Understanding Whisker Phenomenon:
Driving Force for Whisker Formation

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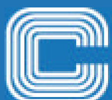
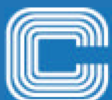
* Part of this work was carried out at Lucent

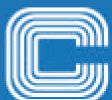


Outline

- Whisker Background
- Whisker Program
  - Phase I, whisker test
  - Phase II, whisker growth rate and whisker growth mechanisms
- Conclusions and Recommendations

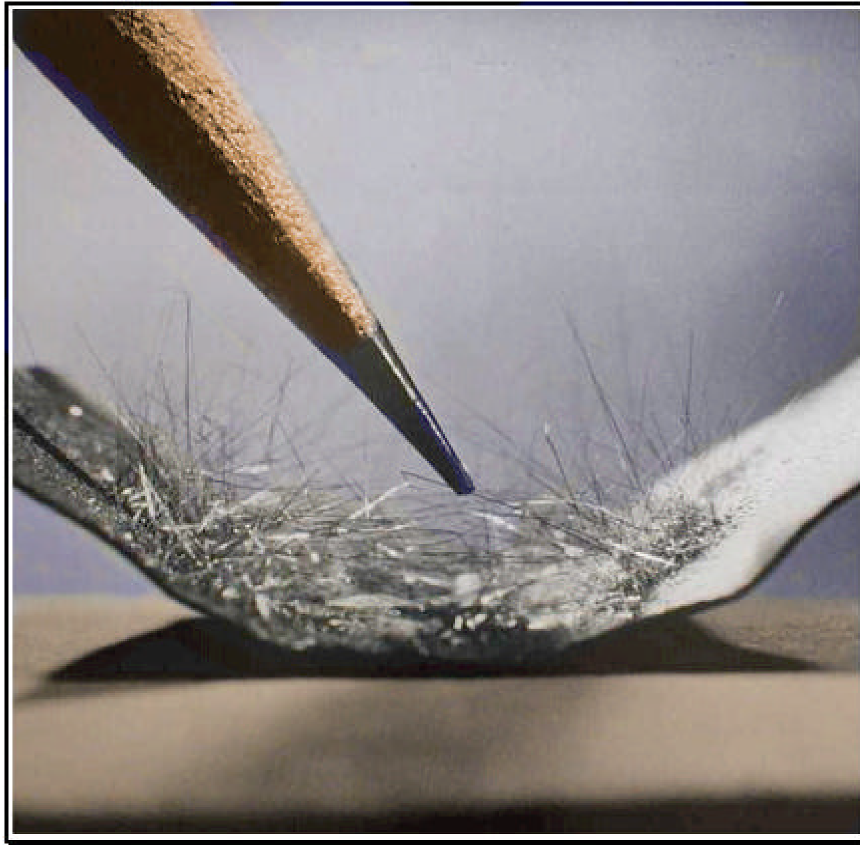


FINISH	ADVANTAGES	CONCERNS/ISSUES
Sn 232 °C	Most cost effective Compatible with soldering alloy Simple process control	Whisker formation
Sn(2-5)Bi 220 – 225 °C	Compatible with soldering alloy Melting point lower	Whisker formation Immersion plating Alloy control & measurement
Sn3.5Ag 221 °C	Compatible with soldering alloy Melting point lower	Whisker formation Very narrow process window Cost increase Environmental issue with Ag
Sn(0.7-1.5)Cu 227 - 270 °C	Compatible with soldering alloy Melting point lower	Whisker formation Immersion plating Accelerated Sn(II) oxidation

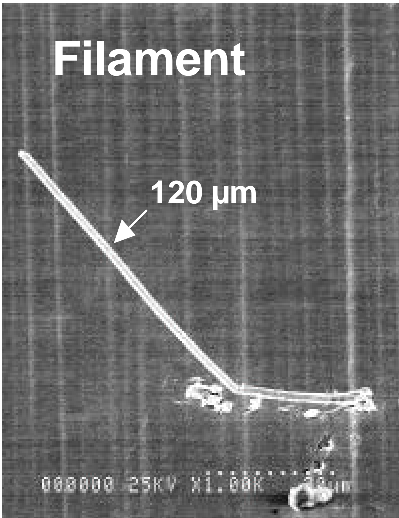


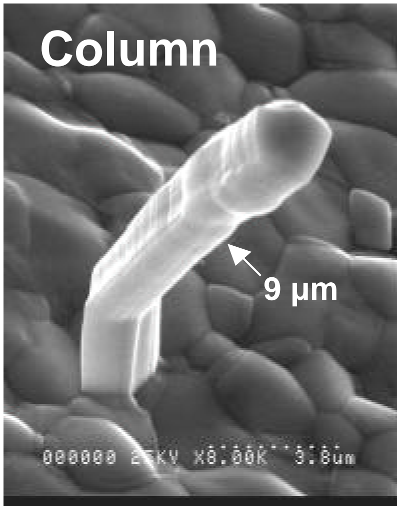
Lead-Free Implementation Barrier

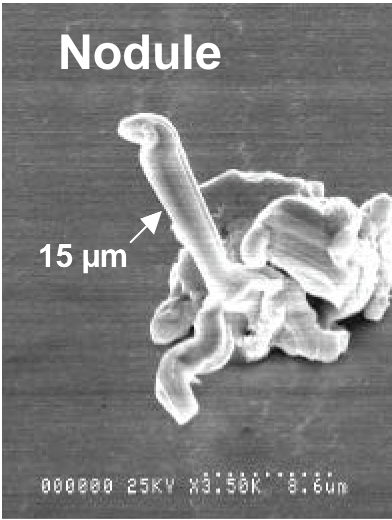
Spontaneous Whisker Growth!

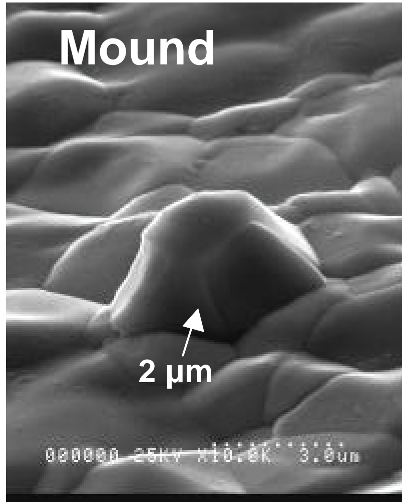


Tin Whiskers





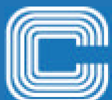




Whisker Program

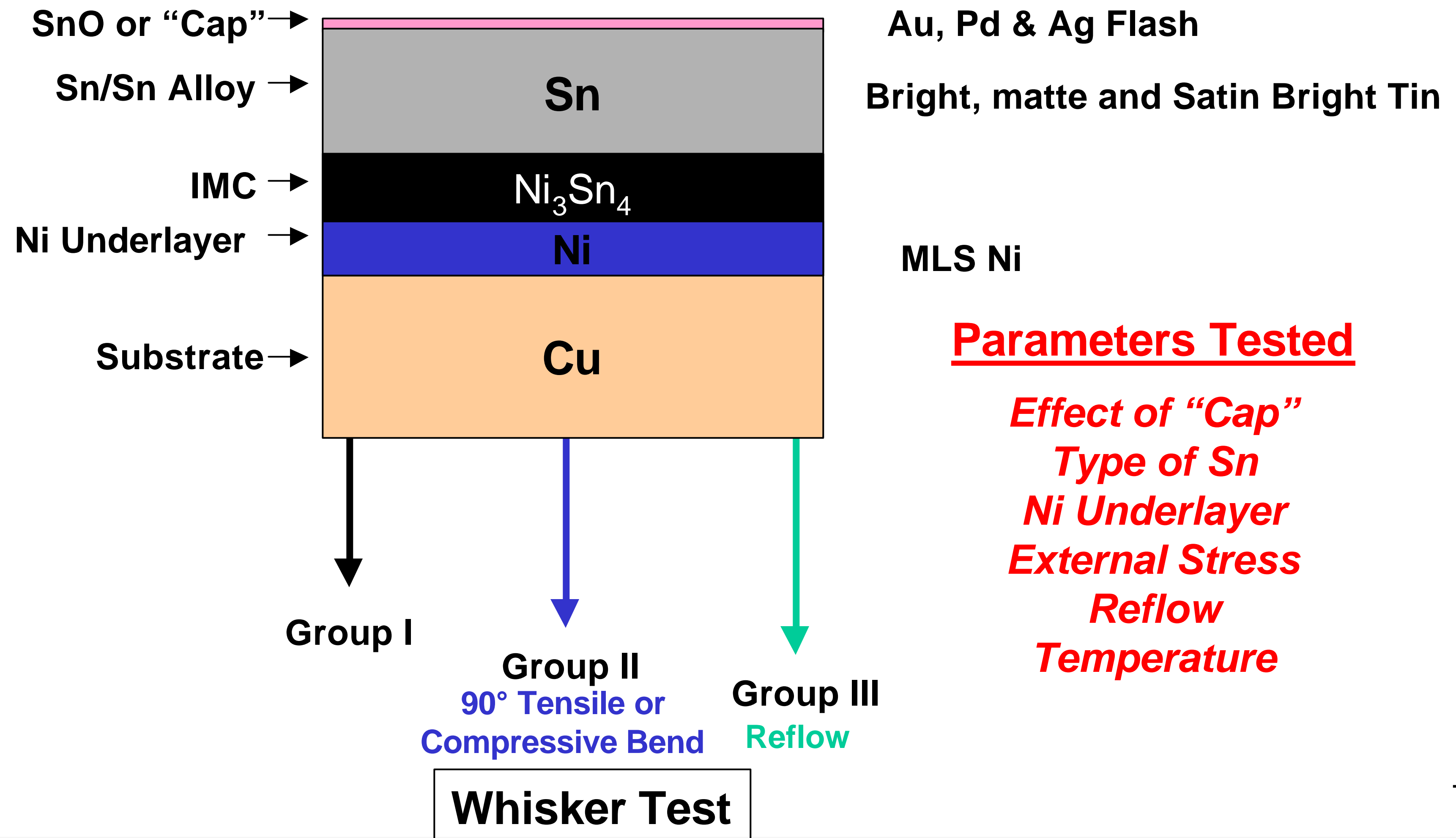
Understanding the Whisker Growth Phenomenon

- Previous Results - Phase I
  - Established a reliable whisker test
    - 50°C, dry heat
    - Office Condition
    - Thermal Cycling
  - Investigated the relative importance of several factors
    - Grain size & shape, carbon content
    - External mechanical bending
    - Temperature & humidity
- Current Work - Phase II
  - Whisker growth rate
  - Whisker growth mechanisms



Phase II & III

Test Matrix



Method of SEM Observation

2 mm

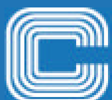
Bent area, stressed

Flat area, not stressed

1 inch

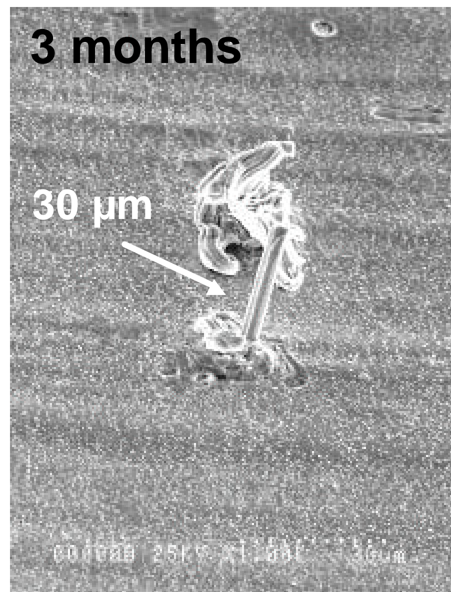
2.5 inches

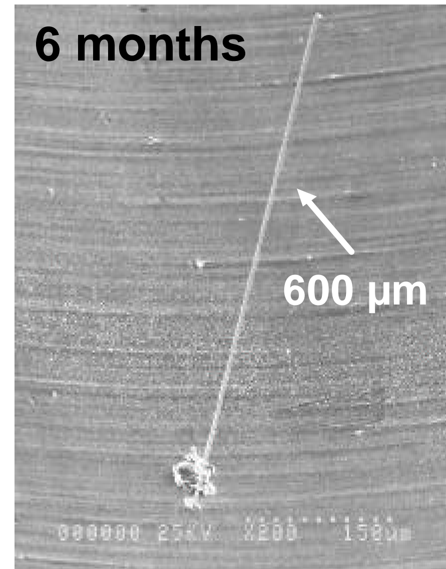
Area of examination: 0.5 mm x 27.4 mm
Four magnifications: 500X, 1K, 5K & 10K

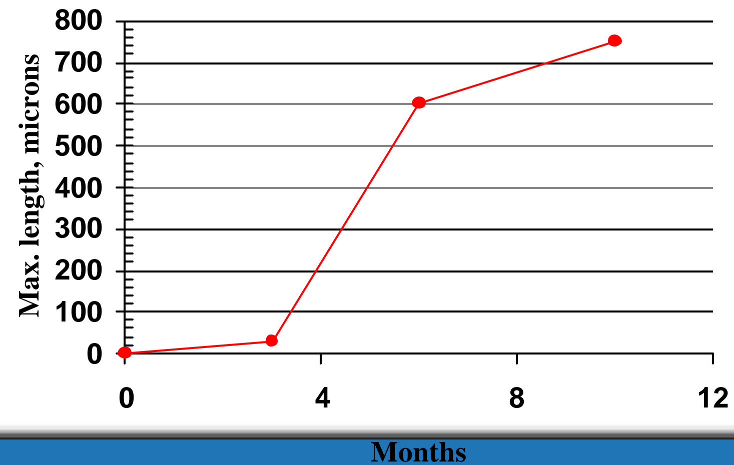


Maximum Length Measurement

Bright Tin

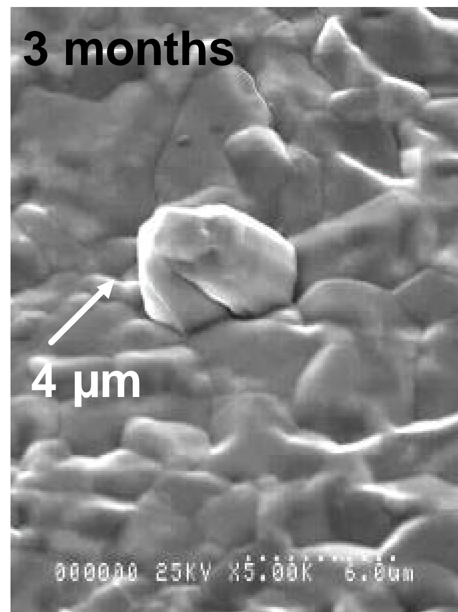


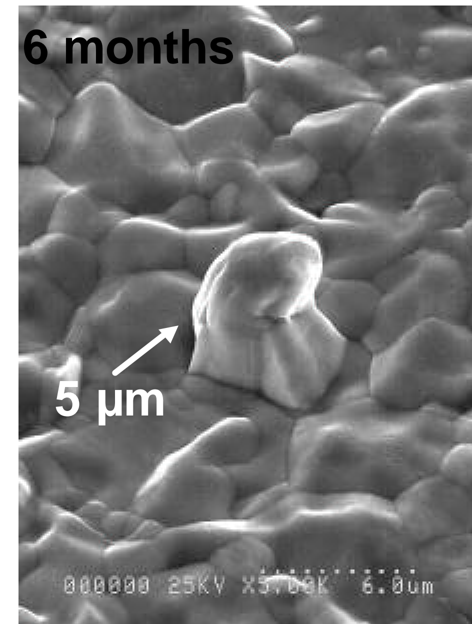


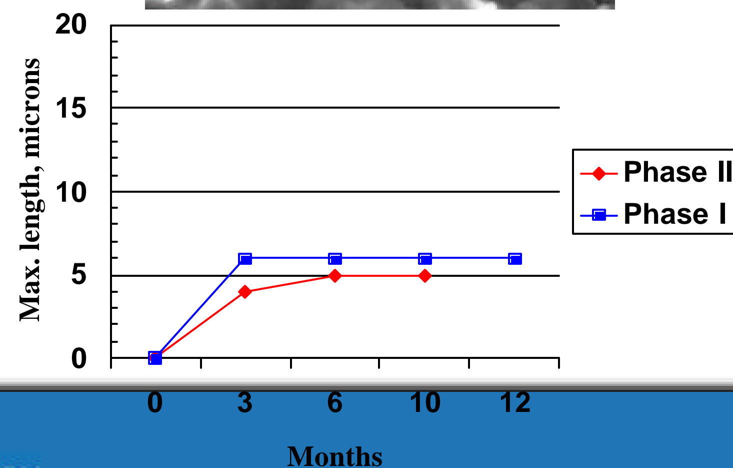


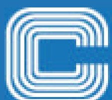
Maximum Length Measurement

Satin Bright Tin









Whisker Index

Measure for Whisker Propensity

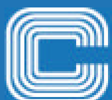
$$WI = S\ n*d*L*f(L)$$

n: number

L: length

d: diameter

f: weight factor on length, L

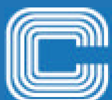


Whisker Index

Relationship between factor f and whisker length

$$WI = S\ n*d*L*f(L)$$

Length, µm	Weight Factor, f(L)
< 1	0
1 – 5	1
5 – 10	5
10 – 50	50
> 50	500



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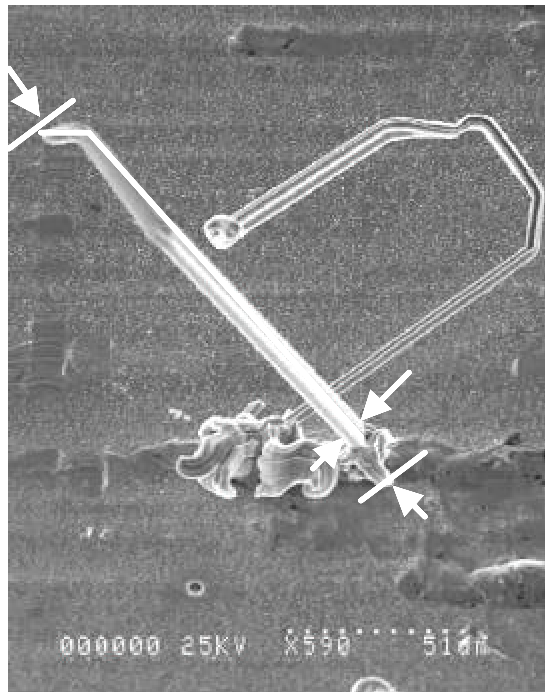
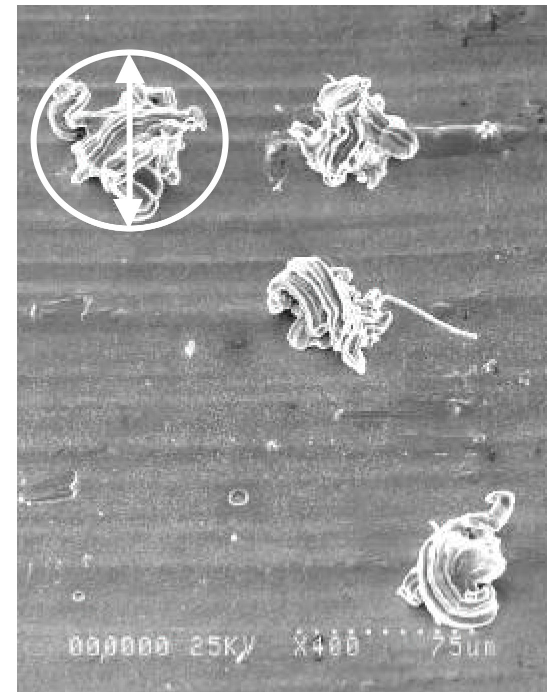
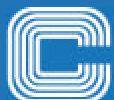
Categorization in Measurement

Bright Tin

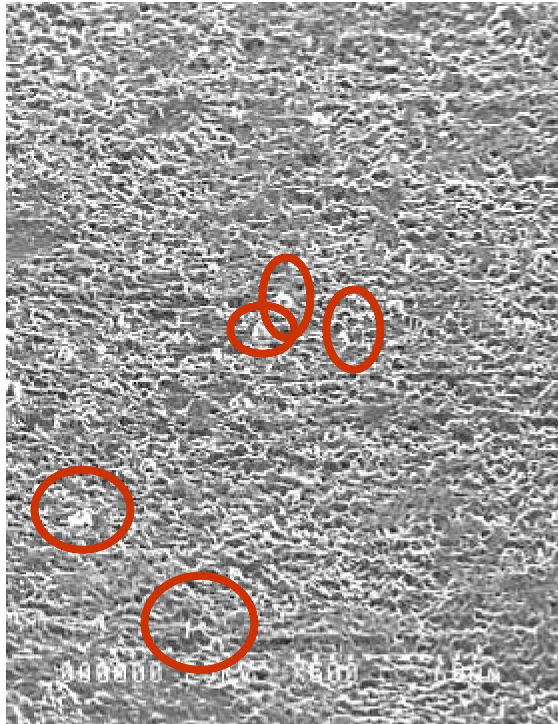


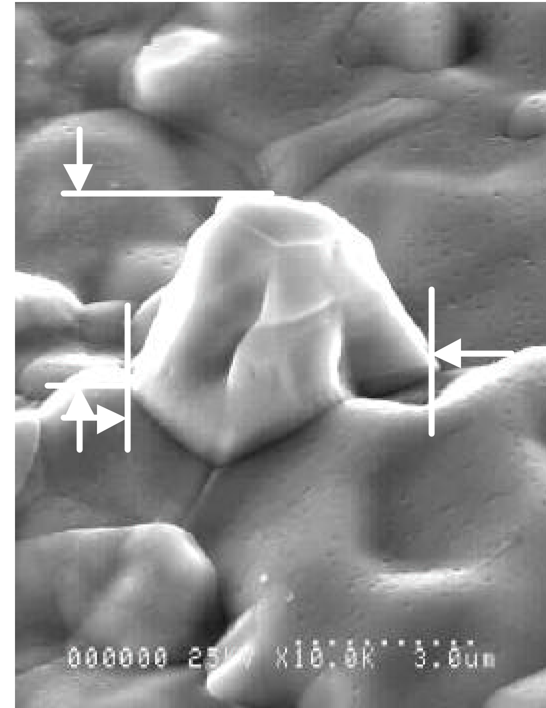




Categorization in Measurement

Satin Bright Tin





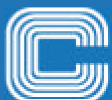
Total number: 5

Whisker Index

|--------------Whisker Index-------------|

FINISH	4 MONTHS	6 MONTHS	10 MONTHS	LONGEST*
Bright	279	13,000	63,400	600
Bright + Tensile	244	2,800	45,200	350
Bright + Compressive	3850	13,500	193,000	750
Satin Bright	3.2	10.5	10	5
Satin Bright + Compressive	30	22	40	5
Satin Bright 90/10	4.1	8.6	907	10
Satin Bright / Reflow	2.1	4.0	8.9	4
Satin Bright / Ni	0.2	0	0	3

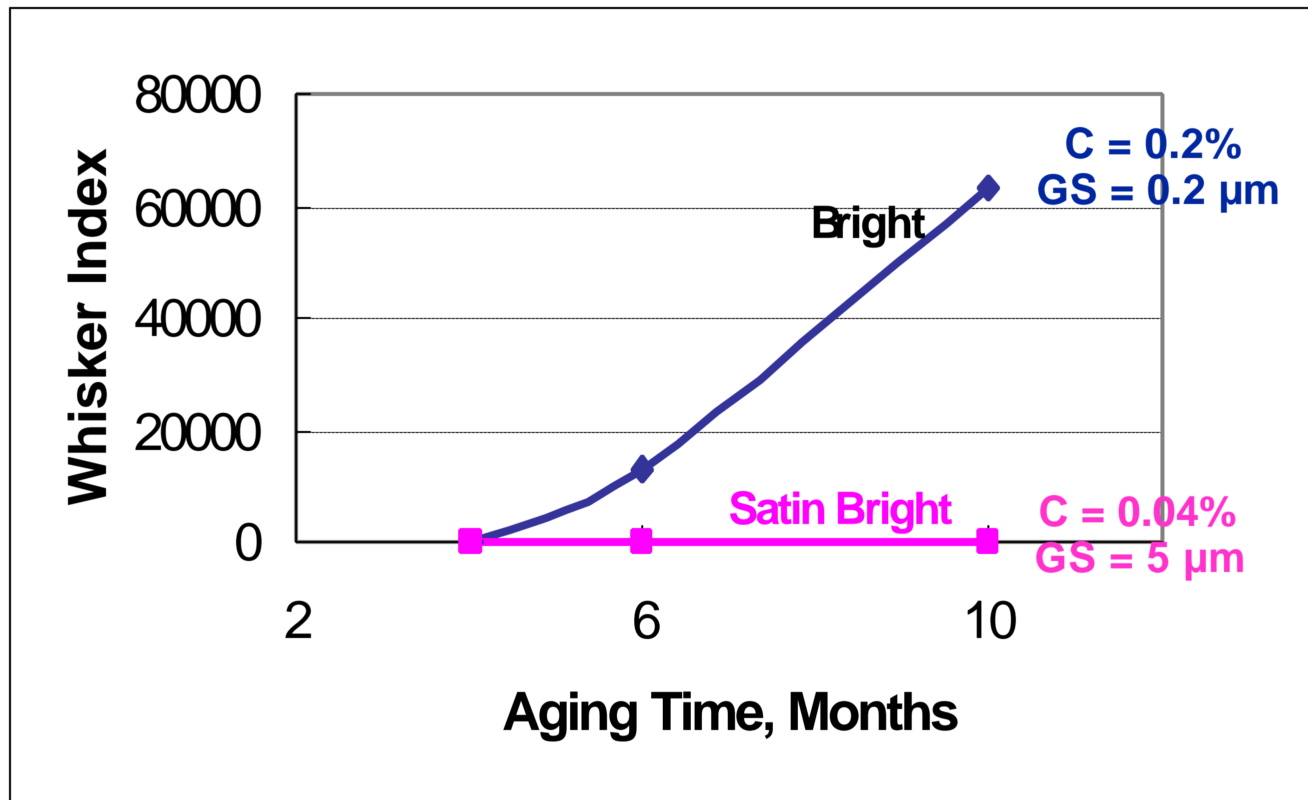
*** Longest whisker (µm) observed up to 10 months**



Whisker Propensity of Different Finishes

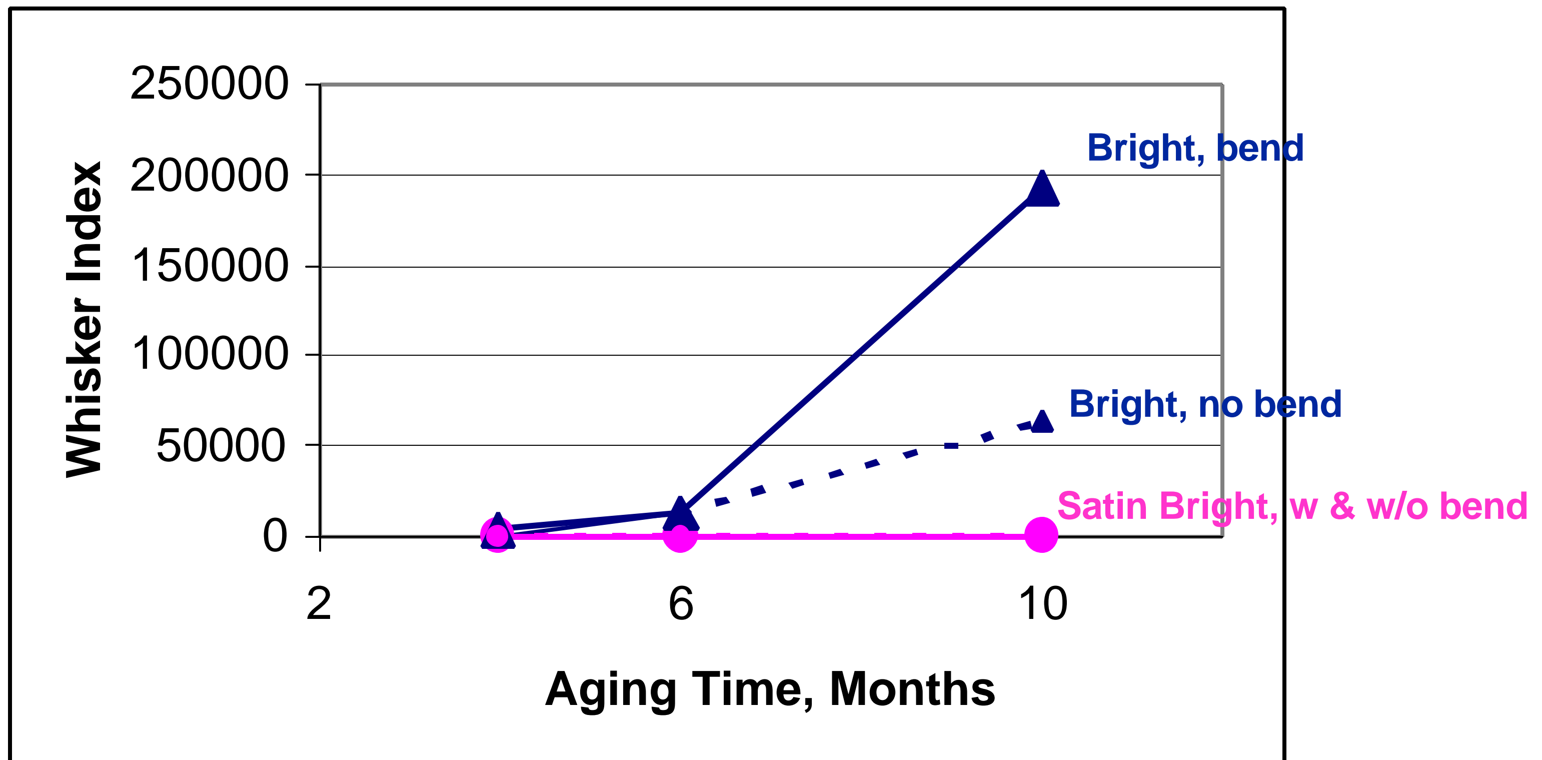
Effect of Grain Size & Carbon Content

Bright Vs. Satin Bright



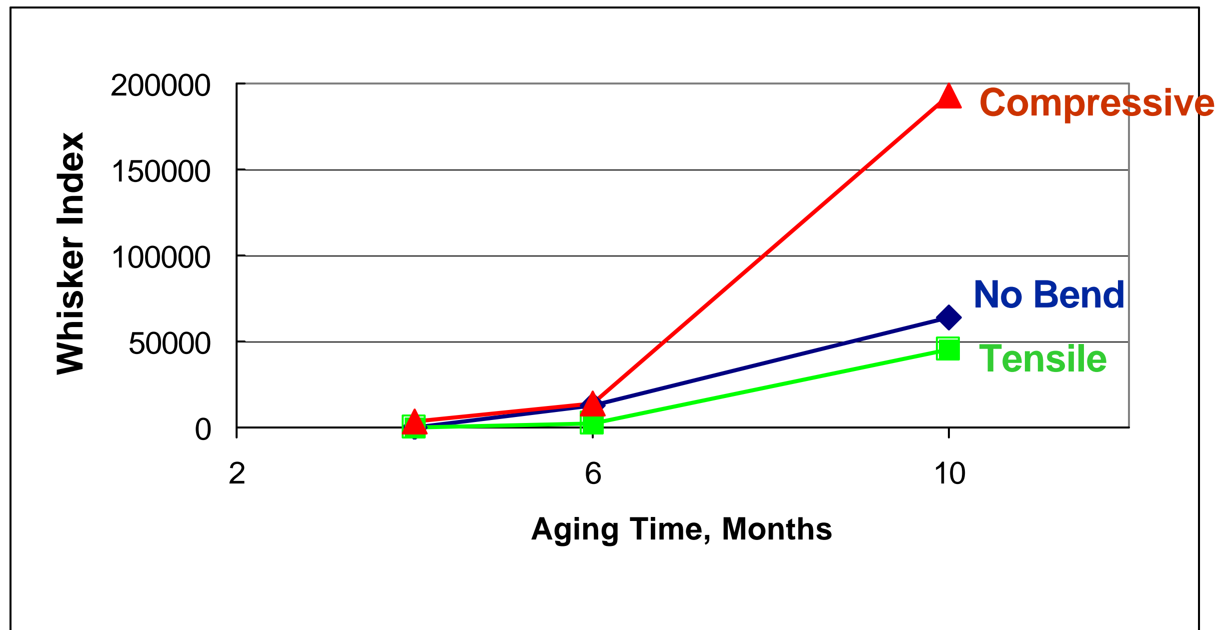
Whisker Propensity of Different Finishes

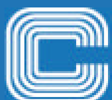
Effect of 90° Compressive Mechanical Bending



Effect of External Mechanical Stress

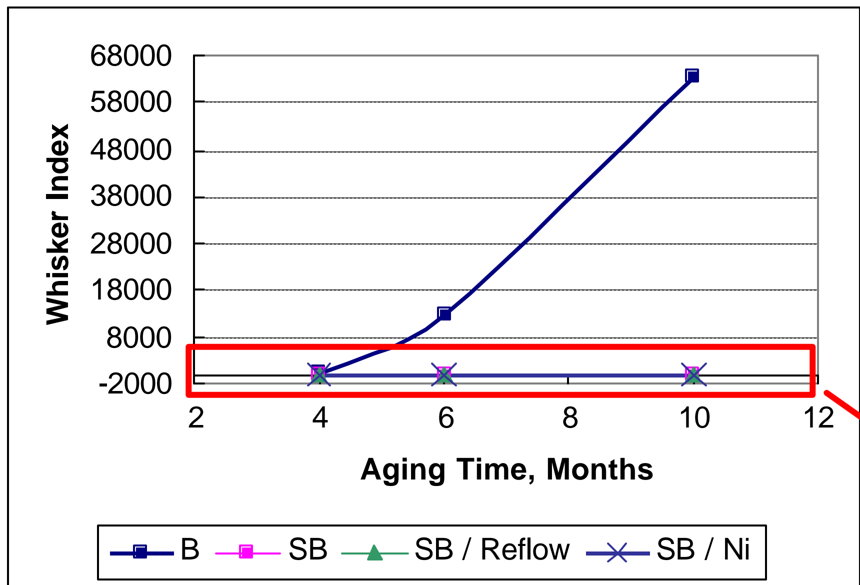
Tensile Vs. Compressive

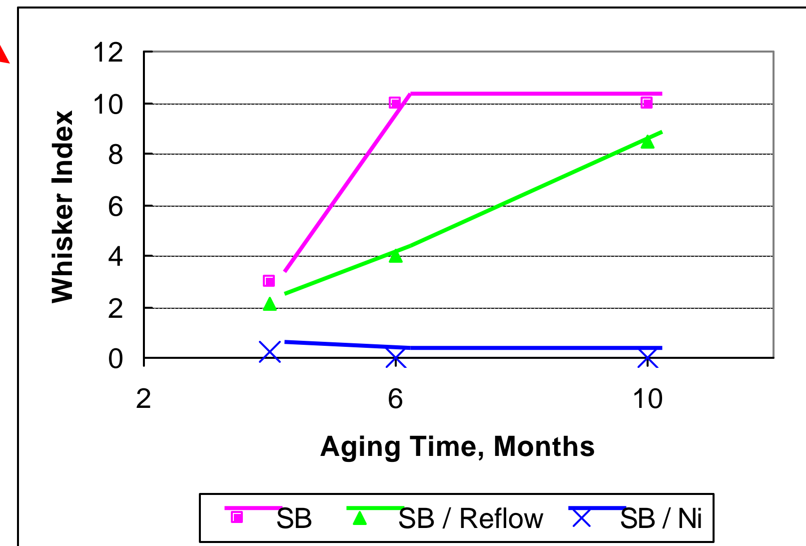




Whisker Propensity of Satin Bright Tin

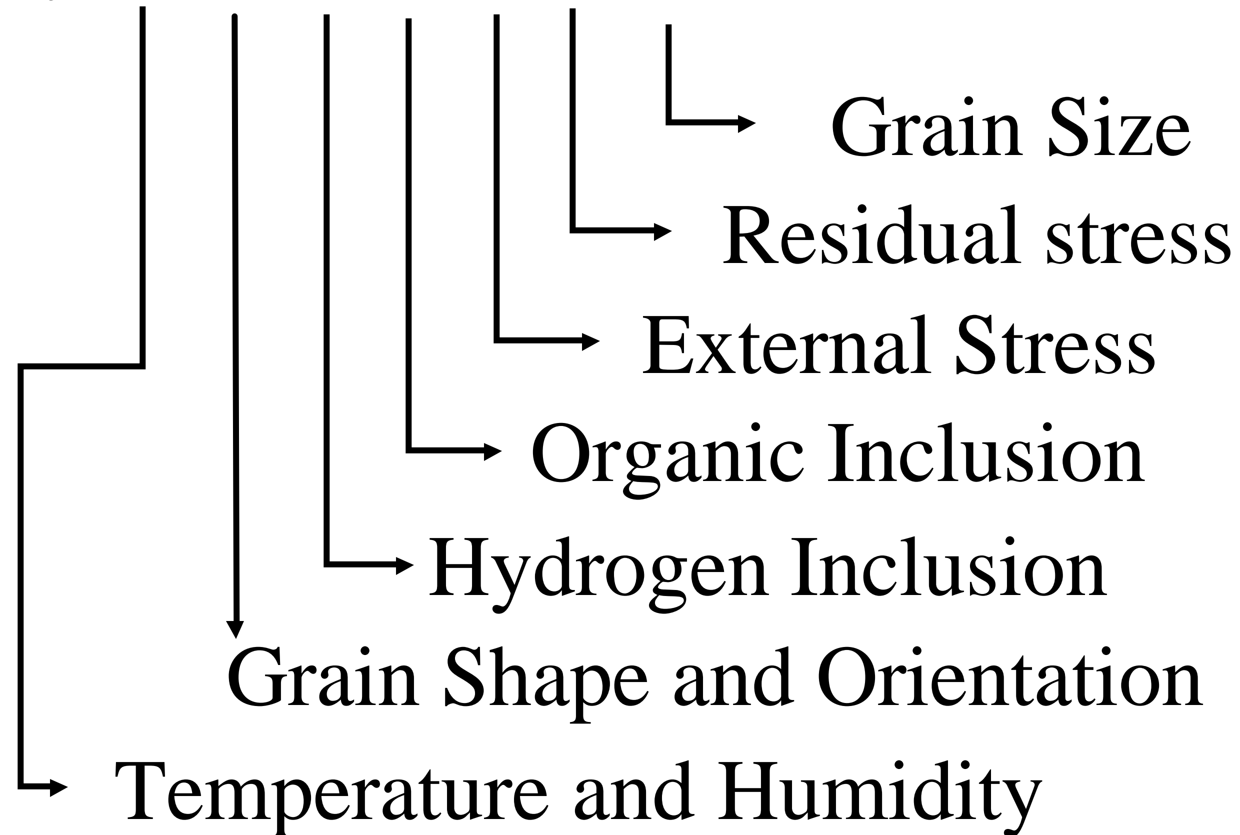
Effect of Reflow & Ni Underlayer





Understanding the Mechanisms — Driving Force

Whisker = f (A, B, C, D, E, F, G........)

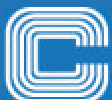


Driving Force vs Factors Affecting Whisker Growth

- Driving Force:

Thermodynamic $DG=DH-TDS$

- Other Factors: Kinetic



Presentation Outline

- What Is Known about the Mechanisms?

- Our Experimental Results:

√ Local Structure by FIB, SEM
√ Residual Stress by XRD

- Conclusion

Mechanisms of Whisker Growth

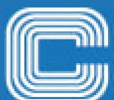
Whisker

SnO_x

Sn

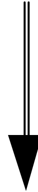
$CuSn_x$

Cu



Mechanism of Spontaneous Whisker Growth

To explain the observed phenomena, two models were developed

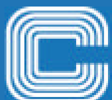


- Dislocation Model

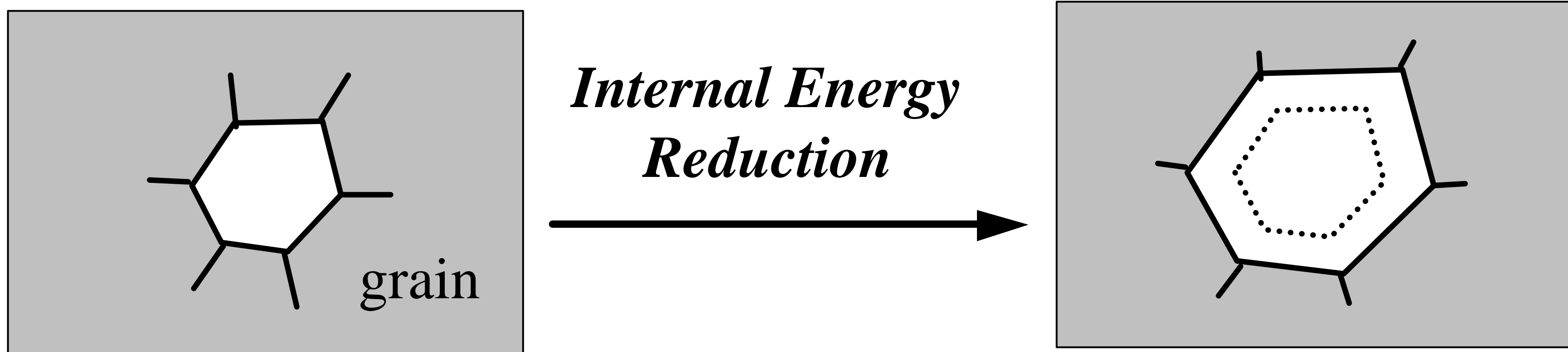
  by Eshelby and Frank

- Recrystallization Model

  by Ellis



Recrystallization and Grain Growth



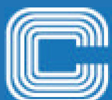
Driving Force:

Residual stress (compressive and tensile)

Grain size

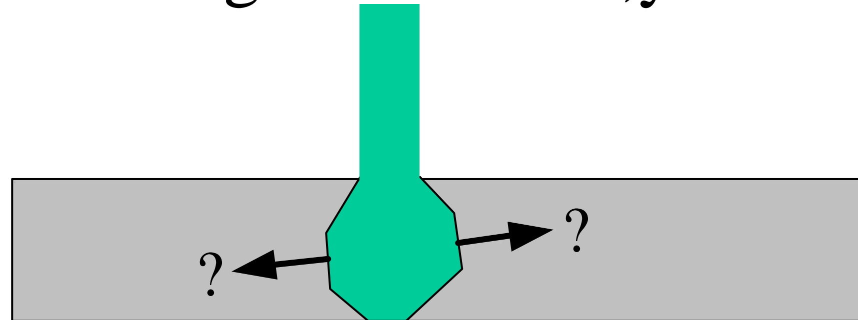
Grain shape, orientation and distribution

Organic and hydrogen inclusion



Open Questions

- Does whisker grow in the x,y-direction ?

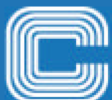


Lateral growth — release → Compressive stress

Lateral growth — release → Tensile stress

Vertical growth — release → Compressive stress

Vertical growth — increase → Tensile stress



Focused Ion Beam (FIB)

Ga^+ Ion Beam

5-200 nm

Detector

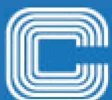
Cutting Through a Whisker

Sn

Cu_6Sn_5

Cu

Whisker



Bright Sn/Cu, aged at RT for 18 months

Whisker

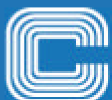
Sn

Cu

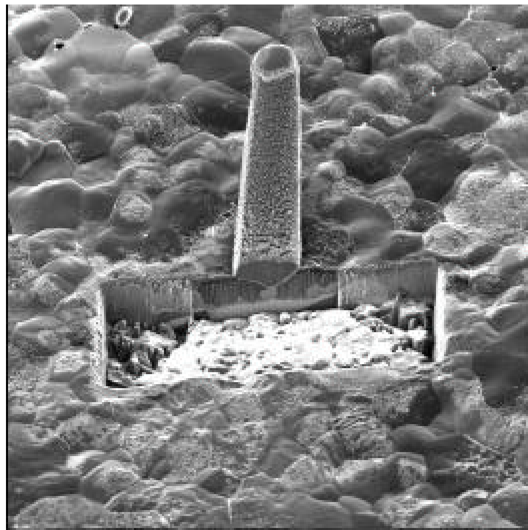
Whisker

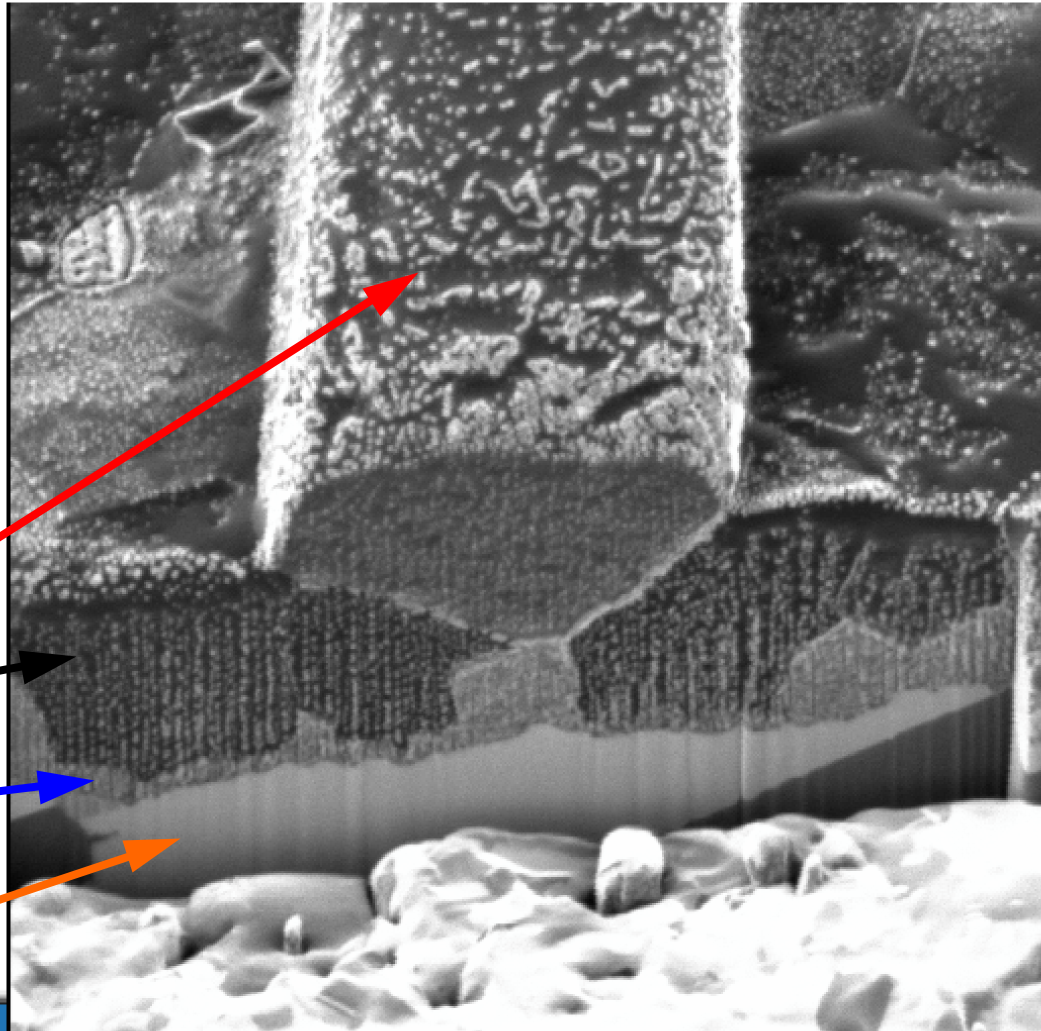
~400 µm

Grain Boundary

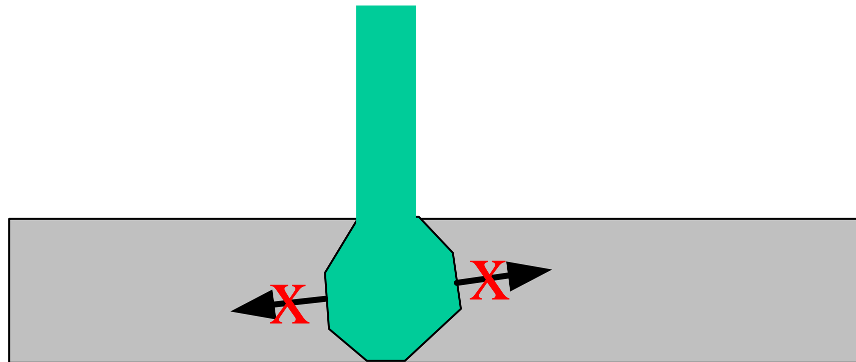


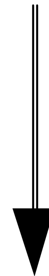
SB Sn/Cu, aged at RT for 18 months





FIB



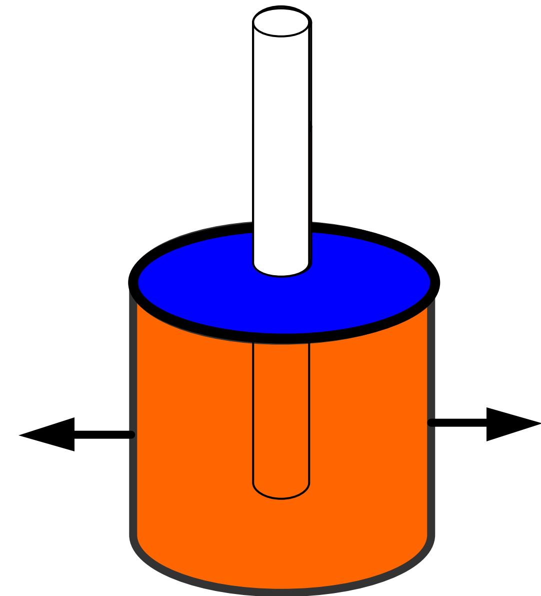


Tensile stress hinders whisker growth

Compressive vs Tensile Stress

Compressive Stress: There will be excessive material in a given volume

Tensile Stress: There will be material deficiency in a given volume



Tensile stress hinders whisker growth

Driving Force vs Factors Affecting Whisker Growth

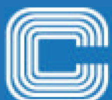
- Driving Force: Thermodynamic

  Compressive Stress : Whisker

  Tensile Stress : No Whisker

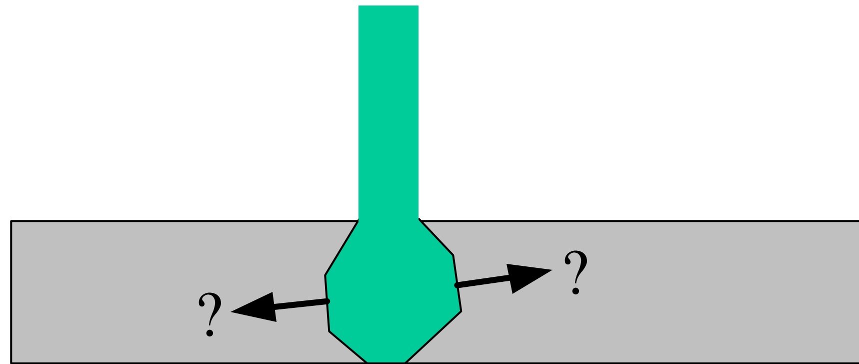
- Other Factors: Kinetic

  Grain Structure, Aging Condition, etc.



Open Questions

•What does tensile stress do ?



•How to measure and control the stress in electroplated Sn?

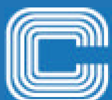
Motivation (cont.)

Why using XRD for the residual stress measurement?

X-ray

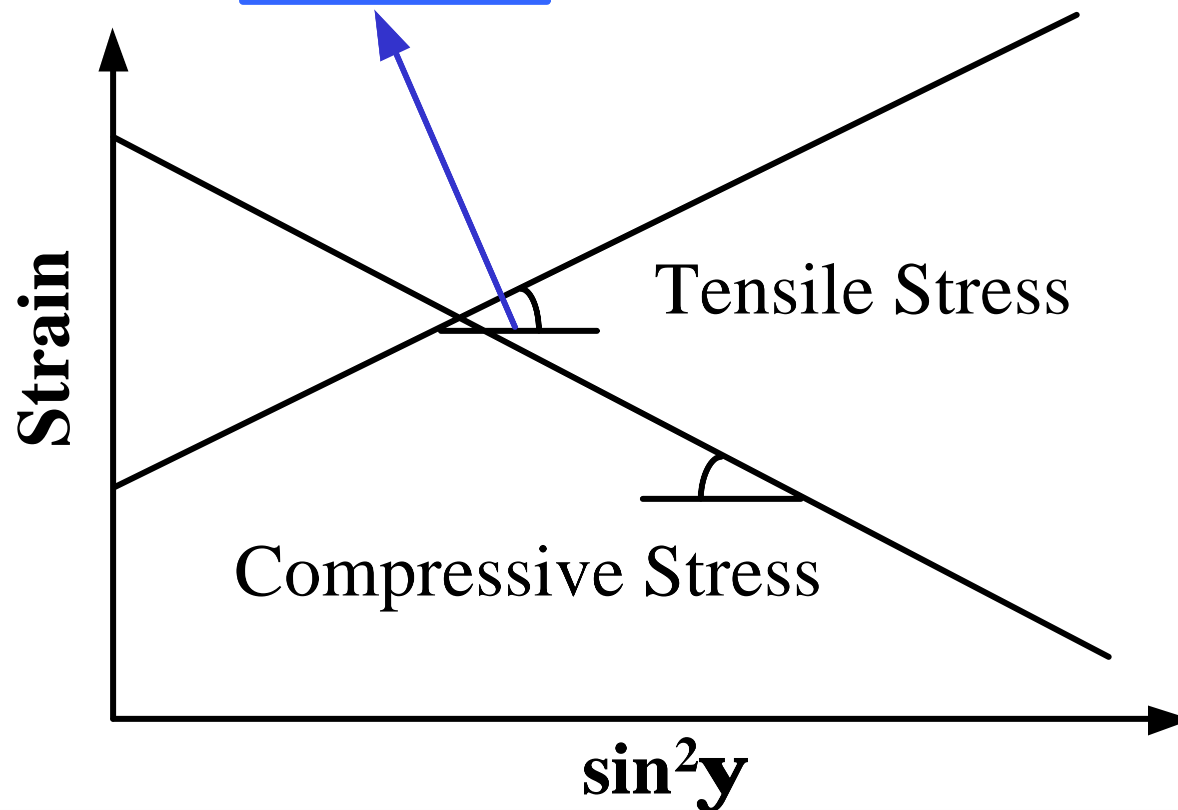
Detector

- Non-destructive and spatial resolved
- Monitoring the stress evolution
- Stress measurement on real part
- Measuring the stress of individual layer



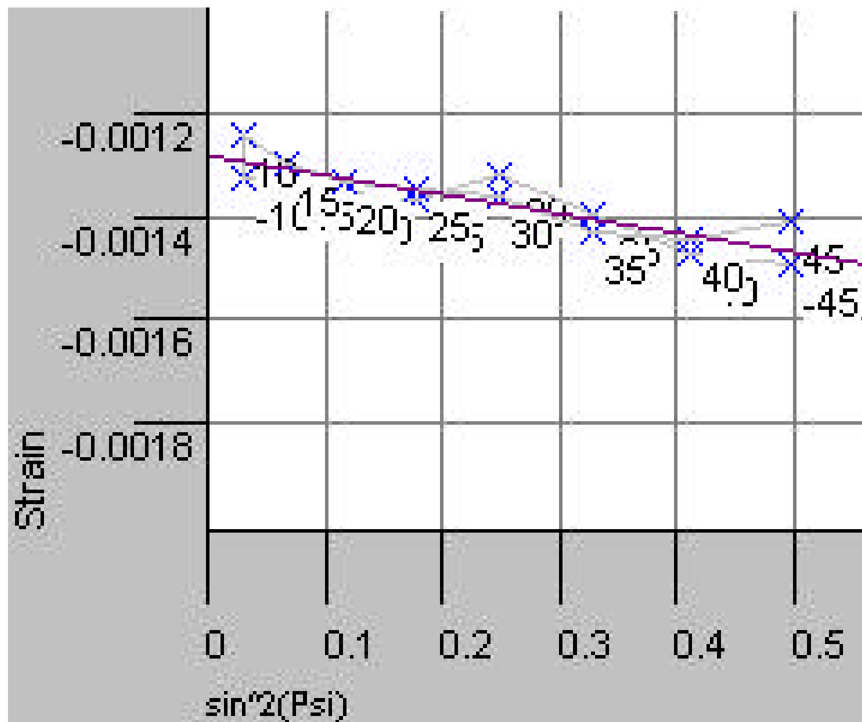
Stress Measurement using XRD

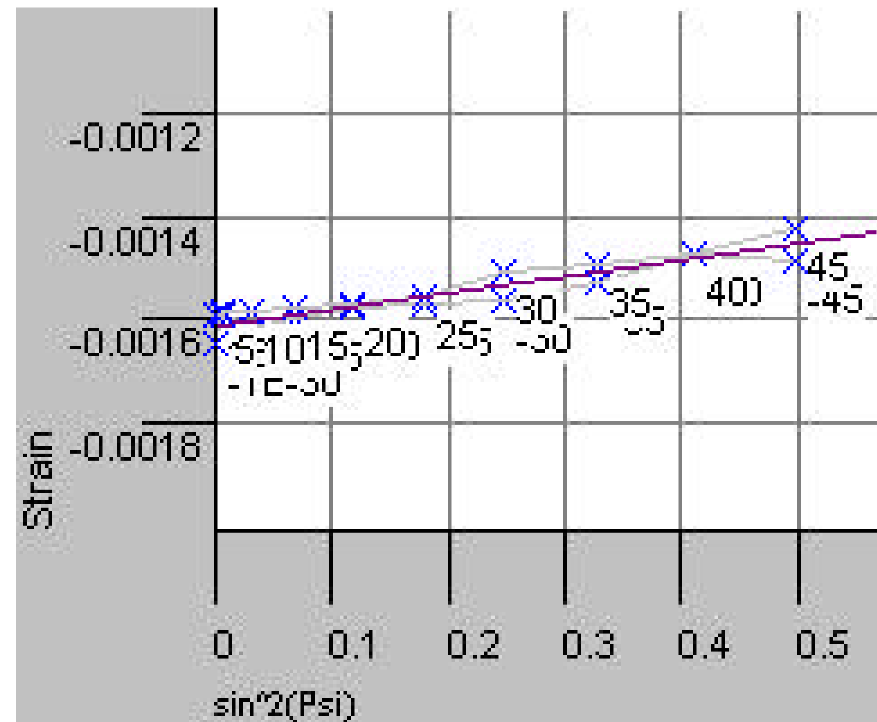
$$\varepsilon_x(\psi) = \frac{\upsilon+1}{E}\sigma_x \sin^2\psi - \frac{\upsilon}{E}(\sigma_x + \sigma_y)$$

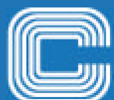


Shear Stress?

3 Months at RT



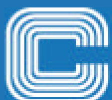




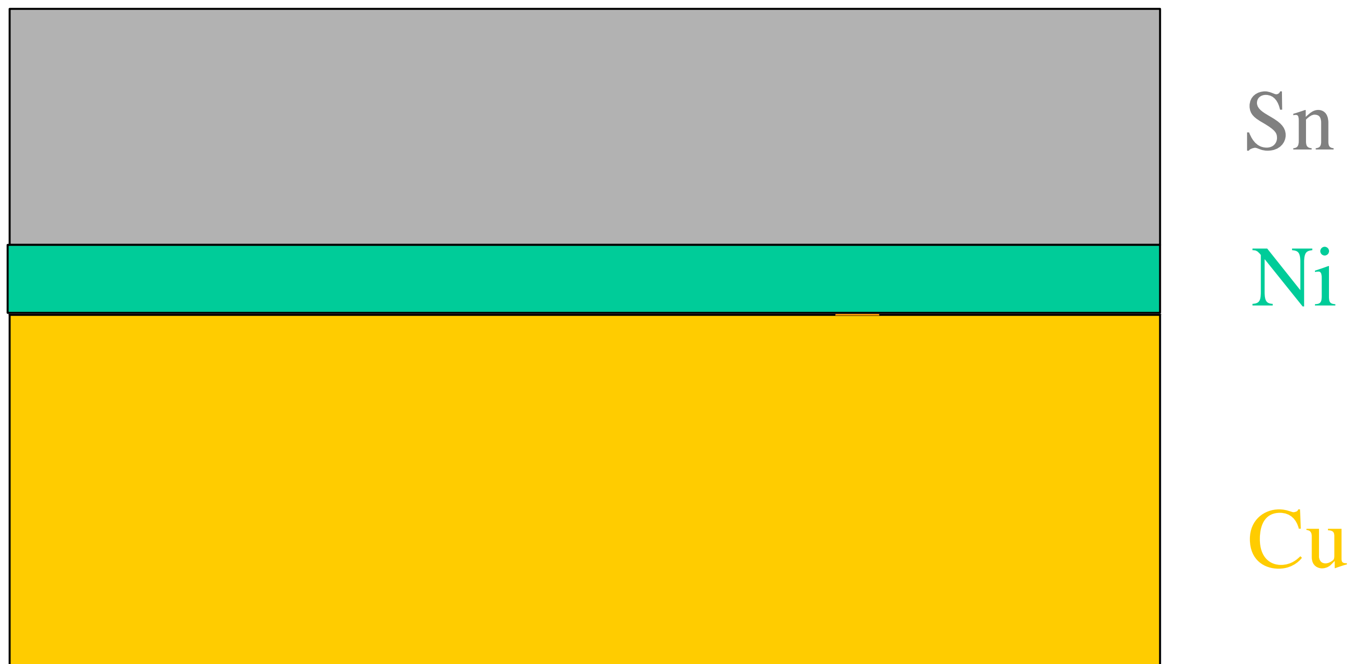
Stress Evolution in Sn Film Plated Directly Over Cu

Stress in MPa

	As Plated	4 Months
Bright	-3±1	-10±1
SB Sn	-1±1	-7±1



Stop Cu-Diffusion into Sn

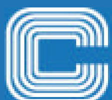


Ni Underlayer on Stress

Samples aged at RT for 4 months

Stress in MPa

	Sn/Cu
Bright	-10±1
SB Sn	-7±1

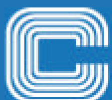


Ni Underlayer on Stress

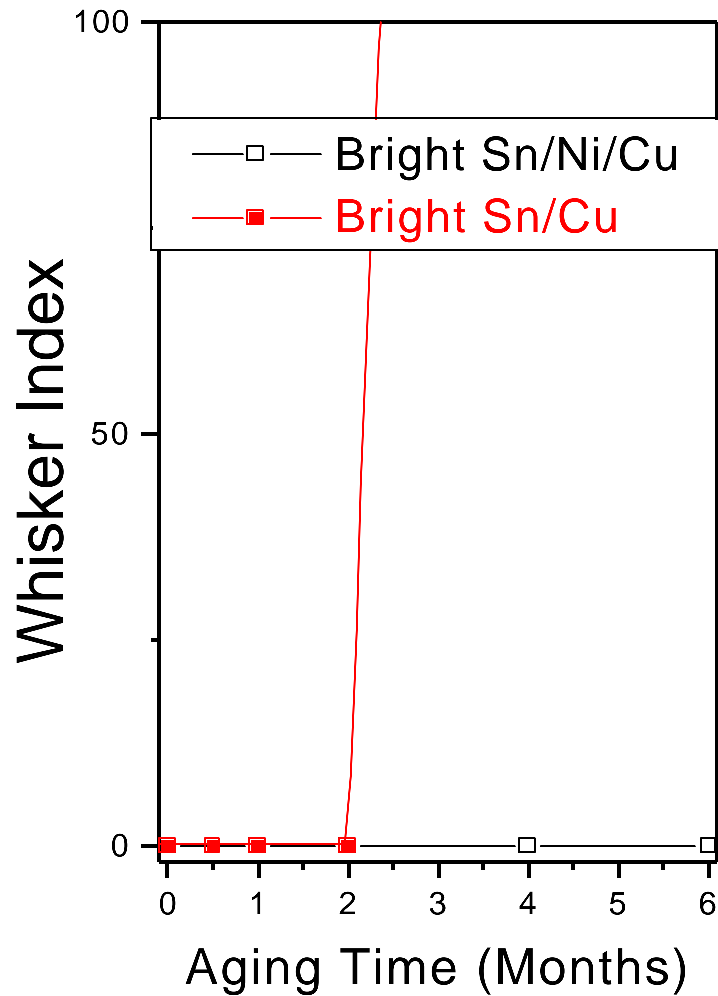
Samples aged at RT for 4 months

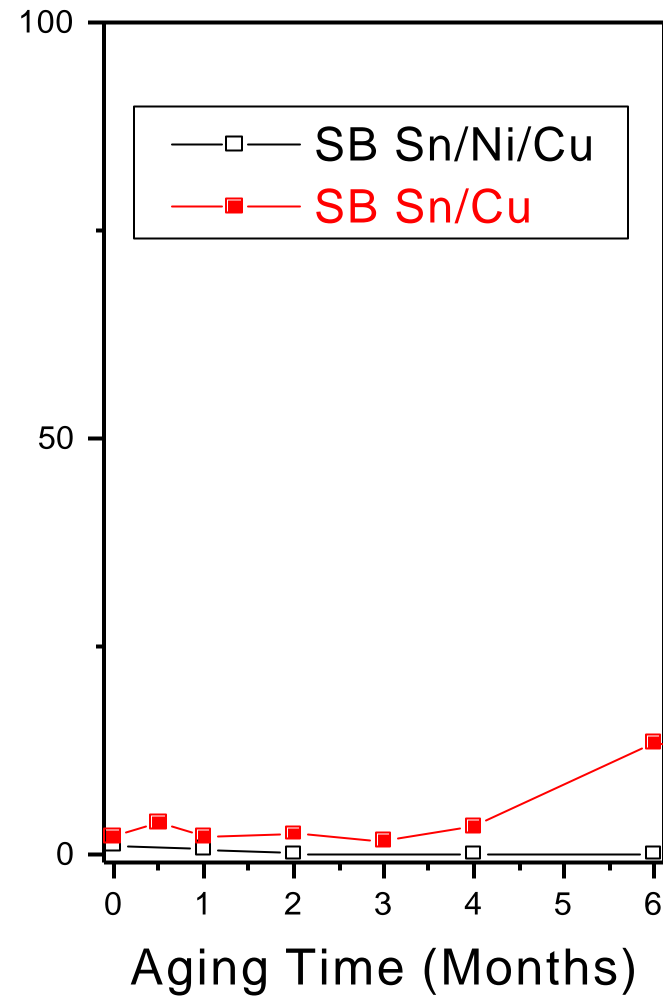
Stress in MPa

	Sn/Cu	Sn/Ni/Cu
Bright	-10±1	9±1
SB Sn	-7±1	7±0

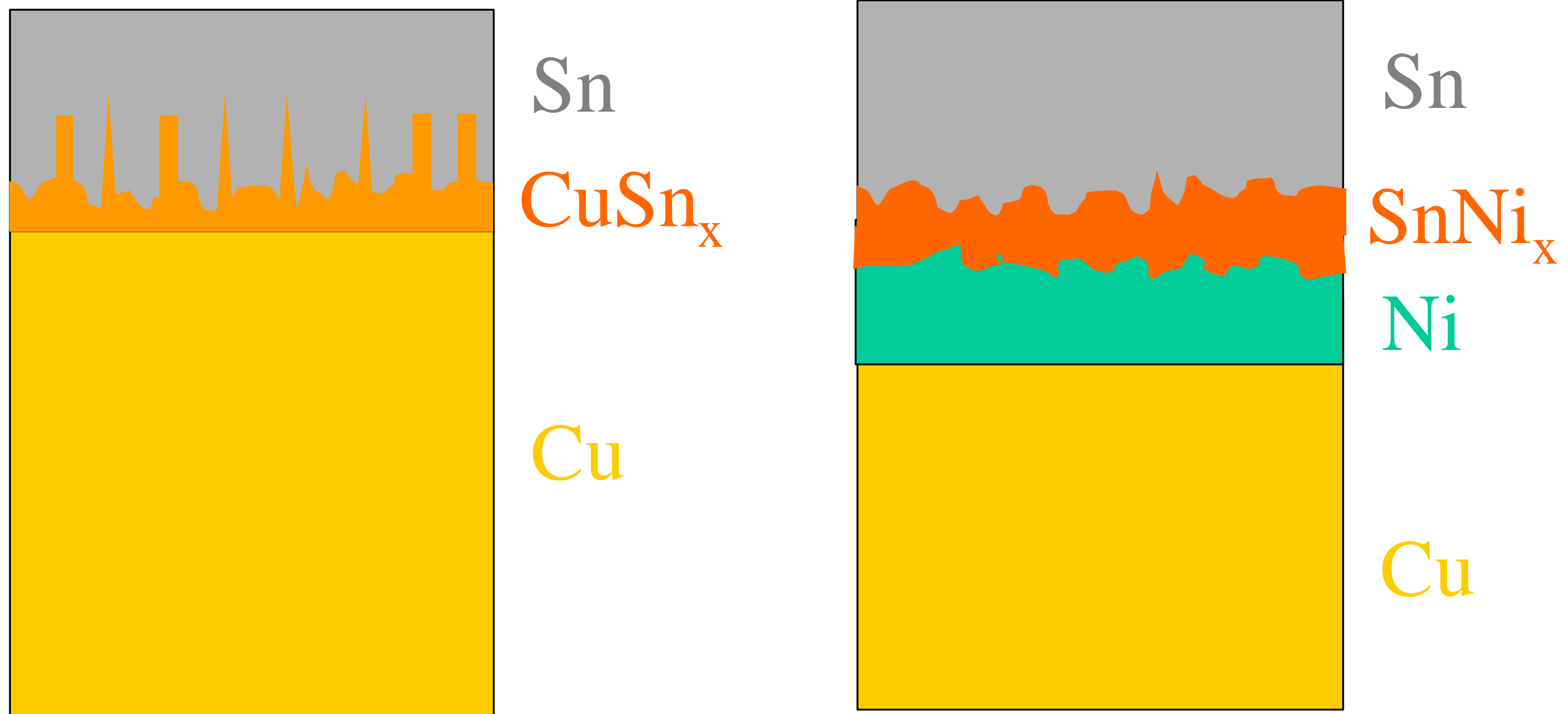


Effect of Ni-Underlayer





Intermetallic Formation
Sn-Cu vs Sn-Ni



Minimizing Whisker Formation Using Thick Sn Coating (8~12 μm)

Thick Sn Coating (8~10 μ)

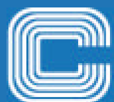
No stress

Compressive stress

Sn

$CuSn_x$

Cu



Thick Sn Coating (8~10 μ)

Compressive stress

Sn

$CuSn_x$

Cu

Whisker Reduction Using Reflow

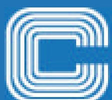
Enthone Confidential

Effect of Reflow

Stress after aging at RT for 12 months

Satin bright Sn (MPa)

	Sn
as plated	-8±3



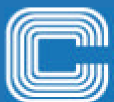
Effect of Reflow

Reflow: Right After Plating

Stress Measurements: 12 Months Aging at RT

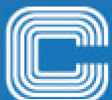
	Sn
as plated	-8±3
reflow	0±2

Effect of Reflow



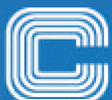
Conclusion

- Tensile stress hinders whisker growth.
- Ni underlayer generates a tensile stress in the Sn film.
- Reflow reduces whisker growth propensity.
- Stress can be measured using XRD.



Recommendations

- SB Sn/Ni/Cu
- SB Sn/Cu, Reflow
- SB Sn(thick)/Cu
- The evolution of the stress in Sn should be monitored and used in conjunction with whisker test for predicting the whisker growth propensity.



Stress Evolution with Time