Electromigration Failure of Solder Interconnects under Non-DC Conditions:

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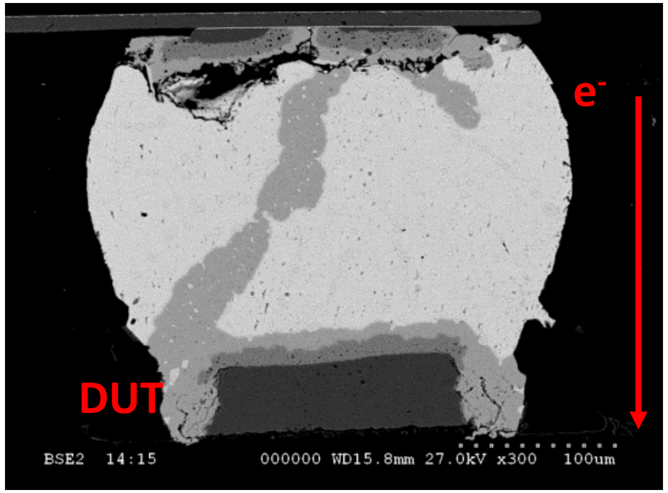
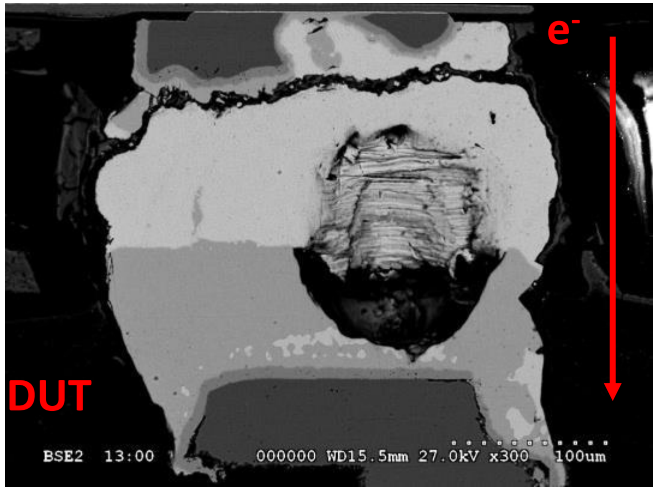
Presentation Overview

- **Electromigration (EM) and challenges in EM study**
  - generalized EM failure mechanism under DC in solder joint
  - motivation for studying non-DC EM
- **Non-DC EM Testing**
  - consideration points of EM under DC, pulsed DC, AC
  - testing circuits
- **Mechanism of EM failure under non-DC conditions**
  - AC: classic mechanism and results
  - pulsed-DC: new failure mechanisms
- **Summary and Implications**

EM failure in WCSP solder joint

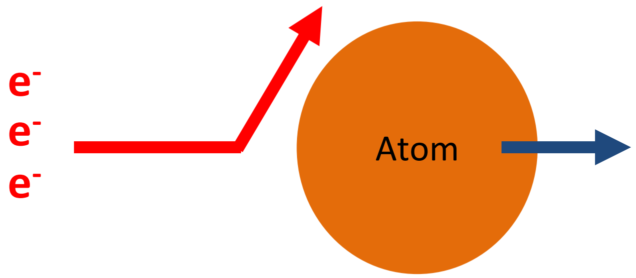




Electromigration and Research Challenges

- **Electromigration (EM)**
  - directional diffusion of atoms driven by high density current
  - known to induce failure in solder interconnects and become a major reliability threat due to aggressive miniaturization
  - Limiting long-term reliability of microelectronic package

- **EM reliability prediction and challenges**
  - Adapt Black's empirical model
  - Failure mechanism details are still not well understood
  - Testing can bias the failure mechanism, leading to the erroneous reliability prediction w/o correction
  - *EM under non-DC conditions are rarely studied w/ difficulty in experimental testing*



$$flux\, J \approx j \times D_0 exp(-\frac{E}{kT})$$

j: current density
E: diffusion activation energy

$$ttf \approx Aj^{-n} exp(\frac{E}{kT})$$

n: current exponent
E: EM activation energy

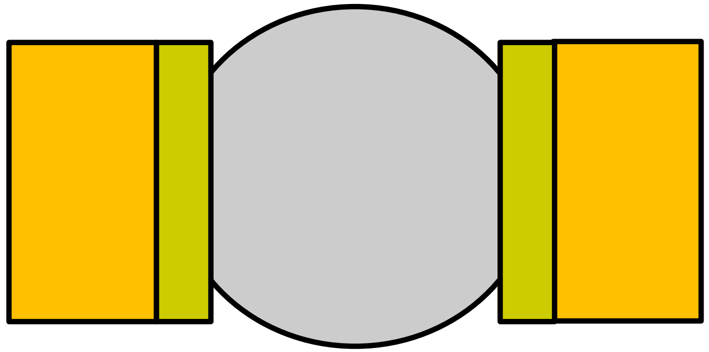
Non-DC EM in Solder Joint

- **Understanding may need completely different approaches from thin film interconnects**
  - EM in thin film interconnect occurs in highly homogeneous system: simple structure, one composition, negligible joule heat
  - Pulsed DC and AC effect is reasonably well understood (damage relaxation mechanism)
- **EM in solder is complex process**
  - Multiple components with different EM/diffusion rates
  - Interface reaction is a part of failure mechanism
  - Considerable level of joule heat can be involved
  - Thermal stress can complicate the failure process

AC-EM: reversed flux

Thin film interconnect: homogeneous system

flux is not necessarily reversible
Or damage can be repaired



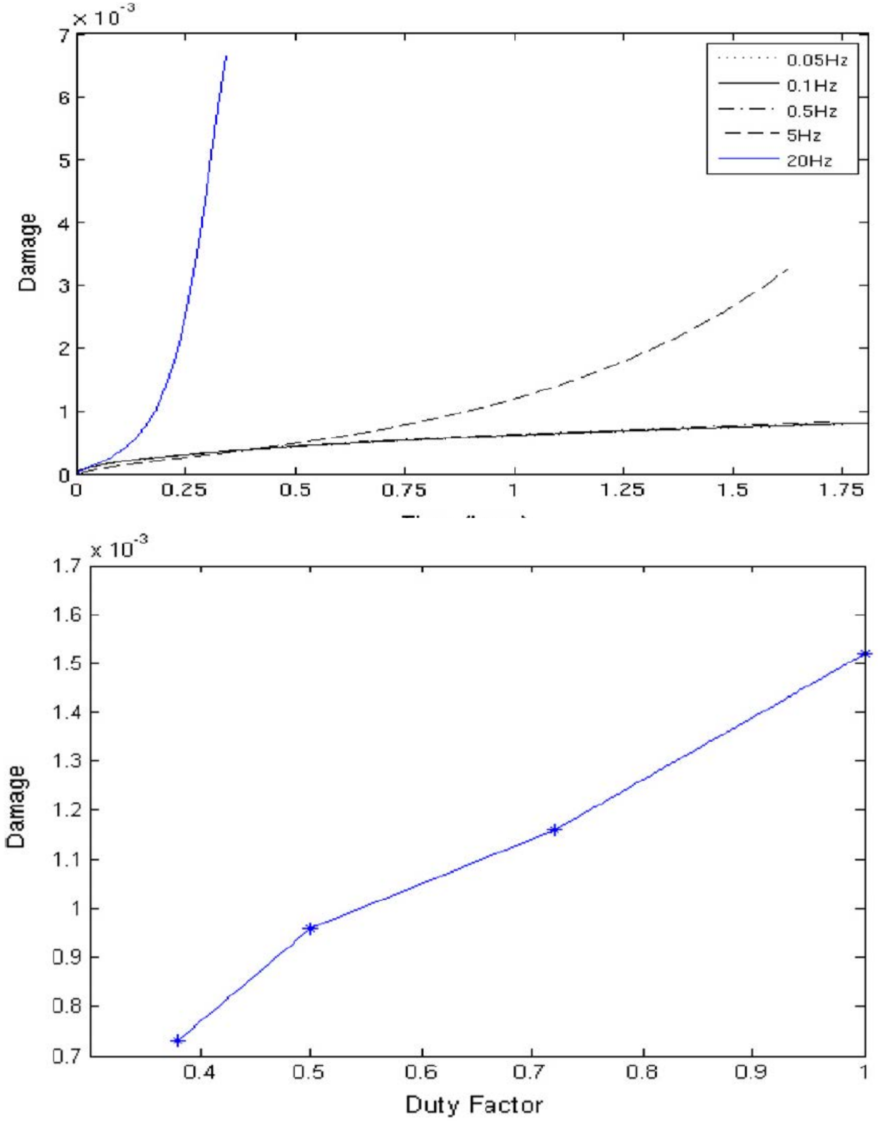
Solder Joint: heterogeneous system

Failure by Non-DC EM: Past Studies

- **Of practical and fundamental importance**
  - EM load on device can be non-DC (pulsed DC, AC)
  - Can reveal key but hidden parameters to consider
  - Understanding is seriously lacking for EM in solder joints

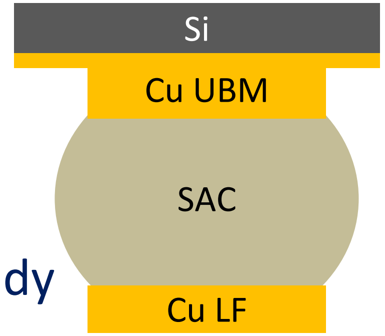
- **Existing studies suggests**
  - Studies are mostly based on classic EM theory (extension of DC to PDC or AC)
  - W. Yao and C. Basaran (2013) computed PDC effect
    higher damage rate at higher frequency
    (because damage relaxation during “off” cannot occur)
  - Z. Zhu, Y. Chan, F. Wu (2019) studied AC effect
    faster growth of IMC under AC
    (AC load was not pure AC but was sinusoidal)

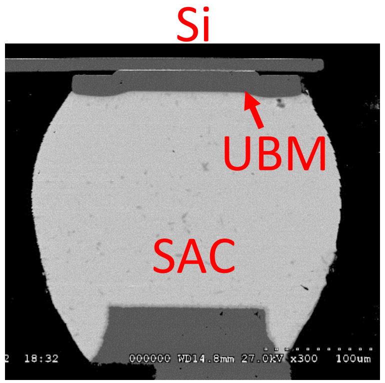
W. Yao and C. Basaran (2013) Comp. Mat. Sci.

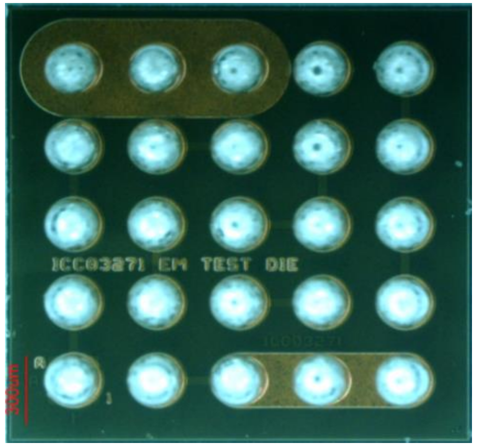


Selected Sample for Research

- **Wafer-level chip scale package (WCSP)**
  - One of the worst EM resistance structures
  - More prone to stress assisted EM failure
  - Easier to do microstructural EM mechanism study

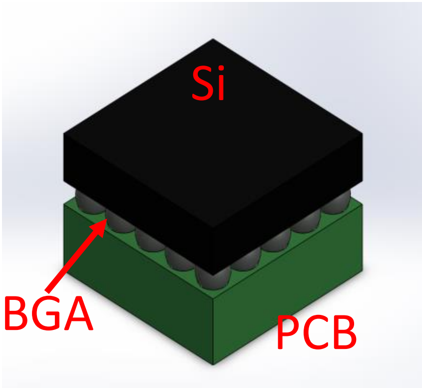




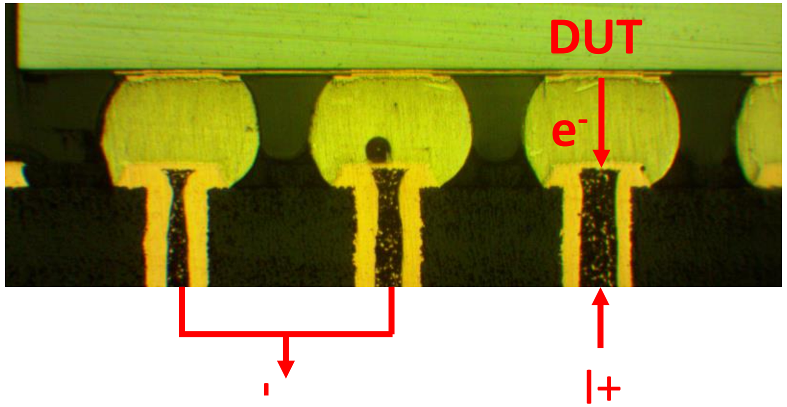


DUT solder array

- **Sample structure**
  - 5x5 SAC solder ball grid array (BGA)
  - Consists of Cu UBM, SAC solder ball, and Cu lead-frame
  - Various thickness of Cu UBM pads (18-50µm Cu UBM)
  - 3 SAC solder bumps are connected for testing
  - Assembled into PCB

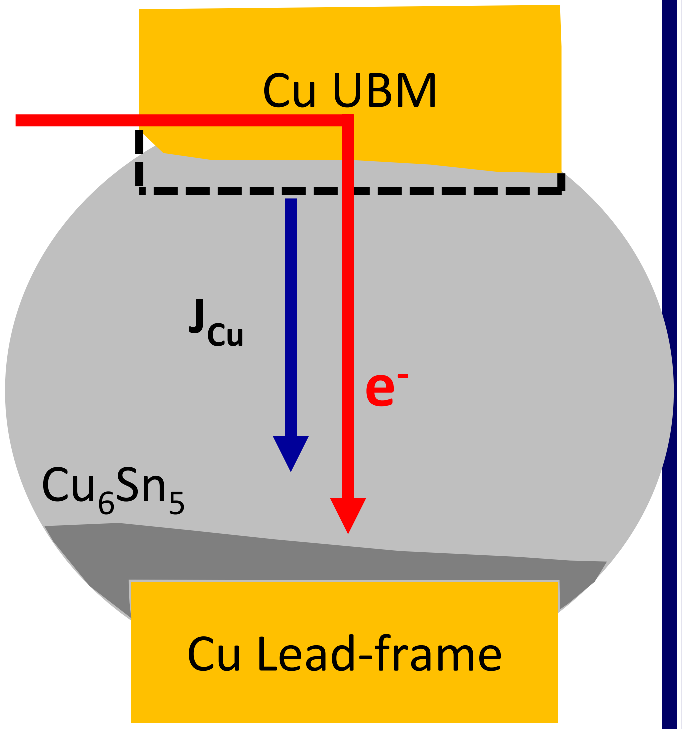


- **Sample preparation**
  - WCSP samples provided by Texas Instruments for research
  - PCB designed at UT Arlington
  - WCSP assembled to PCB at SVT



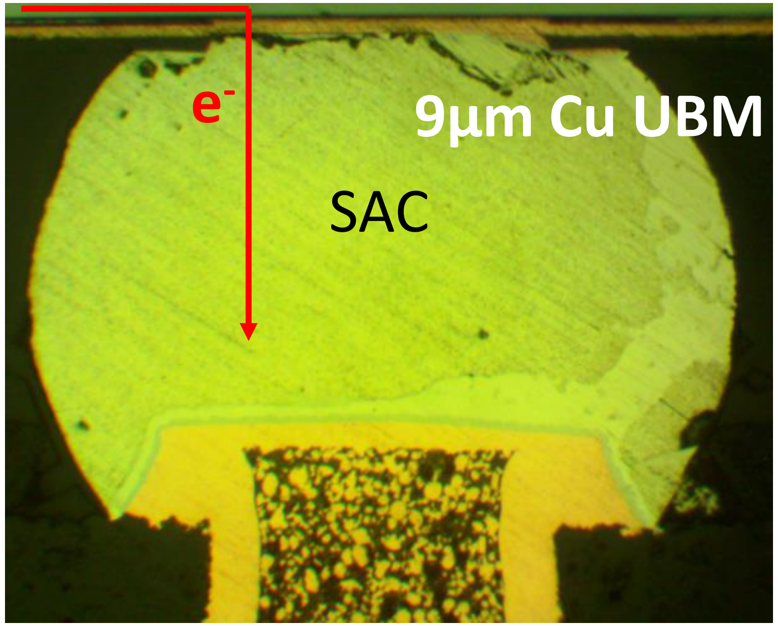
EM Failure Mechanism under DC

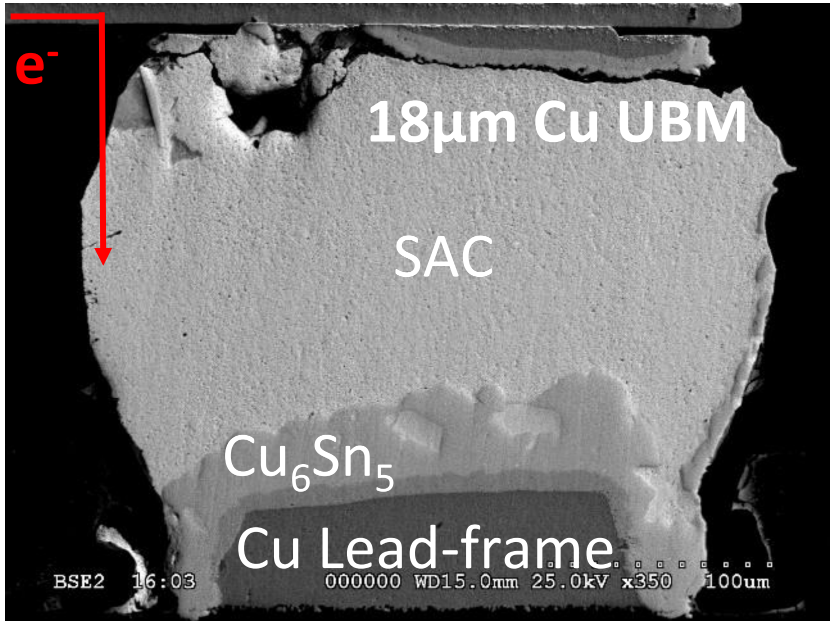
- **Cu EM controls the failure kinetics**
  - Cu EM occurs preferentially and protects Sn from EM, making UBM to dissolve and thick Cu_6Sn_5 to accumulate at the anode
  - Current crowding at the electron entering corner results in a faster dissolution of UBM
  - Voiding starts at the corner and grows to the opposite end of UBM
- **E and n of EM failure**
  - Activation energy (E) is related to the Cu diffusion
  - n represents void nucleation and growth under current crowding (n>2)
- **Contributing factors**
  - UBM thickness: affects amount of Cu supply and thermal stress effect
  - Geometric constraint: affects current crowding and thermal stress

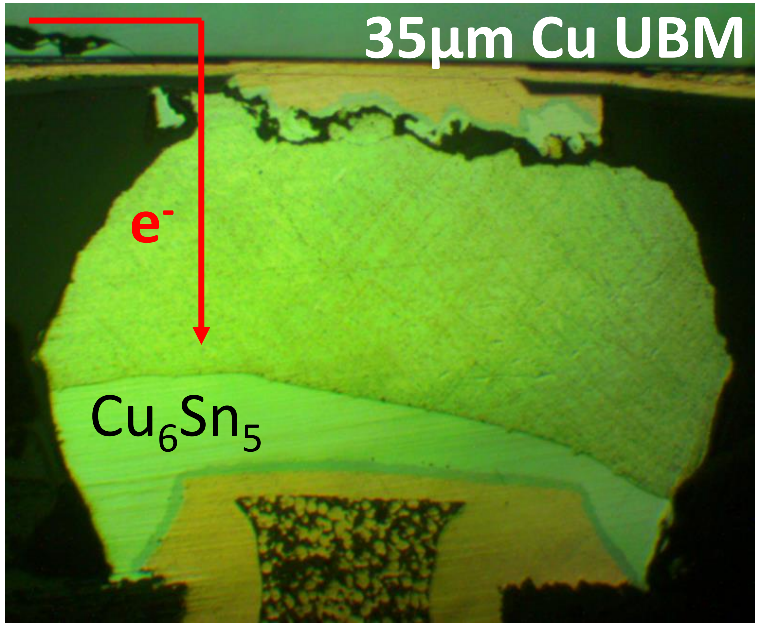


Microstructural Failure Mechanism

- **Typical failure microstructure**
  - Failed by void nucleation and propagation at the cathode side of solder bump
  - Thick Cu_6Sn_5 IMC forms at the anode side while UBM is dissolved away
  - Current crowding effect exists (void starts at the entrance of electron)

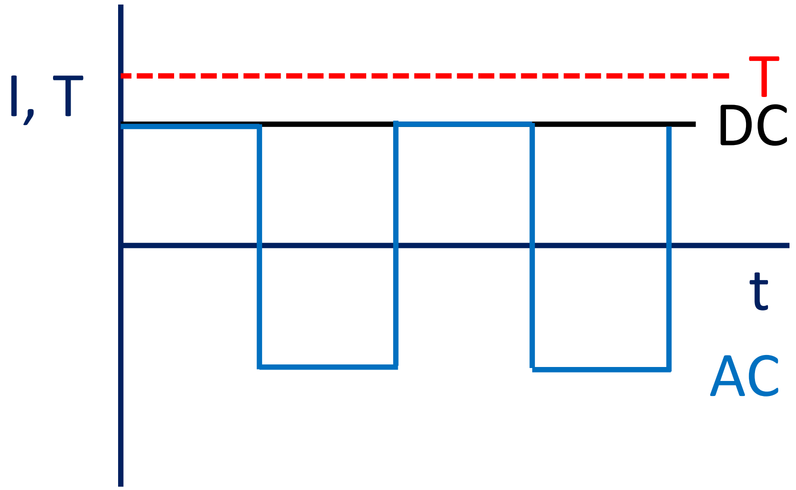


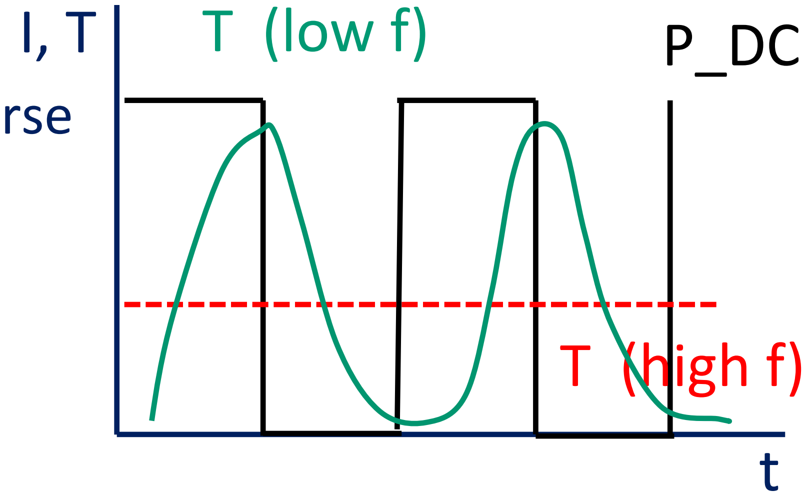




Factors to Consider for Non-DC EM Failure

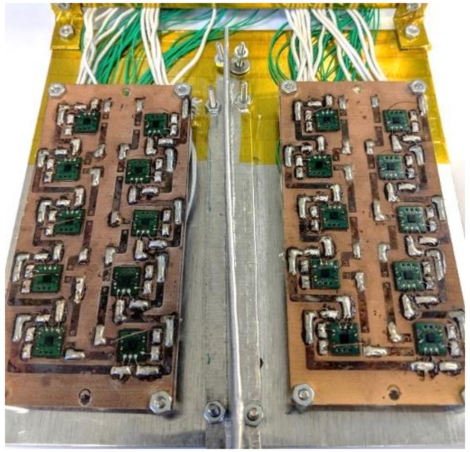
- **EM failure under DC**
  - Isothermal condition (with joule heat included)
  - Kinetic mechanism is simpler and can be descried using the Black's model.
- **EM failure under AC**
  - If square AC, isothermal condition (the same JH to DC)
  - Damage develops by asymmetry flux between "forward" and "reverse" EM.
  - Failure may develop faster at lower frequency when the reverse EM time is longer than the time to reverse the damage.
- **EM failure under pulsed DC**
  - Usually "on-time model": (no recovery is considered)
  - Temperature is not constant at low frequency
  - Failure mechanism can be complicated with pulsing temperature

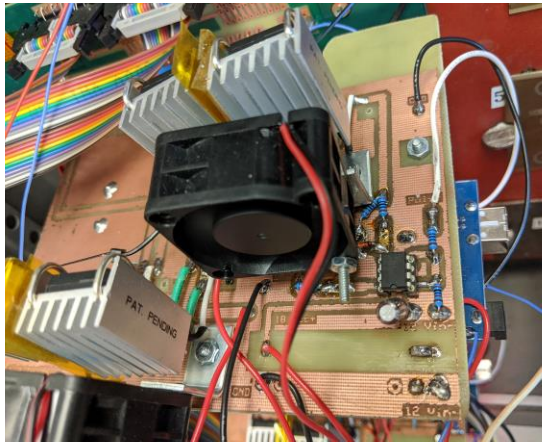


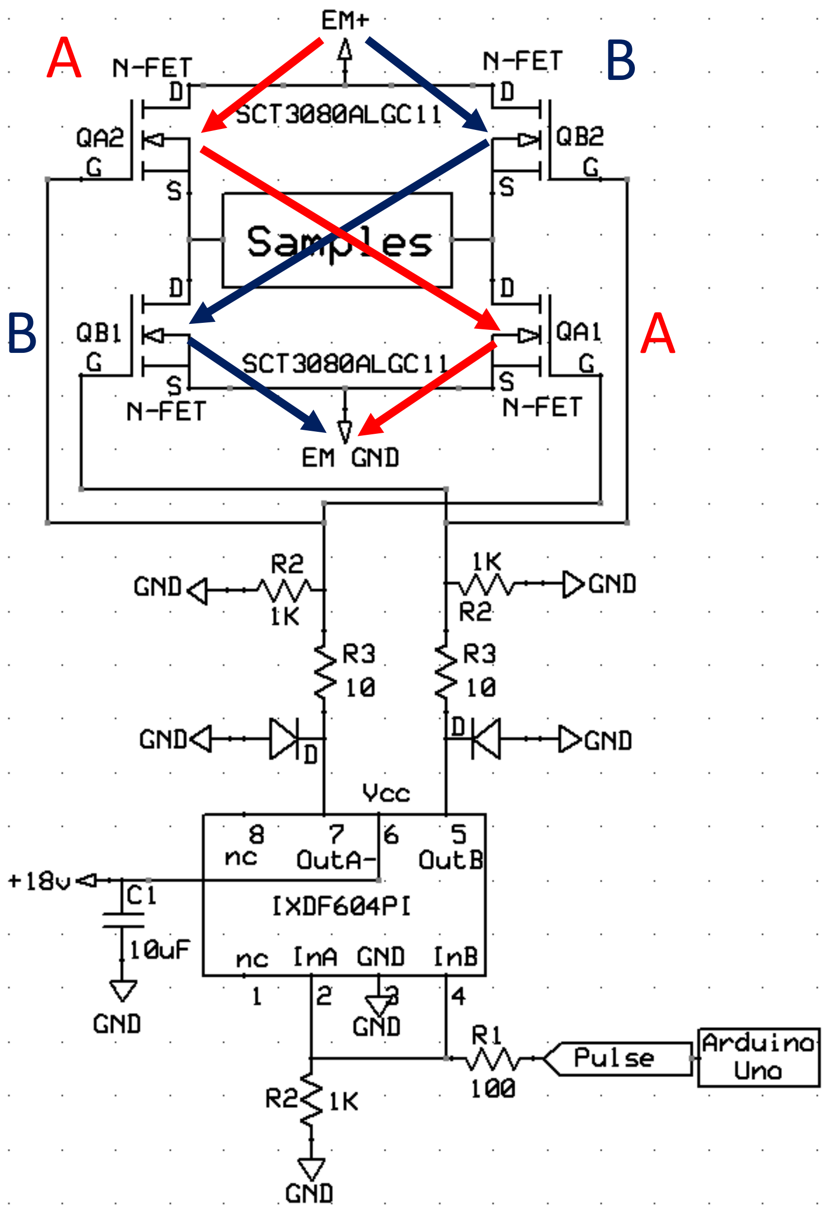


AC Constant Current Module Schematics

- **AC constant current power supply is not available**
- **Design an AC constant current generating PCB module (one of the most challenging tasks)**
- **Based on a H-bridge circuit consists of**
  - 4 MOSFETs, 1 MOSFET driver-2 outputs w/ opposite polarities
  - 1 Arduino as a pulse-width modulation
- **Turns on A MOSFETs to flow a forward AC polarity**
- **Turns on B MOSFETs to flow a reverse AC polarity**







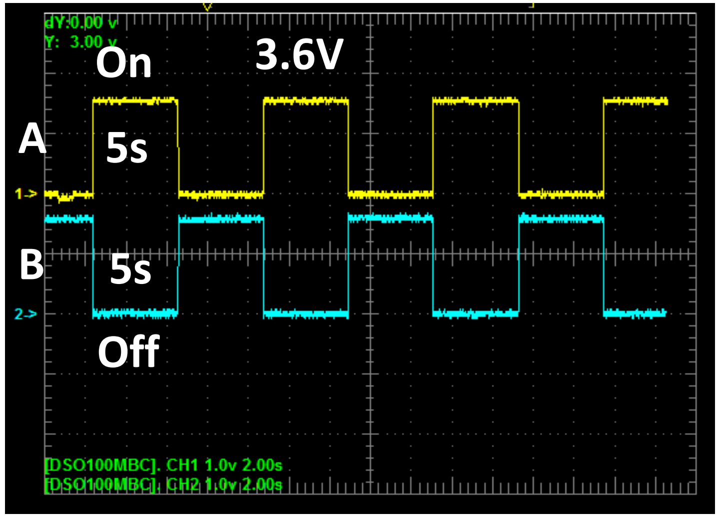
AC EM Test

- **Possible failure behaviors**
  - No temperature fluctuation
  - If EM damage is not repairable,

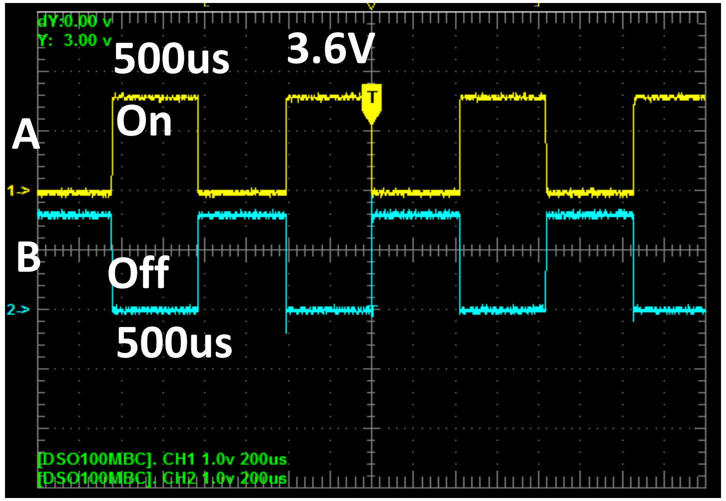
    AC EM failure rate is similar to DC (damaging in both forward and reverse direction)
  - If EM damage is reparable,

    Low frequency AC: longer failure time than DC *(partial repair)*

    High frequency AC: not fail for very long time due to near complete damage repair mechanism
- **Failure kinetics may be developed by extending the Black's model.**
- **But, " repairability" may not be only contributing factor**



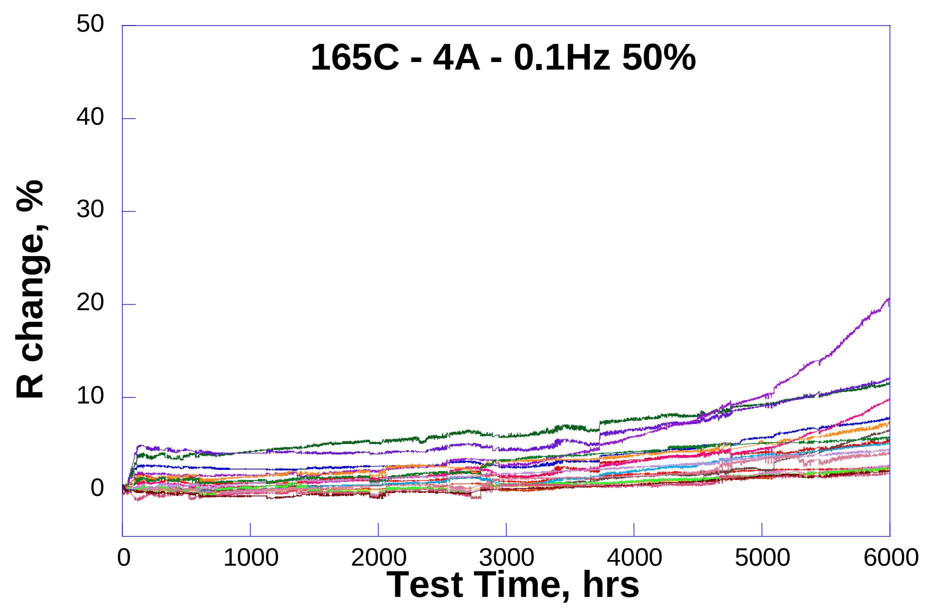
0.1 Hz

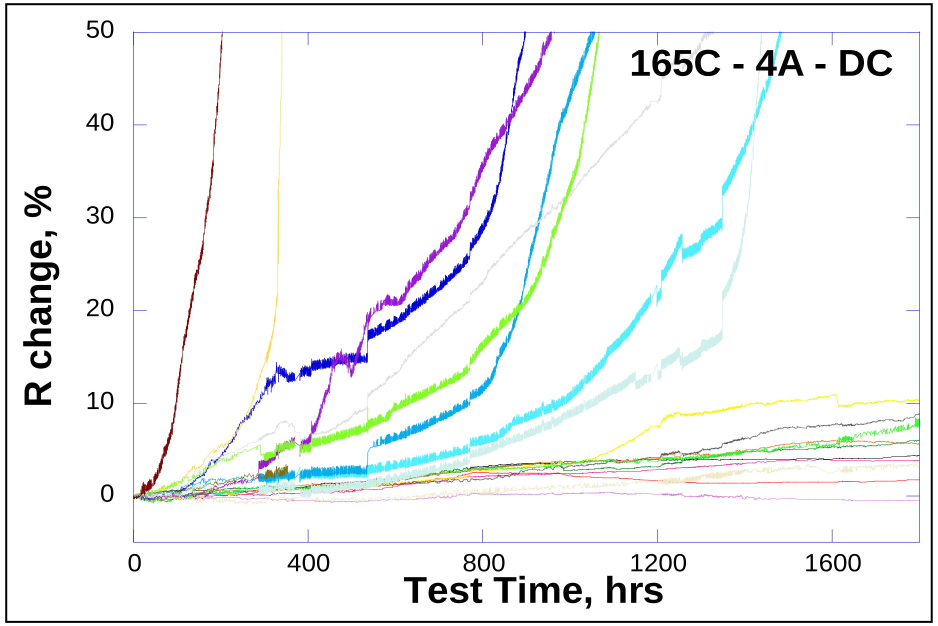


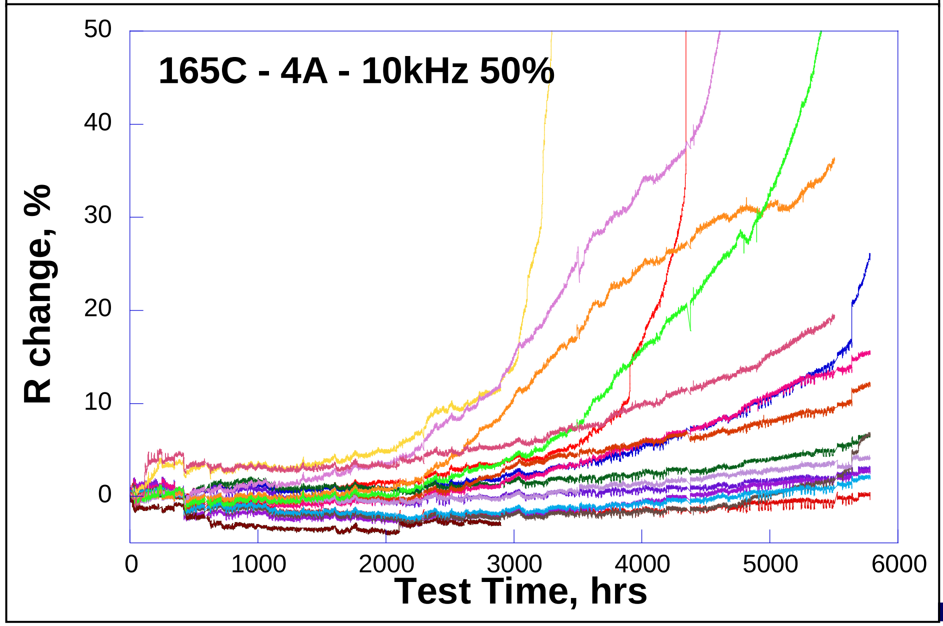
1000 Hz

Failure Behavior under AC-EM Conditions

- **Results are opposite to the expected**
  - *high frequency (10 kHz) fails faster than low frequency (0.1 Hz); true for both at DF=50 and 75%.*
  - Asymmetric AC (75% DF) fails faster than symmetric AC (50% DF).
  - DC fails the fastest

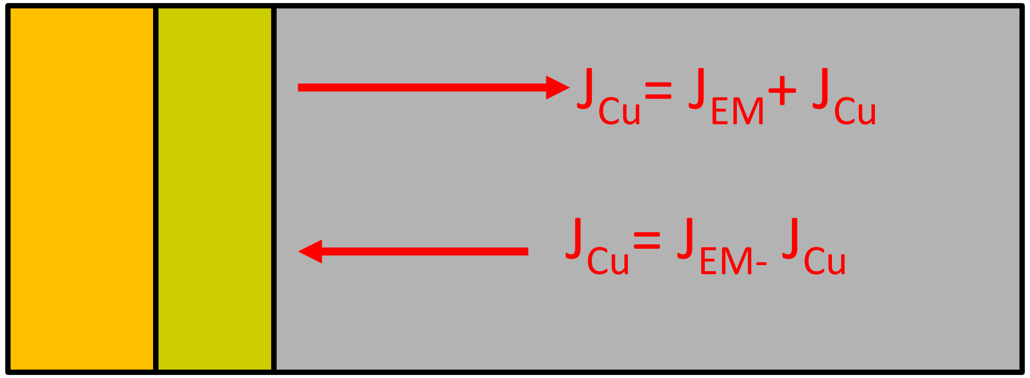


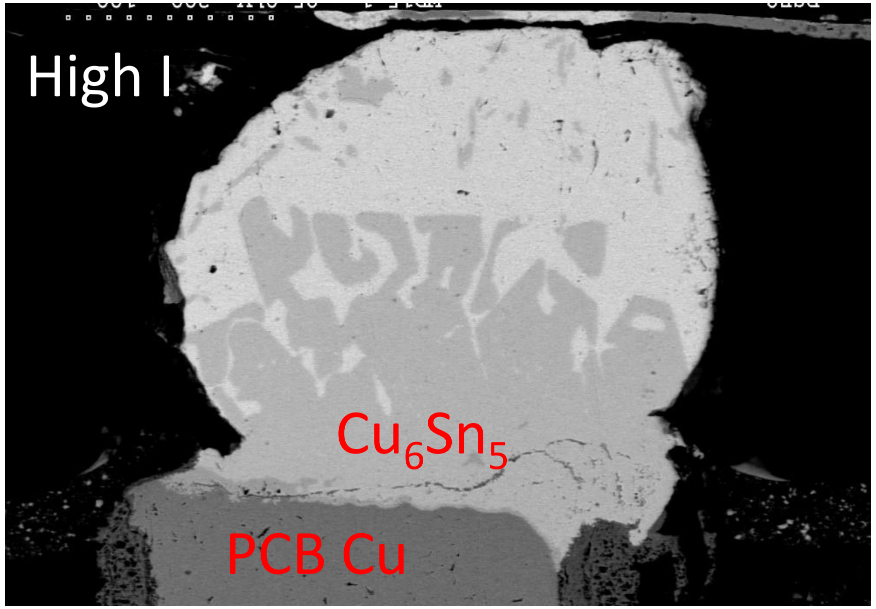


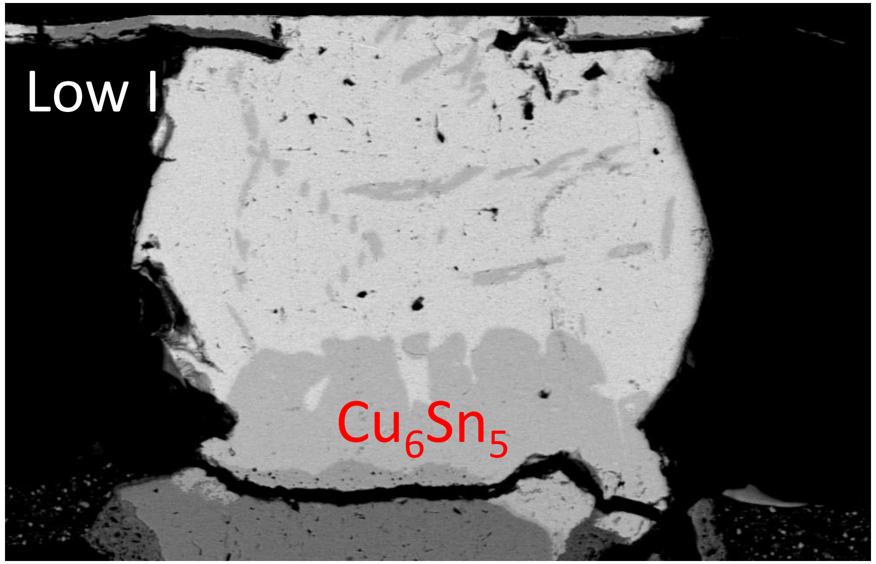


Microstructural Failure Mechanism under AC: 10KHz

- **Solder joint shows significant level of Cu injected into solder joint**
  - significant fraction of Sn-solder transformed into Cu_6Sn_5.
  - faster failure at high frequency is resulted by excessive growth Cu-Sn IMCs.
- **Cu EM at Cu/Sn interface is not reversible**
  - EM assists Cu dissolution but cannot reverse it.
  - EM in IMC and Cu is negligible







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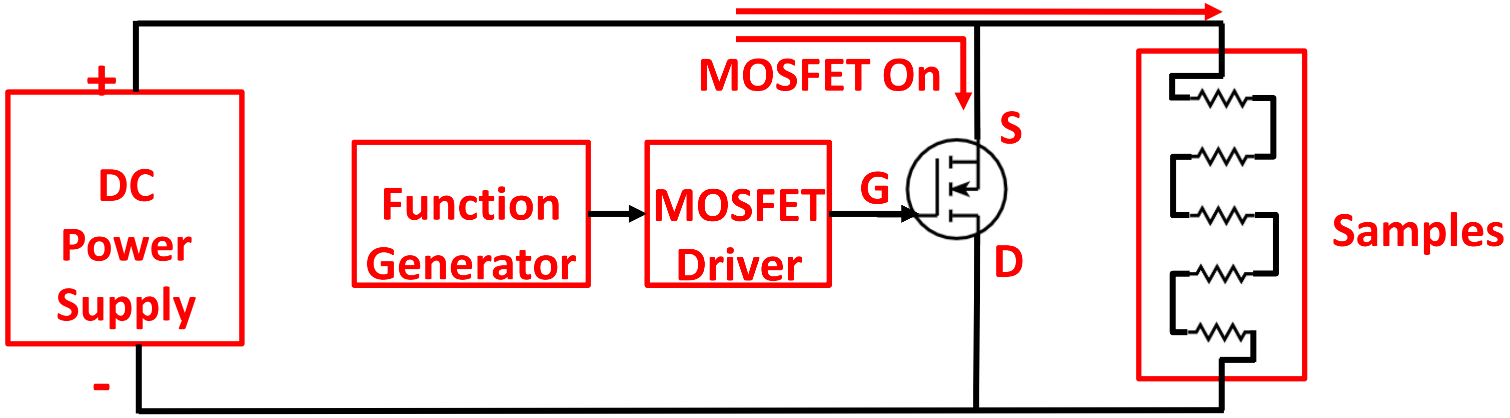
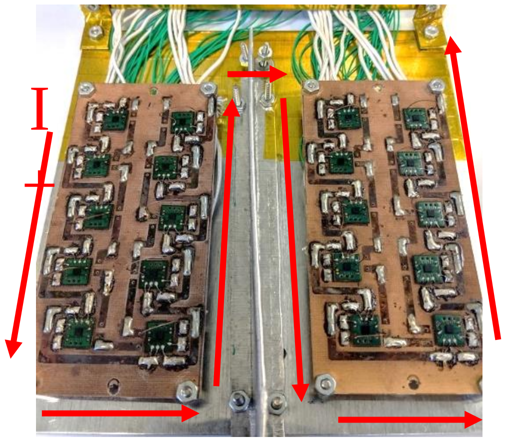
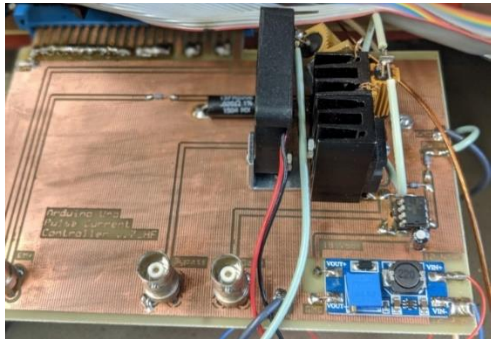
Pulsed DC EM Test: Circuit

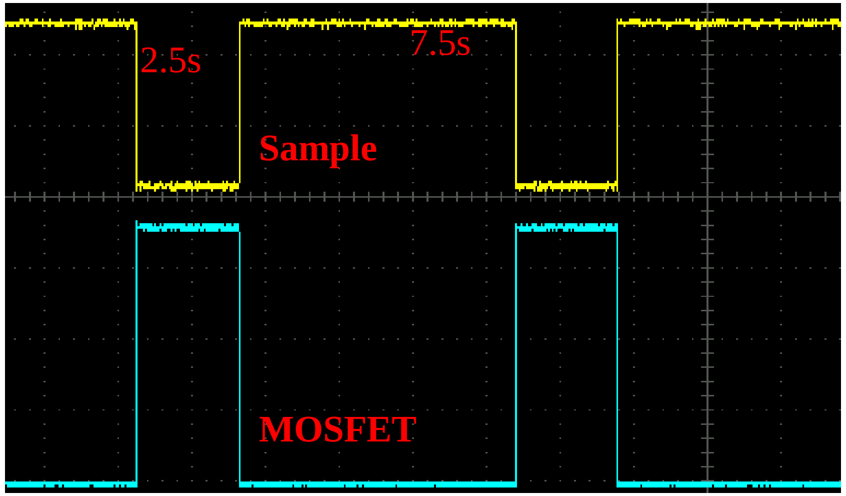
- **“Crowbar” circuit**
  - Function generator controls MOSFET driver
  - When MOSFET is closed, the test current bypasses samples
  - When MOSFET is opened, the test current to samples



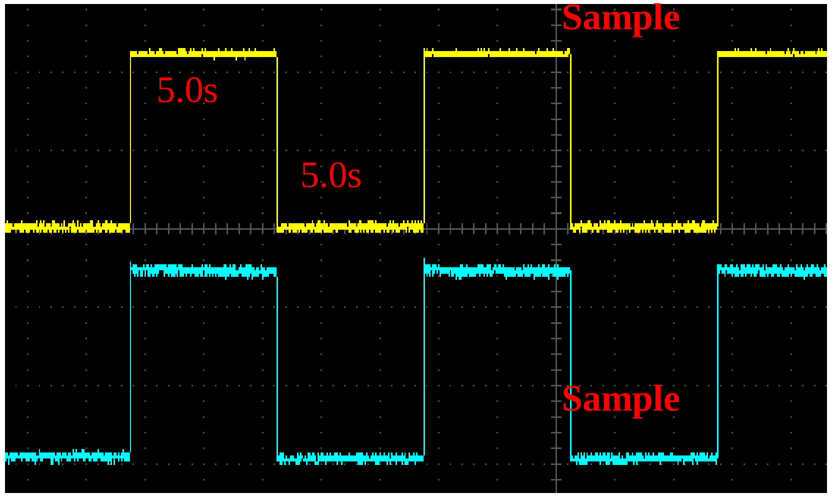


20 Samples
on testing boards





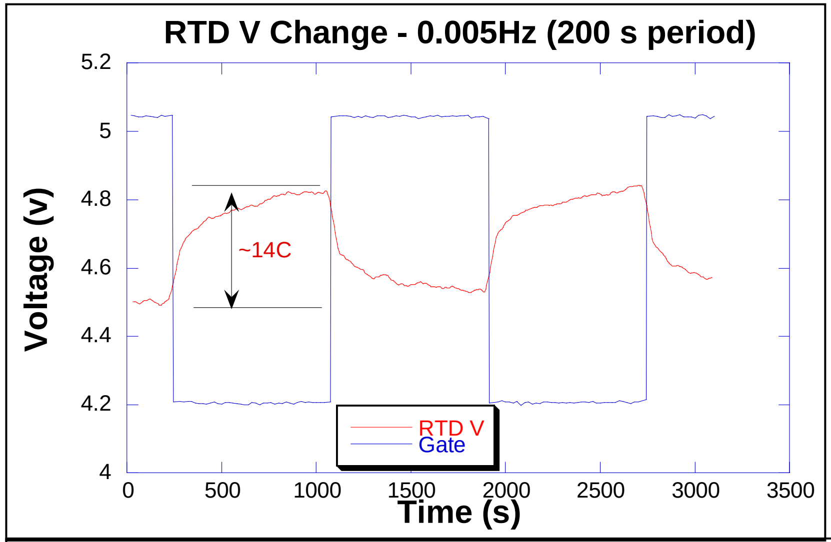
Pulsed DC at 0.1Hz 75% DF

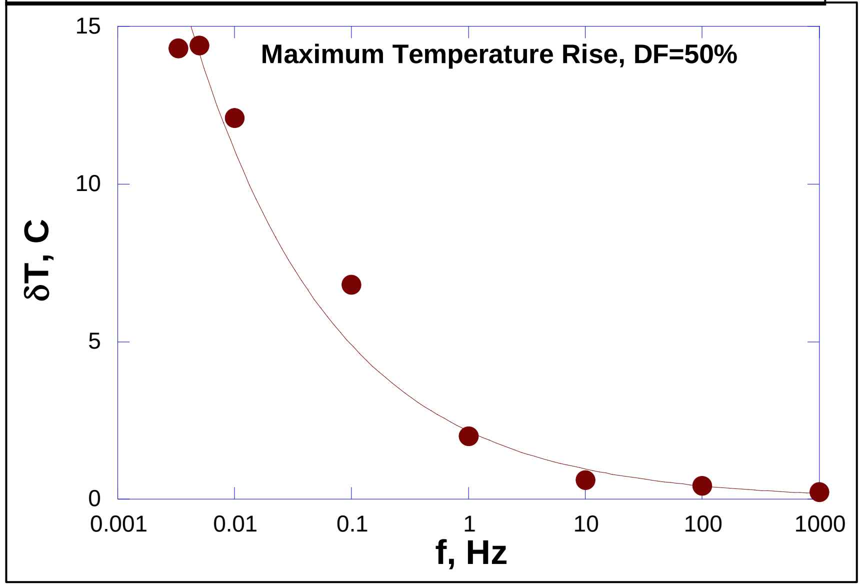


Pulsed DC at 0.1Hz 50% DF

Hidden But Key Factor: Temperature

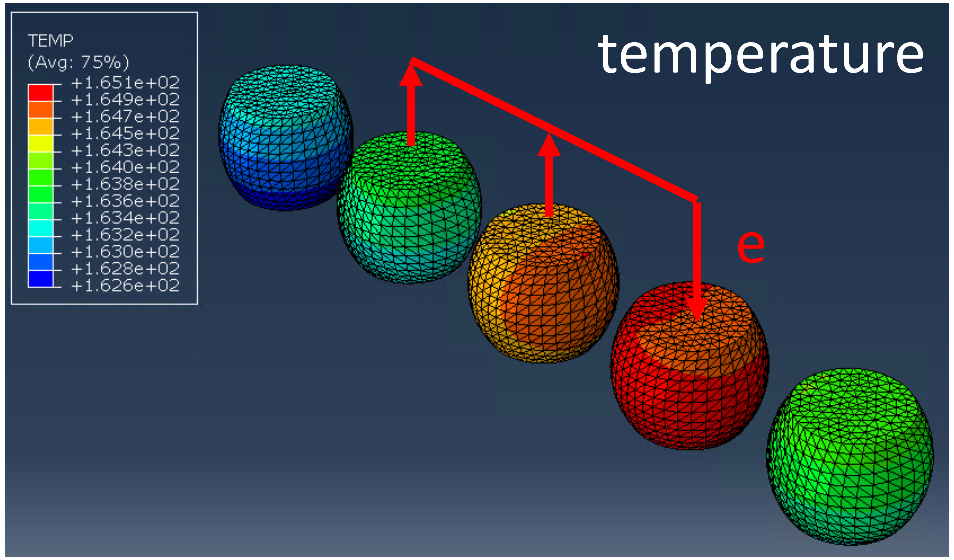
- **Measure at various PDC frequency using RTD**
  - Temperature change plateaus around 0.005 Hz (200s period) at 14 °C
  - 7°C change at 0.1Hz
- **DUT Temperature dependence on frequency**
  - T is low and constant at high frequency (>100Hz)
  - T pulsates along with pulsing current (<100Hz)
- **Pulsating temperature will impact failure**
  - Thermal stress becomes a factor
  - The failure may be assisted by the thermal fatigue

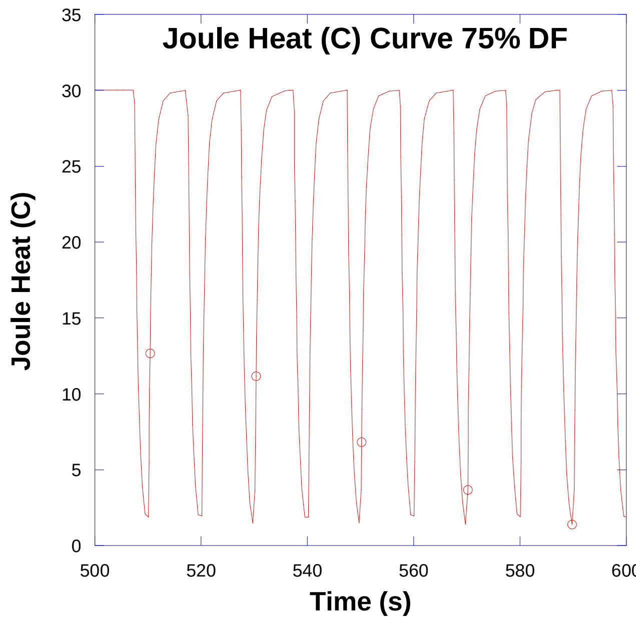


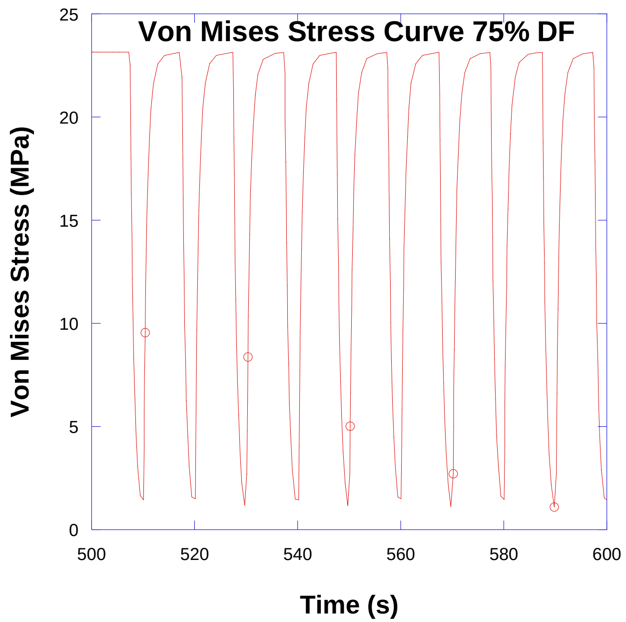


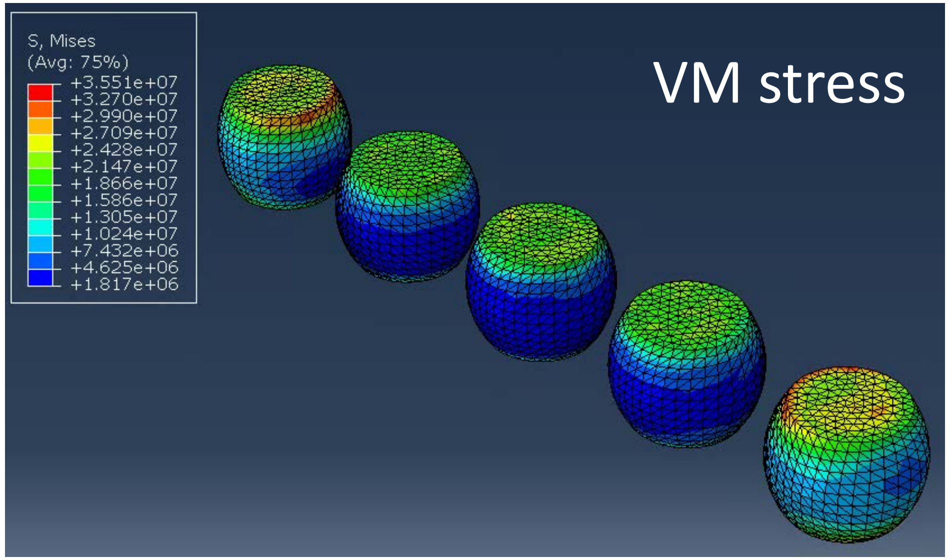
Source of Thermal Stress

- **Difference in Joule heat (JH) (resulting T difference) induces compressive stress on DUT and tension on surroundings**
  - DUT is subjected to higher local JH than the surroundings
  - Higher local JH on DUT causes larger expansion than supporting bumps do, resulting in compression on DUT and tension on surroundings







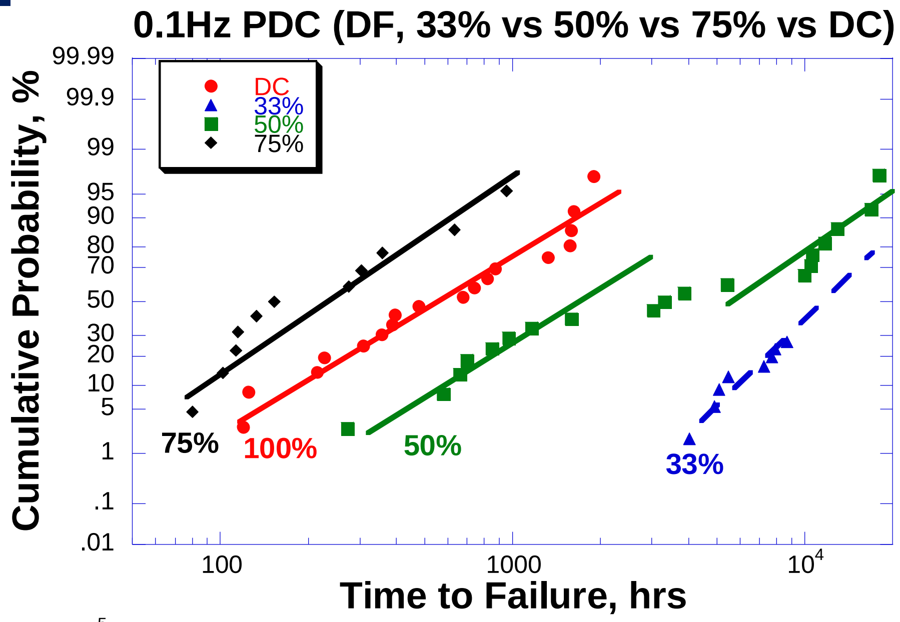


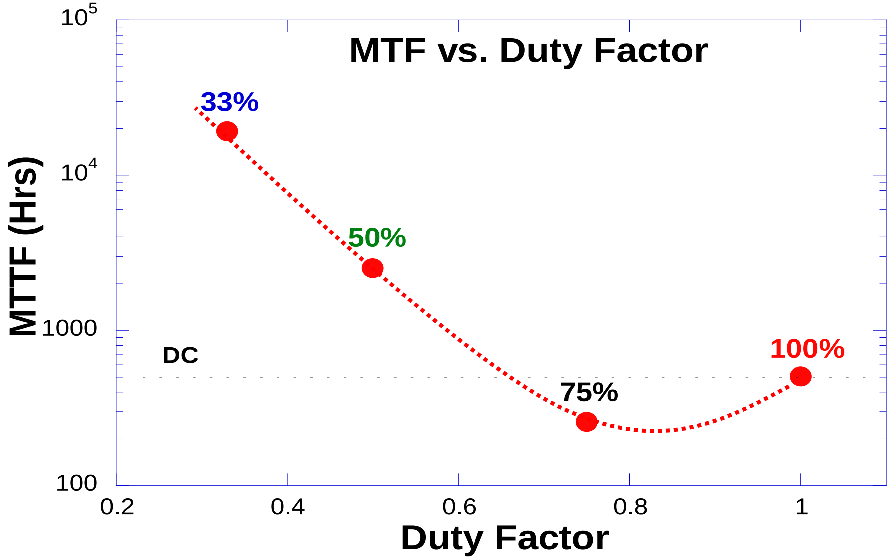
Failure Behavior at Pulsed EM Conditions

- **At f>10kHz: different from the expected**
  - Failure rate is excessively slow (unable to induce failure even after 10k hours at 50% DF.
  - 14C lower DUT temperature may provide partial explanation
  - T_{on}~To_{ff} may allow more active damage relaxation.

- **At f=0.1Hz: different from the expected**
  - 75% DF produces more damage than DC
  - Reduction in DF makes failure rate to be exponentially delayed. (the reduction is again more than T effect)

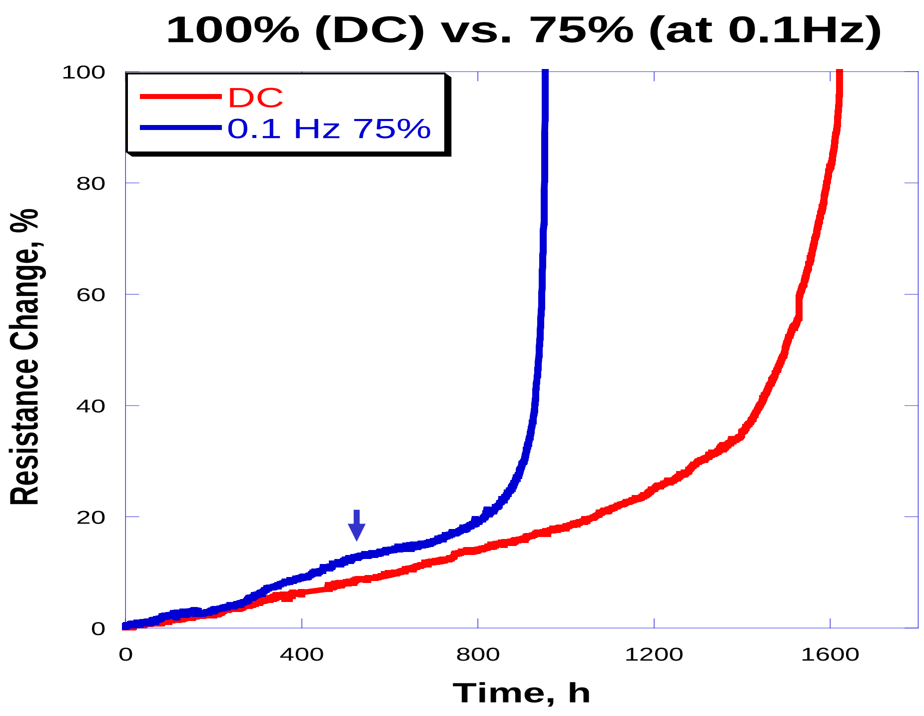
- **Kinetics does not follow the Black's model**

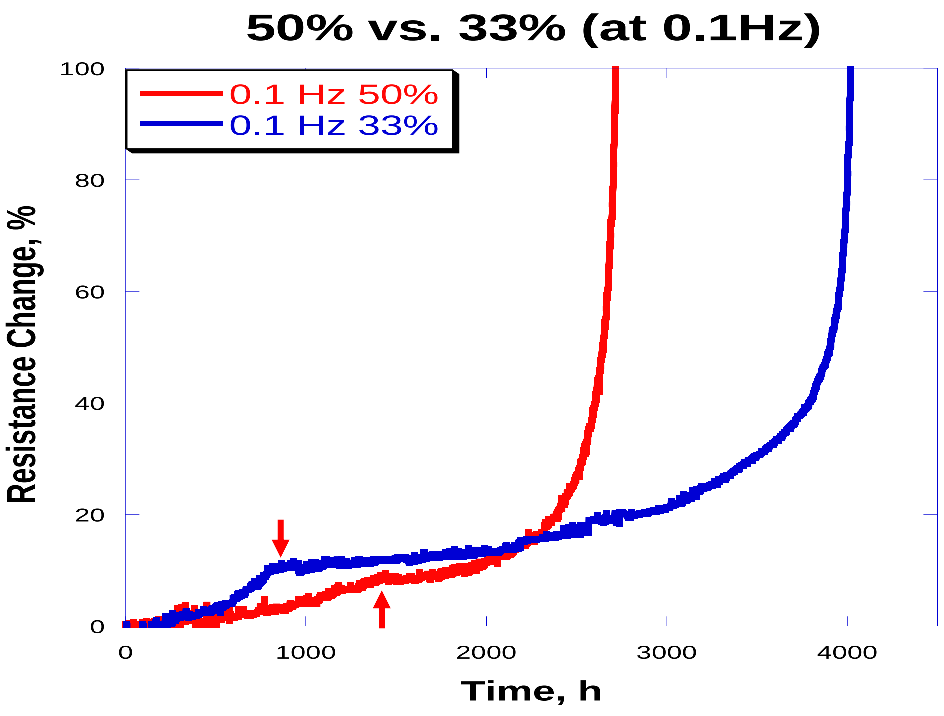




EM Failure Signal under Pulsed-DC Load

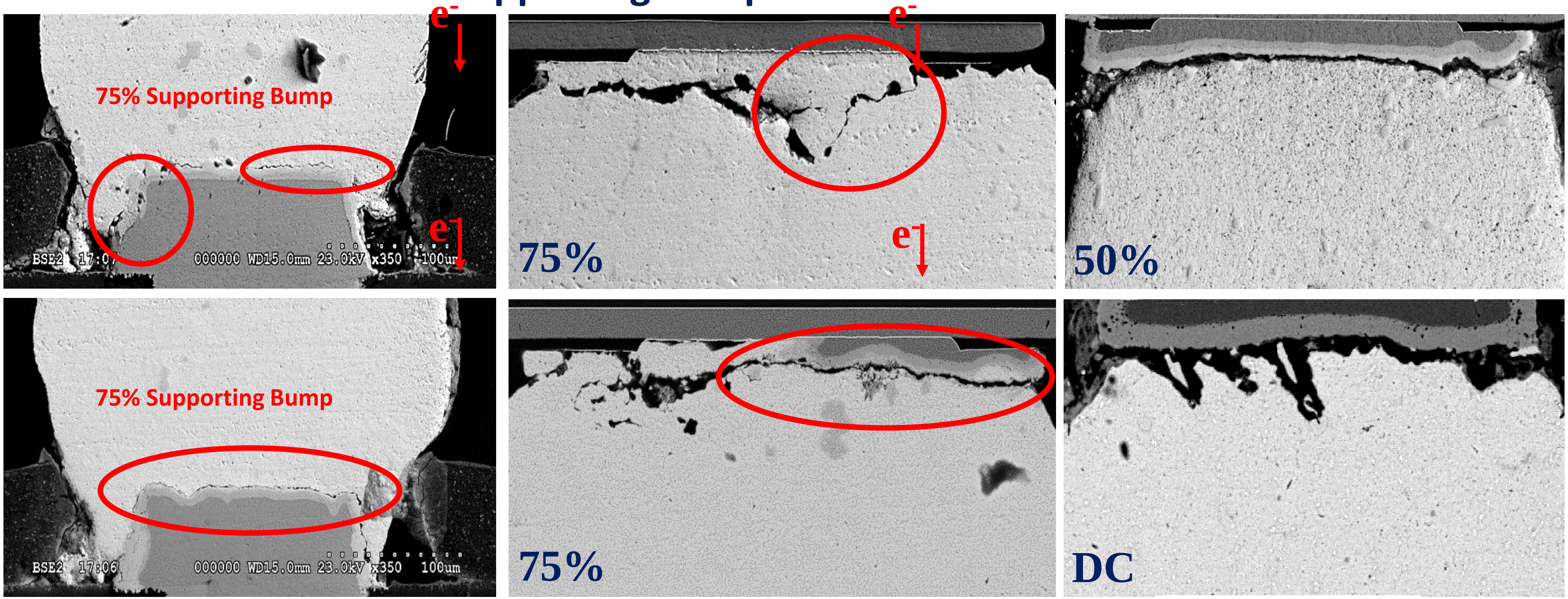
- **Failure Signal**
  - Resistance change shows 2 stage EM failure development under pulsed DC
  - The first stage induces more damages but the failure slows down at the second stage.
  - The transition to second stage occurs faster at low DF.





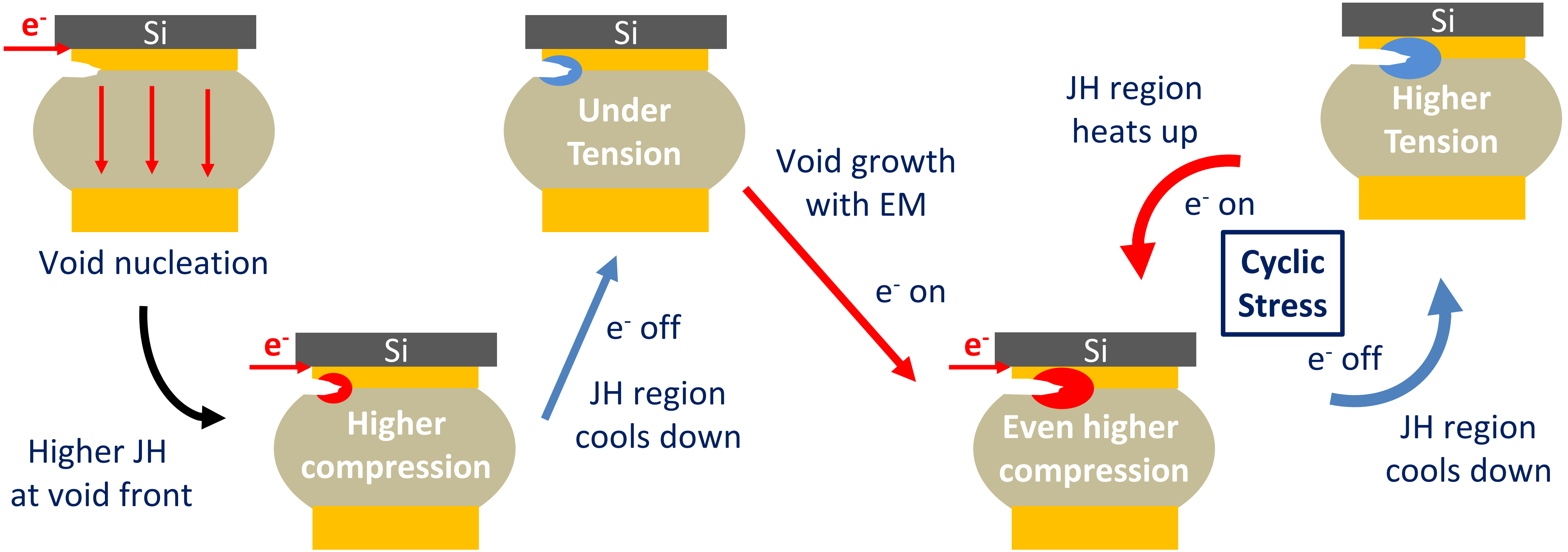
Cracking Assisted EM Failure under PDC

- **Narrow crack through Sn in 75% DF suggest involvement of mechanical fatigue**
  - Not conventional EM failure mechanism
  - Evidence that the thermal fatigue affects the failure w/ pulsating temperature.
- **Crack also exists at the supporting bumps**



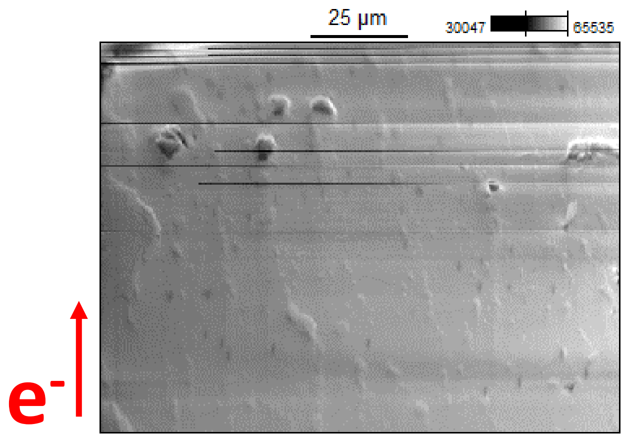
Failure Acceleration by Thermal Fatigue

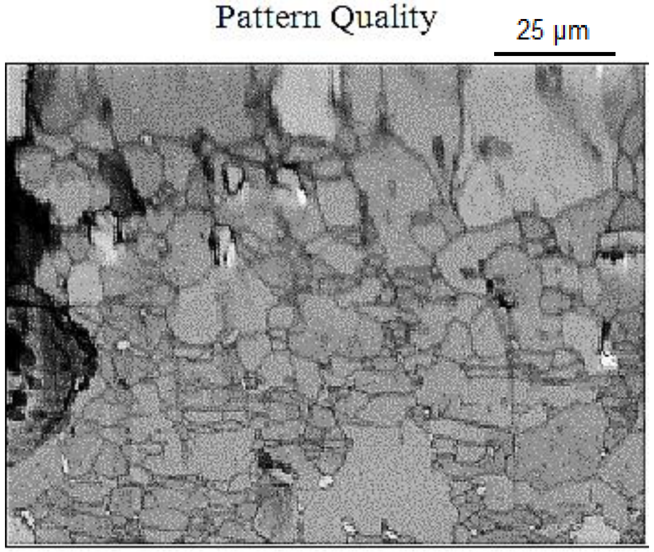
- **Thermal Fatigue + EM under pulsed DC**
  - Most notable at DF=75%
  - Conventional EM voiding combines with mechanical fatigue from thermal fluctuation
  - When stress fluctuation exceeds the yield strength, plastic deformation occurs, activating fatigue

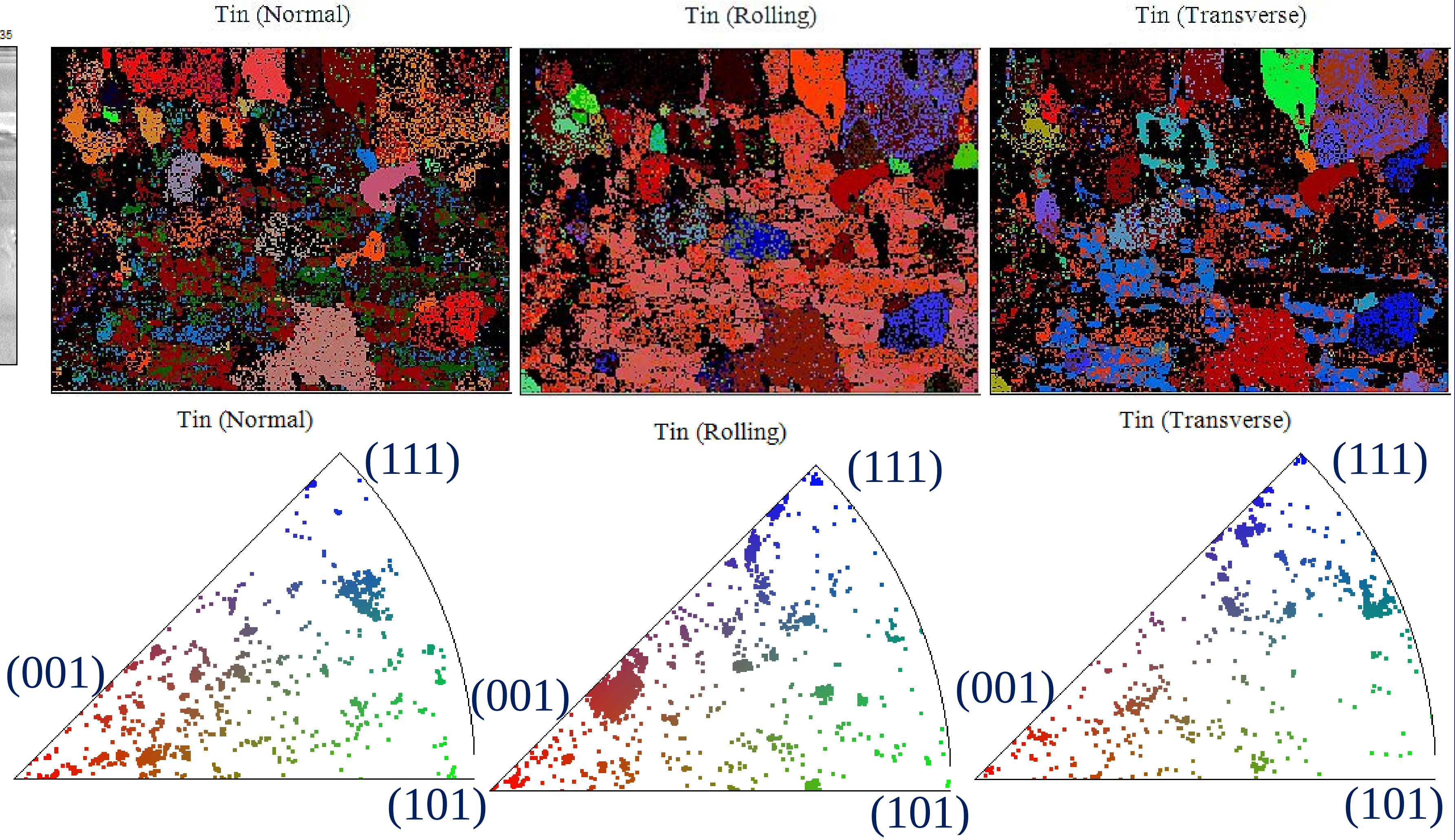


Failure Deceleration by Recrystallization

- **Fine grain boundaries indicate a recrystallization of solder bump, removing fast EM path in Sn grain.**

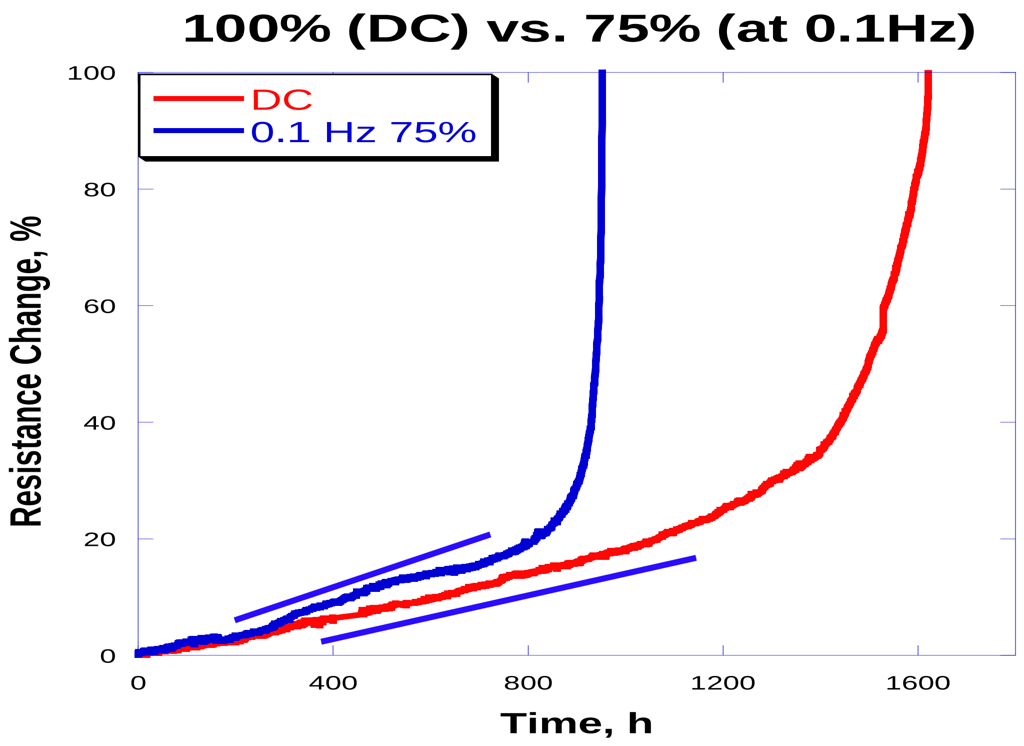


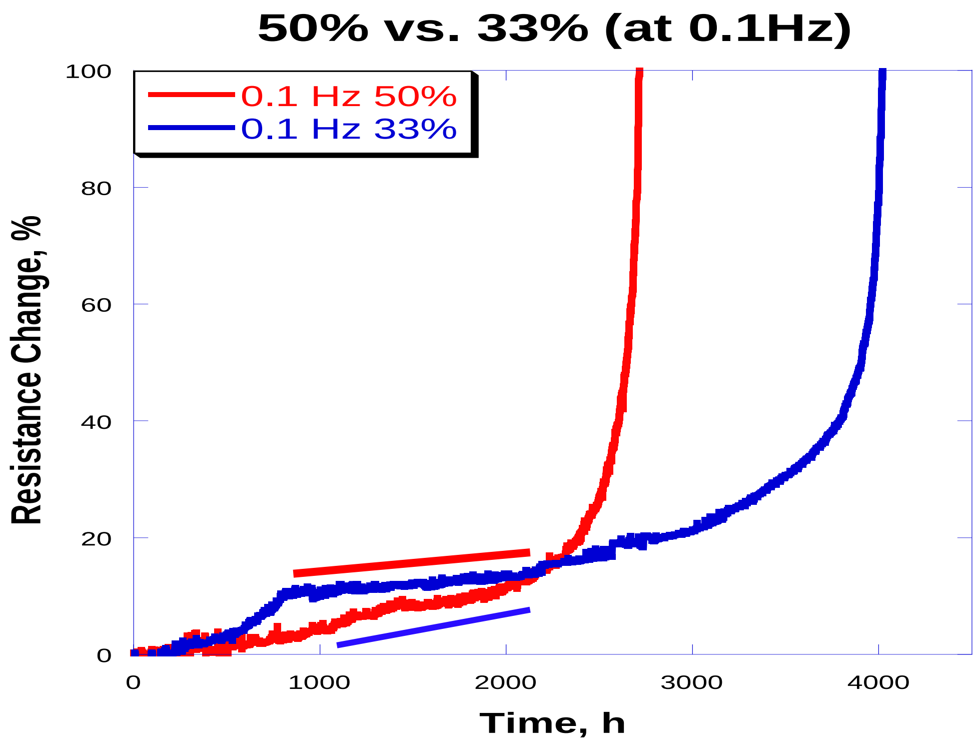




Overall Failure Mechanism at Low Frequency

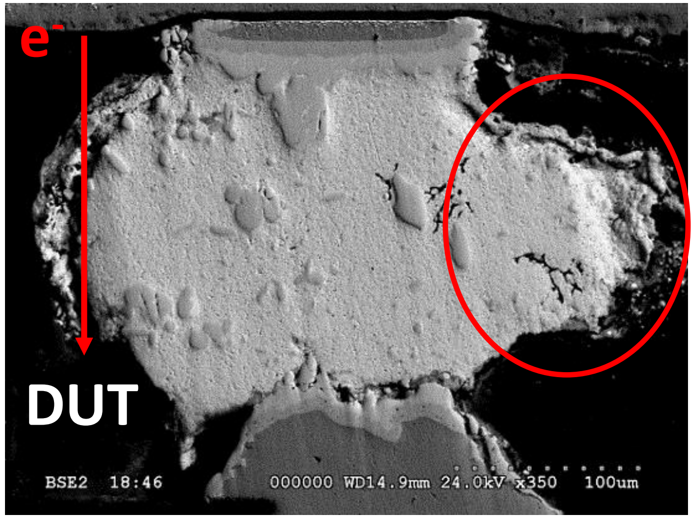
- **Two mechanisms in competition**
  - Failure acceleration: thermal fatigue (more intense at high DF)
  - Failure suppression: recrystallization (more intense at low DF)

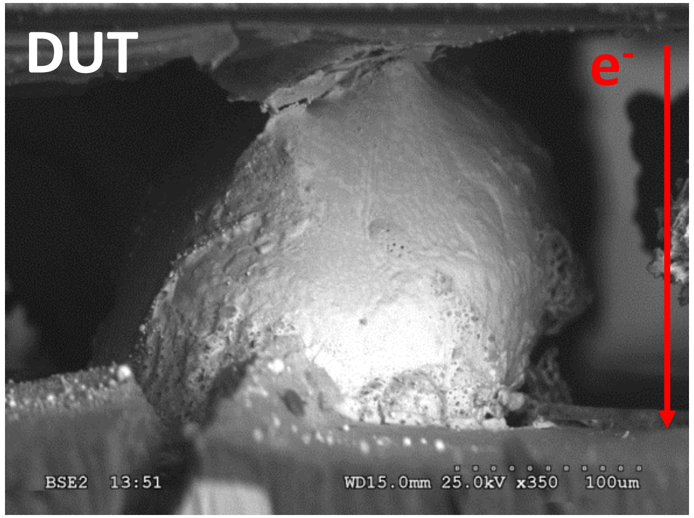


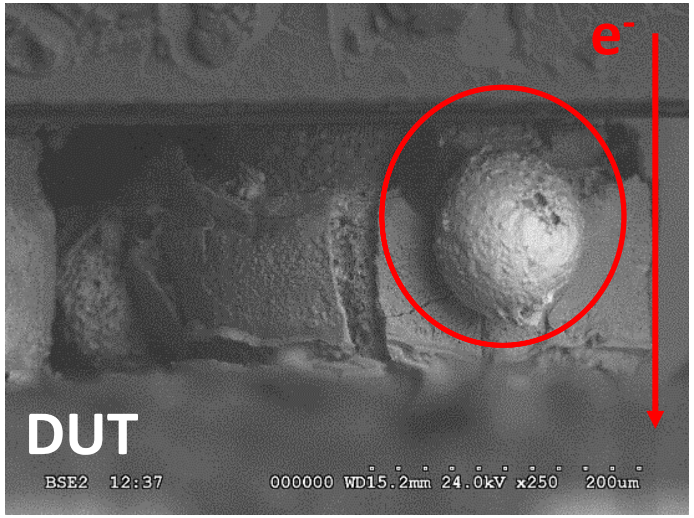


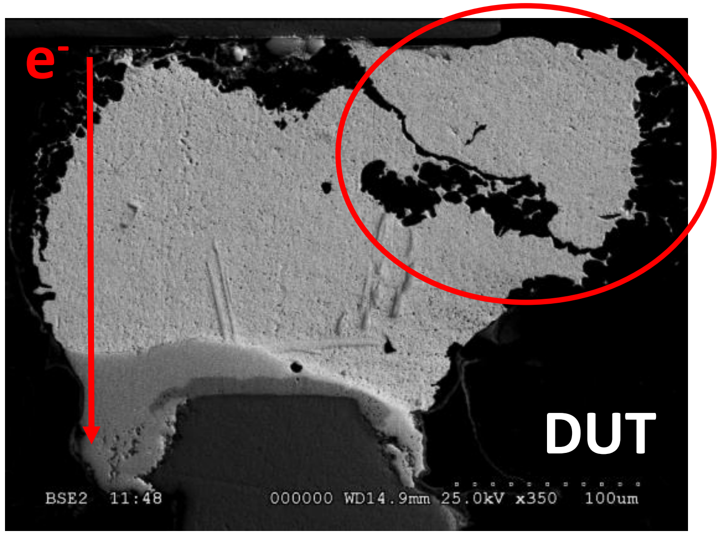
New Failure Mechanism by Superplasticity

- **Superplasticity**
  - Extrusion of solder mass driven by uneven compressive stress
  - Excessive extrusion becomes possible due to superplastic of solder
  - Solder becomes superplastic by dynamic recrystallization effectively removing work hardening of solder
  - Unusual to see this level of deformation because Sn is BCT



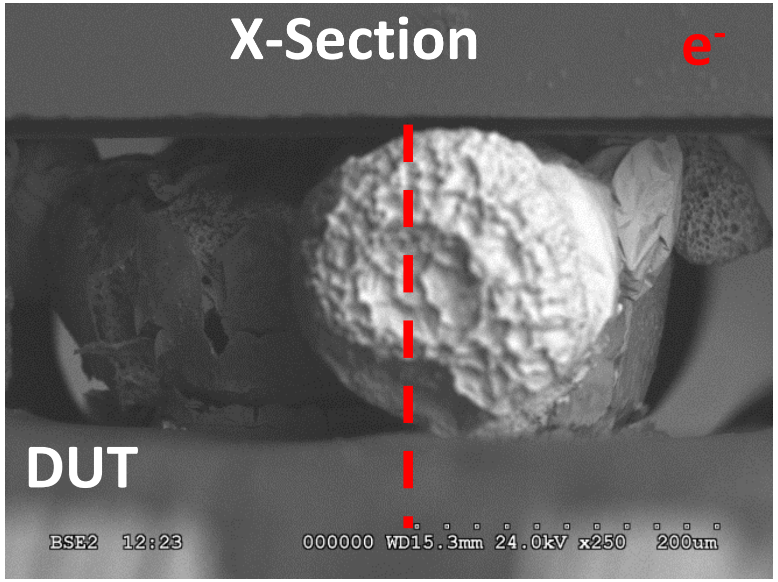


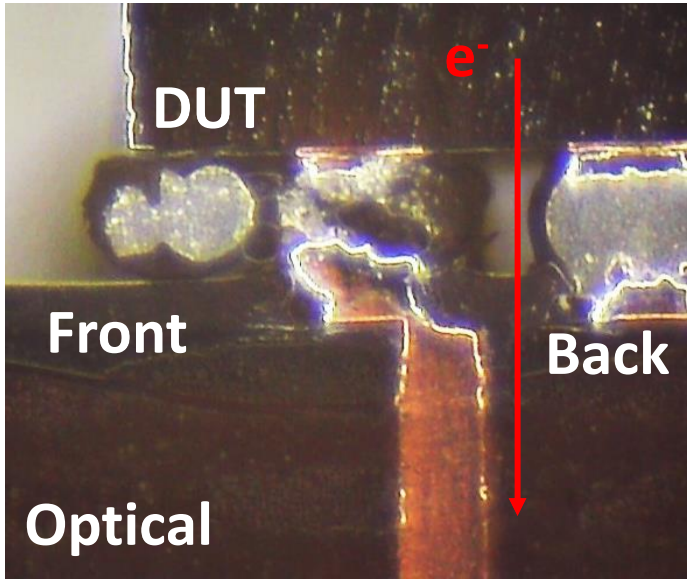


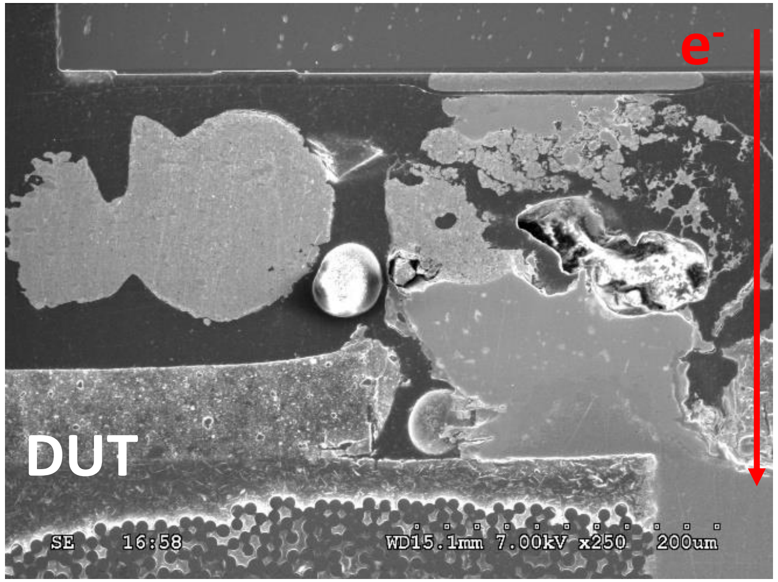


Ratcheting Failure by Extrusion of Solder

- **Sn gets extruded due to uneven stress**
  - Evidences the thermal stress and superplasticity of solder
  - Danger of a short circuit







Summary Experimental Observations

- **Generally understood EM failure mechanism in is not valid for pulsed DC**
  - Stress and its pulsation affects the failure rate and failure mechanisms
  - Thermal fatigue can be included in the failure process at low frequency.
  - Recrystallization is also possible at low frequency.
  - Ratcheting failure is possible only with solder being superplastic
  - High frequency testing may bring new surprises (testing is in progress).

- **Irreversible reaction of Cu at Cu/solder interface dictates the failure rate**
  - Unlike expectation, EM failure does occur and can be serious reliability issue.
  - Damage starts as a format of extensive growth of IMC growth.
  - Damage repair is not as effective as is seen in thin film interconnects.
  - Needs more studies for better understanding.

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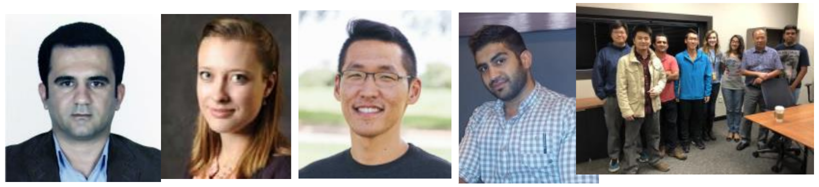

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