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

Dr. Na vid Kazem
CEO & Co-Founder
Arie ca Inc.

Vivek Singh, Phil Marzolf, Jeff Gelorme, Car mel Majidi

Pittsburgh, PA, USA
navid@arieca.com
919.741.7549
Dr. Navid Kazem

• **Bachelor of Science** (2012)
  o Sharif University

• **Master of Science** (2013)
  o Carnegie Mellon University

• **PhD** (2018)
  o Computational Mechanics, CMU
  o Swartz Entrepreneurship Fellow from Tepper School of Business

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

**Moore’s Law**

- Shrinking transistor size
- Increasing heat density

TDP >> 100W for current generation high performance devices

**Physically Constrained Footprints**

**Meets**

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

In-package thermal resistance C.mm²/W:

- Incompatible due to Fluidity
- Expensive (gold metallization), high temperature reflow
- Reliable over the long term

Timeline:
15
12
9
6
3

HVM compatibility

- Polymer TIMs - Gels
  - Aluminum Oxide - Silver
  - Boron Nitride
  - Vertically aligned Carbon

- Solid TIM

- Liquid Metals

- Higher Performance
- Higher TCM $
Existing Solutions - Thermal Interface Materials (TIM1)

- In-package thermal resistance C.mm²/W:
  - 15
  - 12
  - 9
  - 6
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- HVM compatibility:
  - Incompatible due to Fluidity
  - Expensive (gold metallization), high temperature reflow
  - Reliable over the long term

- Polymer TIMs - Gels

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

- Solid TIM
- Liquid Metals

Future directions
**Liquid Metals**

- 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 (σ = 3.4x10^6 S/m, k = 26.4 W/m·K, at ~30°C)
Merging Liquid Metal and Elastomers

- 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) - Polymer

![Graph showing elongation at break and modulus vs.

\[ \phi_{LM} \]

Compliance • Young’s Modulus (Pa)

- Compliance
- 0% 57% 57% 65% 65% 70%
- Gelatinous
- 0% 57% 57% 65% 65% 70%
- Modulus (kPa)
- 00356

\[ \phi_{LM} = 65\% \]
LMEEs maintains excellent adhesion to both nickel and silicon even when heavily loaded to provide low thermal resistance
Thermal Conductivity

Transient Hot wire Method

Platinum wire

ASTM D5470

Volume Fraction $\Phi = 65\%$

$K = 4 \text{ W/mK}$


00358
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 TIM

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°C)
Thermal Resistance Measurement

» Temperatures
  › Sample $T_{S,avg} \approx 25 \, ^\circ C$
  › Heater $T_H = 30 \, ^\circ C$ (set point)
  › Liquid Cold Plate $T_C \approx 15^\circ C$

» BLTs
  › BLTs measured:
    200, 180, ..., 120, 100,
    95, 80, ..., 25, 20 \, \mu m

» Contacting surfaces
  › Material: Cu - Cu
  › Roughness $R_z < 2 \, \mu m$
  › Area $A: 1.33 \, cm^2$

» Measurement method: ASTM D 5470
### BLT (μm) | R (mm²·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
TIMbbber ALT304-90 cure: 1 hr @ 70C, 1 hour ramp to 125C
Lid attach: Dowsil 3-6265, 1 hour cure @ 125C

~80W applied (used for $\Theta_{jc}$ calculations)
Liquid cooling solution
TIM1 joint temperature: ~40°-50°C
Die dimensions: 11mm x 13mm

Thermal Resistance
junction to case
($C^*mm^2/W$)
15.87

- 3.72
- 6.86
- 5.29
- 2100μ +/- 50μ
- 1500μ
- 610μ

Thermal Results – TTV

Power Density = 56W/cm^2

Center $R_{jc}$ 15.87 C-mm^2/W
T₀ Thermal Results – TTV

Die dimensions: 11mm x 13mm

Thermal Resistance
junction to case
(C°mm²/W)
15.87

3.72
6.86
5.29

Thickness
2100µ +/- 50µ

In-package thermal resistance C.mm²/W

15
12
9
6
3

HVM compatibility

Polymer TIMs - Gels

Liquid Metals

Solid TIM

Lid
TIM
Si Die
Reliability Tests

- MIL-STD-883B Compliant
- -55°C (-10°C, +0°C) to +125°C (+10°C, -0°C)
- T₀ 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
**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 refloows, 5min. cool down between runs)

<table>
<thead>
<tr>
<th>Preconditioning $\Theta_{jc}$ Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel #</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>Ave. $\Theta_{jc}$</td>
</tr>
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</table>

TTV Channel Map
Existing Solutions - Thermal Interface Materials (TIM1)

- **In-package thermal resistance C.mm²/W**
  - 15
  - 12
  - 9
  - 6
  - 3

- **HVM compatibility**

### Incompatible due to Fluidity
- Liquid Metals

### Expensive (gold metallization), high temperature reflow
- Solid TIM

### Reliable over the long term
- Polymer TIMs - Gels
  - Parker
  - Shin-Etsu
  - Laird
  - Dupont

- Thermal resistance of less than 7 C.mm²/W and maintained performance during reliability cycles

### Future directions
Next generation TIM performance

- Thermal performance rivaling Solid-TIMs ($R_{jc} \ 3-5 \ \text{C.mm}^2/\text{W}$)
- 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
• Utilizing an ASTM-D5470 Test Setup
• Thermal resistance between Si and Ni interfaces measured, at 5 diodes located on the test chip
Thank You!

Feel free to reach out to me at navid@arieca.com
**Super Cooling:** The ability of liquids to go below melting temperature without becoming solid.

<table>
<thead>
<tr>
<th>Metal</th>
<th>$T_m$ (°C)</th>
<th>$\Delta T_s$ (°C)</th>
<th>$\Delta T_s / T_m$</th>
</tr>
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<tbody>
<tr>
<td>Mercury</td>
<td>-40</td>
<td>58</td>
<td>0.247</td>
</tr>
<tr>
<td>Gallium</td>
<td>30</td>
<td>76</td>
<td>0.250</td>
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<tr>
<td>Tin</td>
<td>232</td>
<td>105</td>
<td>0.208</td>
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<tr>
<td>Bismuth</td>
<td>270</td>
<td>90</td>
<td>0.166</td>
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D. Turnbull, J. Appl. Phy., 1950

Motivation – Thermo-Mechanical Tradeoff

Opportunities for development of novel materials

\[ k_{\text{solids}} = \frac{1}{3} \int C(\omega) \nu(\omega) l(\omega) d\omega \]

Newton-Laplace equation

\[ \nu(\omega) \approx V_{\text{sound}} \approx \sqrt{\frac{E}{\rho}} \]

• 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
Thermal Resistance Measurement

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  › Heater $T_H = 30$ °C (set point)
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