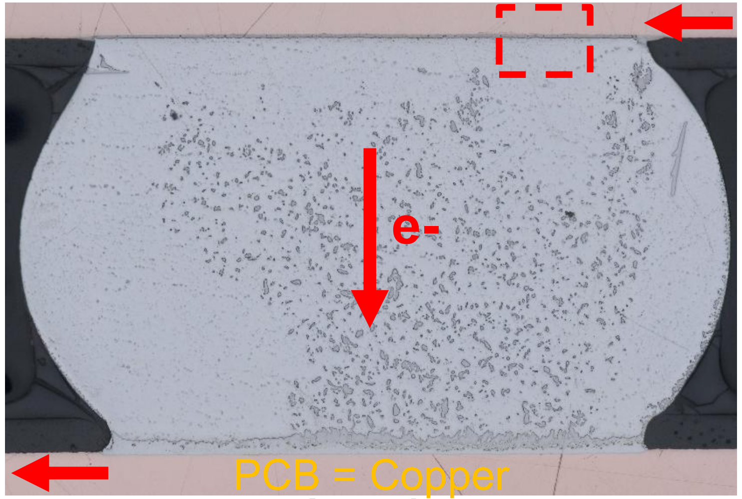
Electromigration Update: SAC305 (and Cyclomax)

Michael Meilunas
April 1, 2026

Nickel Degradation

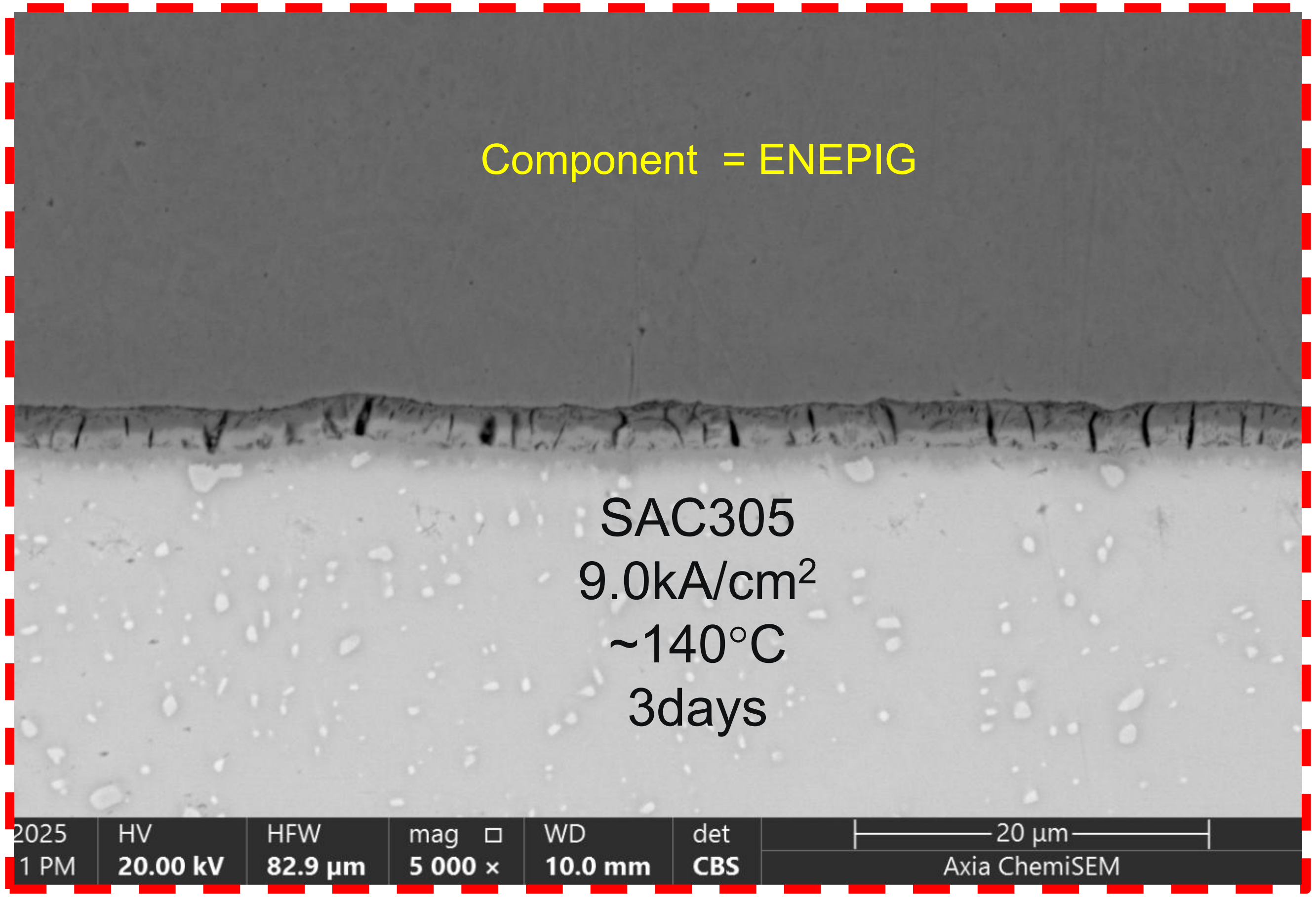
- Nickel barrier issue:
  - Resistance rise due to nickel break-down
  - Solder is in excellent condition
  - Issue is ***most prevalent*** when nickel is at cathode side
  - Observed in ENEPIG and ENIG samples (different suppliers)

Cathode



Anode

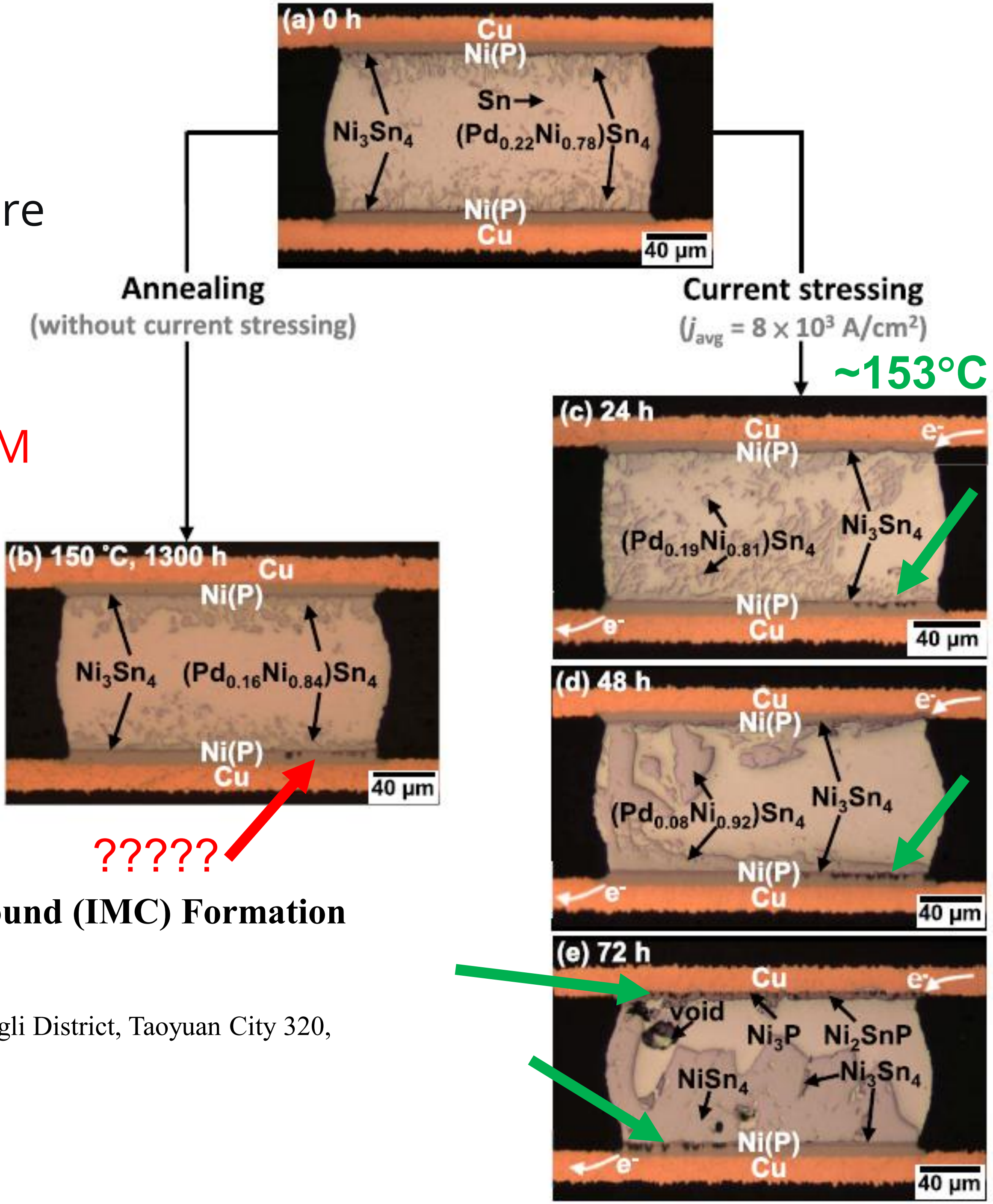
+53% Resistance



Nickel Degradation

- Reported in literature:
  - Observed under high current and temperature
    - Short test duration
    - Both sides of same joint show some effect?
    - Electron flow direction appeared to matter
  - Looks like it may also be present after non-EM “annealing”
    - 1300 hours @ 150°C

My interpretations



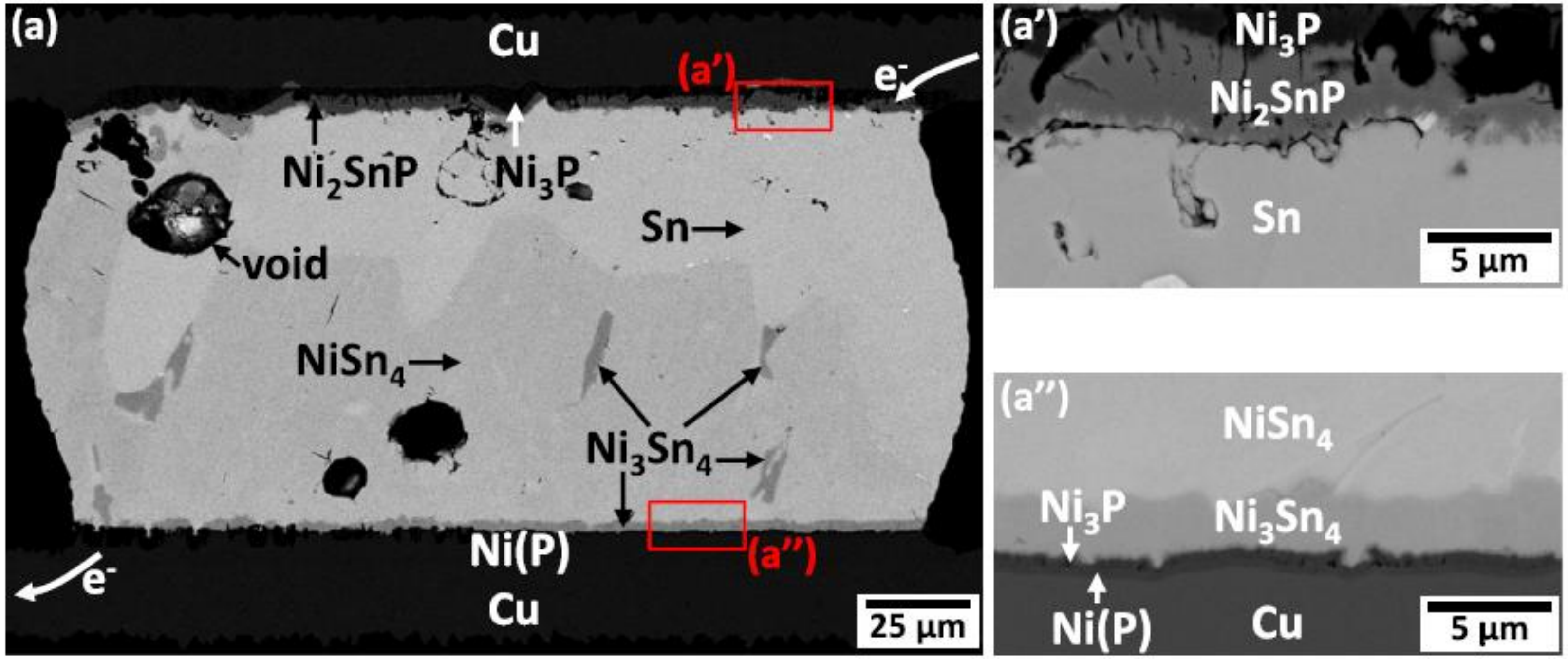
Electromigration-Induced Remarkable Intermetallic Compound (IMC) Formation in Micro Joints and its Prevention

Pei-Tzu Lee, Cheng-Yu Lee, Wan-Zhen Hsieh, Chih-Tsung Chen, Cheng-En Ho
Department of Chemical Engineering & Materials Science, Yuan Ze University, Chungli District, Taoyuan City 320, Taiwan, R.O.C Journal of Materials Research and Technology 2023; 24 : 3889-3900

Nickel Degradation

- In this example, the bottom pad nickel is clearly degraded
- This surprised me given my early findings that showed electron flow from solder to nickel did not seem to induce nickel consumption
  - Joint shown is very hot (NiSn IMCs likely to form)
  - Joints shown are "short" and probably have less electron flow uniformity compared to my samples

~153°C; 72hrs; 8kA/cm^2



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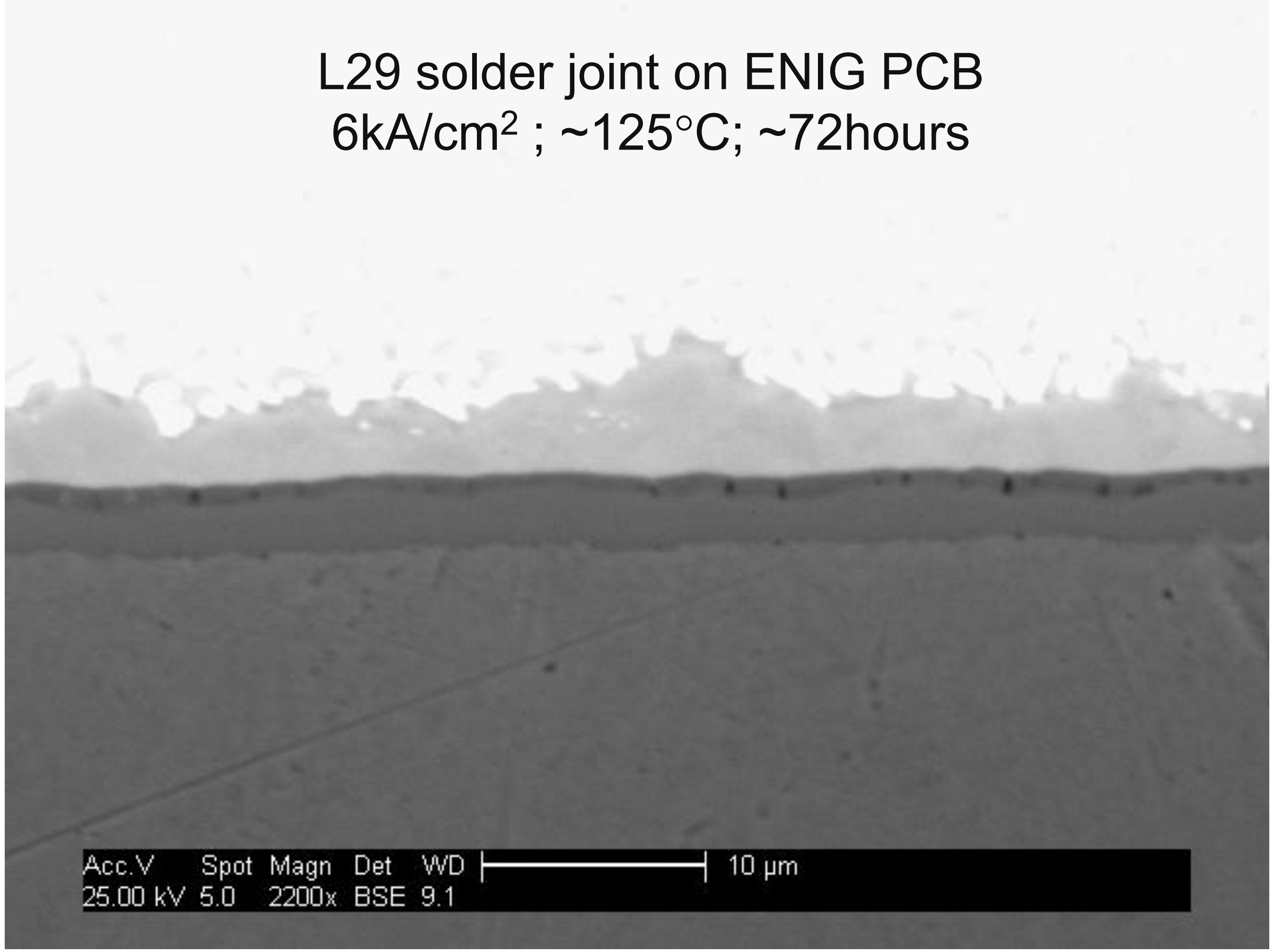
Nickel Degradation

- I reviewed many hundreds of images from AREA's Low-Melt EM projects and found this singular image of possible Nickel degradation
  - These samples only survived a few days before "burn-out", so I did not put much thought into this at the time



L29 solder joint on ENIG PCB

6kA/cm^2 ; ~125°C; ~72hours

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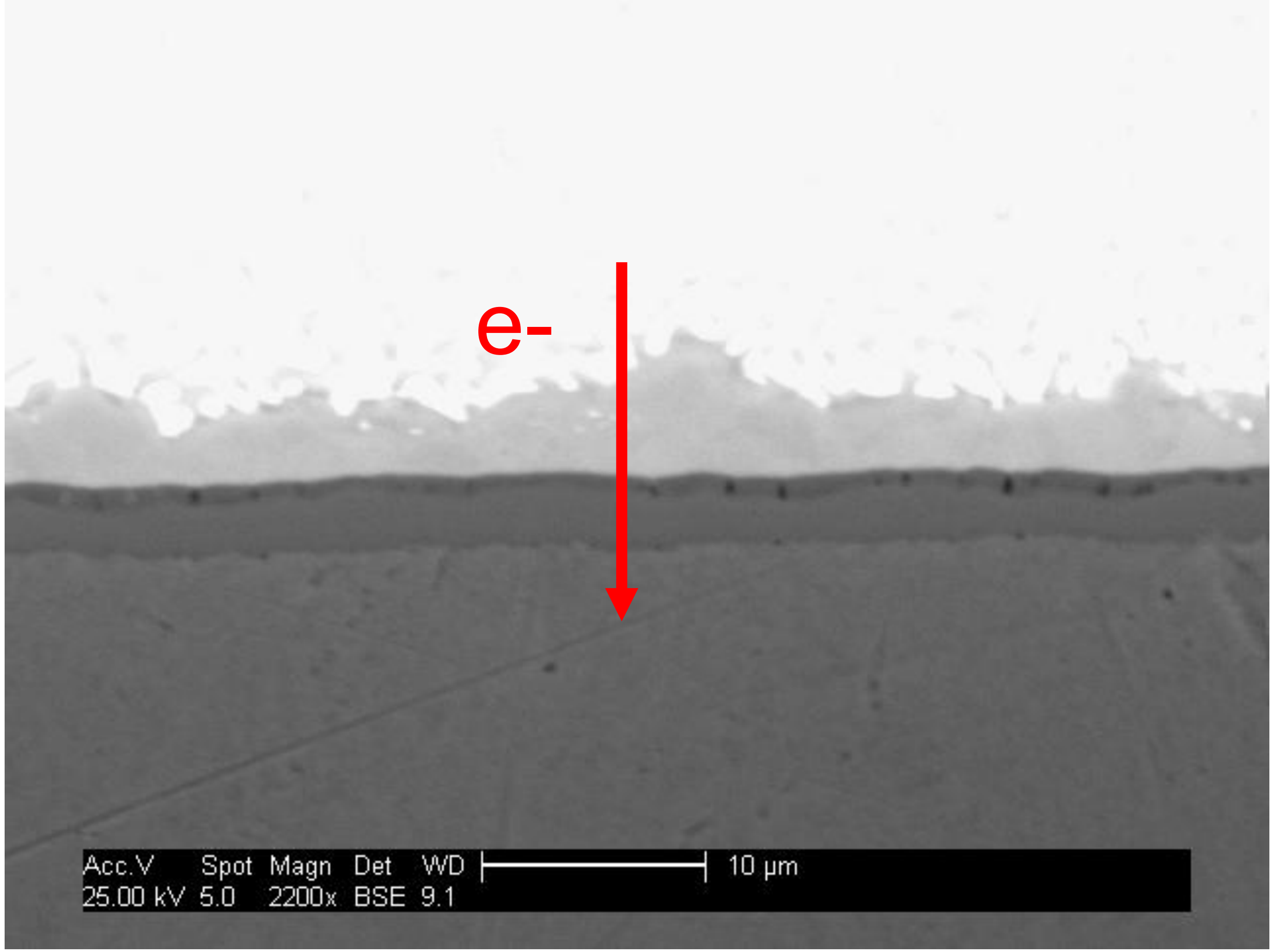
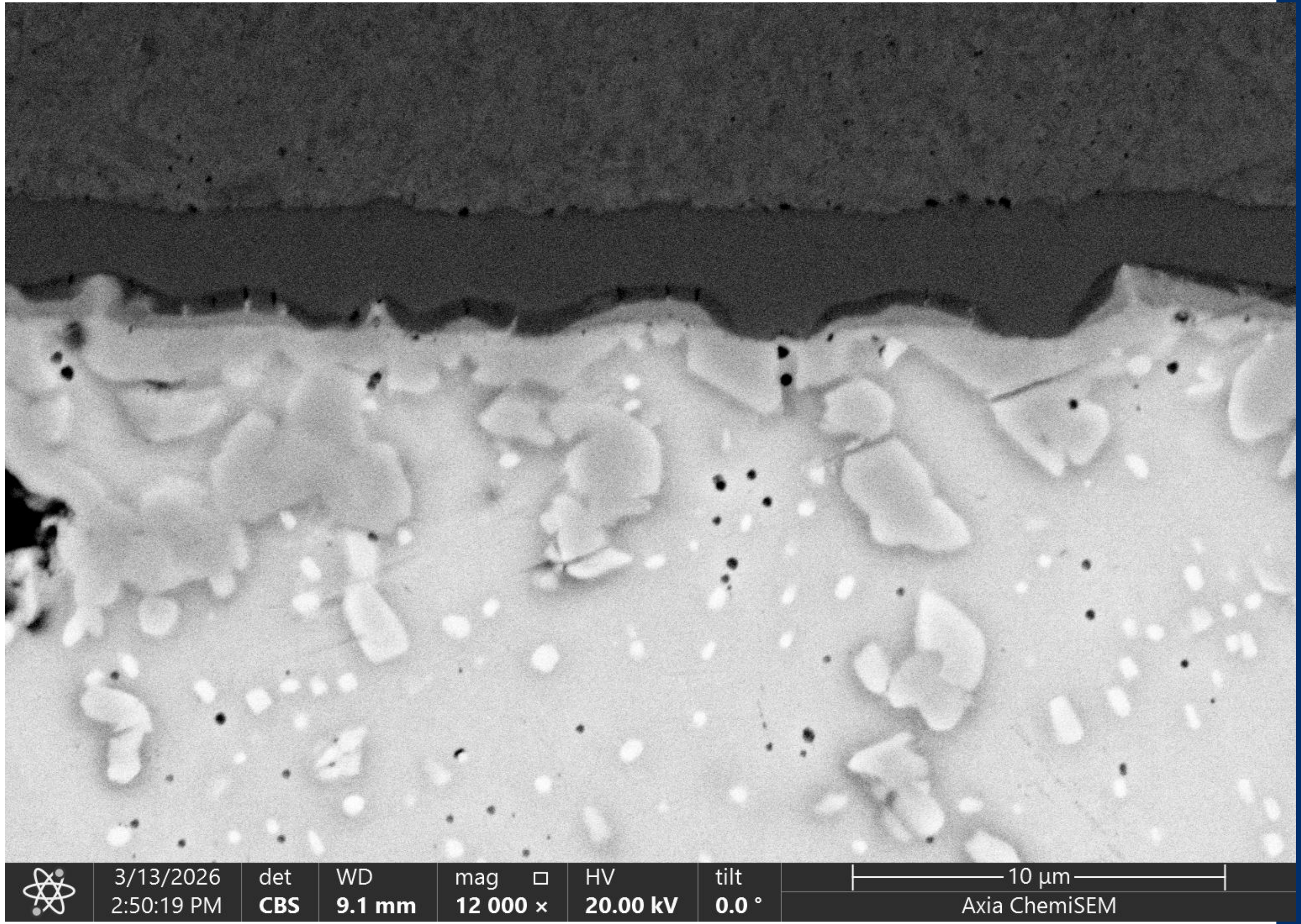
Nickel Degradation

- I can confirm that this joint experienced electron flow “down”
  - This contradicts my previous narrative from October meeting
- Question: where/when does the nickel issue begin?
  - Upon plating?
  - Upon solder ball attach?
  - Upon reflow to PCB?
  - During “annealing”?
  - During EM stressing?



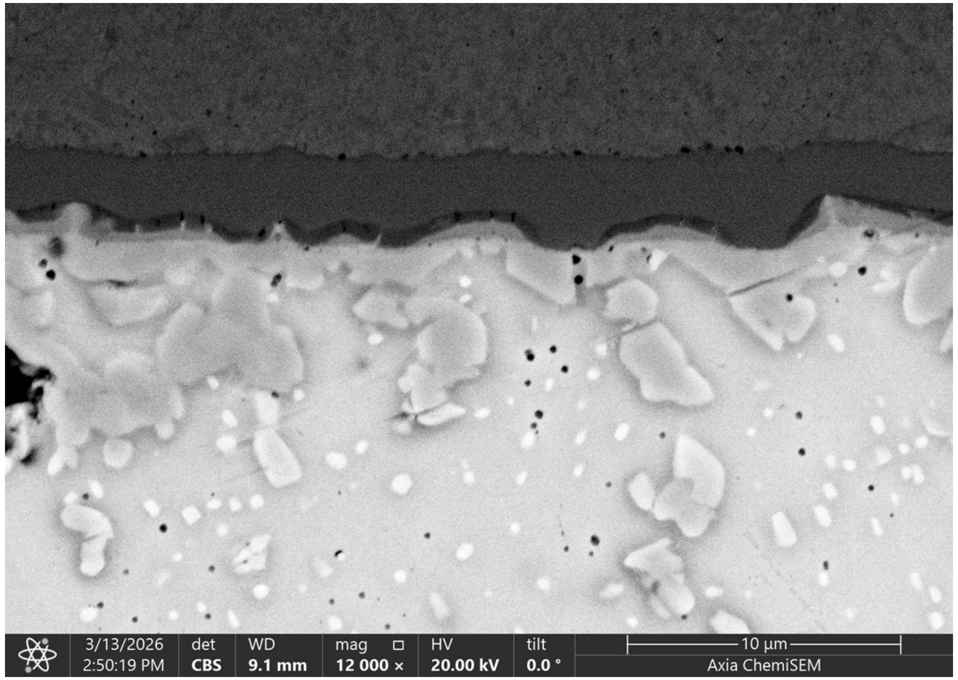
Nickel Degradation

- I re-examined several samples which contained significant nickel damage after EM stress testing
- Examined joints that were not exposed to current (but experienced elevated environmental temperature)
- Observed nickel issue
  - indicating that electron flow was not necessary
  - Some instances were quite bad (see image)

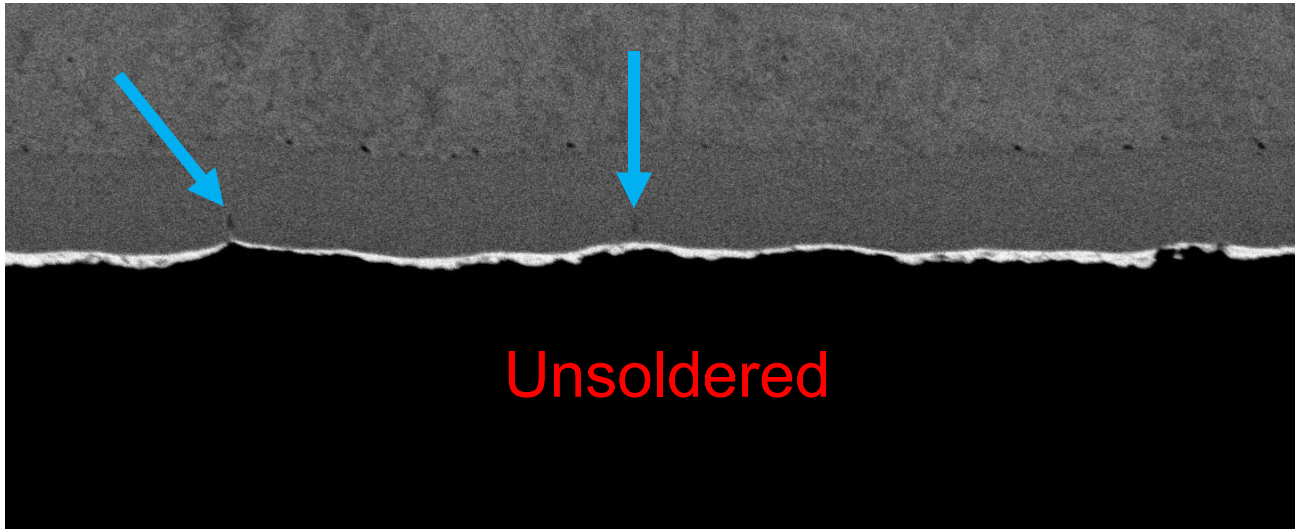


ENIG Component
70°C for 60 days
(no current)

Nickel Degradation



Soldered (SAC305)

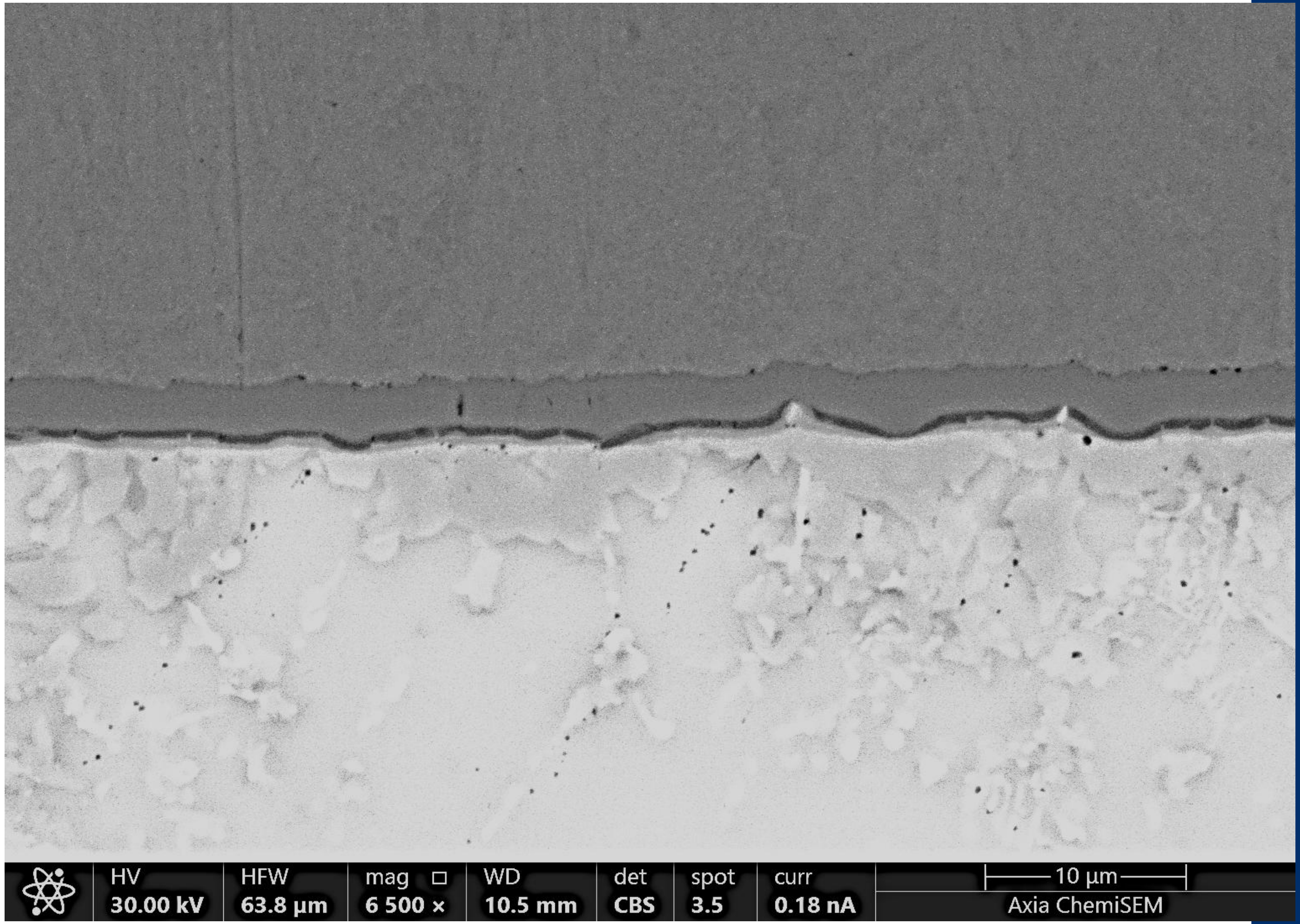


ENIG Component
70°C for 60 days
(no current)

- Pads that were not soldered still contain gold finish with some “divots” in the nickel layer, but nothing that would have led me to suspect a problem

Nickel Degradation

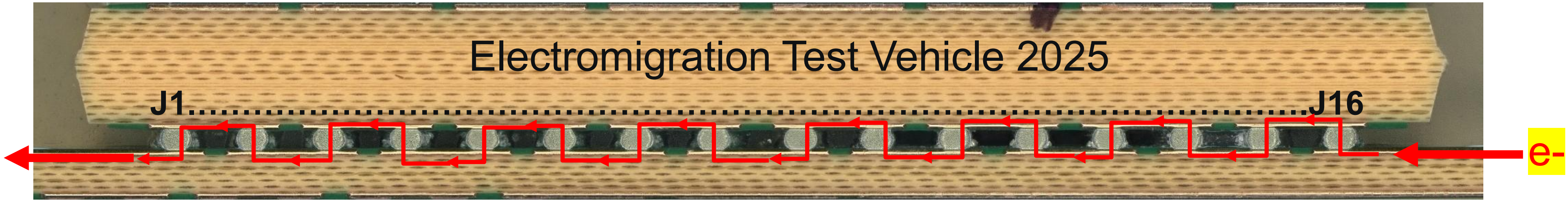
- I was able to find examples of nickel degradation when examining BGA devices that were assembled to PCBs but never tested (room temperature storage)
  - Selectively looking at samples from material sets where severe nickel degradation was observed after EM

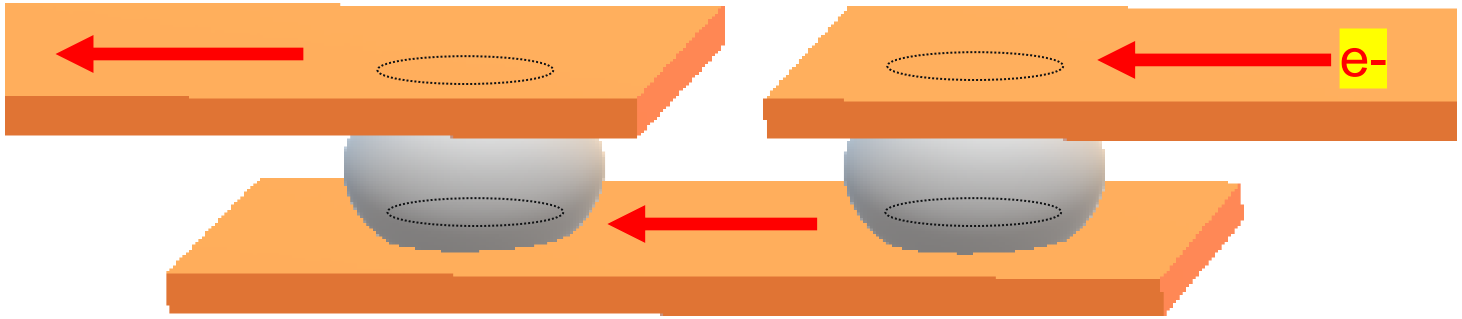


ENIG finish
Cyclomax Solder
Room Temperature ~100 days
No Current

Test Vehicle Concept

- Current flows across multiple solder joints alternating “up” and “down”.
- Voltage can be measured at all stressed locations (EMTV2025) or at select locations (DTV2022)
- Solder mask defined pads and large, thick traces minimize current crowding and copper trace Joule heating





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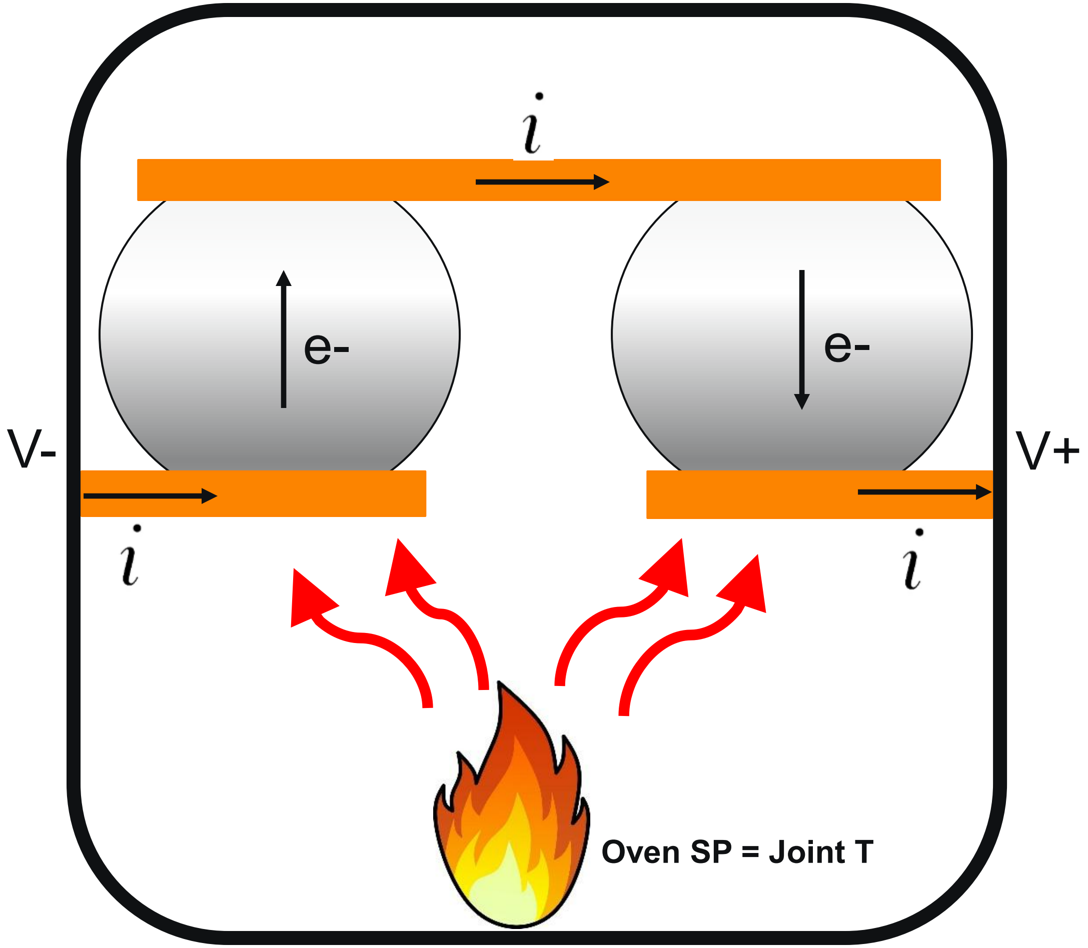
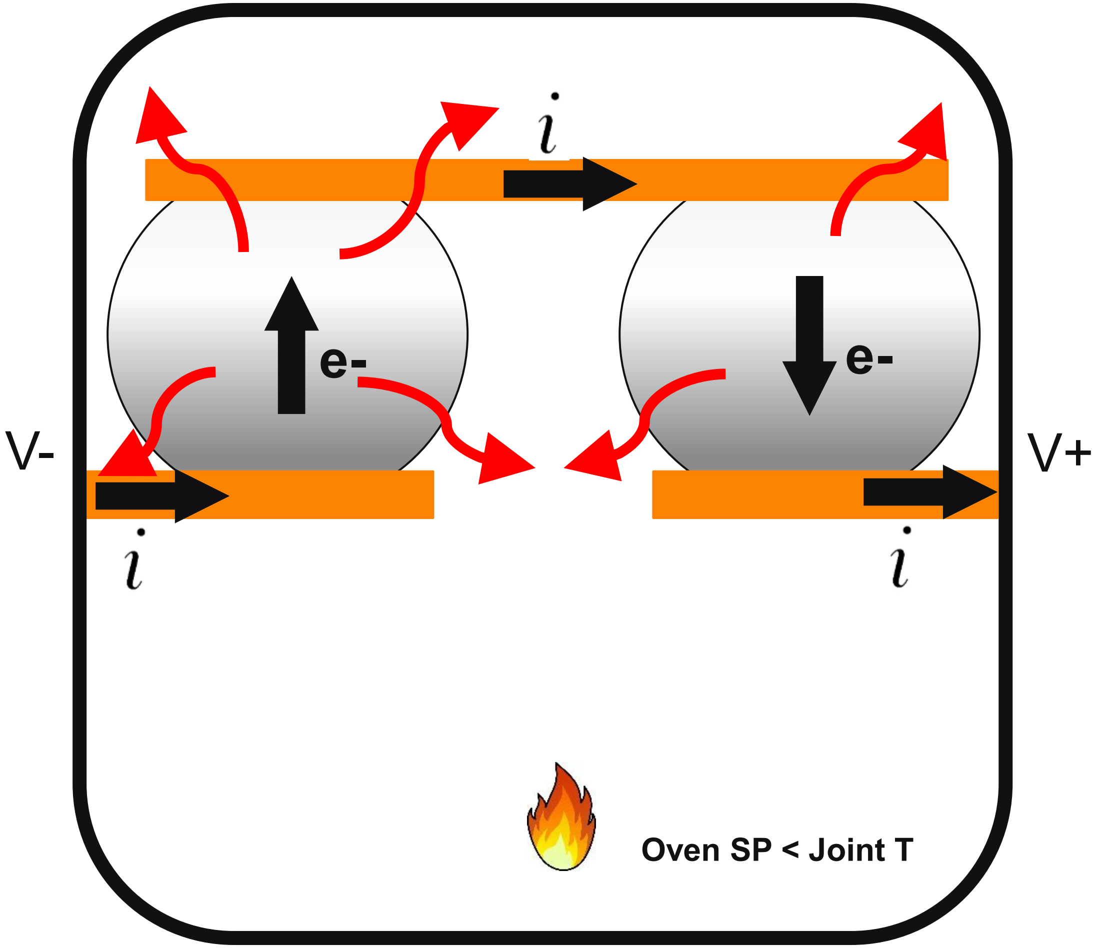
Test Vehicle Concept: $V = I*R_{(T)}$

TEMPERATURE DETERMINATION



Low current; minimal Joule heating
Externally driven temperature;
~uniform joint temperatures

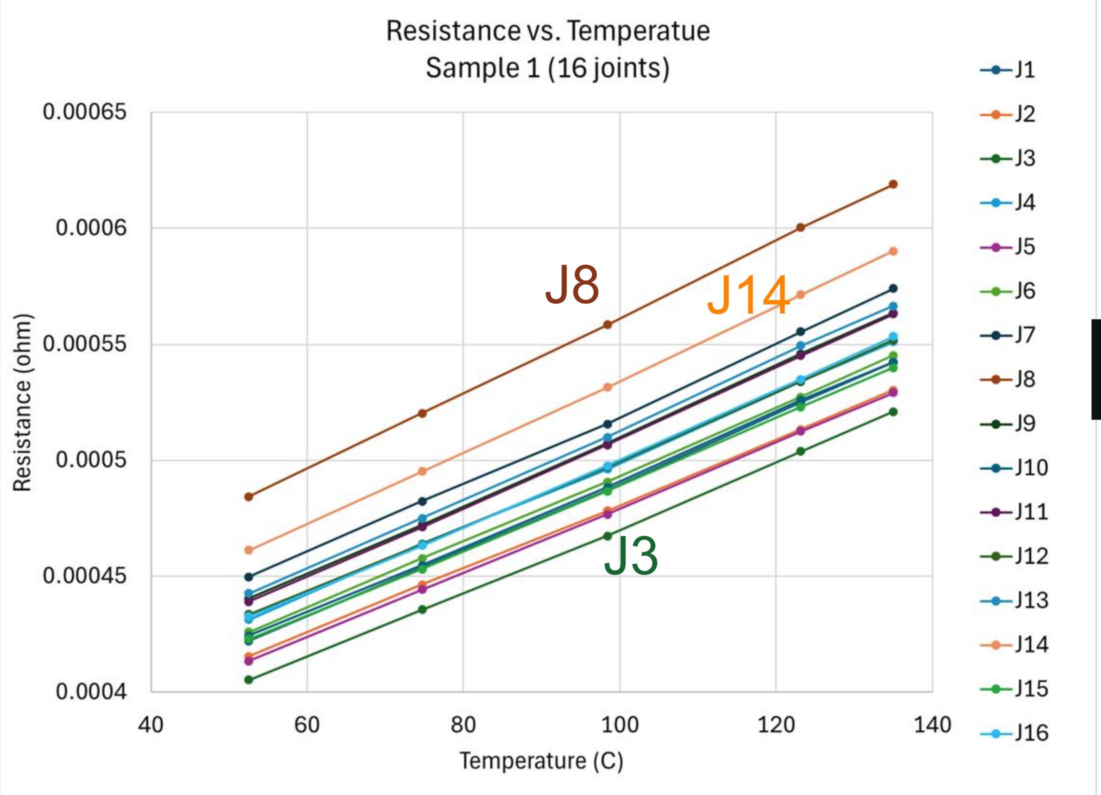
EM TEST METHOD

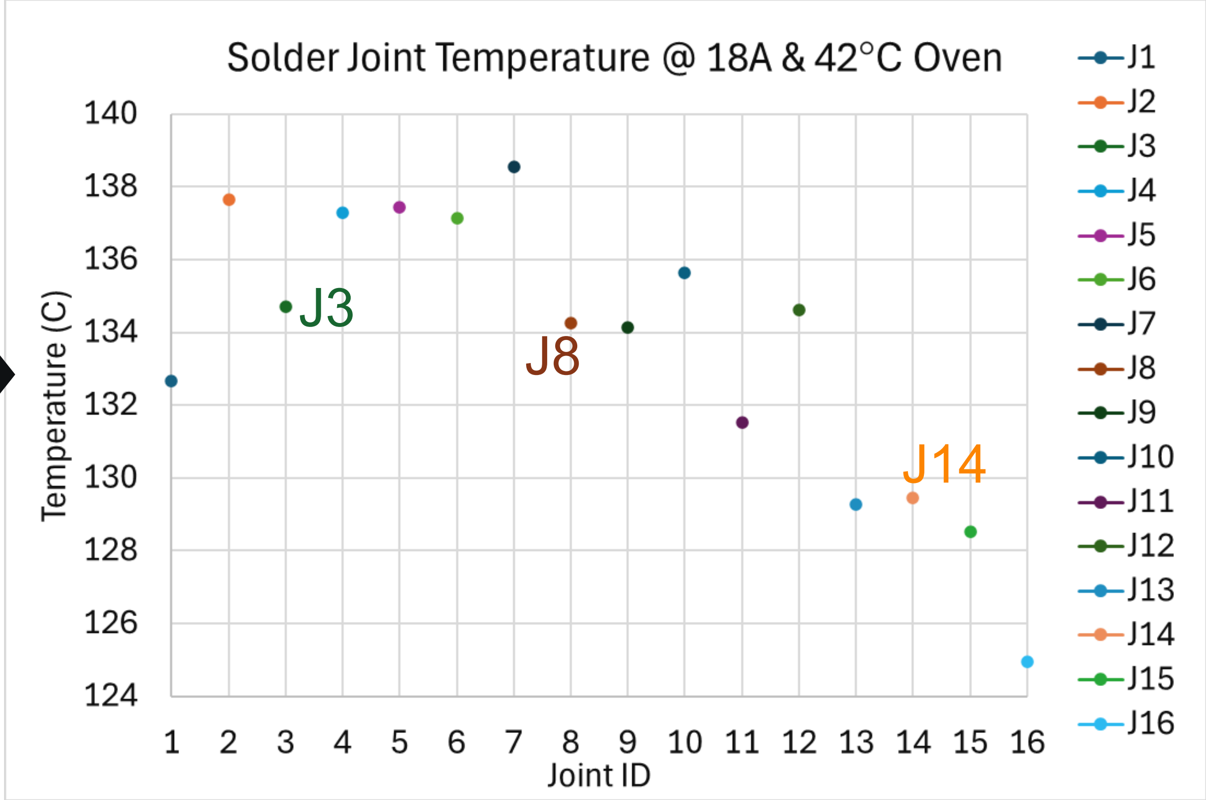


High current; significant Joule heating is possible
environmental temperature “boost”;
non-uniform heating joint-to-joint

Test Vehicle Concept

- Resistance ranking does not equal temperature ranking once EM testing has begun
- R vs. T relationship is valid at start of test, it falls apart as testing progresses

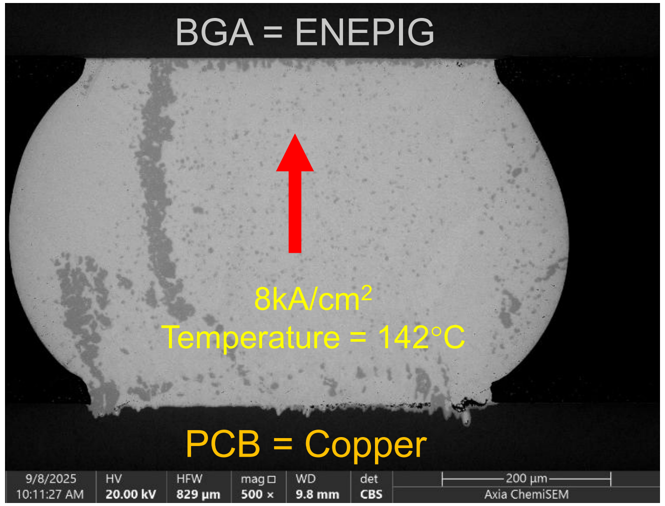




See also: Role of Crystallographic Orientation of β-Sn Grain on Electromigration Failures in Lead-Free Solder Joint: An Overview Muhammad Nasir Bashir et al. Coatings 2022, 12(11), 1752; https://doi.org/10.3390/coatings12111752

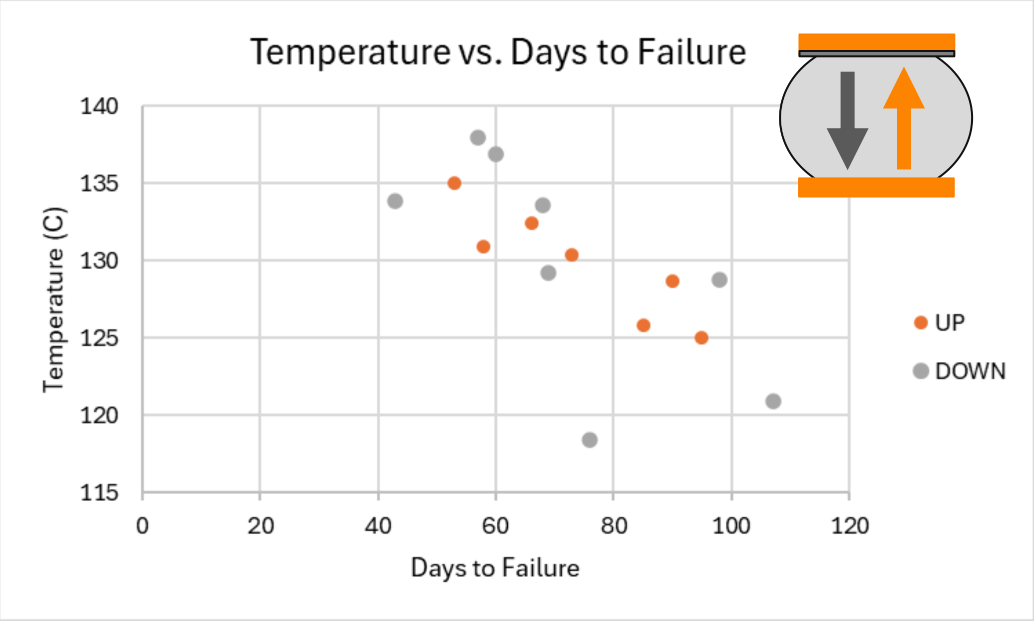
October 2025 Recap (SAC305)

- 9.5kA/cm² @ ~150°C : samples demonstrated fast resistance increase resulting in joint melting and definitive failure in less than 24 hours
  - Some joints may have been as hot as 180°C at start of test
  - Copper pad consumption and nickel layer break-down were observed
- 9kA/cm² @ ~140°C : samples survived less than 3 days **(+50% resistance)**
  - Some joints may have been as hot as 160°C
  - Significant copper pad dissolution observed, but only +5% resistance change
  - Nickel layer degradation resulted in >50% resistance increase
- 8kA/cm² @ ~135°C : samples survived 38 days **(~5% resistance increase)**
  - Some joints as hot as 145°C
  - Significant copper pad degradation observed
  - Nickel break-down was not observed
- Decision: +5% is reasonable failure criteria



October 2025 Recap (SAC305)

- 7.5kA/cm^2 @ ~150°C : samples survived 10 to 15 days **(~5% resistance increase)**
  - Nickel issue drove most failures
- 7.0kA/cm^2 @ ~135°C : samples survive 8 to 25 days **(~5% resistance increase)**
  - Nickel issue appeared at day 8
  - Copper degradation drove most failures
- 5.0kA/cm^2 @ 125°C: 43 to >100 days **(~5% resistance increase)**
  - Joints may be up to ~138°C
  - Nickel issue at 43 days (**DOWN**)
  - Copper degradation at 53 days (**UP**)
- Nickel issue occurs at relatively low temperature / current densities
  - IS THIS A VALID STATEMENT?
  - What are realistic temperatures /current densities?



October 2025 Feedback:

- Responses to “What are realistic conditions at the solder joint level?”
  - “We design for 85°C peak, certainly never above 115°C.”
  - 1.7 kA/cm^2 with joint temperatures up to 125°C.
  - 1.45 kA/cm^2 and around 115-120°C temperature.
  - 3.5kA/cm^2 with joint temperatures ~85°C; up to ~100°C.
  - 9kA/cm^2 with joint temperature of ~110C.
- I did not get feedback on duty cycle / peak usage rate
  - Previous feedback for Low-Temp solders included 70 to 85% “on time”

SAC305 Electromigration (older data)

- 3 populations were evaluated @ 5.0kA/cm^2 with target solder joint temperature of 125°C
  - ENEPIG PCB / ENEPIG BGA
  - ENEPIG PCB / Copper BGA
  - Copper PCB / Copper BGA
- Failure criteria: Loop voltage increase of 5%
  - Individual joint performance is unknown; one joint or multiple joints may be contributing to voltage rise
    - Results are conservative
  - **Joint temperatures are mostly unknown**

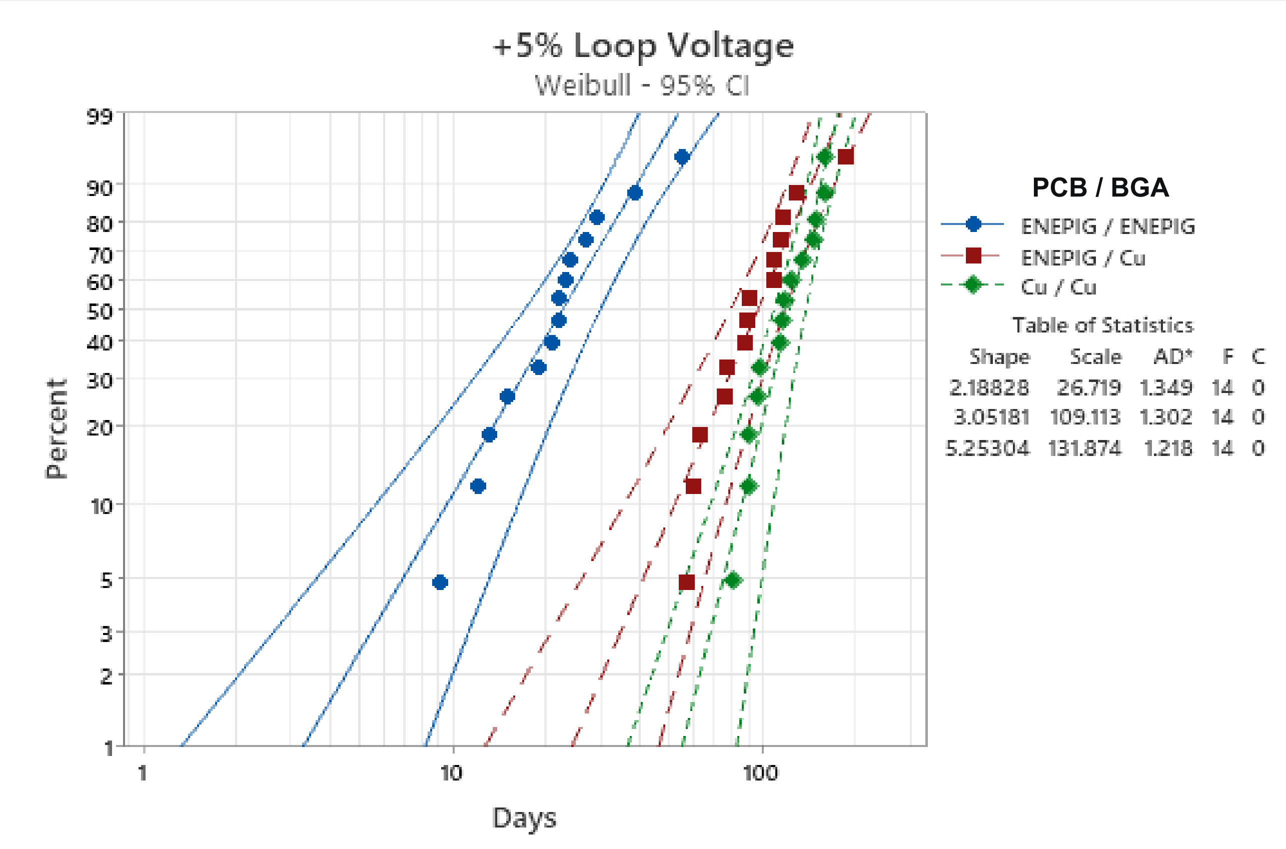


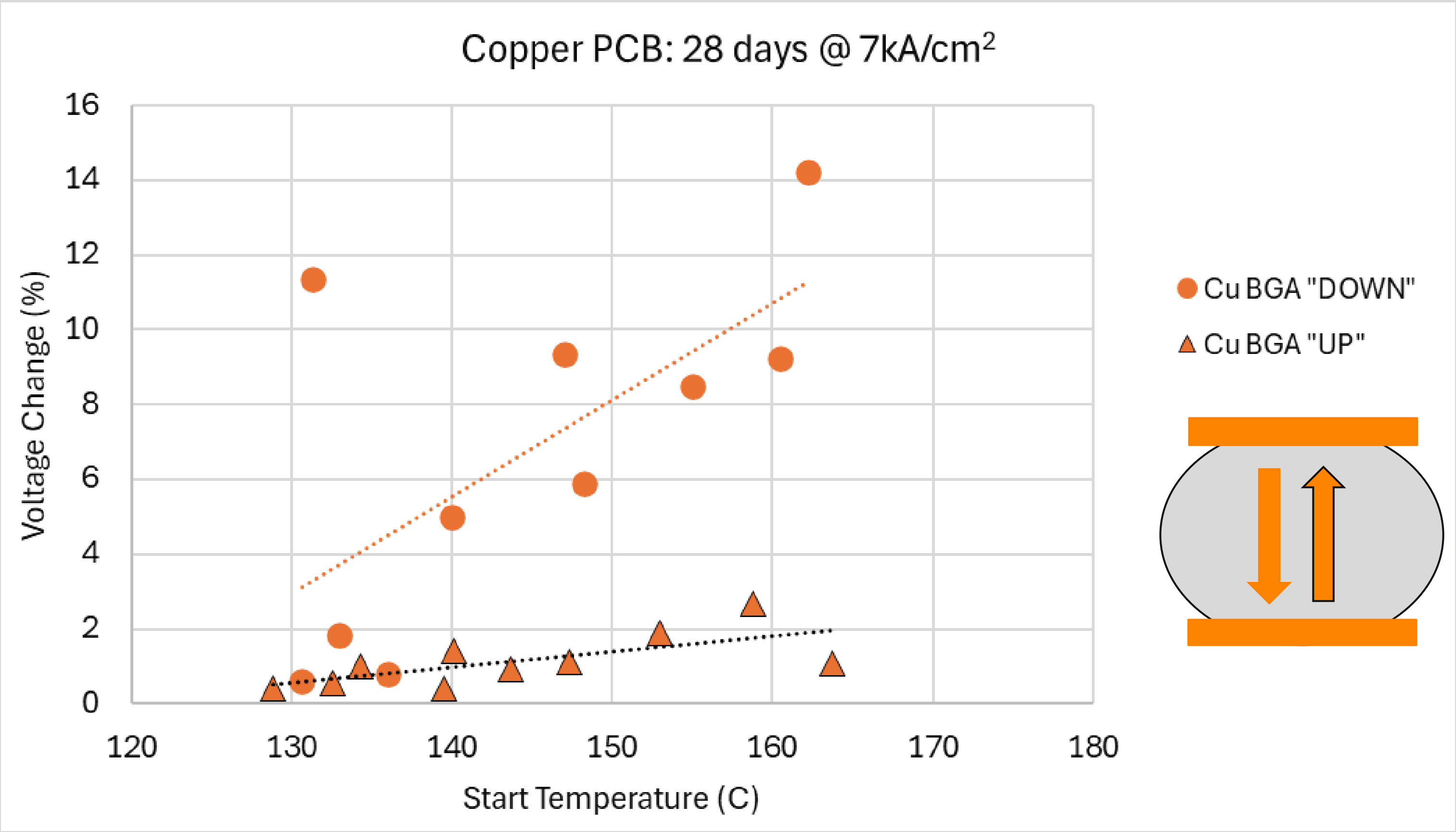
Table of Statistics

Shape	Scale	AD*	F	C
2.18828	26.719	1.349	14	0
3.05181	109.113	1.302	14	0
5.25304	131.874	1.218	14	0

5.0kA/cm^2

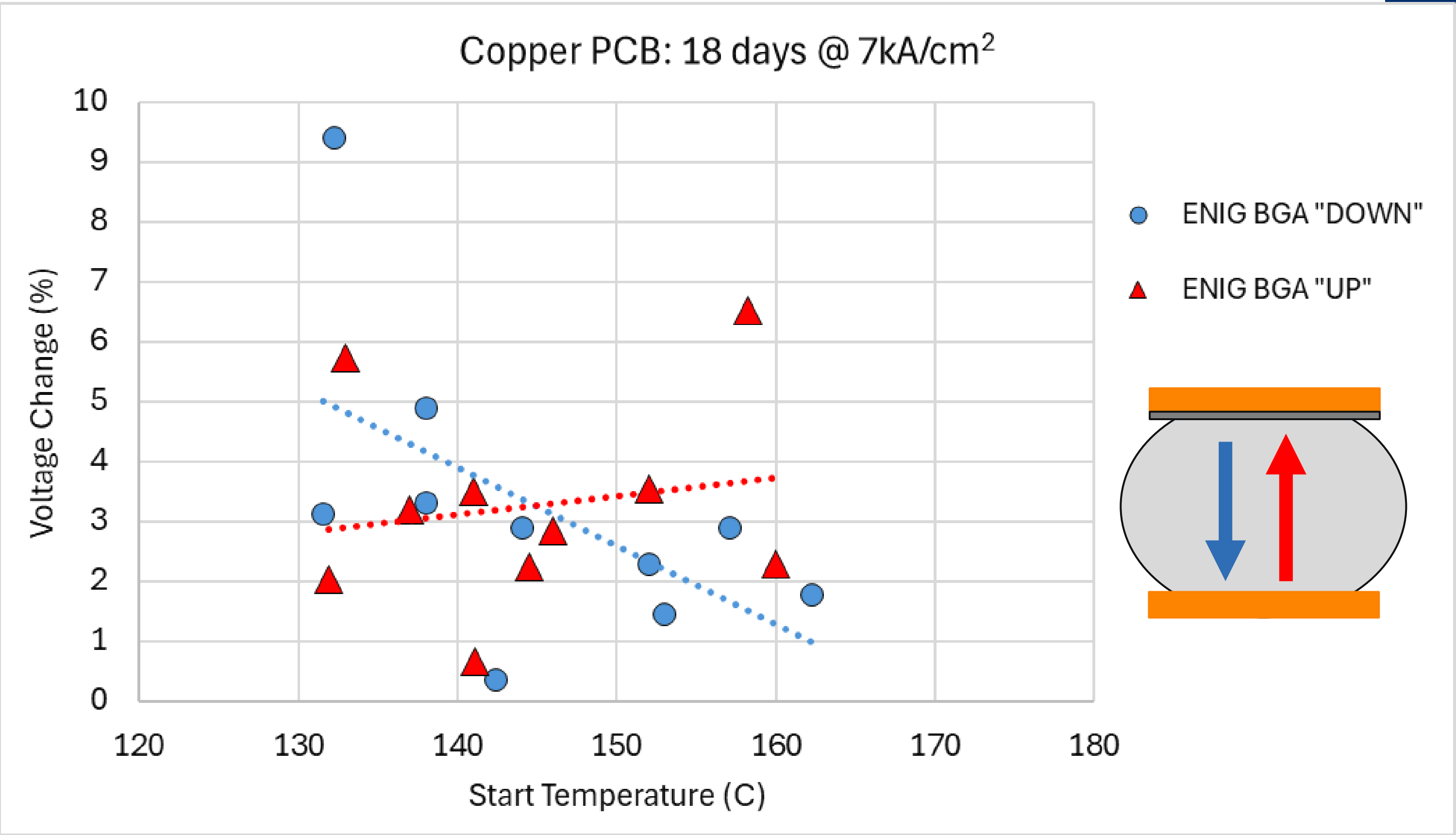
SAC305 Electromigration (older data)

- Copper PCB / Copper BGA is the simplest combination
  - Joints with electron flow from component to PCB (i.e. “Down”) show faster rise in voltage change
    - Possibly implies that joints have a temperature gradient with component side hotter than board side
  - There is a trend with respect to starting temperature for each electron flow direction, but there are outliers



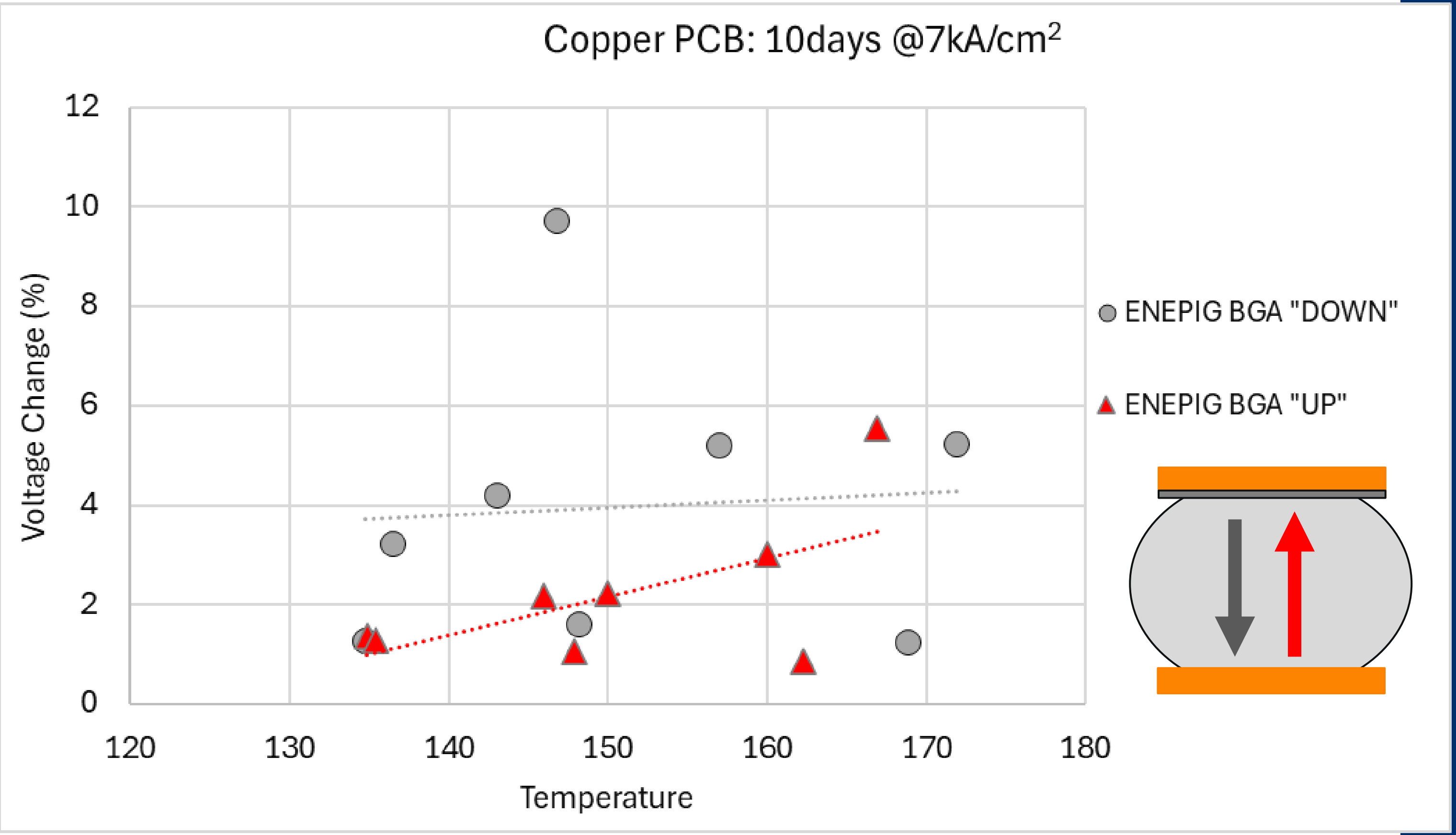
SAC305 Electromigration (older data)

- Copper PCB / ENIG BGA:
  - Example is messy; first joint to +10% is electron flow “DOWN”; but “cold”

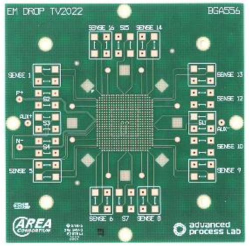


SAC305 Electromigration (older data)

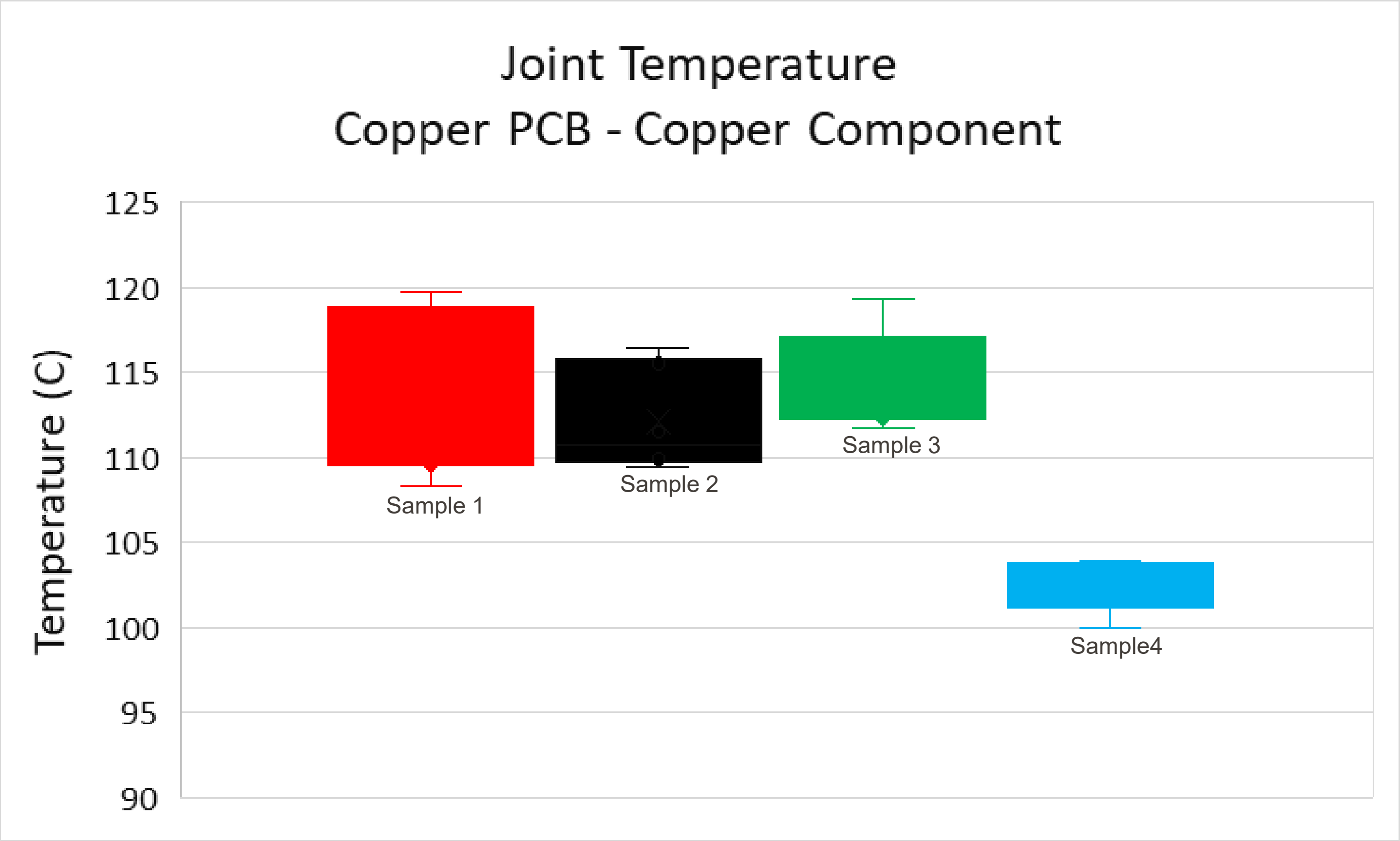
- Copper PCB / ENEPIG BGA:
  - Electron flow “DOWN” shows faster voltage rise
  - Electron flow “UP” shows temperature dependency
    - Much faster rise than Copper/Copper combination?
  - Electron flow “DOWN” does not show temperature dependency



SAC305 Electromigration



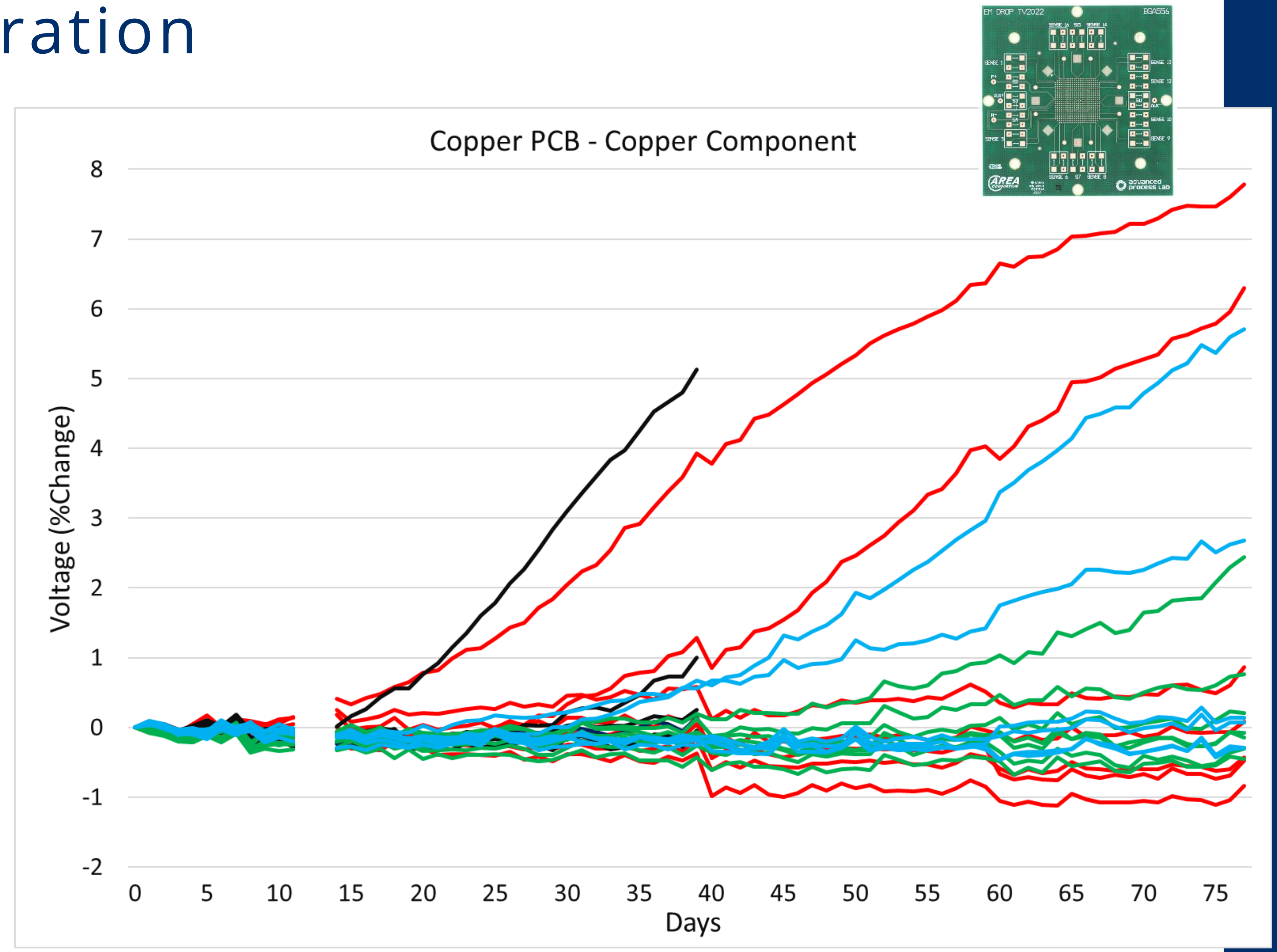
- New samples were constructed and subjected to EM stress while monitoring 6 joints per sample (plus the loop)
- Target temperature was lowered to 115°C
  - Range was 100 to 120°C for Cu/Cu population
- Current Density = 5kA/cm²



5.68A = 5.00kA/cm^2

SAC305 Electromigration

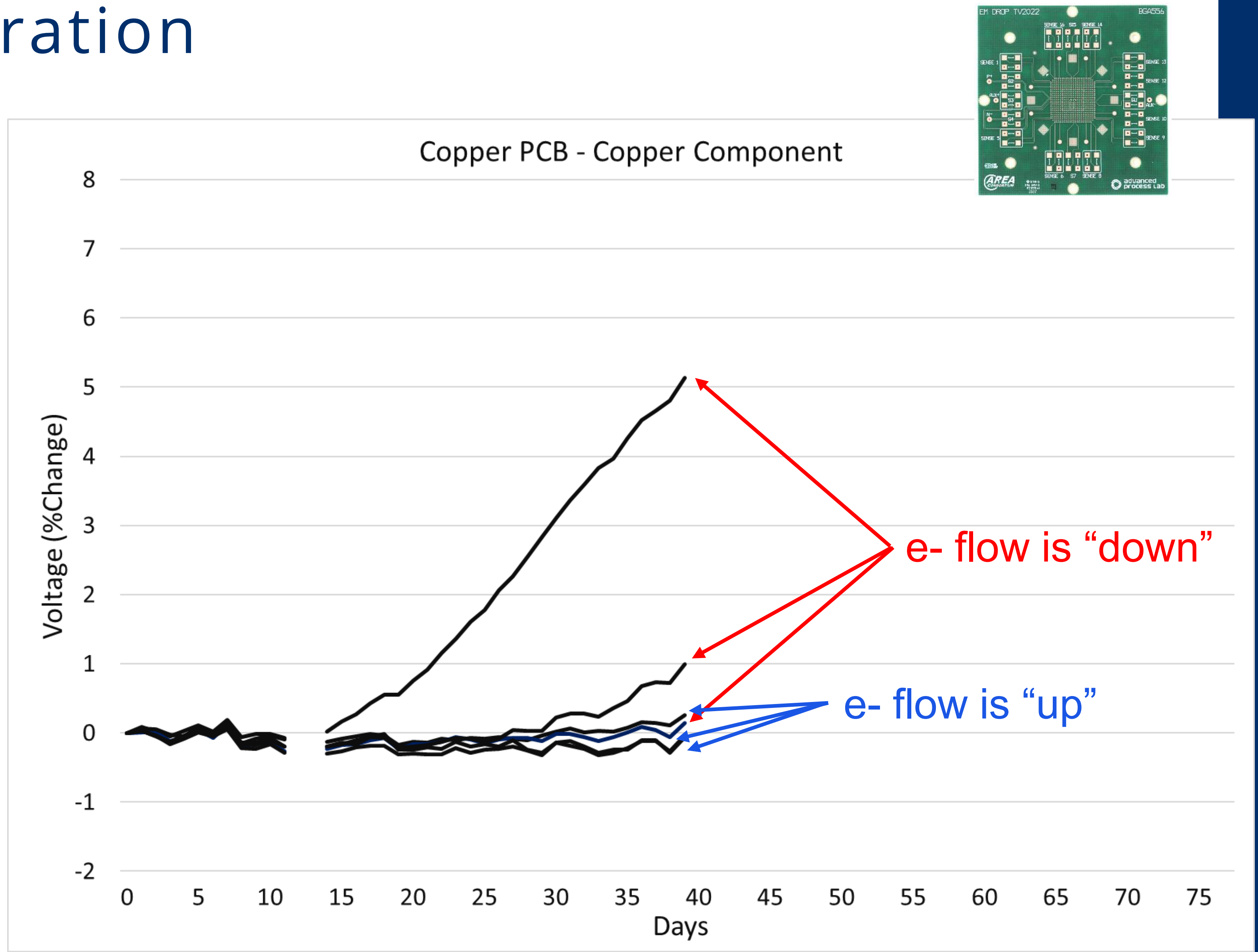
- First solder joint failure (+5%) was detected at day 39
  - Only 7.5% of joints are individually monitored
  - Neighboring joints can impact results – no means to determine this impact



5.68A = 5.00kA/cm^2

SAC305 Electromigration

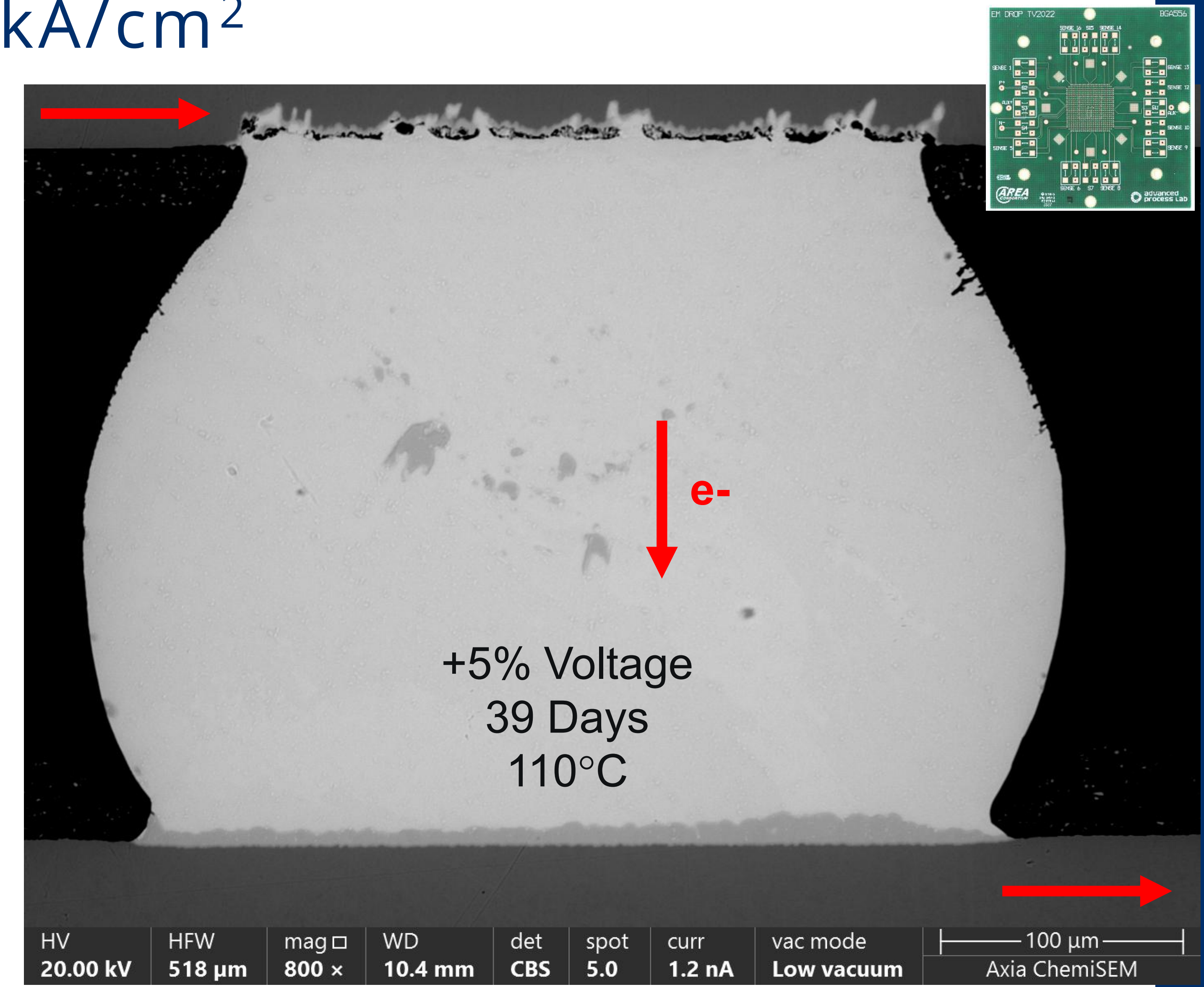
- We need to consider electron flow direction
  - For Copper / Copper combination, electron flow “DOWN” were more likely to demonstrate early voltage rise (Confirming earlier results)



5.68A = 5.00kA/cm^2

Cu PCB / Cu BGA @ 5.0kA/cm^2

- The joint shows significant damage at the component pad interface (copper pad).
  - The actual “solder” appears to be in excellent condition.
- I will argue that this is effectively a failure as mechanical integrity is clearly compromised.
  - I also believe that thermal cycle reliability is severely compromised
- I will note that this joint looks similar to previously tested samples that demonstrated much larger voltage % increases

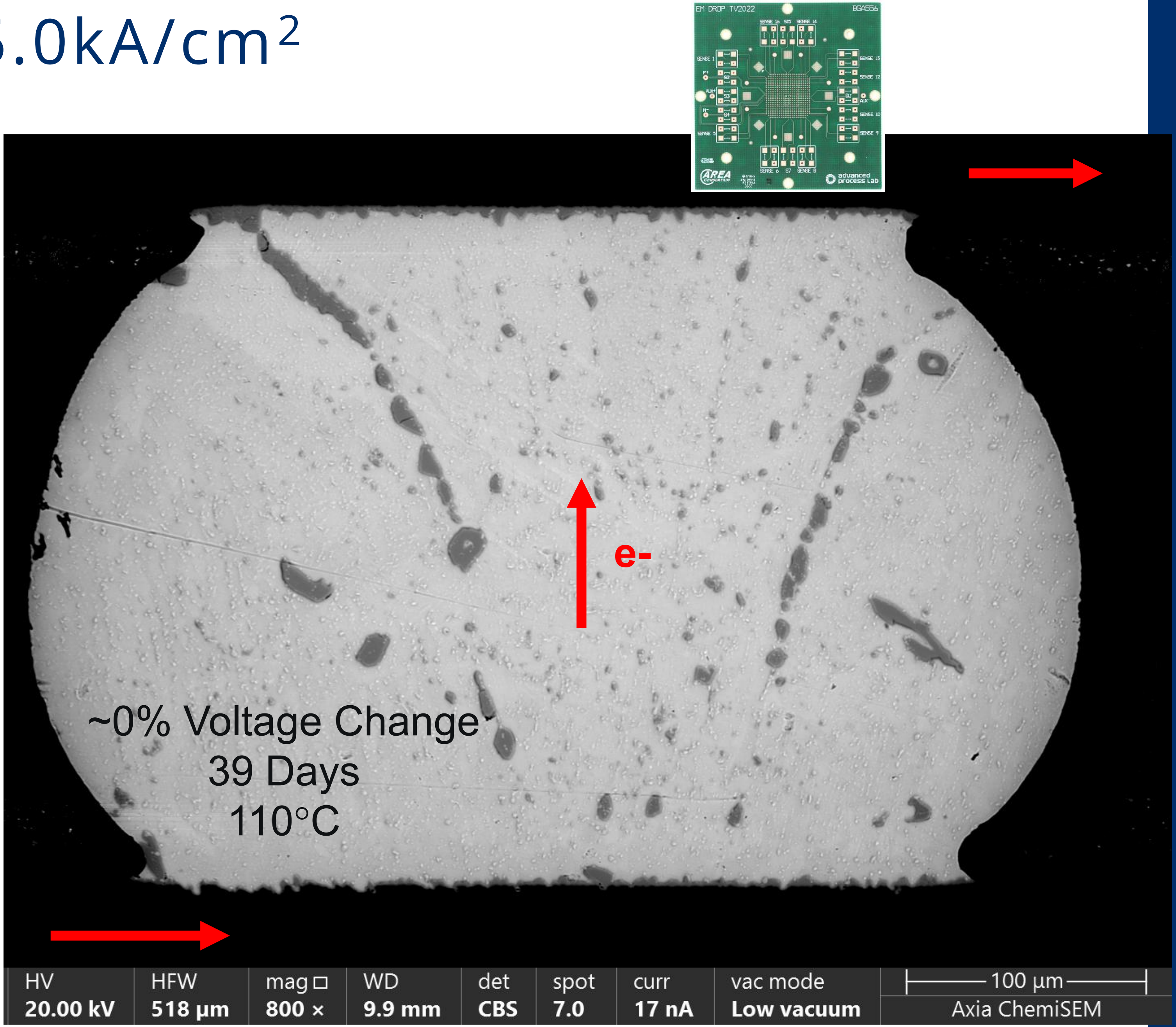


+5% Voltage
39 Days
110°C

5.68A = 5.00kA/cm^2

Cu PCB / Cu BGA @ 5.0kA/cm^2

- Joints with electron flow from PCB to component show less damage with some degree of PCB pad degradation but no voiding at the interface.

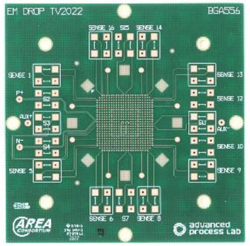


~0% Voltage Change
39 Days
110°C

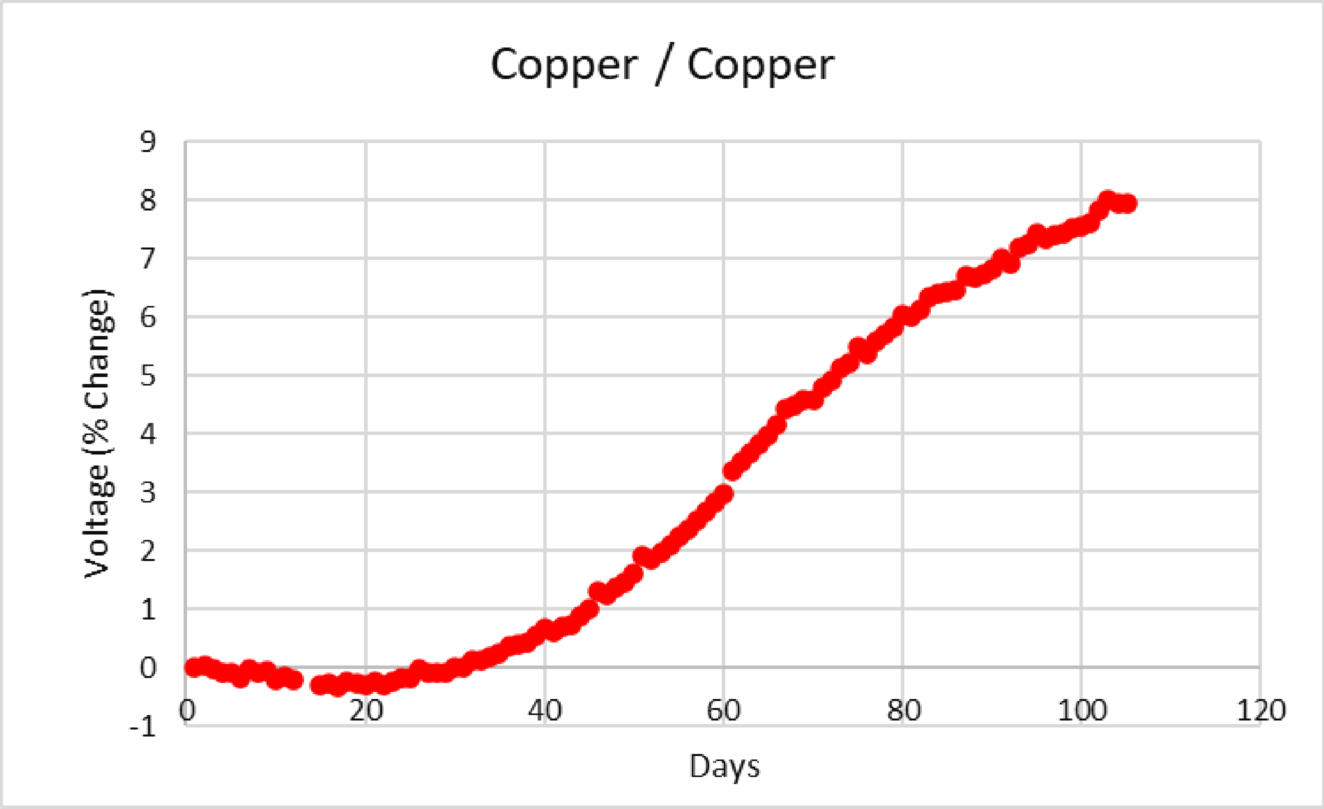
HV	HFW	mag ☐	WD	det	spot	curr	vac mode	100 µm
20.00 kV	518 µm	800 ×	9.9 mm	CBS	7.0	17 nA	Low vacuum	Axia ChemiSEM

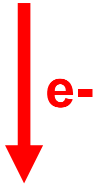
5.68A = 5.00kA/cm^2

Cu PCB / Cu BGA @ 5.0kA/cm^2



- Interestingly, we observed "parabolic" behavior – if we continue testing beyond ~6%
  - Relatively low temperature and reduced current level may not result in "thermal run-away" previously observed under harsher test conditions



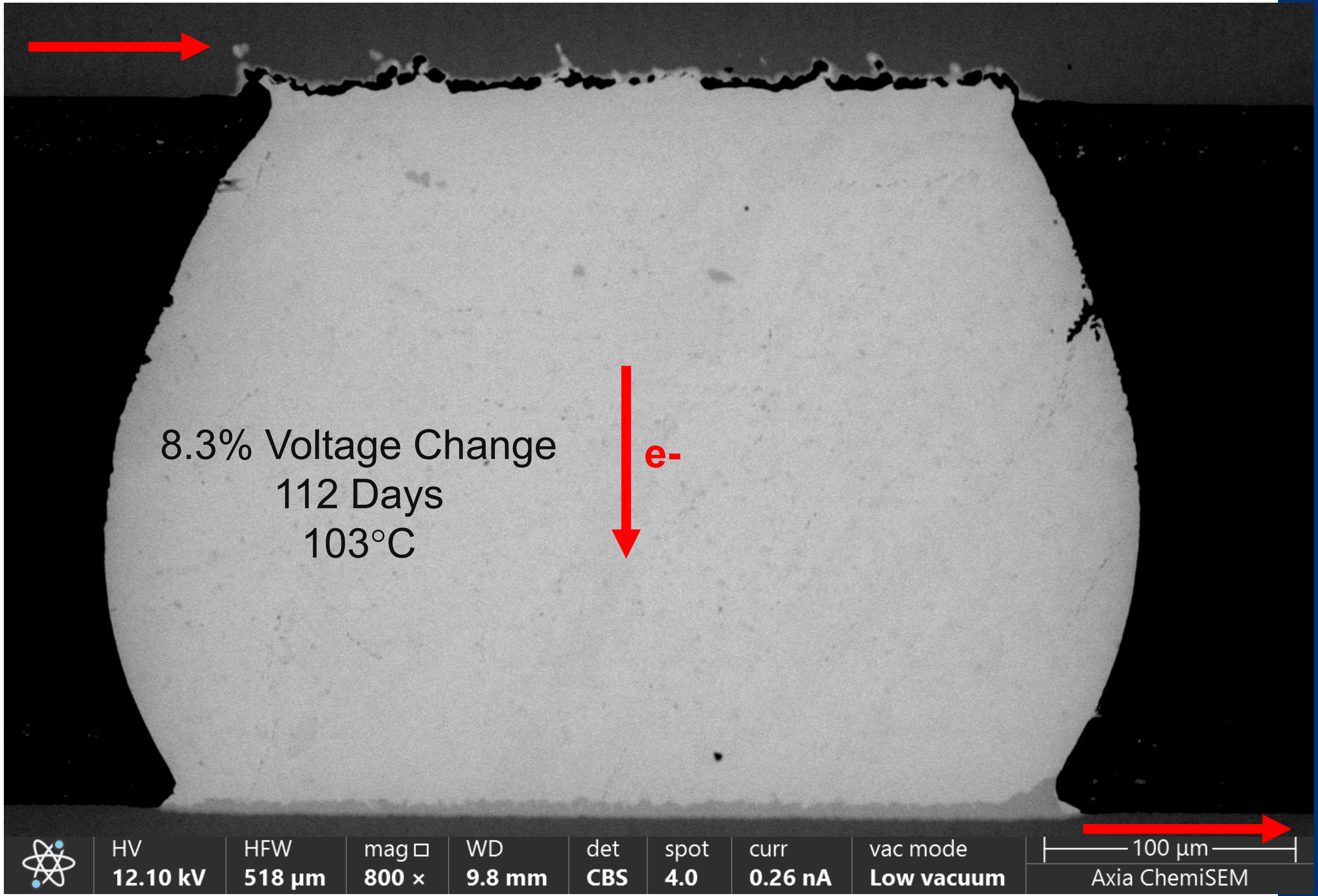


5.68A = 5.00kA/cm^2

103°C

Cu PCB / Cu BGA @ 5.0kA/cm^2

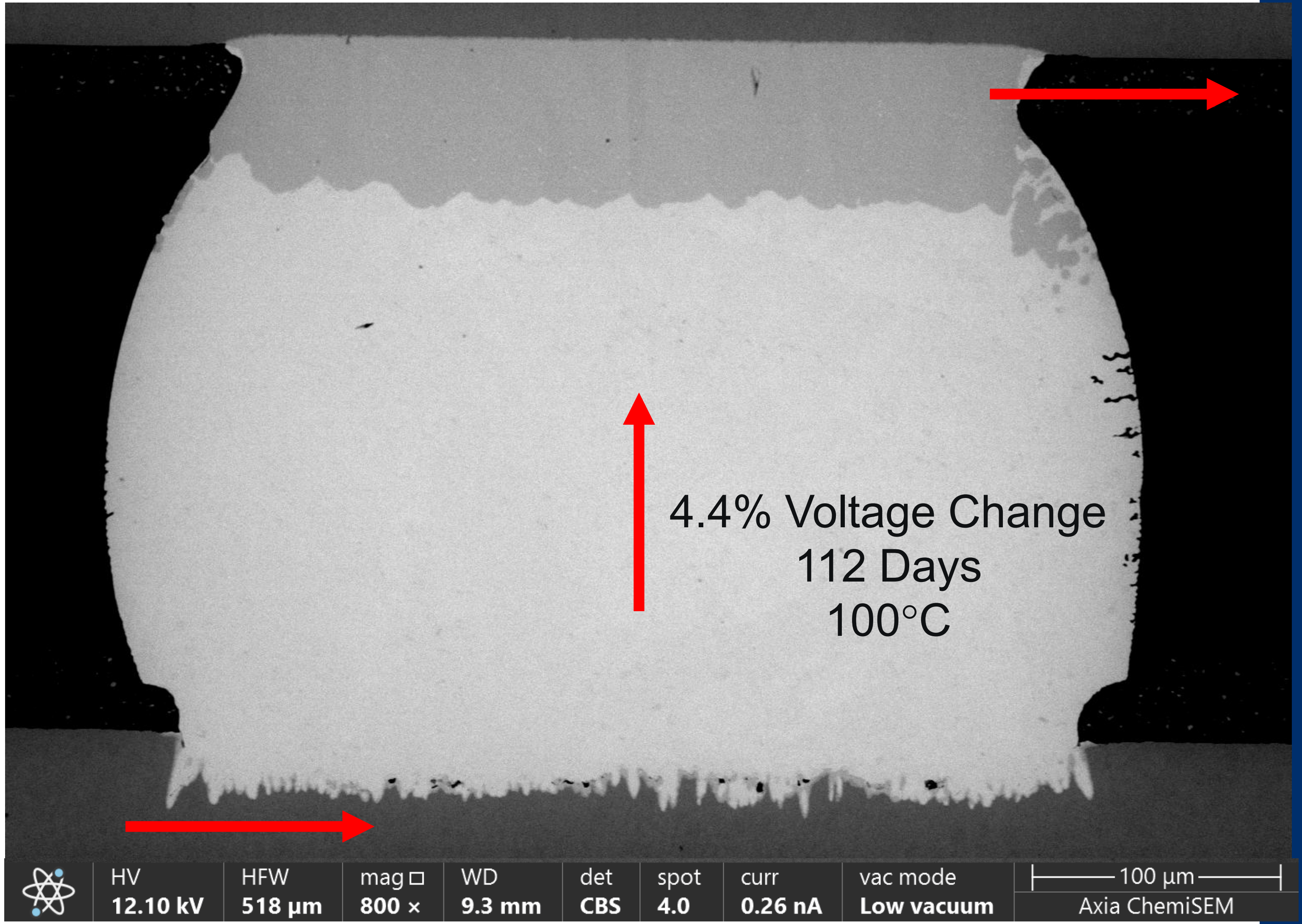
- Pad interface is nearly non-existent at +8.3%
- PCB side intermetallic is relatively thin in cross-section; it is probably thicker elsewhere



5.68A = 5.00kA/cm^2

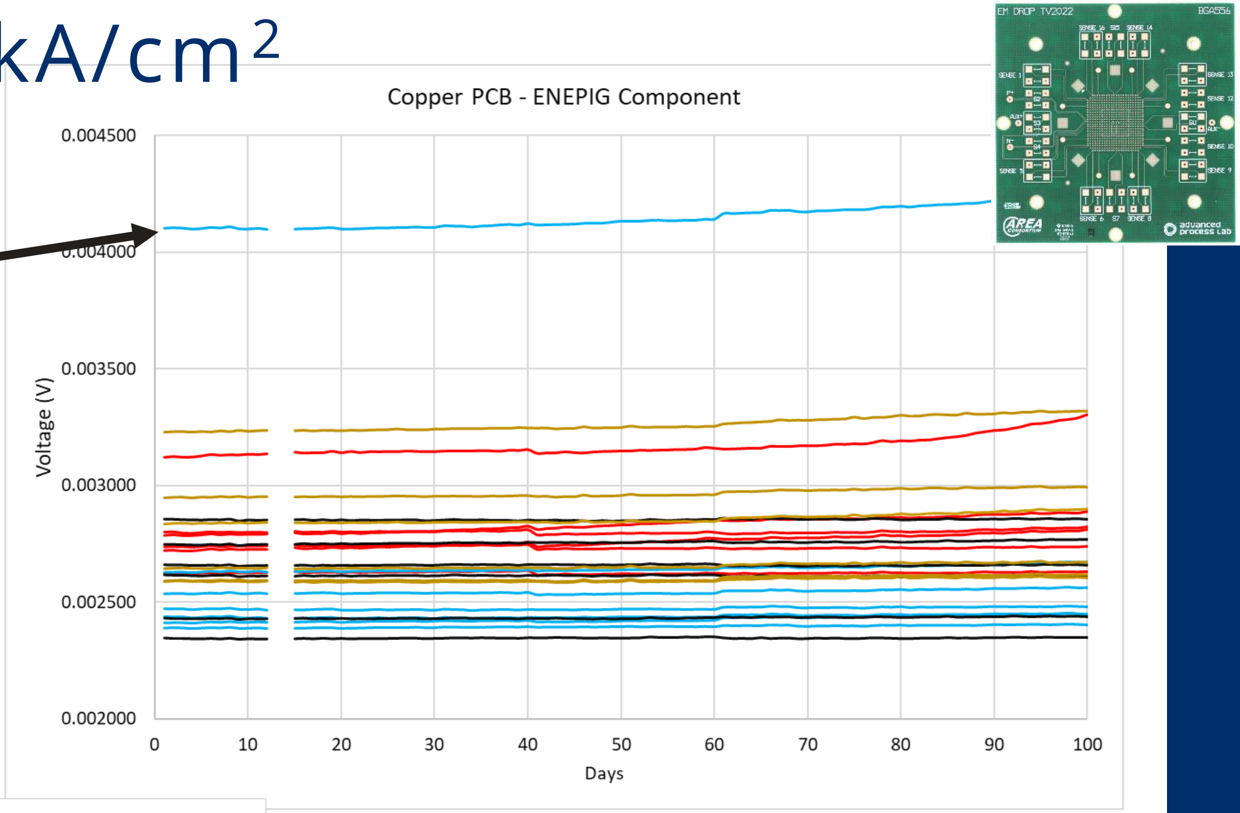
Cu PCB / Cu BGA @ 5.0kA/cm^2

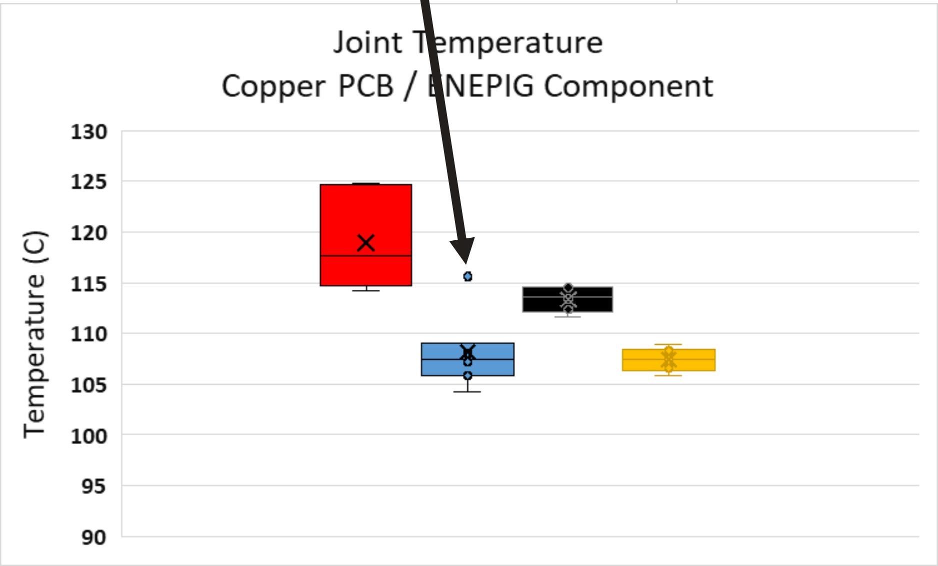
- +4.4%
- PCB side shows pad degradation, but is quite well intact
- What caused resistance increase?
  - CuSn thickness
  - Vacancies at PCB pad



Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

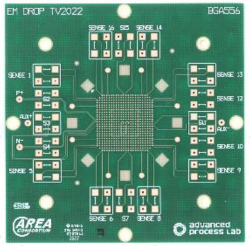
- Copper PCB / ENEPIG BGA combination
  - The voltage & temperature of one solder joint stands out:
  - Samples run about 5°C hotter than Copper / Copper
    - 105 to 125°C range



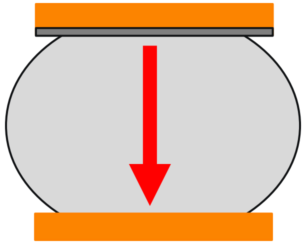


5.68A = 5.00kA/cm^2

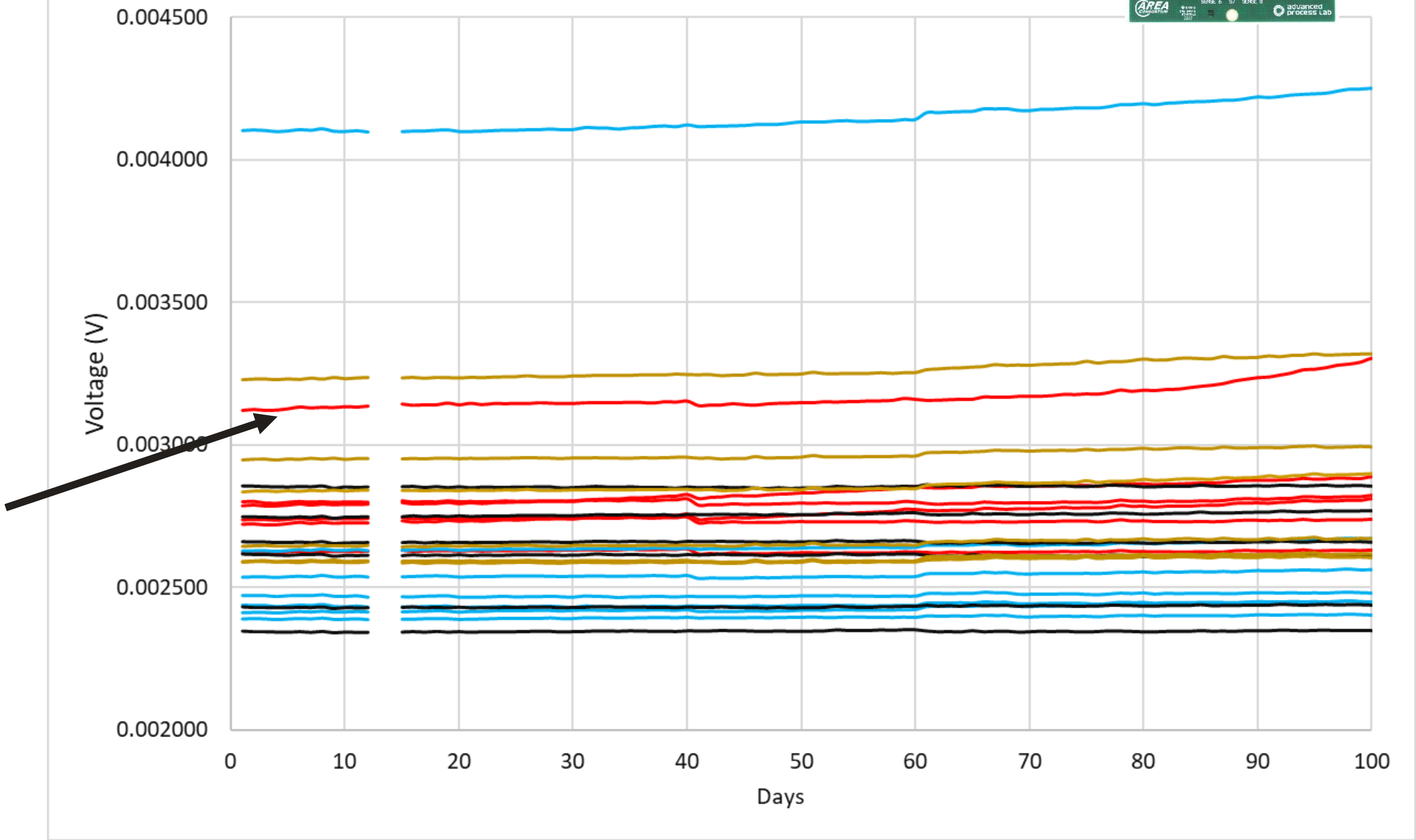
Cu PCB / ENEPIG BGA @ 5.0kA/cm^2



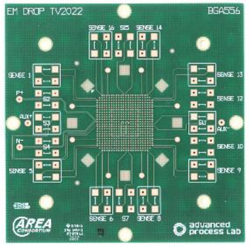
- The first joint to reach+5% was electron flow from component to PCB



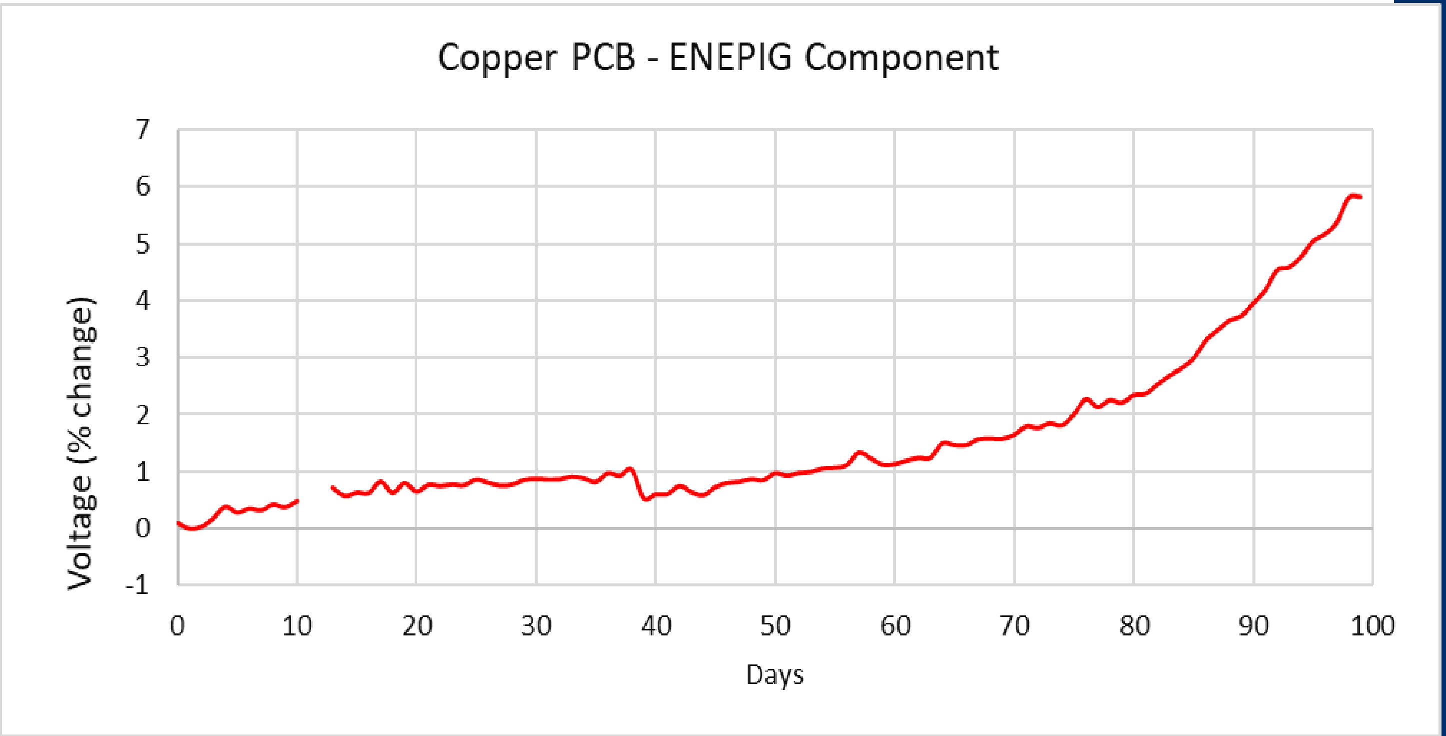
Copper PCB - ENEPIG Component

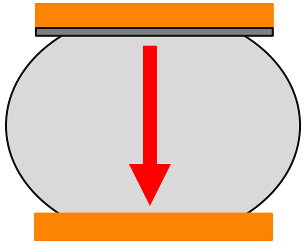


Cu PCB / ENEPIG BGA @ 5.0kA/cm^2



- The first sample (i.e. joint) to reach +5% did so around day 96.
  - Start temperature was 118°C.
  - This joint experienced electron flow from component to PCB.
  - 2.5x more days to +5% than first copper / copper

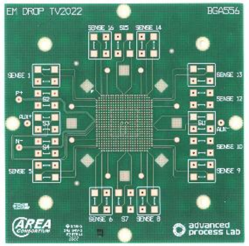




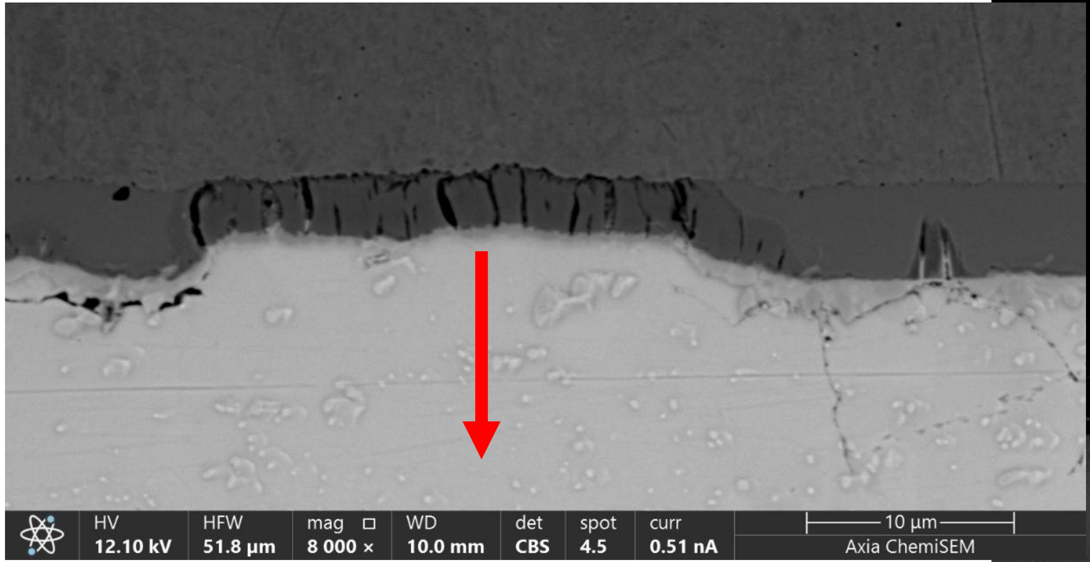
118°C

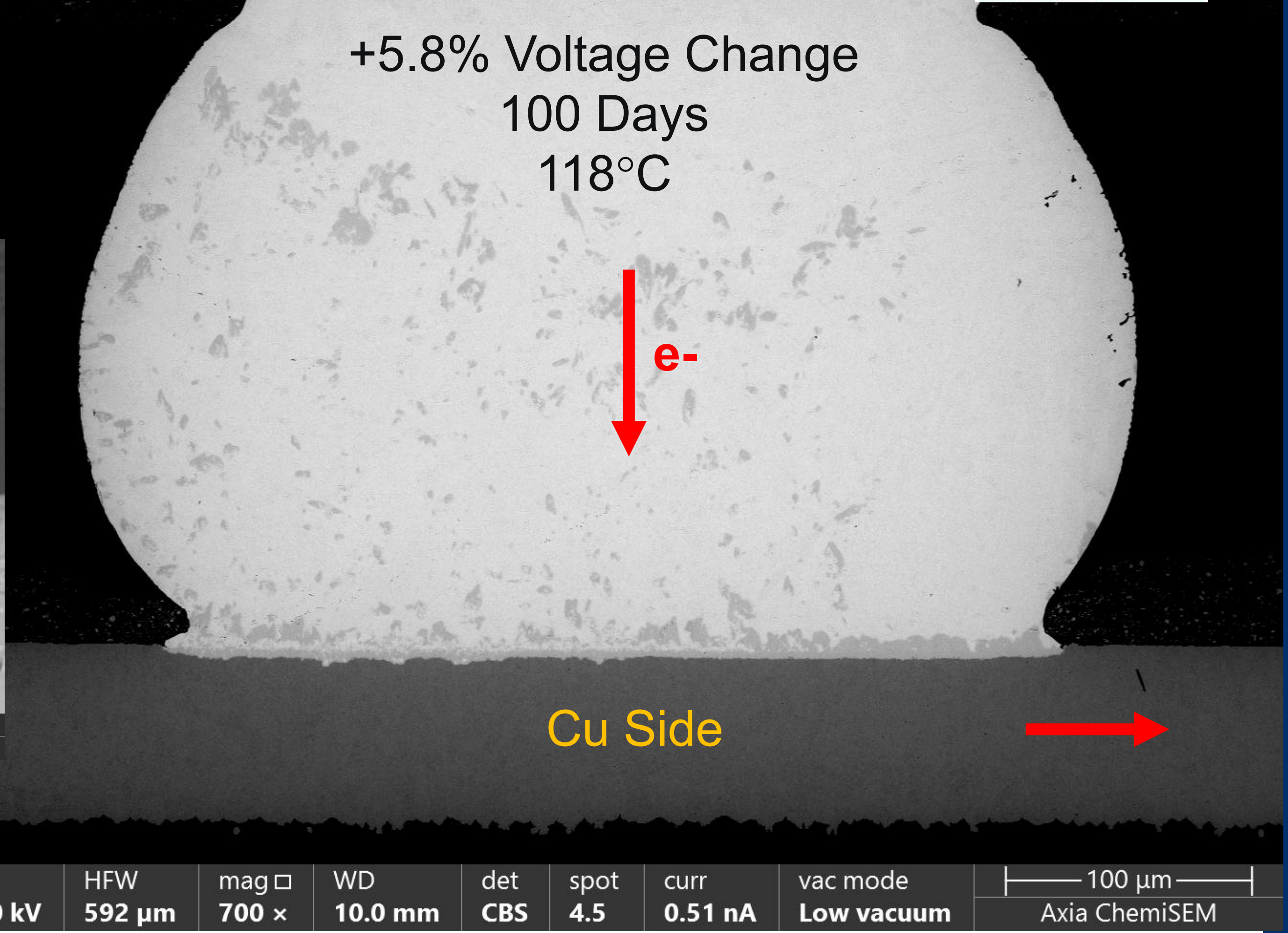
5.68A = 5.00kA/cm^2

Cu PCB / ENEPIG BGA @ 5.0kA/cm^2



- There's a lot going on in this joint, but the primary concern is the ENEPIG nickel layer (BGA pad)

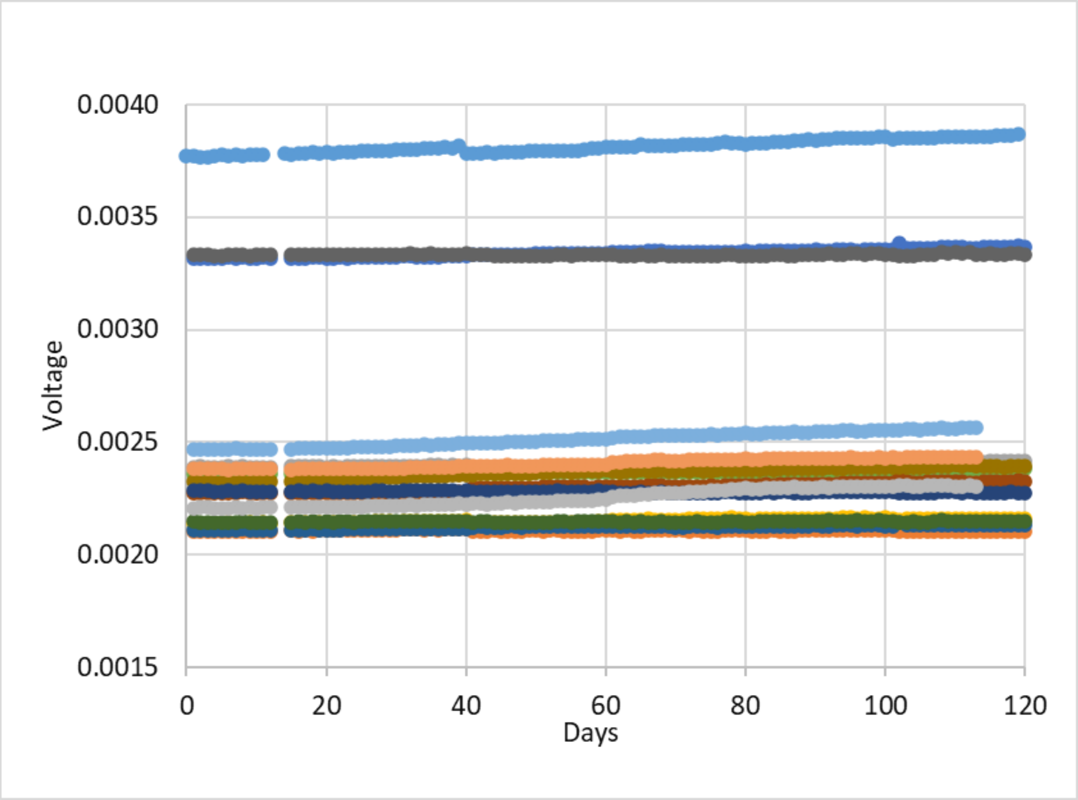


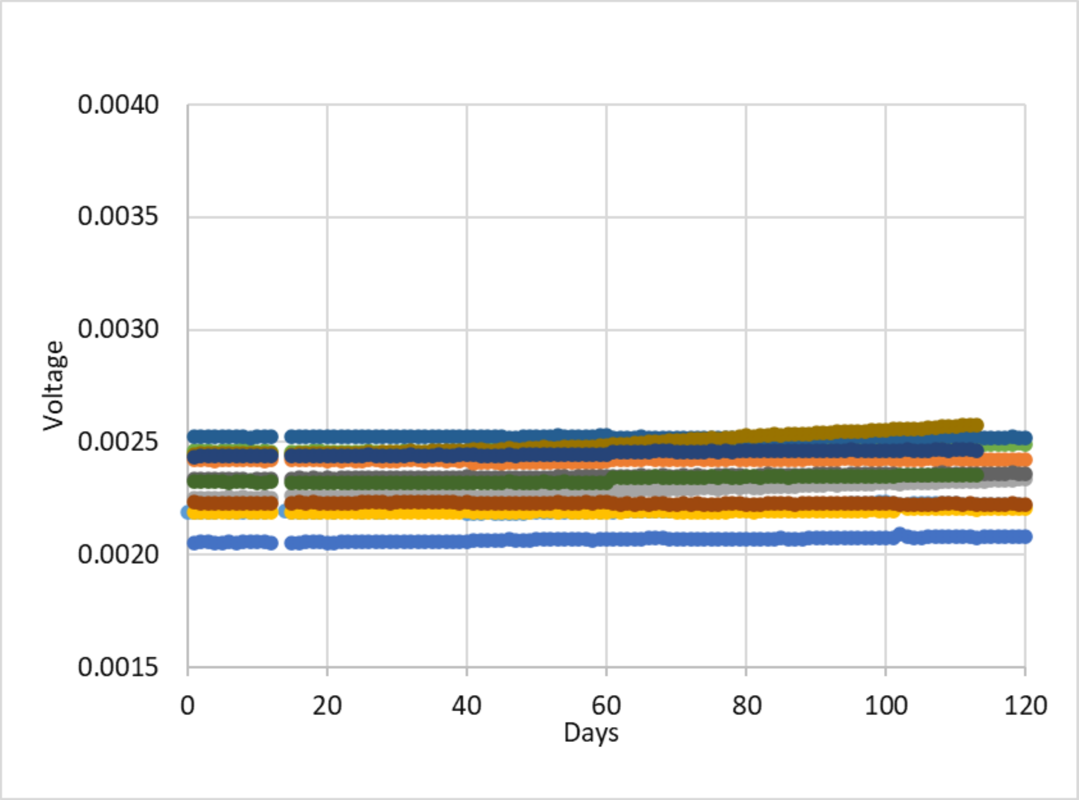


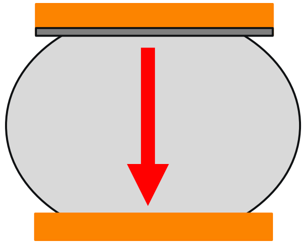
+5.8% Voltage Change
100 Days
118°C

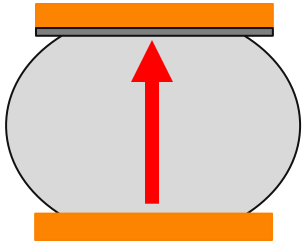
Cu PCB / ENIG BGA @ 5.0kA/cm^2

- Three joints have high starting values (all electron flow “down”)
  - In hindsight, maybe this is an indicator of the nickel issue



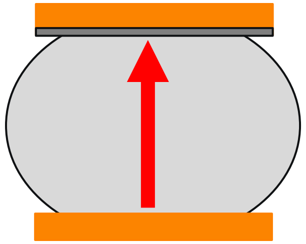


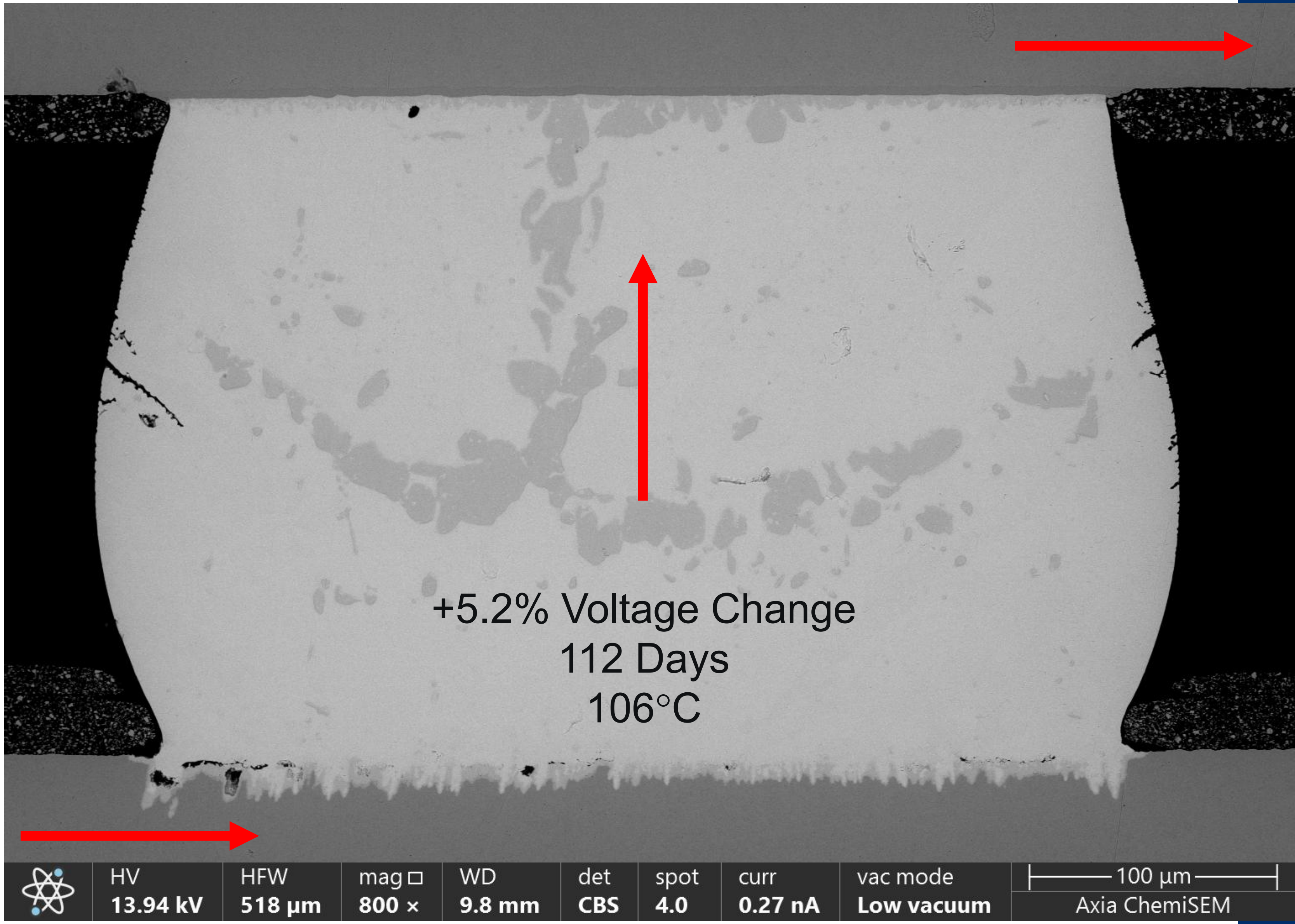




Cu PCB / ENIG BGA @ 5.0kA/cm^2

- Cu / ENIG sample to reach +5% did so at an “electron up” solder joint

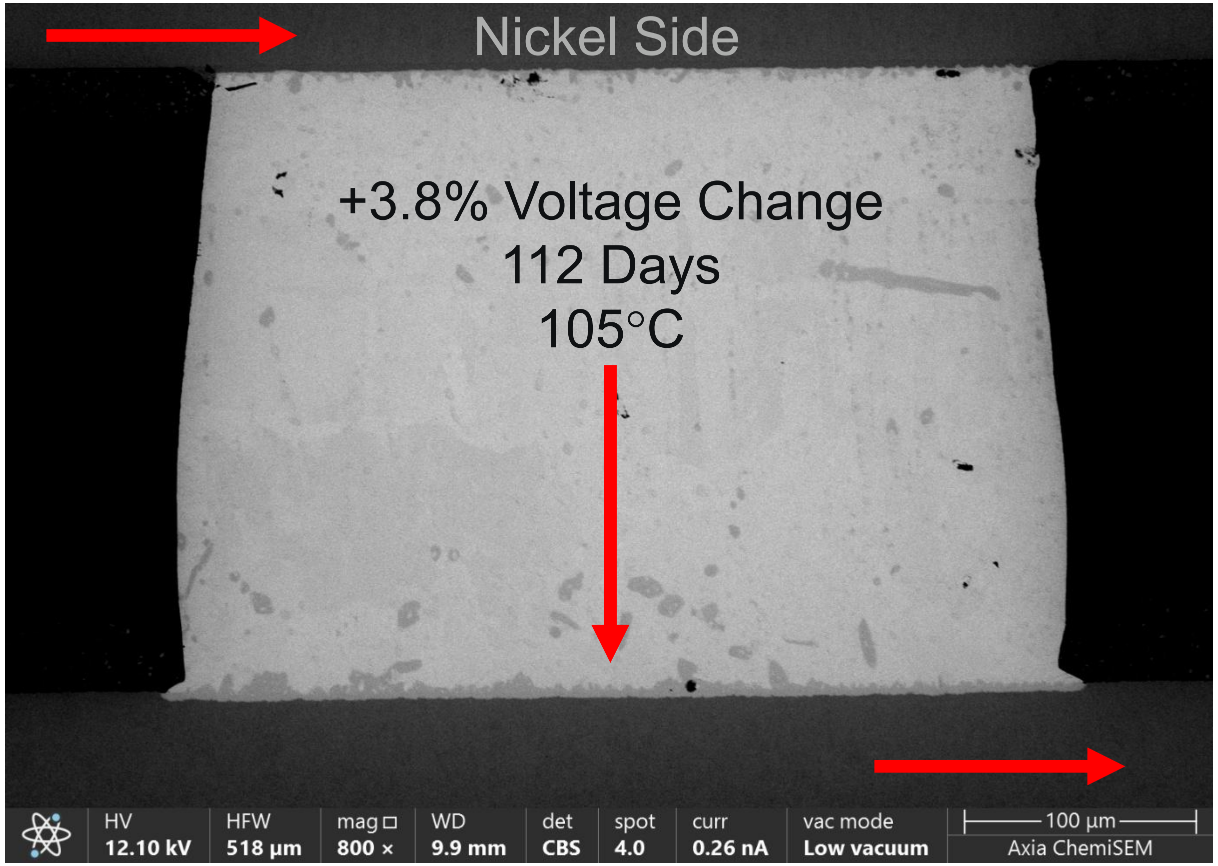


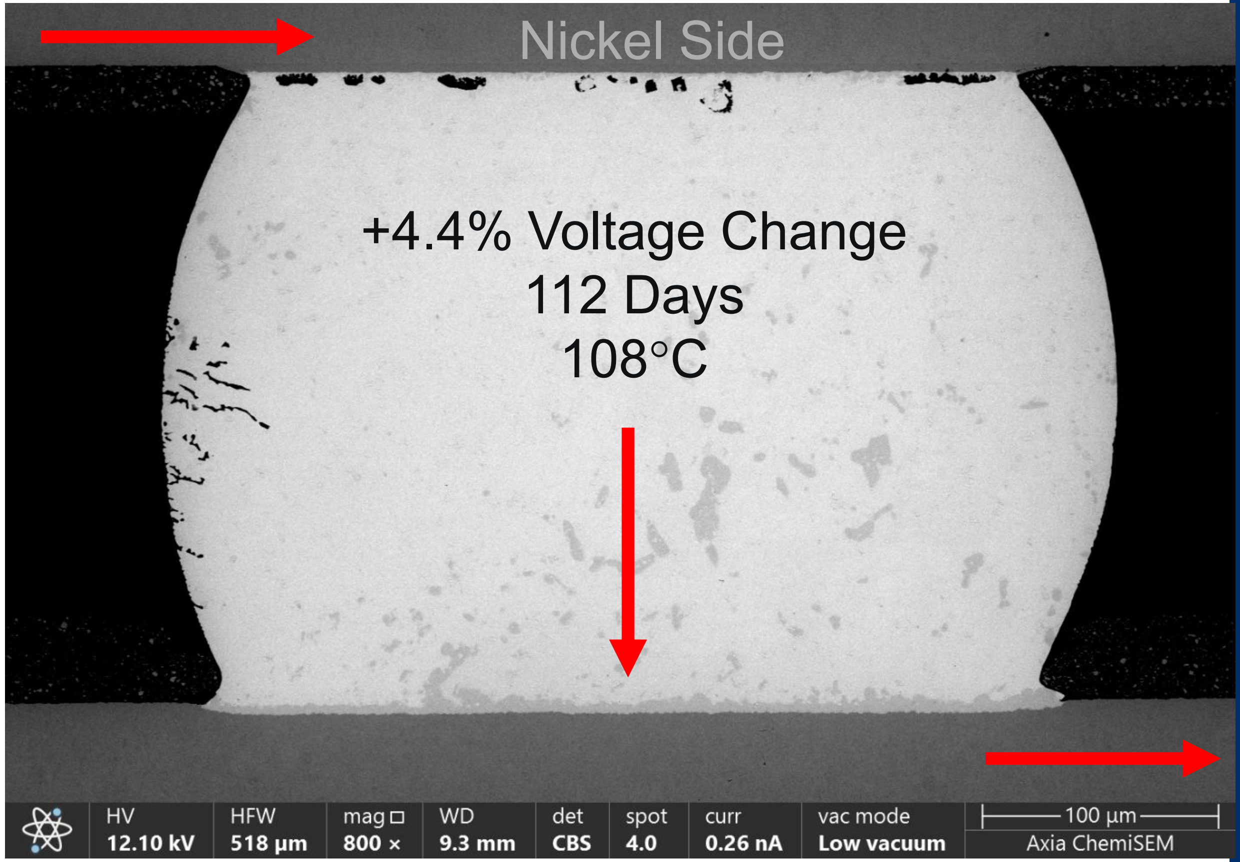


+5.2% Voltage Change
112 Days
106°C

Cu PCB / ENIG BGA @ 5.0kA/cm²

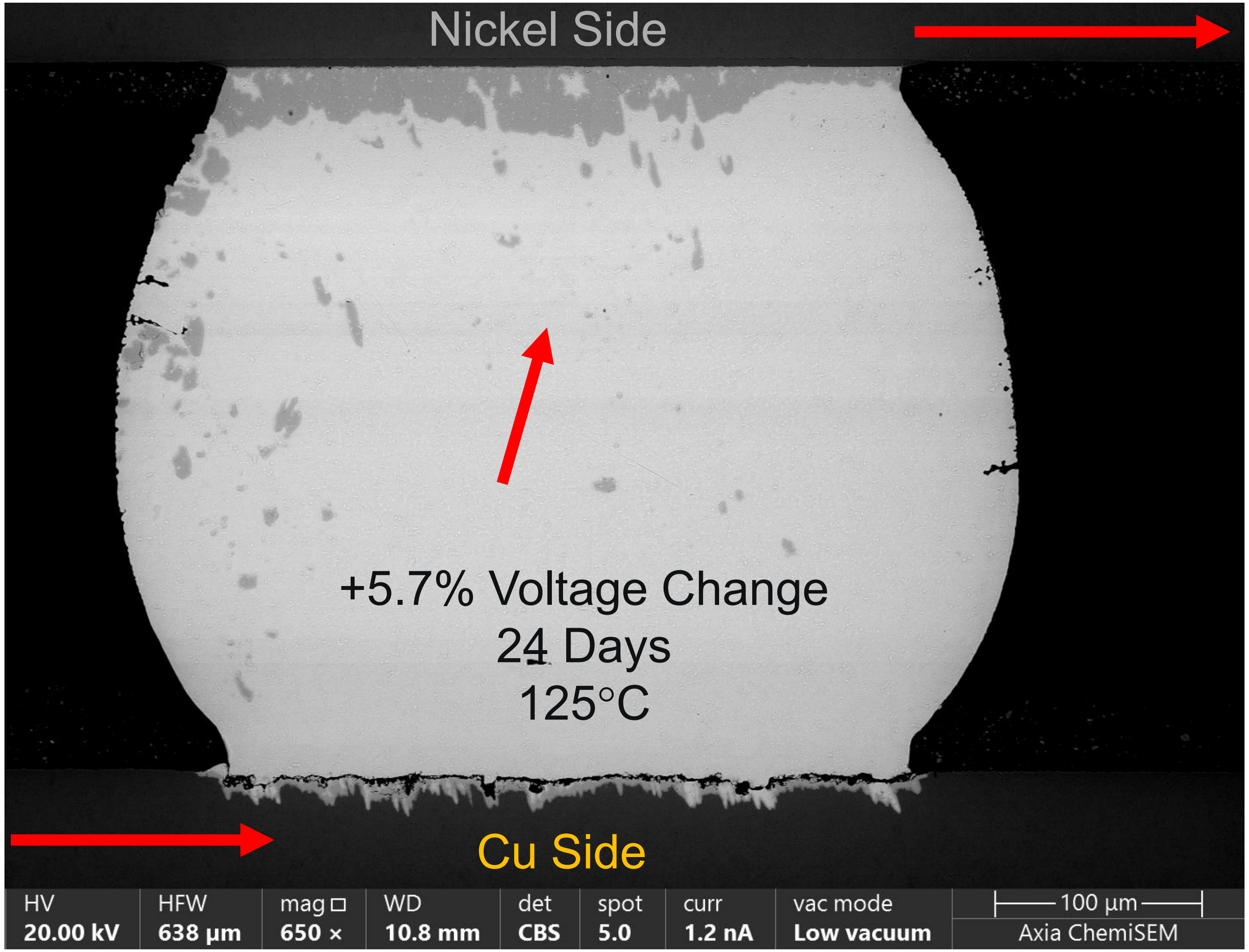
- Ignoring the shape of the left joint, these joints are unusual in that we see voids near the nickel side that look similar to dewetting / hot tearing





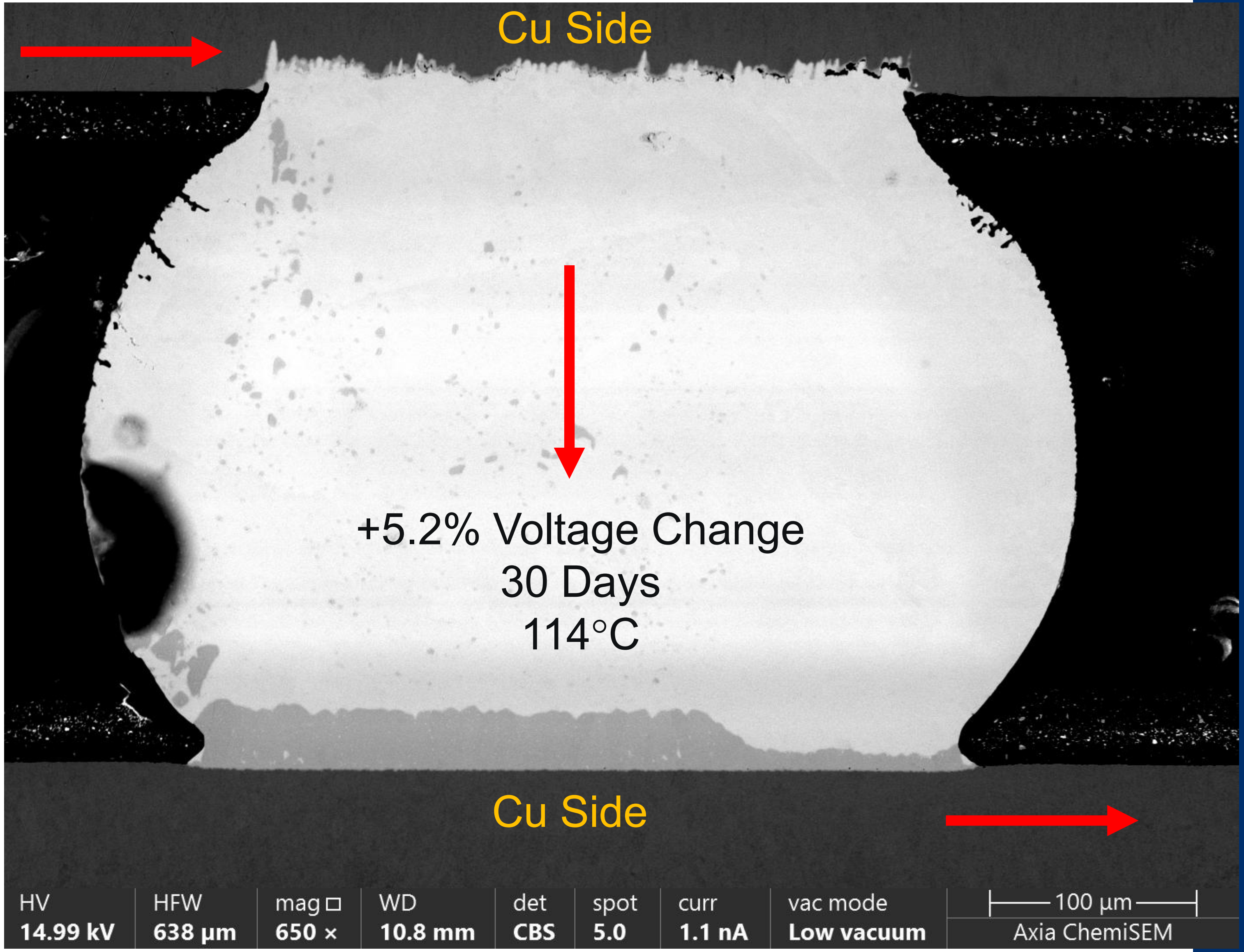
Cu PCB / ENIG BGA @ 5.5kA/cm^2

- First Cu / ENIG sample to reach +5% did so at an “electron up” solder joint
- This joint was believed to be one of the hotter joints in test



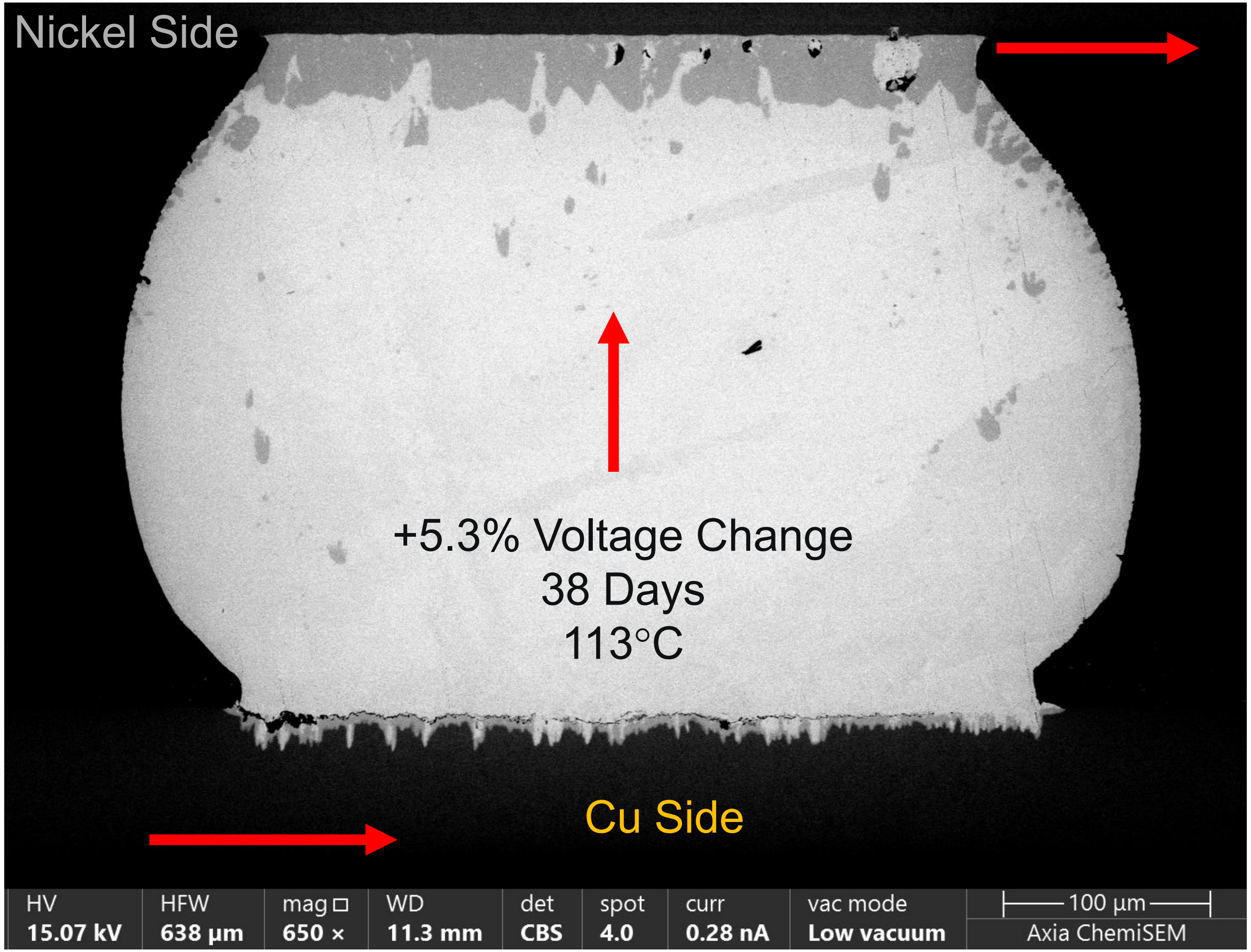
Cu PCB / Cu BGA @ 5.5kA/cm^2

- Cu / Cu combination showing significant component side copper degradation and copper migration to PCB side
  - What drives resistance increase? Vacancies at component side?

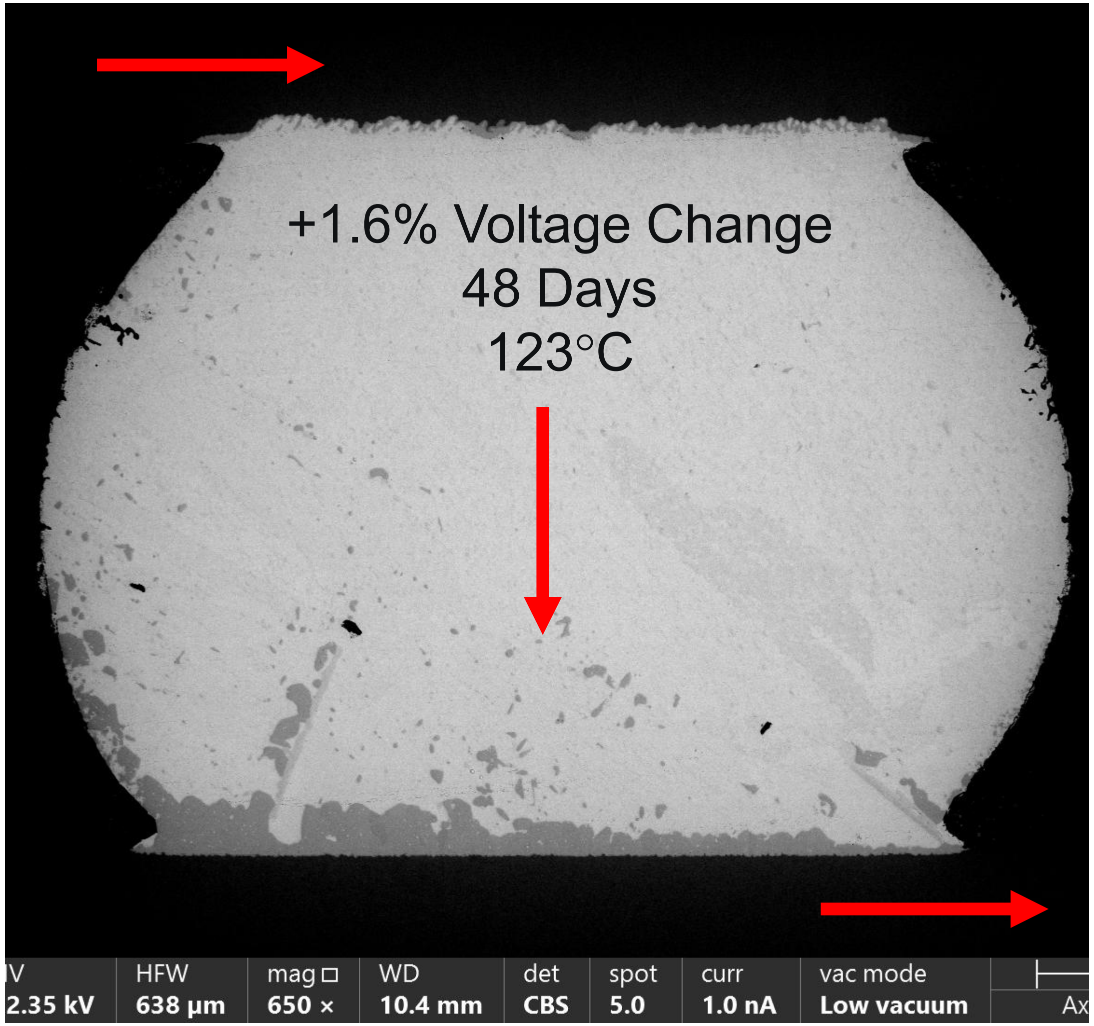


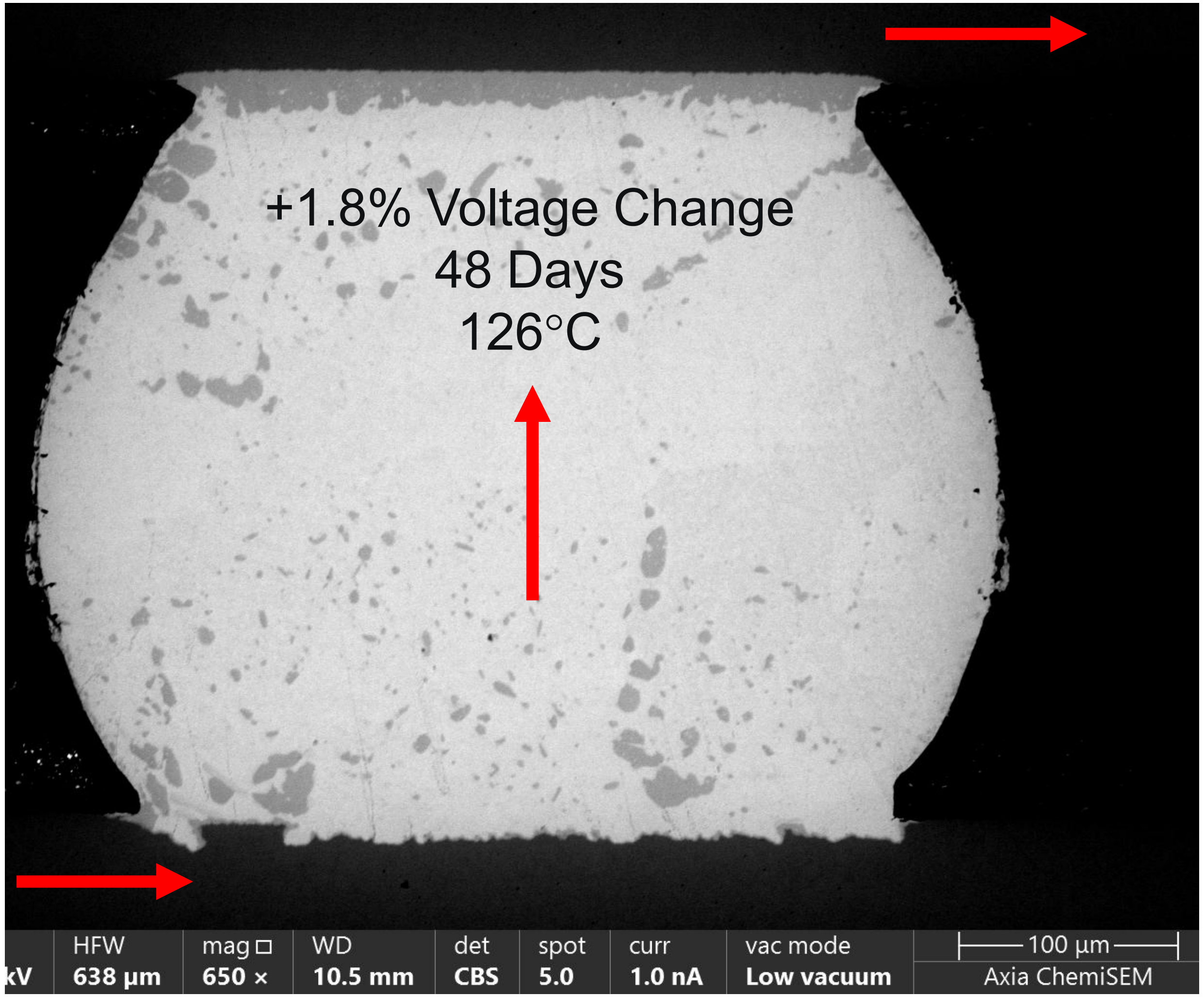
Cu PCB / ENEPIG BGA @ 5.5kA/cm^2

- More of the same… copper pad interface is seriously compromised, yet measured voltage change is just ~5%



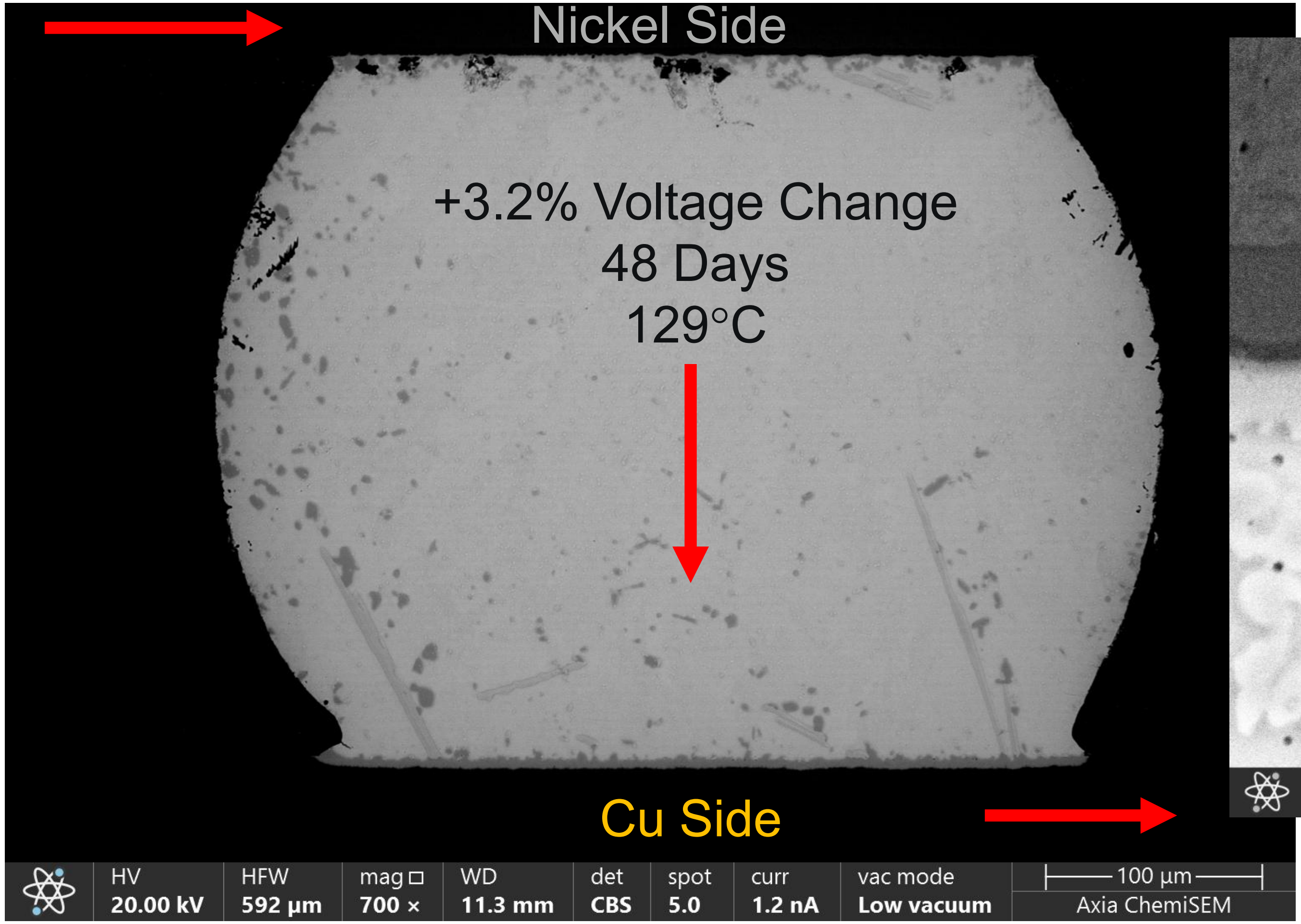
Cu PCB / Cu BGA @ 5.5kA/cm^2

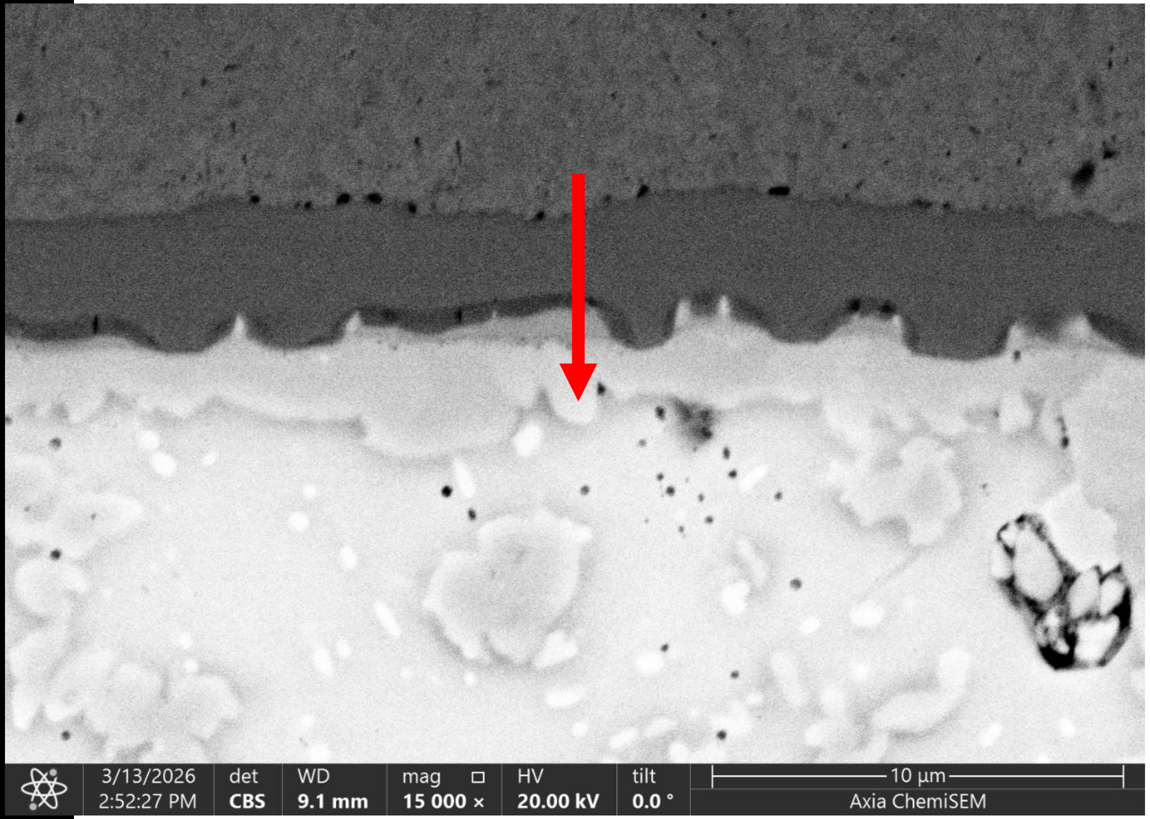




- Cyclomax shows copper degradation, but no discontinuity at less than +2%.

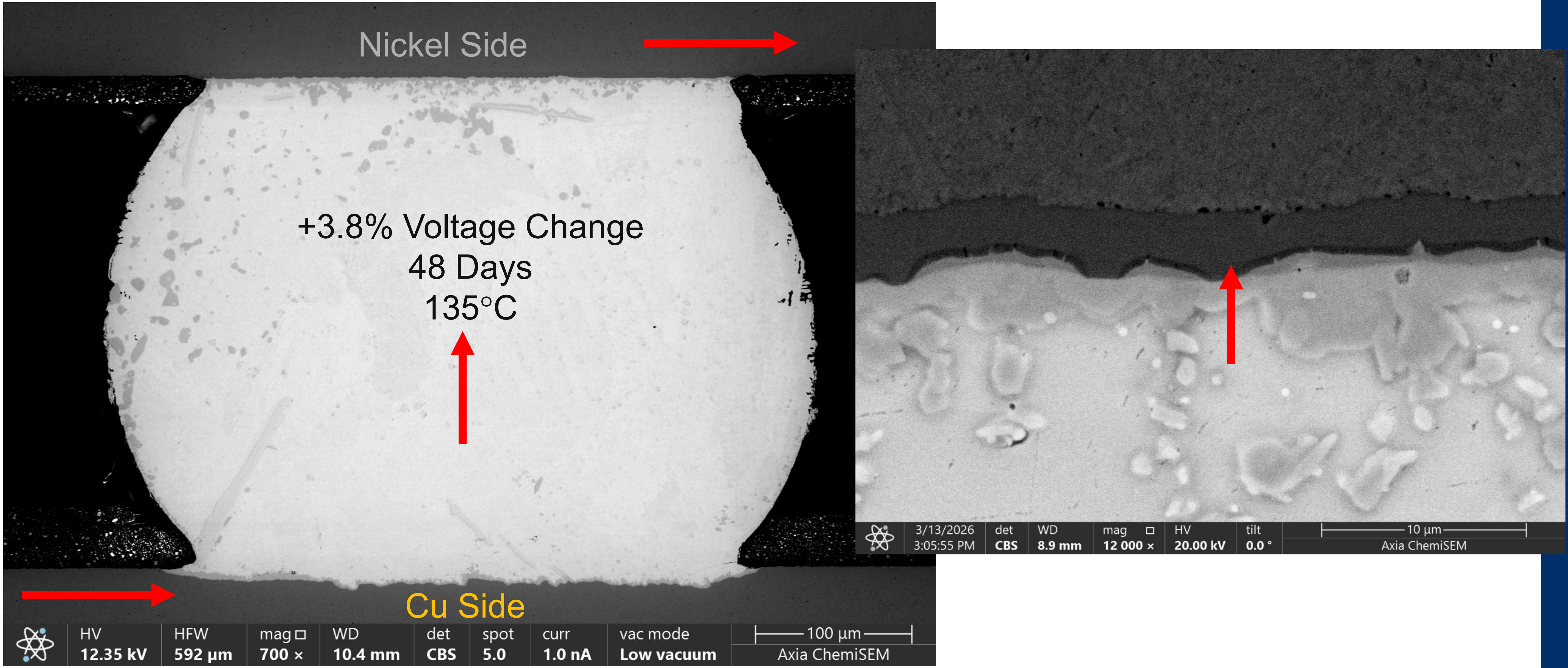
Cu PCB / ENIG BGA @ 5.5kA/cm^2





- Cyclomax shows nickel degradation (as expected at cathode) and some discontinuity at +3%

Cu PCB / ENIG BGA @ 5.5kA/cm^2



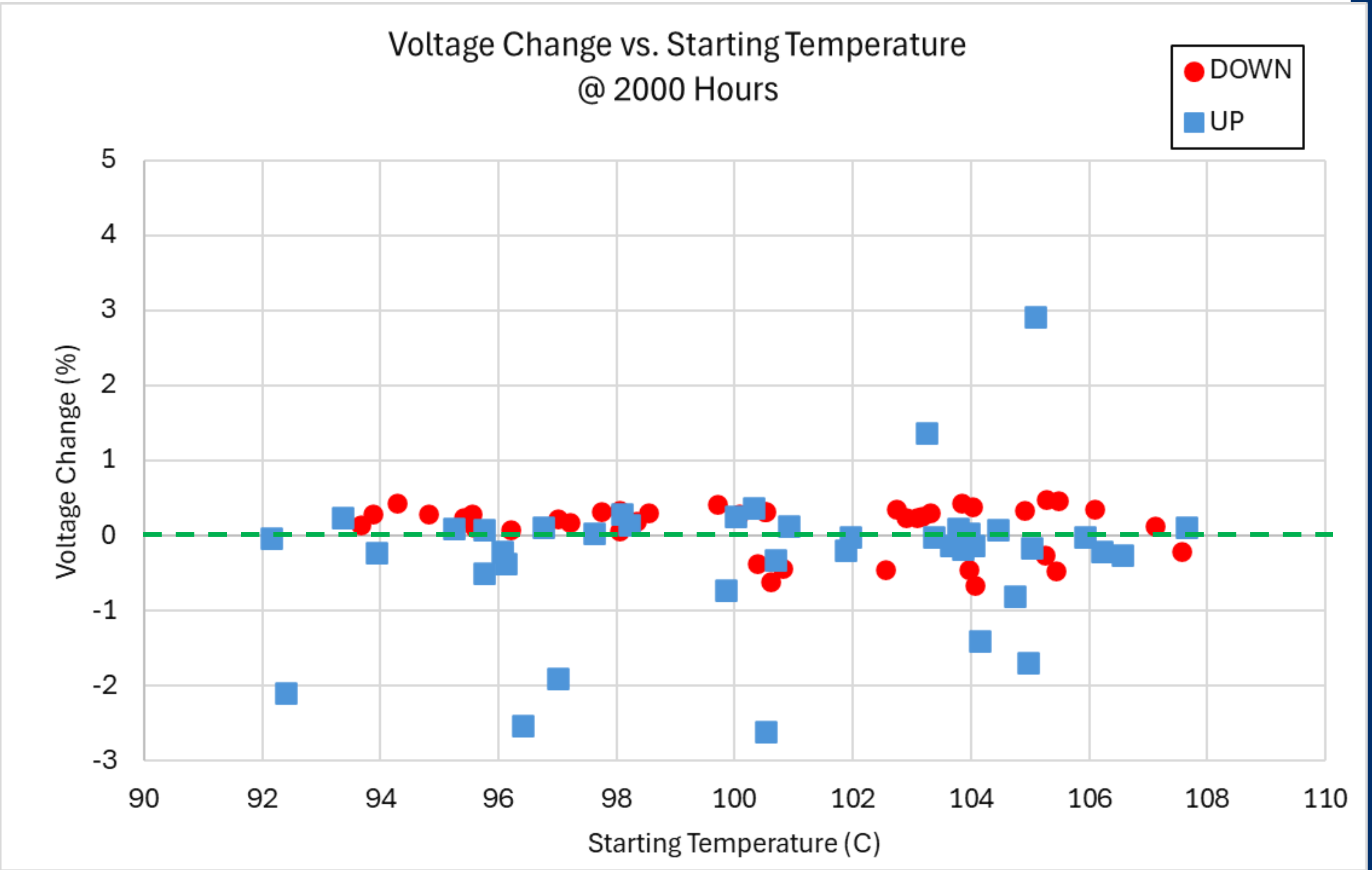
+3.8% Voltage Change
48 Days
135°C

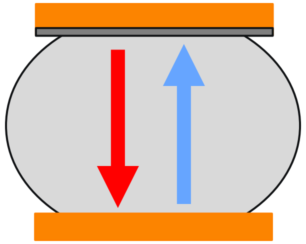
- Cyclomax shows nickel degradation at anode (probably not alloy related)

92 to 108°C Solder Joints:

Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

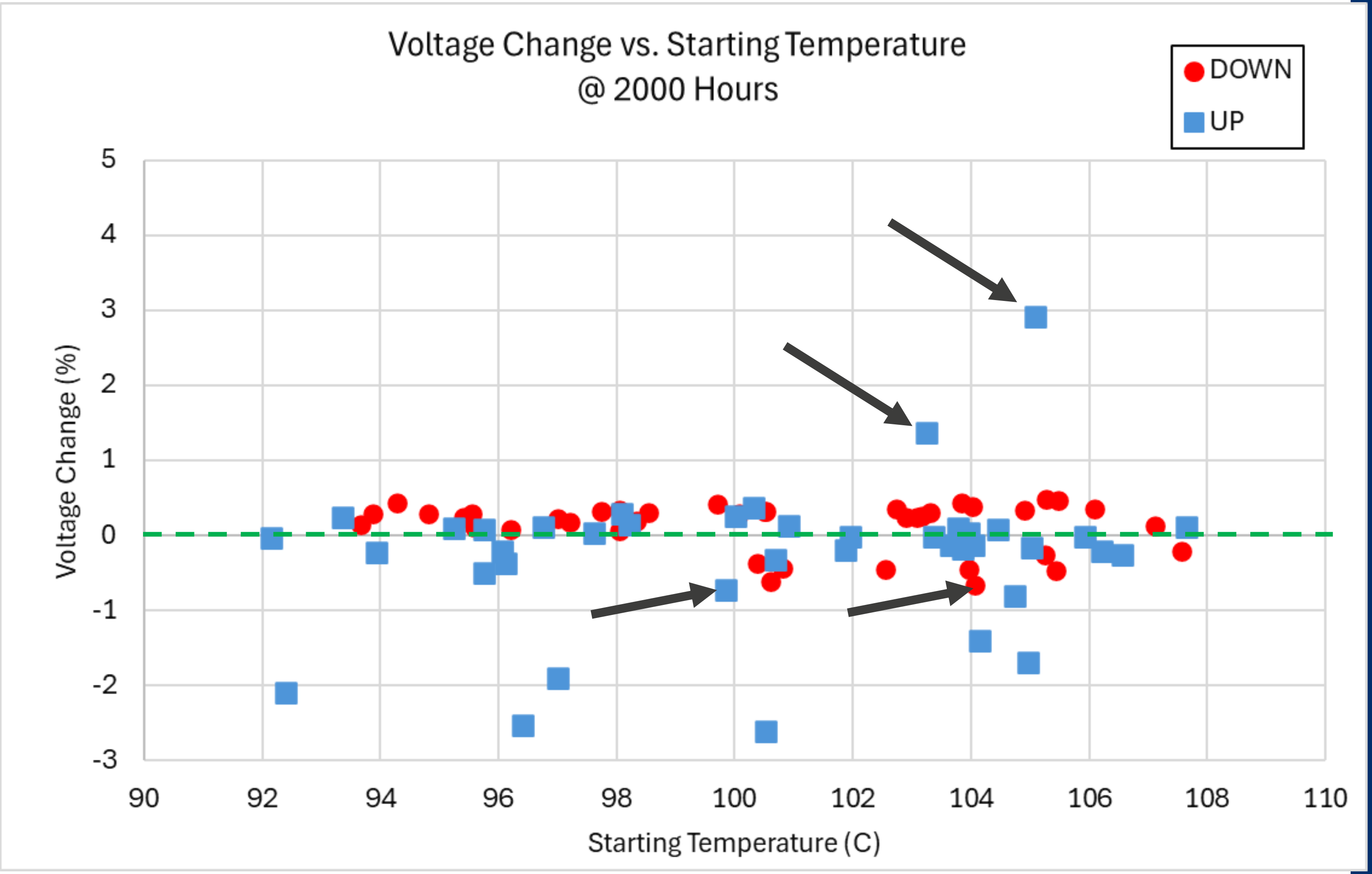
- **~2000** hours of EM stress plotted (Voltage Change vs. Starting Joint Temperature)
- "UP" electron flow:
  - Dip phases
  - Rise phases
  - No changes
- "Down" electron flow:
  - ~No significant change

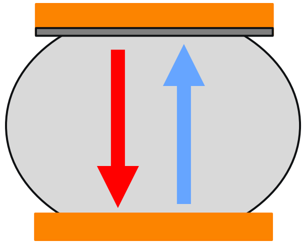




Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

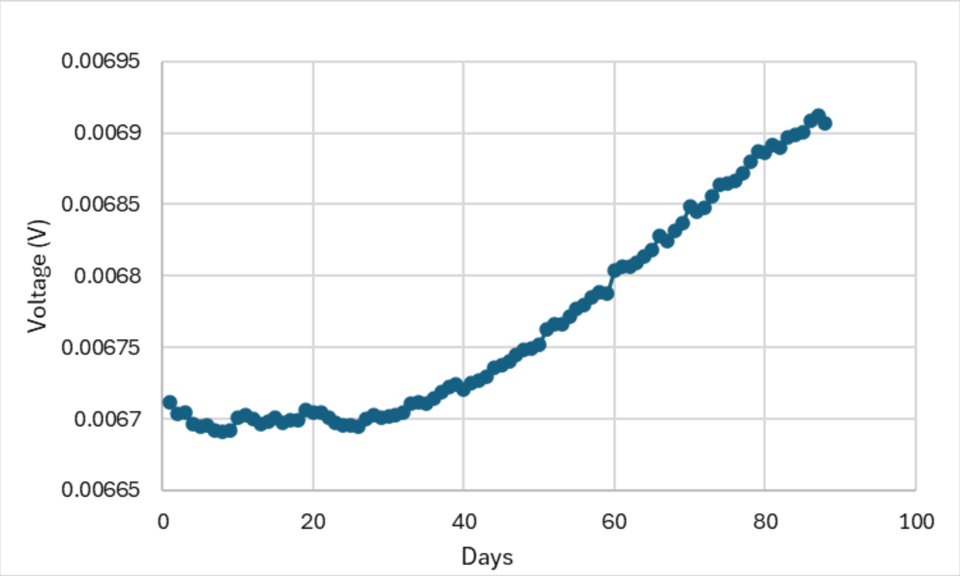
- I got impatient with these samples
- Removed sample with +3% voltage and cross-sectioned
  - +3% joint is on the “hot side” of the spectrum
  - 3 additional joints from sample are included in following slides

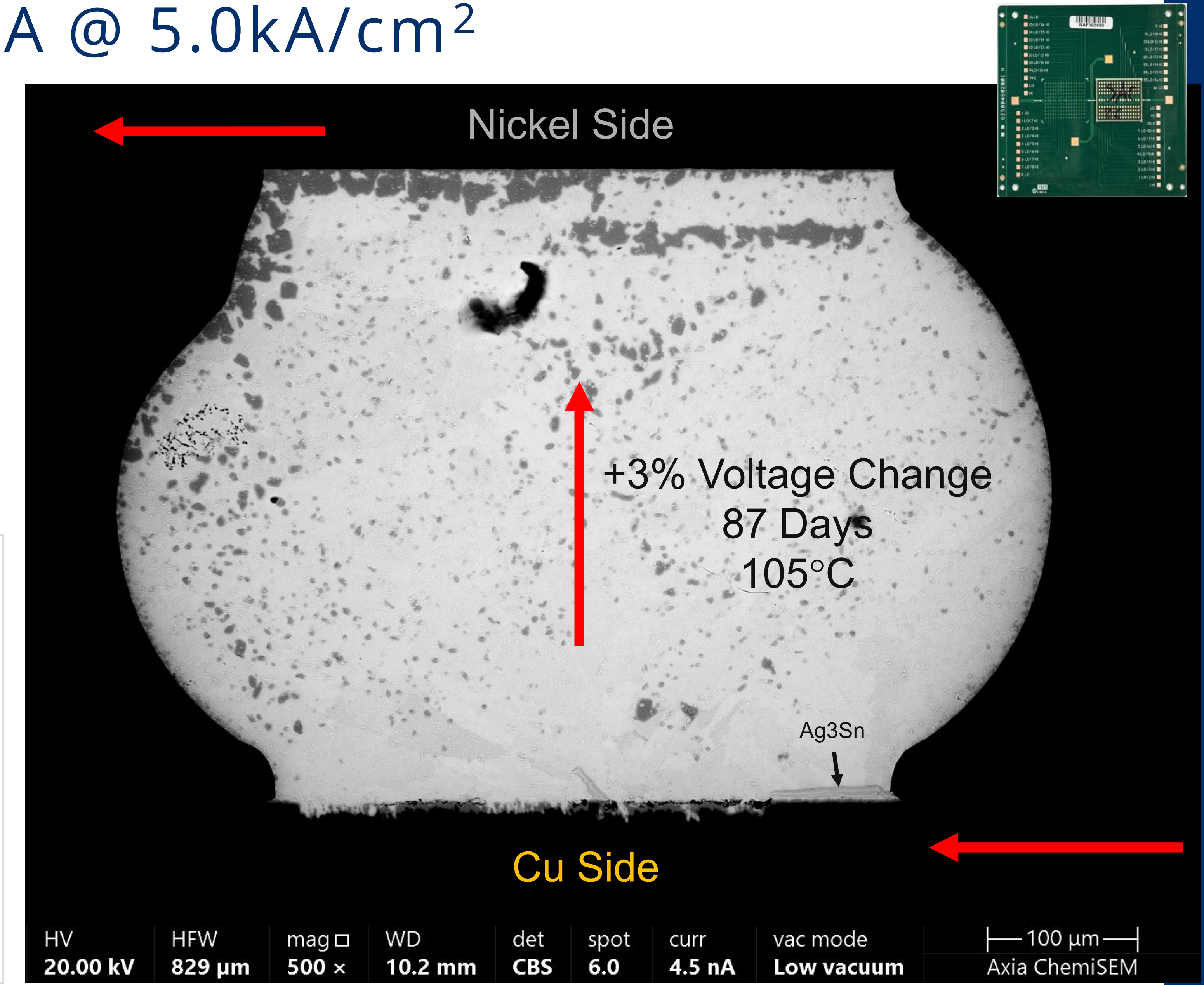




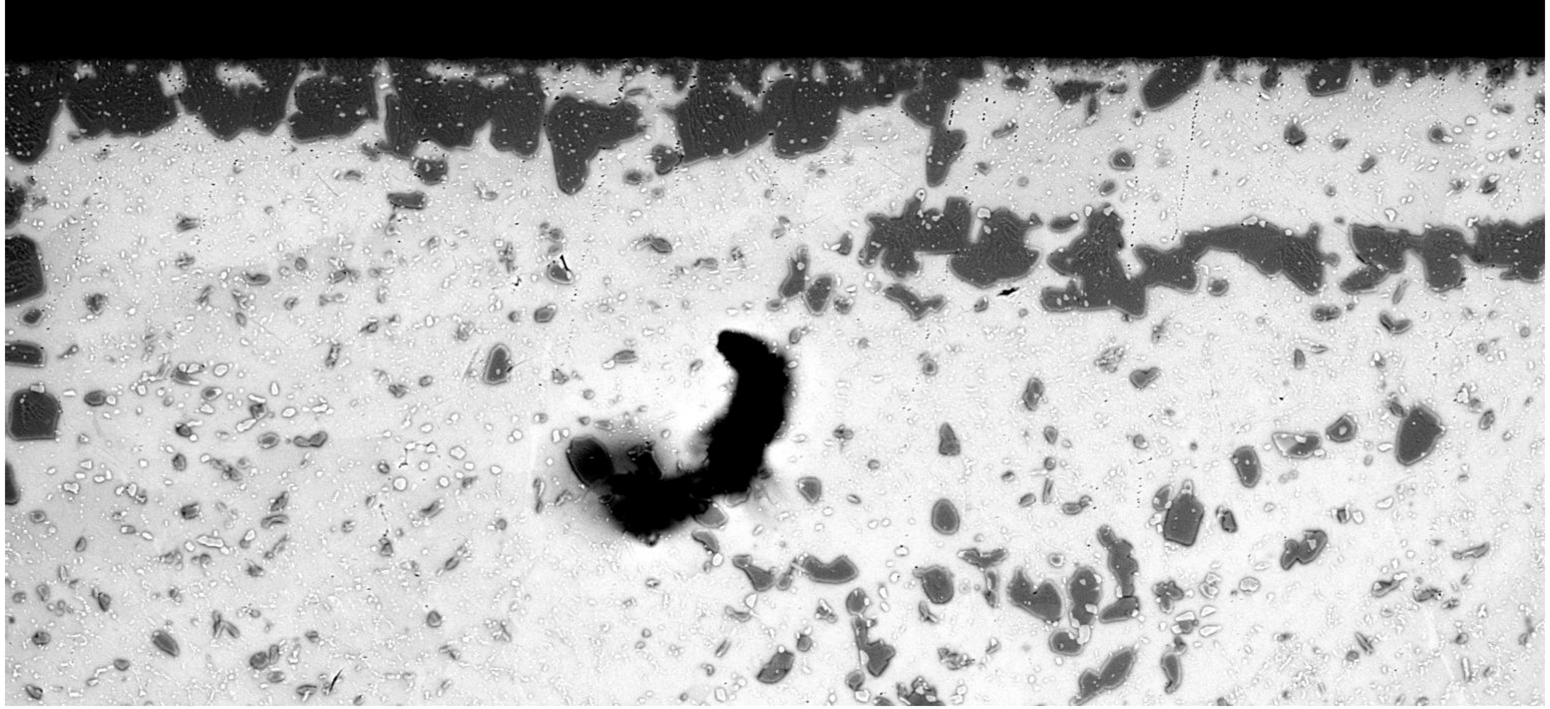
Cu PCB / ENEPIG BGA @ 5.0kA/cm²

- Dip phase was ~35 days
- Rise is ~linear day 40 to 80
- Interesting Ag_3Sn platelet effect

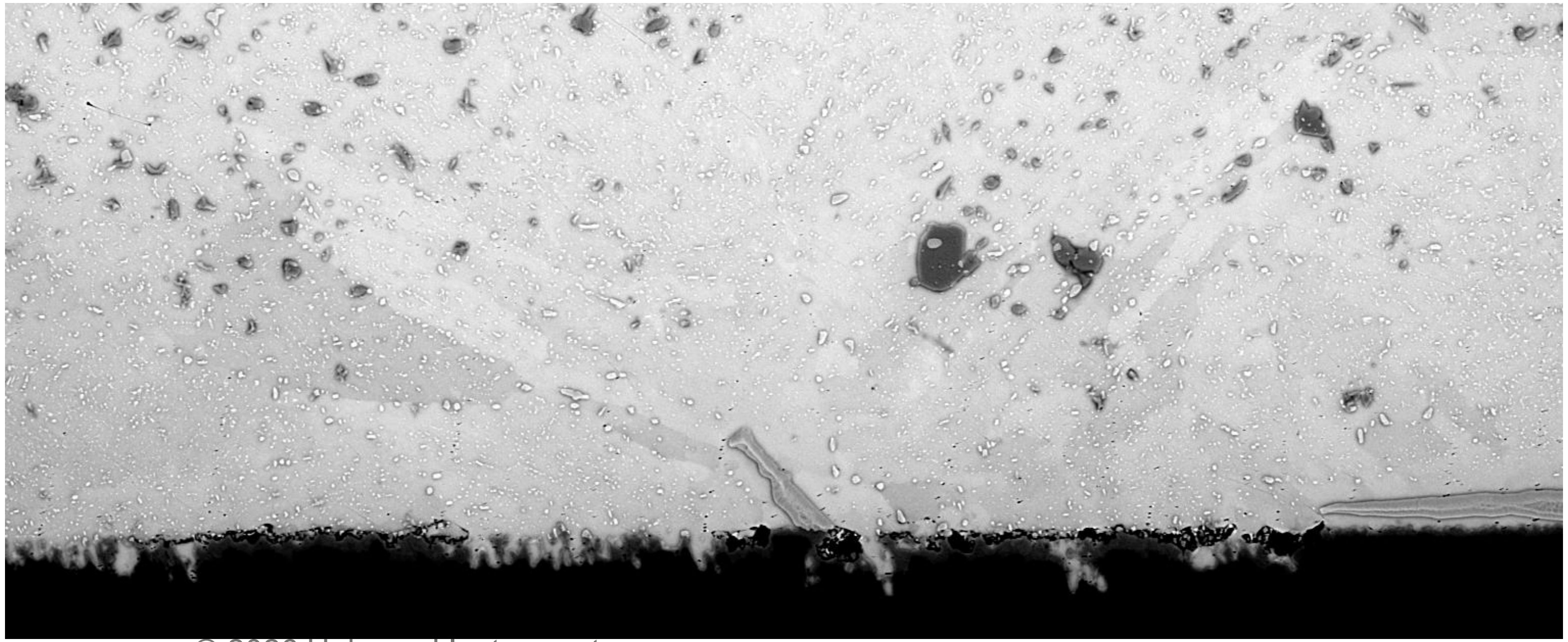




- Here’s some enlarged images
- The CuSn appears to be speckled with Ag

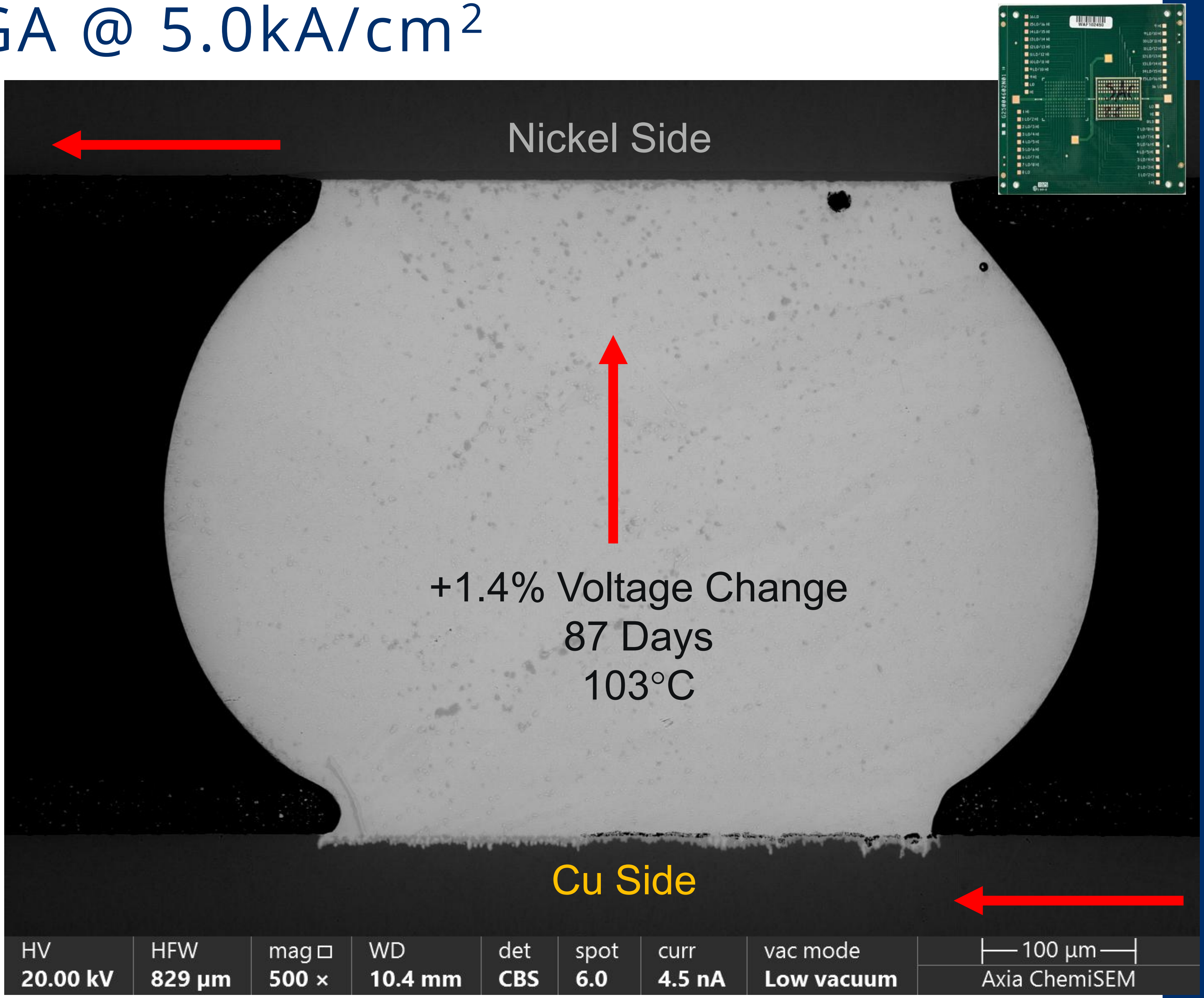


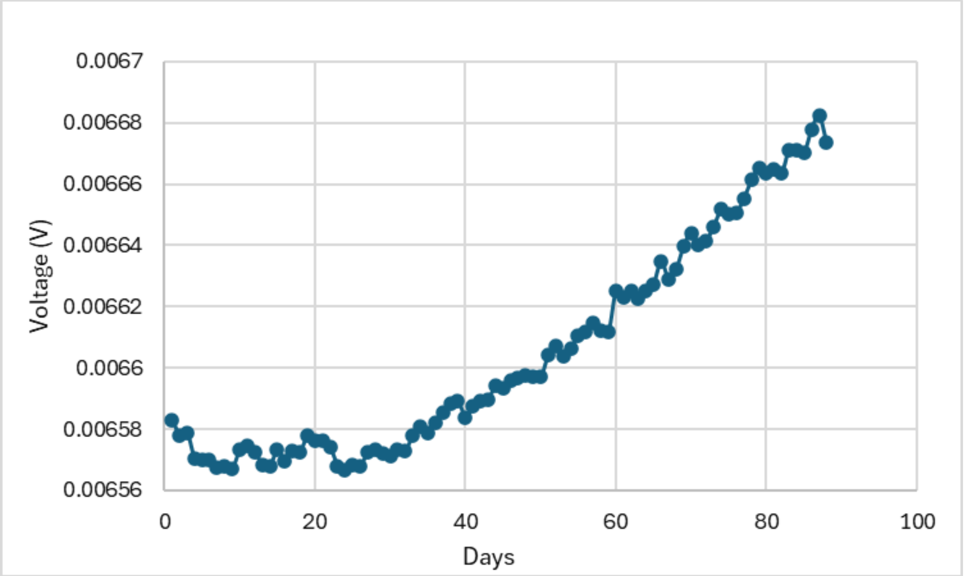
SAC305



Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

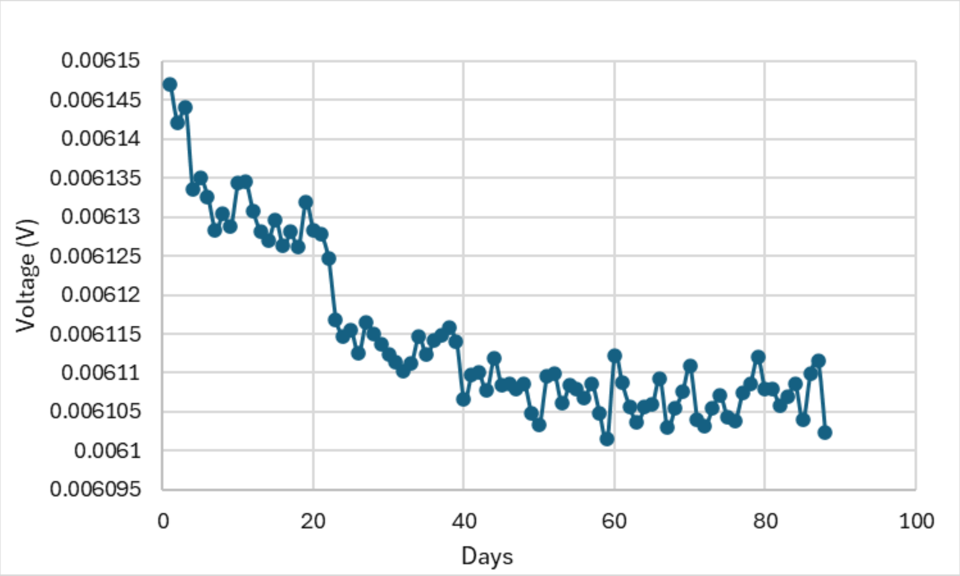
- Significant damage is visible at copper side with just +1.4% voltage rise

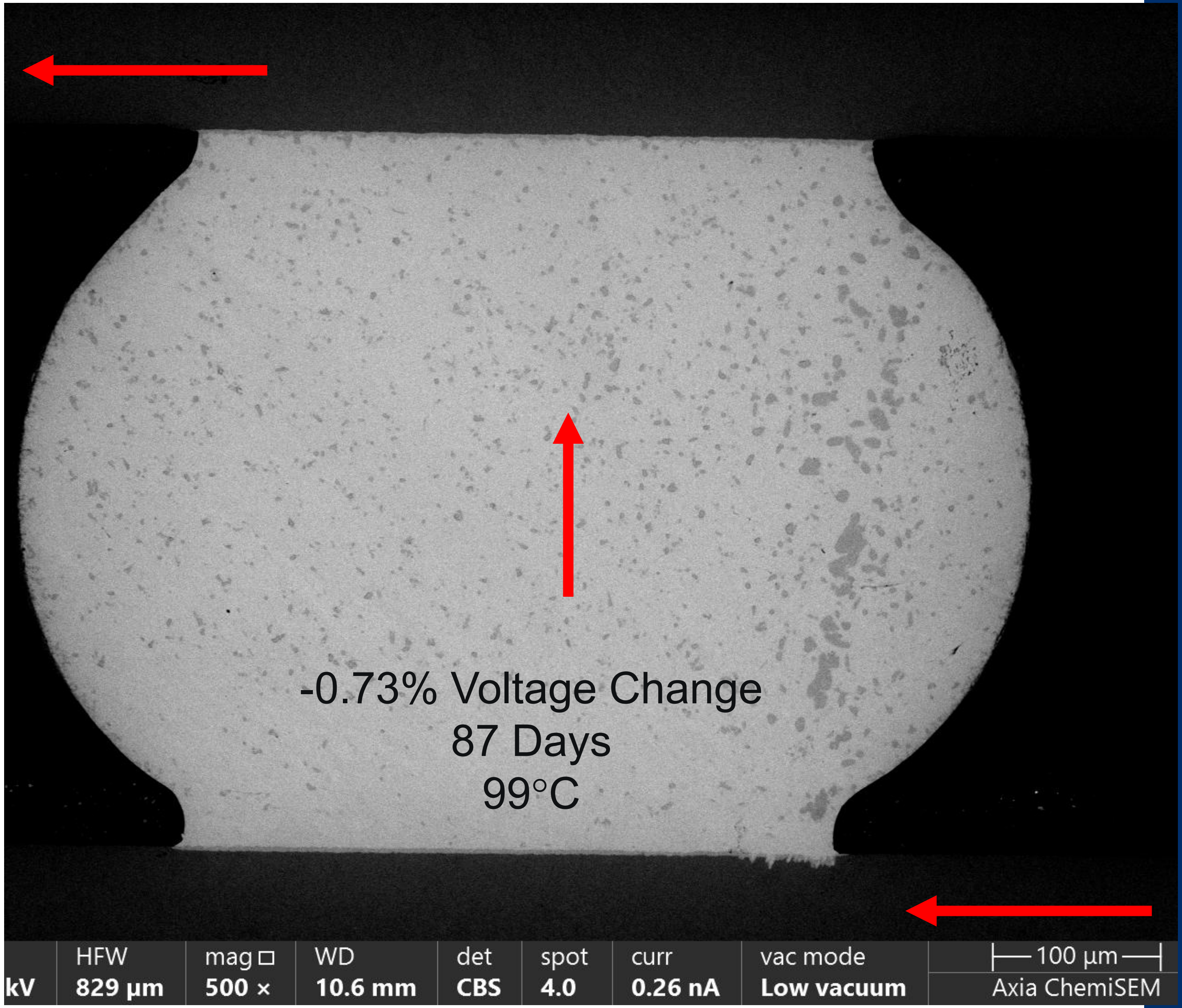




Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

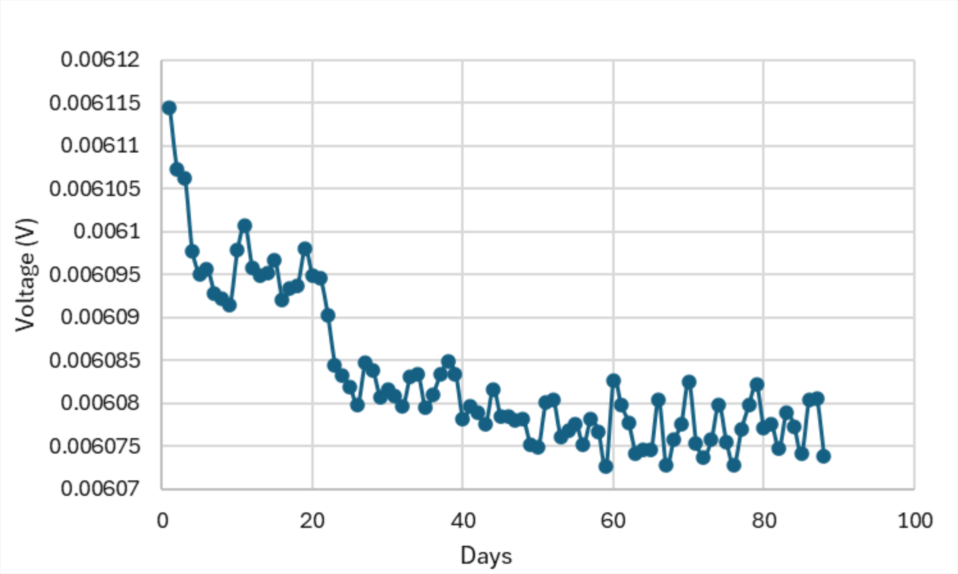
- This was the only “UP” joint not yet showing “rise”
  - -0.73%
  - Average temperature

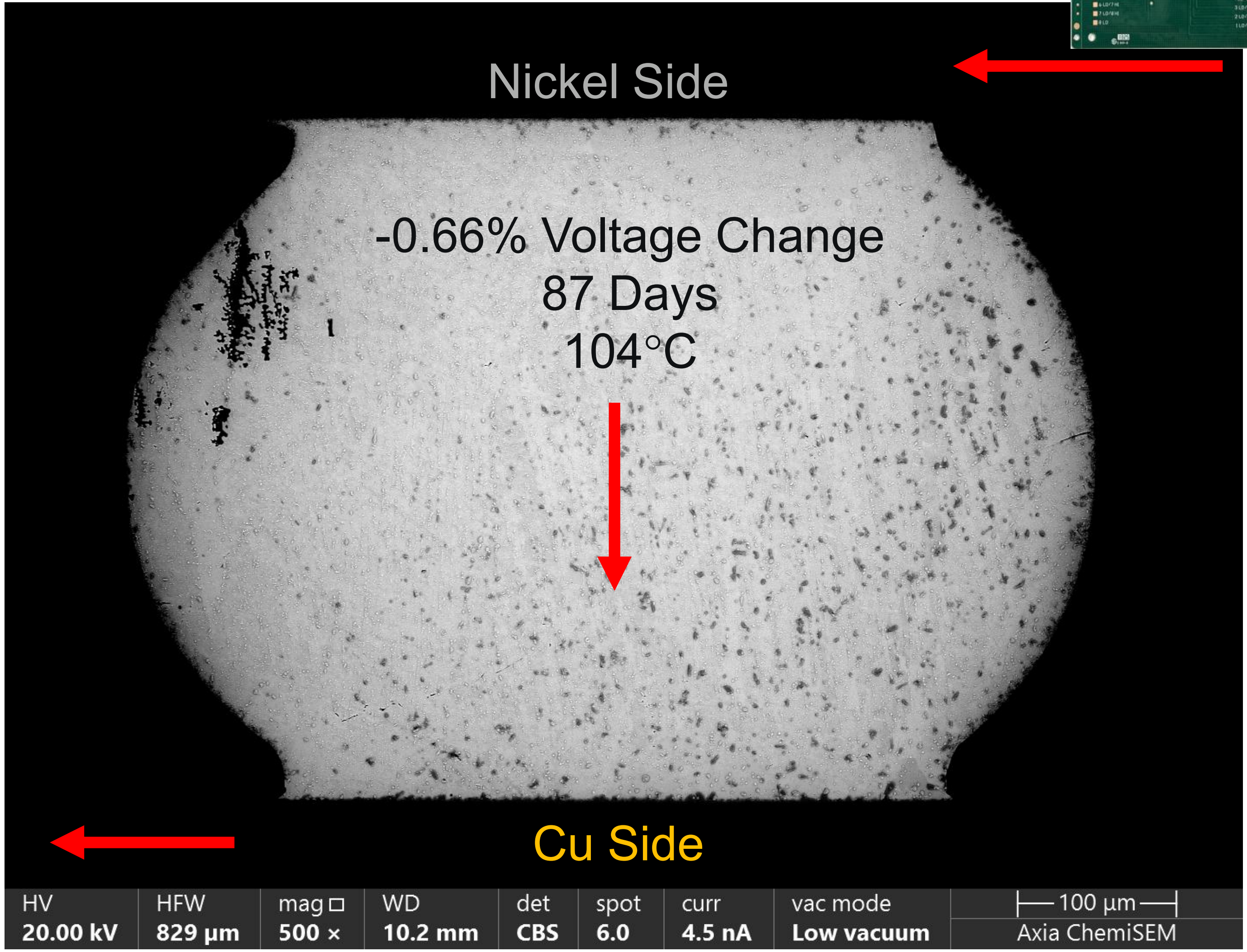



-0.73% Voltage Change
87 Days
99°C

Cu PCB / ENEPIG BGA @ 5.0kA/cm²

- Electron flow down joint
  - No recovery / rise
  - No visible damage

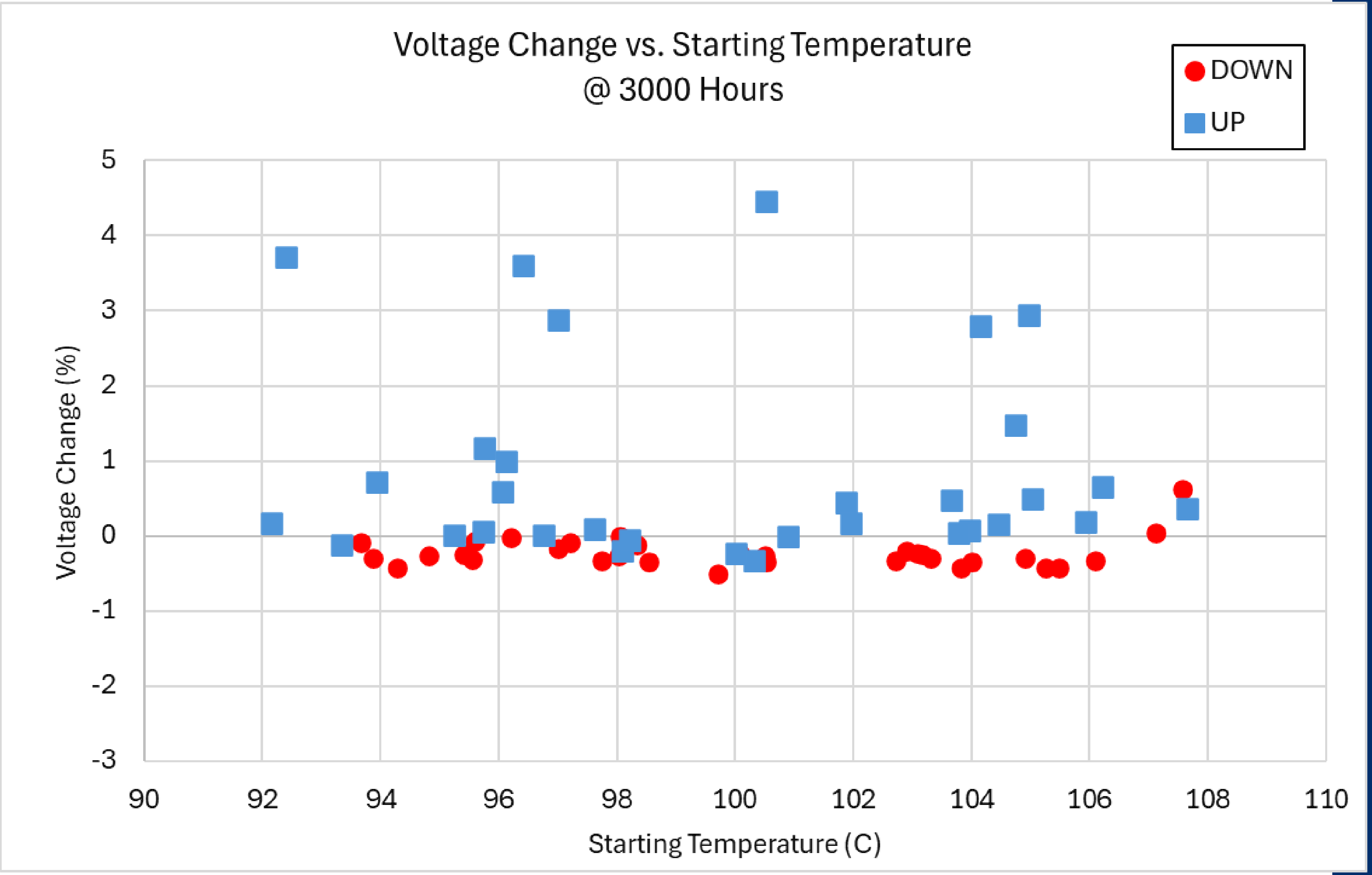


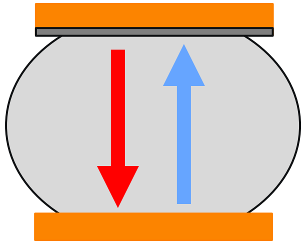


-0.66% Voltage Change
87 Days
104°C

Cu PCB / ENEPIG BGA @ 5.0kA/cm²

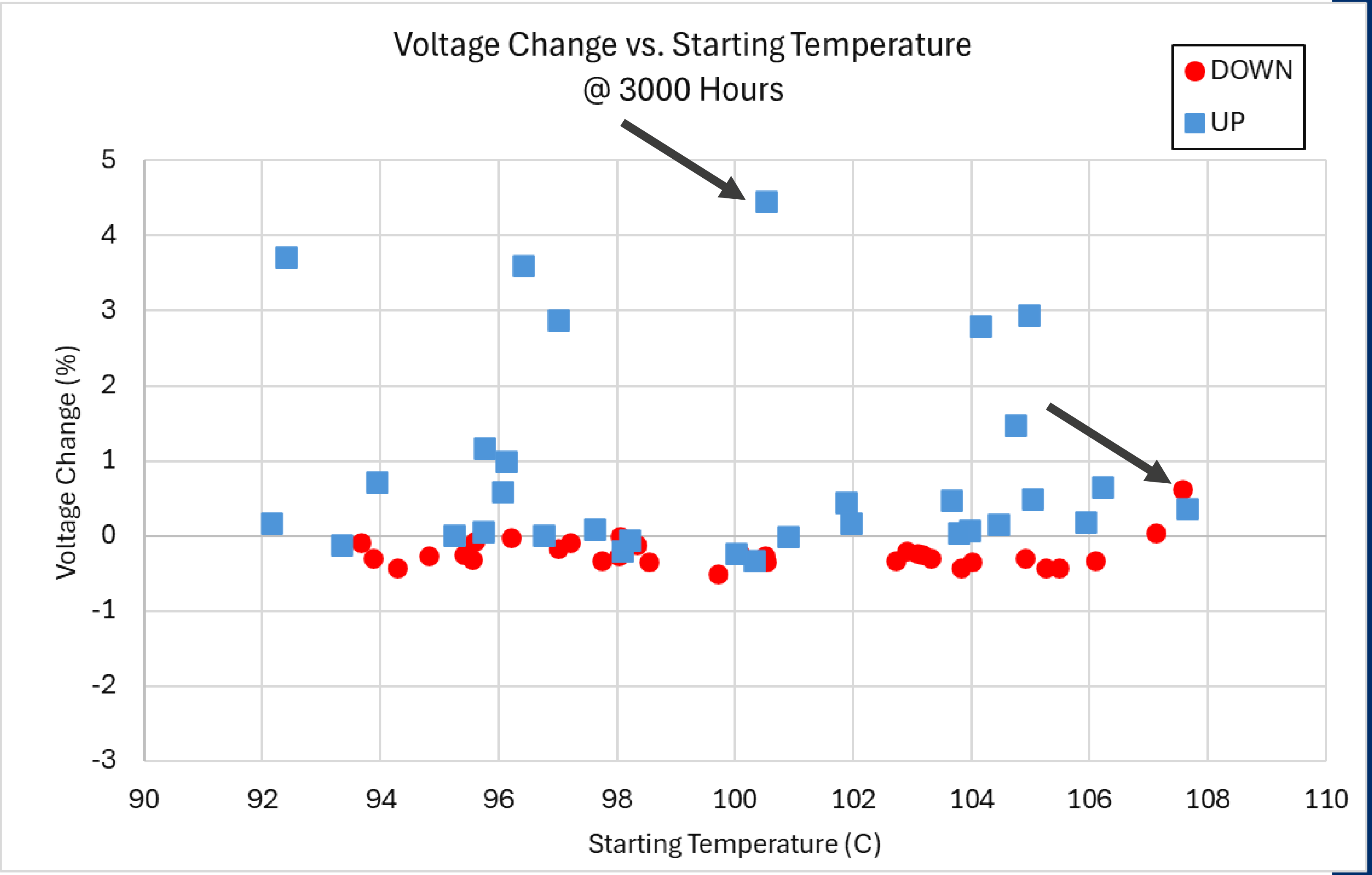
- **~3000** hours of EM stress plotted (Voltage Change vs. Starting Joint Temperature)
- Voltage rise is greater for electron flow from copper PCB to ENEPIG component
- Starting joint temperature (between 92 and 108°C) does not seem to be huge factor affecting which "UP" joints experience voltage rise.

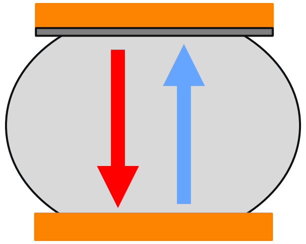




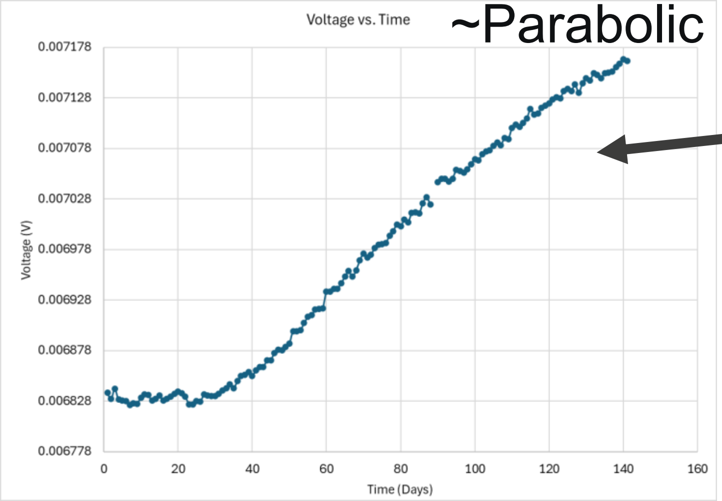
Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

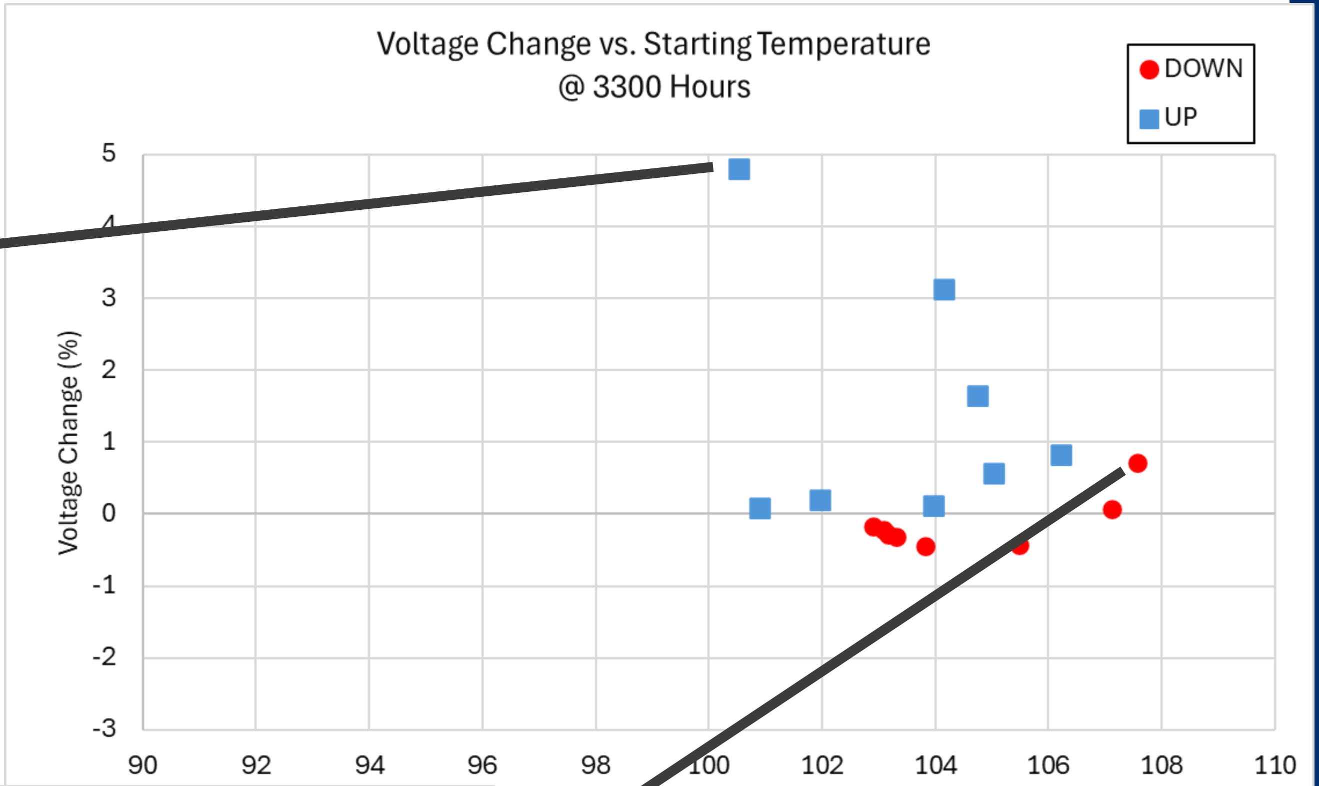
- Sample with largest “UP” rise also contains largest “Down” rise

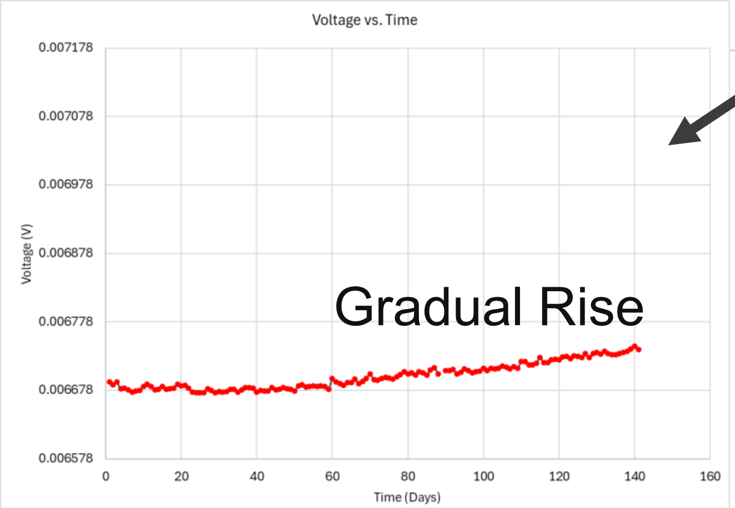


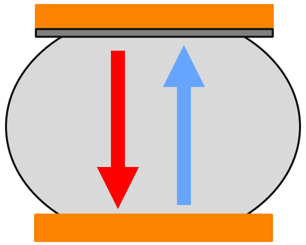


Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

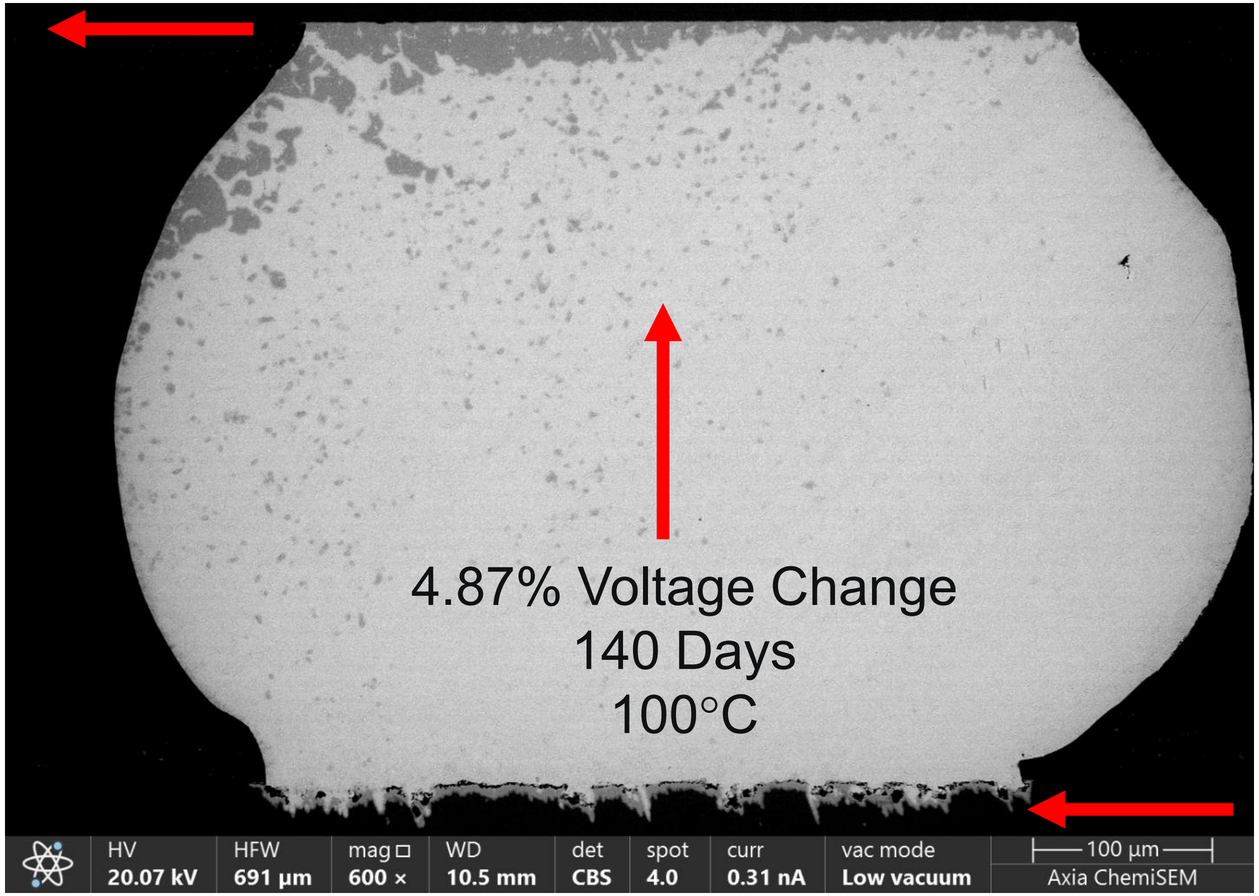


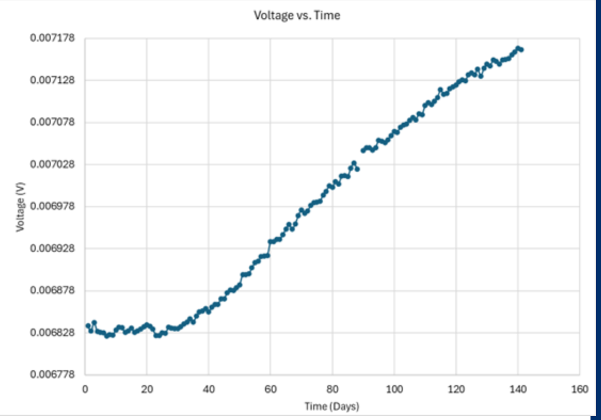






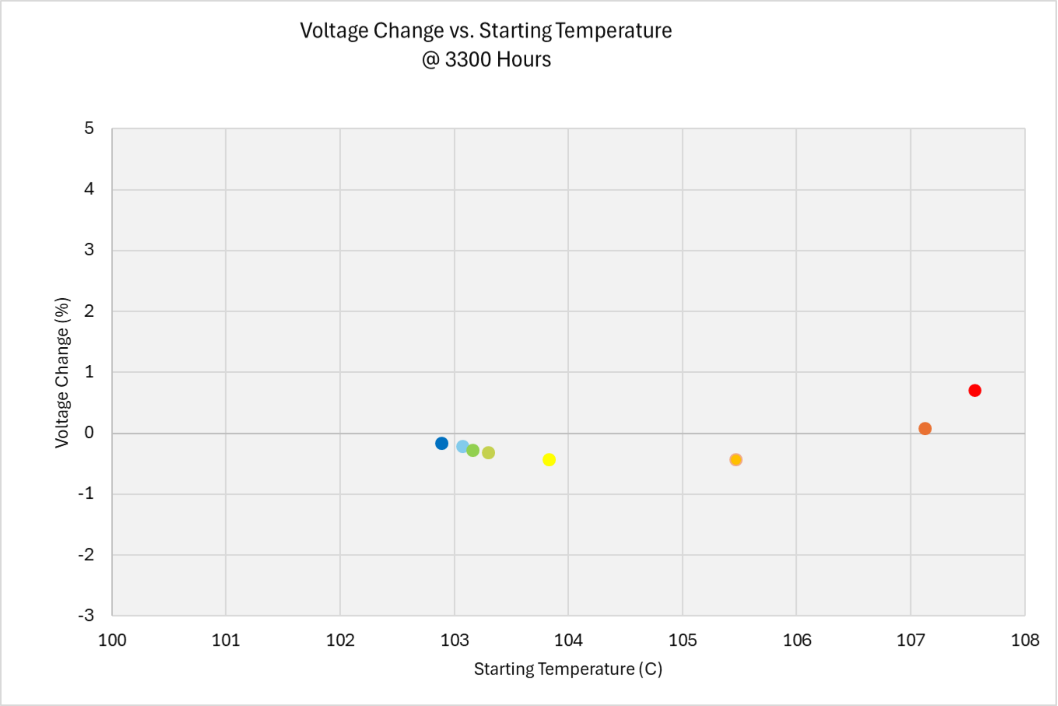
Cu PCB / ENEPIG BGA @ 5.0kA/cm^2

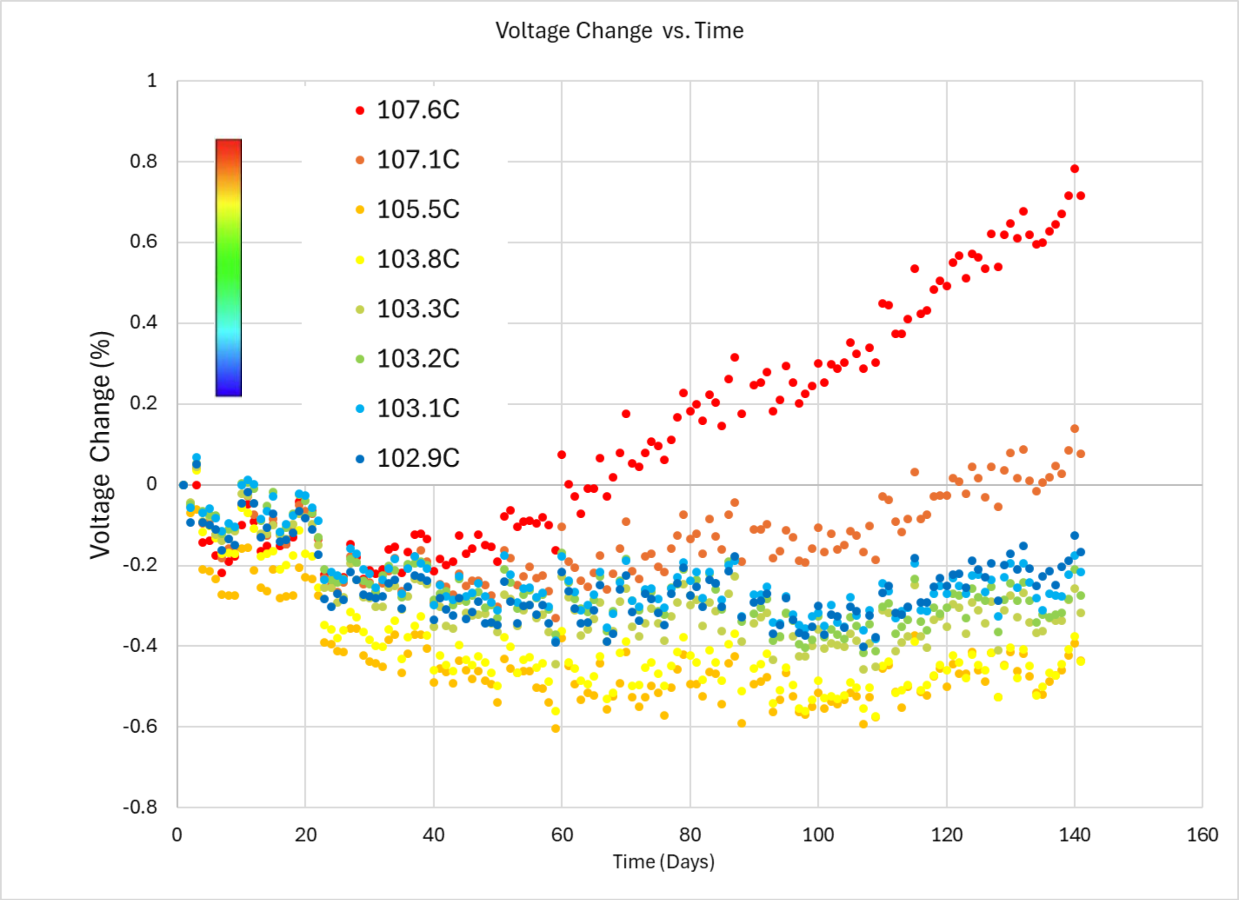

4.87% Voltage Change
140 Days
100°C

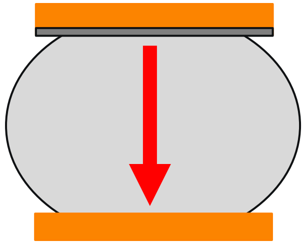


Cu PCB / ENEPIG BGA @ 5.0kA/cm²

Trends with respect to joint temperature is complex?

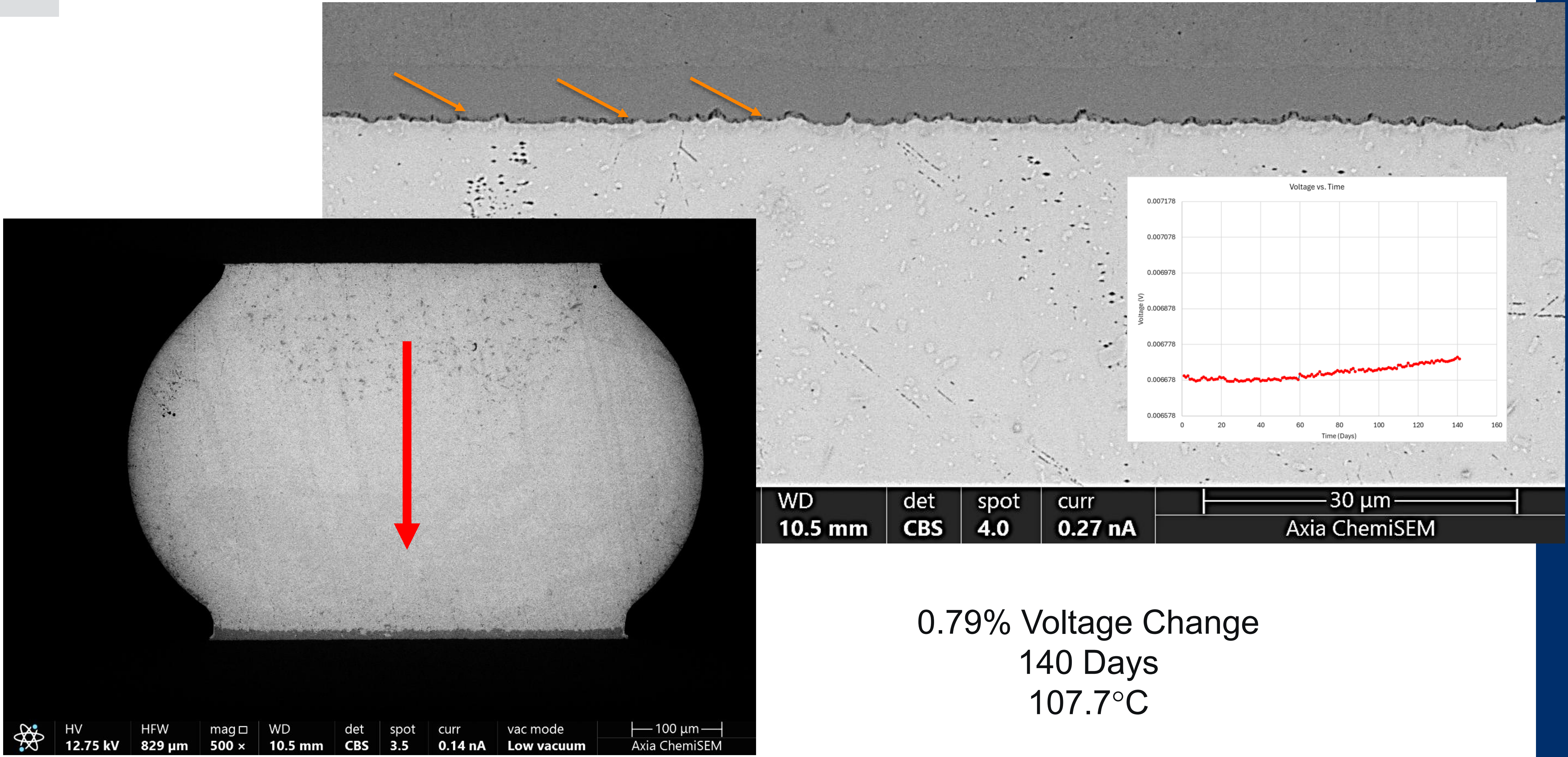






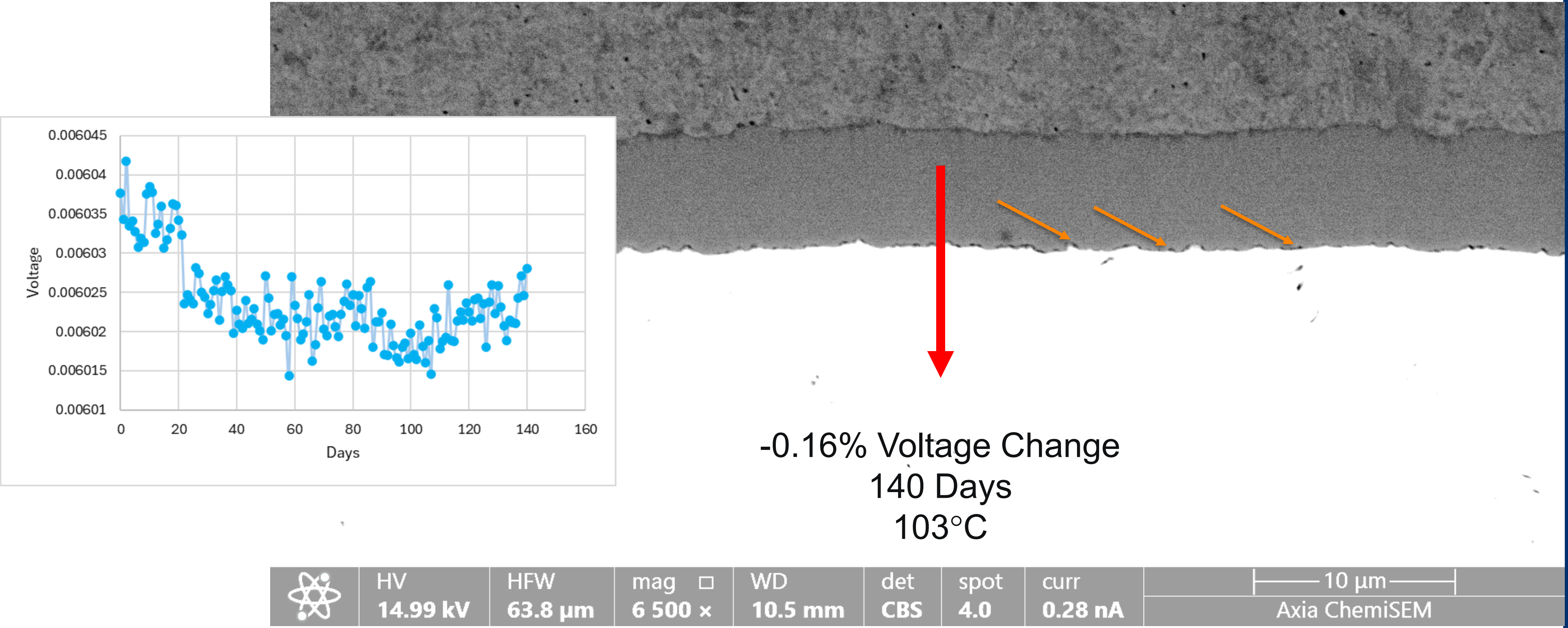
Electron flow “down”:
Possible trends
(but small changes)

Cu PCB / ENEPIG BGA @ 5.0kA/cm²



0.79% Voltage Change
140 Days
107.7°C

Cu PCB / ENEPIG BGA @ 5.0kA/cm^2



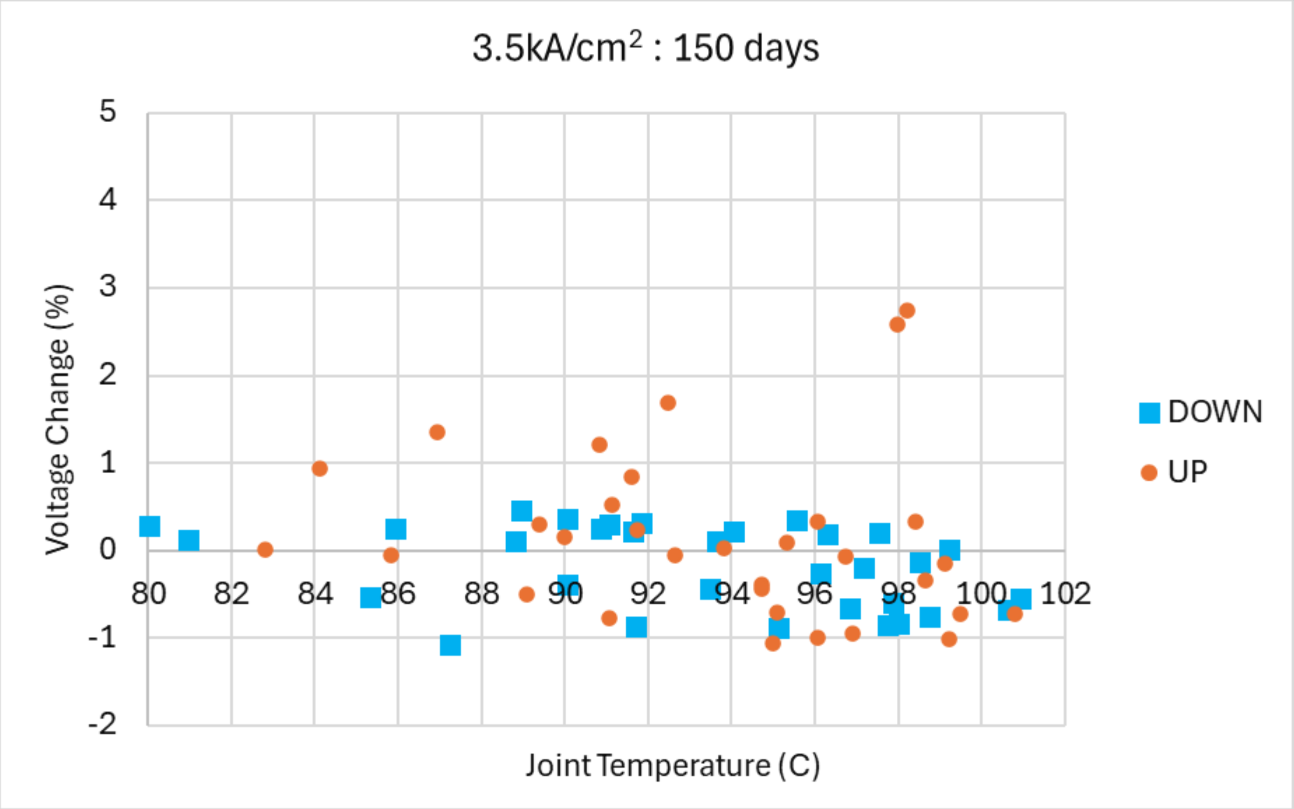
-0.16% Voltage Change
140 Days
103°C

Looks like nickel layer degradation has begun (or was present at start)?

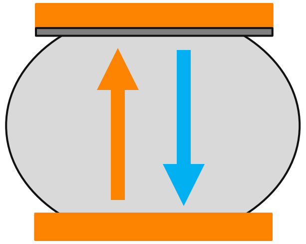
80 to 102°C Solder Joints 3.5kA/cm^2:

Cu PCB / ENEPIG BGA @ 3.5kA/cm^2

- 3.5kA/cm^2 @ 85°C was an operating condition provided after the October 2025 AREA meeting
- 150 days: current flow from PCB to BGA have shown measurable resistance increase.
- Prediction: 275 days to +5% for the two joints that have shown the greatest increase to date
  - If voltage rise remains in the "linear" phase
- Nickel issue may be mitigated / inhibited?



Both data sets contain joints at:
"No change"
Dip phase
Rise phase



Summary

- I have discovered nickel issues in samples that were not subjected to electromigration testing
- Samples subjected to electromigration are far more likely to contain a visible nickel issue
  - When nickel is present at the cathode side during EM testing (flowing from copper through nickel and into solder), the problem is most apparent and can result in relatively quick solder joint failure
- Temperature is a critical factor in both the nickel and copper degradation mechanisms.
  - Evidence suggests nickel degradation is very rapid at >125°C, but slows considerably at lower temperatures such as 100°C
  - Copper degradation is apparent at 100°C and likely occurring at even lower temperatures with Electromigration Stressing

Summary

- +5% voltage change under constant current is associated with significant copper pad and/or nickel barrier damage and IMC growth
  - Individual solder joints can experience 50% voltage increase or more without “burning out”… but 10% rise is indicative of extreme damage

- **Joint to joint behavior is extremely variable**
  - Some joints experience very rapid voltage and temperature increase (surpassing +5% much sooner than other joints subjected to similar conditions)
  - Large sample sizes may be necessary for product level risk assessment

Summary

- 3.5kA/cm^2 will drive electrical failure quite quickly:
  - Predicted time to 5% is a low as 55 days for SAC305 @~120°C
    - Comparable to 5.0kA/cm^2 results at similar temperatures
  - Predicted time to 5% is as low as 275 days for SAC305 @ ~98°C
  - More test time is needed to determine +5% at 80 to 85°C
- Under similar environmental and current stress levels: Cyclomax solder joints were slightly hotter than SAC305 solder joints (3 to 5 degrees)
- Cyclomax vs. SAC305: SAC305 shows faster voltage rise with similar solder joint temperature and current density (for >120°C)
  - Predicted time to +5% is as low as 79 days for Cyclomax @ 130°C and 3.5kA/cm^2
  - More test time is needed to determine +5% for Cyclomax @ 115°C and 3.5kA/cm^2

Questions?

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