demonstrated:

- Stable thermal resistance values achieved during mechanical cycling demonstrated required durability for all three baseline materials tested;
- Visual inspection indicated no visible marking and zero residue on lower body test head surface (equivalent to the case or die surface of DUT);
- Stable thermal and thickness values indicate success of each material type for long-term cycling without tearing or marking of DUT.

TIM Contact Cycle Reliability Testing: Next Steps

- A test stand designed per ASTM D 5470-12 has been utilized with test heads adapted for a test program in three phases, per requirements for semiconductor test and burn-in applications.
- Phase I baseline test results for a mechanical contact cycling test program have been described. All three materials met the baseline test targets.
- Next steps:
  - Phase II – Introduction of strike angle at constant temperature.
  - Phase III – Introduction of strike angle and elevated temperature conditions.

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 the bulk conductivity) have the biggest 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.

Summary of New Material Developments

High Performance Commercial TIM Materials - Examples			
TIM Classification	**Vendor**	**Product**	**Status**
Liquid Metal Alloy	Indium Corporation/USA	Liquid indium	Commercial product
	Enerdyne Corporation/USA	Liquid indium alloy on carrier	(Indeterminate)
Metallic TIM	Indium Corporation/USA	Heat-Spring® patterned TIM	Commercial product
	Indium Corporation/USA	Indium alloy foil	Commercial product
	AIM/Canada	Indium alloy foil	Commercial product
	Kester/USA	Indium alloy foil	Commercial product
	GE Global Research/USA	Fabricated Cu nanosprings/W-foil/Cu-foil/In-solder alloy	Available for licensing
Thermal Grease	Sumitomo/Japan	Nanoparticle Ni/Fe grease	(Indeterminate)

Summary of New Material Developments

High Performance Commercial TIM Materials - Examples			
TIM Class	**Vendor**	**Product**	**Status**
Aligned Carbon Fiber/Polymeric Matrix Carrier Preform	Btech Corporation/USA	Graphite fiber/polymeric carrier preform	Commercial product
	DuPont E&C/USA	Carbon fiber vertical array/polymeric carrier preform	Development
	Honeywell Electronic Materials/USA	Graphite fiber/polymeric carrier preform	Commercial product (withdrawn)
	Hitachi/USA	Carbon fiber vertical array/polymeric carrier preform	Commercial product
CNT-Based	SHT AB/Sweden	Vertically-aligned CNT array in polymeric carrier	Development
	Carbice/Georgia Tech/USA	Infinity™ Vertically-aligned CNT-array in polymeric carrier	Development

TIM Development – Test Equipment Manufacturers

Selected TIM Test Equipment Manufacturers		
Company	**Test Stand General Type**	**Status**
Berliner Nanotest und Design GmbH Berlin, Germany	TIMA ASTM D 5470-12 (Modified)	Production
	LaTIMA In-Plane Bulk Thermal (X-Y) Conductivity Test Stand	Production
	Thermal Test Die, Thermal Test Wafers, Thermal Test Vehicles (TTVs)	Production
	Three-Omega Method Liquids Thermal Conductivity Test Stand	Production
Mentor Graphic Mechanical Analysis Division	"T3Ster" Structure Function Transient Test Stand; DynTIM™ Test Head	Custom
Thermal Engineering Associates, Inc. Santa Clara CA USA	TIM Test Stand per ASTM D 5470-12 (Modified)	Custom

Source: DS&A LLC . Selected vendors shown.

Summary

- Thermal interface materials (TIM) are integral to adequate heat transfer from a semiconductor source to an external environment.
- Specialized TIM materials can be characterized as “well-performing” when measured against challenging requirements for critical applications.
- A range of metallic, carbon fiber, CNT, and other TIM types have been developed, for specialized semiconductor test and burn-in requirements.
- Specialized TIM testing platforms are available commercially.
- Mechanical contact cycling testing has been shown as an example of specialized reliability testing designed for semiconductor test applications.

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Market analysis and product strategy for electronics thermal management: Advanced thermal materials, components, and systems.

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