Enhancing AI and High-Speed Computing Tests with High-Performance TIMs

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Contents

- Introduction
- Issues faced in the Industry
- Points to Ponder
- Types of TIMs for Validation
- TIM Specs
- Test Methods, Results & Findings
- Q & A

Introduction

- Thermal management has become a highly critical challenge for high-speed computing chips as power density increases. Advanced packaging technologies, such as chiplet & heterogeneous architectures, are becoming popular in driving higher performance, compactness and cost improvements.
- Localized hotspots, higher power density (W/cm^2) and heat distribution for chiplets create more challenges in managing heat transfer, eg AI chip. In future AI chips, High Bandwidth Memories (HBMs) can generate as much power (W/m^2) as the processor chip.
- This advancement comes with new challenges of package warpage, uneven heights between chips & higher heat generated due to higher processing speed & density. Testing criteria in the production of IC devices becomes more stringent which includes the review of test program & parameters, test temperature & test time.
- While Thermal Interface Material (TIM) is just a small component in the whole testing or package stack-up, it is critical to have high transfer efficiency and surface compliance to handle warpage.
- This paper provides an insight of different high performance TIMs used to handle the testing of the high power / high speed IC devices and to do a comparison between the different TIMs.

Issues Faced in the Industry

With the higher power expectation for device testing, it is important to ensure that the test temperature is maintained consistently throughout the whole test process. Some common issues faced as follows:

- **Temperature Overshooting** - This issue happens when there is a sharp increase in power utilisation during the testing & the ATC is not be able to react promptly to do the compensation. Most of the heat issues are not uniformly distributed, but can be localized hotspots.

- **Device Warpage** - As warpage in IC packages are getting more serious, there is a need to ensure that sufficient force is applied onto the package to minimize the warpage. Even with sufficient force, there will still have some warpages towards the 4 edges of the package.

- **Chips' Height Variation** – Advanced packaging will have multiple dies within a package, and each manufacturers have different specs for the height variance and tolerance range for each of the chips.

Points to Ponder

- **Thermal Testing** – Manufacturers of thermal testing equipment are adopting ASTM-D5470 standard for the measurement. However, it has been seen that the thermal conductivity or impedance has a wide deviation when tested with different brand of testers. There may also be data variance even when testers of the same models are used.

- **Know your Test Conditions** – Test parameters are different for different brand of testers/handlers & devices. Some of which includes pressure, test temperature, test duration, device size, warpage specs, test program, etc. All these may have an impact on the selection of the TIMs.

- **Thermal Head Design** - Apart from getting the better TIMs, reducing the contact resistance of each layer in the stack-up of the thermal head. Improving the efficiency of the liquid cooling head & automatic thermal control (ATC) design is also important in the improvement. One example is to consider the use of vapor chamber (VC) for the liquid cooler.

Type of Tests for Validation

The objective of this paper is to run different test validation for different TIMs to determine the followings:

- Thermal Resistance (TR) vs Pressure
- Compressibility vs Pressure
- Stain Test
- Power Ramp Up
- CPU Benchmark

**Note :*
- *To minimize the error margin of the test results, all the testing is carried out using the same test equipment & environment.*
- *We are only using some of the test methods which might be important considerations when used in final test, SLT or burn-in production environment.*
- *As the test parameters in the production process and equipment will be slightly different, it is recommended for the users to design their own DOEs and run the validation for verification.*

TIMs used for Validation

As we are focusing on high performance TIMs, the test targets used for the validation includes :

- Indium
- Graphene Thermal Pad
- Carbon Fiber Thermal Pad
- Thermal Grease

Material Specification

s/n	Parameters	Unit	Indium	Indium with AluClad	Graphene Thermal Pad	Carbon Fiber Thermal Pad	Thermal Grease
1	**Part Number**	-	HSD	HSK	GT90Pro	WTP50	Arctic MX-4
2	**Composition**	-	90In / 10Ag	99.99In with 0.0005"Alu Foil	Graphene	Carbon Fiber	Grease
3	**Thickness**	mm	0.2	0.2	0.2	0.2	Thin Bondline
4	**Thermal Conductivity**	W/m-K	75 ~ 86	75 ~ 86	90	50	< 10
5	**Operating Temperature**	°C	-50 ~ 130	-50 ~ 130	-40 ~ 200	-40 ~ 200	-50 ~ 150

Thermal Resistance vs Pressure (Test Method)

1. Heat Flux Calculation

Hot Side Heat Flow $Q_h = K_m A \dfrac{T_{h3} - T_{h1}}{X_1 + X_2}$

Cold Side Heat Flow $Q_c = K_m A \dfrac{T_{c1} - T_{c3}}{X_3 + X_4}$

Average Heat Flow $Q = \dfrac{Q_c + Q_h}{2}$

2. Interface Temperature (T_{hs} & T_{cs})

Hot Side Surface Temp. $T_h = T_{h1} - \dfrac{X_3}{X_1 + X_2}(T_{h3} - T_{h1})$

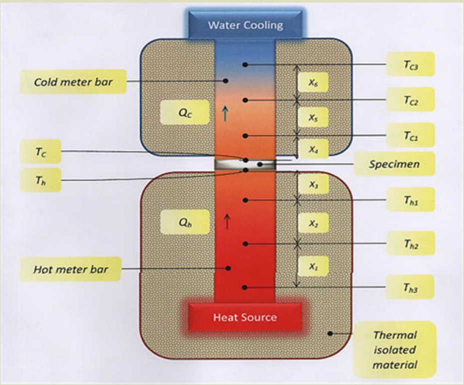
Cold Side Surface Temp. $T_c = T_{c1} - \dfrac{X_3}{X_1 + X_2}(T_{c1} - T_{c3})$

3. Thermal Resistance (°C/W)

Thermal Resistance $R = \dfrac{T_{hs} - T_{hc}}{Q}$

Thermal Impedance $Imp = R \ X \ A = \dfrac{T_h - T_c}{Q_{ave}} \ X \ A$

Test Diagram



Test Procedure

- The testing for all the samples are carried on the same thermal test (LongWin), which is in compliance to the ASTM-D5470 standard.
- To ensure result consistency. the test will run for at least 20 mins before the result is collected for each pressure step.
- All the data are collected in steady state condition.

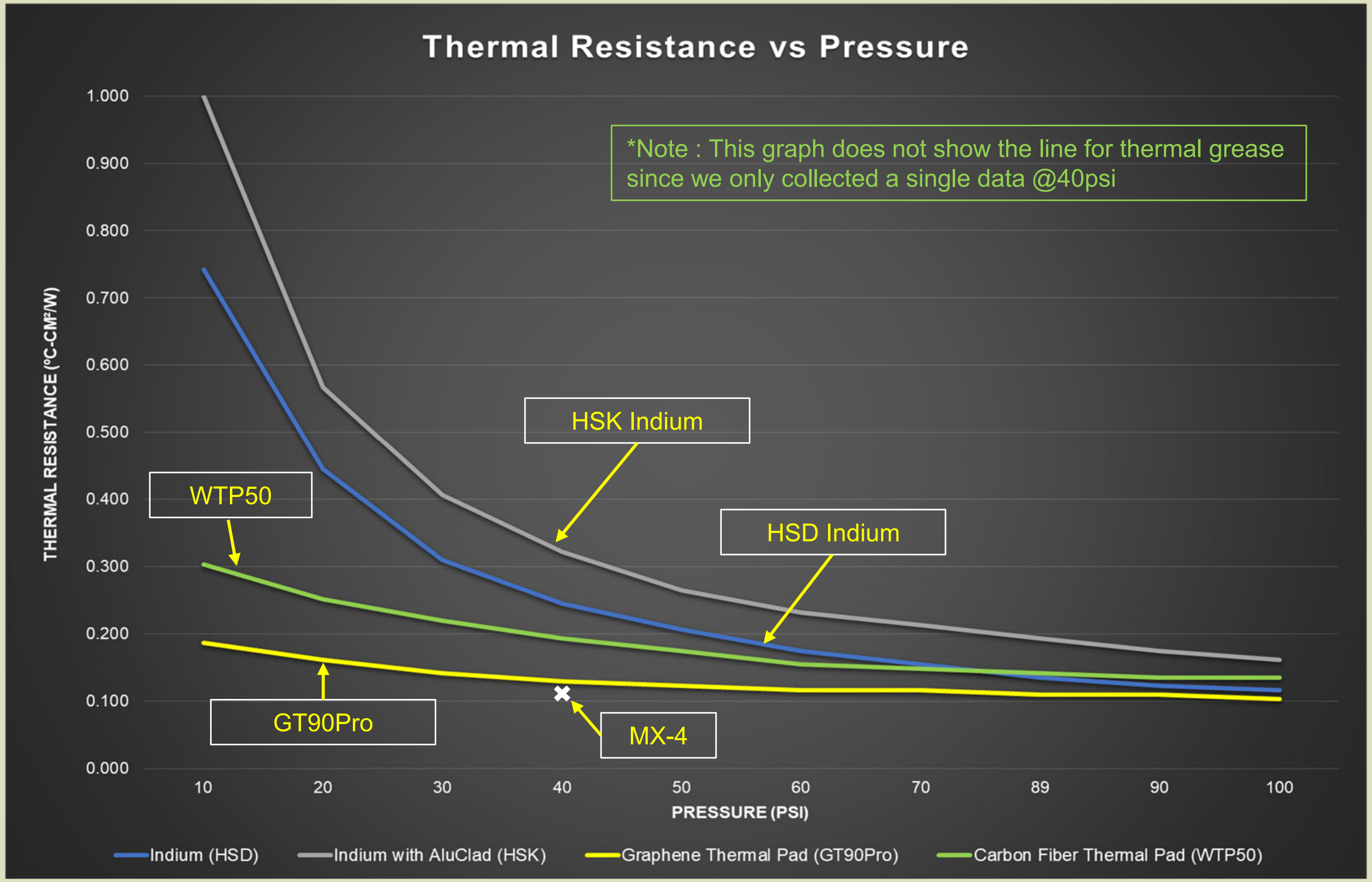
Thermal Resistance vs Pressure (Results)

- Tester Type : LongWin (LW-9389)
- Test Method : ASTM-D5470
- Test Temperature : 80°C
- TIM Size : 25.4mm x 25.4mm
- TIM Thickness : 0.2mm

Description	Pressure (psi)	Unit (TR)	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (MX-4)
Thermal Conductivity (Based on Mfr's TDS)	-	W/m-K	75 ~ 86	75 ~ 86	90	50	< 10
TR @20psi	20	°C-cm²/W	0.445	0.568	0.161	0.252	NA
TR @40psi	40		0.245	0.323	0.131	0.194	0.129
TR @60psi	60		0.174	0.232	0.116	0.155	NA
TR @80psi	80		0.135	0.194	0.110	0.142	
TR @100psi	100		0.116	0.161	0.103	0.135	

** Unit of measurement is in °C-cm²/W*

Thermal Resistance vs Pressure (Results)



Thermal Resistance vs Pressure (Findings)

- For Arctic MX-4, the bond-line thickness of the thermal grease is already small (ie 20um to 50um) at low pressure. At 40psi, it already exhibit the lowest thermal resistance. It is very messy during installation & difficult to assess the correct amount to apply to achieve best results. In this test, we apply extra amount to ensure a complete coverage of the surface.
- GT90Pro performs very well and shows low thermal resistance, and stabilized with minimal drop above 50psi.
- HSD Indium shows lower thermal resistance only when the pressure increases beyond 60psi. The thermal resistance is higher below 30psi. Increased pressure improved the surface compliance between the surfaces as the protrusion in the Indium fills the unevenness.
- WTP50 shows low thermal resistance and shows consistency through the whole pressure test.
- HSK Indium has the highest thermal resistance among all the TIM material. One likely reason is be the use of aluminium foil in the stack-up which will lead to some losses in the heat transfer. The thinner the Alu foil, the better the performance.
- While the each manufacturers shows their thermal conductivity on the data sheet, however, the actual test outcome for the thermal resistance does not reflect the same outcome proportionally.

Compressibility vs Pressure (Results)

- Tester Type : LongWin (LW-9389)
- Test Method : ASTM-D5470
- TIM Size : 25.4mm x 25.4mm
- TIM Thickness : 0.2mm

Pressure (psi)	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (MX-4)
10	10.0%	19.0%	28.6%	14.9%	The MX-4 thermal grease will have very small bond-line thickness at start of compression.
20	20.0%	29.4%	30.1%	21.6%	
30	21.0%	33.7%	32.1%	28.7%	
40	26.6%	35.1%	33.2%	28.8%	
50	30.0%	36.9%	34.2%	31.5%	
60	36.3%	38.4%	34.7%	33.2%	
70	37.7%	39.8%	36.7%	35.4%	
80	39.7%	40.9%	40.3%	38.1%	
90	41.0%	41.6%	42.9%	39.8%	
100	43.8%	42.3%	46.6%	45.3%	

Compressibility vs Pressure (Findings)

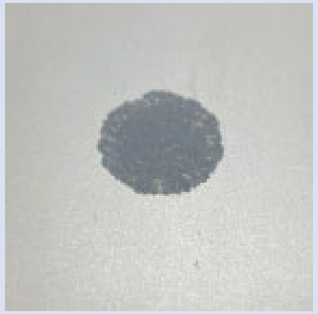
- WTP50 & GT90Pro has exhibited good compressibility at different pressures. This can possibly be useful to compensate for height variation or warpage of the IC device. Both material has reasonable bounce-back effect.
- For HSD & HSK Indium, before the start of the thermal test, the thickness of the material is 30% higher than the actual thickness HSD Indium. The protrusion on the Indium will be flattened upon increased pressure, and will form the good surface compliance. At 60psi onwards, the compressibility reduces significantly. Once the Indium TIM crosses a certain pressure threshold, there will be minimal compressibility. There is minimal bounce-back effect for Indium.
- There is no compression data for Arctic MX-4 since it is a paste.

Stain Test (Method)

Test Parameters

- Test Temperature : 110°C
- Pressure : 70psi
- TIM Size : 25.4mm x 25.4mm
- TIM Thickness : 0.2mm (except for hybrid type)
- # of Cycles : 1K
- Procedure : The TIM is cycled repeatedly on a nickel-plated metal plate, & a new plate is put to be cycled once to check for stain.

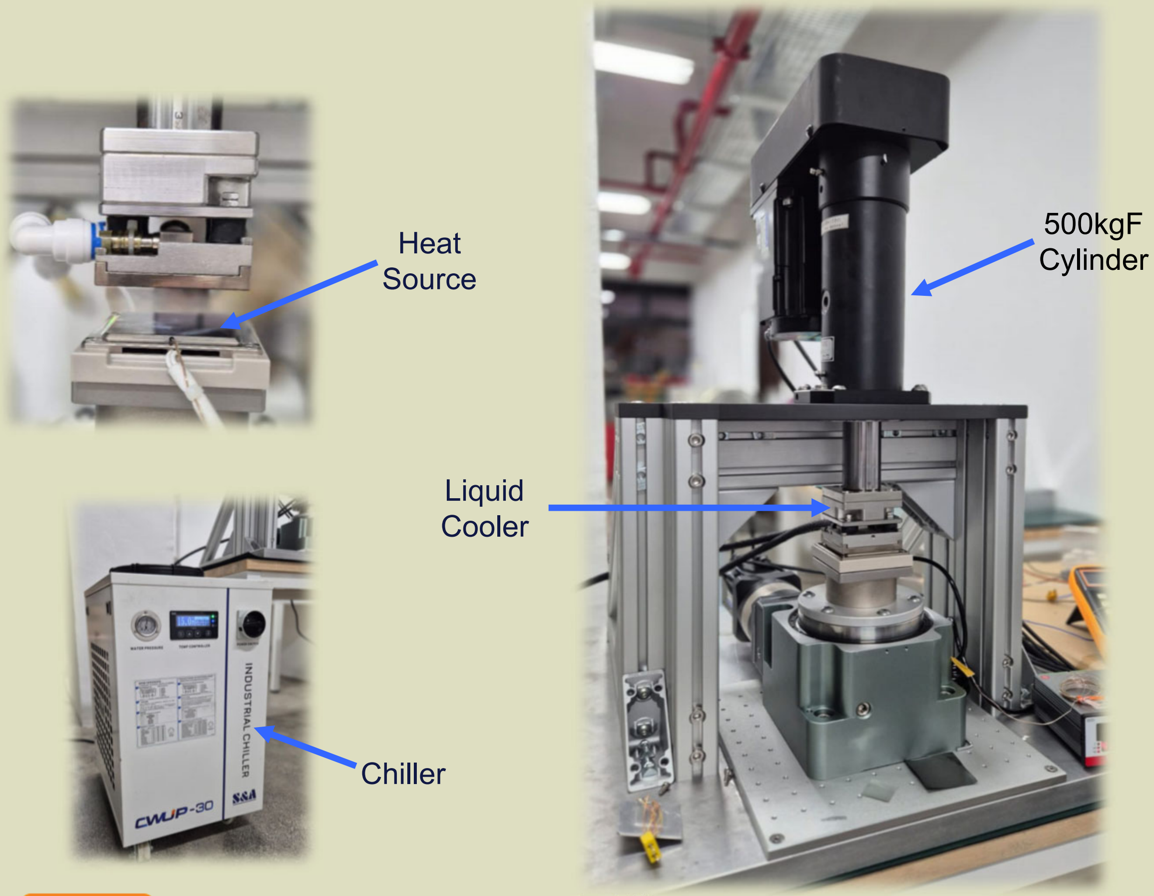
Stain Test (Results)

Description	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (MX-4)
Stain Result	Yes	No	Yes	Yes (Light Stain)	Yes (Messy)
Image					

Stain Test (Findings)

- Thermal grease (MX-4) is in liquid paste form and is messy on the device. It will have serious stain or potential flow-over issue. It is not suitable for FT/SLT/BI production testing.
- HSD Indium shows clear stain.
- HSK Indium does not show any stain.
- GT90Pro shows clear stain.
- WTP50 has light stain on the surface.

Power Ramp-Up (Method)



Set-Up Parameters

a. Chiller
- Temperature : 15°C
- Flowrate : 6L/min

b. Cylinder
- Pressure : 70psi

c. Heat Source
- Power : 400W

d. TIM Sample
- Size : 25.4 X 25.4 (mm)

e. Test Method
- Temperature monitoring is at the heat source. When the cylinder is down, the power will switch on 100% starting from 30°C, and the data logger will track every sec for 120sec.

f. Comments
- All parameters are fixed for the whole experiment, and the only variable in this data collection will be the change of the TIM material. If a TIM performs well, the measured temperature on the heat source must be as low as possible.

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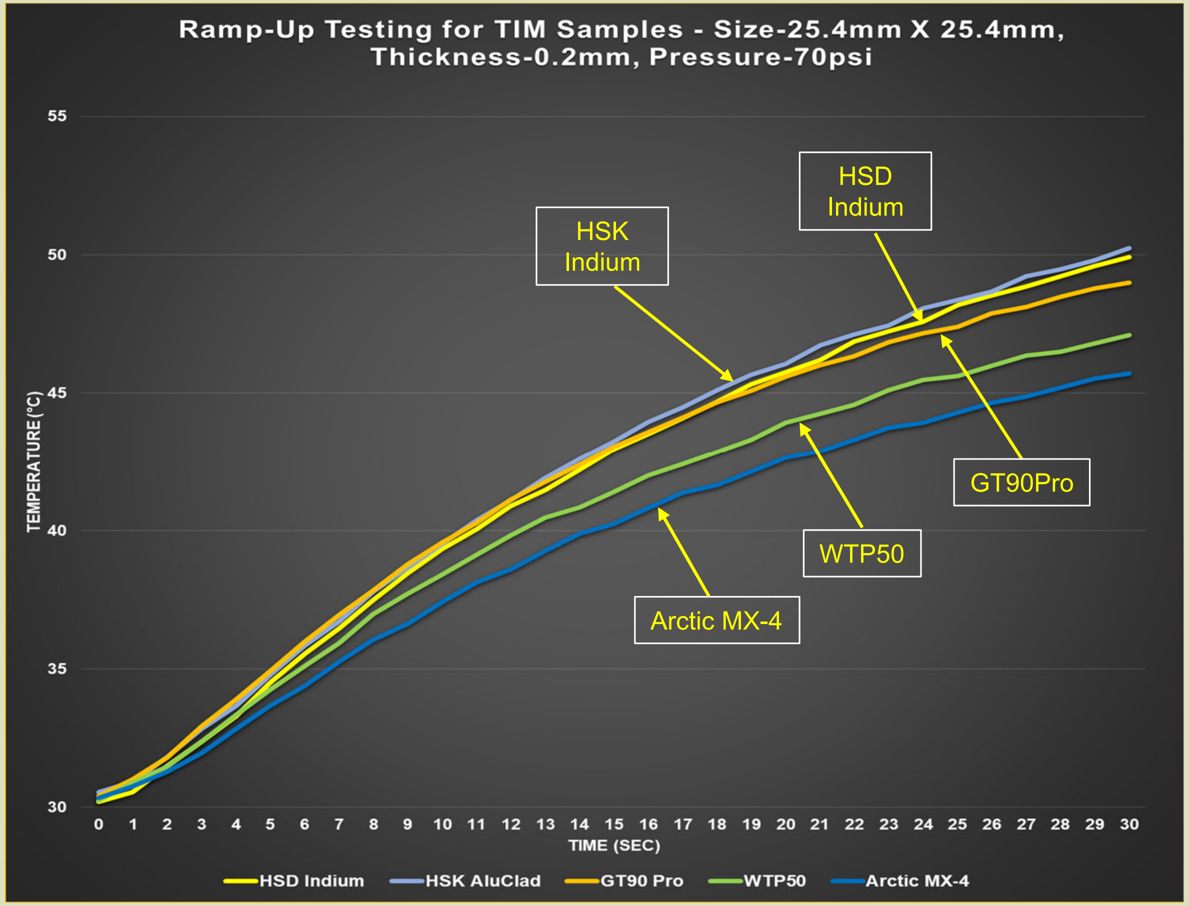
Power Ramp-Up (Results)

4	5	3	2	1
HSD Indium	HSK AluClad	GT90Pro	WTP50	Arctic MX-4
30.2	30.6	30.4	30.2	30.3
30.6	30.9	31.0	30.9	30.8
31.5	31.8	31.8	31.5	31.3
32.4	32.8	32.9	32.4	32.0
33.3	33.7	33.9	33.3	32.9
34.5	34.8	34.9	34.3	33.7
35.5	35.8	36.0	35.1	34.4
36.5	36.7	37.0	35.9	35.3
37.5	37.8	37.8	37.0	36.1
38.5	38.7	38.8	37.7	36.6
39.3	39.5	39.6	38.4	37.4
40.1	40.4	40.3	39.1	38.1
40.9	41.1	41.1	39.8	38.6
41.5	41.9	41.8	40.5	39.3
42.2	42.6	42.4	40.8	39.9
42.9	43.2	43.0	41.4	40.3
43.5	43.9	43.6	42.0	40.8
44.1	44.5	44.1	42.4	41.4
44.7	45.1	44.7	42.9	41.7
45.3	45.7	45.1	43.3	42.2
45.8	46.1	45.6	43.9	42.6
46.2	46.7	46.0	44.3	42.9
46.9	47.1	46.3	44.6	43.3
47.2	47.4	46.8	45.1	43.7
47.6	48.1	47.2	45.5	43.9
48.2	48.4	47.4	45.6	44.3
48.5	48.7	47.9	46.0	44.6
48.8	49.2	48.1	46.3	44.9
49.2	49.5	48.5	46.5	45.2
49.6	49.8	48.8	46.8	45.5
49.9	50.2	49.0	47.1	45.7



Power Ramp-Up (Results)

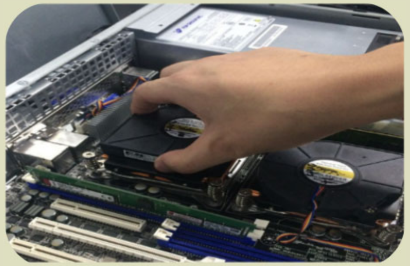
Description	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (Arctic MX-4)
Tcase @30sec	49.9°C	51.9°C	49.0°C	47.1°C	45.7°C
Tcase @100sec	56.8°C	59.2°C	55.2°C	54.1°C	50.9°C
Ranking (Overall)	**4**	**5**	**3**	**2**	**1**

Power Ramp-Up (Findings)

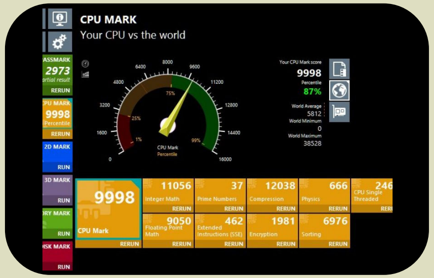
- Thermal grease, MX-4 performs the best in this ramp-up testing. While the thermal conductivity of MX-4 is < 10W/m-K, the performance is very impressive due to its ability to fill up all the unevenness between the 2 surfaces. Upon application of pressure, in comparison to the 0.2mm thick TIM material in this testing, MX-4 have small bond-line thickness, which can be 20um to 50um.
- WTP50 performs best in this test amongst the solid-type test samples.
- GT90Pro & HSD also perform well with only 2°C to 3°C variance.
- The HSK Indium with aluminium foil shows the highest temperature in this ramp-up testing. The likely reason being that the aluminium foil increases the thermal resistance of the overall TIM stack-up.

CPU Benchmark Test (Method)

Test Instrument	: AMD Ryzen 9 7900X (Raphael) (Lidded)
Thermal Design Power	: 170W
# of Cores/Threads	: 12 / 24
Sample Size	: 25mm x 25mm
Test Environment	: Test comparison at room temperature
CPU Load Test Duration	: 15 mins
CPU Load Rate	: 50% & 100% Load
Software Used	: CineBench (Benchmark) & HWInfo (Temperature Monitoring)



Test Program



Test Result

CPU Benchmark Test (Results)

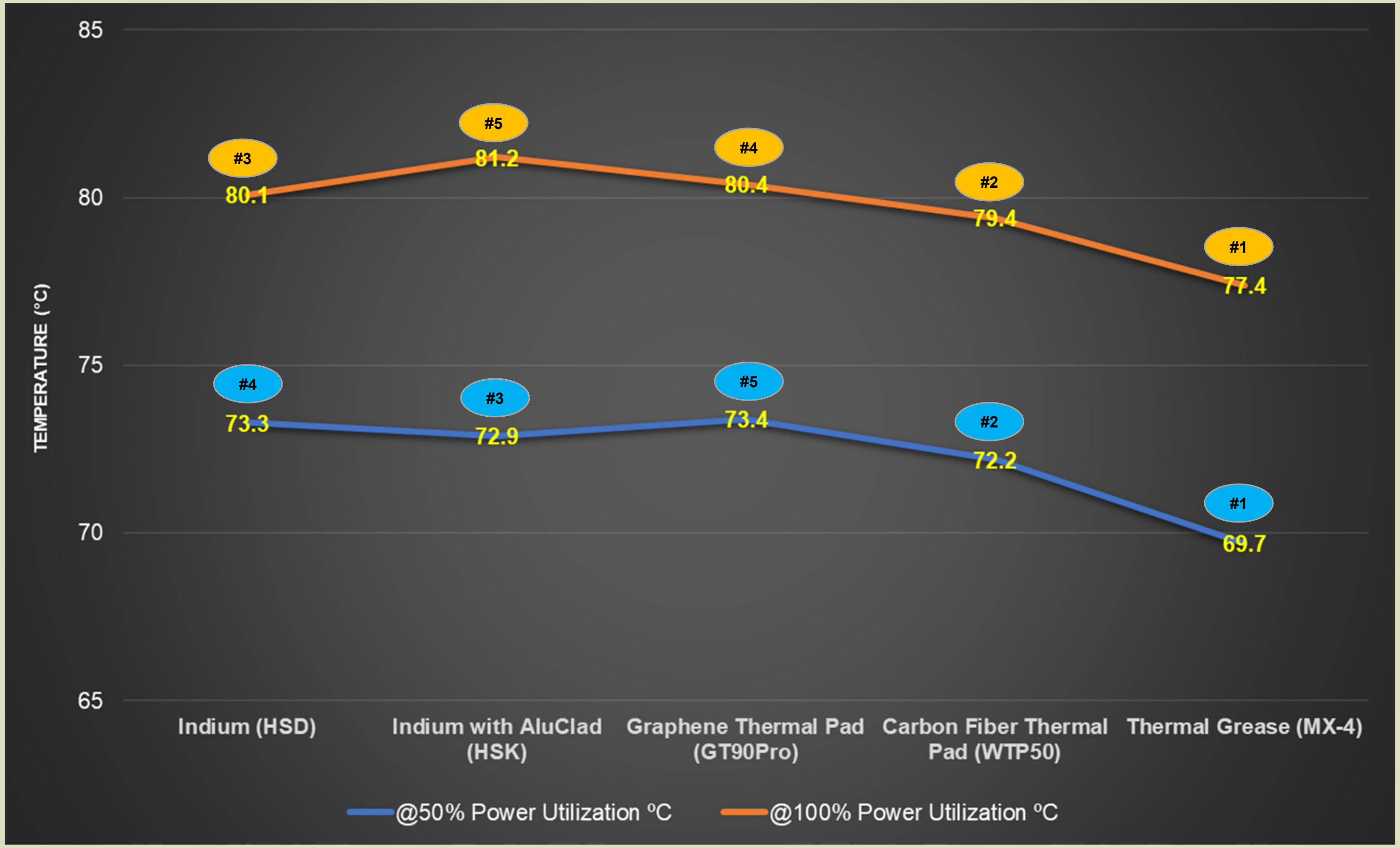
- **Consolidated Results**

Description	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (MX-4)
@50% Power Utilization	73.3°C	72.9°C	73.4°C	72.2°C	69.7°C
@100% Power Utilization	80.1°C	81.2°C	80.4°C	79.4°C	77.4°C

Things to note:

- *Indium (ie HSD & HSK sample) has to be pre-conditioned for at least 20 cycles@70psi first to ensure proper surface compliance before testing. If this is not carried out, the thermal resistance will be higher.*
- *For some TIMs, the thermal performance may be directly affected by the applied pressure.*

CPU Benchmark Test (Results)



CPU Benchmark Test (Findings)

- Thermal grease, MX-40 has shown very good thermal performance with the lowest average temperature for the T_{case}. One key challenge faced will be ensuring sufficient grease was applied consistently onto the device. If insufficient, this can drastically affect the thermal efficiency.
- WTP50 consistently shows slightly better performance in the benchmark test for the 50% and 100% power loading.
- HSD Indium, HSK Indium & GT90Pro exhibit similar data in the benchmark test.

Comparison Table

Description	Indium (HSD)	Indium with AluClad (HSK)	Graphene Thermal Pad (GT90Pro)	Carbon Fiber Thermal Pad (WTP50)	Thermal Grease (MX-4)
Thermal Resistance@40psi (Ranking)	4	5	2	3	1
Thermal Ramp-up (Ranking)	4	5	3	2	1
Benchmark@100% (Ranking)	4	5	3	2	1
Surface Compliance	High	High on ped. / Low on device	High	High	High
Compressibility	High at initial, low after % pressure	High at initial, low after % pressure	High	High	High
Recovery Rate	Minimal	Minimal	High	High	NA (Paste)
Stain	Yes	No	Yes	Yes (Light Stain)	Yes (Messy)
Life Cycle	Moderate	Moderate	High	High	NA (Paste)
Breakage - XY	No	No	Yes (1 dir.)	No	NA (Paste)
Breakage - Bending	No	No	Yes (Both dir.)	No	NA (Paste)
Handling & Installation	Easy	Easy	Handle with extra care	Easy	Medium
Overall Assessment	**3**	**4**	**2**	**1**	**Not Suitable**

Summary

- As a thermal grease, MX-4 exhibits the best thermal performance. It fills the unevenness of the surfaces completely and has very thin bond-line. Other factors needs to be considered includes the installation process, possible stain on device & issue of pump-out or dry-up over time. It is not suitable for TIM#2/#3/#4 for SLT or final test, unless there is a complete wrap over.
- Indium has high thermal conductivity by itself, and will have good compression at the initial part of the compression. Once the protrusion are flattened out, there will be minimal compressibility. In this test, above 60psi, the thickness change on the material is reduced significantly. There is also no bounce-back in this material. It will become molten above 150°C.
  - For HSD Indium, it has high performance but has shorter life usage, staining issues & occasional localized melting due to high power switch during testing.
  - HSK Indium overcome the stain issue & localized melting by having the aluminium clad to contact the device. However, the thermal performance will be reduced.
- GT90Pro has good thermal performance and compressibility. The material is weak in the grain structure in 1 direction and must be handled very carefully. It causes stain, which can be very obvious on lidded package.
- WTP50 has good thermal compression & compressibility and is easy to handle.

Summary

- The test outcome using the thermal tester, ramp-up tester and benchmark tester shows some variance between the TIM material.
- Unless all the TIM material are tested using the same brand of test equipment with the same test parameters, it will be difficult for us to compare datasheet for each manufacturers.
- As we are testing only high performance TIM material, there will be a smaller deviation gap in the results.
- There is no TIM material that can be a one-fit for the many different product models in the factory.
- Datasheet should only be used as a reference, and it will be strongly recommended for the users to design their DOEs to fit the actual application. Some critical factors in the DOEs will be:
  - Single chip / multi chips / chiplet
  - Lidded / lidless (bare chip)
  - Die / Package Size
  - Warpage distribution
  - Heat density
  - Test temperature, etc…
- Each portion in the stack-up of the thermal head design, including the ATC is important to improve the performance & thermal response during the testing.

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