

HiTEC & APPE Joint Session

Albuquerque, NM

1:30 - 2:00PM

Tuesday, April 15, 2025



International Microelectronics
Assembly & Packaging Society

Considerations for Aluminum Wire Bonds in Next-Generation Power Electronic Systems

Presenter: Whit Vinson

Advisor: Dr. David Huitink (dhuitin@uark.edu)

University of Arkansas
Mechanical Engineering



Wire Bond Types & Capabilities

UA Empire Lab

Wire Bond Types:

➤ Material selection (Wire & Pads)

- Aluminum
- Copper
- Gold
- Silver
- Platinum

➤ Geometry selection

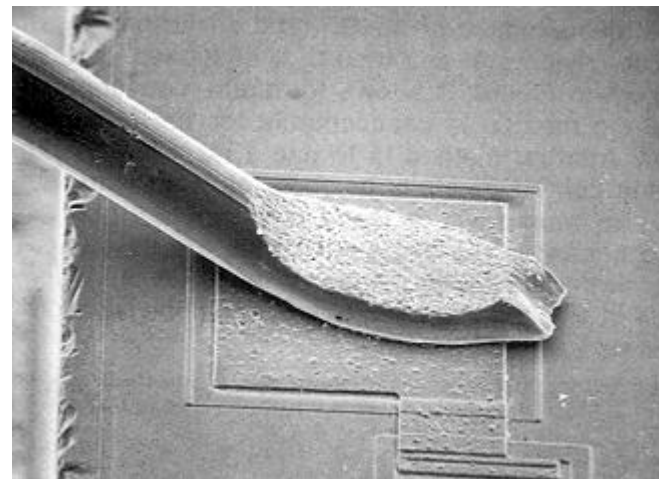
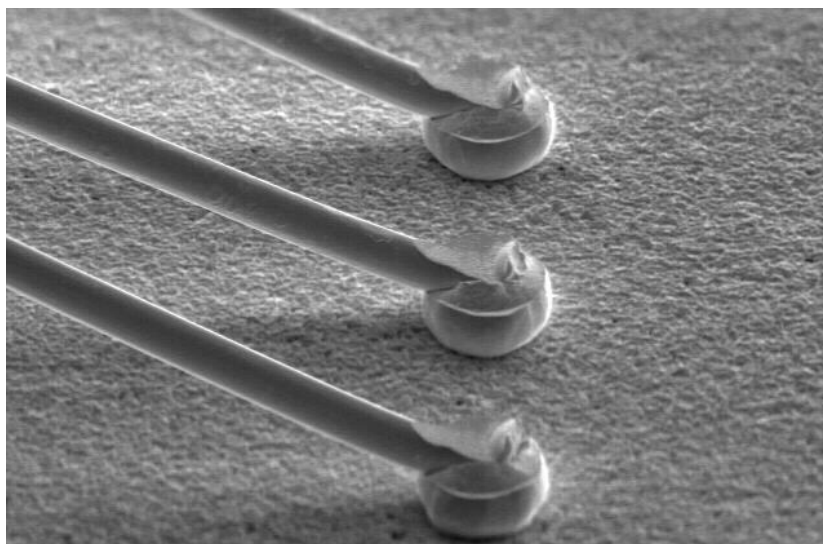
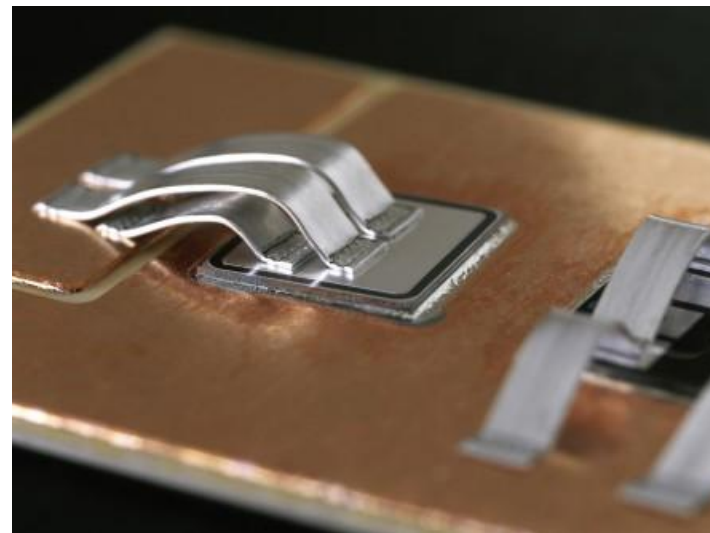
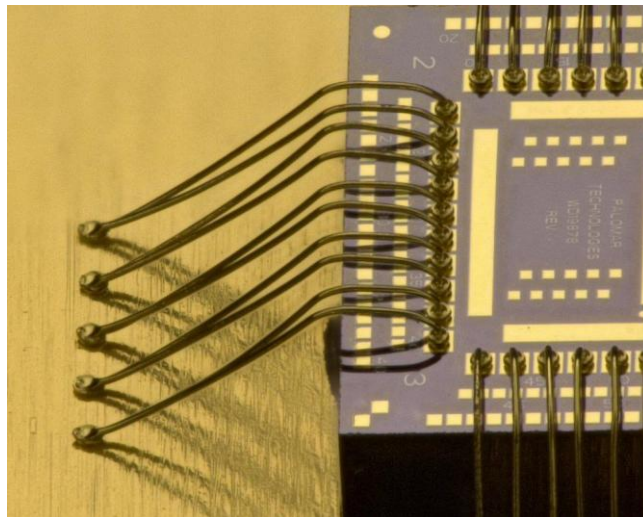
- Cylindrical
- Ribbon

➤ Bond type

- Ball Bonding
- Wedge Bonding

➤ Bond Mechanism

- Thermocompression
- Ultrasonic
- Thermosonic



Wire Bond Types & Capabilities

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➤ Aluminum (Al)

- Usually alloyed w/ 1% Si or Mg
- Key note:
Can be bonded @ room temp. w/out inert environment. (ultrasonic or thermocompression)

➤ Copper (Cu)

- Usually alloyed w/ 0.01-1% Pd
- Key note:
Requires inert environment to be bonded (ultrasonic or thermocompression) – oxidation is an issue

➤ Gold (Au)

- Key note:
Requires increased ambient temperature to be bonded (thermosonic or thermocompression)

https://www.heraeus.com/media/media/het/doc_het/products_and_solutions_het_documents/bonding_wires_documents/Brochure_Bonding_Wire.pdf

R. K. Ulrich and W. D. Brown, *Advanced Electronic Packaging*, 2nd ed. IEEE, 2006. doi: 10.1109/9780471754503.

J. W. Dally, *Packaging of Electronic Systems: A Mechanical Engineering Approach*. McGraw-Hill, 1990. [Online]. Available: <https://books.google.com/books?id=ovtQgAACAAJ>

"Physical property algorithms. J. F. Stelzer, Karl Thiemig AG, Publ. 1984. ISBN 3-521-06144-2. (pbk.) No. of pages: 501. Price: 68 D.M., "International Journal for Numerical Methods in Engineering, vol. 20, no. 5, p. 980, May 1984, doi: <https://doi.org/10.1002/nme.1620200514>.

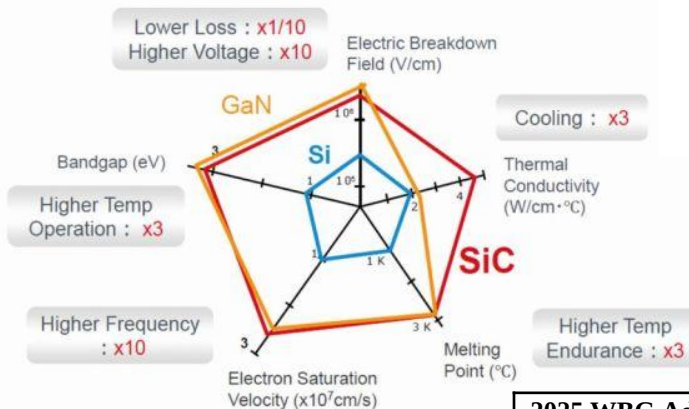
Y. Cengel and A. Ghajar, *Heat and Mass Transfer: Fundamentals & Applications*, 5th ed. McGraw Hill Education, 2015.

Wire Bond Material Properties				
Property	Units	Aluminum	Copper	Gold
Cost	[\$/oz]	0.07	0.22	1768.45
Melting Point	[°C]	658	1083	1063
Density	[g/cm ³]	2.7	8.9	19.3
Constant Pressure Specific Heat	[J/g·K]	0.9	0.386	0.126
Thermal Conductivity	[W/m·K]	237	401	317
CTE	[10 ⁻⁶ /°C]	23.1	16.5	14.2
Electrical Resistivity	[10 ⁻⁸ ·Ωm]	2.65	1.7	2.2
Youngs Modulus	[GPa]	70	130	78
Tensile Strength	[MPa]	150	290	170

Increasing Power Density Demands

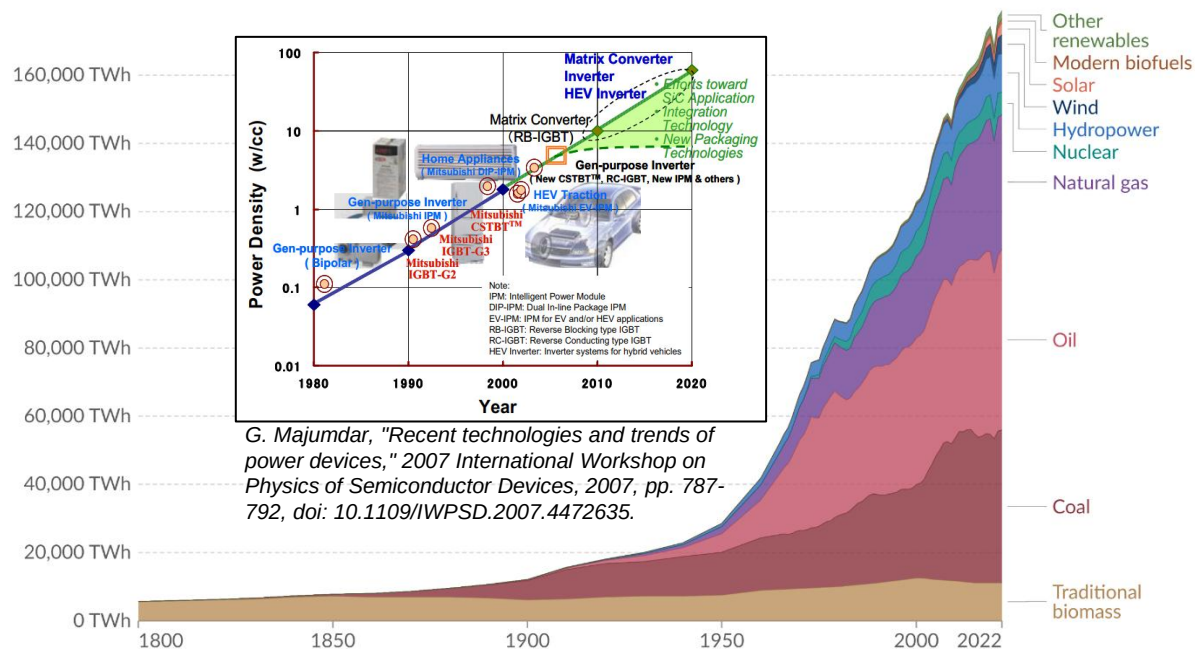
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- **Systems & devices are increasing in power density**
 - Increasing energy demands
 - Desired size and weight reductions
 - Increased or maintained power requirements
- **Enabled by materials & packaging strategy & technology improvements**

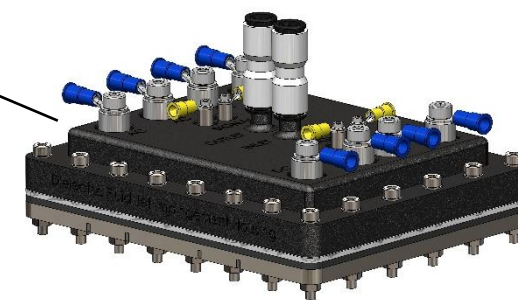
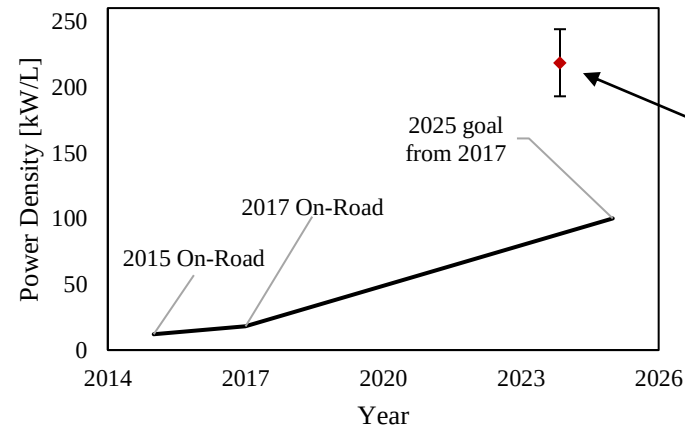


"Demystifying SiC MOSFETs challenges" Power Electronics News Editorial Staff, July 2020
<https://www.powerelectronicsnews.com/demystifying-sic-mosfets-challenges/>

2025 WBG Advanced Integrated Power Module Goals for R&D	
Peak Power [kW]	200
Continuous Power [kW]	110
Voltage Rating [V]	1200
Max. Device Current [A]	200
Max. Junc. Temp. [°C]	250
Amb. Temp. Range [°C]	-40 - +125
Useful Life [years]/[miles]	15/300,000
Power Density [kW/L]	100



Hannah Ritchie, Max Roser and Pablo Rosado (2024) - "Energy". Published online at OurWorldInData.org. Retrieved from: '<https://ourworldindata.org/energy>' [Online Resource]



Huitink Lab Dielectric Jet Module
(Q4 2023): 190-245 [kW/L]

2017 Electrical & Electronics Technical Roadmap from Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (US DRIVE)
Partnership between U.S. DOE, FCA, Ford, GM, BP, Chevron, Phillips 66, ExxonMobil, Southern California Edison and DTE Energy, and Electric Power Research Institute
<https://www.energy.gov/eere/vehicles/articles/us-drive-electrical-and-electronics-technical-team-roadmap>

Increasing Power Density Demands

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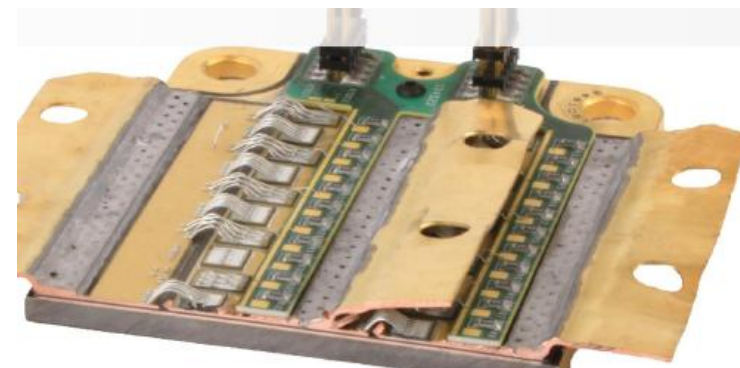
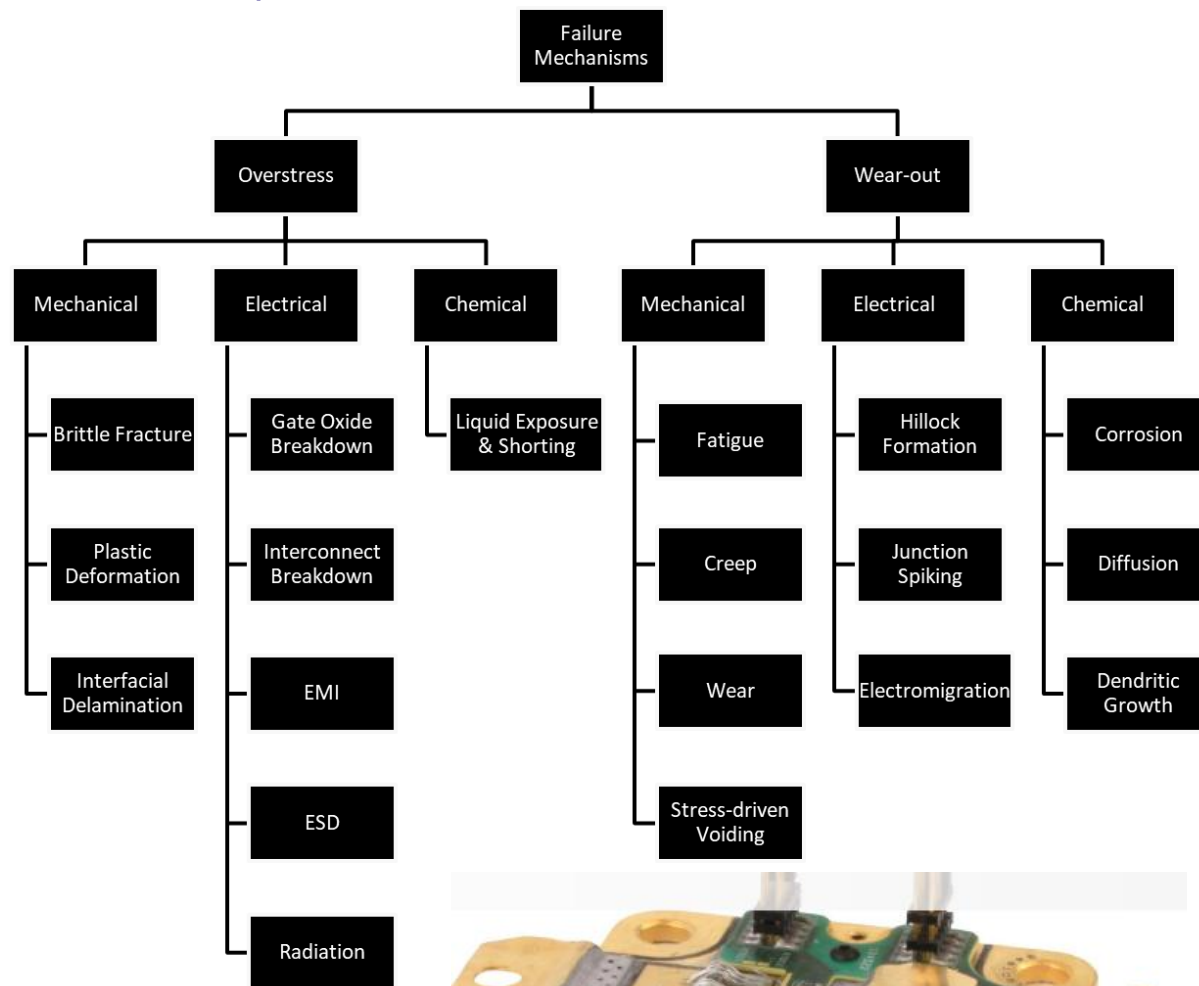
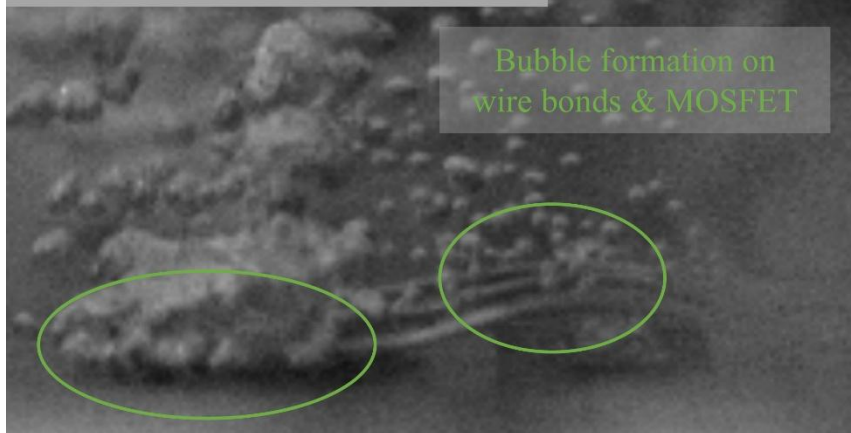
- A slew of downstream effects will occur as a result of increased power density, all related to package reliability

- Particularly worrisome at the interconnect level of packages

- Heat Flux Pathway
- Current Density Bottleneck

- Continued use Interconnects: Wire Bonds

3x 12 [mil] aluminum wire bonds
1.2 [kV] SiC MOSFET
HFE-347 dielectric fluid immersion
 $I_{\text{Drain}} = 21 \text{ [A]}$



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Inherent Effects of Increasing Power Density

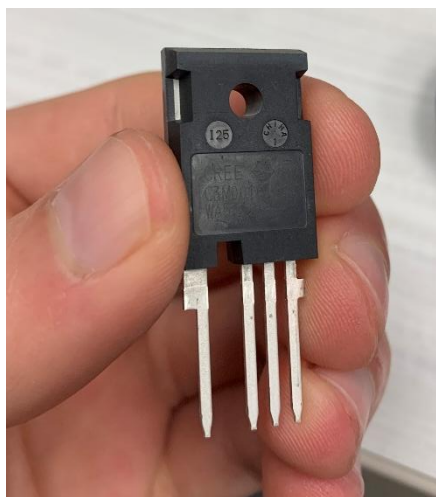
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M. Bhatnagar and B. J. Baliga, "Comparison of 6H-SiC, 3C-SiC, and Si for power devices," in *IEEE Transactions on Electron Devices*, vol. 40, no. 3, pp. 645-655, March 1993, doi: 10.1109/16.199372.

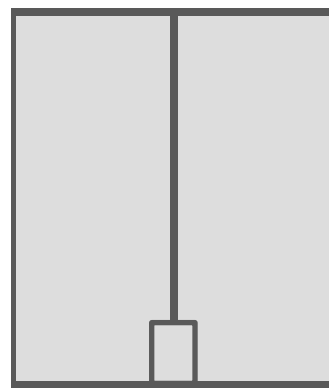
Wolfspeed, "A Designer's Guide to Silicon Carbide: Quality, Qualification, and Long-Term Reliability," MOSFETs Knowledge Center, <https://www.wolfspeed.com/knowledge-center/article/a-designers-guide-to-silicon-carbide-quality-qualification-and-long-term-reliability/>

Contextualization Example:

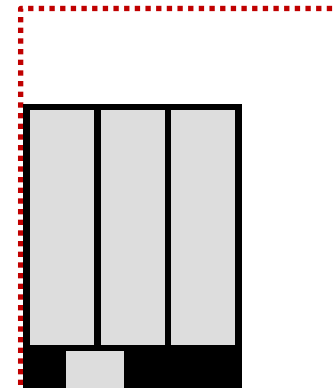
- Increasing operating temperatures (or the capability to do so)
- Decreased device & package footprints
 - Reduced redundancy or reduced form factor of interconnects
 - Increasing current density



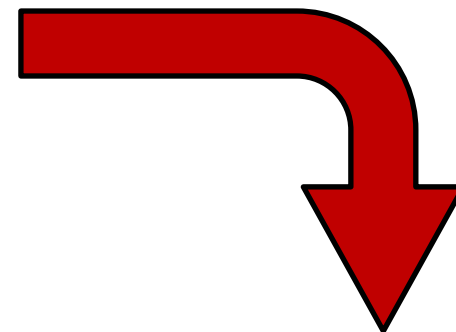
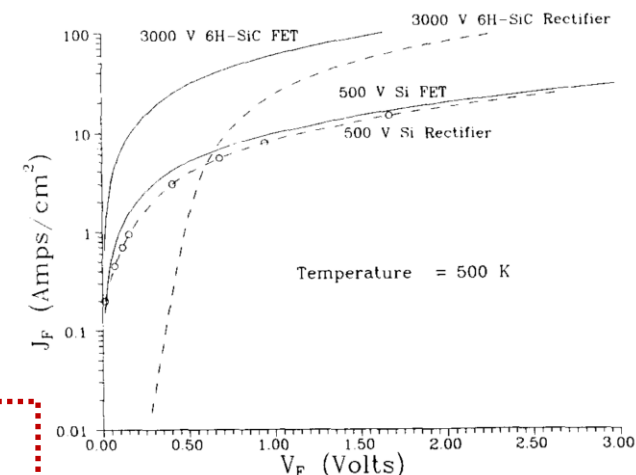
- 20x current density improvement w/ SiC for same size device
- 2-3x reduced attach area today



Si DMOSFET



6H-SiC MOSFET



Assumptions:

- Discrete device
- Same WB size and spacing for both die materials
- DC continuous drain current operation

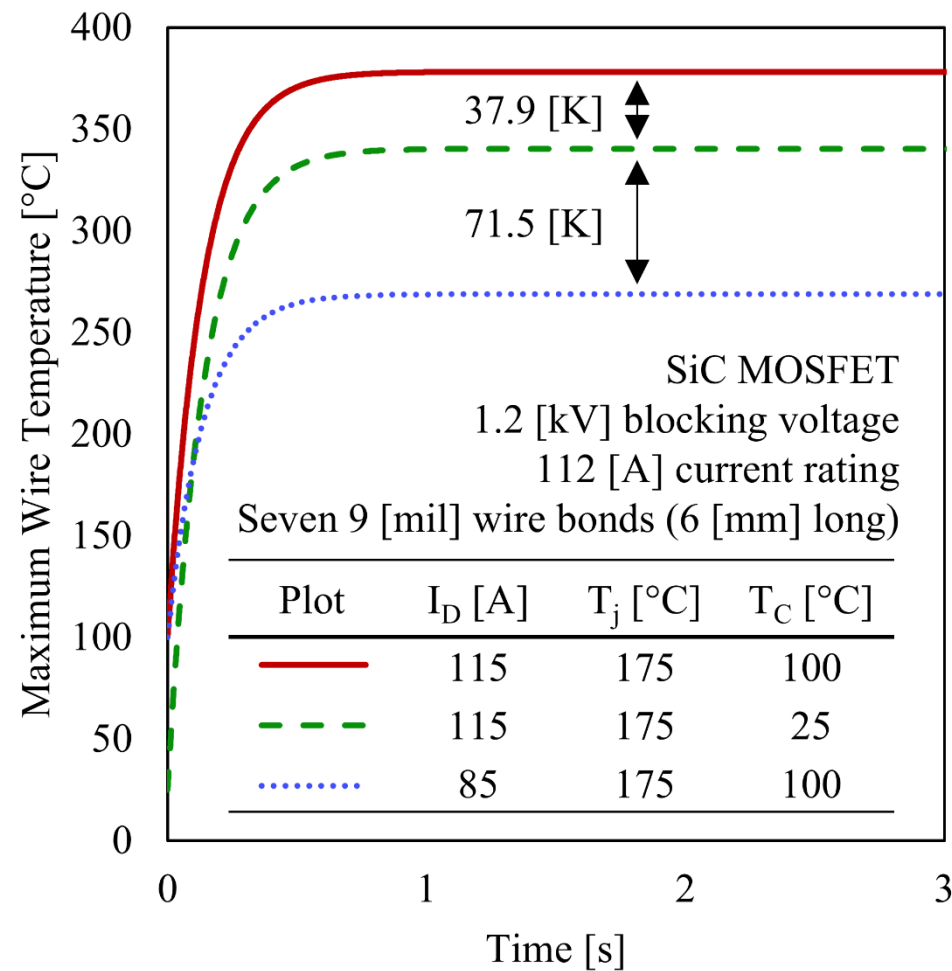
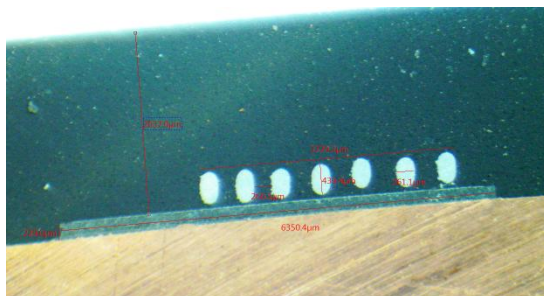
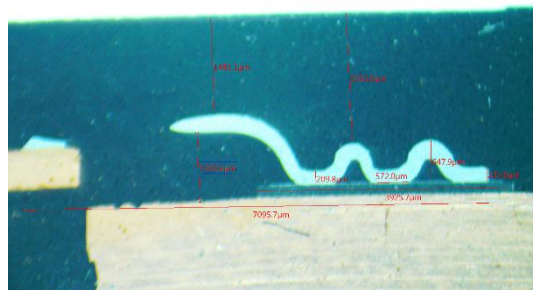
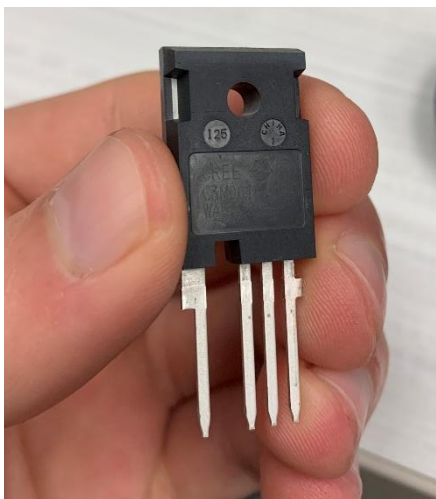
Device	Current Rating [A]	No. WBs (9 [mil])	j_{WB} [A/cm ²]
Si	40 (calc. val.)	9	10,829
SiC	115	7	40,027

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Modeling Wire Bond Operation

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- **Examine SOA device operation conditions to understand wire bond temperature response**



Increasing Therm.-Elec. Stressing - Electromigration Failure

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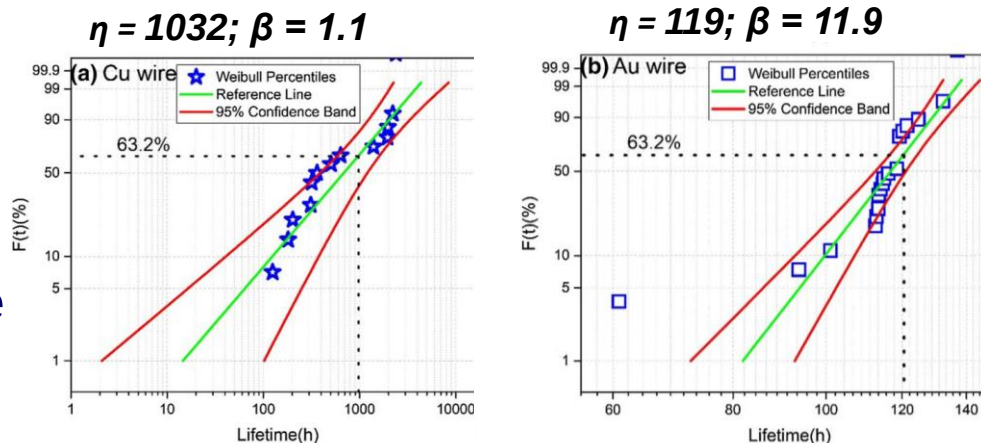
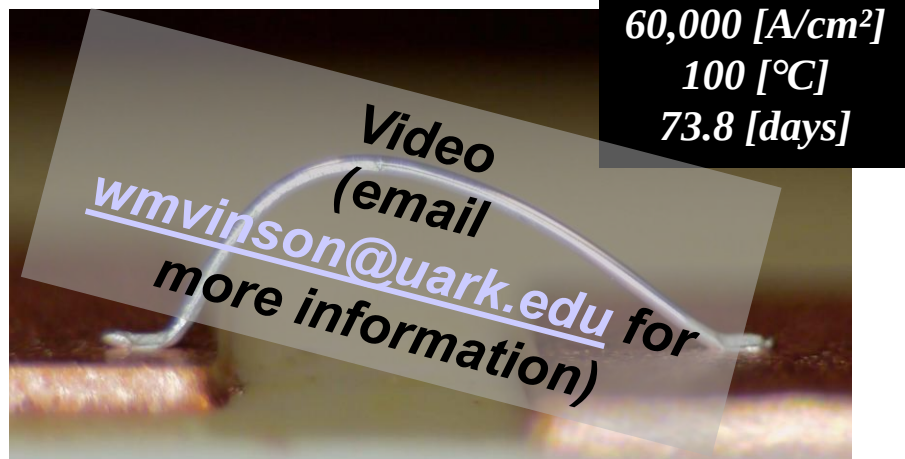
Electromigration (EM)

EM Mechanism:

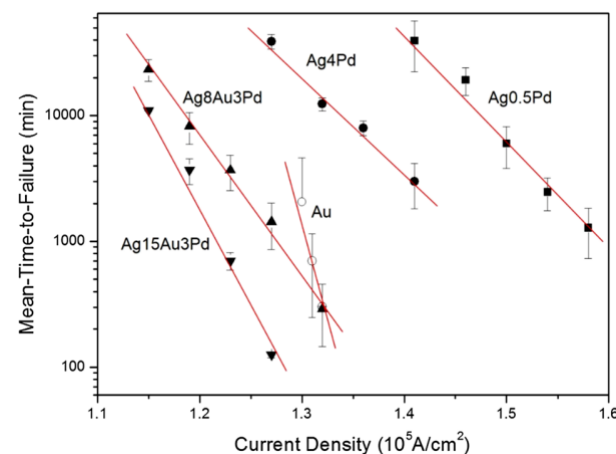
- Elevated current density
- Elevated ambient temperature

EM Mode:

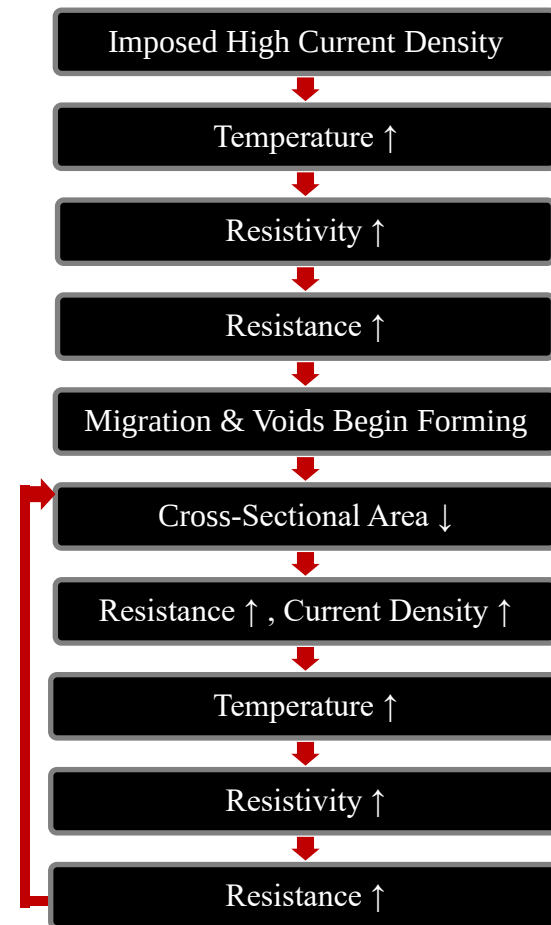
- Metal migration & voiding
- Intermetallic growth



Du, Y., Gao, LY., Yu, D. et al. Comparison and mechanism of electromigration reliability between Cu wire and Au wire bonding in molding state. *J Mater Sci: Mater Electron* 31, 2967–2975 (2020). <https://doi.org/10.1007/s10854-019-02840-6>



Chuang, TH., Lin, HJ., Wang, HC. et al. Mechanism of Electromigration in Ag-Alloy Bonding Wires with Different Pd and Au Content. *J. Electron. Mater.* 44, 623–629 (2015). <https://doi.org/10.1007/s11664-014-3558-7>



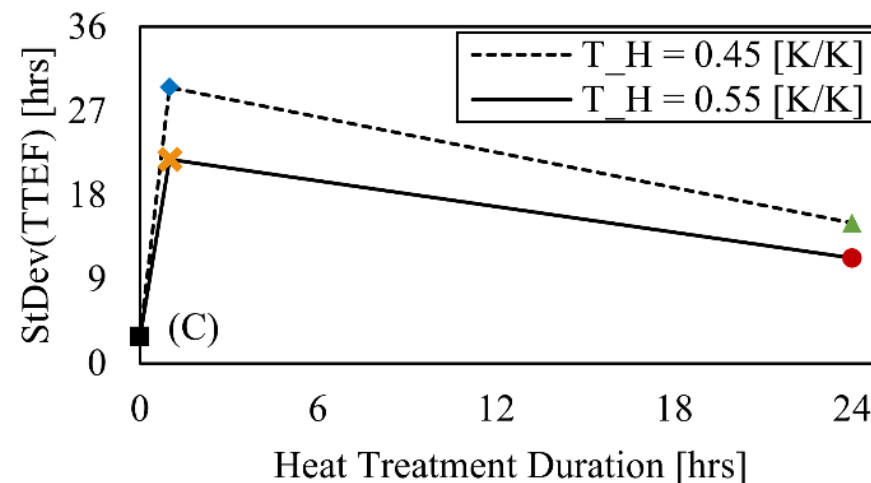
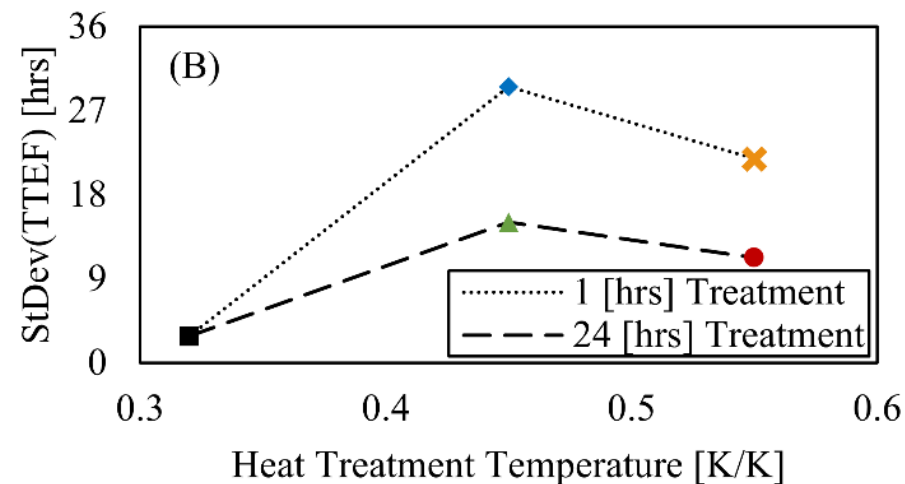
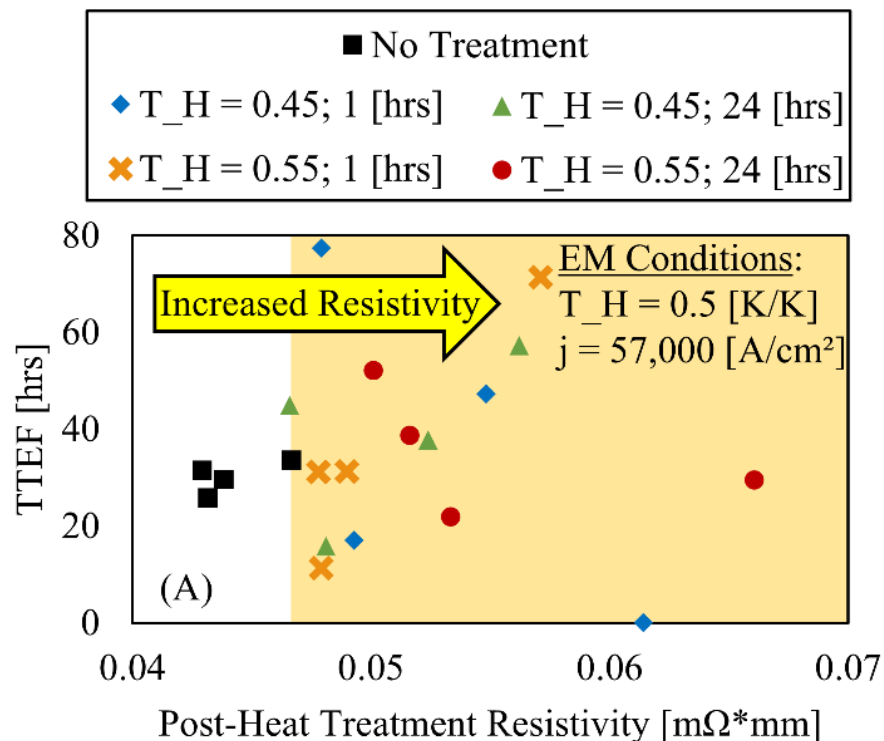
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Note on Temperature Exposure vs Operation

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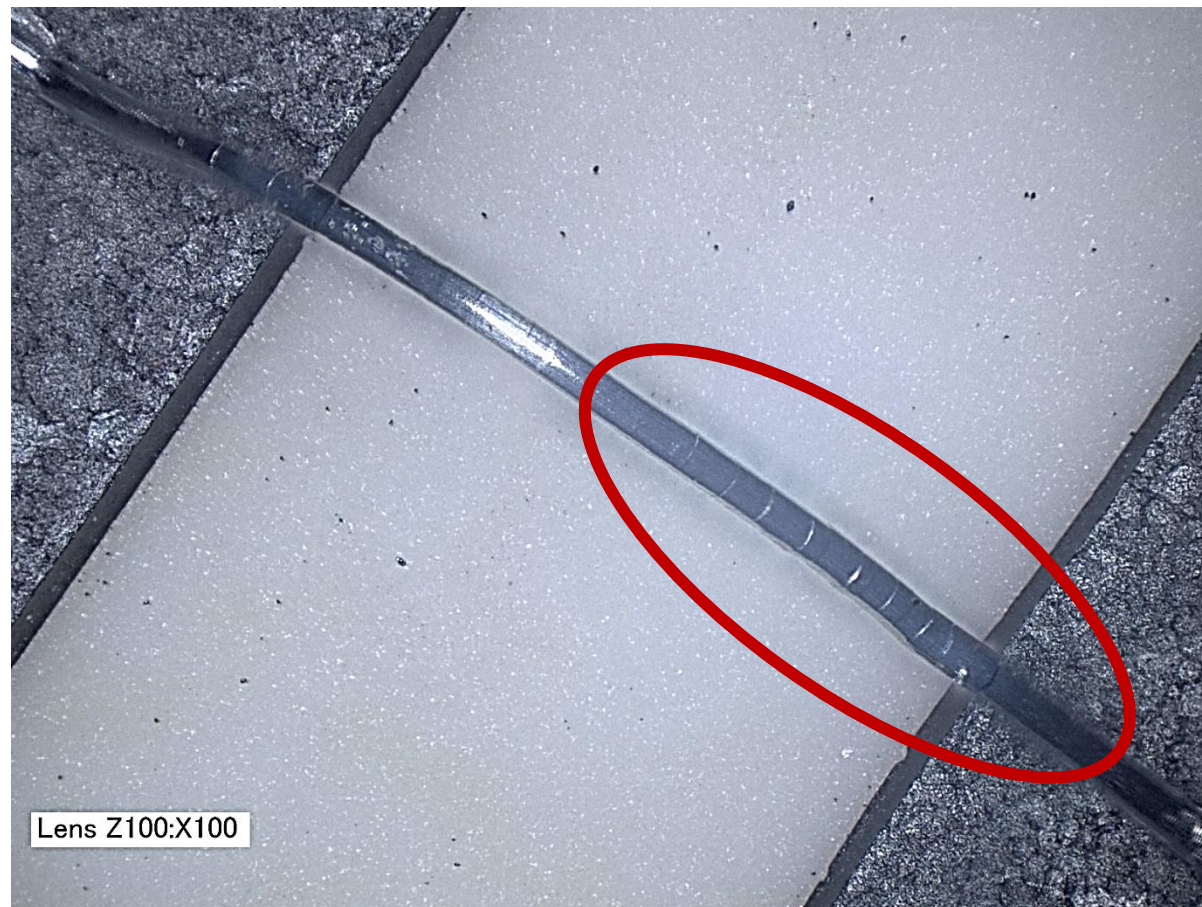
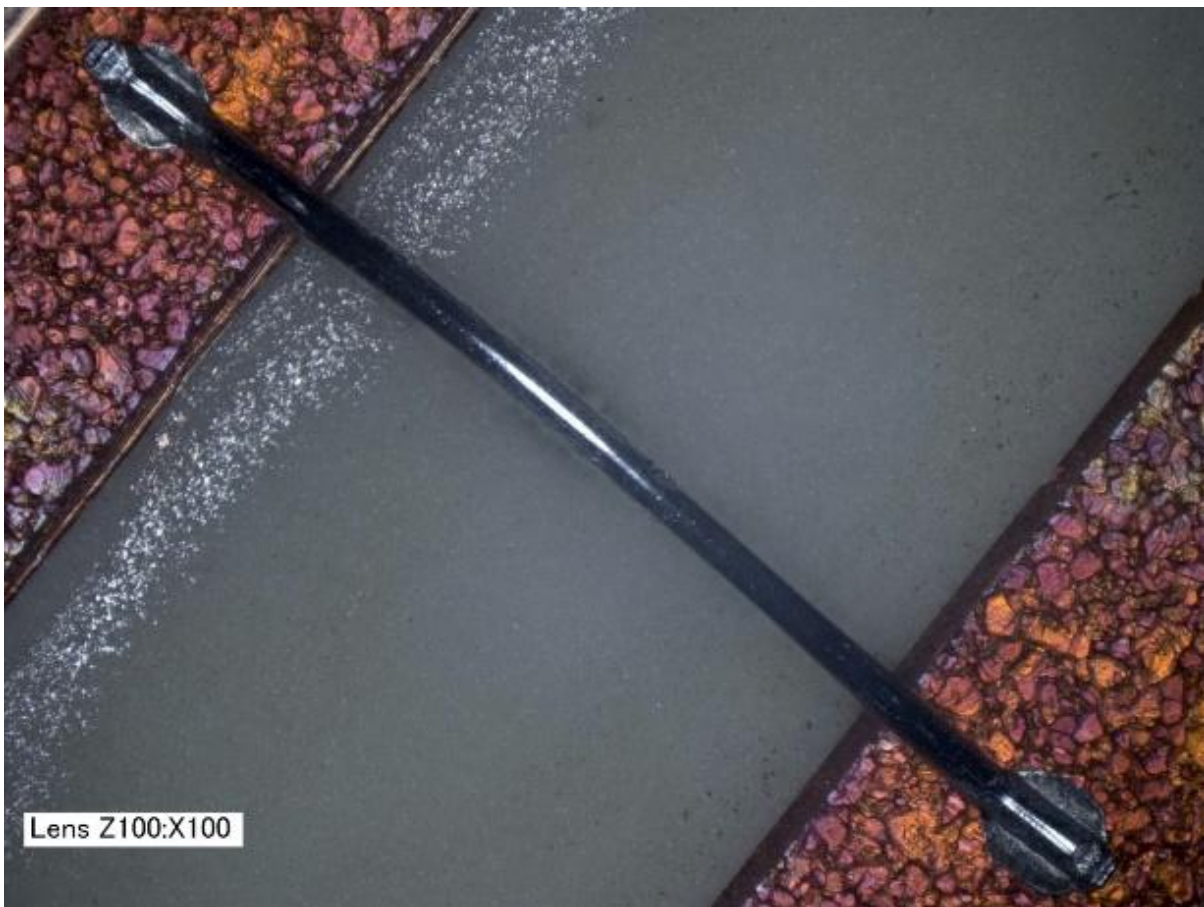
- Increasing ambient temperature with maintained current density will reduce lifetimes
- Temperature exposure & compromising bond quality



Thermal-Electric Stress - Electromigration Failure

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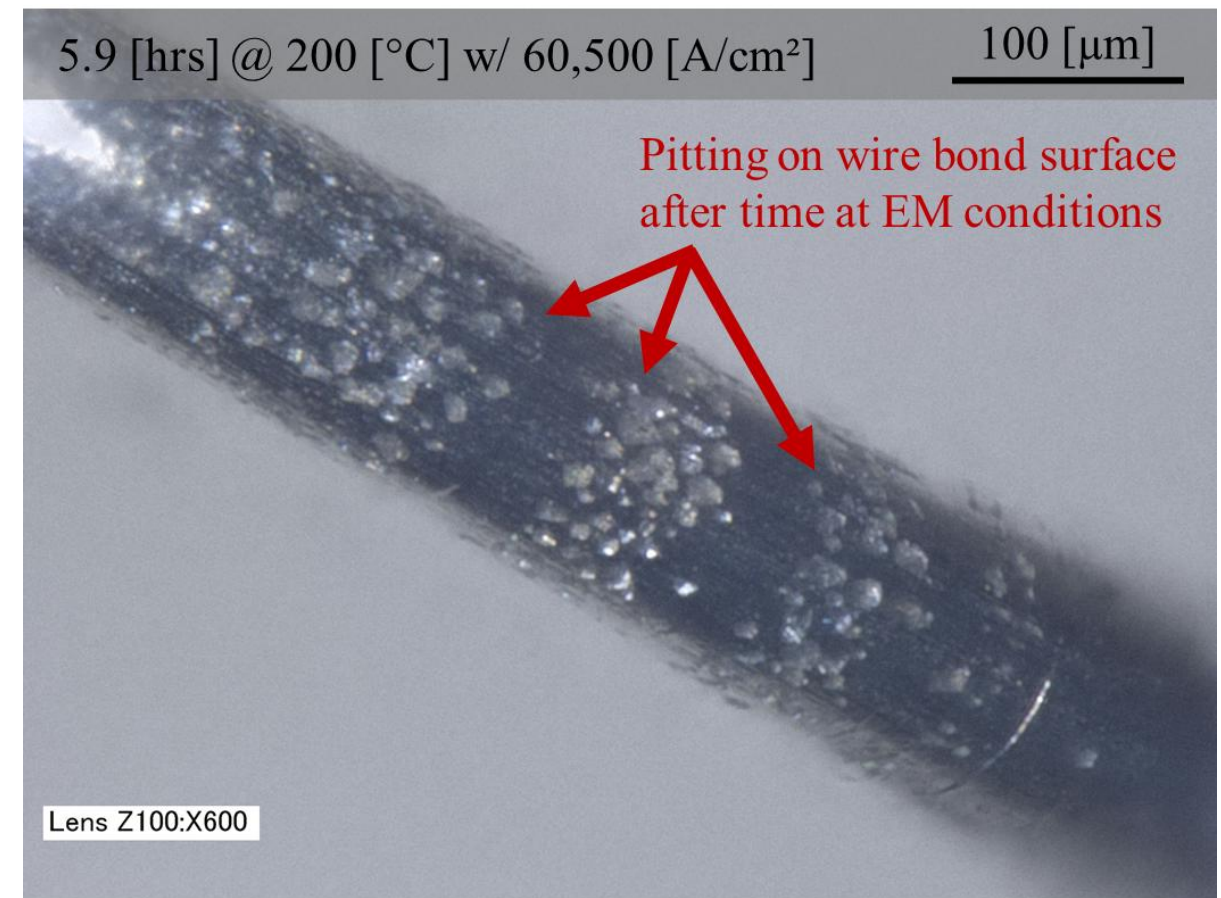
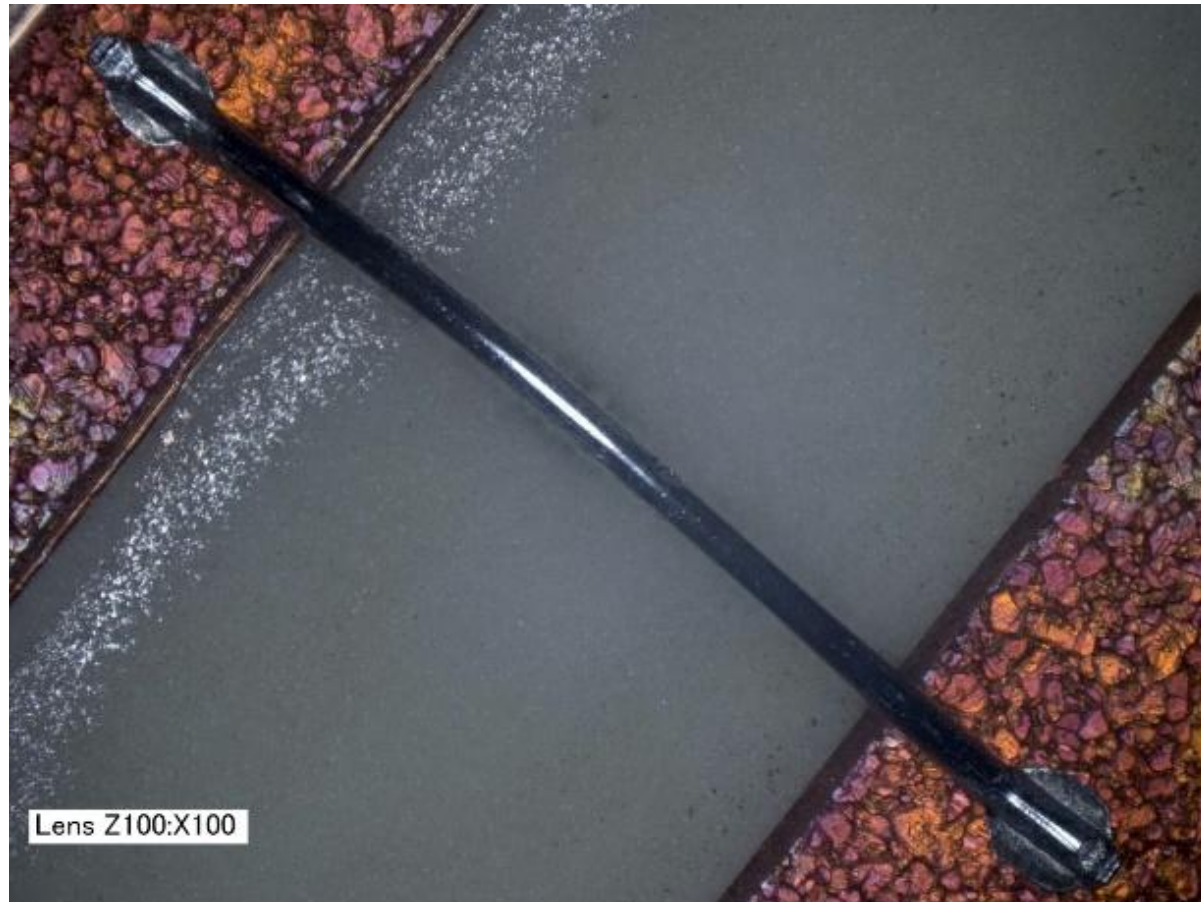
“Bambooning”



Thermal-Electric Stress - Electromigration Failure

UA Empire Lab

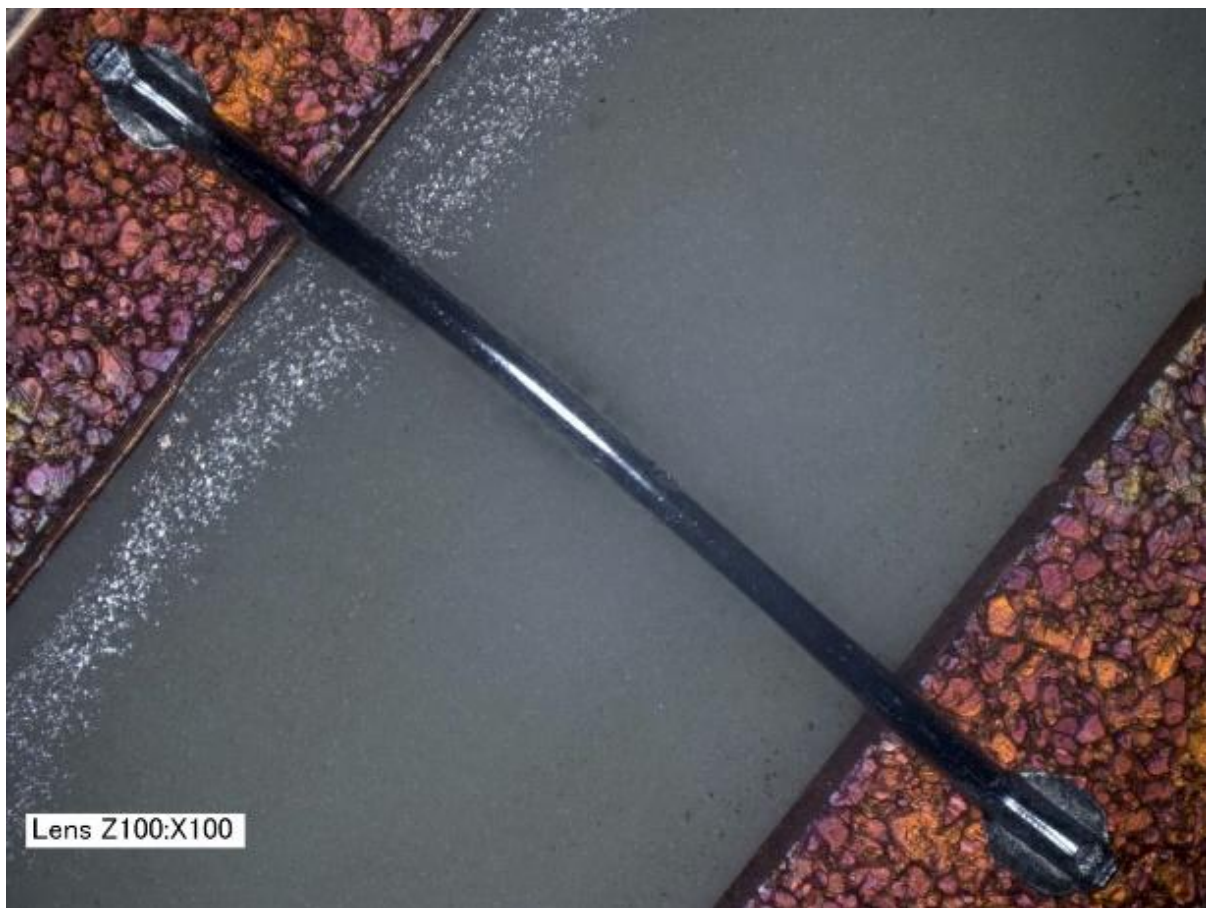
Pitting



Thermal-Electric Stress - Electromigration Failure

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Total Failure:
EM voiding – $CS_A \downarrow$ & local Joule heating $\uparrow$



Further Increasing Current Density – Fuse Failure

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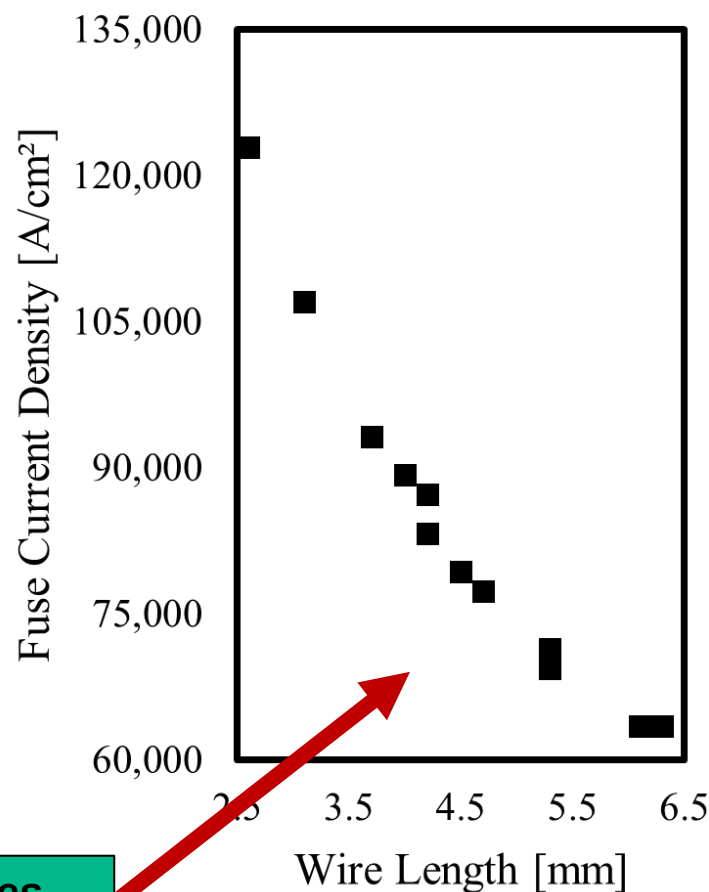
Fuse Failure

Mechanism:

- Elevated current density

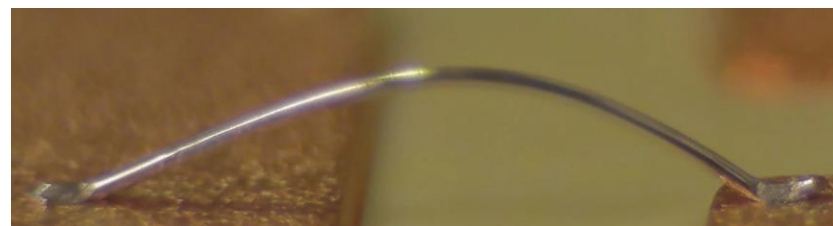
Mode:

- Joule heating causing abrupt conductor meltdown



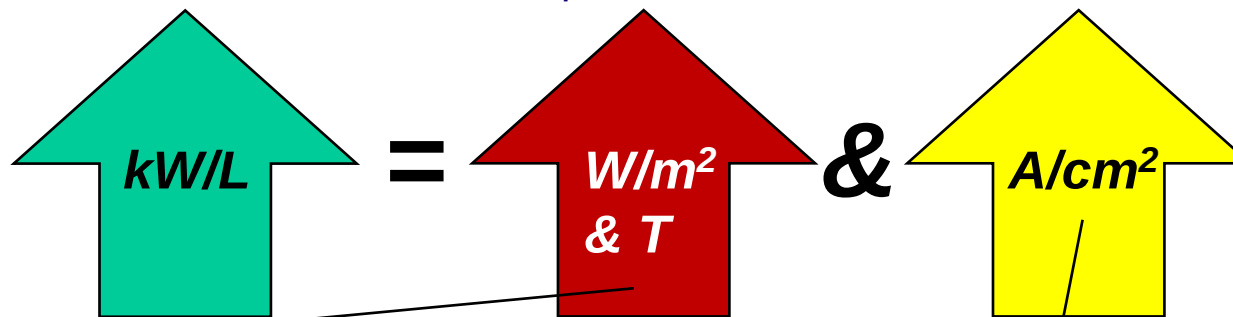
Thermal-electric failures depend significantly on conductor length

Frames from video of wire bond fuse failure when current density causes wire to melt



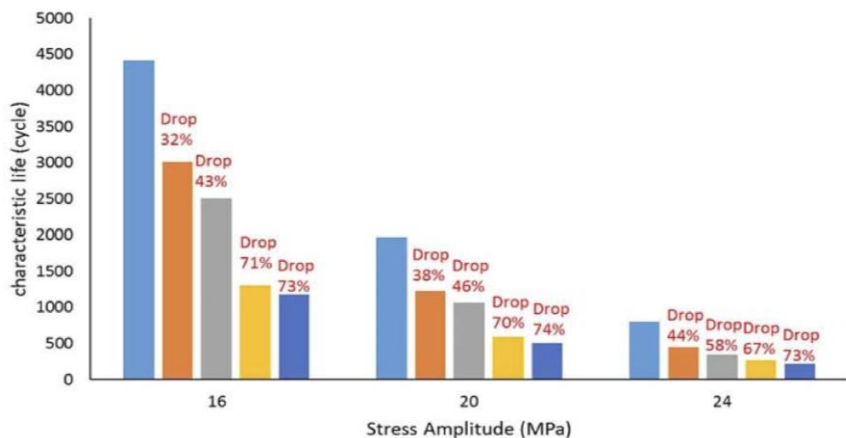
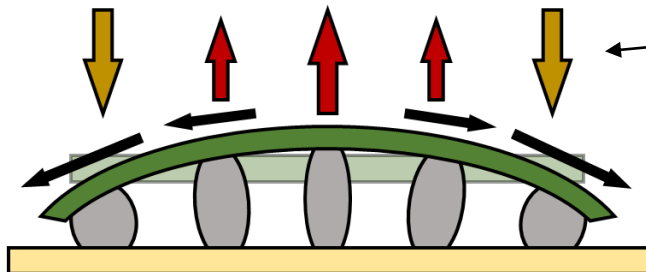
More Relevant Use Case – Multi-Stress Operation

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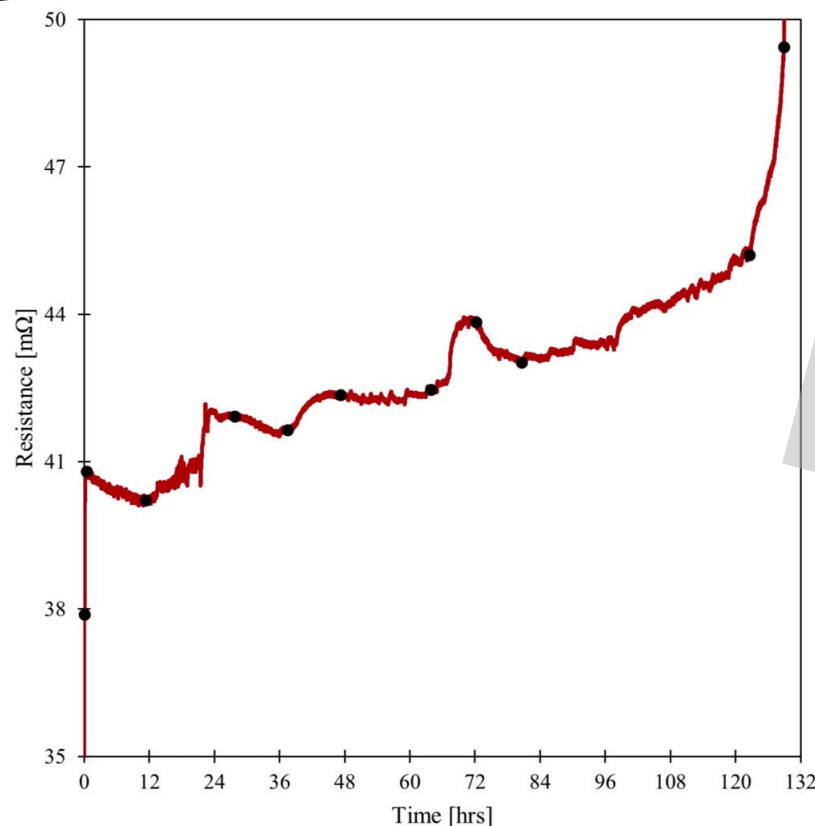


Cyclic or Constant Stresses

Tension, Compression, & Shear

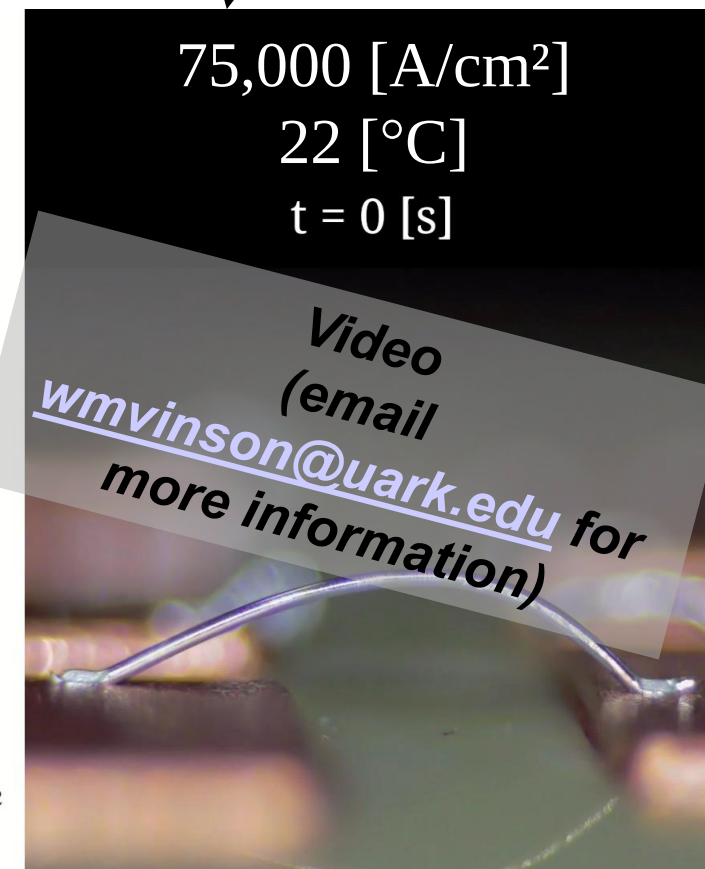


R. A. Athamneh et al., "Effect of Aging on the Fatigue Life and Shear Strength of SAC305 Solder Joints in Actual Setting Conditions," 2019 18th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM), Las Vegas, NV, USA, 2019, pp. 1146-1154, doi: 10.1109/ITHERM.2019.8757269.



75,000 [A/cm²]
22 [°C]
t = 0 [s]

Video
(email
wmvinson@uark.edu for
more information)



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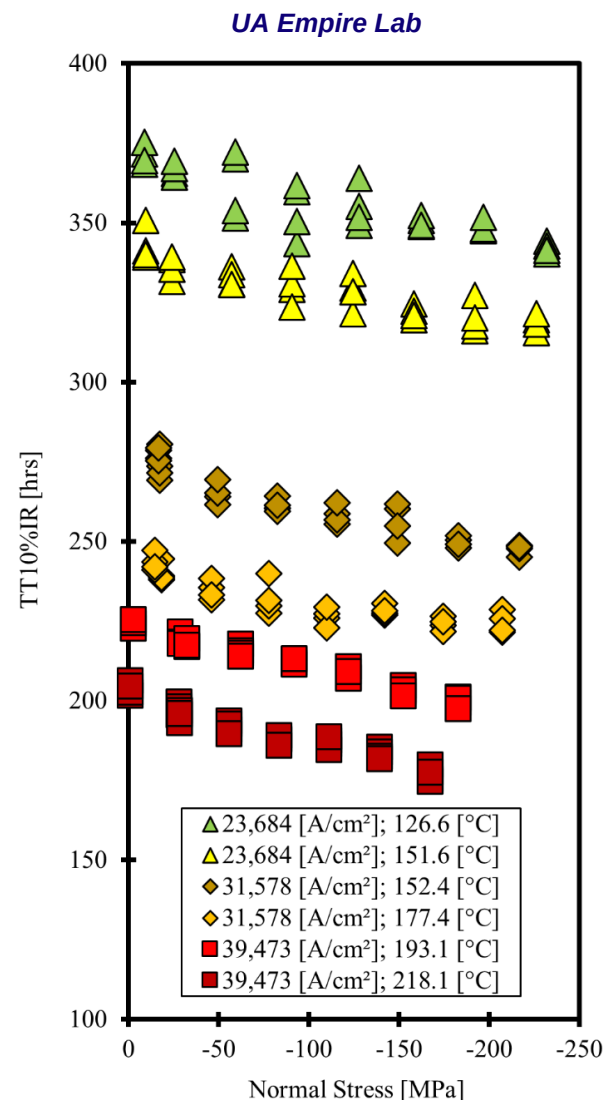
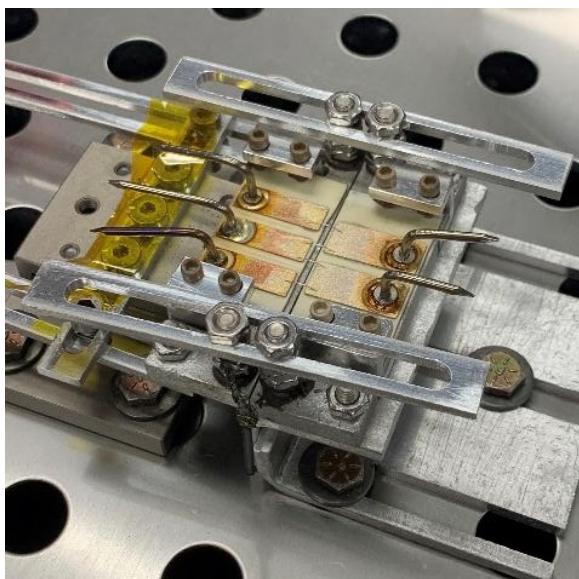
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Electromigration and Mechanical Stressing

- Increased power density
=> Opportunity for *overlapping failure mechanisms*

Two to consider in combination:

- Electromigration
- &
- CTE-related stresses



W. Vinson and D. Huitink, "Mechanical stress state consideration for enhanced electromigration life prediction in aluminum wire bonds," in *Microelectronics Reliability*, vol. 149, Oct. 2023, <https://doi.org/10.1016/j.microrel.2023.115185>

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Black's Equation:

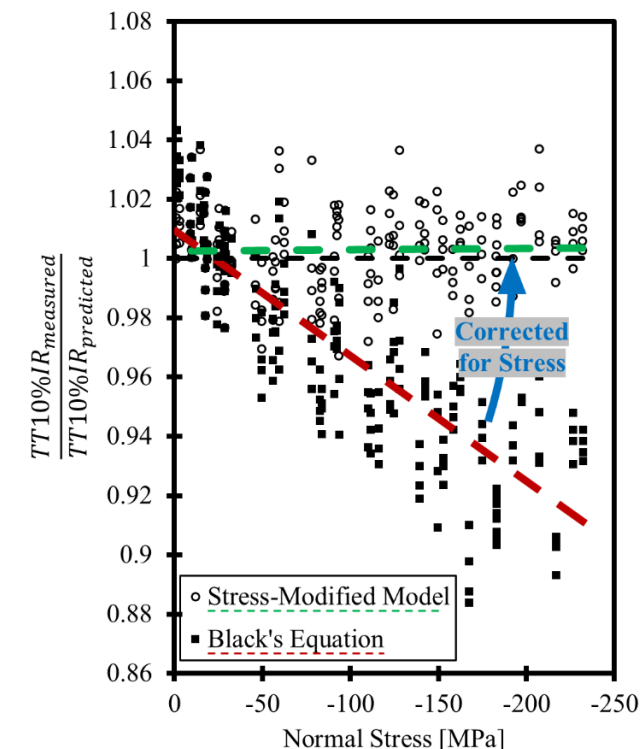
$$TT10\%IR = \frac{A}{j^n} e^{\left(\frac{E_a}{k(T_{amb})}\right)}$$

A	n	E _a [eV]
9.63 ± 9.3%	1.83 ± 3.6%	0.85 ± 7.8%

Stress-Modified Model:

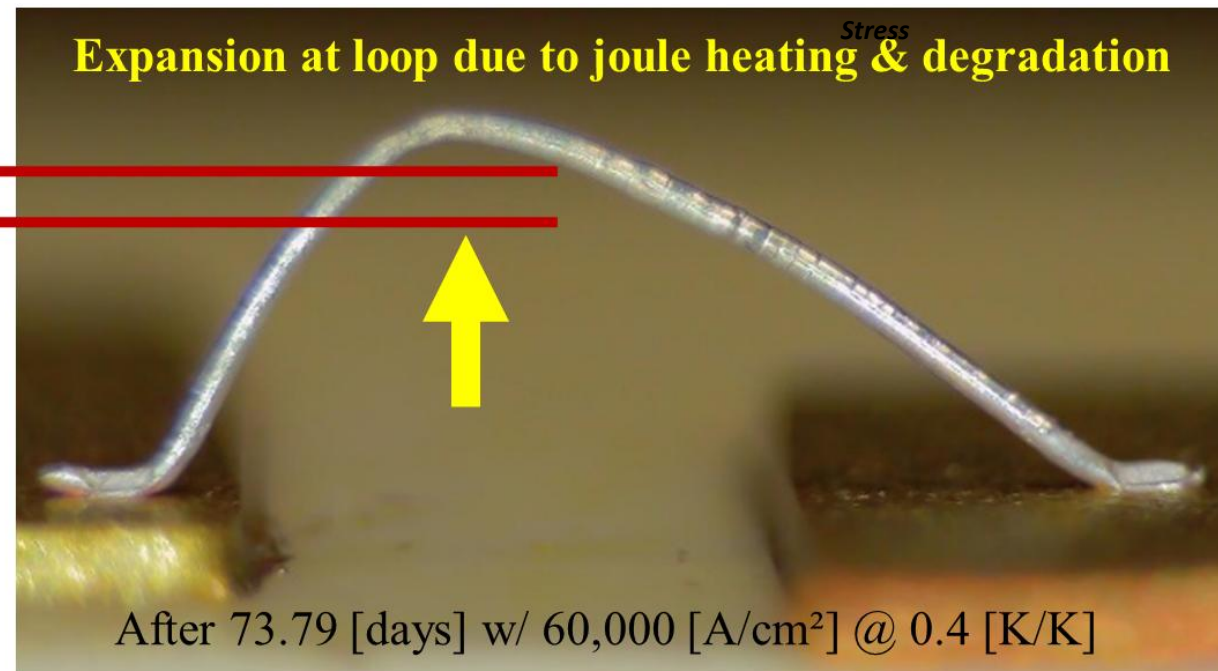
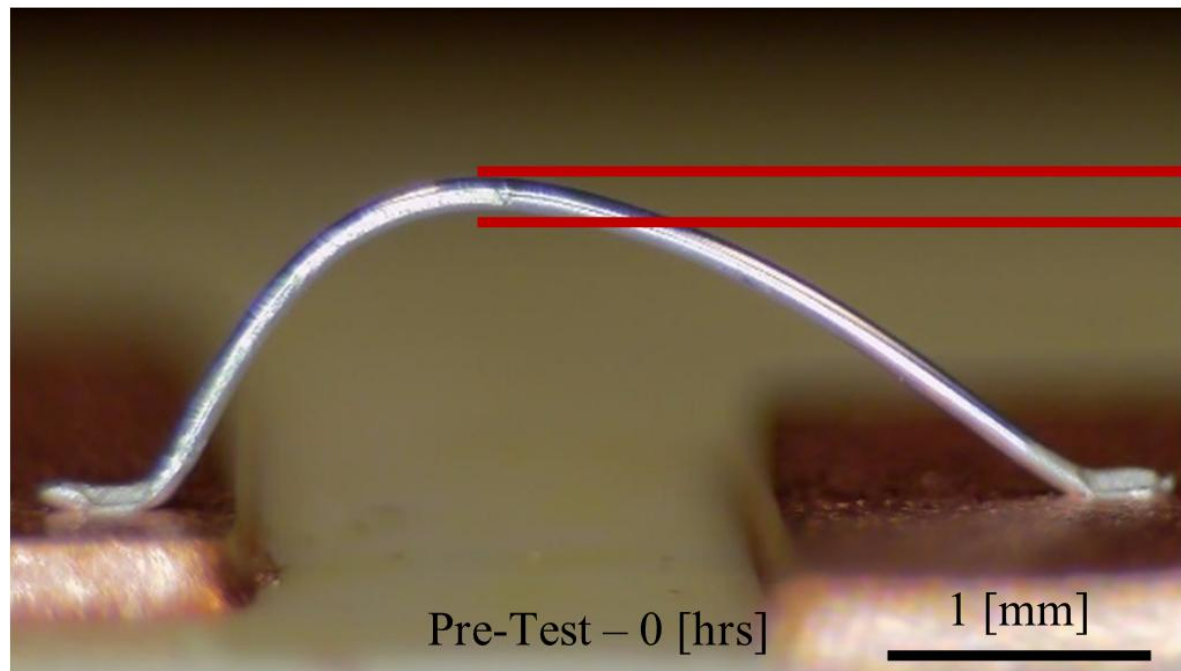
$$TT10\%IR = \frac{A}{j^n} e^{\left(\frac{E_a}{k(T_{amb} + T_{Shift})} + \frac{\sigma}{\gamma}\right)}$$

A	n	E _a [eV]	γ [MPa]
9.57 ± 2.8%	1.83 ± 3.6%	0.85 ± 7.8%	2247 ± 41.1%



Mitigation Strategies – Combatting Degradation

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Mitigation Strategies – Combatting Degradation

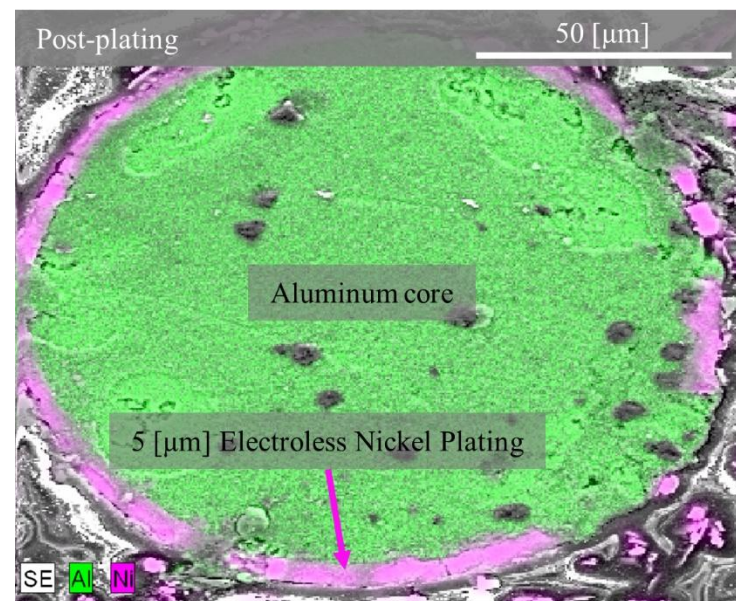
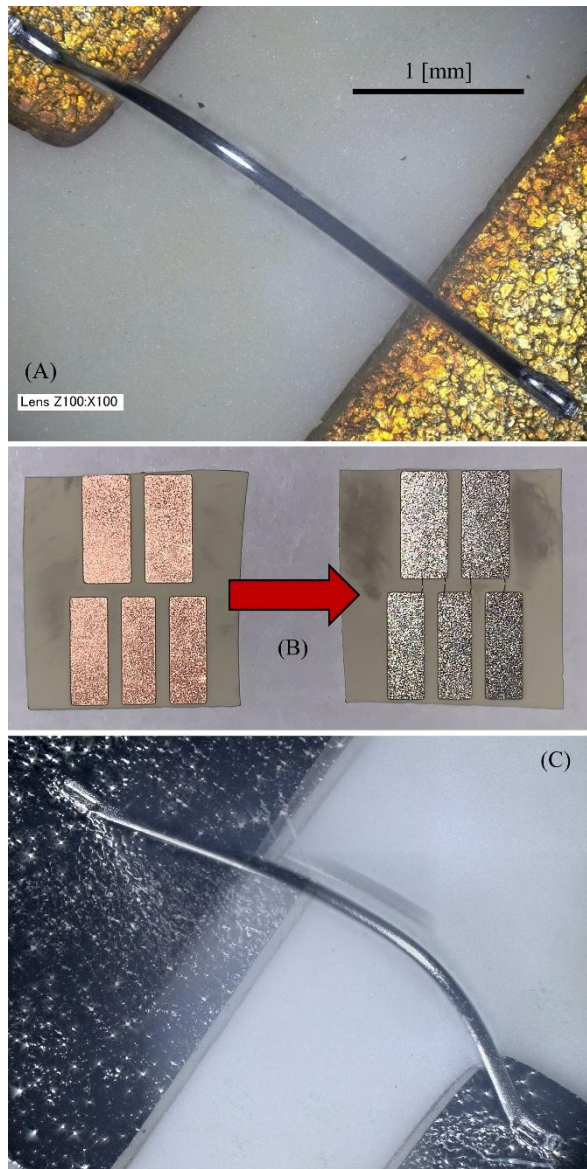
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➤ Coatings

- “Bare” (i.e. Standard)

-VS-

- 5 [μm] Electroless Nickel Plating
 - Effective diffusion barrier
 - Shown to attenuate electromigration as dopant in solder
- 10 [nm] Atomic Layer Deposited Al_2O_3 (Meng Nano & Energy Lab)
 - Shown to improve thermal cycling lifetime as a coating on fine Au wire bonds



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Mitigation Strategies – Combatting Degradation

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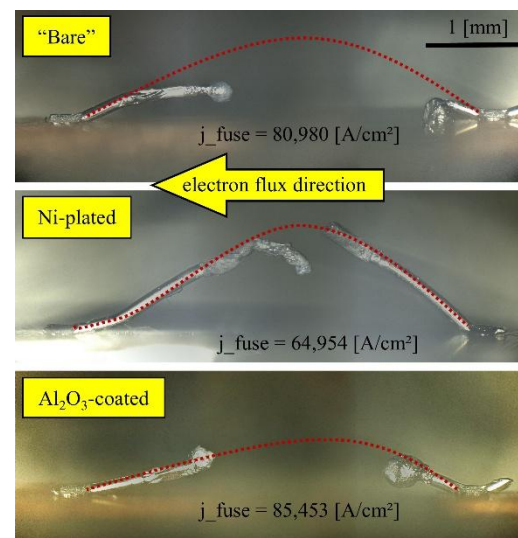
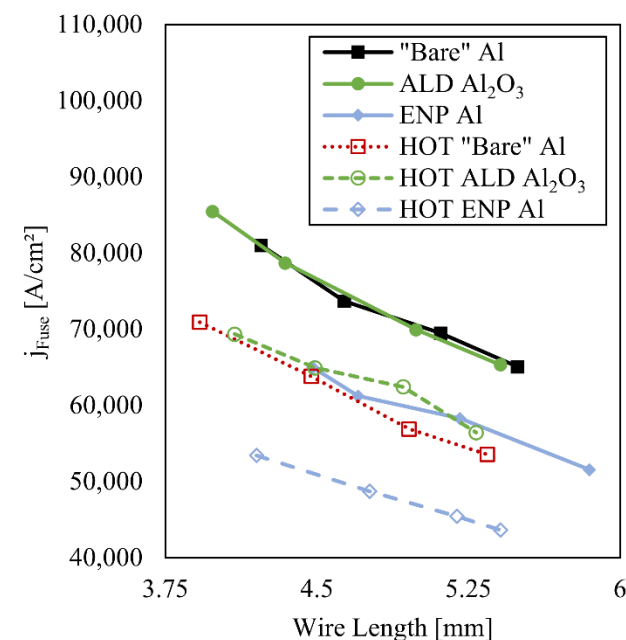
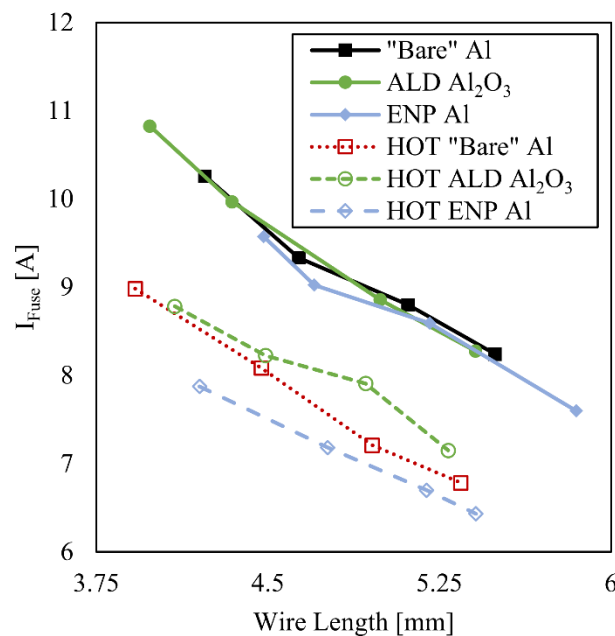
➤ Fuse current testing

• ENP

- Marginally reduced current carrying capacity despite increased conductive cross-sectional area – current density therefore is significantly reduced

• Al_2O_3

- Similar current carrying capacity to “Bare” bonds



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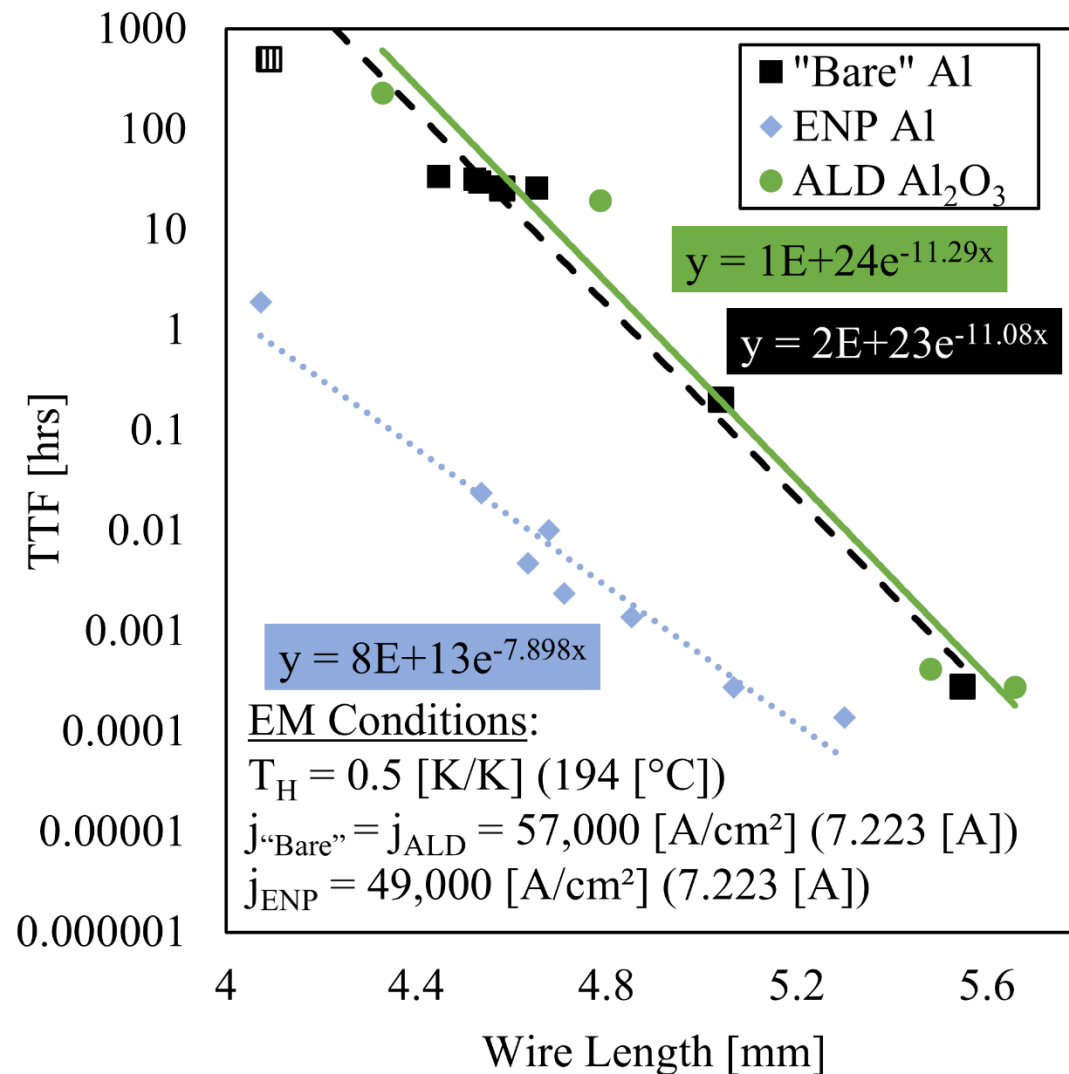
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Mitigation Strategies – Combatting Degradation

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➤ Electromigration Testing

- ENP
 - Significant drop off in lifetime compared to other two groups
- Al_2O_3
 - Similar if not slightly improved EM lifetime (limited dataset)
- Other Future Ceramic Options?
 - AlN ?
 - AlON ?



Mitigation Strategies – Combatting Degradation

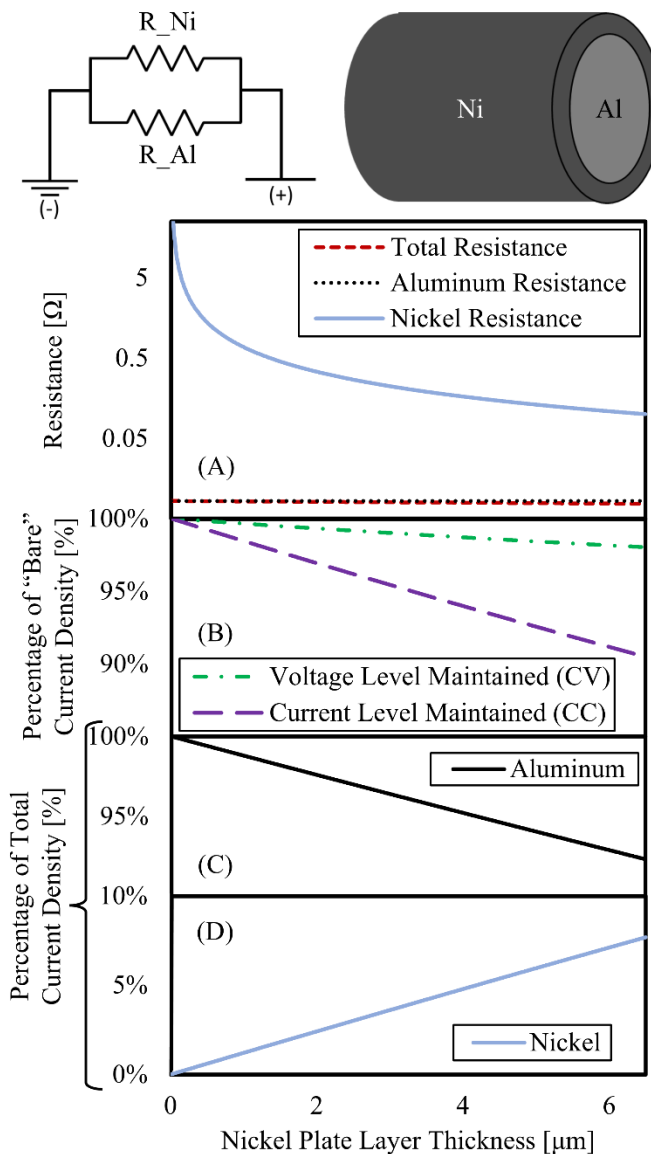
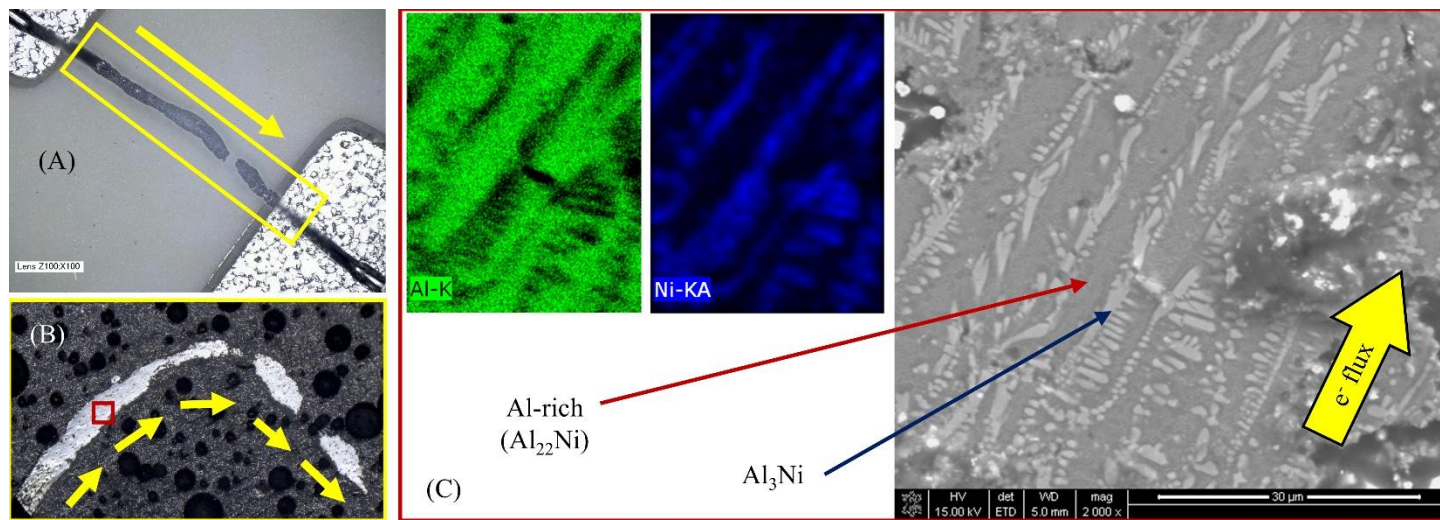
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➤ Cause of ENP early failure

- Rapid AlNi IMC growth due to elevated current density

Platings & Coatings study accepted to ASME Journ. Electronic Packaging on 4/8/2025

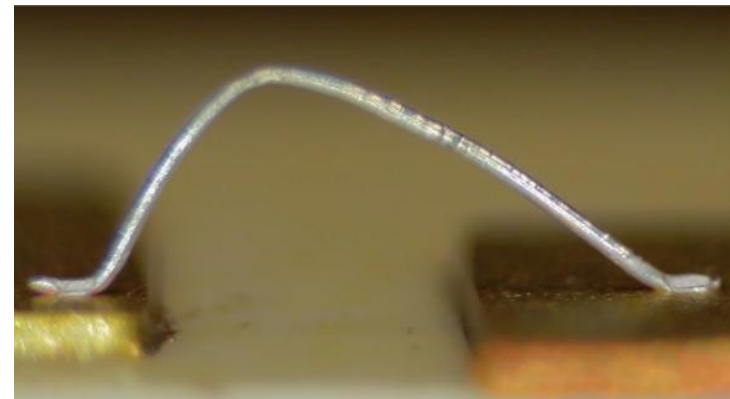
Compound	ΔH_f [kJ/mol]	H_{needed} [J] (based on experimental conditions for this test)	$H_{\text{obtained}} = I^2 R t$ [J] (this test)
Al_3Ni	-51 - -41	0.0387	24.97



Conclusions & Outlook

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- Expect that Al Wire Bond use will continue in upcoming generations of PE systems due to ease of integration
- Heightened power and thermal demands put them at risk of thermal-electric failure modes
 - Electromigration Failure
 - Fuse Failure
 - Multi-Stress Scenarios Reducing expected lifetimes
- Investigation of individual failure drivers has improved understanding of their contribution to failure and provided the opportunity to suggest possible performance enhancing fabrication techniques
 - Sustained temperatures reduce bond quality and increase sensitivity to interconnect length
 - Electrically conductive coatings could show promise if generation of high-resistance IMCs can be avoided
 - Ceramic coatings show promise from thermo-mechanical perspective and (when thin enough) do not appear to negatively impact performance



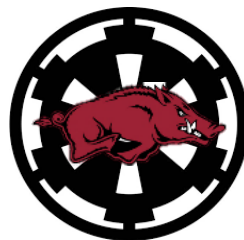
Q&A + Acknowledgements

UA Empire Lab

- University of Arkansas
- High Density Electronics Center
- Korea Electrotechnology Research Institute
- National Science Foundation (POETS)
- Office of Naval Research (DEPSCoR)
- Nitride Global Inc. (GRAPES)



UNIVERSITY OF
ARKANSAS
COLLEGE OF ENGINEERING



GRAPES
GRI-d-connected Advanced Power Electronic Systems



NITRIDE
GLOBAL

