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Design of a Four-Phase Mechanical Cycling Reliability Test Program and Evaluation Results for TIMs for Semiconductor Test Applications

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Purpose: TIM Contact Cycle Testing for Semiconductor Test

This presentation describes a reliability testing program for thermal interface materials (TIMs) for semiconductor test and burn-in applications:

- Survey, semiconductor test industry requirements for test parameters;
- Mechanical contact cycling and thermal resistance measurement of TIMs;
- Four program test phases, to test under increasingly rigorous cycling;
- Test results, Phases I - IV;
- Analysis.

The overall purpose of this test program is to evaluate durability of selected TIMs under mechanical contact cycling equivalent to semiconductor test.

Thermal Interface Materials

Thermal interface materials (TIM) are integral to adequate heat transfer from a semiconductor source to an external environment.

- Required for many different types of semiconductor packages and component interfaces.
- Typical requirement is for a single placement for an assembly, to contact the semiconductor device once only.

Specialized TIM materials are selected for challenging requirements for critical applications, including:

- Required thermal resistance value to meet a package heat transfer goal;
- Suitability for applicable surface flatness, roughness, available clamping force, operating environment.

“Well-Performing” TIMs

What is meant by “well-performing”?

- No compound run-out due to temperature, for a polymer system;
- No dry-out of a carrier compound due to temperature;
- No compound pump-out due to mechanical stress, for a polymer system;
- No silicone bleed, outgassing, or redeposition on critical system elements for a silicone-containing polymer or thermal grease;
- No edge shredding, cracking, or other fragmentation for graphitic and metallic materials.

Thermal Interface Materials: Development Requirements

Table 2. 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.*

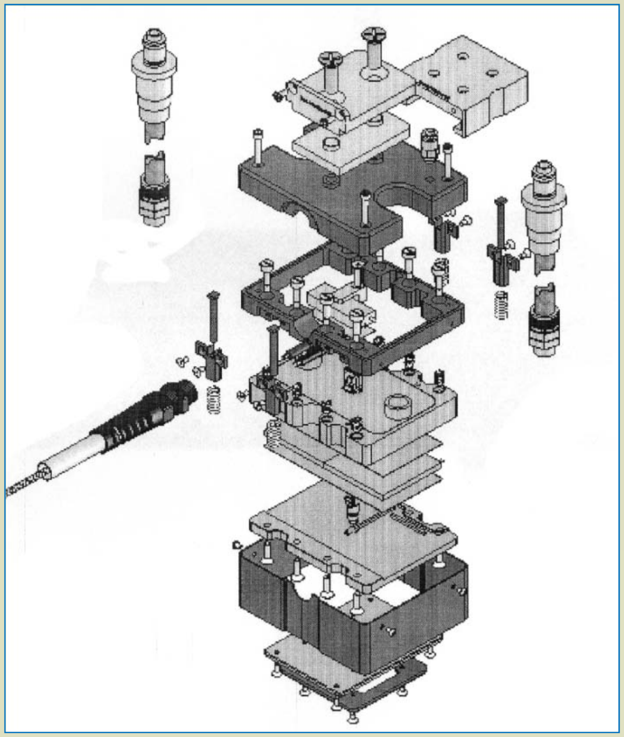
Thermal Interface Materials for Semiconductor Test

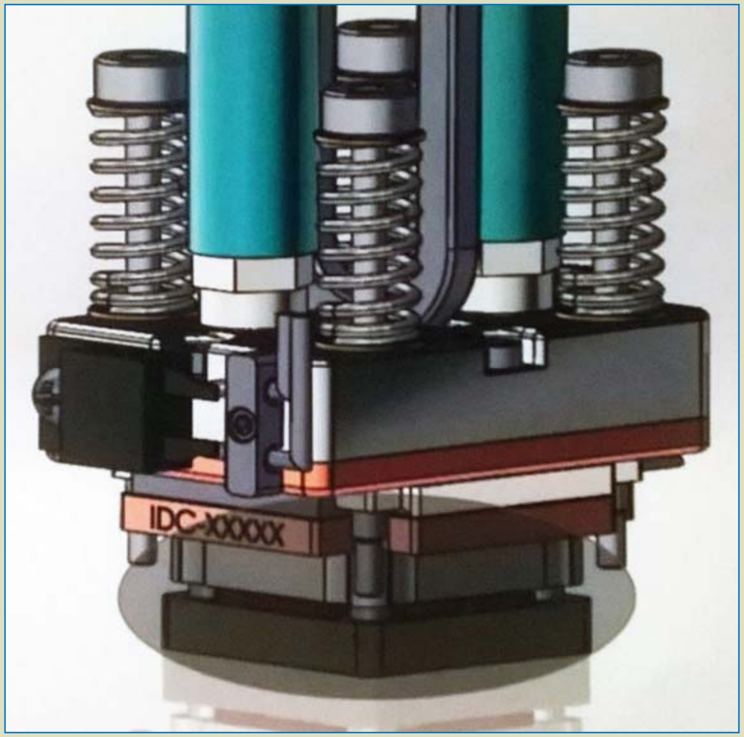
Additional TIM application requirements specific to semiconductor test:

- Required product life and reliability;
- Durability for *multiple contact cycles with a single TIM: 50 – 5,000 cycles*;
- Ease of initial placement, rework, and cleaning;
- Zero residue or marking of DUT for semiconductor test applications;
- Ability to adapt to non-flat contact surface (“strike angle”);
- Resistance to high temperatures for testing and burn-in.

Proper TIM testing is critical to proper selection for each application.
Specific testing methods are needed to understand performance in unusual conditions for semiconductor test and burn-in applications.

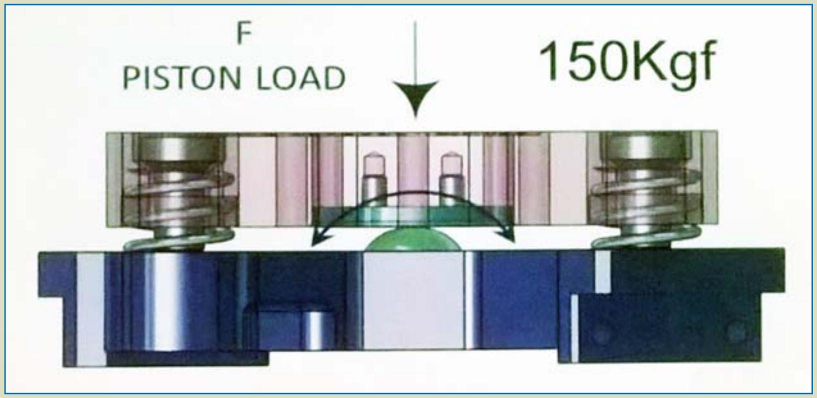
Semiconductor Test System Head Assemblies -- Examples

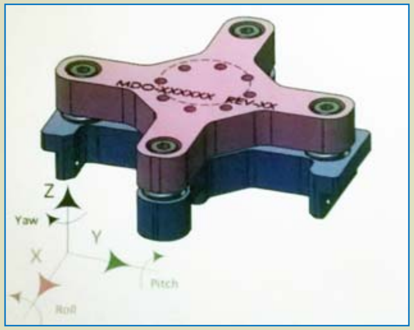




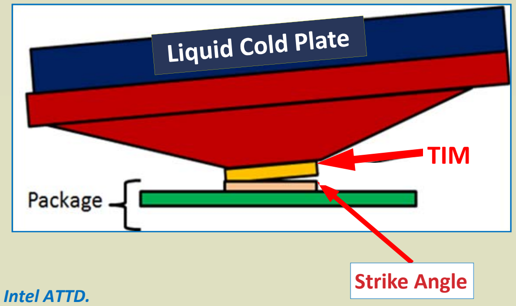
Sources for illustrations:
Left, Antares Advanced Test Technologies, Inc..
Right, Intel ATTD.

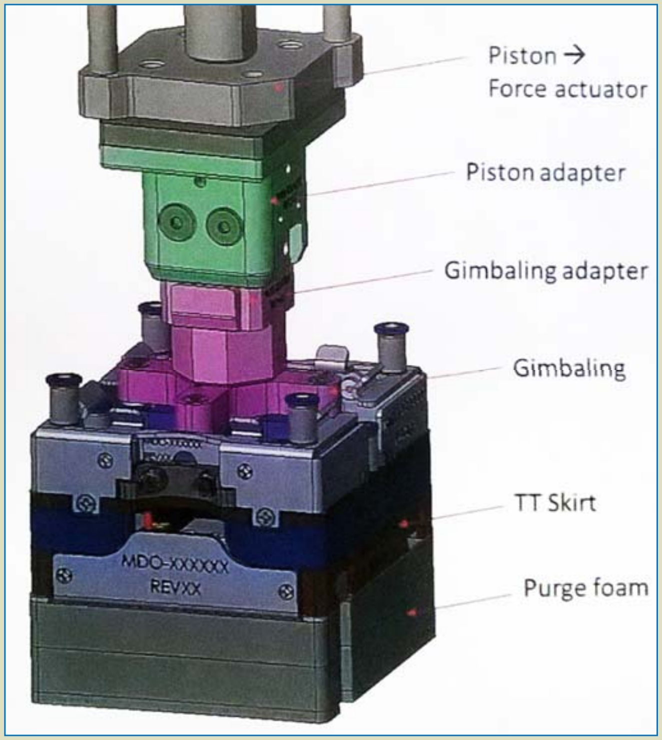
Semiconductor Test System Head Assemblies -- Examples



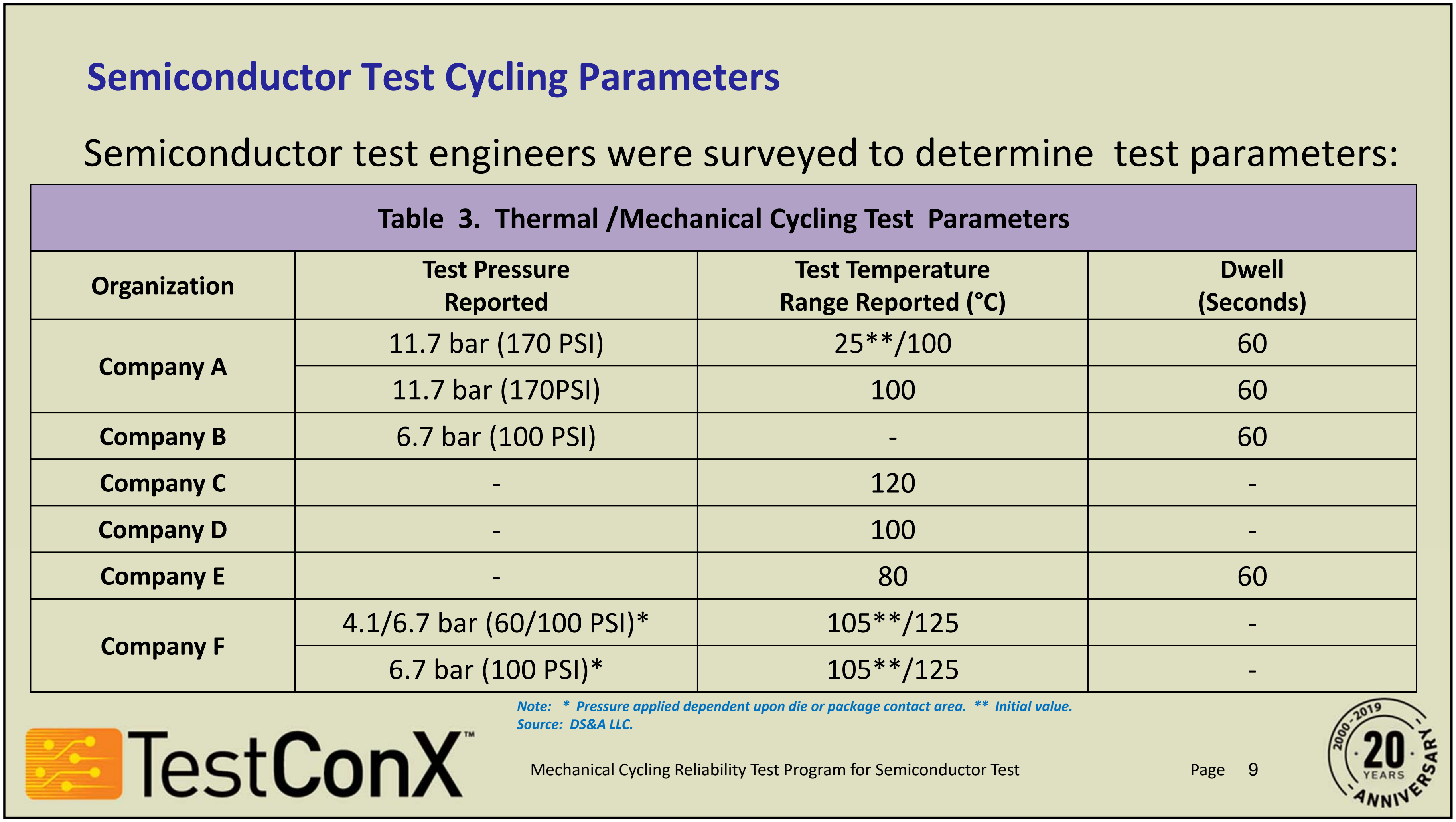


Gimbaled Test Head Illustration





Source: DS&A LLC. Above: Intel IDC (Israel). Right: Intel ATTD.



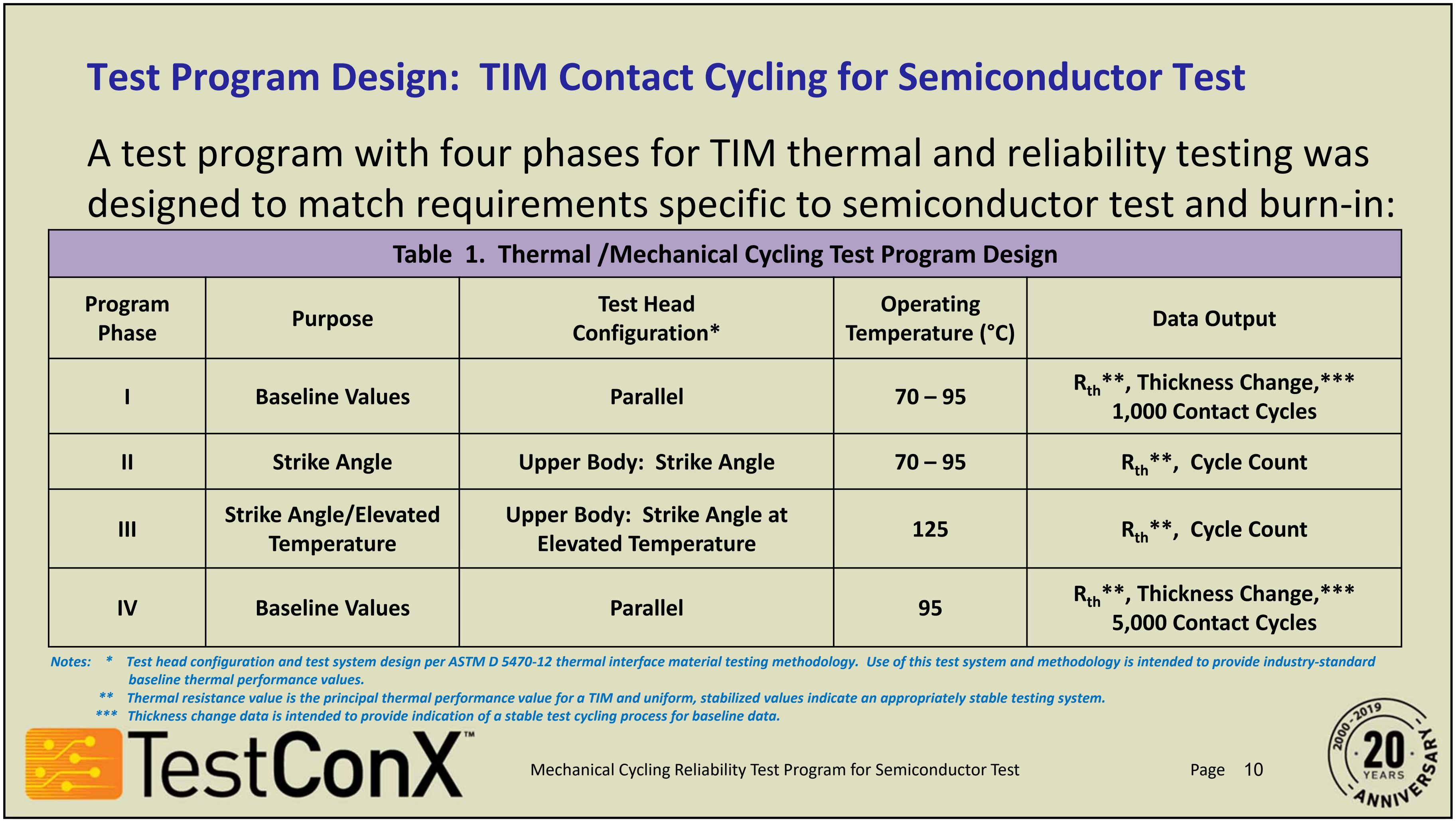
Semiconductor Test Cycling Parameters

Semiconductor test engineers were surveyed to determine test parameters:

Table 3. Thermal /Mechanical Cycling Test Parameters

Organization	Test Pressure Reported	Test Temperature Range Reported (°C)	Dwell (Seconds)
Company A	11.7 bar (170 PSI)	25**/100	60
	11.7 bar (170PSI)	100	60
Company B	6.7 bar (100 PSI)	-	60
Company C	-	120	-
Company D	-	100	-
Company E	-	80	60
Company F	4.1/6.7 bar (60/100 PSI)*	105**/125	-
	6.7 bar (100 PSI)*	105**/125	-

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



Test Program Design: TIM Contact Cycling for Semiconductor Test

A test program with four phases for TIM thermal and reliability testing was designed to match requirements specific to semiconductor test and burn-in:

Table 1. 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,*** 1,000 Contact Cycles
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
IV	Baseline Values	Parallel	95	R_{th}**, Thickness Change,*** 5,000 Contact Cycles

Notes: * *Test head configuration and test system design per ASTM D 5470-12 thermal interface material testing methodology. Use of this test system and methodology 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.*

Thermal/Mechanical Test System Design

Testing utilized a commercial ASTM D 5470-17 (modified) test stand:

Table 4. Thermal /Mechanical Cycling System Design

Property	**Value**
System	Berliner Nanotest TIMA5
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 (5.0bar/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.*

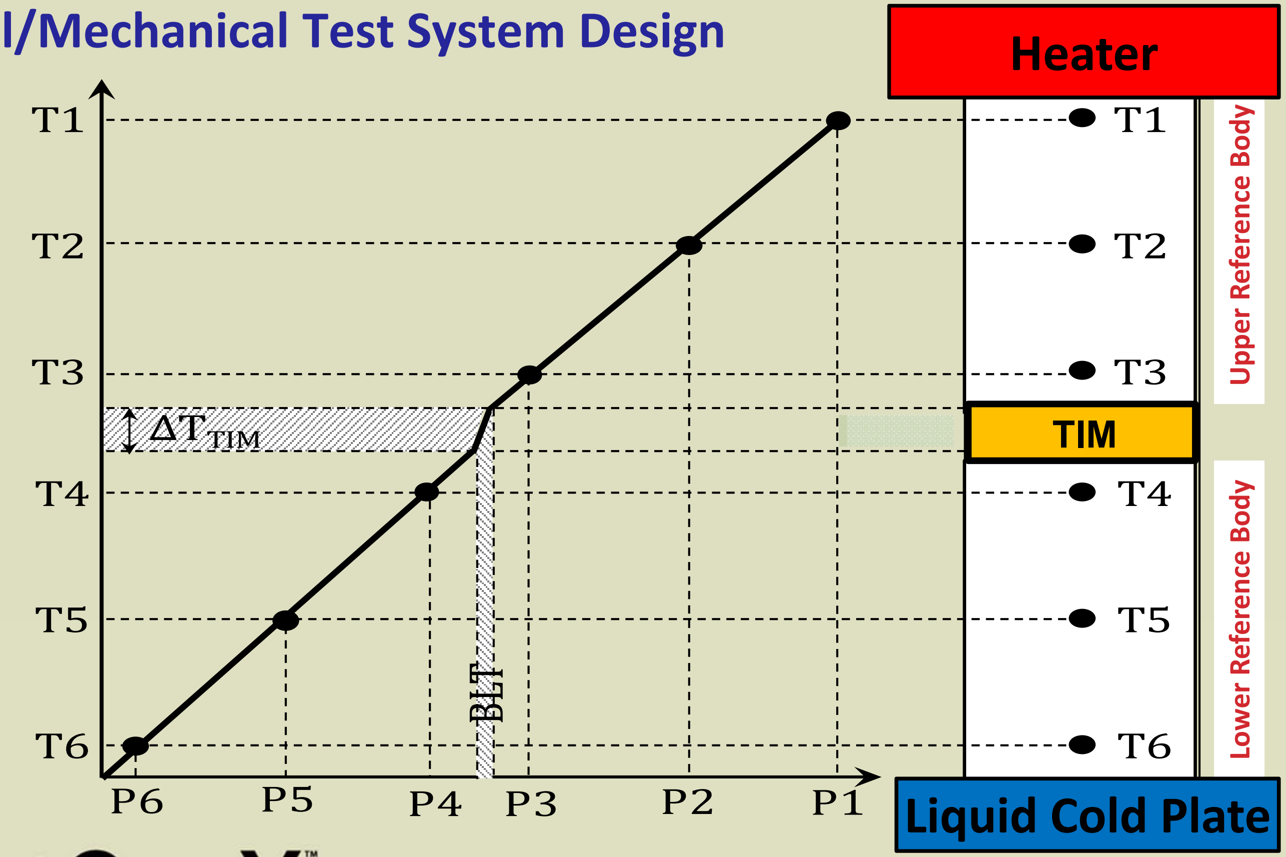
Thermal/Mechanical Test System Design

Berliner Nanotest commercial ASTM D 5470-17 TIM test stand utilized for this program:

- ASTM D 5470-17 is the industry standard test methodology for comparative TIM testing;
- System measures force applied, known power (heat) applied, temperature, thickness – with precise and uniform heat flow.
- Measures thermal conductivity and precisely measures force applied. Reports derived thermal interface material resistances.

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

Thermal/Mechanical Test System Design

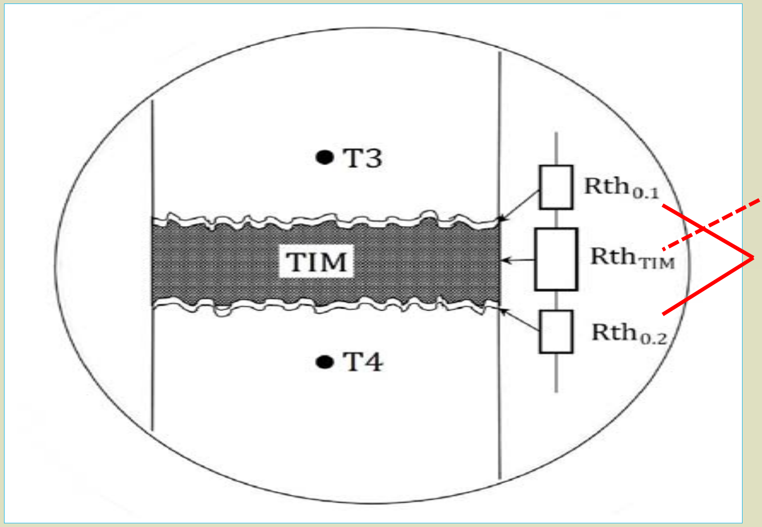


Thermal/Mechanical Test System Design

Thermal interface material testing with ASTM D 5470-17:

- Provides 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)

=

TIM Thermal Resistance (Total)

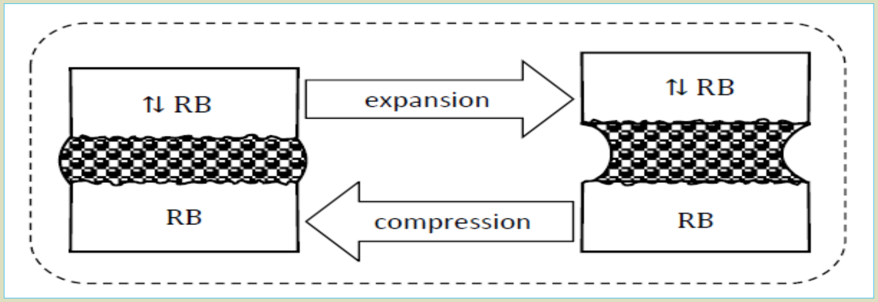
Cycling Reliability Testing: Berliner Nanotest Previous Work

- 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.

Cycling Reliability Testing: Gap-Filler TIM

Examples: Examine long-term thermal and mechanical performance of TIMs.

- Mechanical compression/relaxation cycling of gap-fillers:

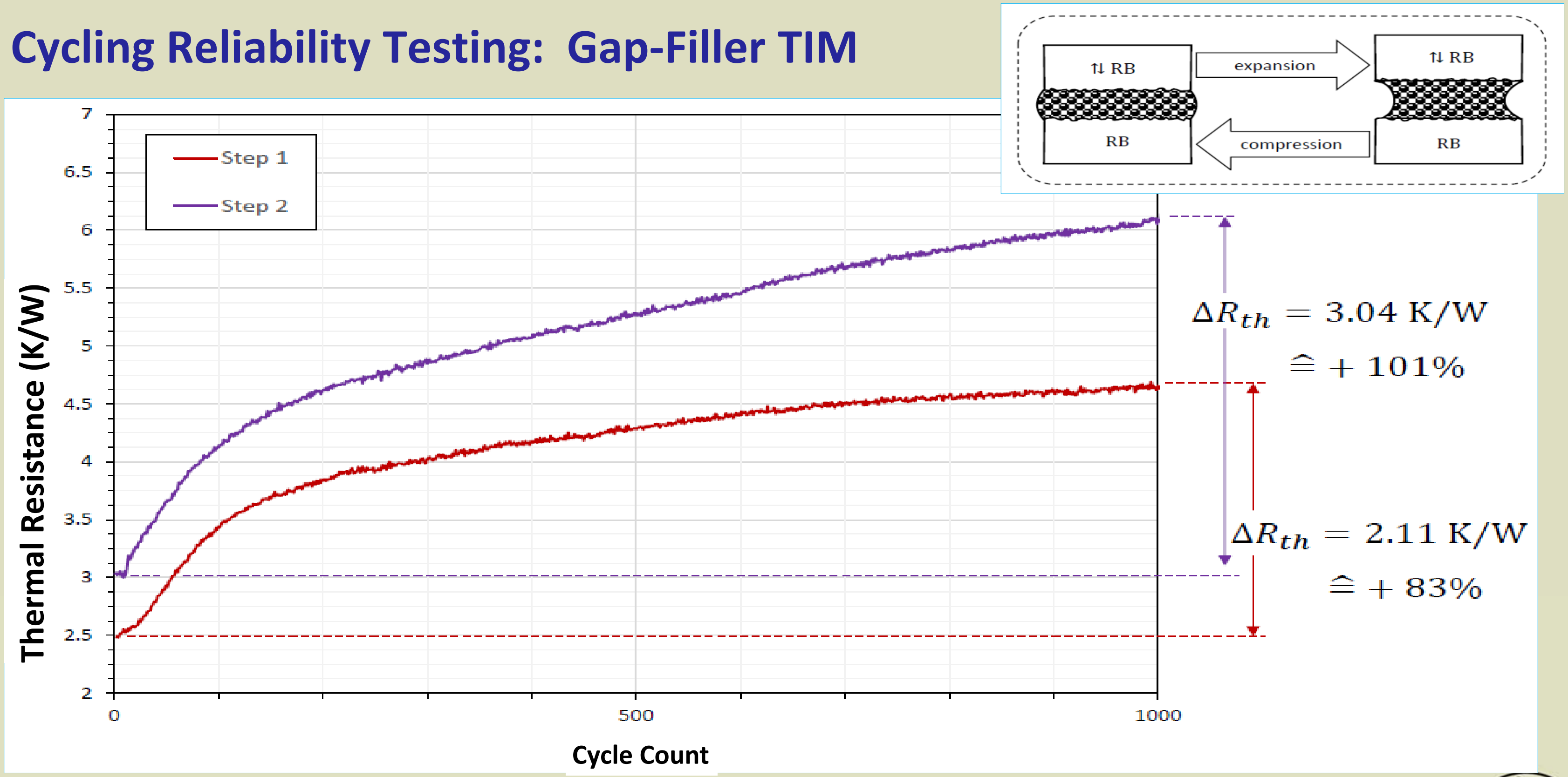


Data analysis:

- Evaluating for *time zero thermal resistance* values is *not adequate;*
- *Increasing thermal resistance over time* and cycling indicates a potential failure mechanism and increasing junction temperature.

Source: Berliner Nanotest und Design GmbH, 2018.

Cycling Reliability Testing: Gap-Filler TIM

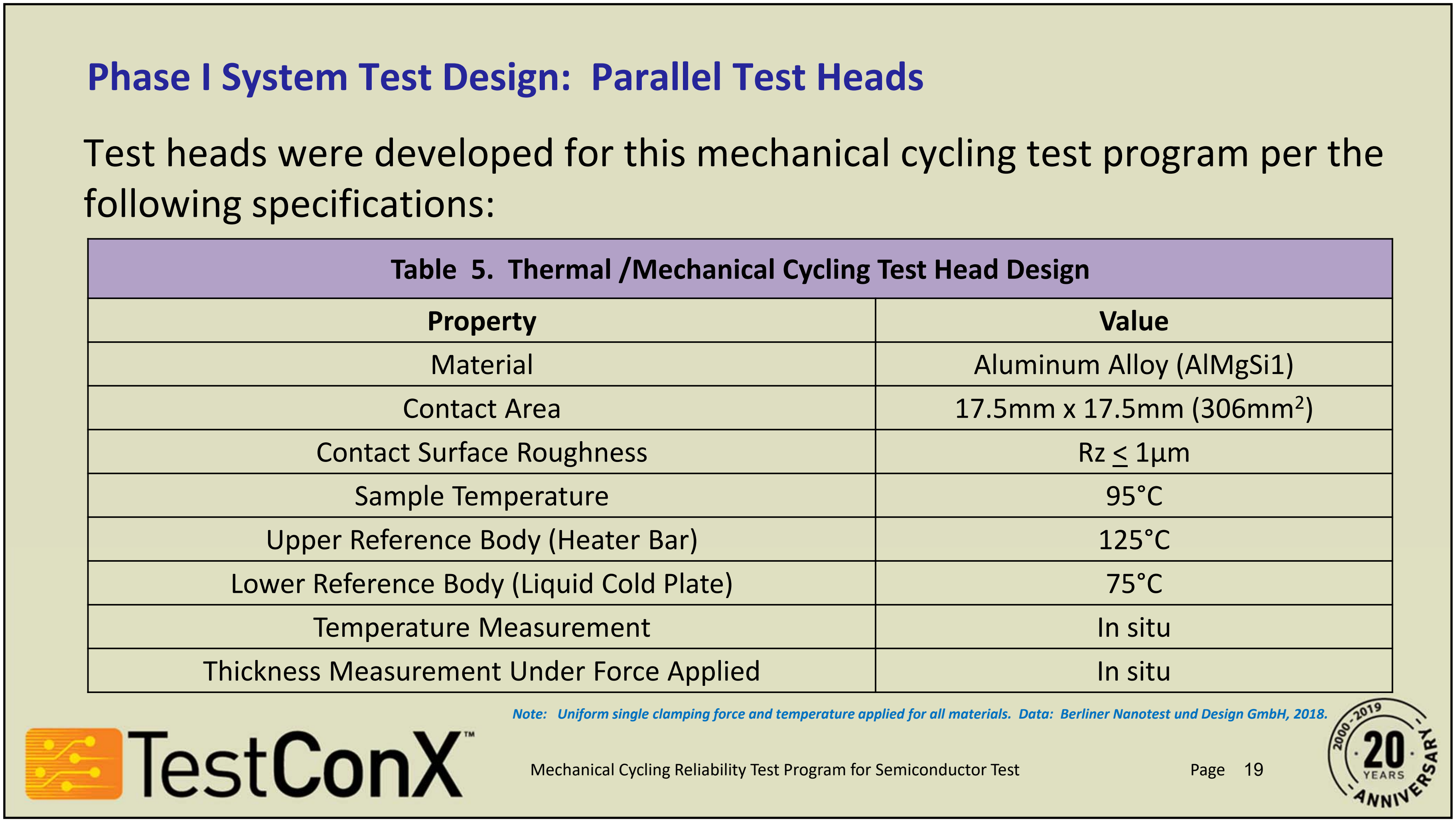


Source: Berliner Nanotest und Design GmbH.

Phase I System Test Design: Parallel Test Heads

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.



Phase I System Test Design: Parallel Test Heads

Test heads were developed for this mechanical cycling test program per the following specifications:

Table 5. 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 ≤ 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

Note: Uniform single clamping force and temperature applied for all materials. Data: Berliner Nanotest und Design GmbH, 2018.

Phase I System Test Design: Test Sample Materials

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

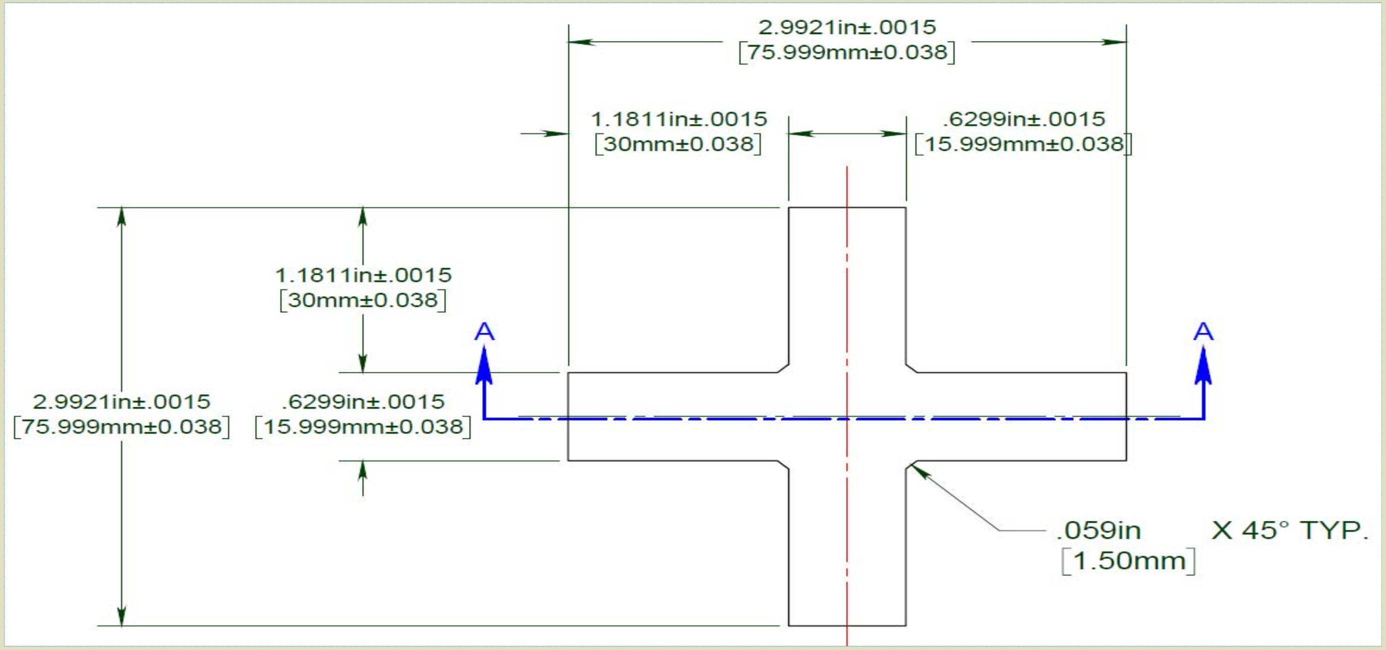
Table 6. Thermal Interface Materials Tested

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.

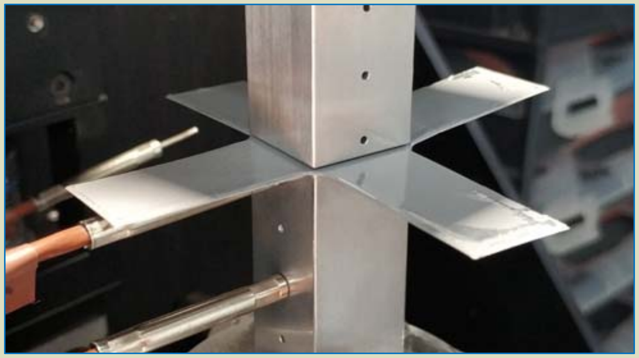
Phase I System Test Design: Test Sample Format

“Red Cross” test material designed for head attachment:



Phase I System Test Design: Test Sample Format

Test material attachment to test head:



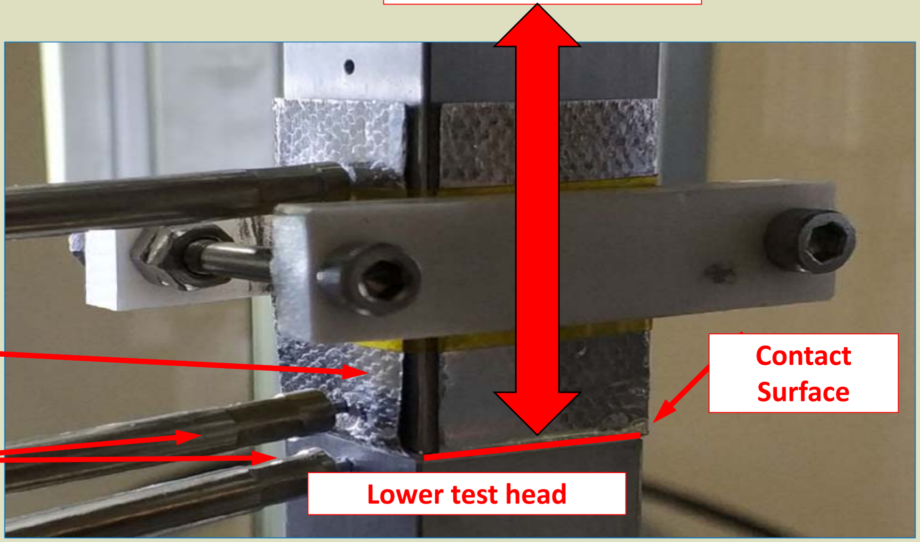
Preparing to attach Al-clad TIM to upper test head for Phase I.

Inserting RTDs prior to Phase I start.

Phase I System Test Design: Parallel Test Heads

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

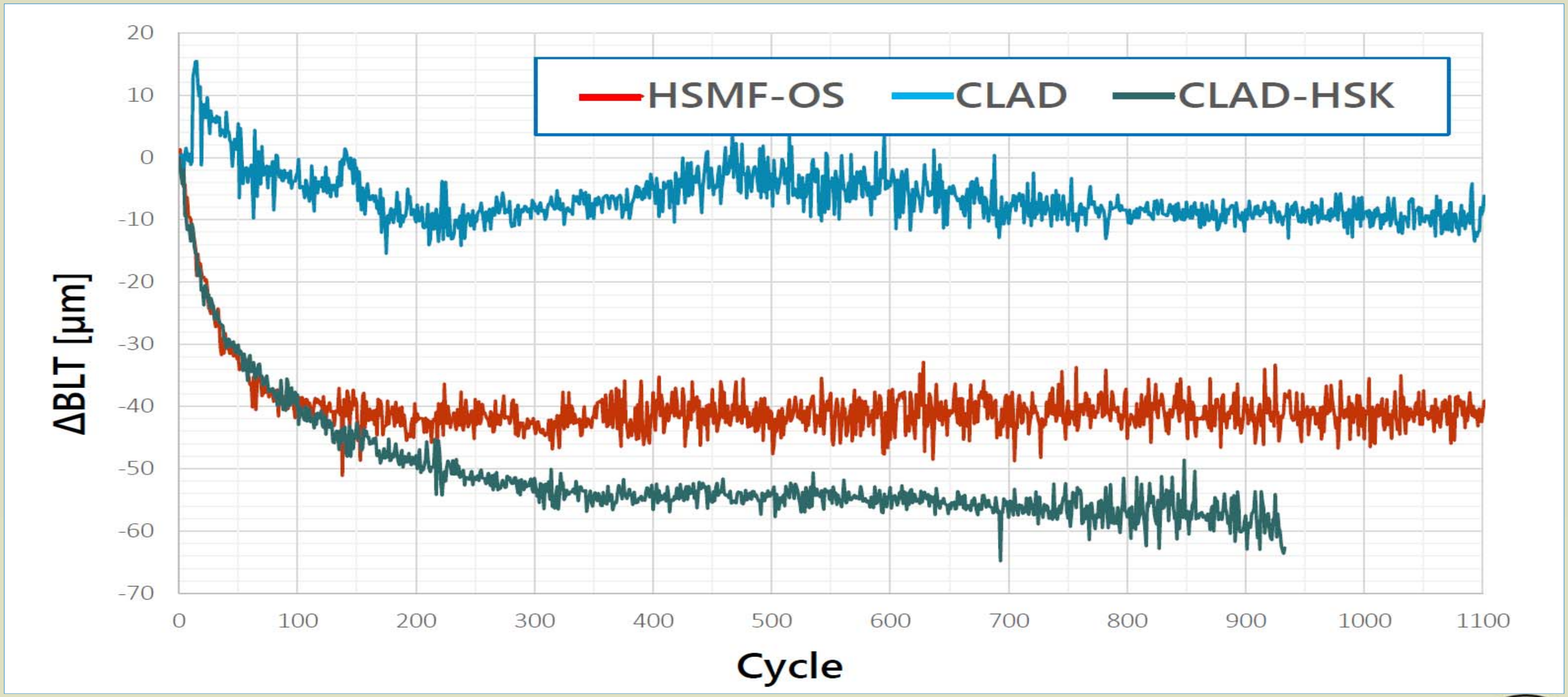


Upper test head with Clad HSK patterned indium foil TIM applied

RTDs inserted into test heads (3 places shown)

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

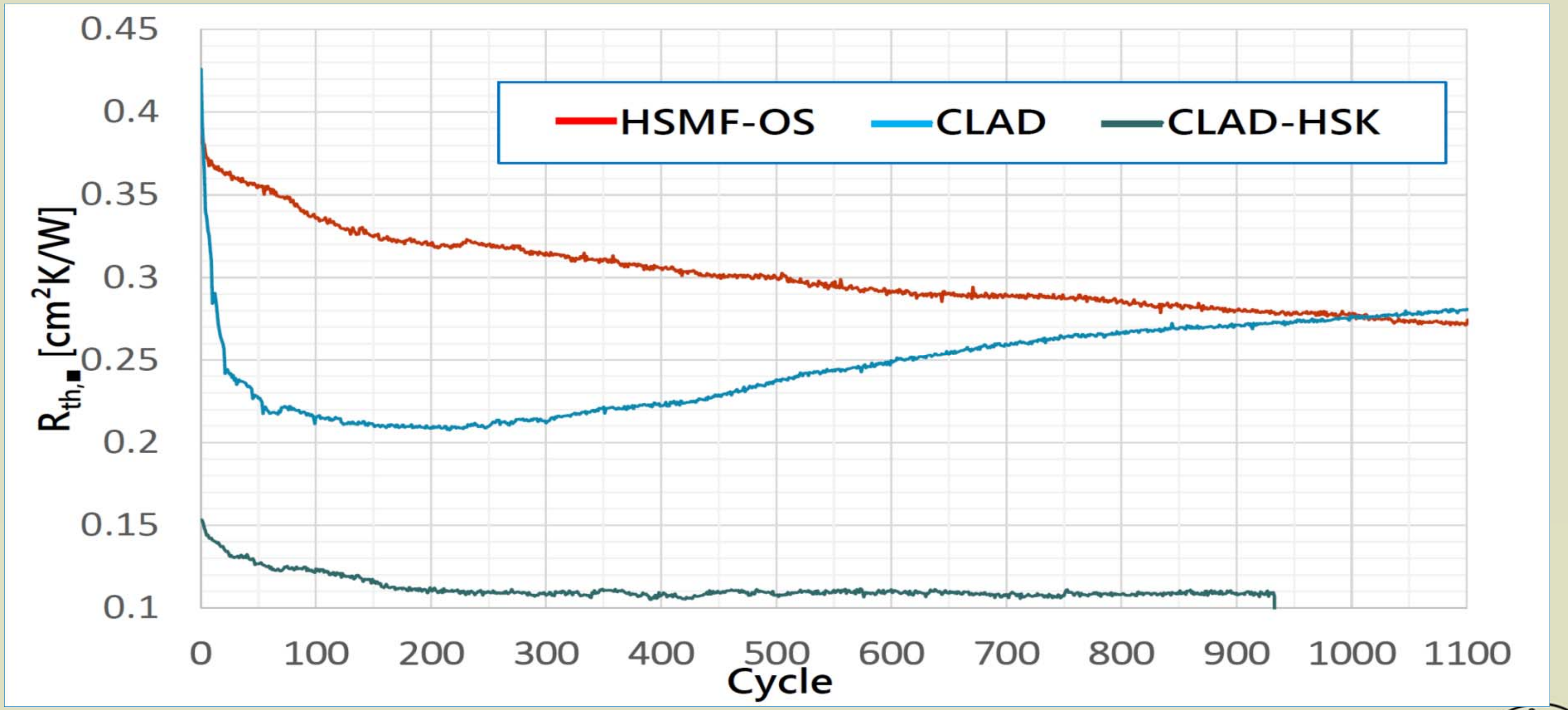
Test Data, Phase I: Thermal Resistance vs. Thickness Change



Source: Berliner Nanotest und Design GmbH.

Note: Power supply failure at 940 cycles, CLAD-HSK material; test was subsequently completed successfully to >1,000 cycles.

Test Data, Phase I: Thermal Resistance vs. Contact Cycling



Source: Berliner Nanotest und Design GmbH.

Note: Power supply failure at 940 cycles, CLAD-HSK material; test was subsequently completed successfully to >1000 cycles.

Test Data, Phase I: Analysis

Phase I testing is intended to establish a baseline set of date to demonstrate:

- Mechanical cycling results with parallel test head surfaces, the most common application characteristic for semiconductor test;
- Thermal resistance during cycling: stable test values across full regime *(Note that this is a control mechanism only)*;
- Thickness measurement during cycling: stable test values, full regime;
- Stable thermal resistance and thickness values fitting a typical test curve are important indicators of:
  - Properly performing, stable test platform and procedure;
  - Thermal and mechanical performance per expectations for values and shape of curve.

Test Data, Phase I: Analysis

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

- HSMF-OS: 0.102mm (0.004”)-thick aluminum foil, coated one side only with non-silicone thermal compound. Applied with Al surface facing DUT.
- 99.99% flat indium foil [0.30mm (0.012”) thickness, including clad (one side only) with 0.1µm (0.0005”) aluminum]. Applied to test head with aluminum surface facing DUT.
- Indium Corporation Heat-Spring® HSK patterned 99.99% indium foil, clad one side only with 0.1µm (0.0005”) aluminum . Total thickness: 0.559mm (0.0220”). Applied to test head with bare aluminum surface facing DUT.

Test Data, Phase I: Observations

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 that each material type has successfully passed test for long-term cycling without tearing or marking.

Phase II System Test Design: Strike Angle

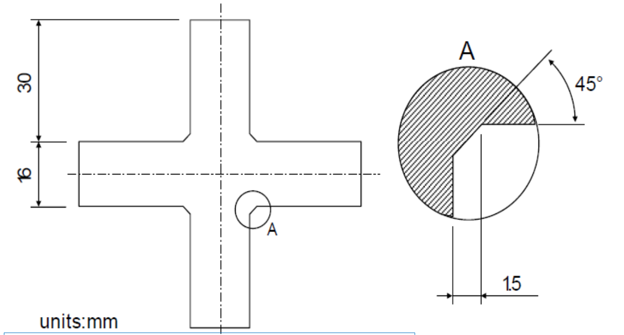
Phase II introduces an angled test head to create what is termed the “strike angle” in semiconductor test and burn-in:

- Test head w/TIM applied strikes at 7.5° angle, creating a knife edge contact for the TIM to the second test head;
- 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*.

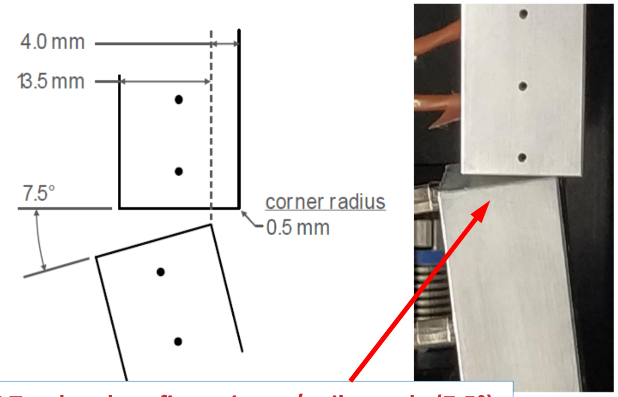
Phase II System Test Design: Strike Angle

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

- Test assembly shown with TIM under test applied as “Swiss Cross”;
- Test head (lower) strikes test head (upper) at 7.5° angle, to mimic actual conditions;
- TIM applied to upper test head;
- Nanotest TIMA5 test stand is servo-driven, enabling use of this test stand to test with automated mechanical cycling for repeated, precise contact control.



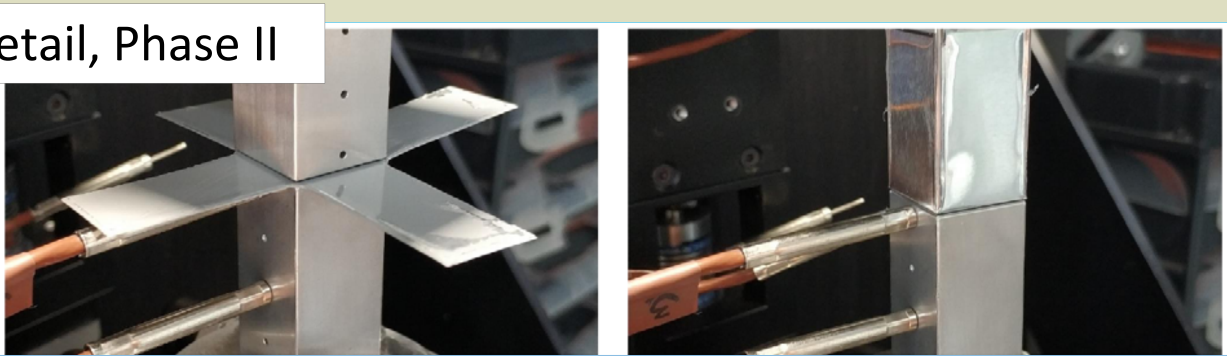
“Swiss cross” die-cut TIM2 (above)



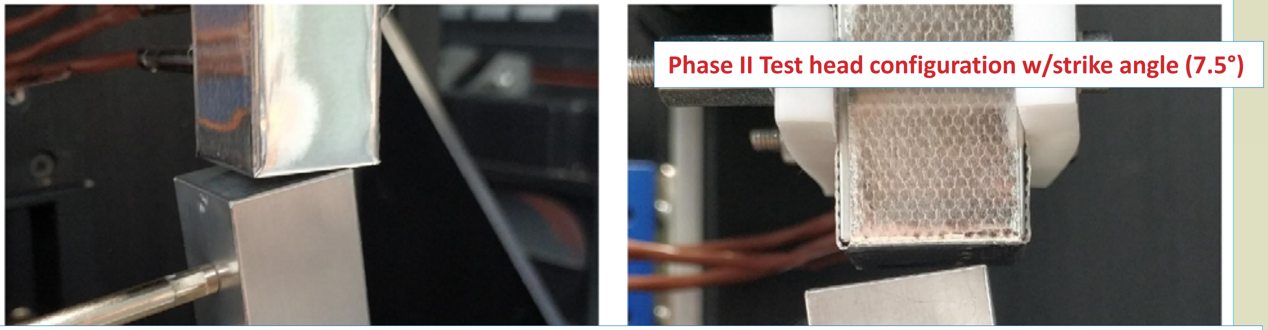
Phase II Test head configuration w/strike angle (7.5°)

Phase II System Test Design: Strike Angle

Test head detail, Phase II



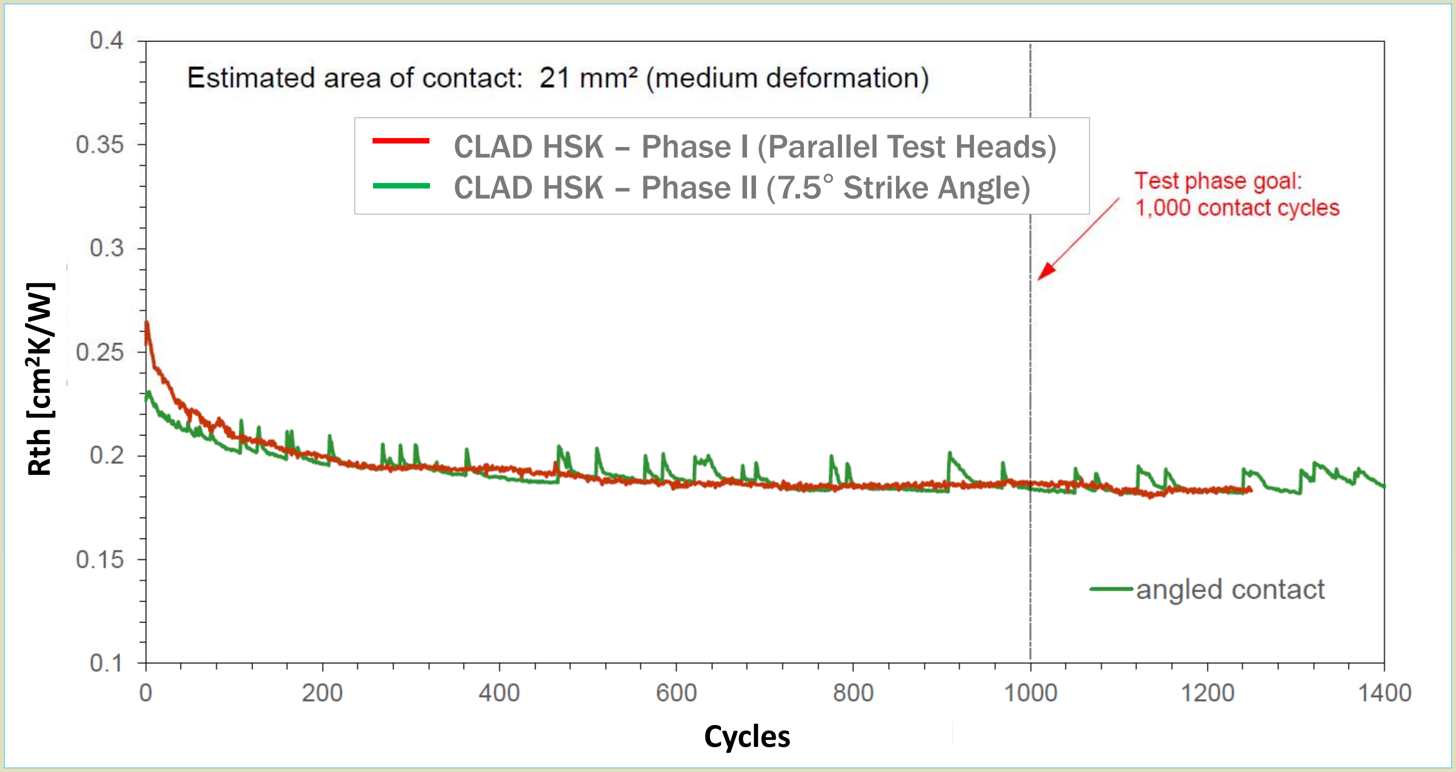
(1) "Swiss cross" die-cut TIM2 (above) prior to application to test heads; (2) Final configuration, Al-Clad In TIM2 sample.



Phase II Test head configuration w/strike angle (7.5°)

(3) Strike angle, lower test head – TIM2 applied to upper head (above); (4) Final configuration, In "Heat-Spring" TIM2.

Phase II System Test Design: Strike Angle



Source: Berliner Nanotest und Design GmbH. Initial data report, October 10, 2018.

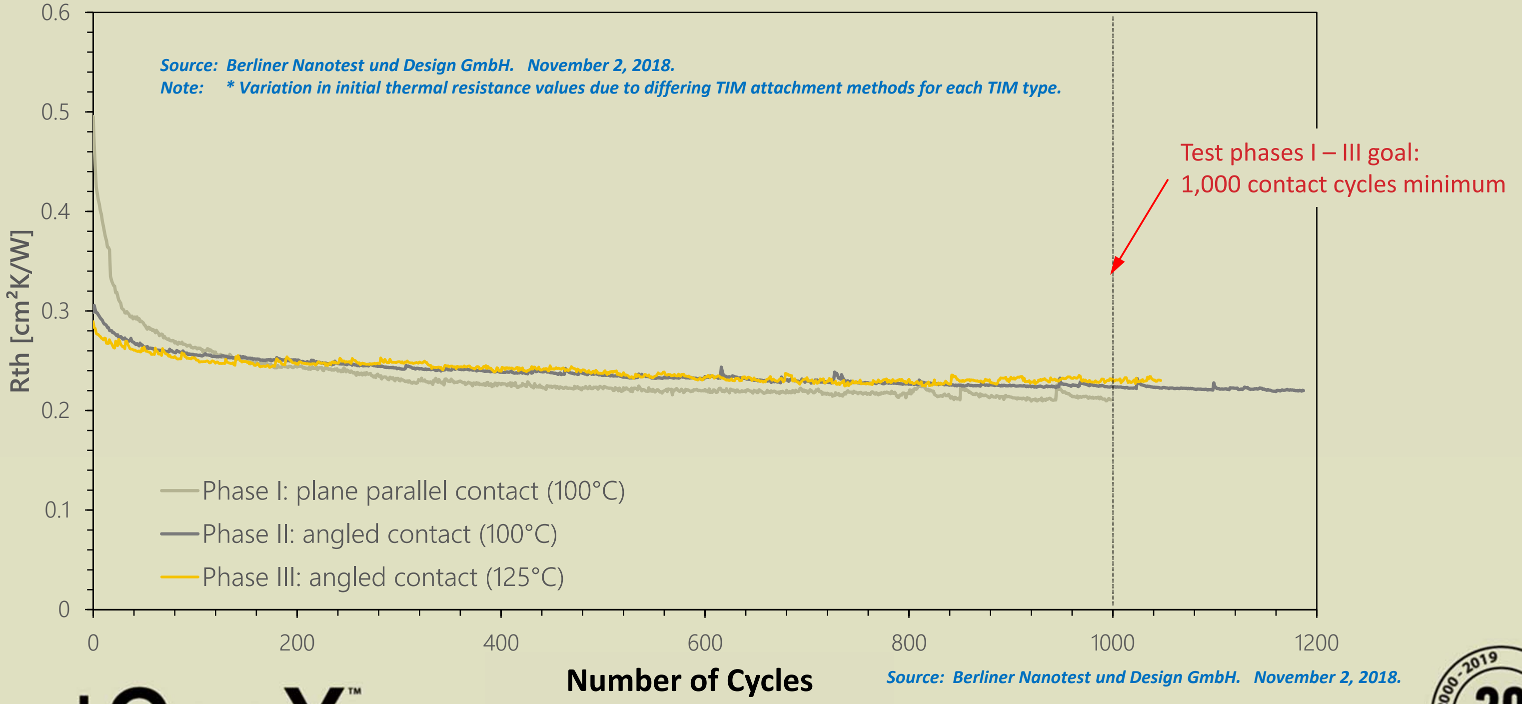
Phase III System Test Design: Strike Angle + High Temperature

This phase consists of the introduced strike angle and identical test routine at higher temperature:

- 125C test temperature applied at the test head;
- Characteristic of semiconductor burn-in temperatures;
- Characteristic of test system designs incorporating a gimbaled head, for contact with multiple package sizes and types. Examples:
  - Lidded processor or ASIC;
  - Bare die packages with different die sizes, lot to lot.
- *Please keep in mind that this test system is intended to be a mechanical durability test; as such, thermal resistance values generated are solely a control mechanism.*

Phase III System Test Design: Strike Angle + High Temperature

Initial test data report, Phase III*:

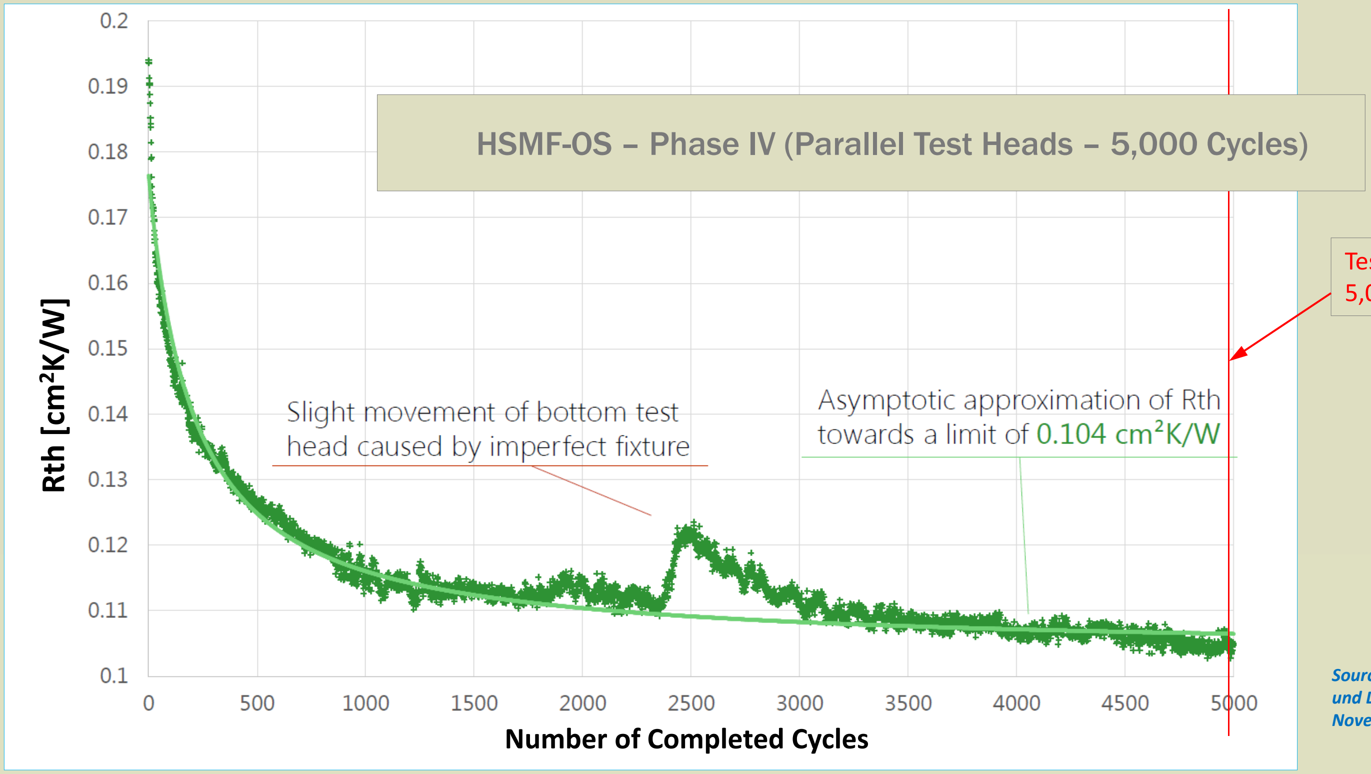


Source: Berliner Nanotest und Design GmbH. November 2, 2018.
*Note: * Variation in initial thermal resistance values due to differing TIM attachment methods for each TIM type.*

Test phases I – III goal:
1,000 contact cycles minimum

Source: Berliner Nanotest und Design GmbH. November 2, 2018.

Phase IV System Test Design: Parallel Heads, 5,000 Cycles



HSMF-OS – Phase IV (Parallel Test Heads – 5,000 Cycles)

Slight movement of bottom test head caused by imperfect fixture

Asymptotic approximation of Rth towards a limit of 0.104 cm²K/W

Test phase goal:
5,000 contact cycles

Source: Berliner Nanotest und Design GmbH; November 2, 2018.

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 TIMs developed for specialized semiconductor test applications requiring performance and reliability in challenging conditions.

- A mechanical cycling reliability test program has been designed to reproduce semiconductor test conditions to determine robustness of specialized TIMs:
  - Phases I - IV of this test program have been completed.
  - All materials tested passed all cycling test goals successfully. Data analysis is reported.

References

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2. C. Lasance, C.T. Murray, D.L. Saums, M. Renz, "Challenges in Thermal Interface Material Testing," Proceedings, Semitherm Symposium 22, Dallas TX USA, March 13-15, 2006.

3. R.N. Jarrett et al., "Comparison of Test Methods for High Performance Thermal Interface Materials," Proceedings, Semitherm Symposium 23, San Jose CA USA, March 2007.

4. J.A. Sanchez, Intel Corporation, "Challenges of Thermal Interface Materials in Test of IC Packages," IMAPS Advanced Technology Workshop on Thermal Management 2013, Los Gatos CA USA, November 5-7, 2013.

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6. Indium Corporation Heat-Spring® and HSMF-OS product data sheets (www.indium.com).