Liquid Metal Embedded Elastomers (LMEEs) as TIM1 with Highly Reliable & Extremely Low Thermal Resistance Performance

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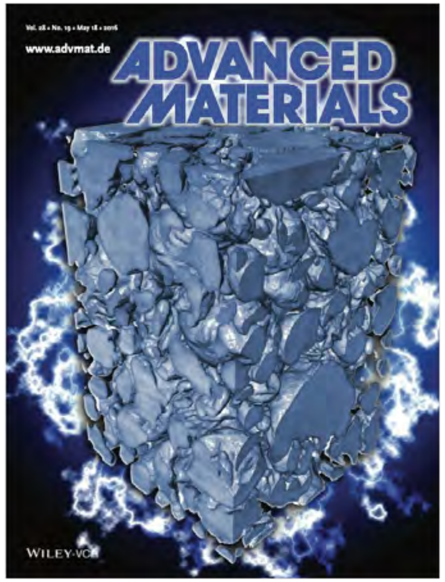
Speaker Introduction

Dr. Navid Kazem

- **Bachelor of Science** (2012)
  - Sharif University
- **Master of Science** (2013)
  - Carnegie Mellon University
- **PhD** (2018)
  - Computational Mechanics, CMU
  - Swartz Entrepreneurship Fellow from Tepper School of Business



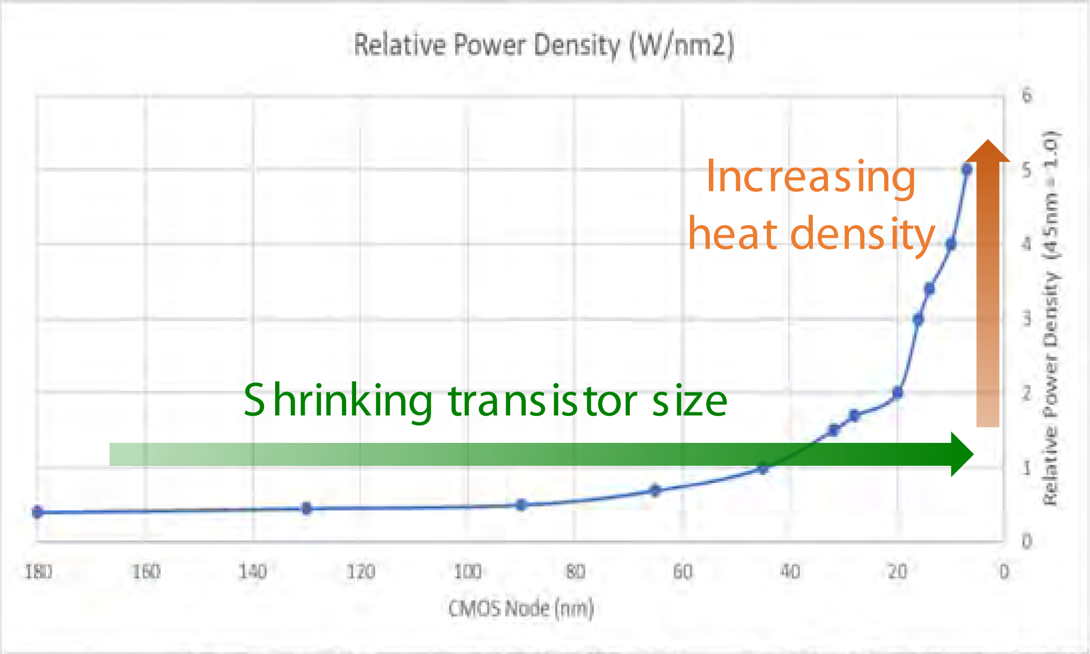
- **Co-Founder and CEO at Arieca** (2018-Present)
  - VC backed advanced materials startup
  - Developing modern materials for a connected society

Semiconductor Market Challenge

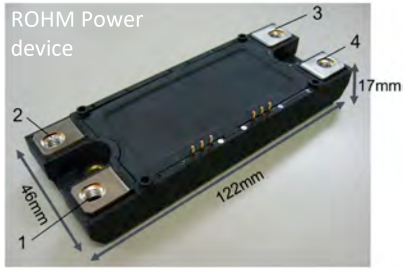
Moore's Law

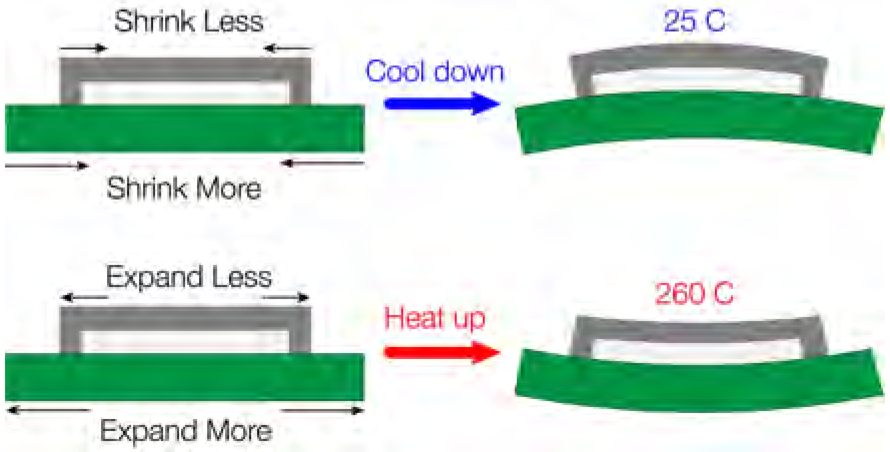
Meets

Physically Constrained Footprints



Source: Stillwater, Bass "Scaling equations for the accurate prediction of CMOS device performance from 180 nm to 7 nm", Integration June 2017





TDP >> 100W for current generation high performance devices

Semiconductor Market Challenge

Moore's Law Meets Physically Constrained Footprints

Source: Stillwater, Bass "Scaling equations for

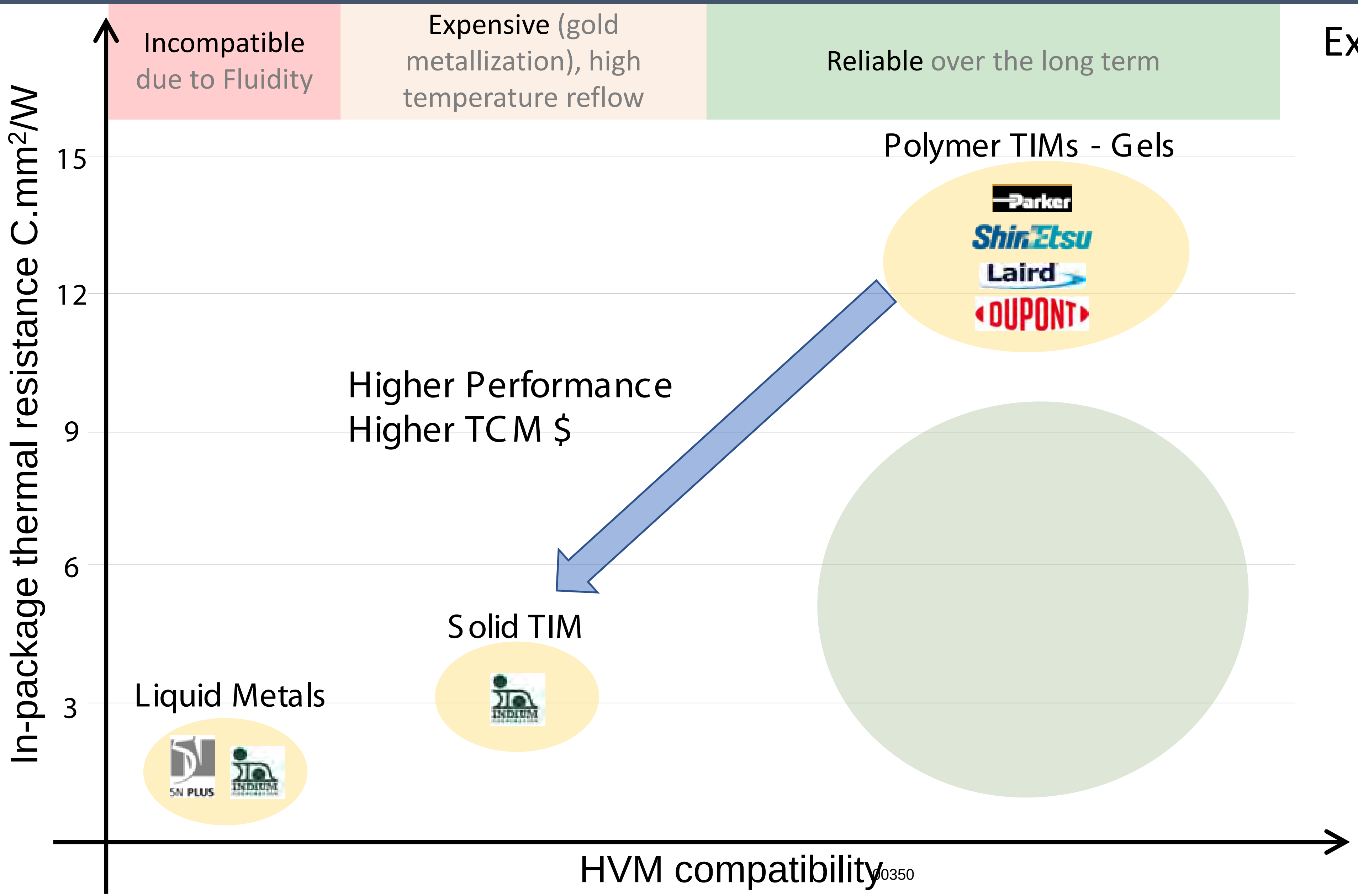
Expand More

TDP >> 10
high pe

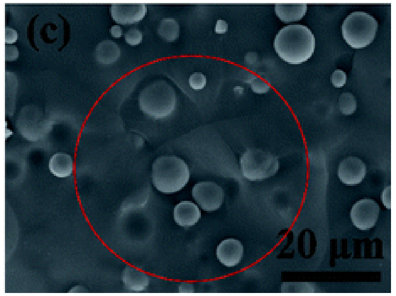
Objective: To Develop Thermal Interface Materials (TIM1) with

- Thermal Resistance approaching of Liquid Metals
- Mechanical Reliability Performance of Polymer-TIMs
- Ease of Semiconductor Packaging Manufacturing of Greases

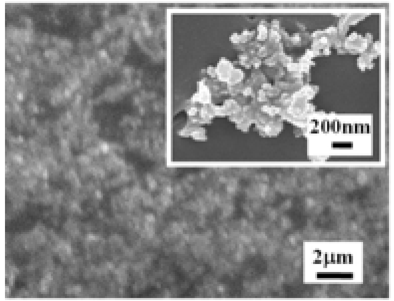
Existing Solutions - Thermal Interface Materials (TIM1)



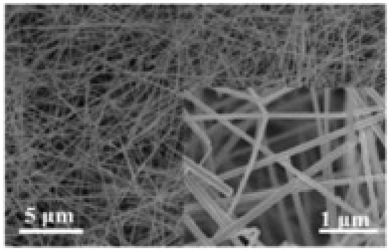
Existing high-performance TIMs have tradeoffs



Aluminum Oxide - Silver

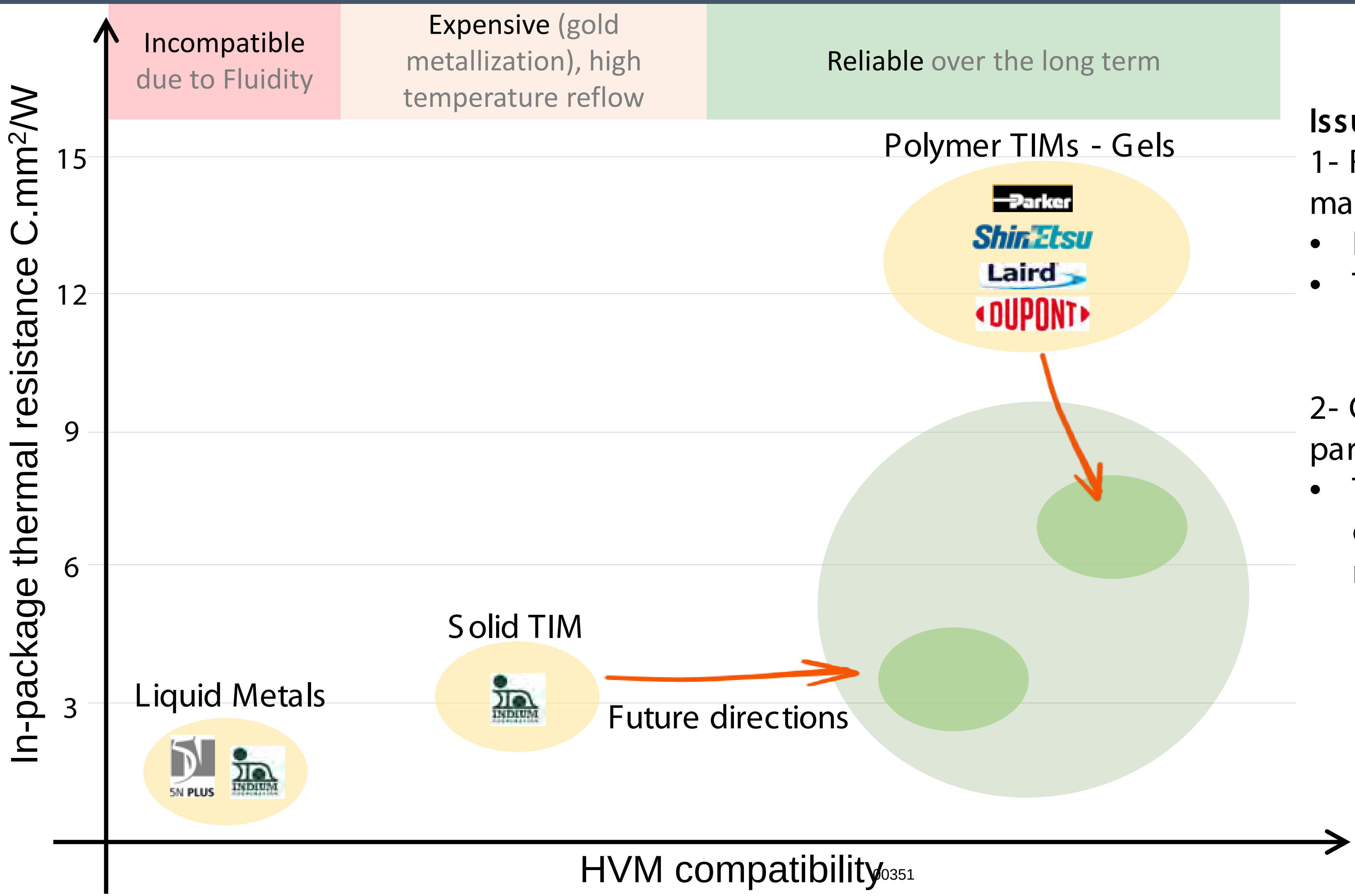


Boron Nitride



Vertically aligned Carbon

Existing Solutions - Thermal Interface Materials (TIM1)



Issues:

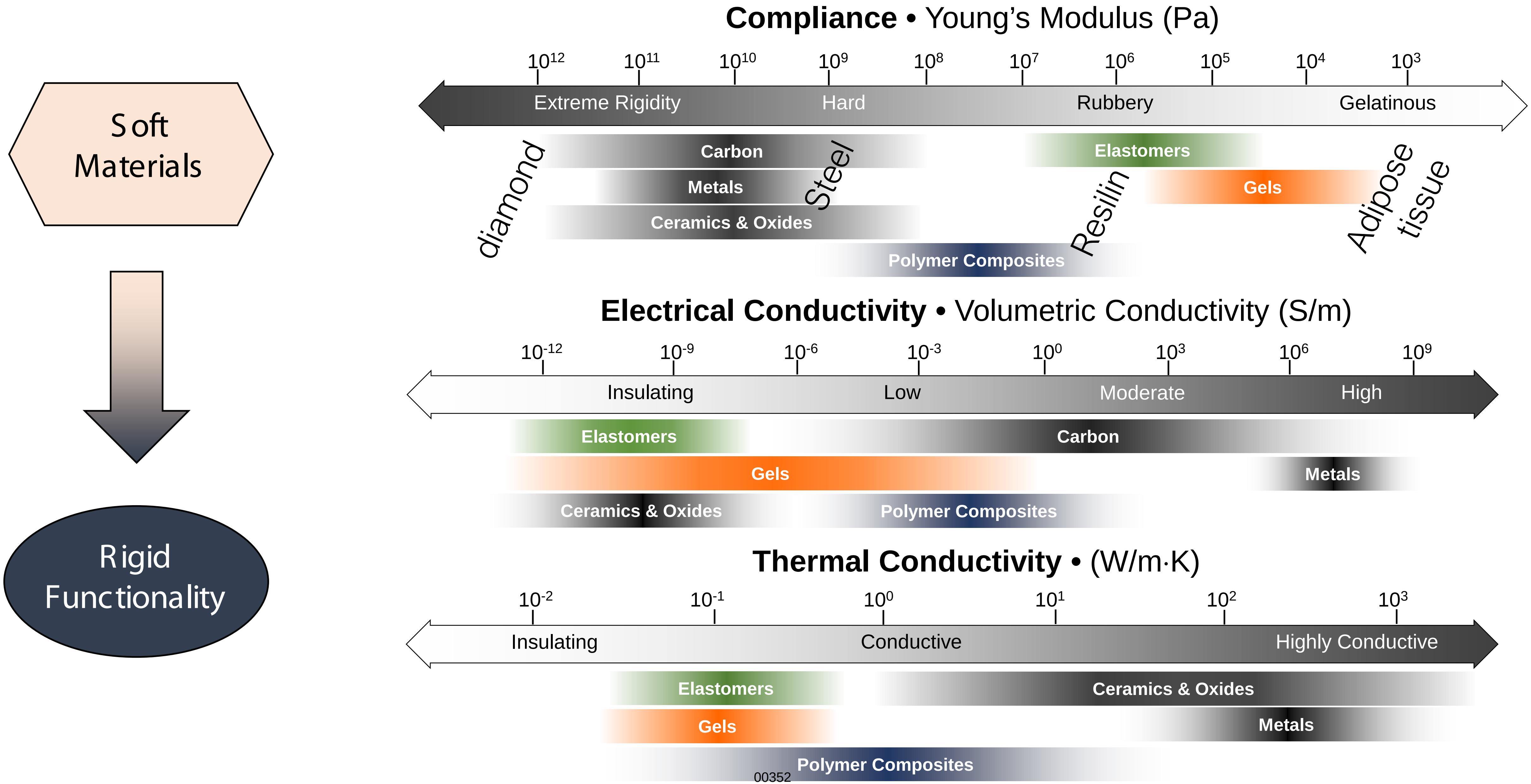
1- Reducing the BLT while maintaining Reliability

- Pressure requirements
- Thermal Shock

2- Contact resistance between particles

- The struggle of thermal conductivity vs thermal resistance

Soft Matter Engineering



Liquid Metals

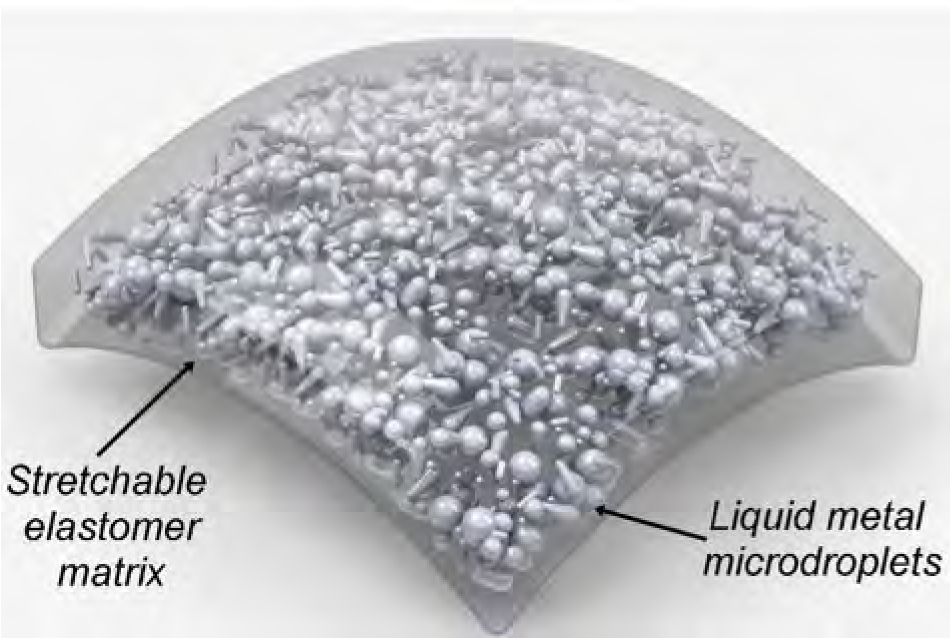
Indium Corp.
5N plus

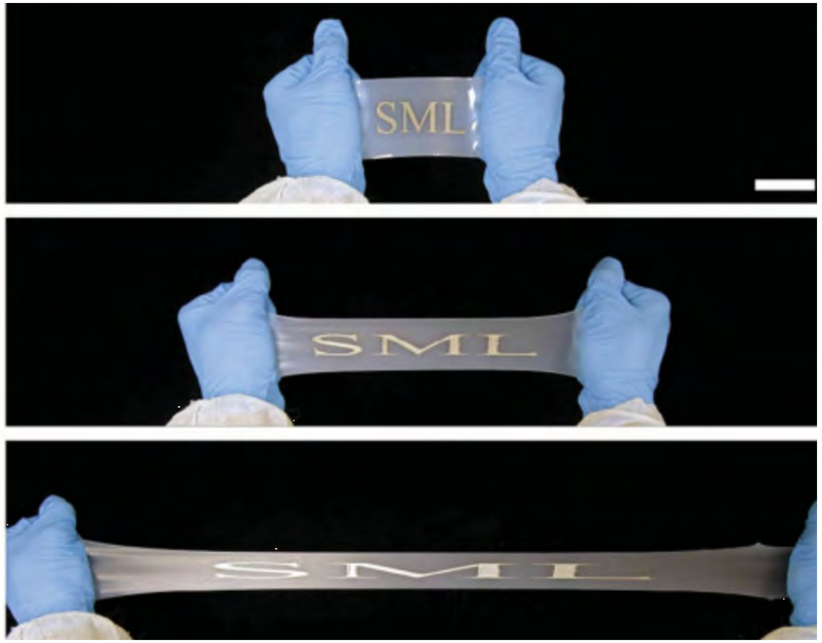
Chiechi et al., Angew. Chemie - Int. Ed. 2008

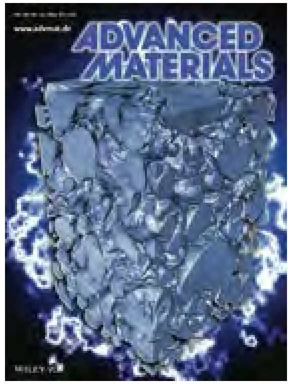
Joshipura et al., J. Mater. Chem. C., 2015.

- Eutectic Gallium Indium (74.5% Ga, 24.5% In; by weight)
- Low melting point ~ 15.5°C
- Negligible toxicity
- Low viscosity 1.99 mPa·s
- High electrical and thermal conductivity ($\sigma = 3.4\times10^6$ S/m, k = 26.4 W/m·K, at ~30°C)

Merging Liquid Metal and Elastomers



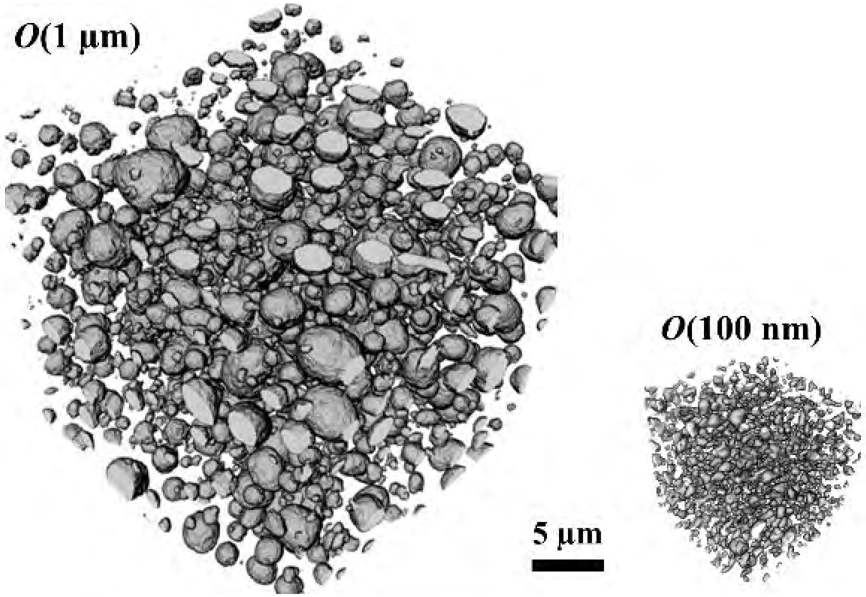




nature materials
PNAS
ADVANCED MATERIALS
The Washington Post
PBS (scitech)now

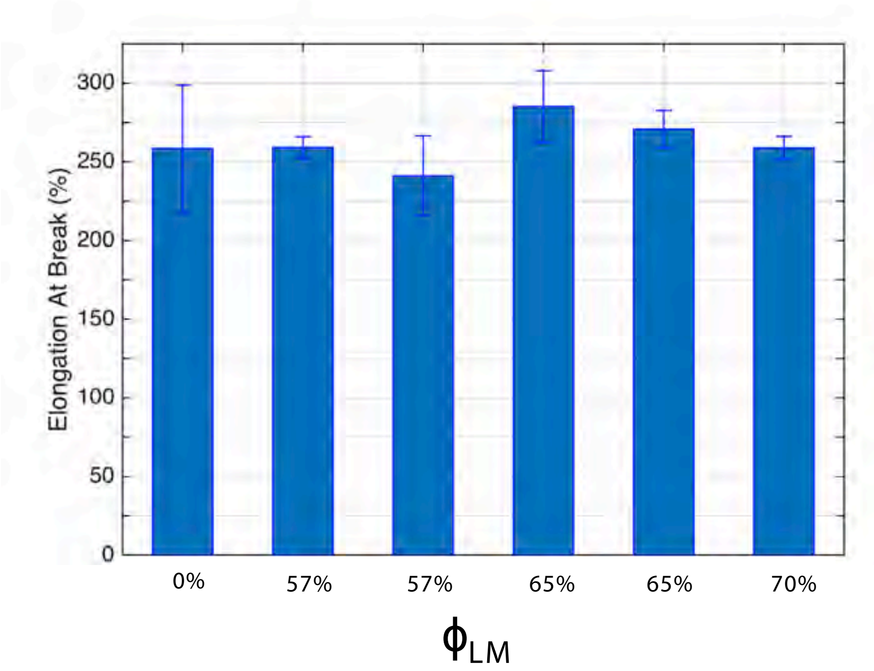
- Breakthrough material architecture that uniquely combines elasticity & printability of rubber with conductivity of metal
- Transforms the way liquid metal can be used in computing and electronics
- Our academic publications on LM-elastomer composites are among the top 0.1% most highly cited papers in materials engineering

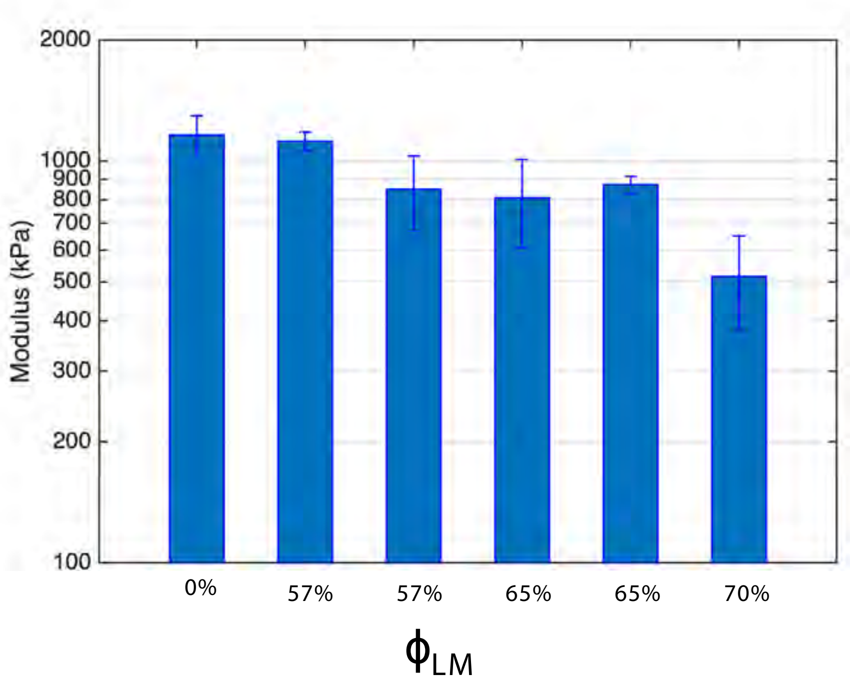
Liquid Metal Embedded Elastomers (LMEE) - Microstructure

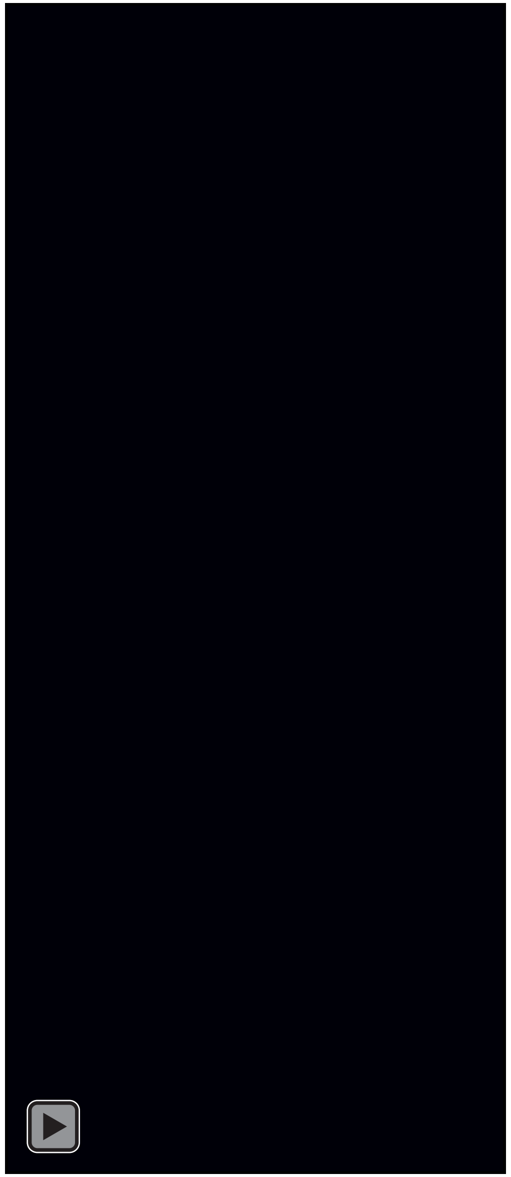


C. Pan *et al.*, "A Liquid-Metal–Elastomer Nanocomposite for Stretchable Dielectric Materials," ***Adv. Mater.***, vol. 31, no. 23, pp. 1–10, 2019.

Liquid Metal Embedded Elastomers (LMEE) - Polymer

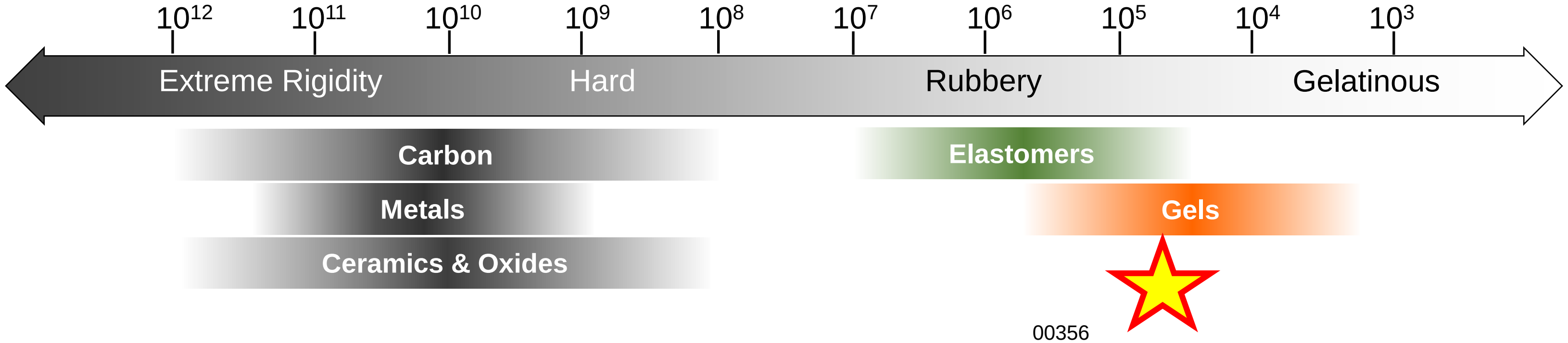






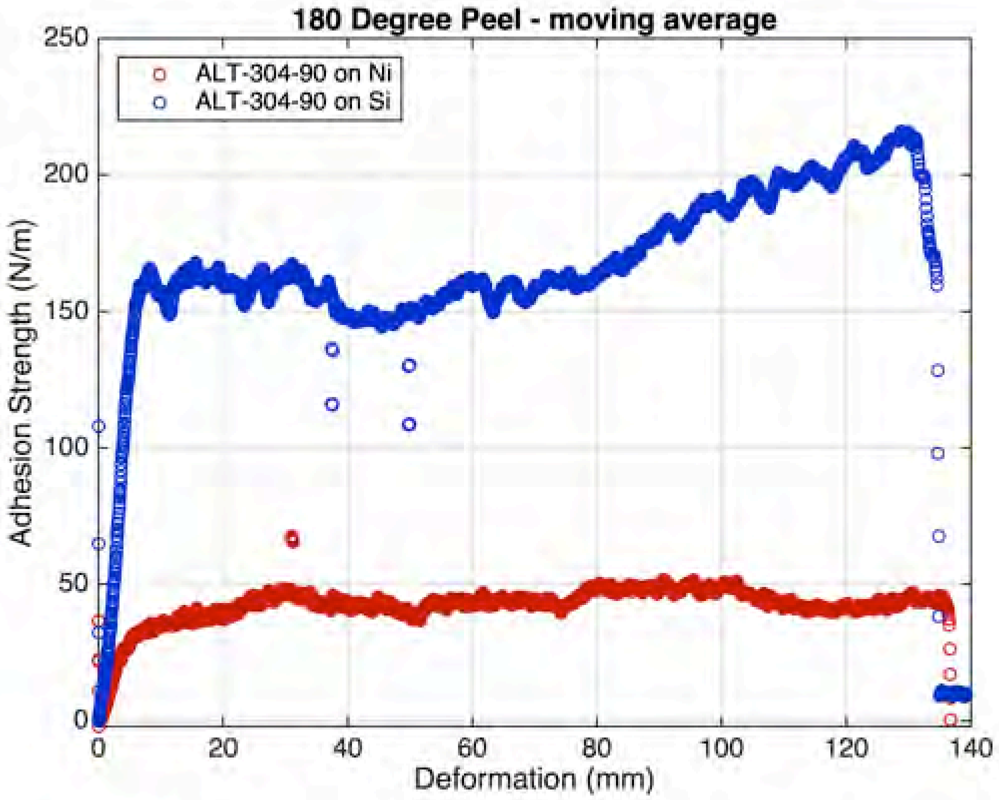
$\phi_{LM} = 65\%$

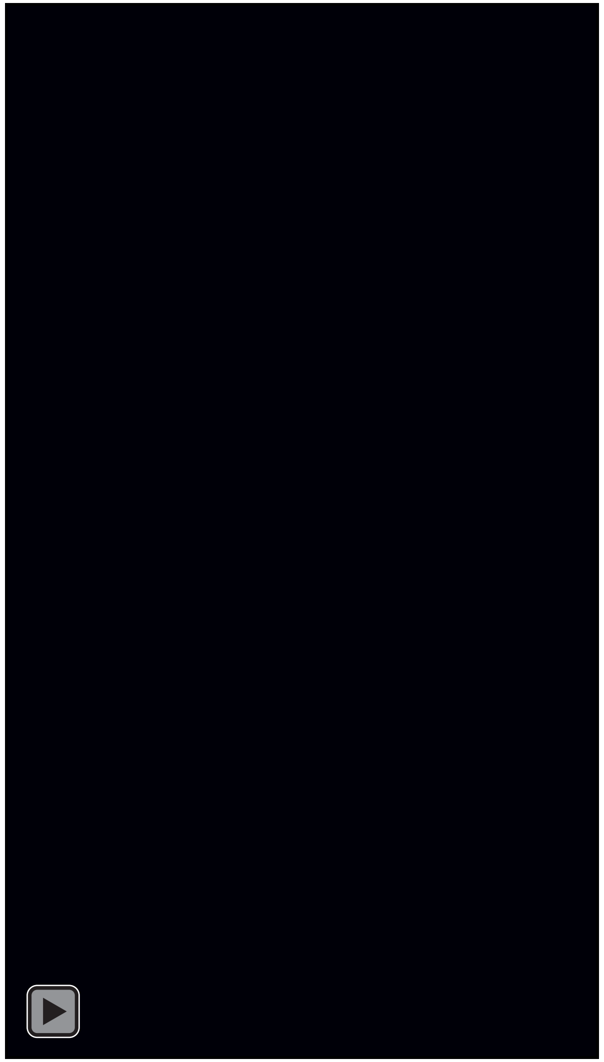
Compliance • Young's Modulus (Pa)

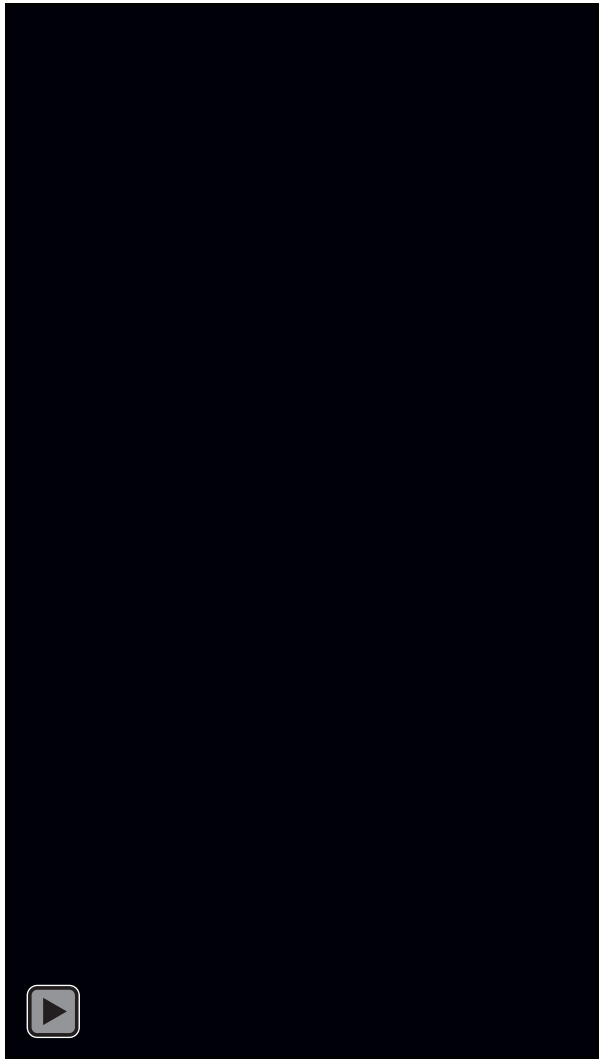


Liquid Metal Embedded Elastomers (LMEE) – Polymer Adhesion

LMEEs maintains excellent adhesion to both nickel and silicon even when heavily loaded to provide low thermal resistance

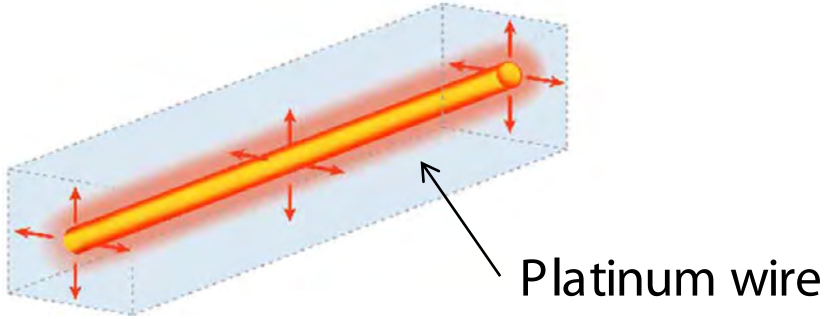




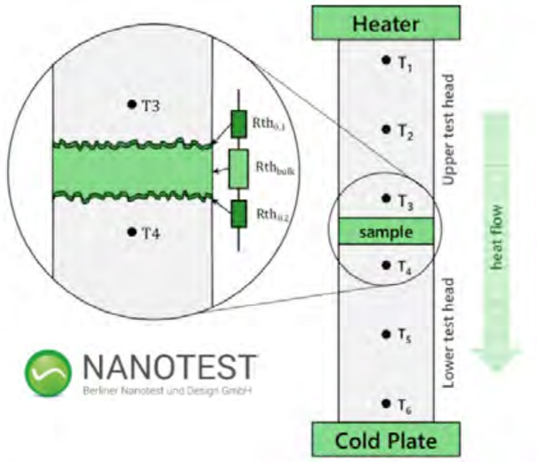


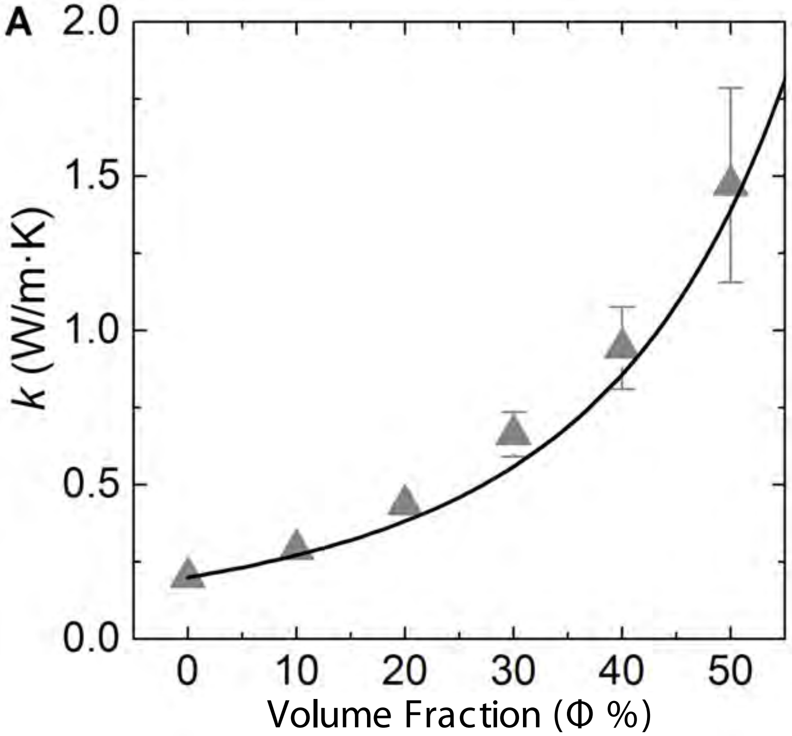
Thermal Conductivity

Transient Hot wire Method



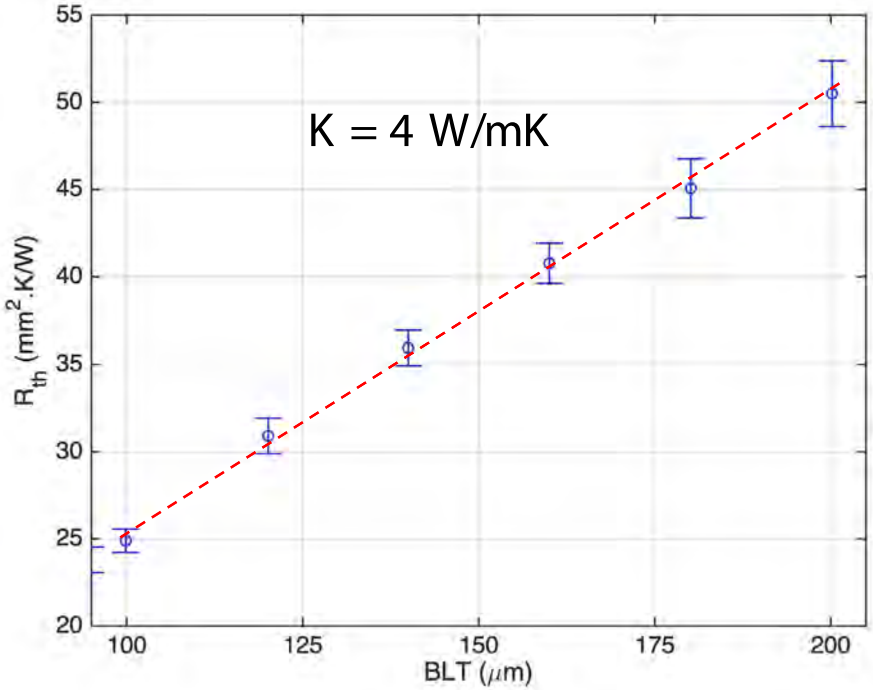
ASTM D5470



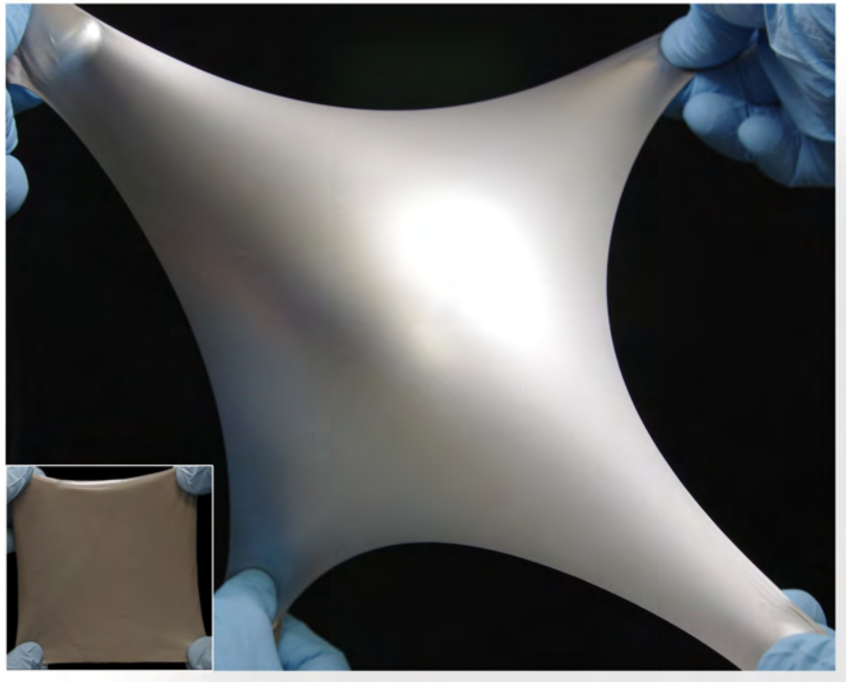


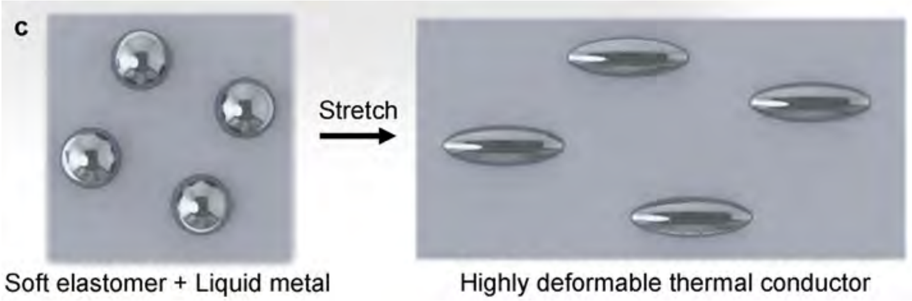
M. D. Bartlett *et al.*, "High thermal conductivity in soft elastomers with elongated liquid metal inclusions," ***Proc. Natl. Acad. Sci.***, 2017. 00358

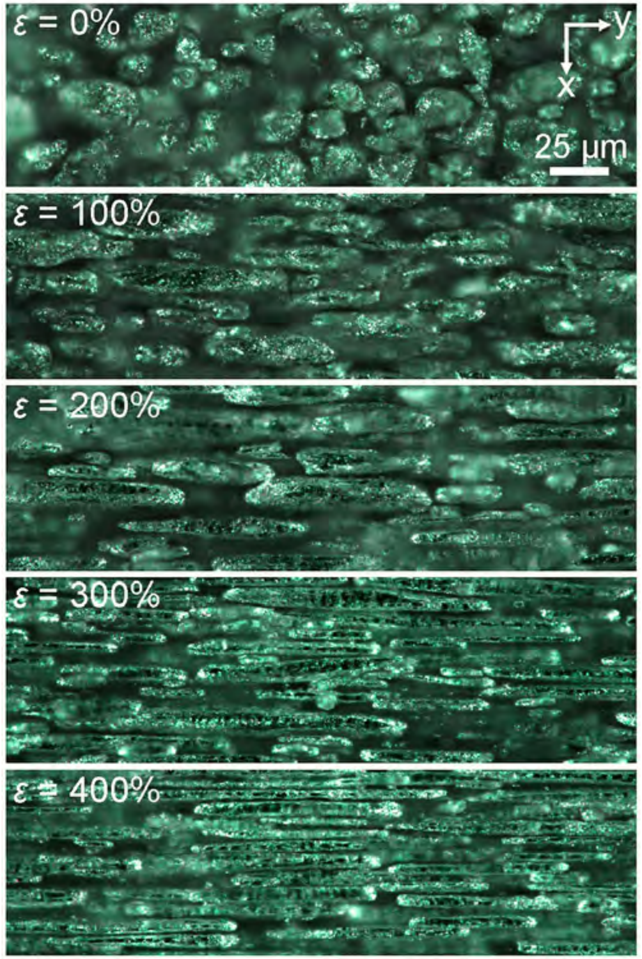
Volume Fraction Φ = 65%

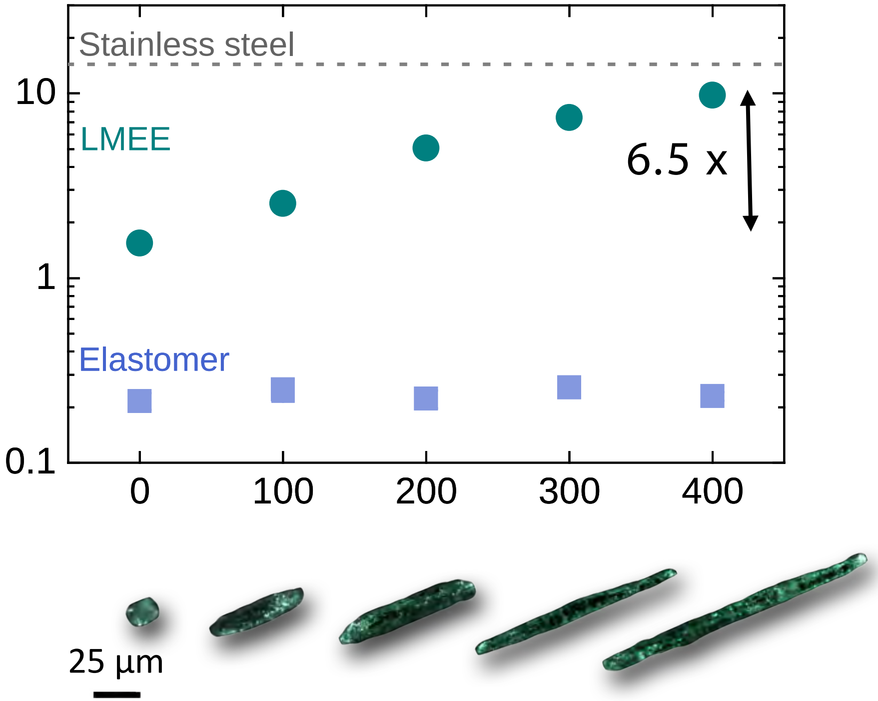


Thermal Performance Through Extreme Deformability









M. D. Bartlett *et al.*, "High thermal conductivity in soft elastomers with elongated liquid metal inclusions," ***Proc. Natl. Acad. Sci.***, 2017.

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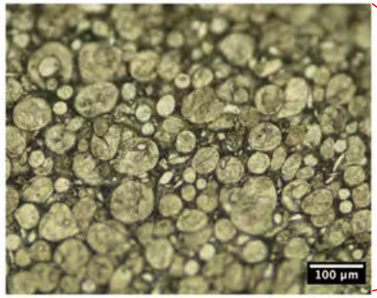
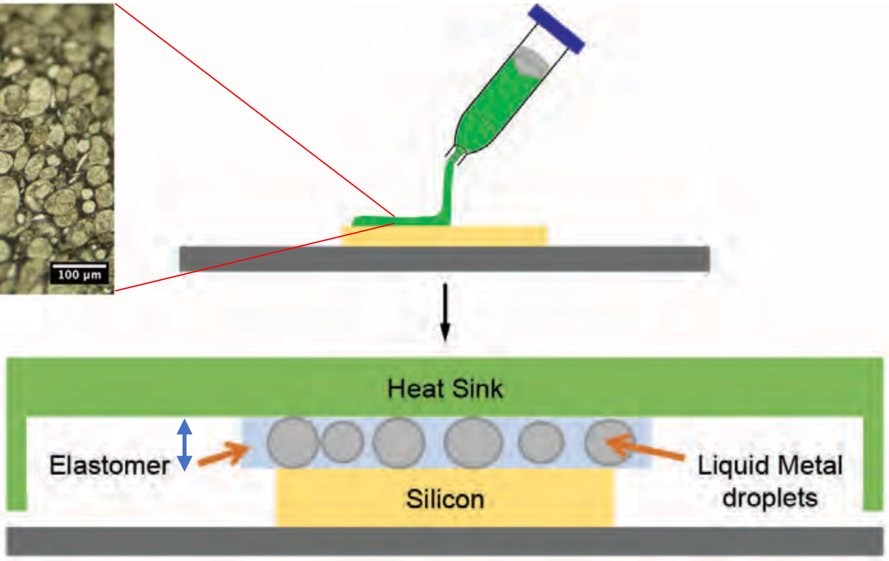
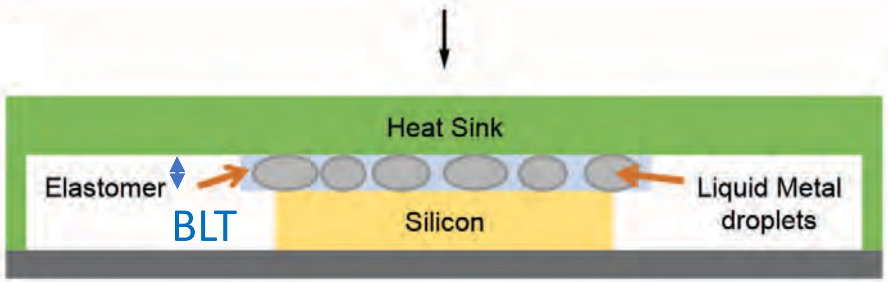
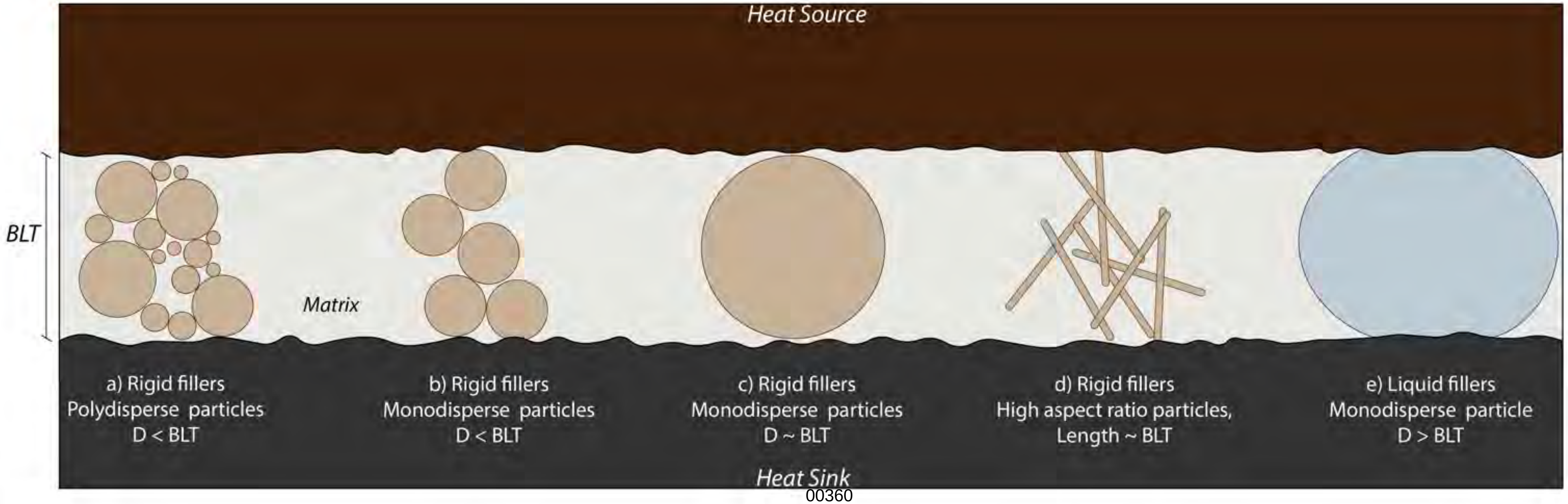
Novel Microstructure for TIM1





- Bond-Line Thickness < Particle Sizes
- Extremely deformable Liquid Metal fillers
- Increase in contact area
- Decrease in contact resistance



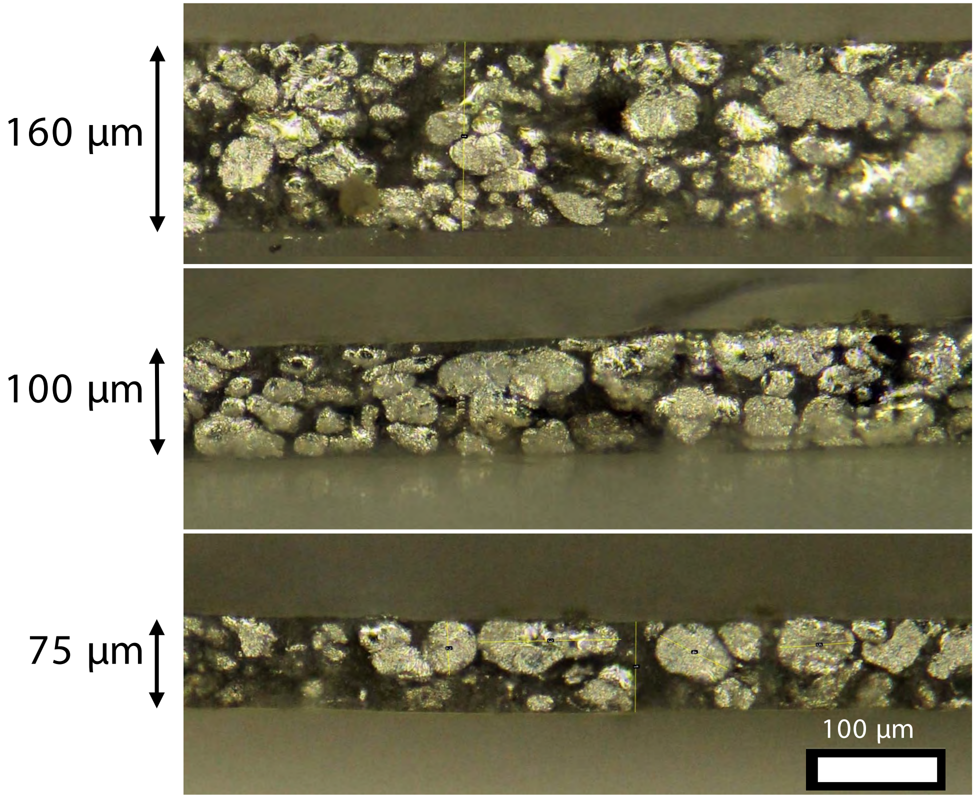


Novel Microstructure for TIM1

TIM being applied to IC with standard techniques

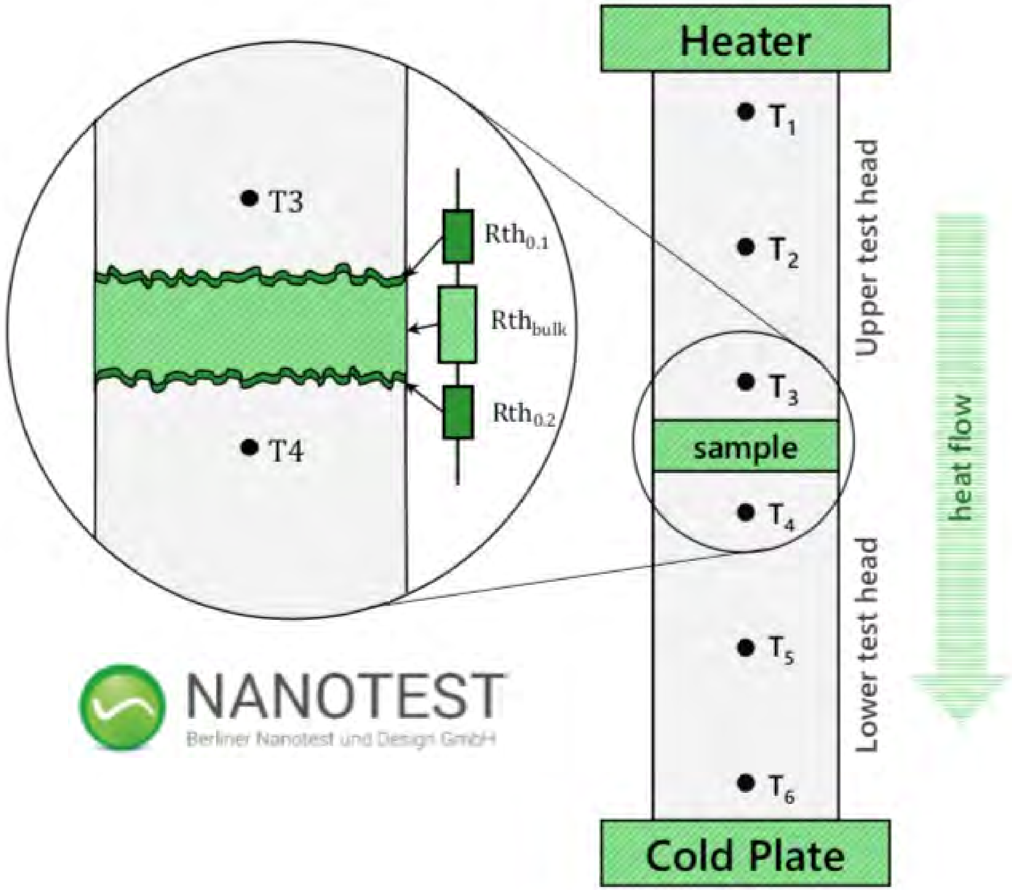
Clamping video showing deformation in Liquid Metal droplets

Cross Sectional images of Liquid Metal compression while frozen (using liquid nitrogen < −60℃)

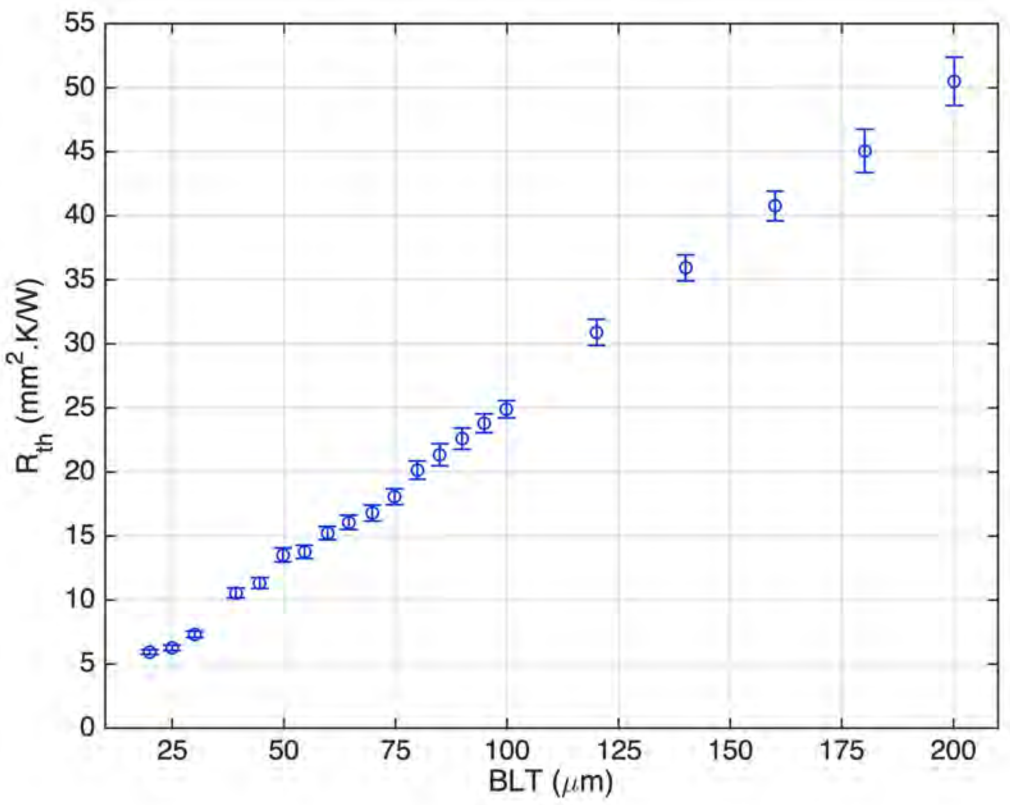


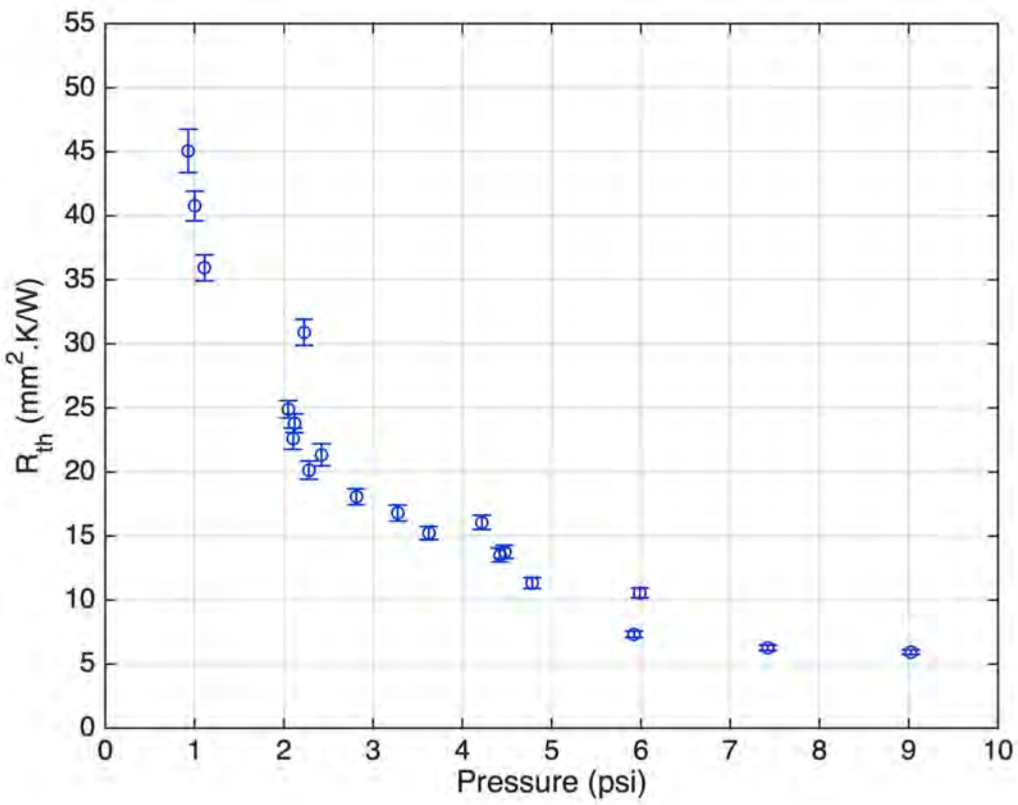
Thermal Resistance Measurement

- Temperatures
  - Sample $T_{S,avg}$ ≈ 25 °C
  - Heater T_H = 30 °C (set point)
  - Liquid Cold Plate T_C ≈ 15°C
- BLTs
  - BLTs measured:
    200, 180, ..., 120, 100,
    95, 80, ..., 25, 20 µm
- Contacting surfaces
  - Material: Cu - Cu
  - Roughness *Rz* < 2 µm
  - Area *A*: 1.33 cm^2
- Measurement method: ASTM D 5470



ASTM D-5470

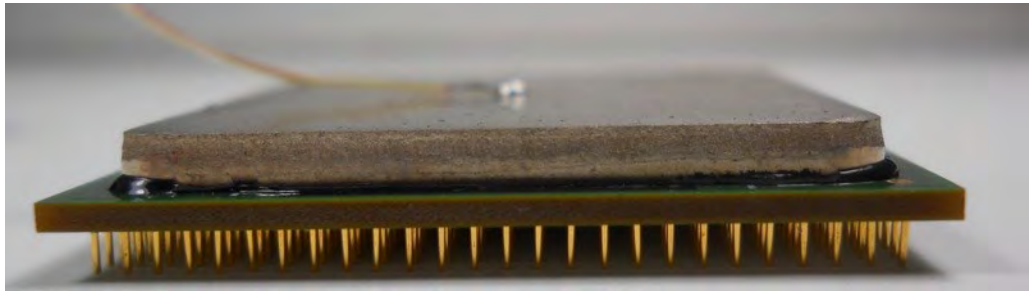




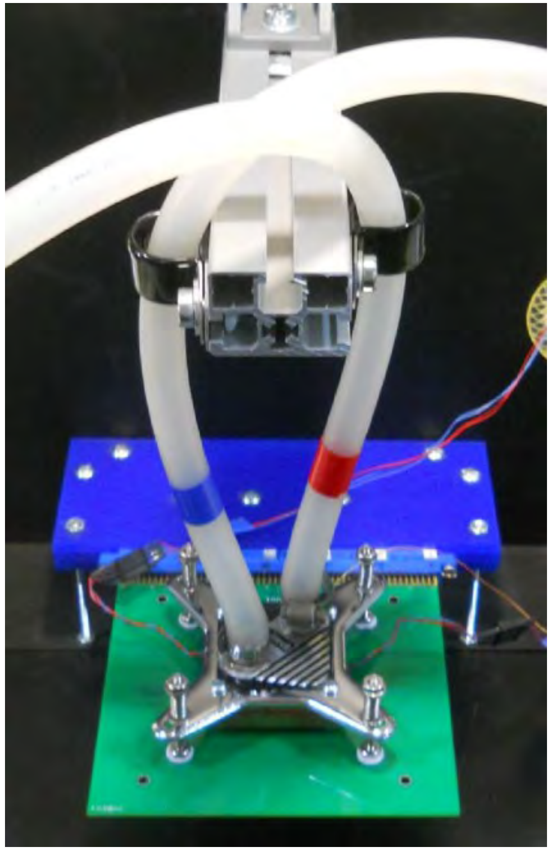
BLT (µm)	R (mm^2.K/W)	P (psi)
20	5.9	9
30	7.3	5.9
40	10.3	4.4

Thermal Test Vehicle

General TTV Characteristics

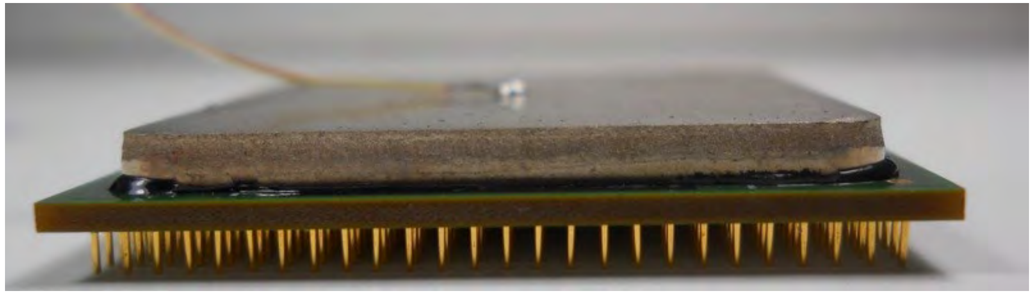


Partner Proprietary TTV (x2)
~11mm x 13mm active die
Integrated heater network and thermal diodes
TIMbber ALT304-90 cure: 1 hr @70C, 1 hour ramp to 125C
Lid attach: Dowsil 3-6265, 1hour cure @ 125C



~80W applied (used for Θjc calculations)
Liquid cooling solution
TIM1 joint temperature: ~40°-50°C

T_0 Thermal Results – TTV



Die dimensions: 11mm x 13mm

Thermal Resistance junction to case (C*mm²/W)

15.87

Thickness

2100µ +/- 50µ

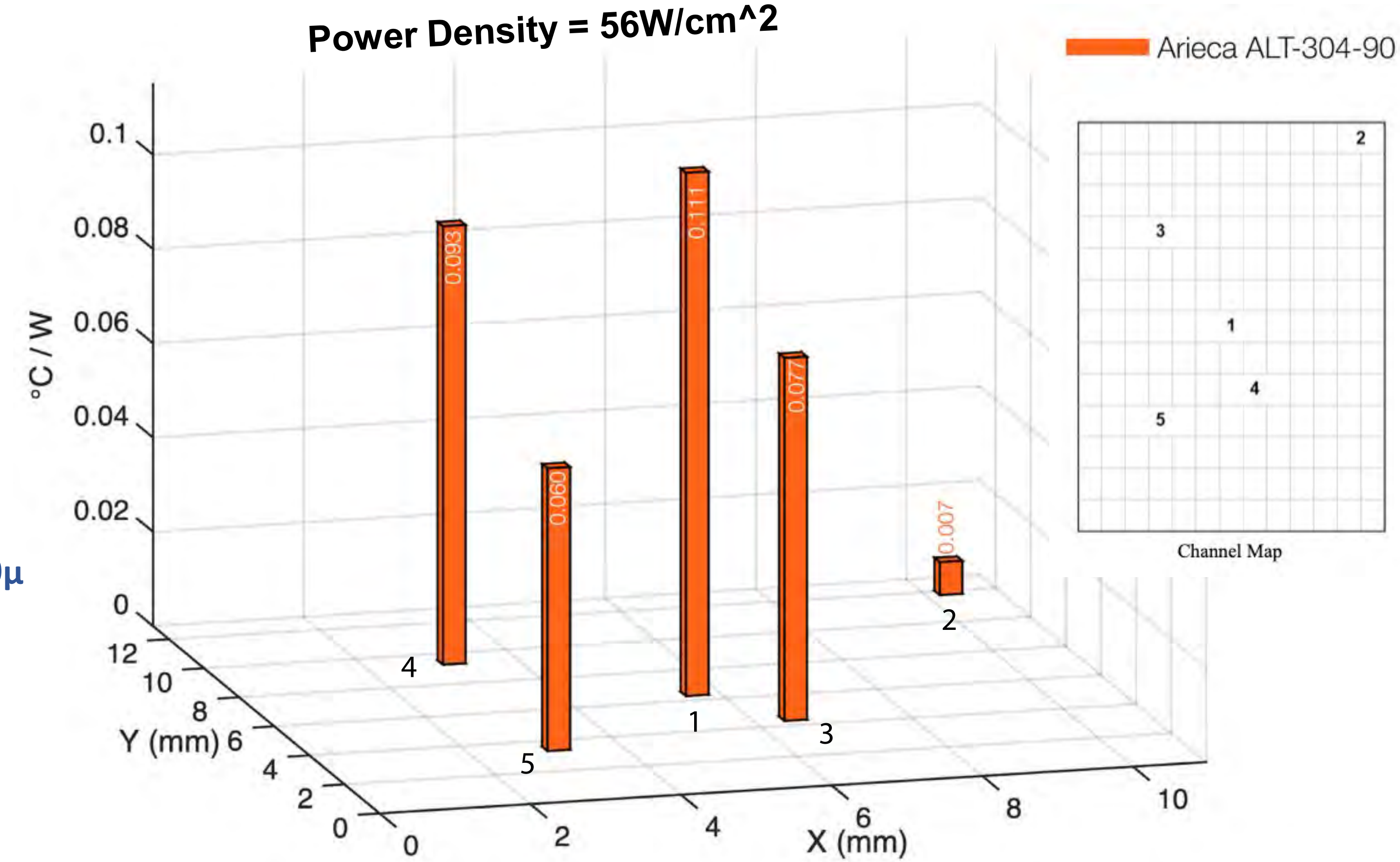
3.72

6.86

5.29

1500µ

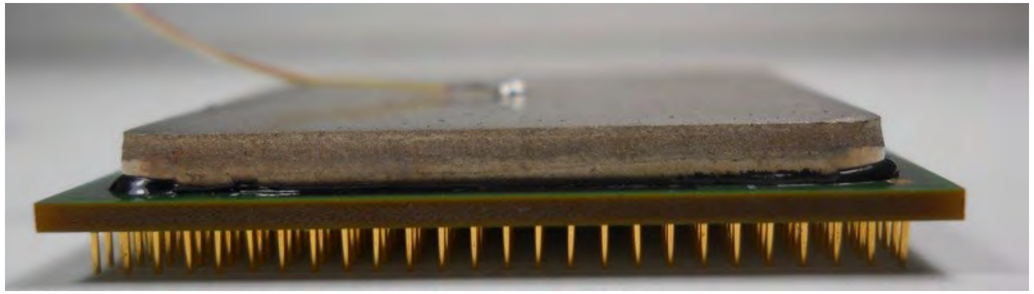
610µ



Center R_{jc} 15.87 C-mm²/W

T_0 Thermal Results – TTV

ENERDYNE SOLUTIONS



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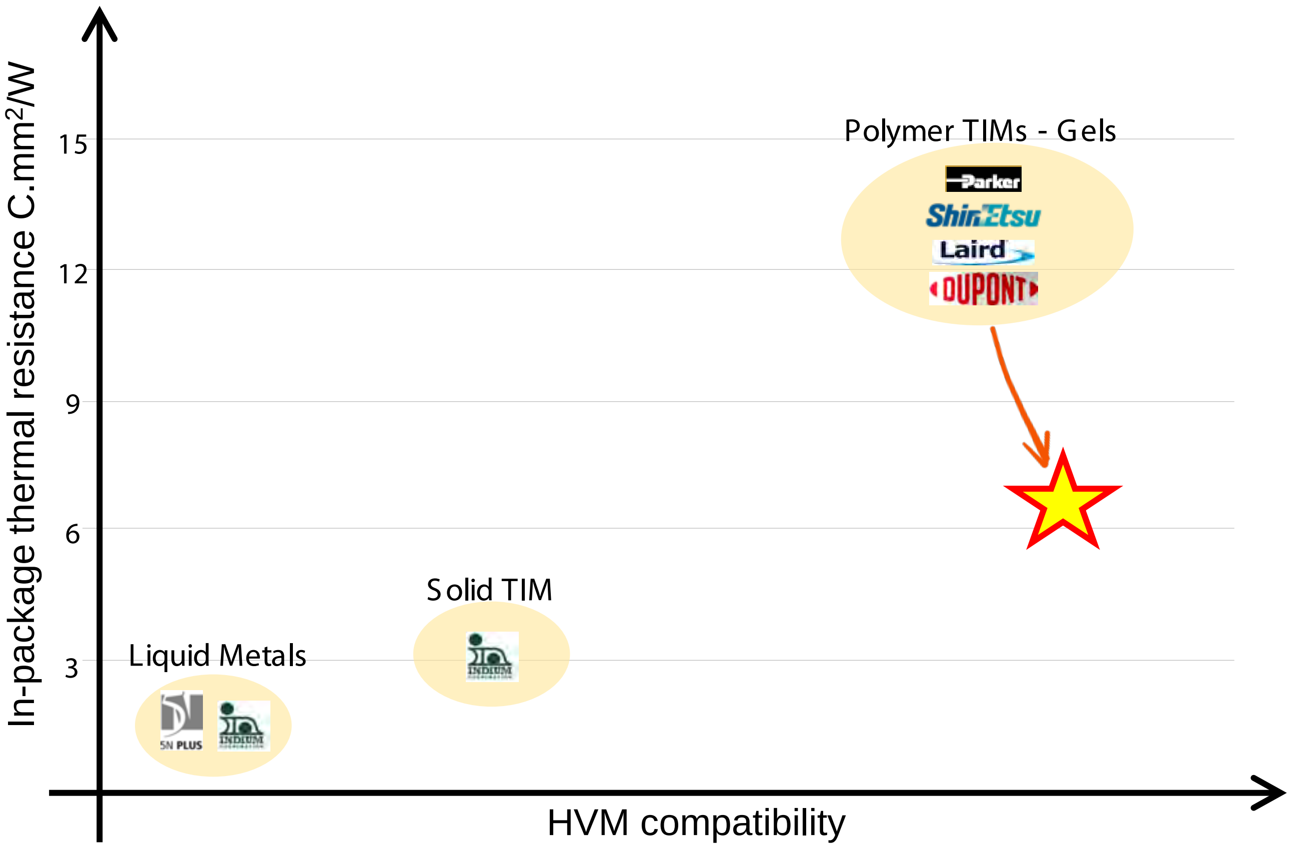
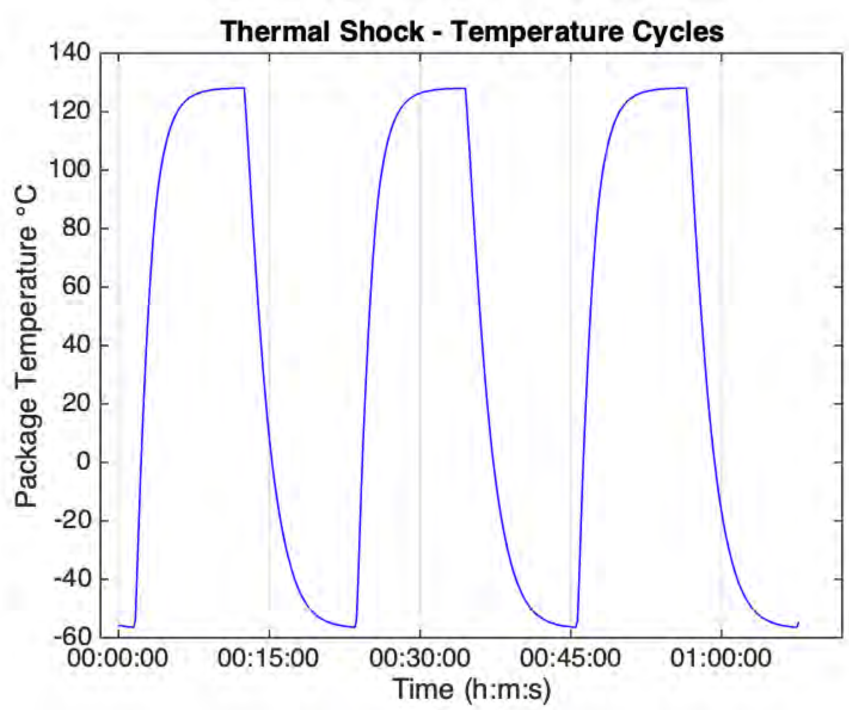
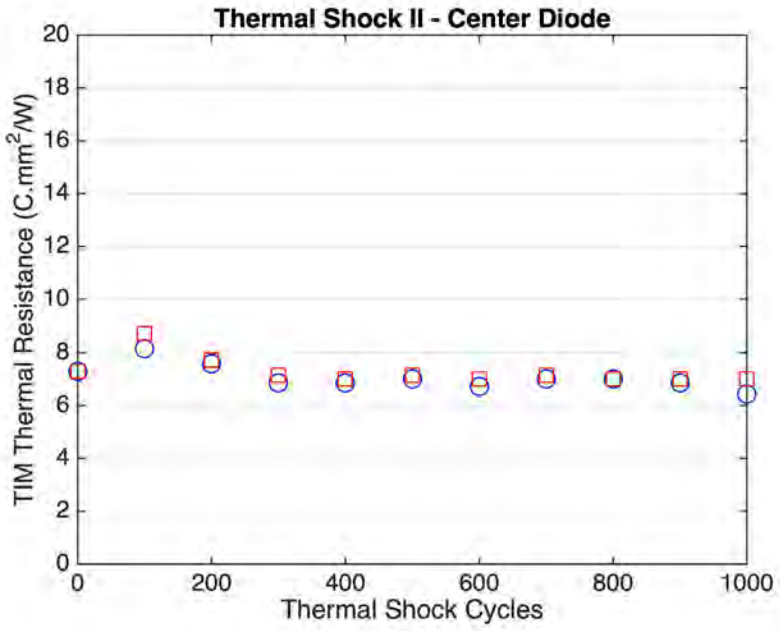


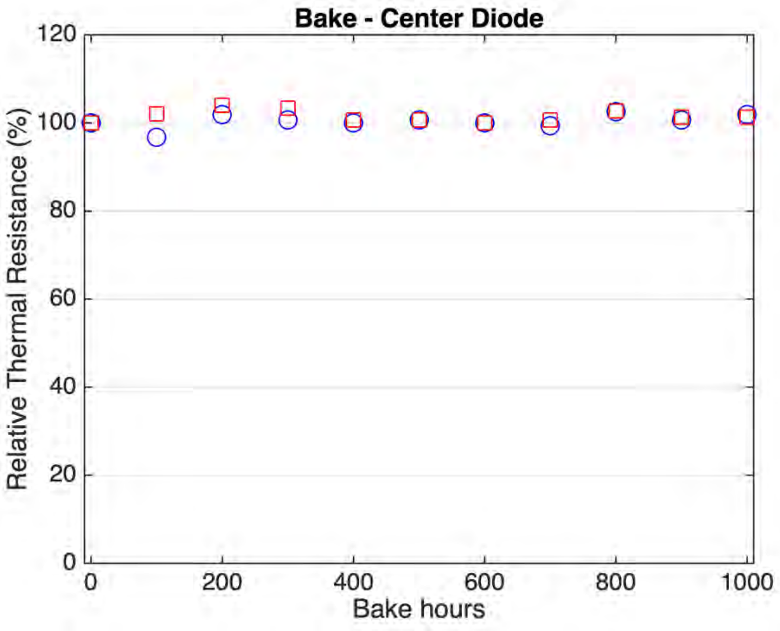
Reliability Tests

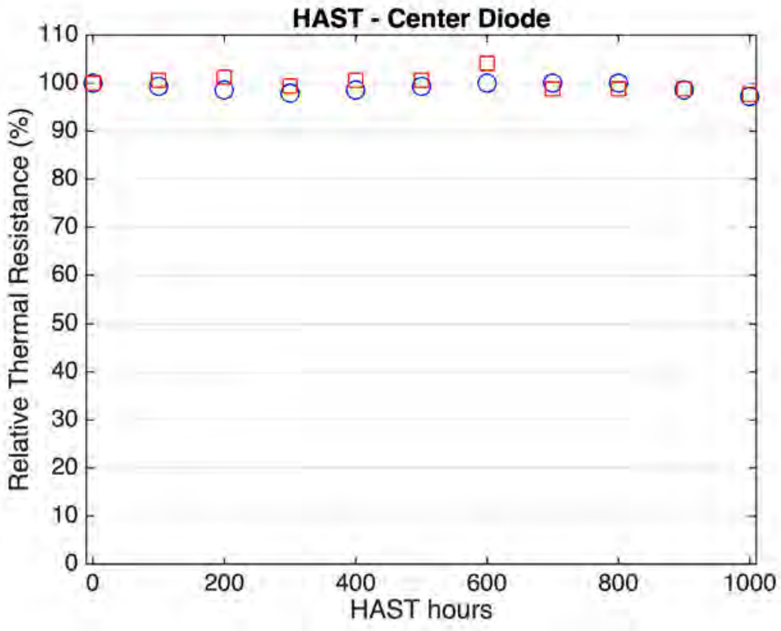


- MIL-STD-883B Compliant
- -55°C (-10°C, +0°C) to +125°C (+10°C , -0°C)
- T_0 thermal characterization
- Re-characterization following each batch of (100) thermal shock cycles

Long Term Reliability







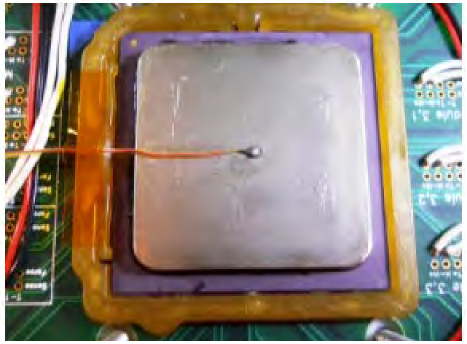
Thermal shock
per MIL-STD-883B:
Test area shall at -55°C (-10°C, +0°C) and +125°C (+10°C , -0°C) for a minimum of 10 minutes

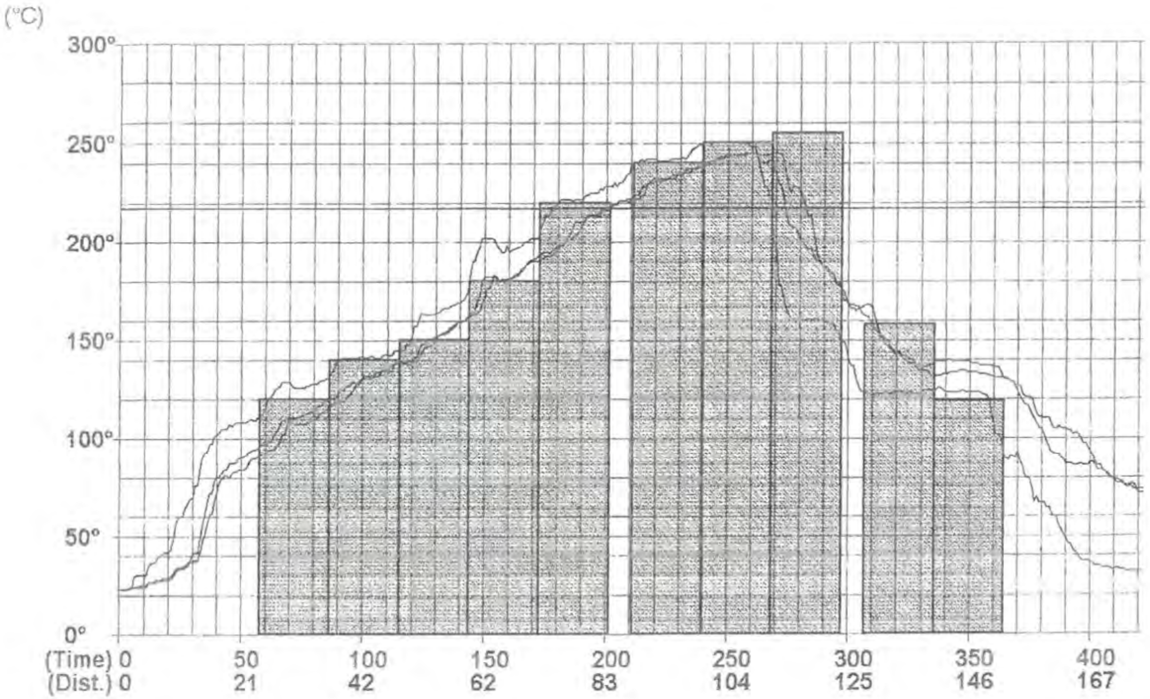
High Temperature Storage
per JEDEC 22-A103 Condition A:
+125°C (-0°C, +10°C).

HAST (85/85)
per JEDEC 22-A101:
85 ±2°C, 85 ±5%RH

5x Reflow

Passes 5x Reflow Test





Precon sequence: 125°C bake (24hrs), transferred (within 30min.) to 60°C/60%RH (40hrs), transferred (within 2hrs) to outsourced MSL3 reflow (5X reflows, 5min. cool down between runs)

Preconditioning Θjc Results		
Channel #	**TimeØ**	**Post-Precon**
1	0.096	0.087
2	0.093	0.084
3	0.069	0.060
4	0.047	0.038
5	N/A	N/A
Ave. Θjc	**0.076**	**0.067**

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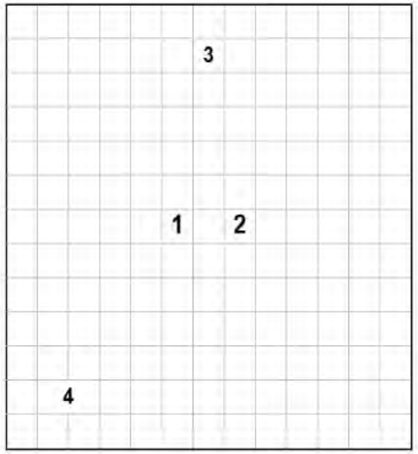
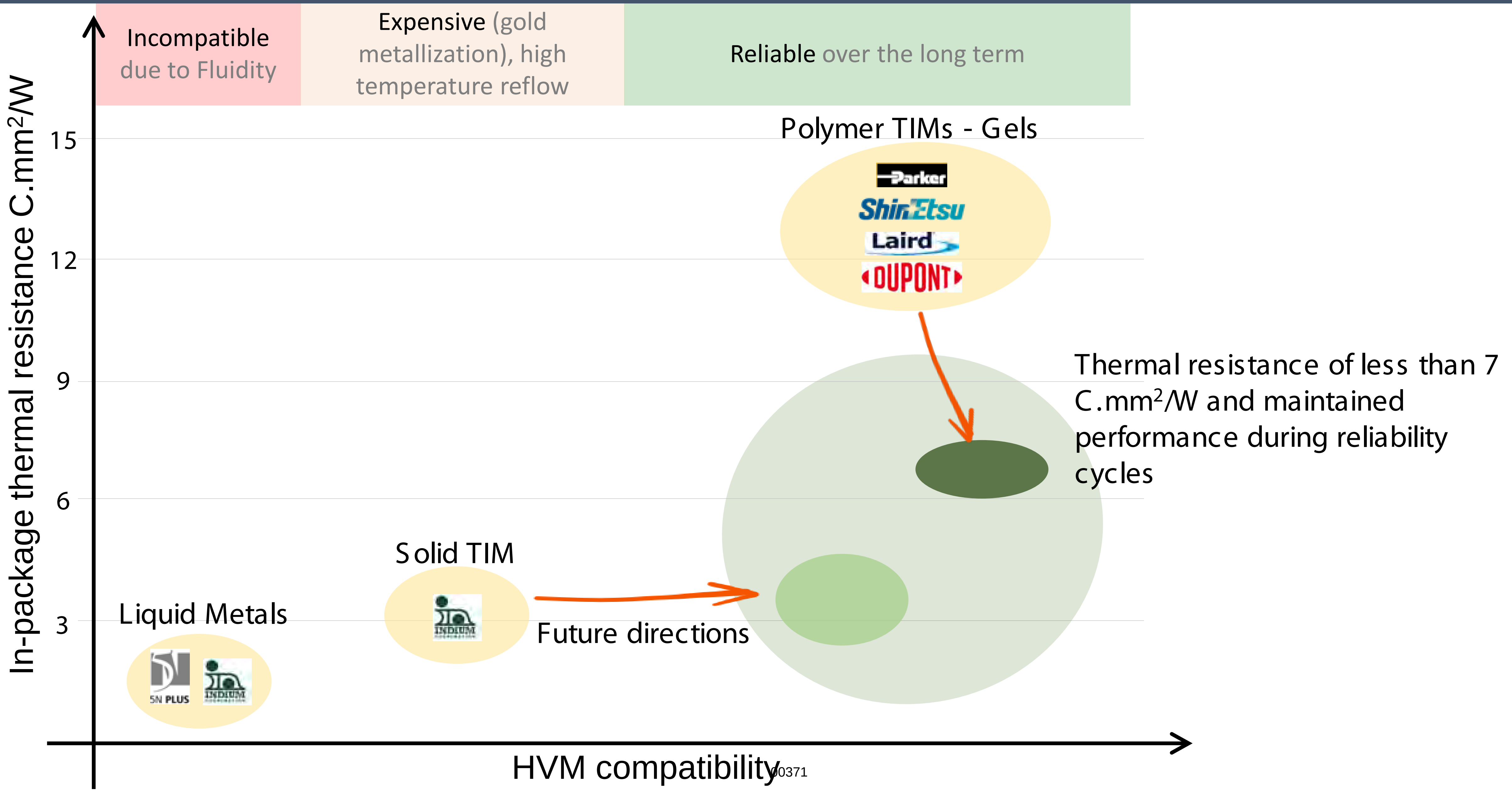


TTV Channel Map

Existing Solutions - Thermal Interface Materials (TIM1)



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Next Generation TIM Development

Next generation TIM performance

- Thermal performance rivaling Solid-TIMs (R_{jc} 3-5 C.mm^2/W)
- Polymer-TIM HVM compatibility (liquid dispensed)

Liquid Metal Microstructure Development

- Morphology and Polydispersity
- Volume Loading

Polymer Development

- Rheology optimization
- Adhesion formulation

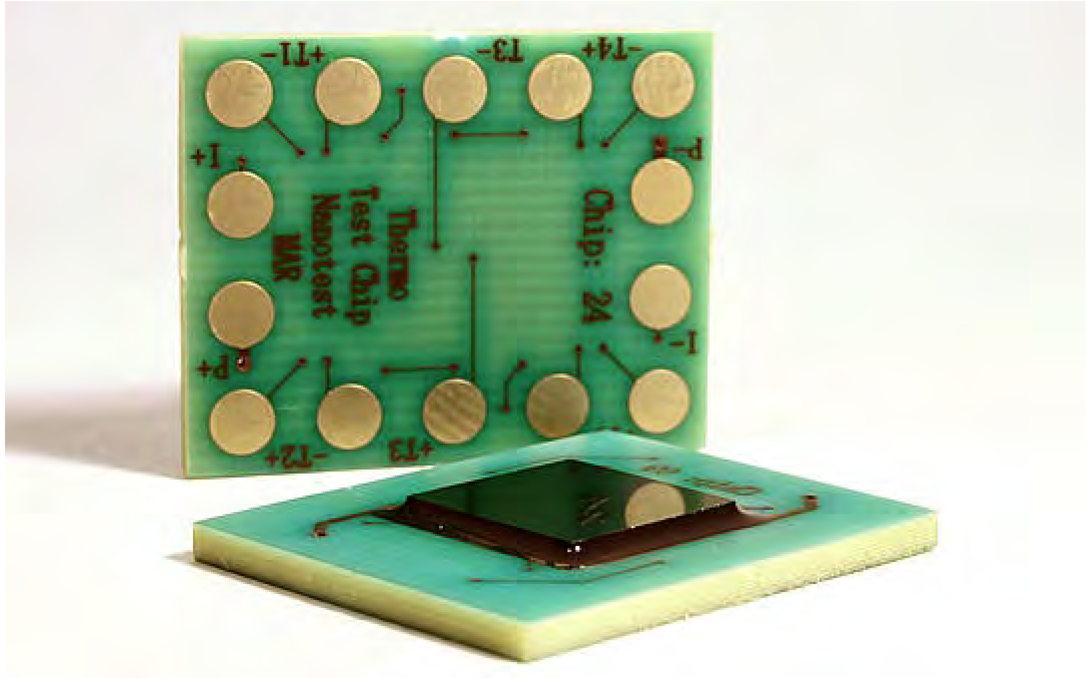
Packaging Process Development

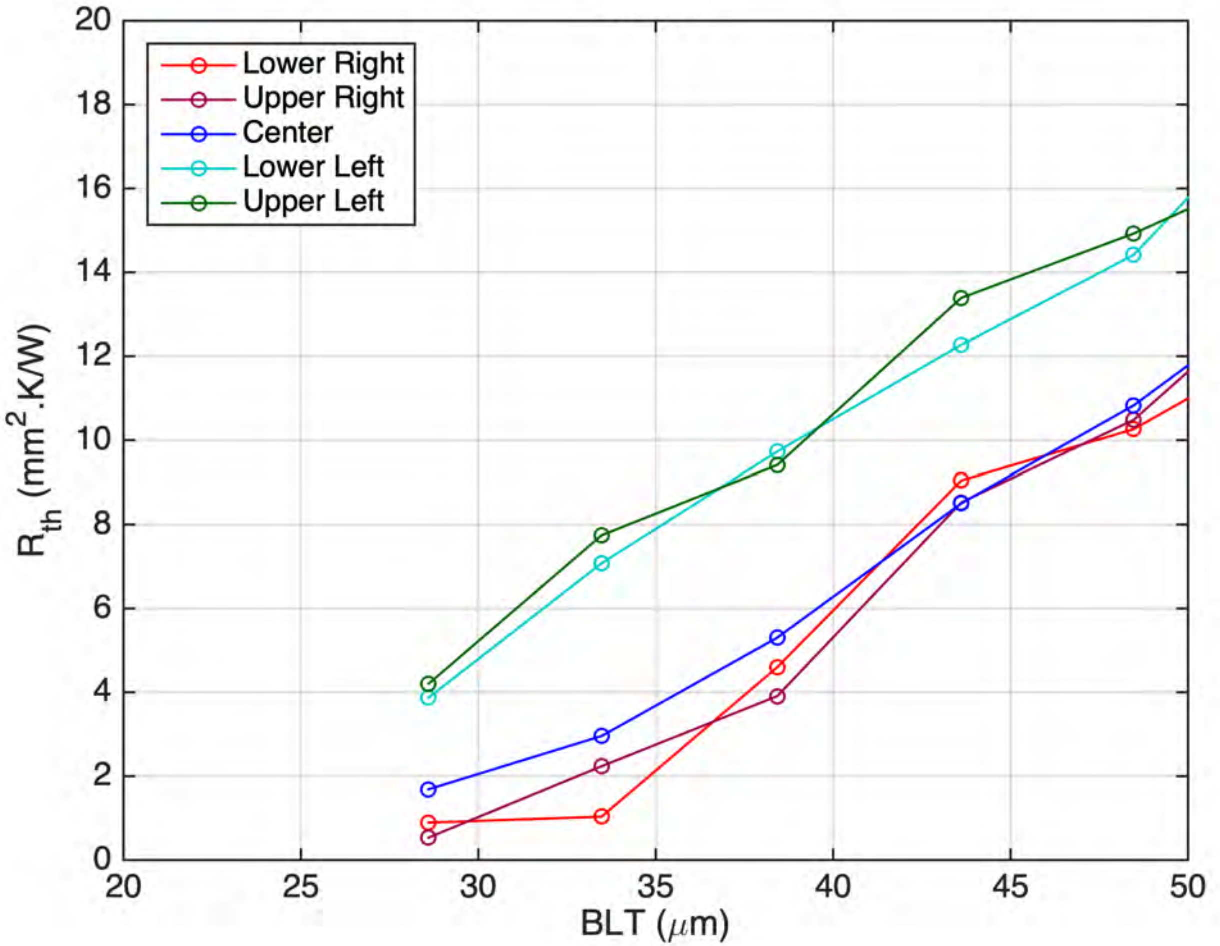
- BLT optimization
- Cure kinetics

ASTM D5470 - Thermal Test Chip

NANOTEST
Berliner Nanotest und Design GmbH

- Utilizing an ASTM-D5470 Test Setup
- Thermal resistance between Si and Ni interfaces measured, at 5 diodes located on the test chip






ARIECA
Thank You!
Feel free to reach out to me at navid@arieca.com

Low Temperature Performance - DSC

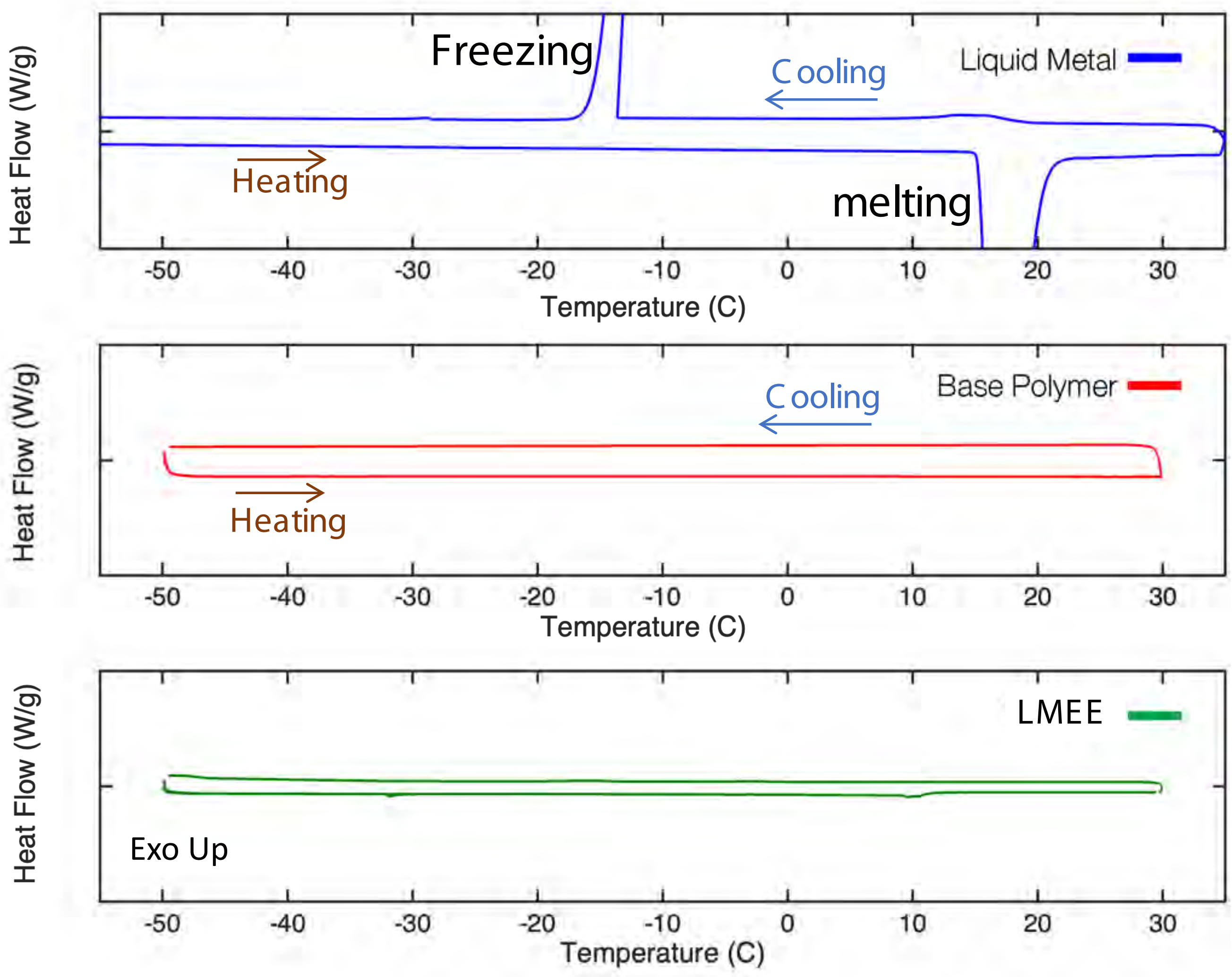
Super Cooling: The ability of liquids to go below melting temperature without becoming solid

Size Effects

Droplets with 50μm radius

Metal	T_m (°C)	ΔT_s (°C)	$\Delta T_s / T_m$
Mercury	-40	58	0.247
Gallium	30	76	0.250
Tin	232	105	0.208
Bismuth	270	90	0.166

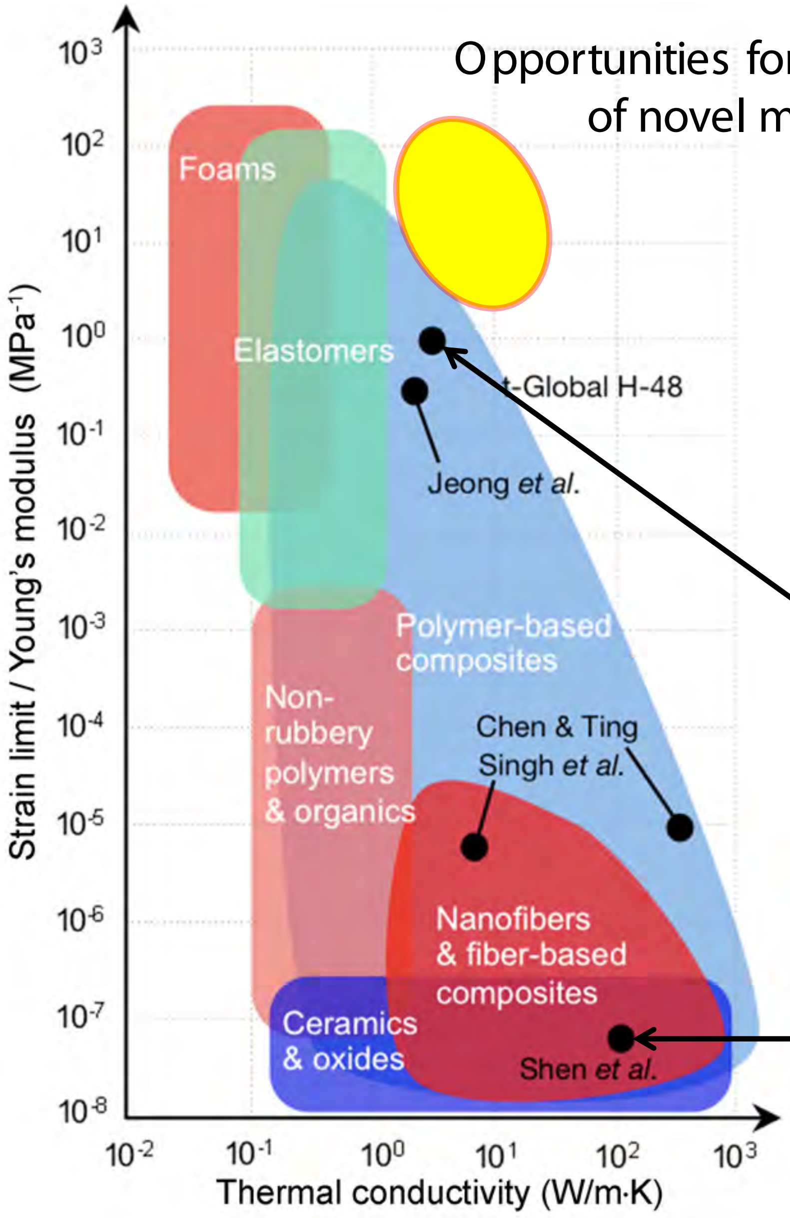
D. Turnbull, **J. Appl. Phy., 1950**



M. H. Malakooti *et al.*, "Liquid Metal Supercooling for Low-Temperature Thermoelectric Wearables," ***Adv. Funct. Mater.***, vol. 29, no. 45, 2019.

Motivation – Thermo-Mechanical Tradeoff

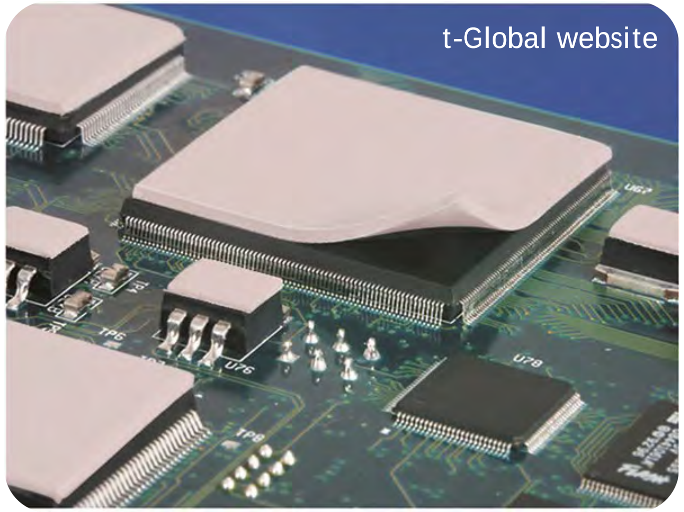
Opportunities for development of novel materials



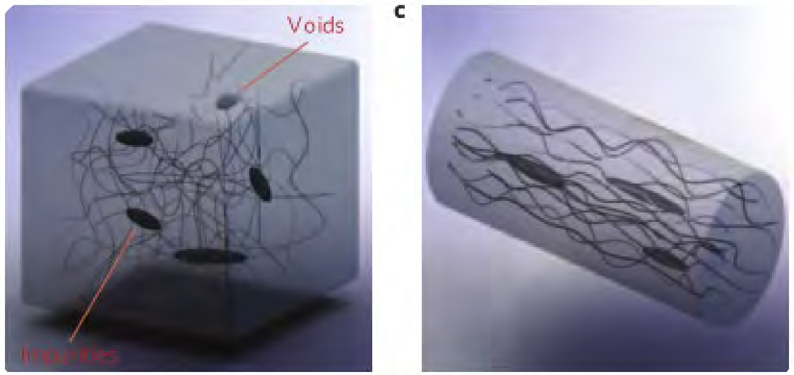
$$k_{solids} = \frac{1}{3}\int C(\omega)v(\omega)l(\omega)d\omega$$

Newton-Laplace equation

$$v(\omega) \approx V_{sound} \approx \sqrt{E/\rho}$$



Shen et al, ***Nature Nano*** (2010)

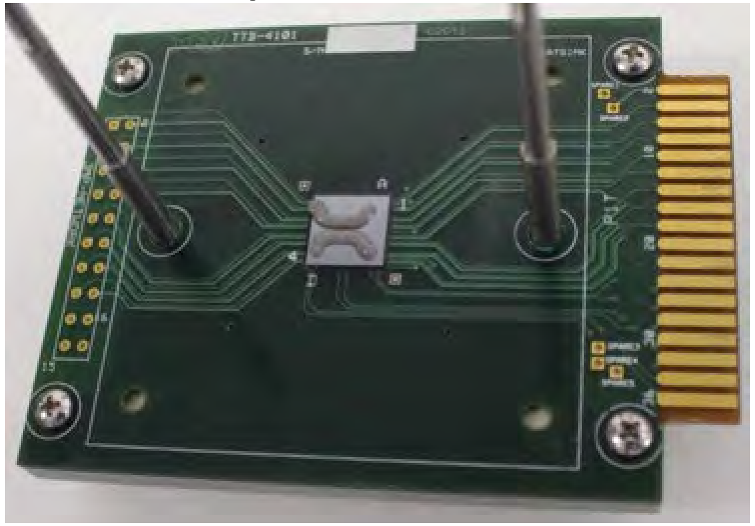


TIMbber™: The World's Most Adaptable TIM

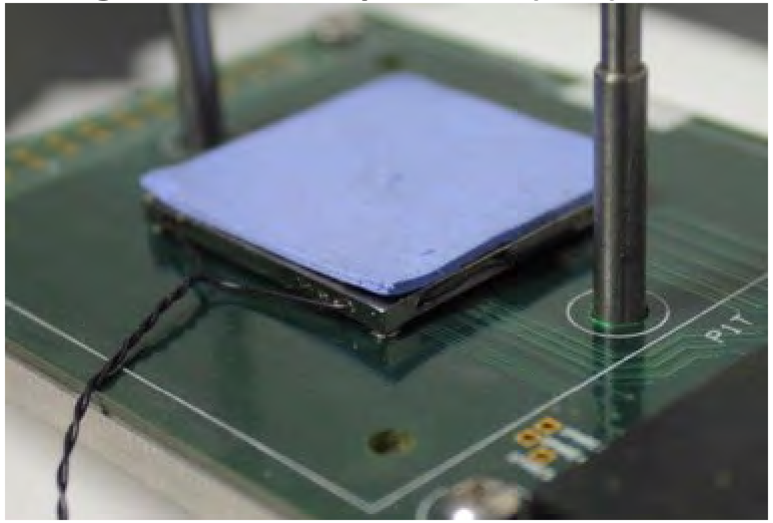
- **TIMbber**™ is a spring-like thermal interface material
- Eliminates the trade-off between thermal performance and reliability imposed by current TIM solutions, allowing designers to push power limits

TIM being applied to IC with standard techniques

Completed TIM trace

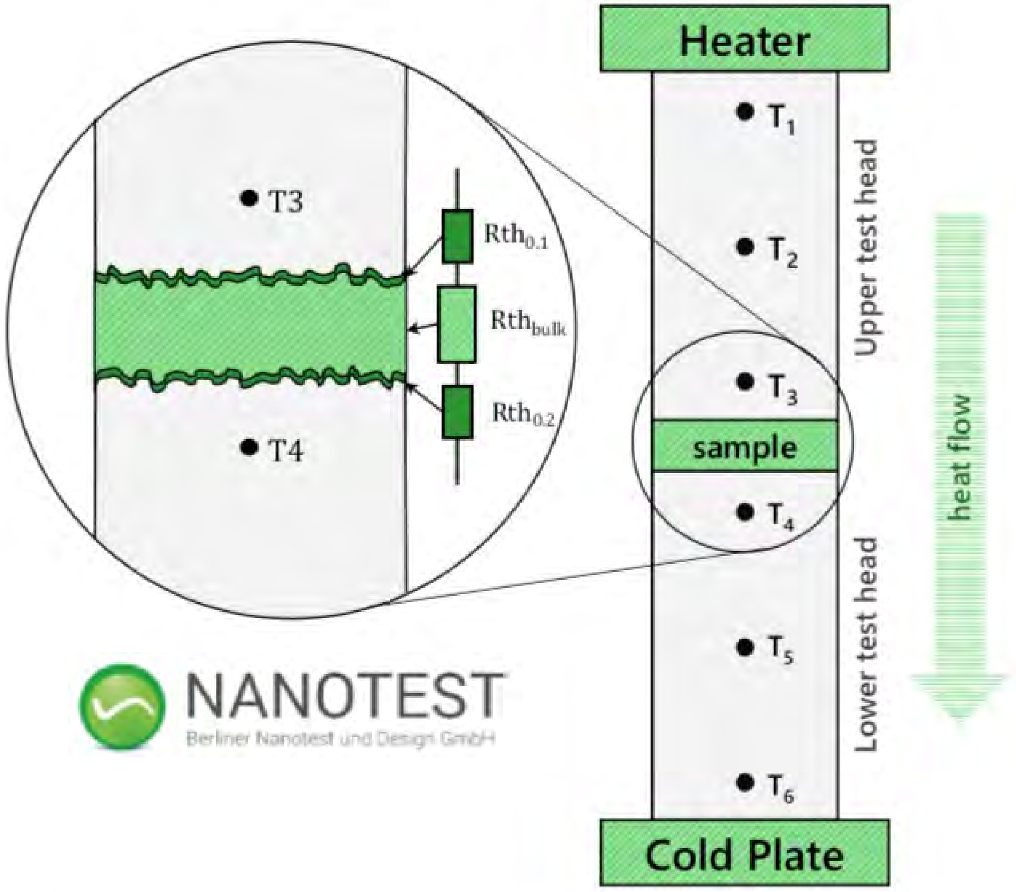


Integrated Heat Spreader (IHS) added

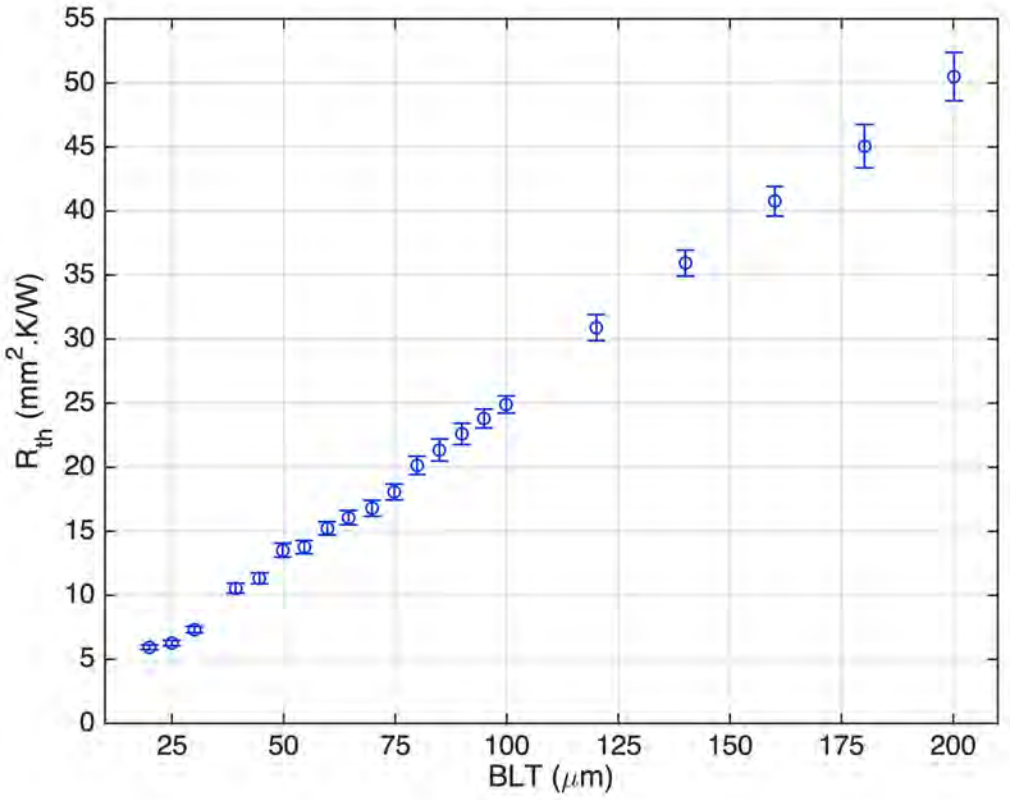


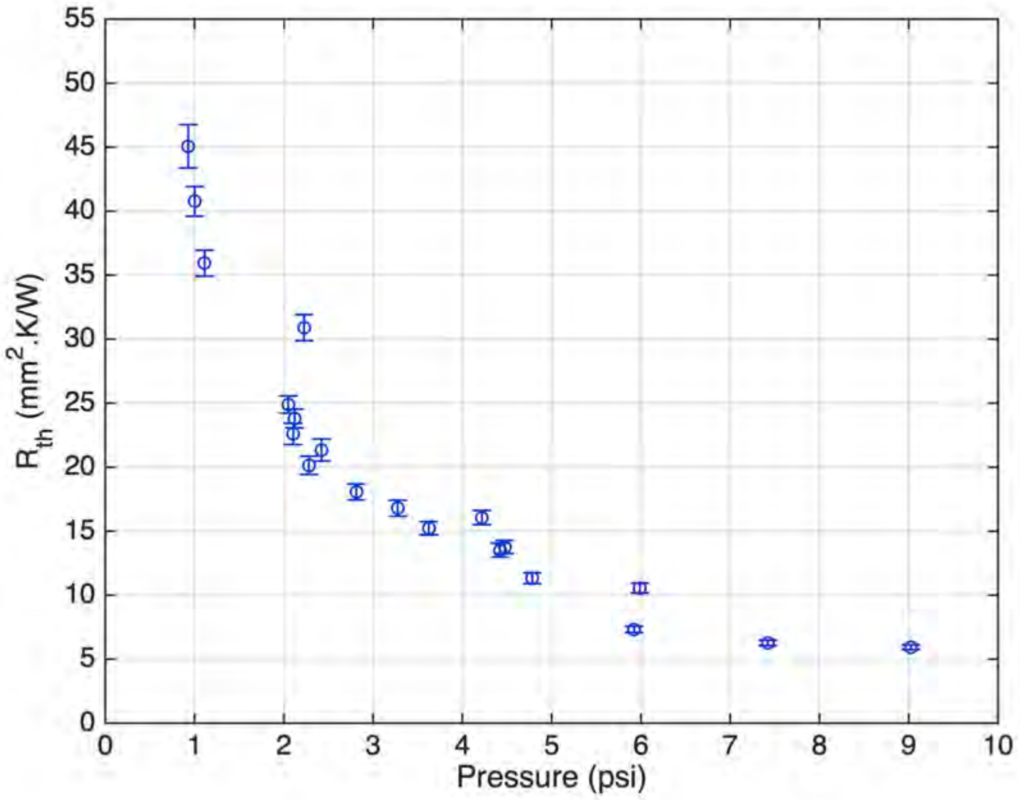
Thermal Resistance Measurement

- Temperatures
  - Sample $T_{S,avg} \approx 25$ °C
  - Heater $T_H = 30$ °C (set point)
  - Liquid Cold Plate $T_C \approx 15$°C
- BLTs
  - BLTs measured: 200, 180, ..., 120, 100, 95, 80, ..., 25, 20 µm
- Contacting surfaces
  - Material: Cu - Cu
  - Roughness *Rz* < 2 µm
  - Area *A*: 1.33 cm²
- Measurement method: ASTM D 5470



ASTM D-5470





BLT (µm)	R (mm^2.K/W)	P (psi)
20	5.9	9
30	7.3	5.9
40	10.3	4.4

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