LIME: Liquid Metal for Semiconductors

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About Me

- Loughborough University, UK, 2007 – 2011
- Aalborg University, DK, 2013 – 2020
- Denmark Independent Research Fund, 2020 – 2022
- IFSTTAR, FR, 2014 – 2015
- University of Alabama, 2022 – Present

Research Interests:

- **Electronics Packaging**
- **Reliability**
- **Temperature Measurements**
- **Liquid Metals**

1700V/1000A Power Semiconductor Failure

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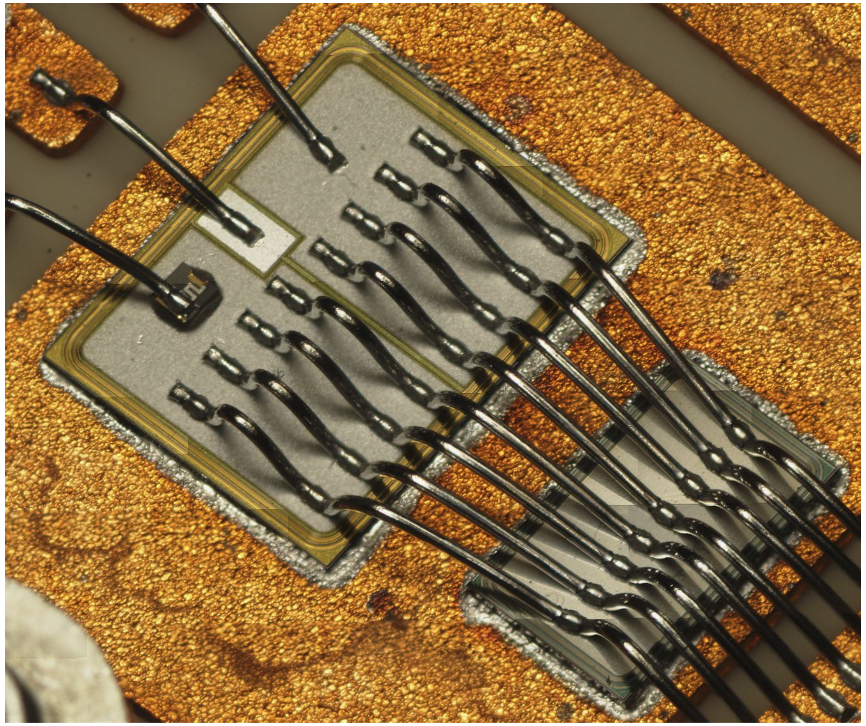
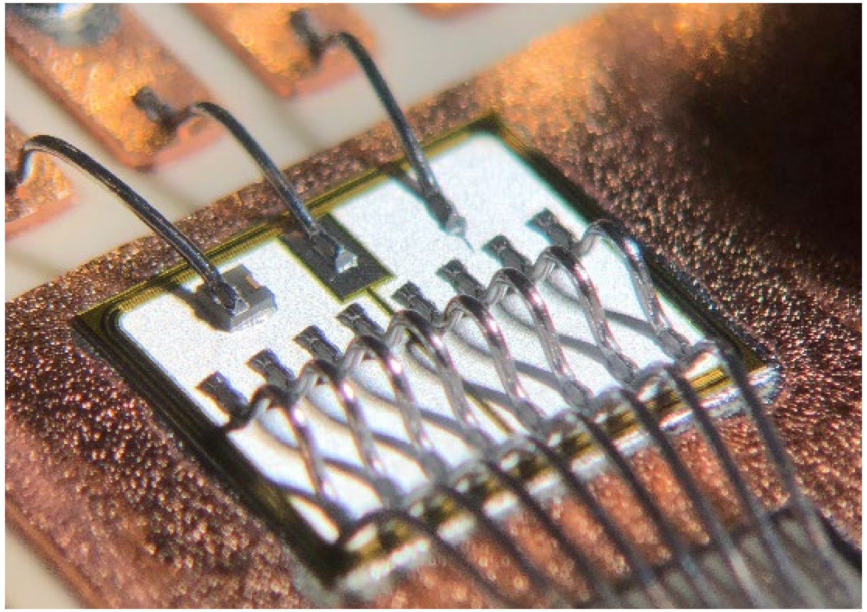
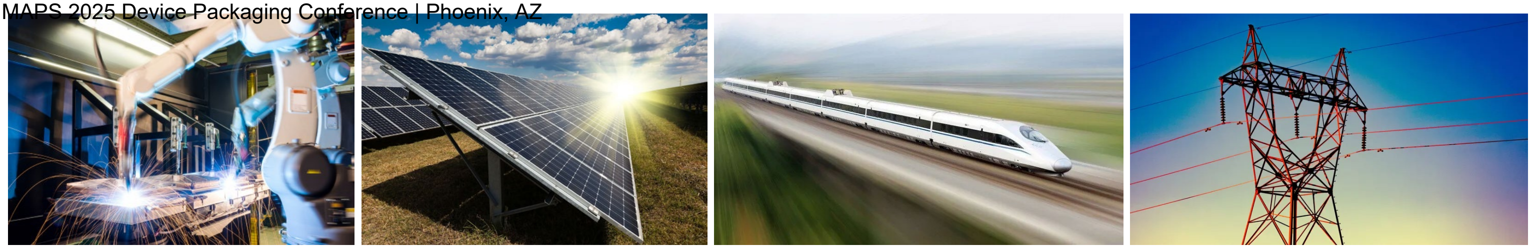




LIME



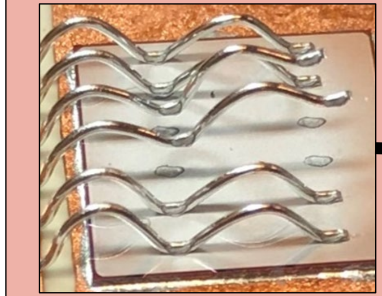
Power Semiconductors are the fundamental component in electrified transport, energy generation, distribution and industrial machines.

LIME Semiconductor

We use liquid metals to manufacture ultra-reliable, lightweight, high-power semiconductors

✗ **Problem:** Power semiconductor failures are caused by thermo-mechanical stress.

Systems are oversized to compensate for this



Failure due to thermo-mechanical stress

→

Power semiconductor failure

→

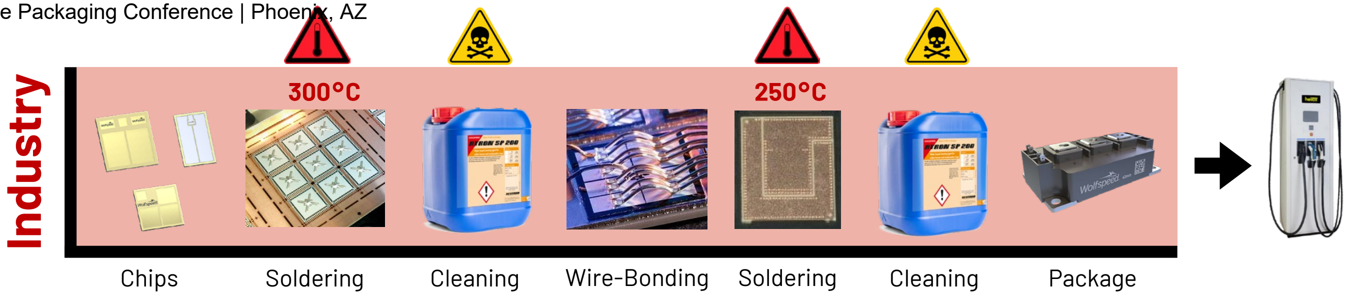
System failure

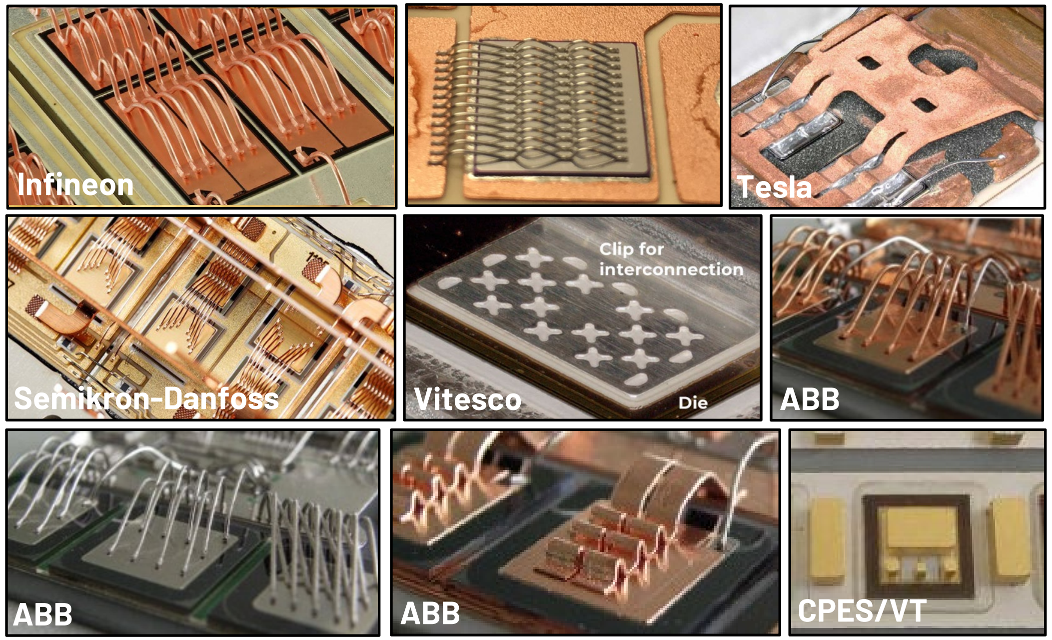
✓ **Solution: Liquid metal** is inherently resistant to thermo-mechanical stress.

- ✓ **40x - 80×** increased **lifetime**
- ✓ **80%** reduced **system weight**
- ✓ **80%** reduced **system cost**
- ✓ **Non-toxic** gallium alloy
- ✓ Patent Pending

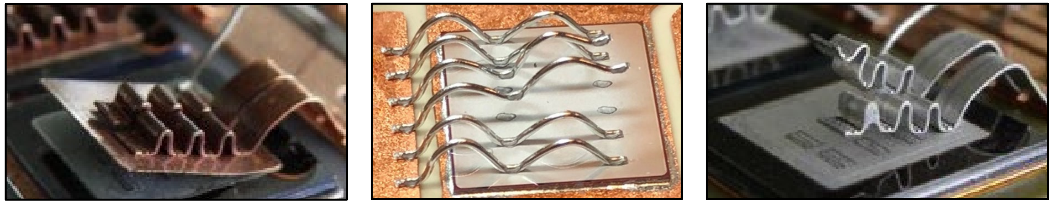
How semiconductors fail

Competing technologies use **solid metals** manufactured with **high-temperature** and **high-pressure**

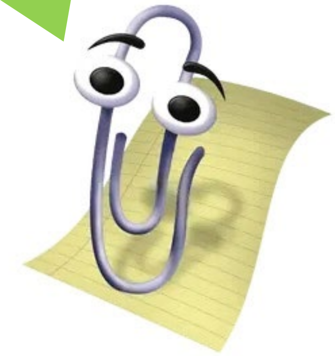




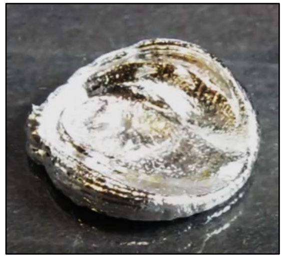
All degrade under **thermomechanical stress**

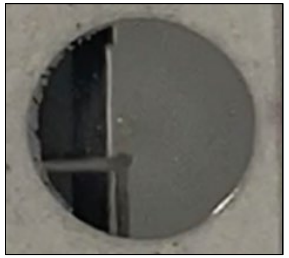


LIME uses **liquid metals**



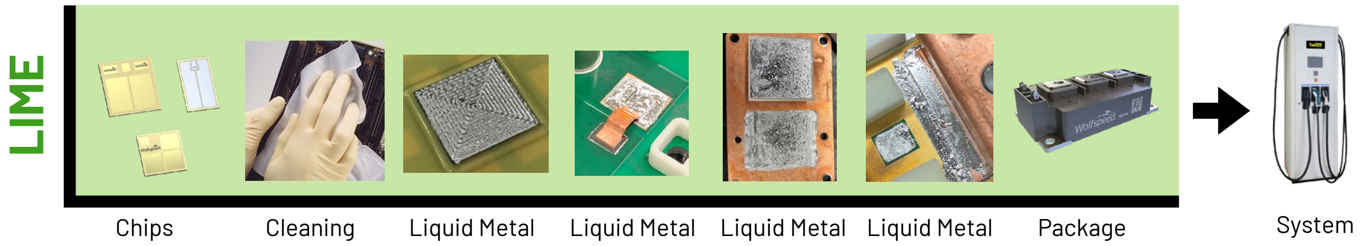
How LIME works

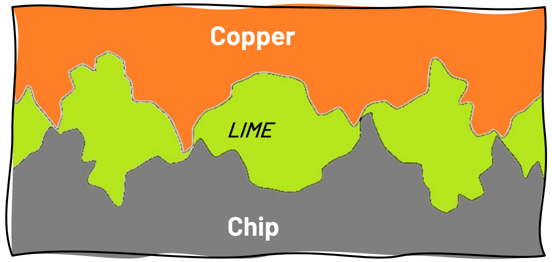




LIME uses liquid metal pastes with enhanced viscosity.
All interfaces are manufactured at a low temperature with a **single dispensing process**.

LIME is a **simple**, low temperature process without hazardous chemicals



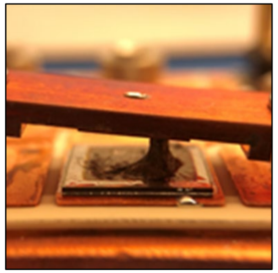


All fragile solid interconnects are replaced by **liquid metal** interfaces.

1× lifetime

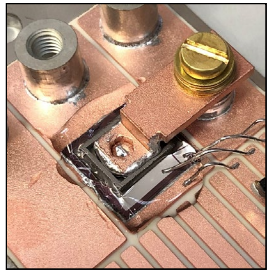
Industry
Standard process

1.8×



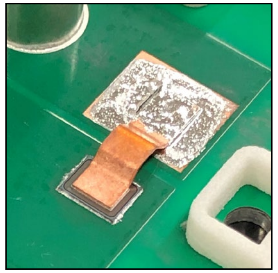
2020
LIME initial concept

2.4×



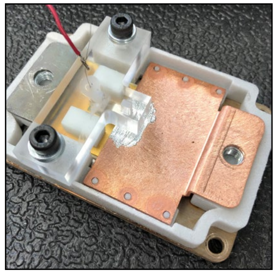
2022
Si IGBT

3.4×



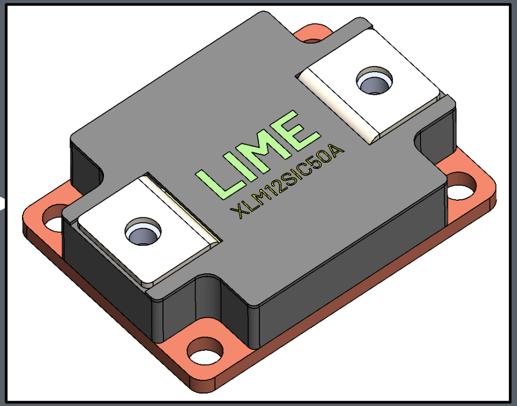
2023
Si Diode

40x - 80× lifetime



2024
SiC MOSFET

LIME SiC MOSFET



2025

LIME First Versions (2019 – 2022)

2019-2020: 200 V Silicon Schottky Diode
2022: 600 V Silicon IGBT

- Recess/Cavity/Guard Ring/Floating based
- Use of pure Ga on Aluminium – barrier layer of Titanium

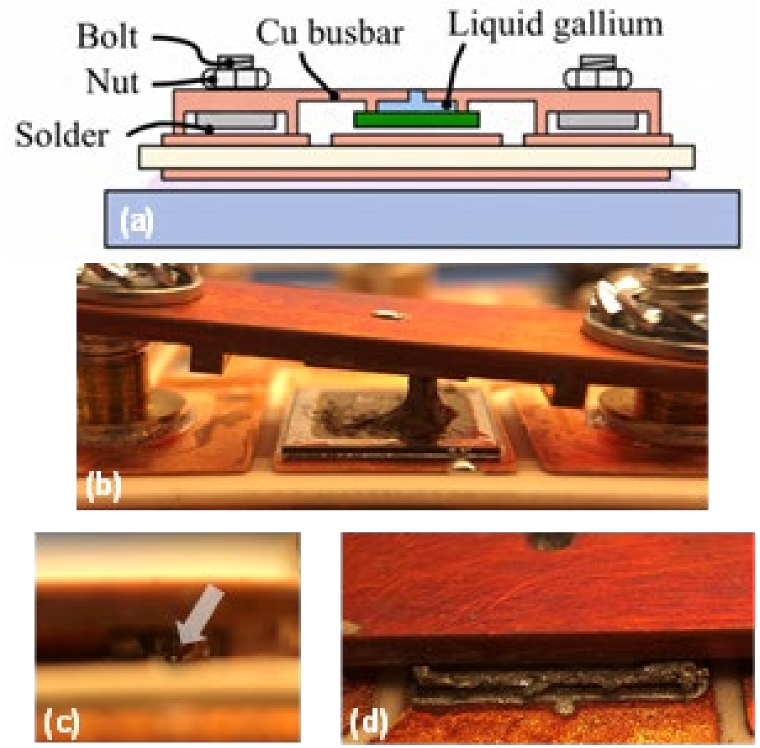


Fig. 2. Images of LM-1 on 200 V Silicon diode.
(a) Schematic of LM-1
(b) Photo of LM-1 showing Ga on topside
(c) Ga leak causing short-circuit
(d) Ga topside after power cycling

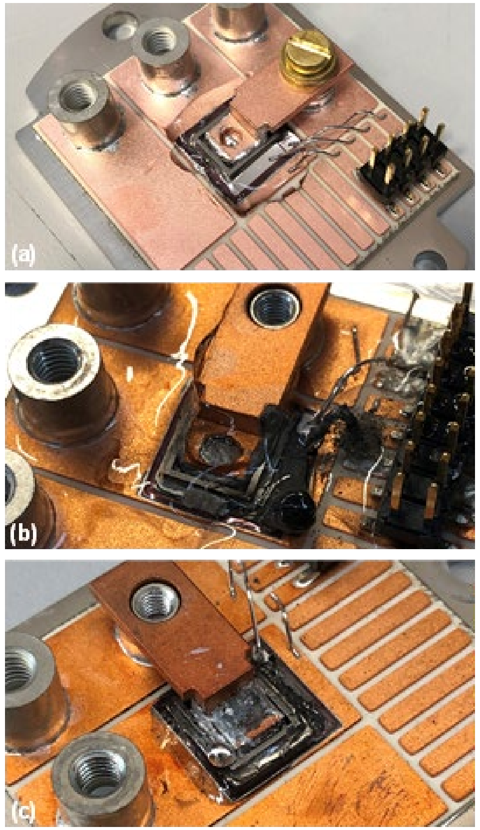


Fig. 6. LM-2 on a Si IGBT
(a) LM-2 prior to power cycling
(b) Corrosion of topside after power cycling
(c) Corrosion of topside after power cycling

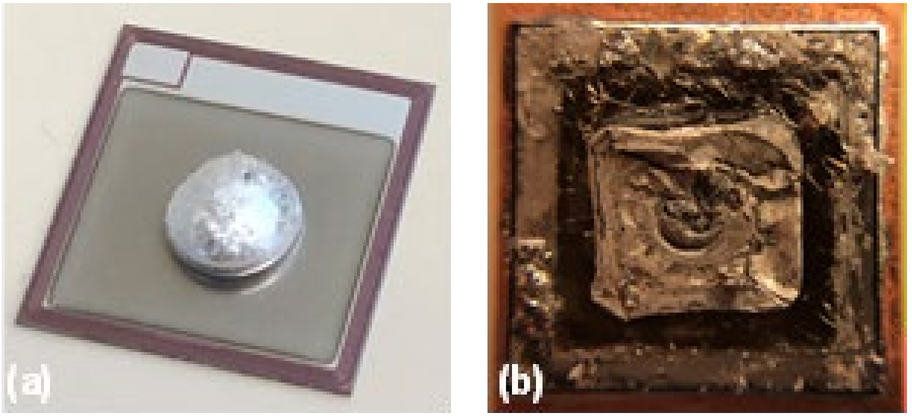


Fig. 3. (a) Ga on Ti barrier layer of Al metallized IGBT
(b) Barrier layer rupture on Si diode after power cycling

LIME First Versions (2019 – 2022)

- High electrical instability – wetting issues
- <u>Barrier layer didn't work</u> - Corrosion of Al and Ga
- Guard-ring/recess did not work – Ga leakage
- Power Cycling vs. SAC305 and Al wirebonds
- 2 samples from each failed almost instantly

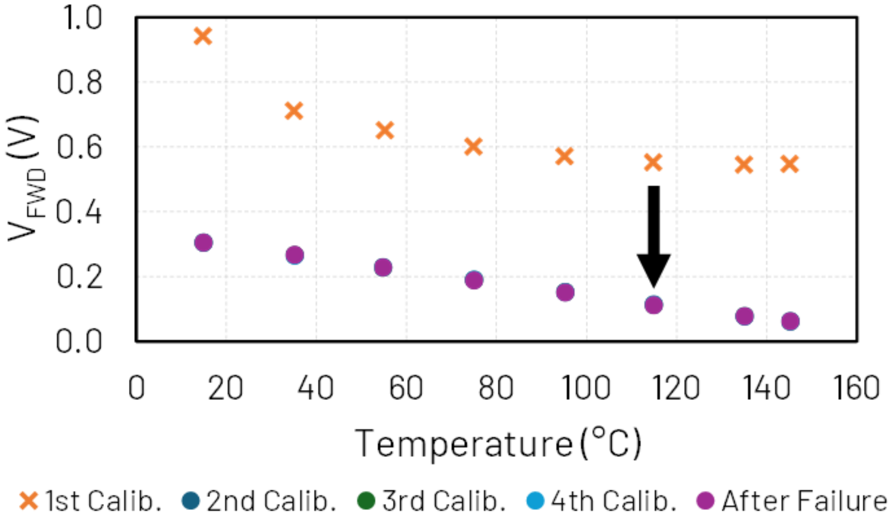


Fig. 4. Calibration of $V_{CE}(T)$ of LM-1 after successive calibration routines.

LIME First Versions (2019 – 2022)

- High electrical instability – wetting issues
- Barrier layer didn't work - Corrosion of Al and Ga
- Guard-ring/recess did not work – Ga leakage
- Power Cycling vs. SAC305 and Al wirebonds
- 2 samples from each failed almost instantly
- 1 sample from each achieved 6x – 8x lifetime

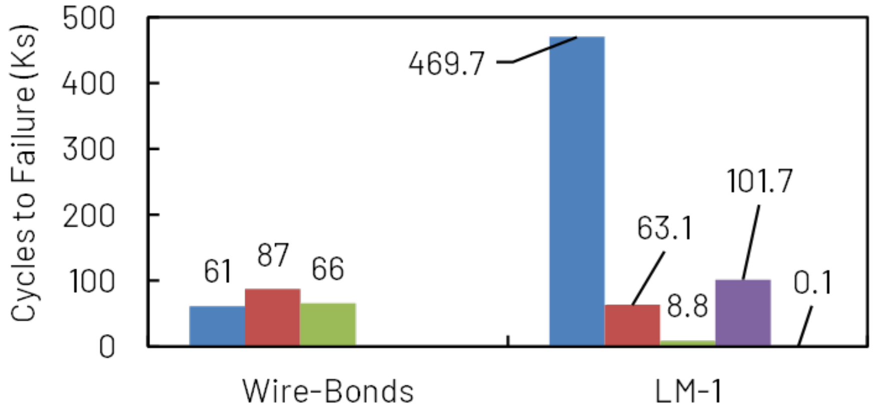


Fig. 5. Cycles to failure for LM-1 and Al wirebonded diodes during power cycling.

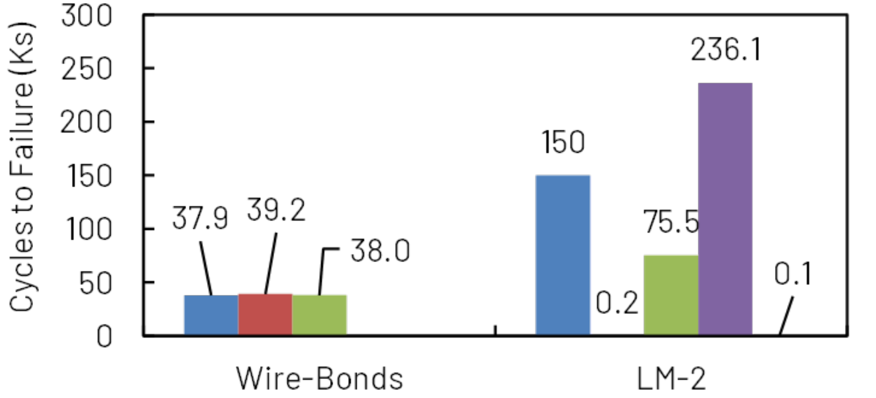
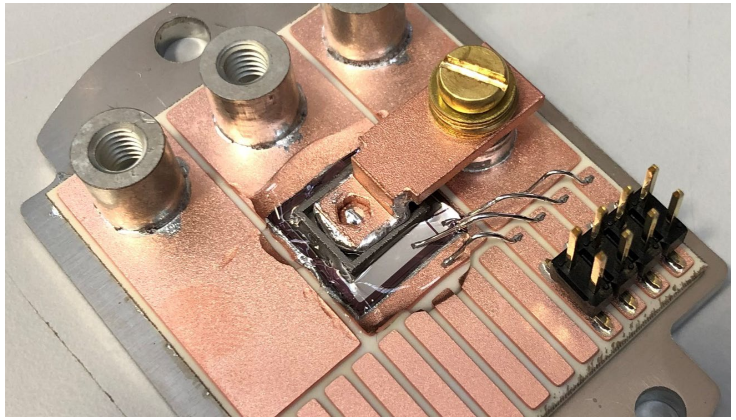
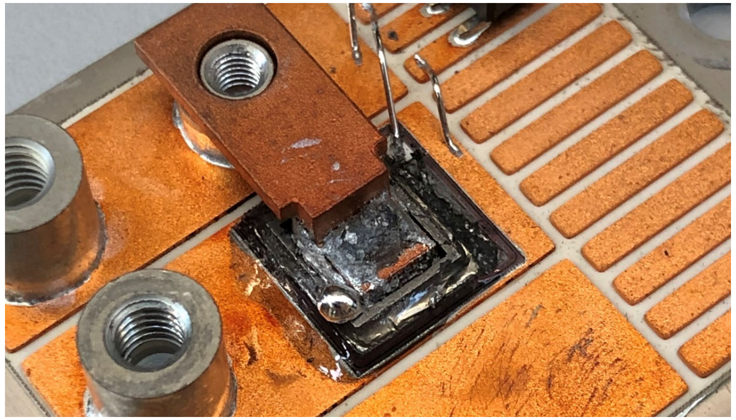


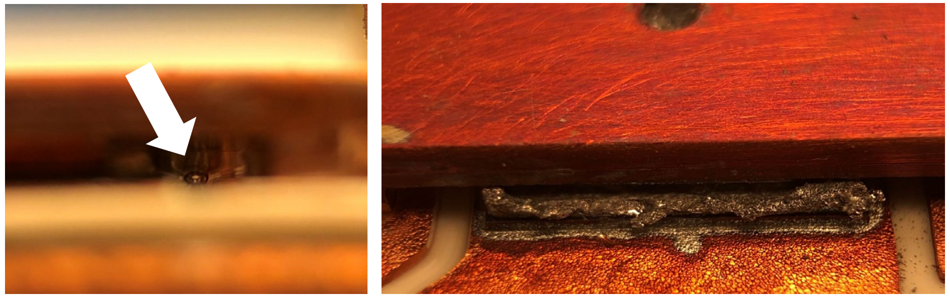
Fig. 7. Cycles to failure for LM-2 and Al wirebonded Si IGBTs during power cycling.



Before



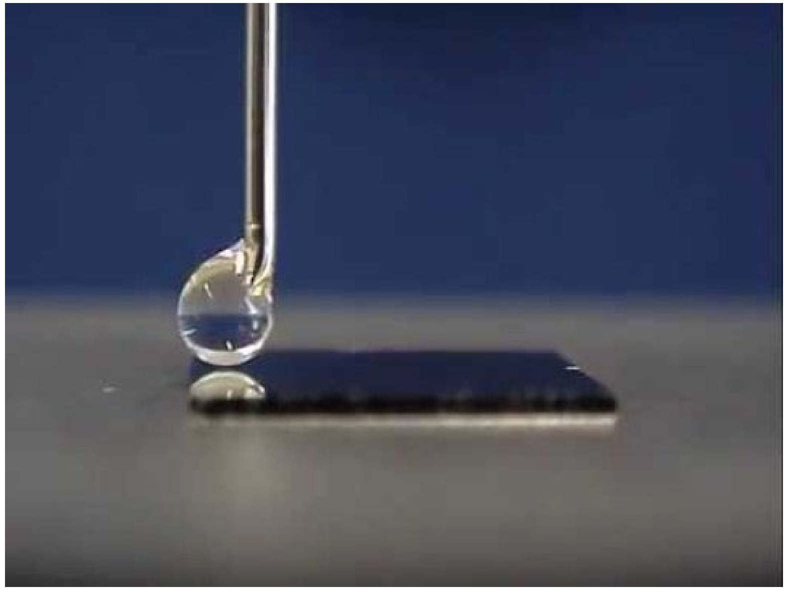
After



LIME Takeaway

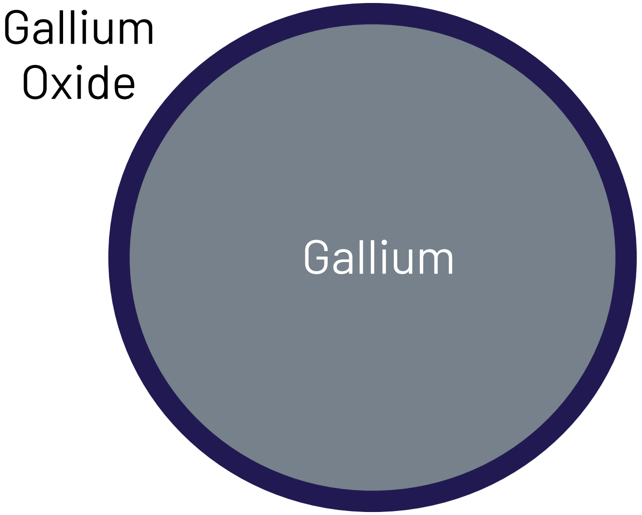
Recess/Cavities/Guard Rings don’t work

Control Adhesive/Cohesive Forces for containment



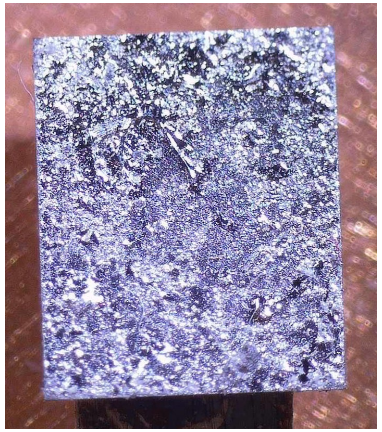
https://www.youtube.com/watch?v=puYo9w4cu0c

Liquid Metal Pastes



LIME uses **Gallium based alloys**. Gallium forms Gallium Oxide, a solid, on its surface. This oxide is very thin and brittle and can be broken easily.

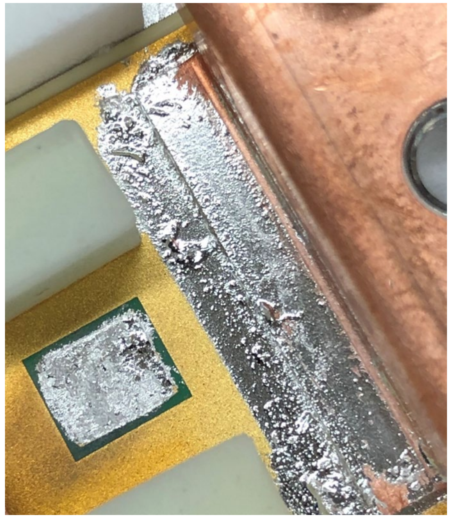
Continuous mixing of Gallium in air can form a **paste like material** – part Gallium and part Gallium Oxide



Gallium/Gallium Oxide paste

LIME can also use **Indium** or **Bismuth** based alloys. However, **Gallium** based alloys are more **corrosion resistant.**

Gallium based alloy **(bottom-side of chip)**



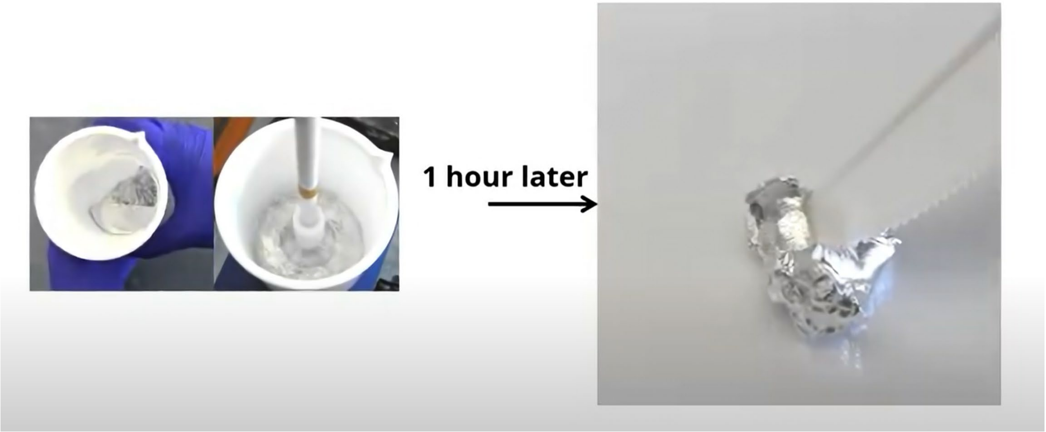
Indium based alloy **(topside of chip)**

Manufacturing Process

- **Just mix with in air**
- How to manufacture the paste? Mixing time, vacuum step, Ga only, GaIn, or GaInSn? Adding particles?
- How to dispense the paste? Mix with alcohol? https://youtu.be/RuWJfXTZDsU?t=348
- Humidity/moisture is the main failure mechanism – how to prevent expansion?
- Intermetallic reaction with Gold, Silver, Palladium, Copper?

- Longer video: https://youtu.be/qs-wn1oXFP8

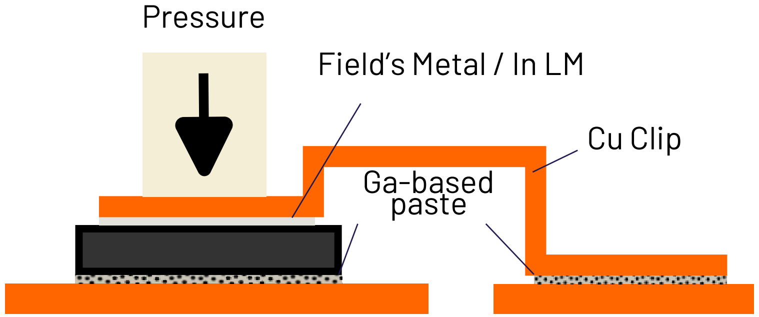
Manufacturing Process and Moisture Impact

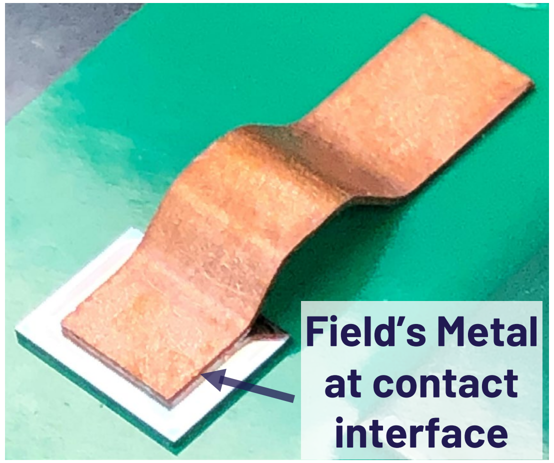


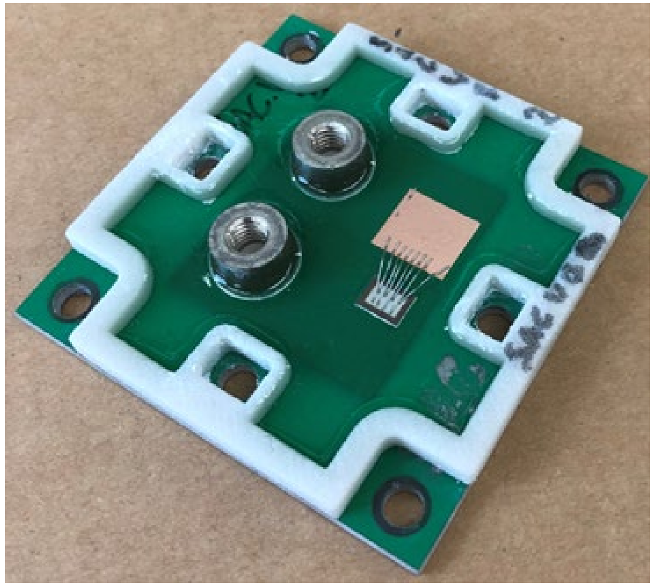
https://www.youtube.com/watch?v=2fAU56Sy-Mw

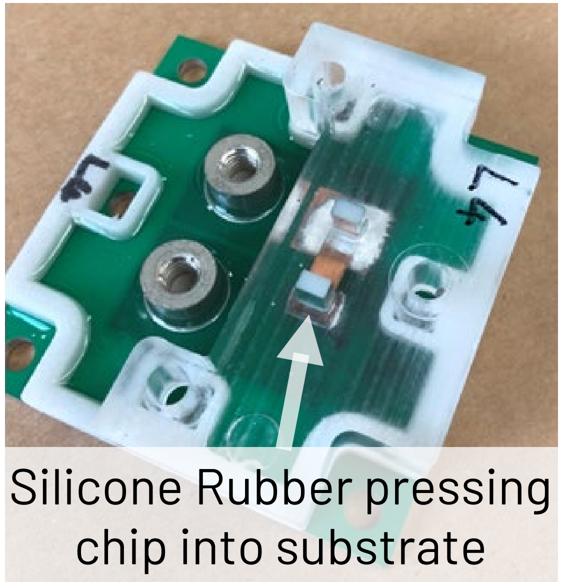
LIME Version 1 – 600 V Si Diode (2023)

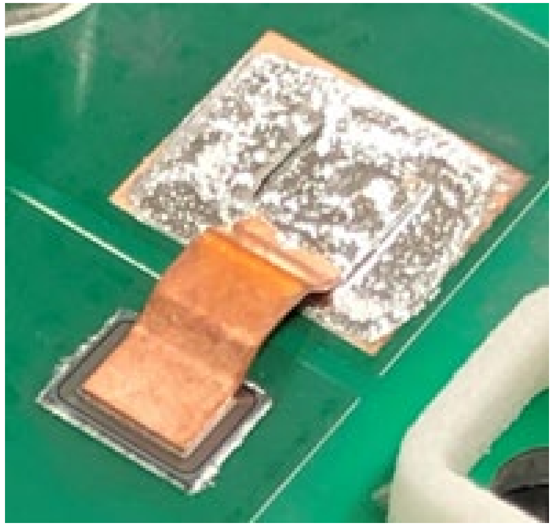
- Avoid all contact between Ga and Al
- Field's Metal used for topside connection
- Only capillary forces and viscosity of paste used to constrain LM
- Pressure to minimize bondline thickness
- **Pre-aging process applied**




Field's Metal at contact interface

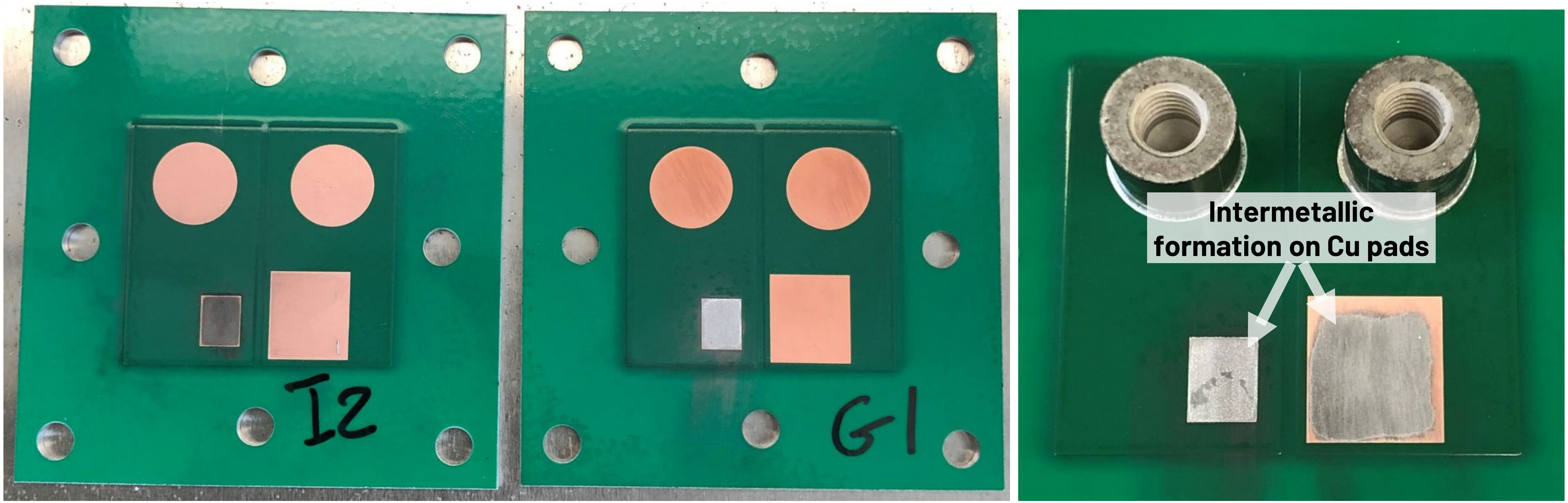



Silicone Rubber pressing chip into substrate



LIME Version 1 – 600 V Si Diode

- Pre-aging process
- **Apply LM to pad and place on hotplate at operating temperature for 2 hours**
- Then re-apply LM materials

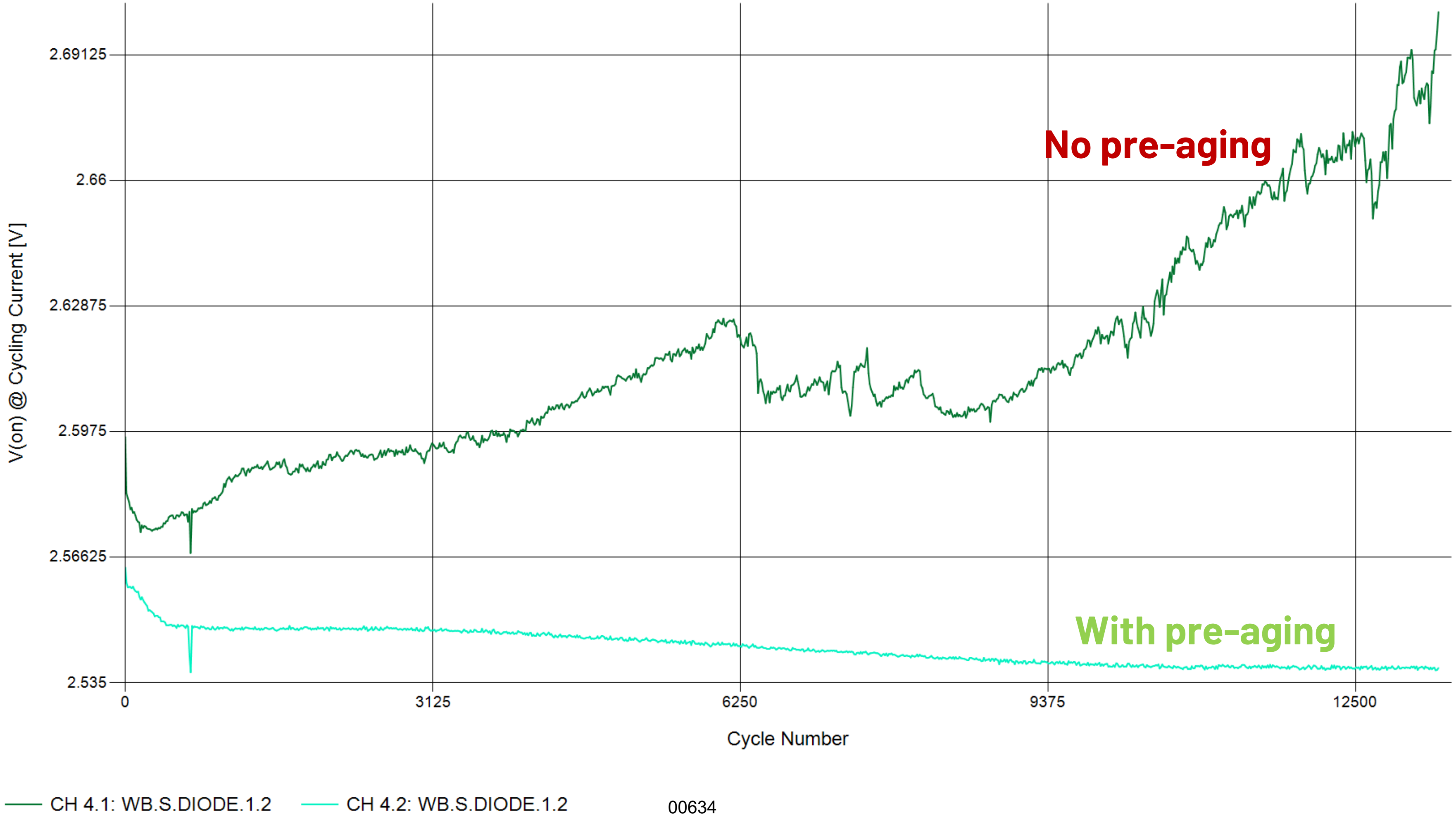


Intermetallic formation on Cu pads

Sample Size: 1

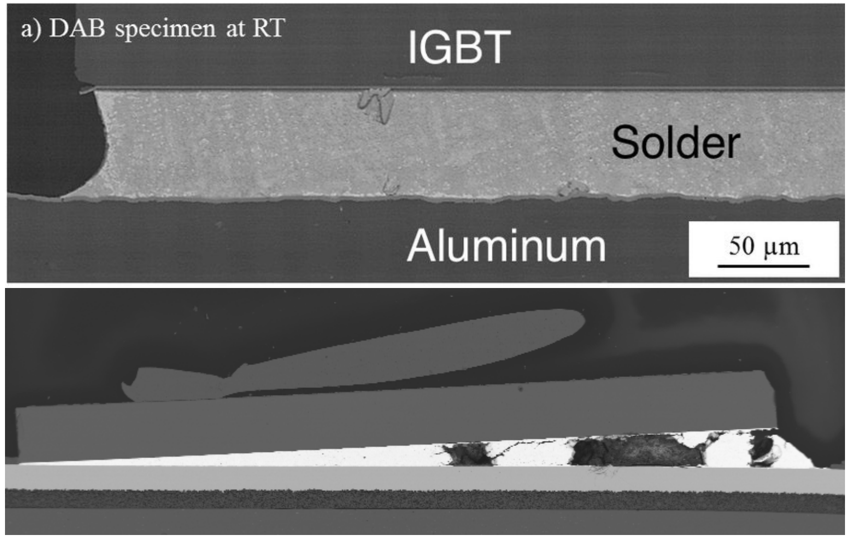
LIME Version 1 – 600 V Si Diode

- Pre-aging process
- **Impact at start of power cycling test**

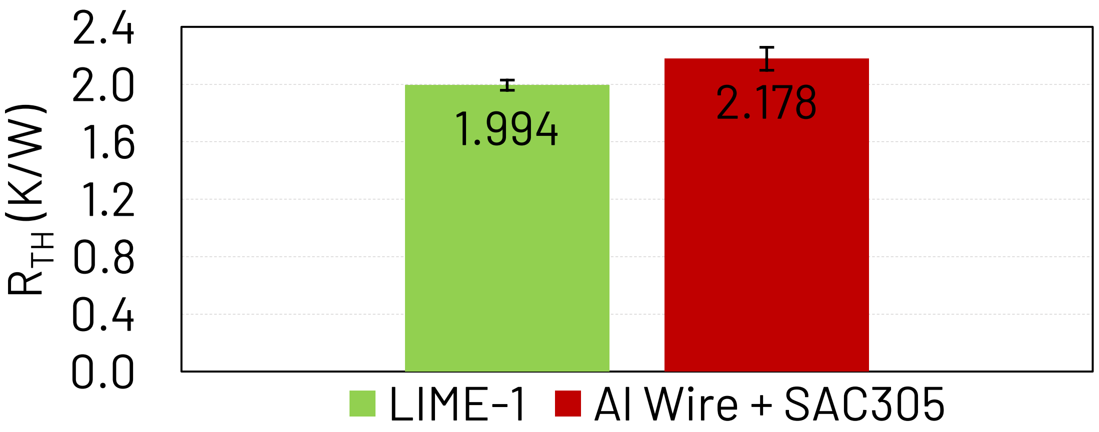


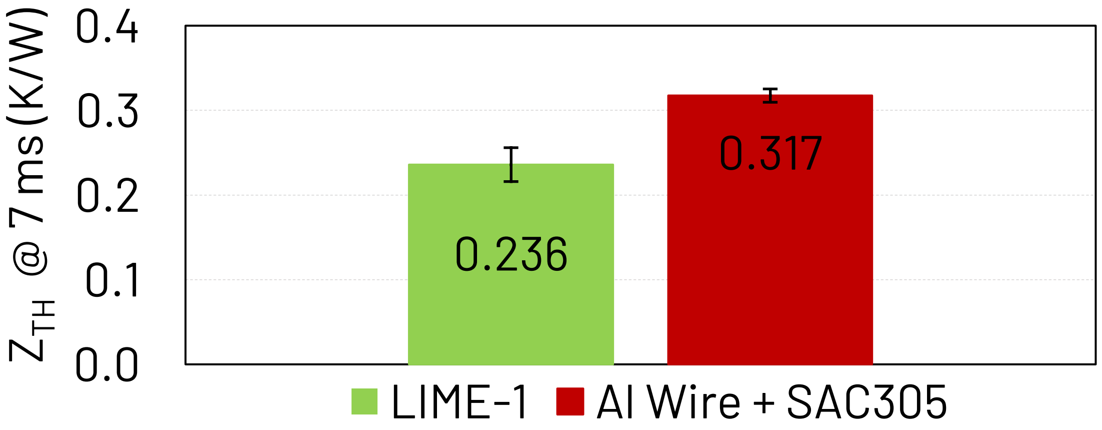
LIME Version 1 – 600 V Si Diode

- 10% improved $R_{TH(J-A)}$
- **25% improved Z_{TH} @ 7-milliseconds**
- In comparison to SAC305 solder and Al wirebonds
- 6 samples each



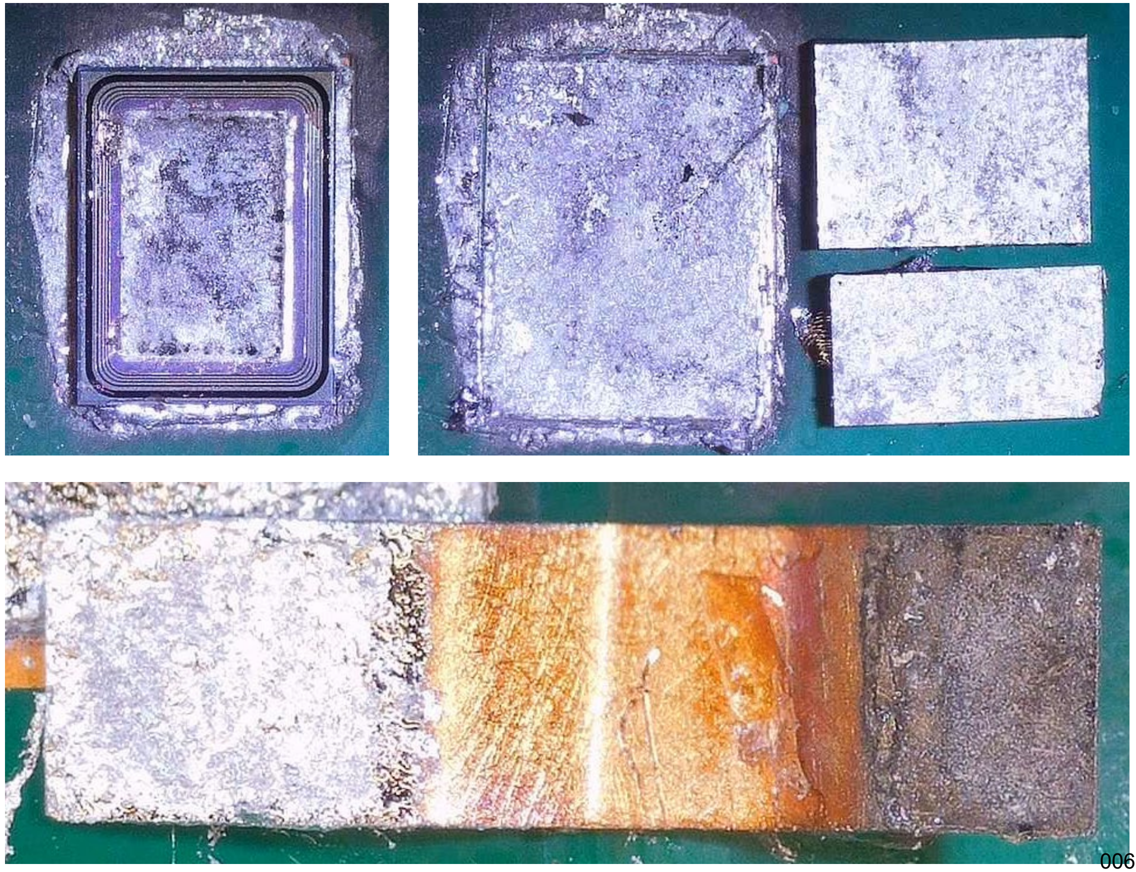
Die-Attach Solder Layer is most influential at 7-milliseconds
N. Carlson, IWIPP 2025

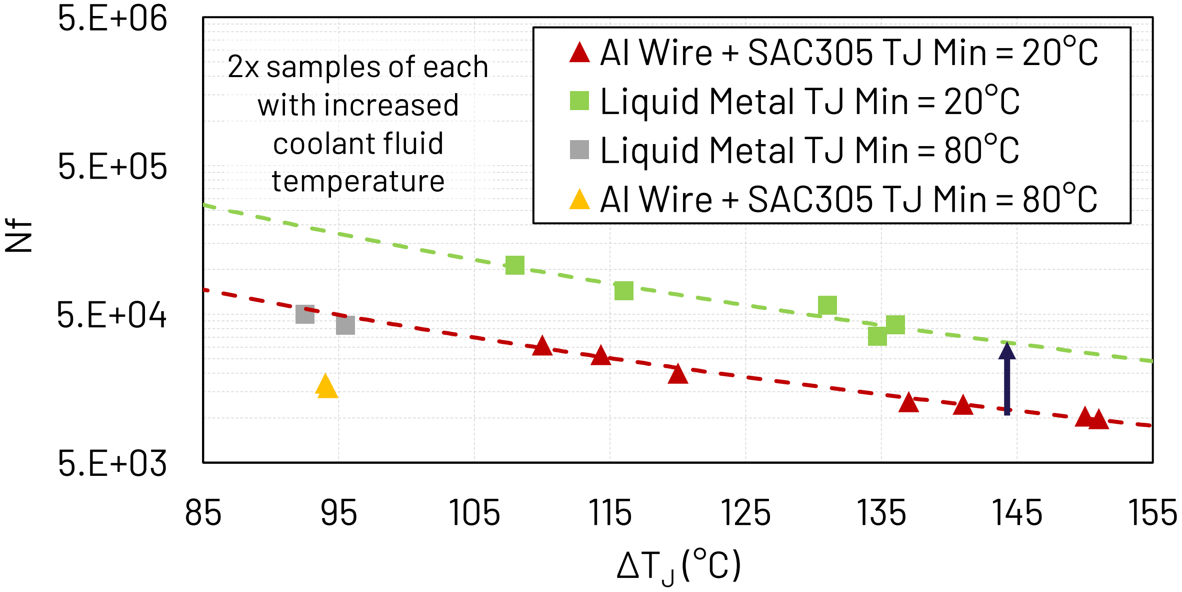




LIME Version 1 – 600 V Si Diode

- 3.3x increased power cycling lifetime
- No liquid left at Cu pad on die-attach
- Field's Metal corrosion (and pump-out)





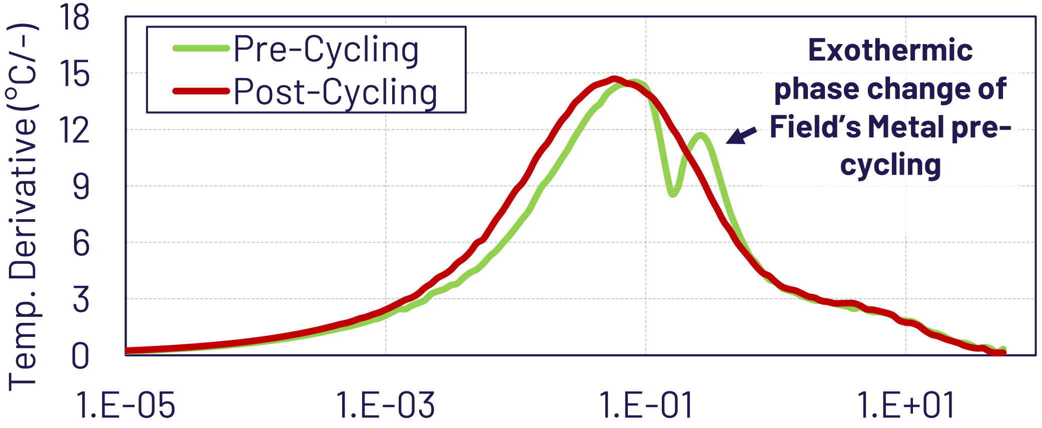


Fig. 7. Cooling rate over time from an $R_{TH(J-A)}$ measurement pre and post power cycling of an LM packaged diode.

LIME Version 1 – 600 V Si Diode

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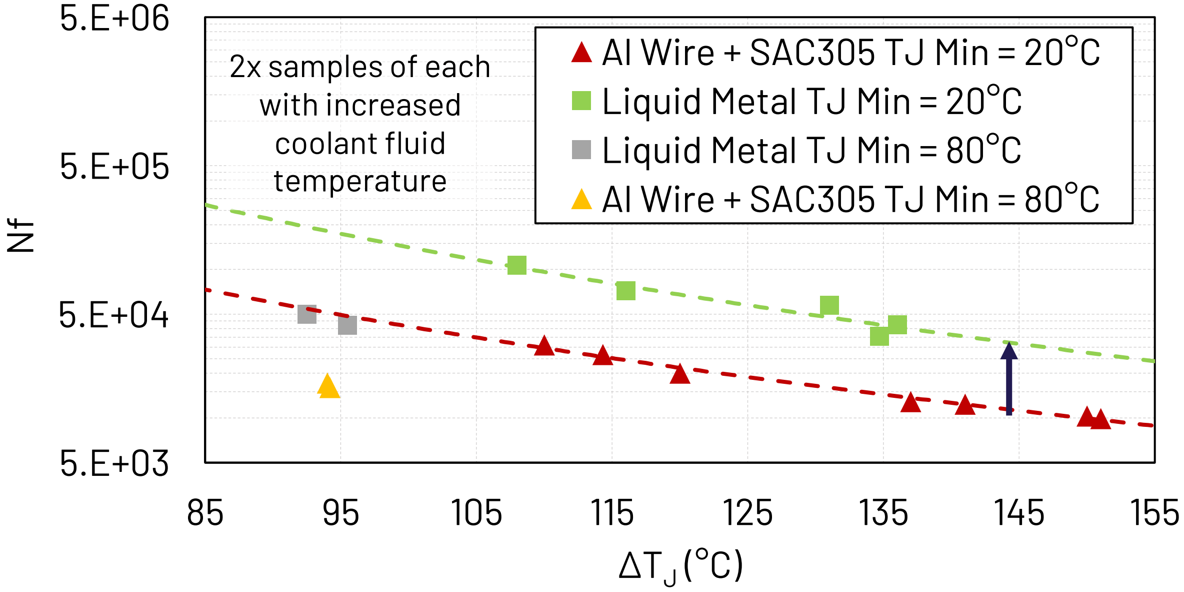

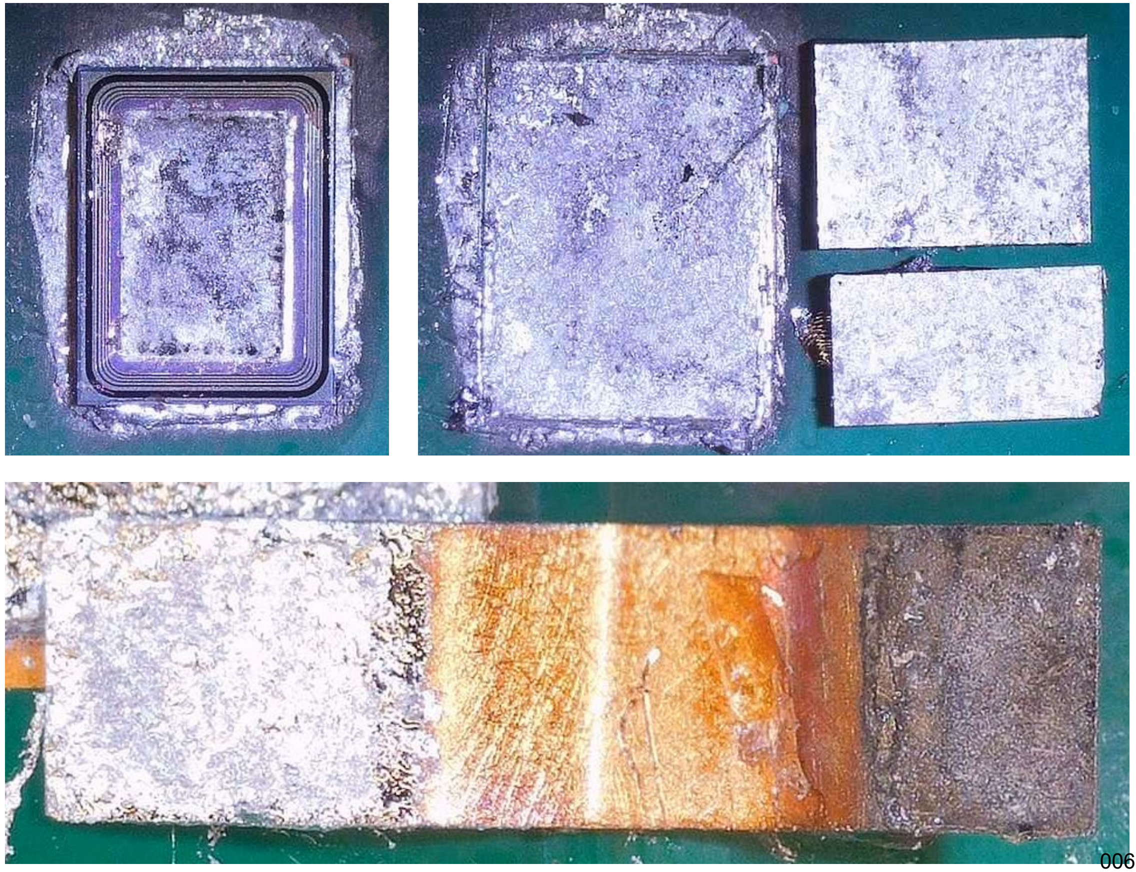

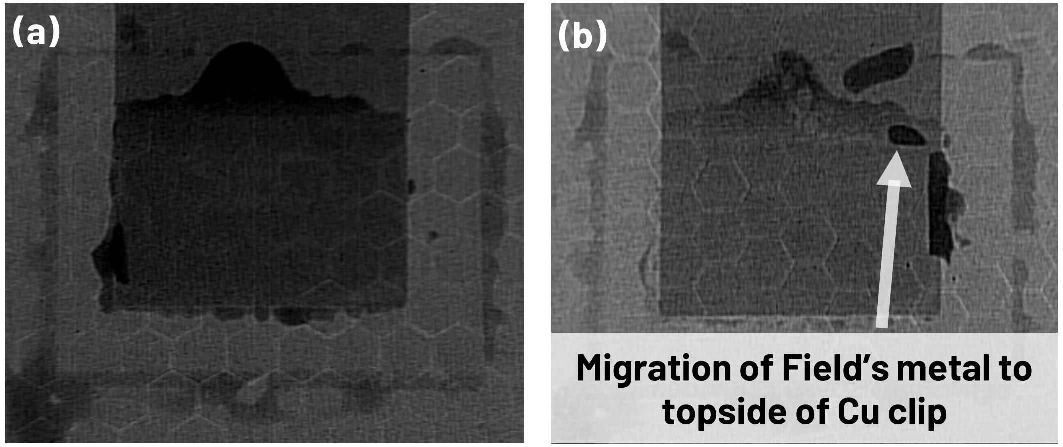

Fig. 8.(a) X-ray image of LM packaged diode before power cycling
(b) X-ray image of LM packaged diode after power cycling

LIME Version 1 – 600 V Si Diode

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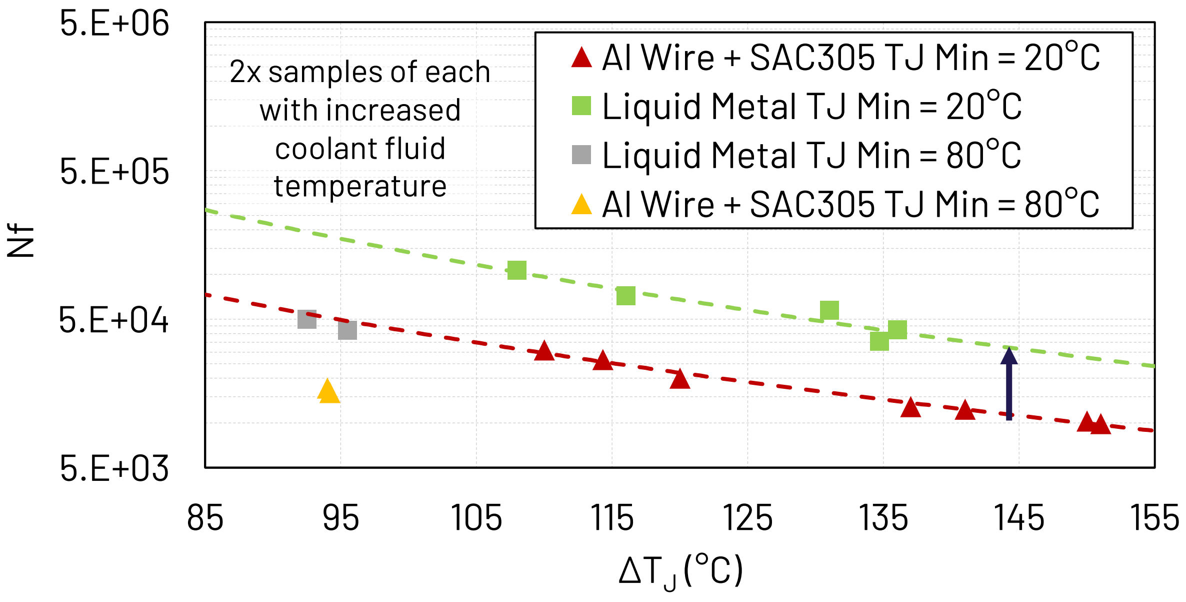
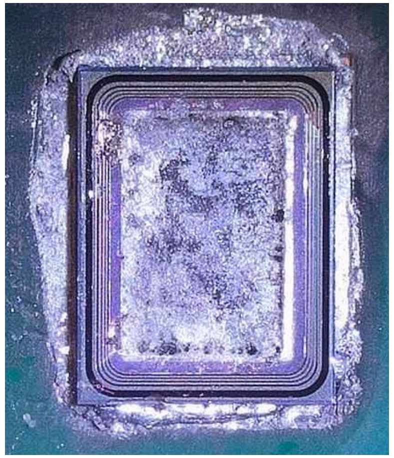
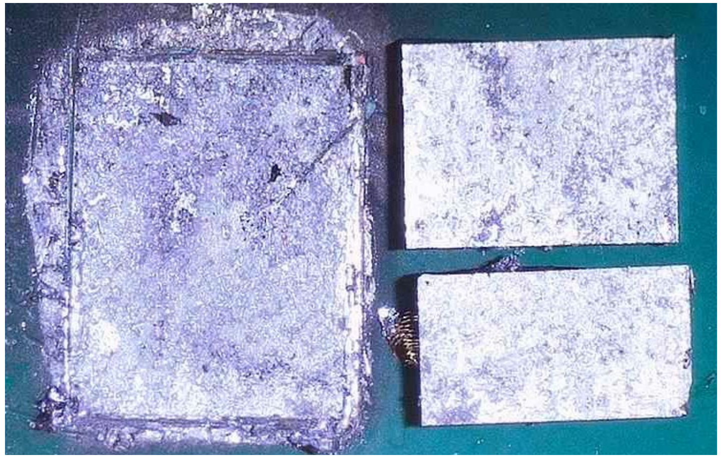
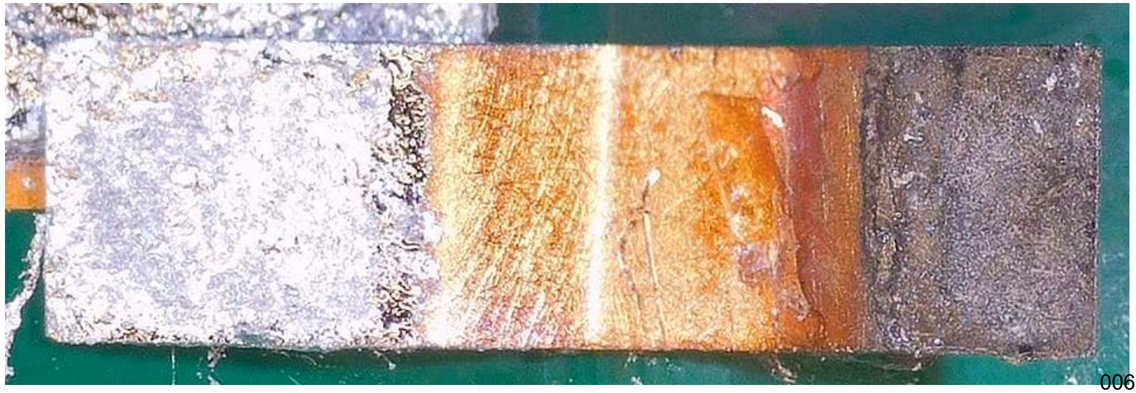




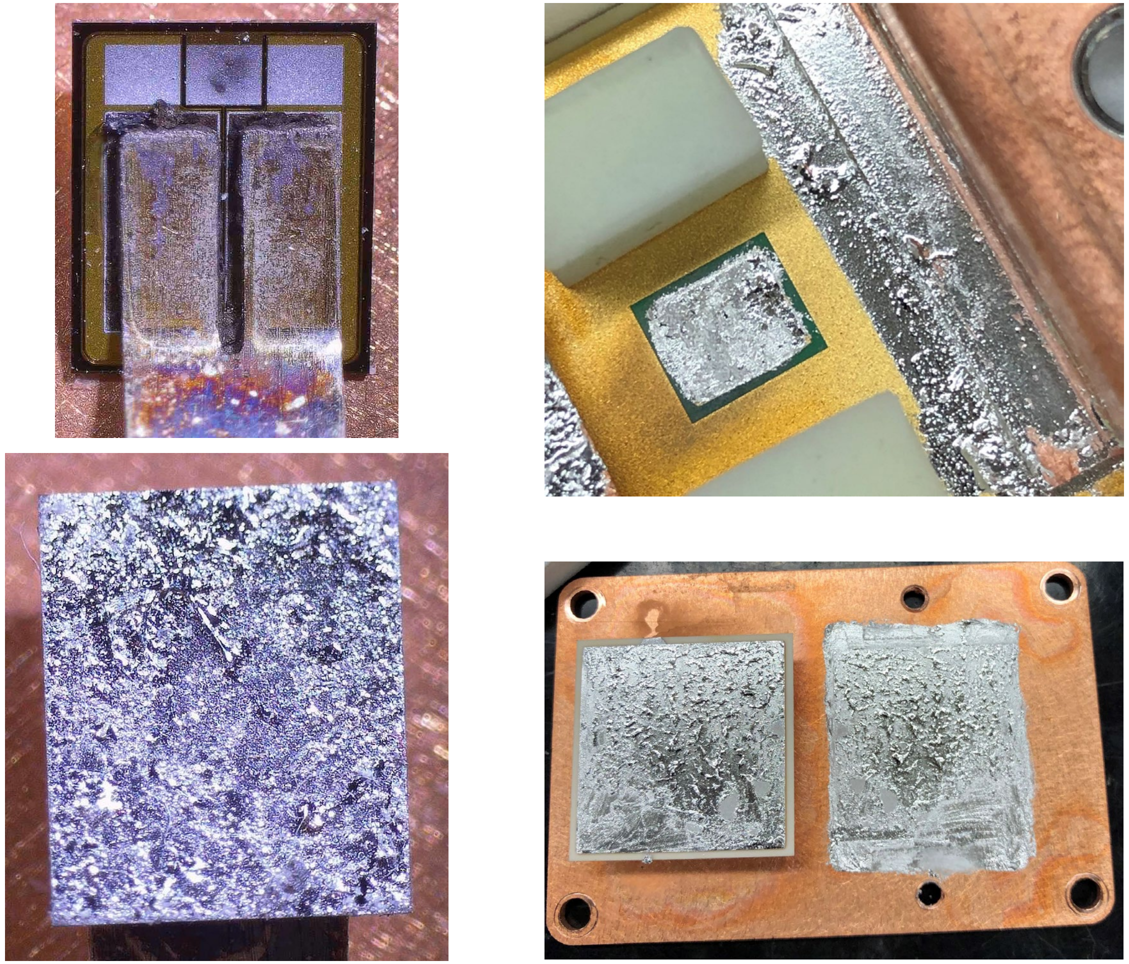




1. https://www.youtube.com/shorts/wauVAXqpS7E

LIME Version 2 – 1200 V SiC MOSFET (2024)

- Al pads are coated with TiNiAg
- Field's Metal, InSn and InAg tested
- Ga-paste still for die-attach
- NiAu coating on Cu DBC
- Copper baseplate
- No solid interconnects remaining – all interconnects are liquid based



LIME Version 2 – 1200 V SiC MOSFET

- Rth 1% lower than SAC305 + Al Wirebond SiC MOSFET
- 13% improvement in Zth @ 7-milliseconds

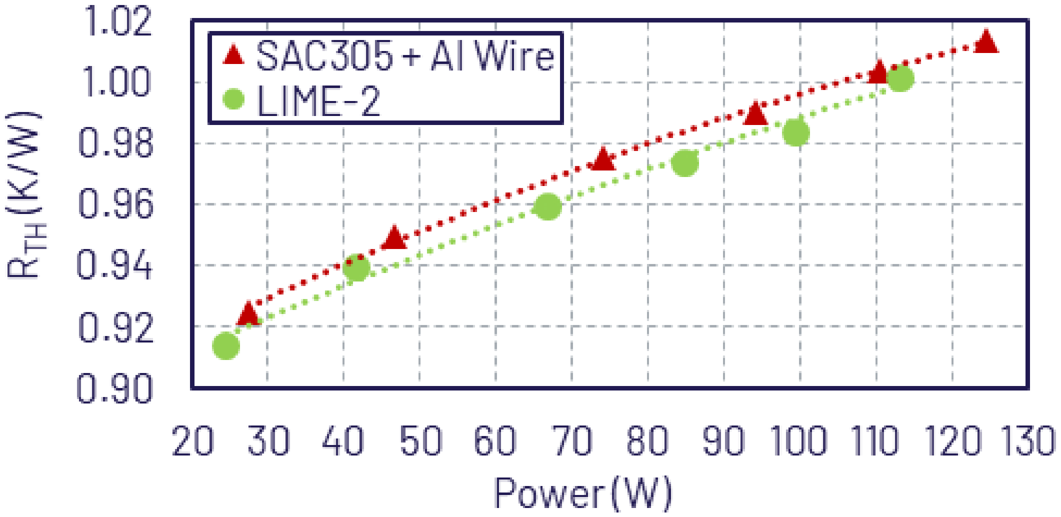


Fig. 18. $R_{TH(J\text{-}A)}$ vs. power dissipation for LIME-2 and SAC305 and Al wirebonded SiC MOSFET.

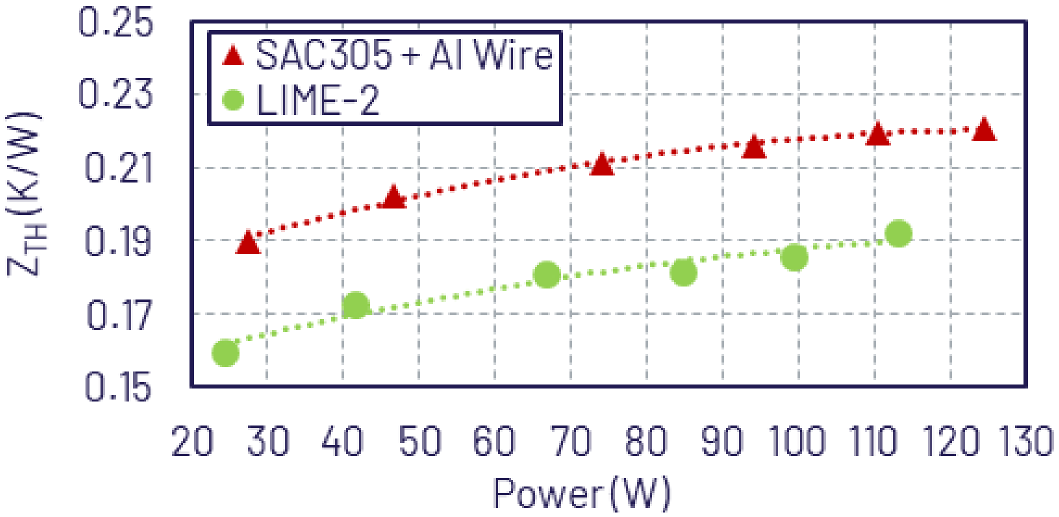
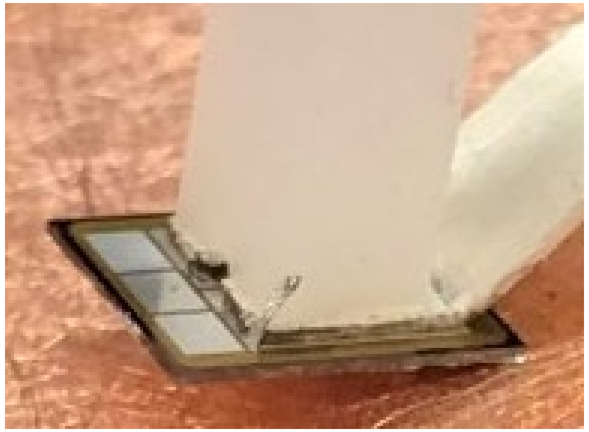
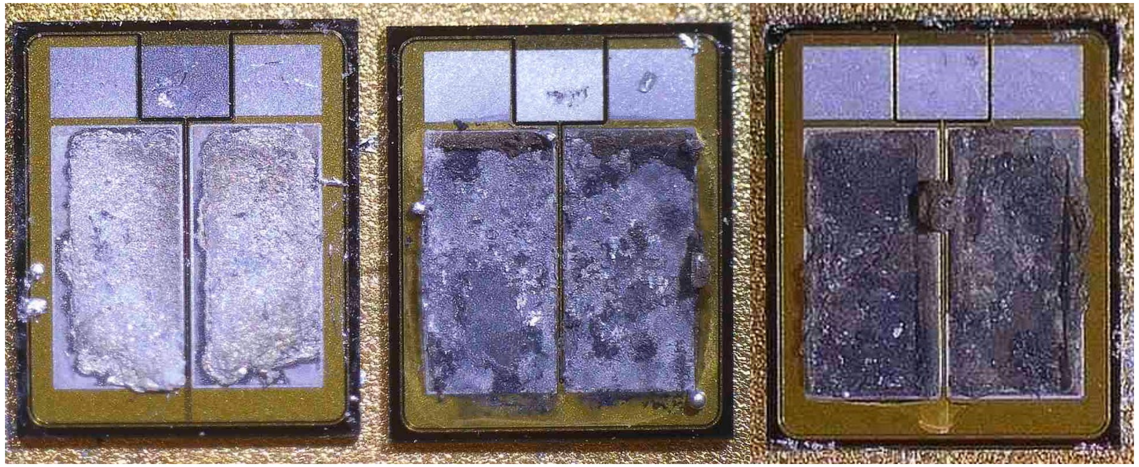


Fig. 19. Z_{TH} at 7-milliseconds vs. power dissipation o n a SiC MOSFET.

LIME Version 2 – 1200 V SiC MOSFET

- 40x – 60x increased power cycling lifetime
- Indium-based corrosion is again failure mode





10k Cycles **60k Cycles** **147k Cycles EOL**

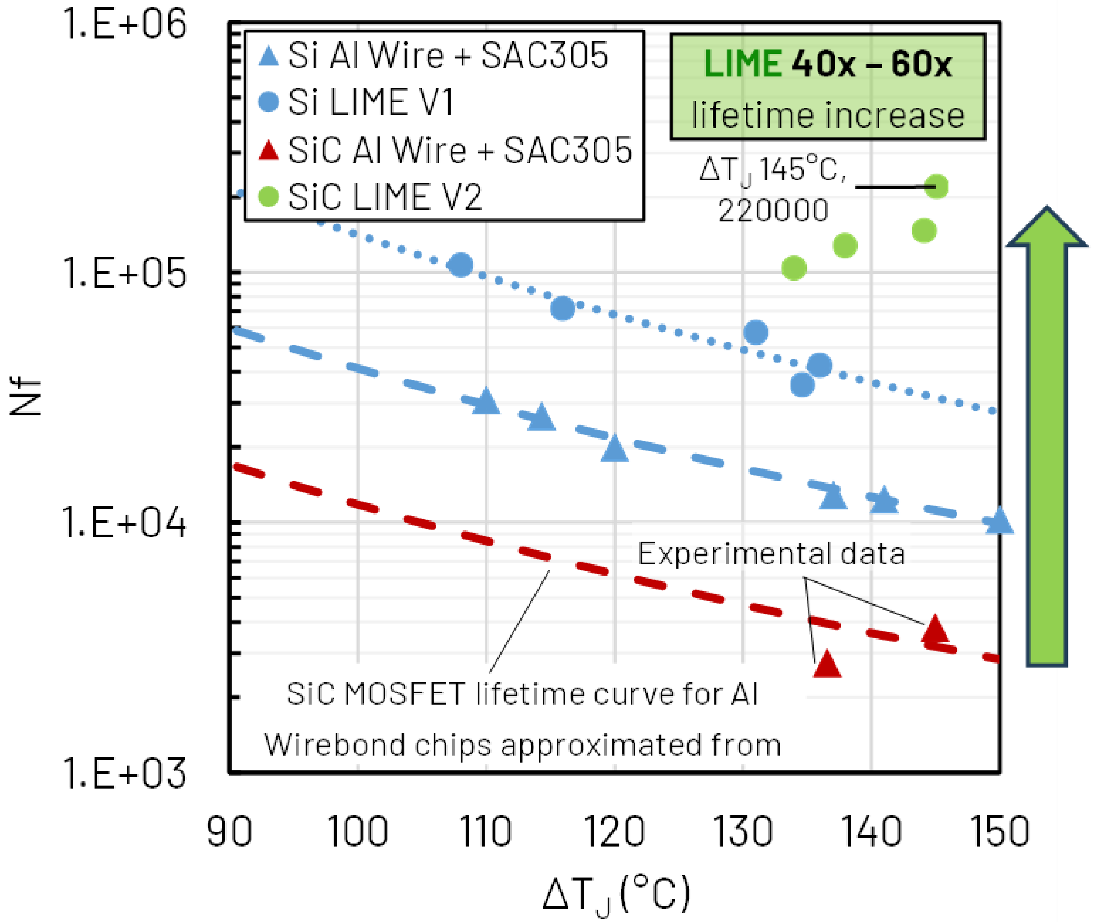
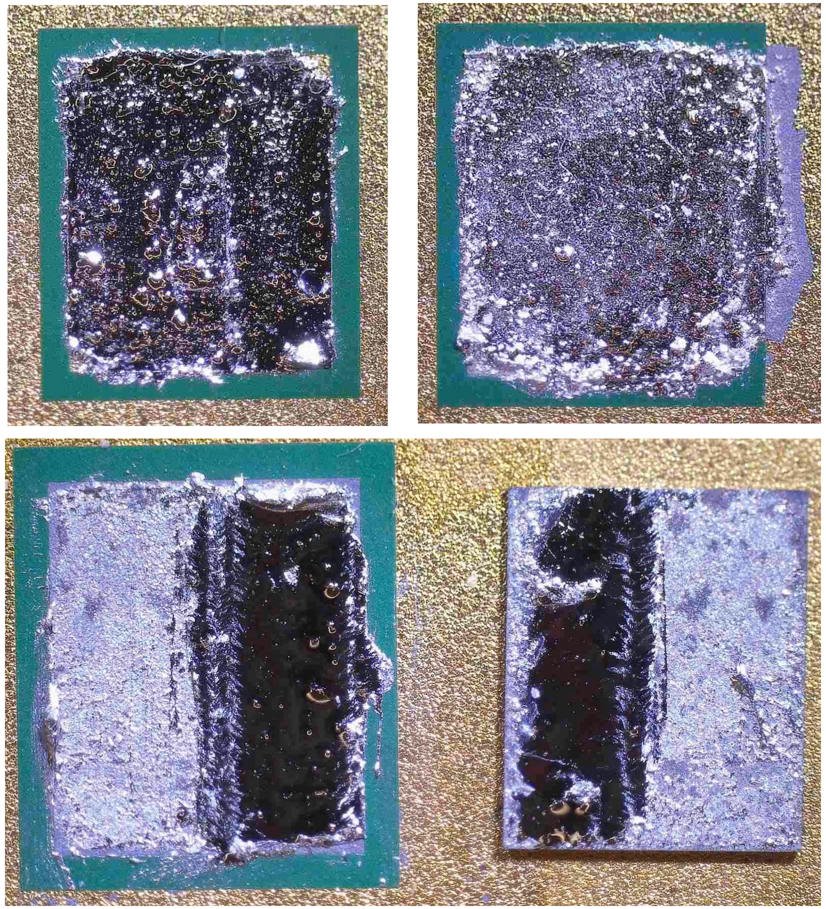


Fig. 14. Power cycling test results for LIME vs. Aluminium wirebonds and SAC305 solder.

LIME Version 2 – 1200 V SiC MOSFET

- Ga-paste die-attach not yet EOL
- NiAu – easy to separate chip



Pre-assembly

Post-Power Cycling

Scratch to reveal LM underneath

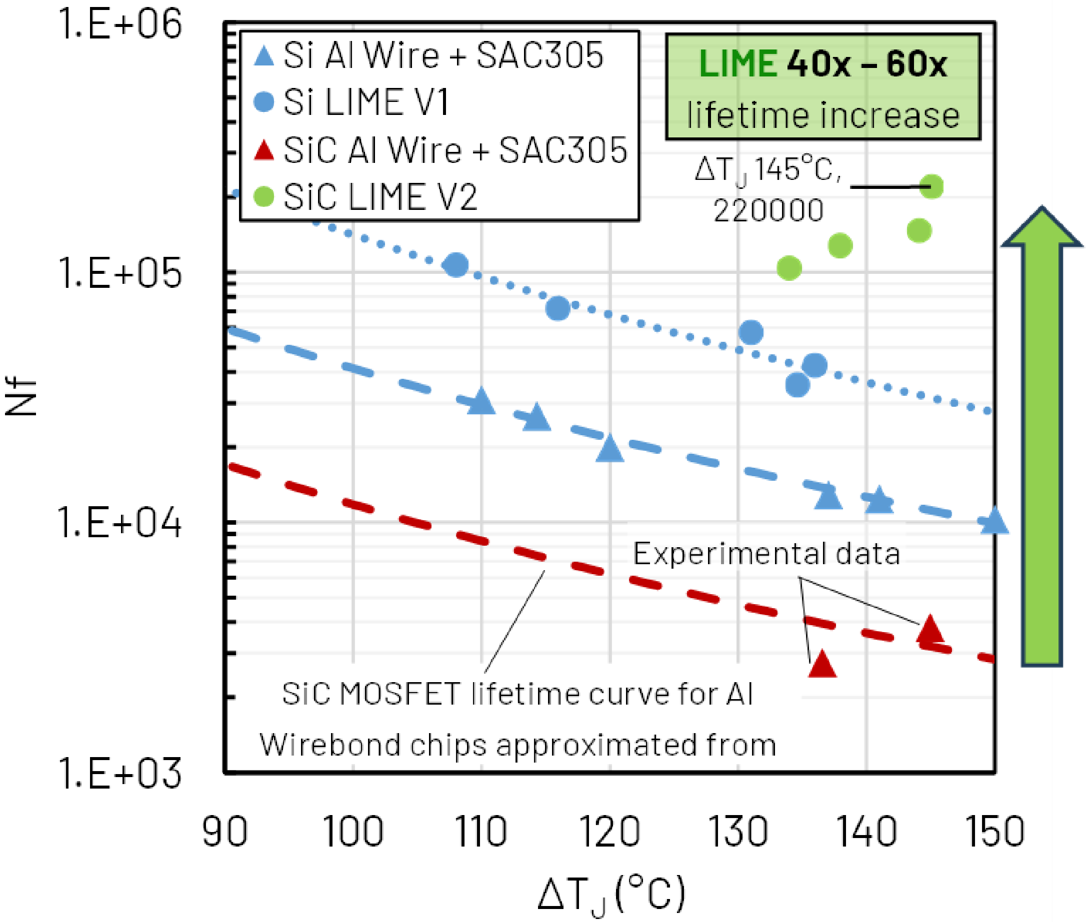
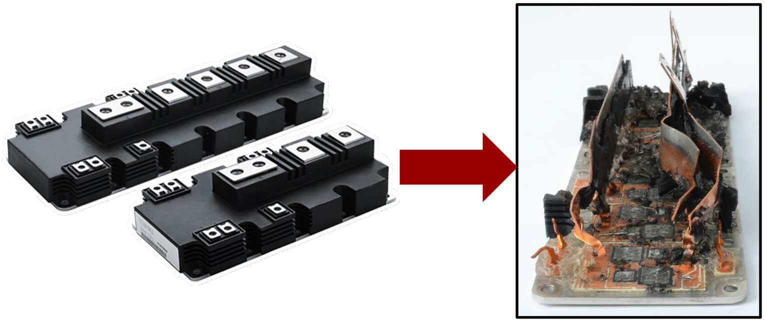


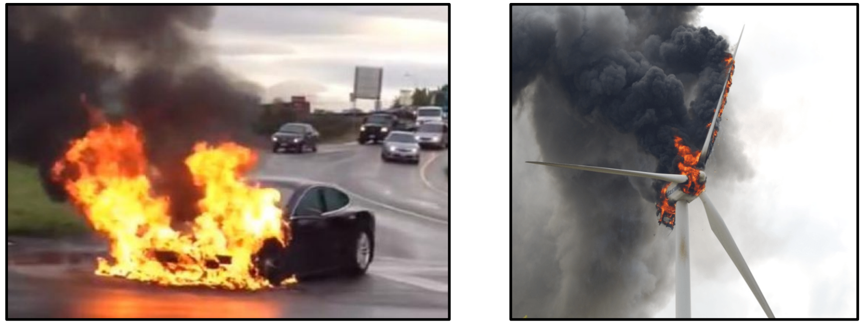
Fig. 14. Power cycling test results for LIME vs. Aluminium wirebonds and SAC305 solder.

The Cost of a Failure

- Power semiconductor failures are explosive and **lead to economic costs far exceeding the entire system.**
- Semiconductor related system failures can be up to 25% within the first 5 years of operation[1]
- **Revenue is lost from downtime**
- Logistical costs of repairs
- Total system replacement
- Costly failure analysis
- **Product recalls and cancelled orders**



Before and after failure. Failures are explosive and destroy the component and surrounding system.



Power applications often have stringent safety requirements (e.g. transportation)

$12,500

loss per average hour of unplanned downtime (Rockwell Automation 2022)

Public cases of losses due to recalls from semiconductor failures:

- Toyota recalls 400k+ cars in 2014 due to overheating of semiconductors (2nd recall again in Oct 2018)
- Dynex Semiconductor loses $1m+ orders due to unresolved explosions in power semiconductors in 2015
- Tesla recalls 127,785 Model 3 Sedans in China over Semiconductor Faults (2022)

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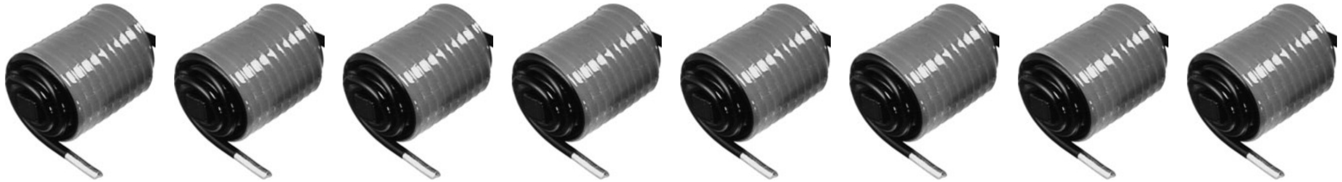
[1] **T. J. Formica, H. A. Khan and M. G. Pecht, "The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems," in IEEE Access, vol. 5, pp. 21336-21343, 2017.**

LIME Potential Miniaturization

- For the same lifetime, a power converter could be made 60% - 80% lighter by increasing the switching frequency

SAC305 + Al
Wirebond
Si IGBT

SAC305 + Al
Wirebond
SiC MOSFET

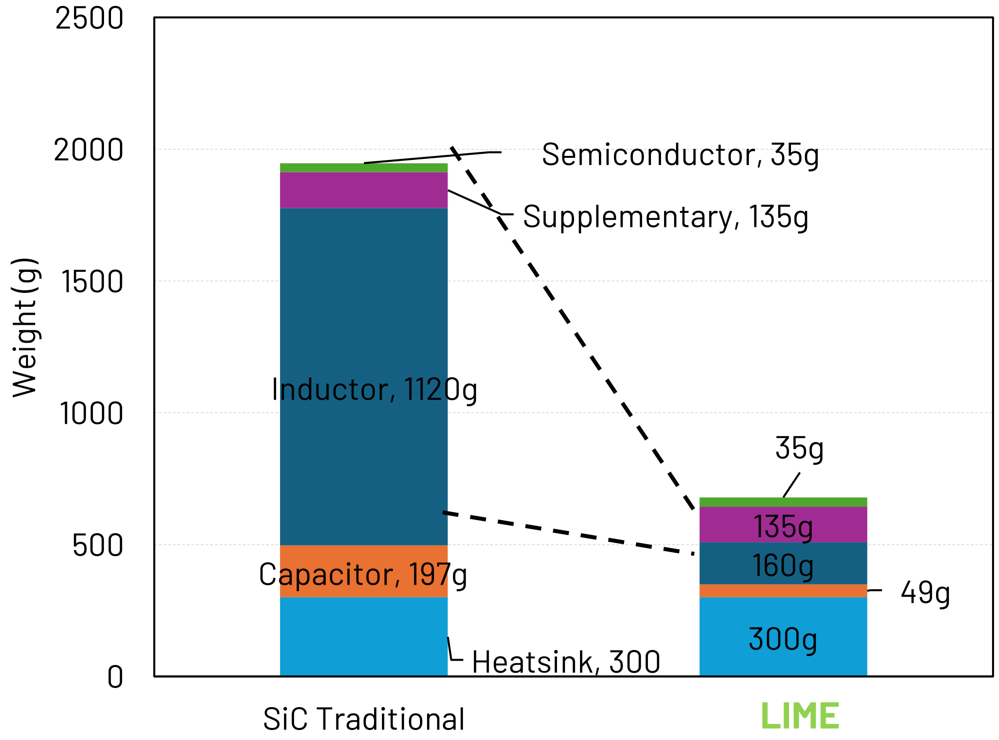


LIME
SiC MOSFET

Inductors required for a 20 kW Boost Converter, designed for 125,000 charge cycles

LIME Potential Miniaturization

- Like for like – same chip, DBC, heatsink, etc
- Other possible advantages: low temp manufacturing process could lead to thinner or higher performance materials



Approx. 65% reduction in weight for a SiC Converter designed for the same lifetime

1.95 kg -> 0.68 kg

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