Metallic Thermal Interface Material Testing and Selection for IC, Power, and RF Semiconductors

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Thermal Interface Materials

- 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
  - A classification system is useful for guiding selections of materials to meet specific application requirements.
  - Testing and evaluation of TIMs is critical to proper selection for a specific application.
- Specialized TIM materials can be characterized as "well-performing" when measured against challenging requirements for critical applications, including:
  - Required thermal resistance value to meet stated heat transfer requirement
  - Suitability for applicable surface flatness, roughness, available clamping force
  - Suitability for anticipated operating environment – temperature, gases, humidity
  - Required product life and reliability
  - Suitability for a specific application and assembly process, handling, storage.
- Thermal conductivity is not the sole criteria for selection of a TIM.

Thermal Interface Materials

- Selecting an appropriate thermal interface material:
  1. Degree of surface wetting achieved is critical to overall performance, to minimize contact thermal resistance at each of two contact surfaces.
     - Contact resistance dominates overall TIM resistance for many materials.
     - Driving to highest wetting and thinnest clamped or applied thickness is critical to successful TIM selection.
  2. Clamping force uniformly applied is intended to achieve:
     - Maximized surface wetting;
     - Thinnest possible TIM thickness (to minimize influence of bulk thermal conductivity);
     - Metal-to-metal contact for surfaces.
  3. Relatively good bulk thermal conductivity.
- Above statements are intended to apply for applications where low or lowest thermal resistance is required.
- These are general statements across all TIM types.

Thermal Interface Materials: General Categories

Table 1: General Functions and Categories of Thermal Interface Materials *Adhesive Types* *© 2016 DS&A LLC*		
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 low 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

*Notes: * Generally, available as liquid-dispensed adhesive compounds and as die-cut preforms with adhesive, one or two surfaces.*
Source: DS&A LLC.

Thermal Interface Materials: General Categories

Table 2: General Functions and Categories of Thermal Interface Materials *Medium Rth Thermal Performance**		© 2016 DS&A LLC
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 materials to fill large air gaps between two surfaces • 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 available materials • Wide range of thermal performance, cost
Electrical insulation w/minimized thermal resistance	**Electrically-Isolating**	• Relatively uncommon, higher cost • Lower thermal performance due to dielectric layer

*Notes: Gap-filler TIMs are available as die-cut preforms and as liquid-dispensed compounds. * Generally, available with and without adhesive layer one surface, for die-cut preforms.*
Source: DS&A LLC.

Thermal Interface Materials: General Categories

Table 3: General Functions and Categories of Thermal Interface Materials ***High 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 high Rth and high bulk thermal conductivity • Between die and heat spreader • Multiple material types available for TIM1 evaluation

Notes: Thermal greases, Phase-change TIMs are available as die-cut preforms and liquid-dispensed compounds. # Development materials at present.
Source: DS&A LLC.

Thermal Interface Materials: General Categories

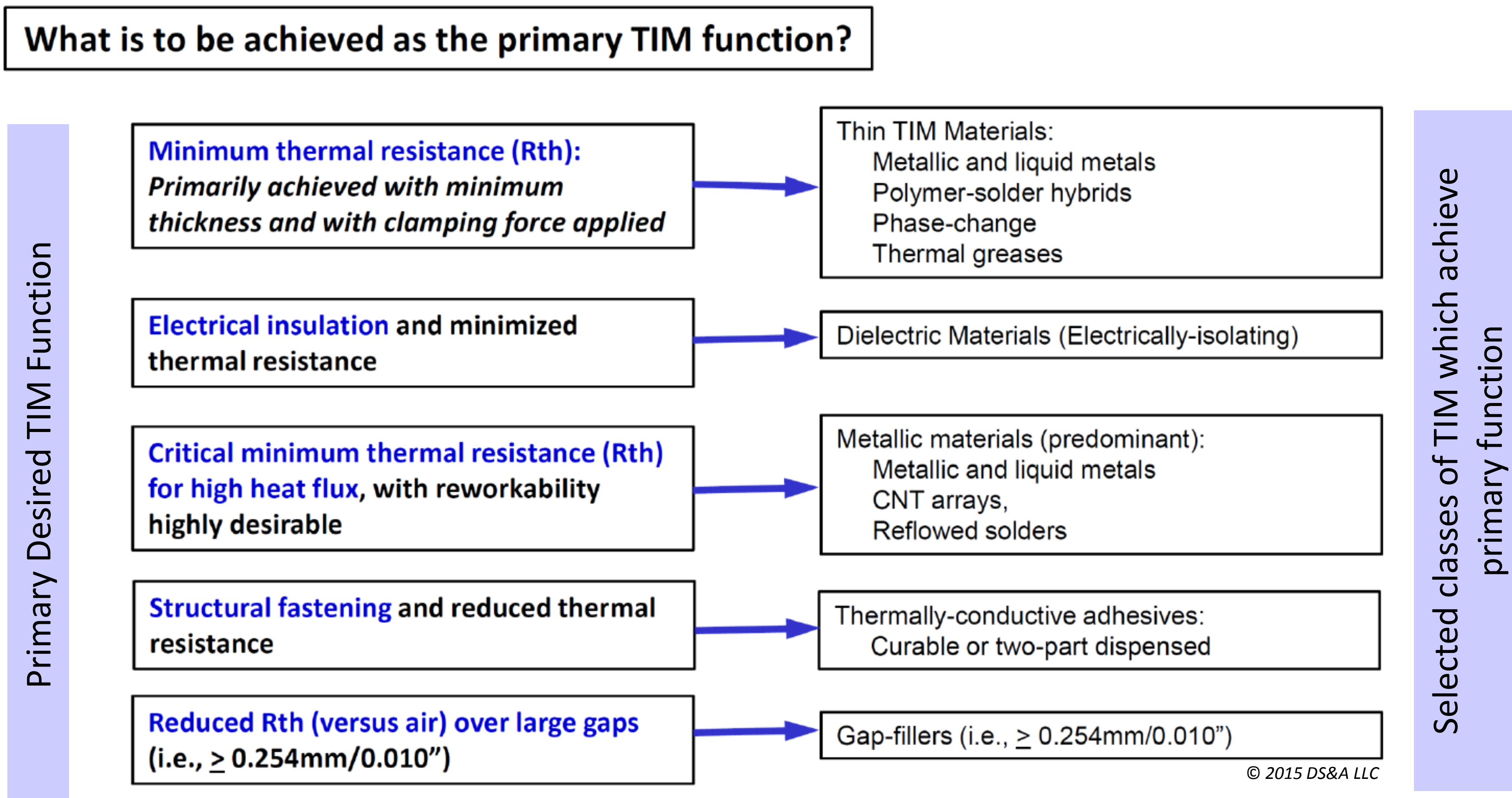
Table 4: General Functions and Categories of Thermal Interface Materials
Highest Rth Performance

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 Rth commercially available currently • Higher cost • Require mechanical fastening
	Carbon Nanotube-based Arrays: Vertically-Aligned CNT (VA-CNT)#	• Lowest Rth projected, as commercial products (future) • Higher Cost • Require mechanical fastening
Critical minimum Rth for high heat flux; reworkability highly desirable, with CTE control	**Metallic Preforms, Liquid Metals**	• Lowest Rth commercially available currently • Variety of metal alloys and patterns available • Higher cost • Require mechanical fastening

Notes: Thermal greases, Phase-change TIMs are available as die-cut preforms and liquid-dispensed compounds.   # Development materials at present.
Source: DS&A LLC.

Thermal Interface Materials: Functions

Figure 1 – Primary TIM Function Organized by Functional Requirements



"Well-Performing" TIMs

What is meant by "well-performing"?

- 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.
- These specialized requirements may include, for example:
  - Higher operating temperature range;
  - Minimized thermal resistance, with 100% surface wetting;
  - Higher dielectric properties with improved thermal resistance;
  - Resistance to extreme mechanical stress due to power cycling;
  - *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

“Well-Performing” TIMs

What is meant by “well-performing”?

- *Prioritization of these specialized requirements* may alter product thermal performance in the final TIM selection.
- Newer materials available include:
  - Vertically-oriented carbon fiber arrays in an organic carrier material
  - High bulk thermal conductivity metallic thermal interface materials
- These TIM categories require mechanical fastening for high relative clamping force to minimize thickness, maximize surface wetting, and maximize thermal performance.

“Well-Performing” TIMs

Improvements:

- In many applications, a very significant (> 5 - 10X) improvement must be made in TIM bulk thermal conductivity in order to impact package thermal performance.
- Carriers such as silicone oil are a primary challenge for reliability, toxicity, chemical constituents, and shelf life of existing TIM materials – but this is still not widely recognized or accepted across the electronics industry.

Metallic Thermal Interface Materials

Patterned Metallic TIMs

Flat metallic foils have been used as TIM materials for more than forty years:

- Typically indium metal or copper shims
- Historically, extensive use in telcom, military, and aerospace applications for RF devices and discrete power semiconductors.

Indium Corporation introduced a family of patterned metallic foils (2008):

- Intended to address a broader range of application types with increased compliancy and no significant increase required in metal thickness.
  - Increased range of metal alloys and patterning introduced.
- "Heat-Spring®" patterned metallic TIMs are selected for applications based on several factors related to application specifics:
  - Alloy
  - Patterning
  - Thickness

Note: US Patent 7,593,228-B2.

Patterned Metallic TIMs

Selection of alloys currently available:

Table 5. "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

Data Source: G. Wilson, Indium Corporation. "Heat-Spring" is a registered mark of Indium Corporation.

Patterned Metallic TIMs

Suggested maximum operating temperatures for metallic TIMs are based on the alloy and composition:

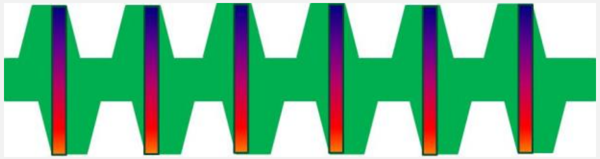
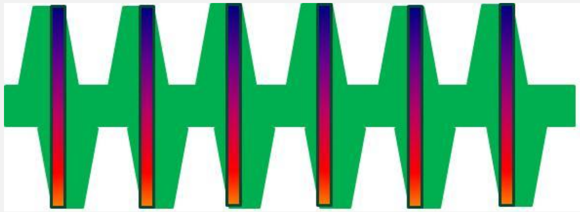
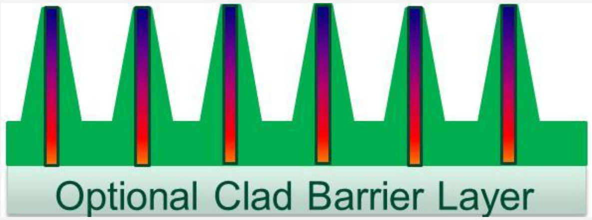
Table 6. Maximum Suggested Operating Temperature for Metallic TIMs

Metallic TIM Composition	Suggested Maximum Operating Temperature (°C)
Indalloy 1E	100
80 In/20 Sn	110
In/Al Clad	125
Sn, "Sn+"	200
100 Pb	250
100 Cu	750

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

Data Source: R. Jarrett, Indium Corporation

Patterned Metallic TIMs

Table 7. 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.

Patterned Metallic TIMs: Reliability

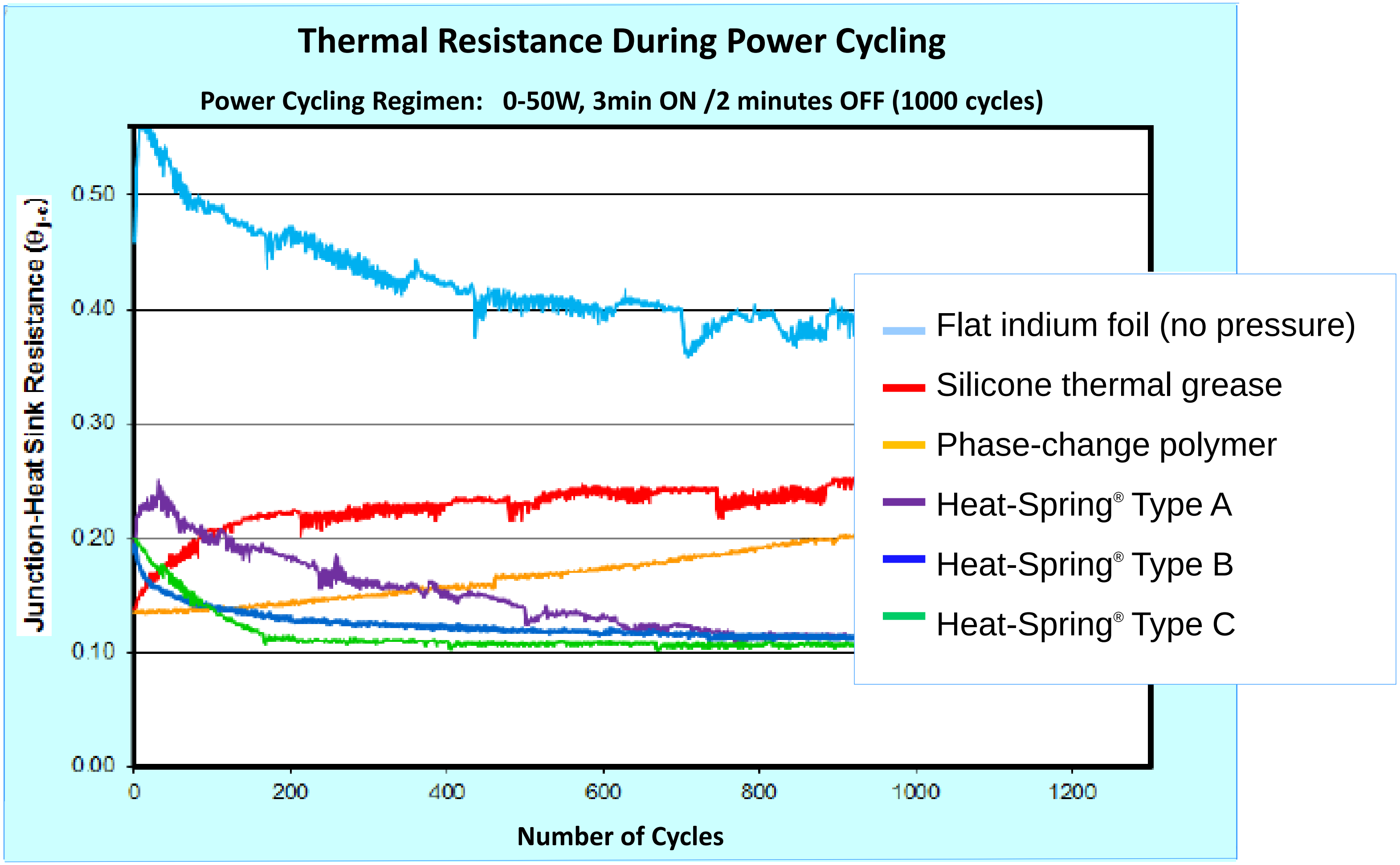


Figure 2– Thermal Resistance During Power Cycling Testing

Data source: Indium Corporation

Patterned Metallic TIMs: Reliability

Figure 3A - Patterned Indium Alloy Metallic TIM **Figure 3B - Baseline: High-Performing Silicone Thermal Grease**

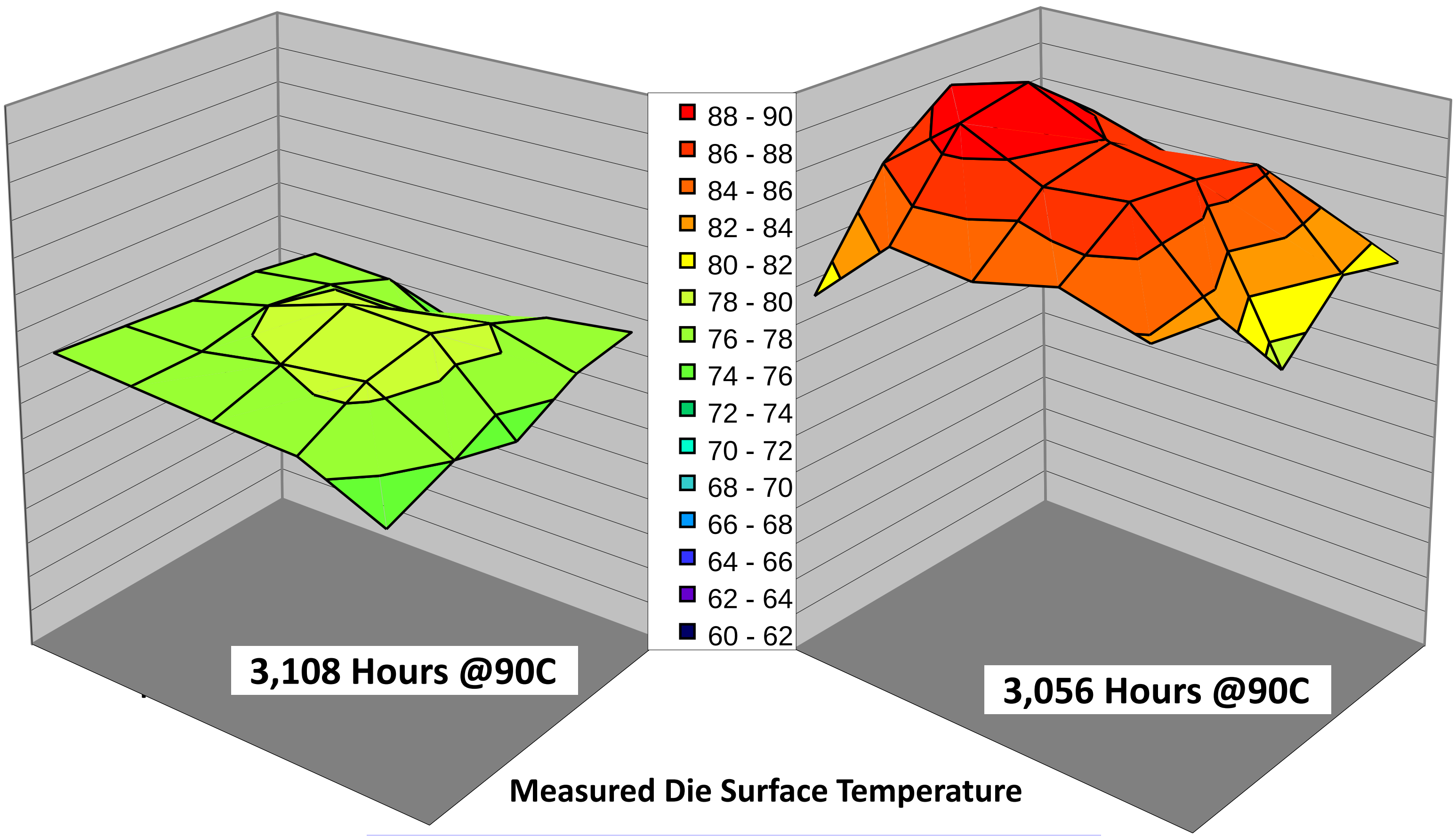


Figure 3 – Comparative 3,000-Hour Reliability Bake Test

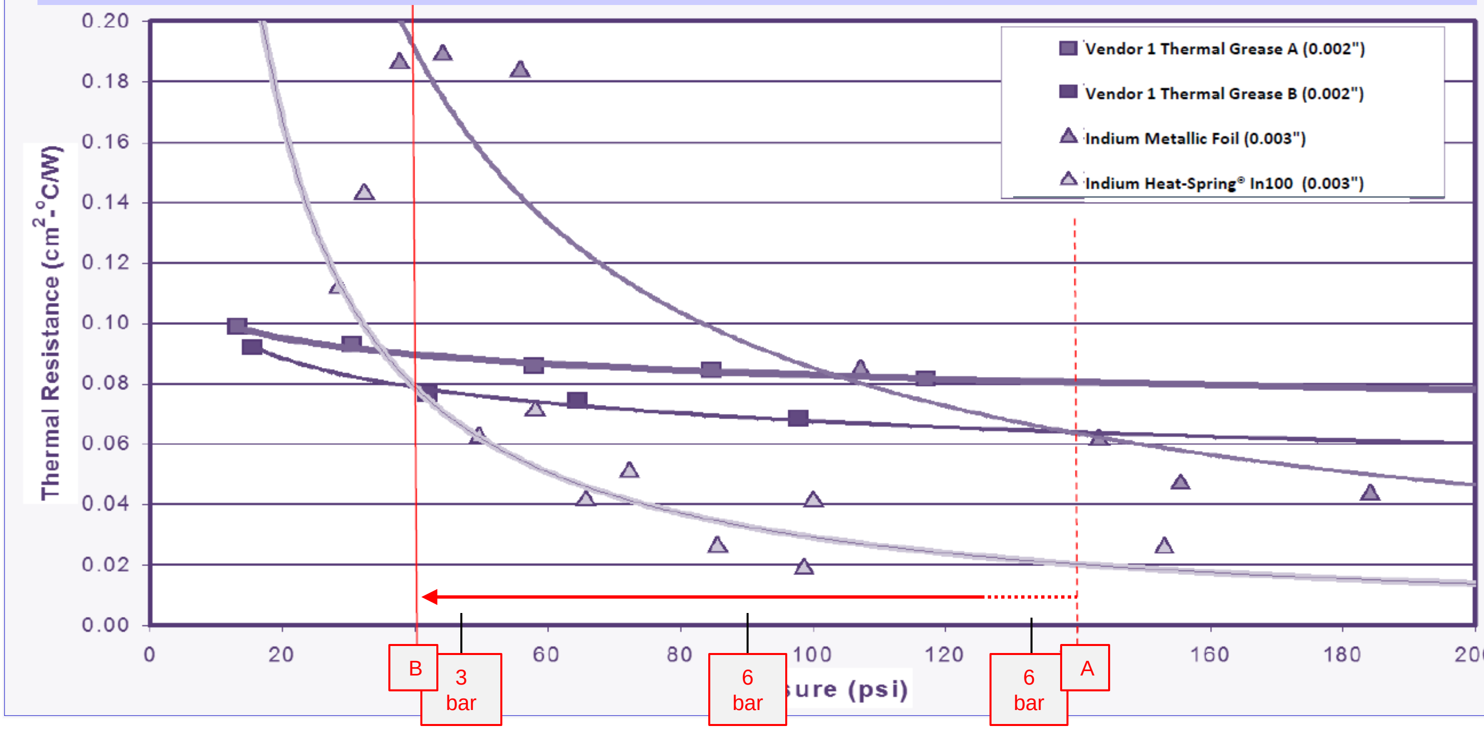
Note: Measured die surface temperature at time zero was shown to be approximately equivalent. Above test data taken after 3,000-hour bake test. Increased die surface temperature for Figure 9B reflects increased thermal resistance due to dry-out of silicone oil in the tested premium silicone-based thermal grease. Data source: Indium Corporation. Die thermal test vehicles provided by Intel Corporation.

Patterned Metallic TIMs

Comparative test data for indium flat foils versus Indium Corporation “Heat-Spring” patterned In100 foil and common 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).

Figure 4 – Patterned Metallic TIM versus Silicone Thermal Greases, Tested Performance



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

Summary

- Thermal interface materials (TIM) are integral for 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 thermal interface materials have been developed and described, for specialized applications requiring performance and reliability in challenging conditions.
- Selection of a specialized TIM must be considered against a range of specific application requirements, as described.

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