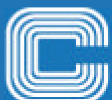
Stress in Electroplated Sn: Its Measurement and Implication in Spontaneous Whisker Growth

Chen Xu

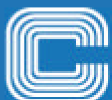
Cookson Electronics PWB Materials & Chemistry



Outline

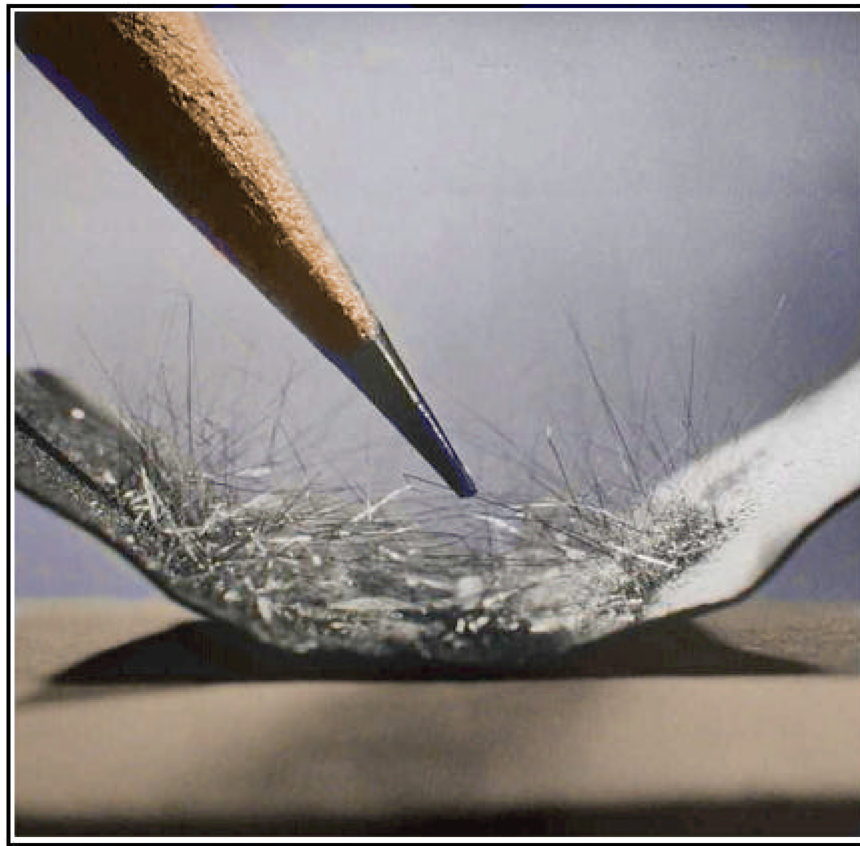
- Whisker Background
- Stress Measurement
- Results
- Conclusions

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

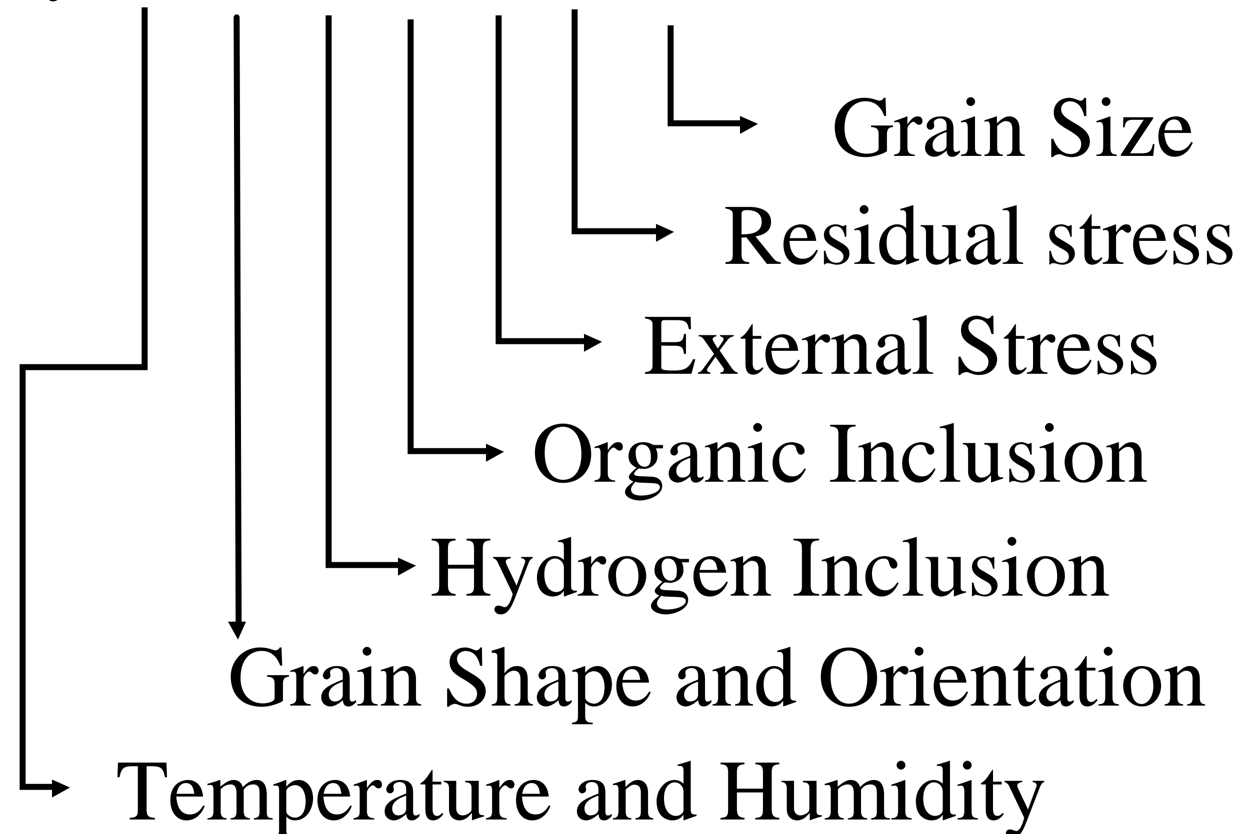


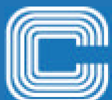
Lead-Free
Implementation Barrier

Spontaneous Whisker Growth!



Understanding the Mechanisms — Driving Force

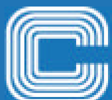




Whisker Program

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
  - Structural and Chemical Characterization

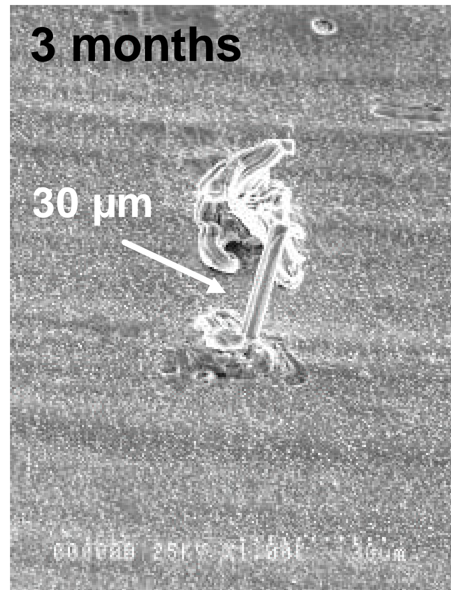


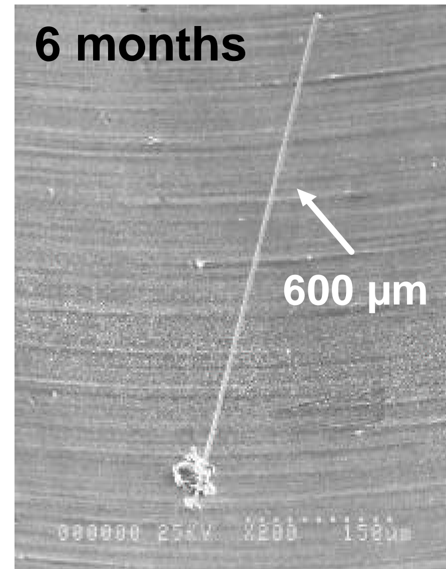
Current Work - Phase II

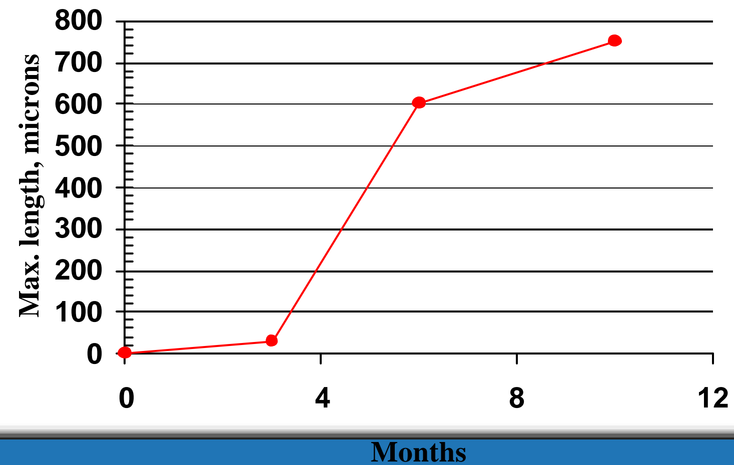
- Whisker growth rate
- Structural and Chemical Characterization

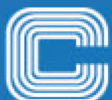
Maximum Length Measurement

Bright Tin

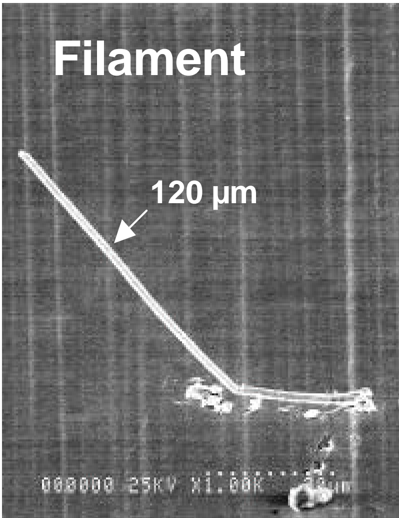


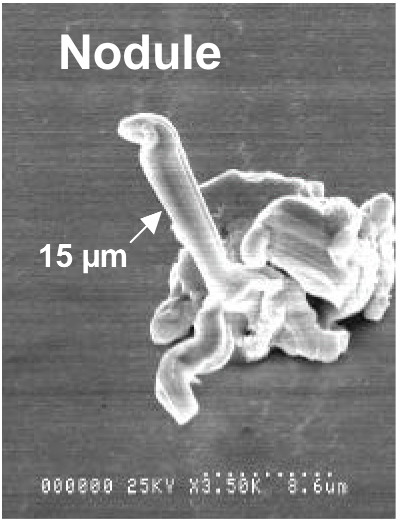


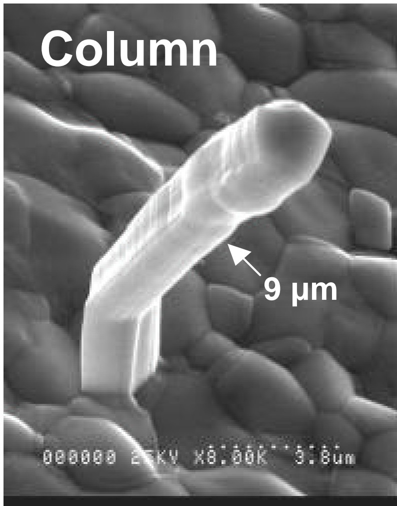


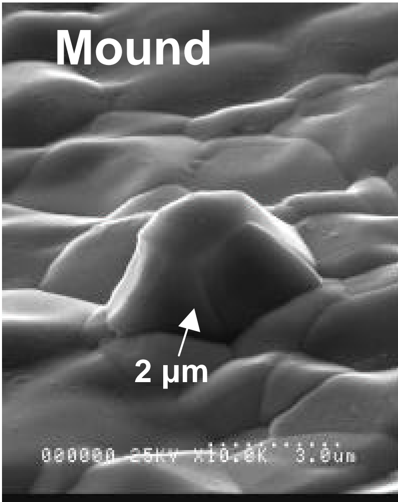


Tin Whiskers









Whisker Index

Measure for Whisker Propensity

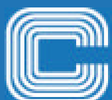
$$WI = S\ n*d*L*f(L)$$

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

Whisker Index

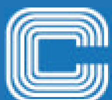
|--------------Whisker Index-------------|

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**

Structural and Chemical Characterization

- Residual Stress by XRD
- Local Structure by FIB, SEM
- Elemental Analysis Using AES and EDS



Outline

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- Stress Measurement
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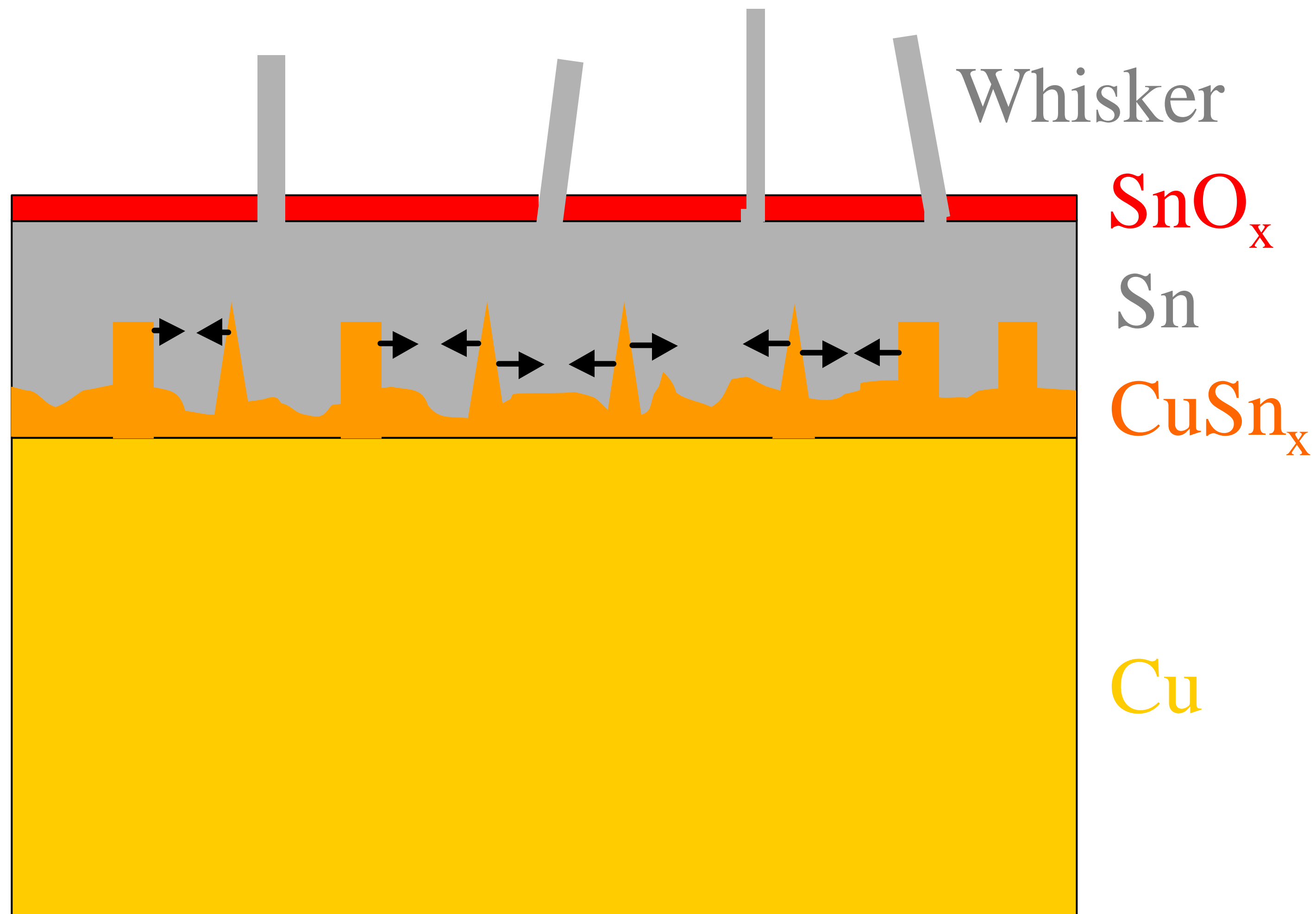
Mechanisms of Whisker Growth



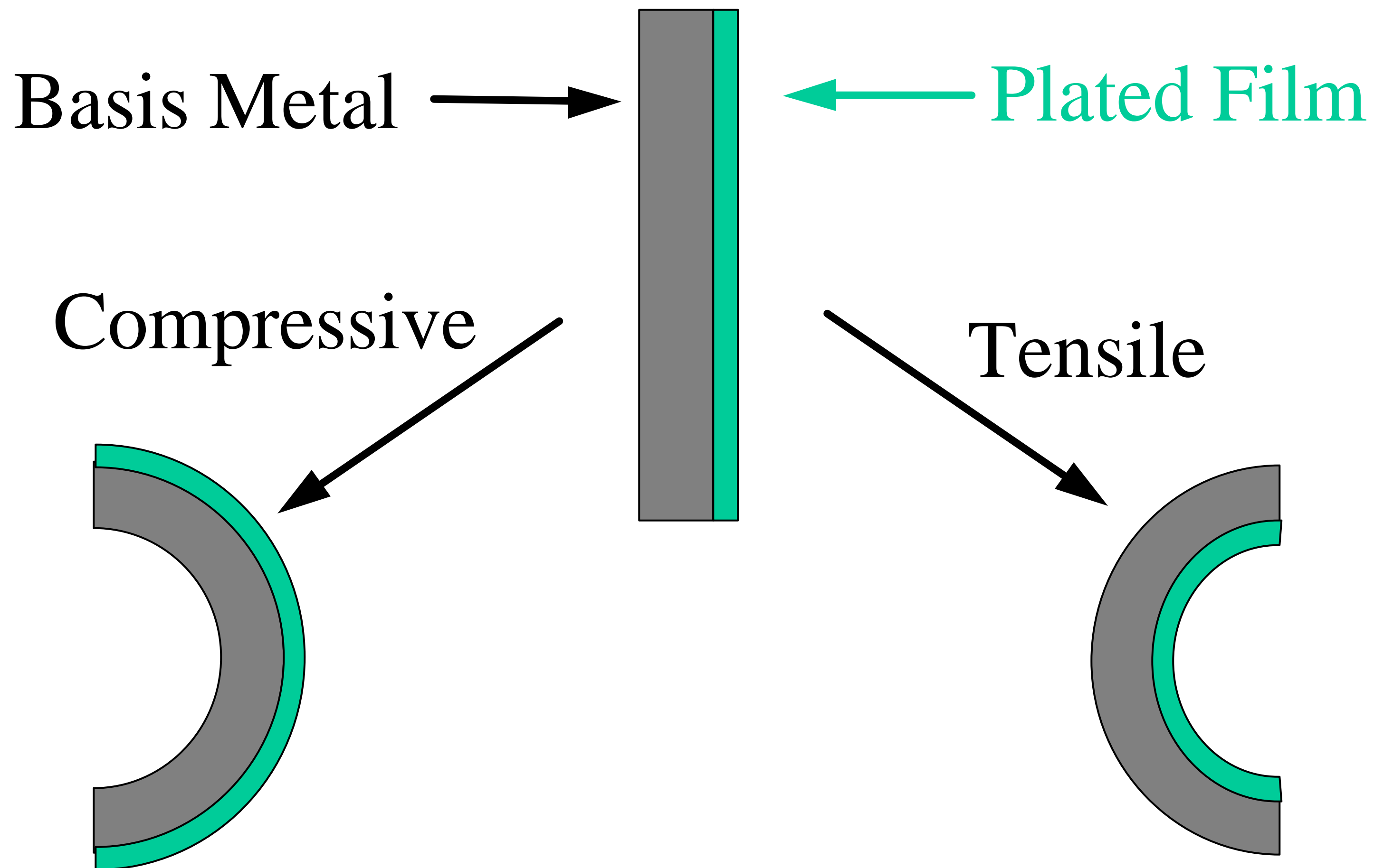
Driving Force vs Factors Affecting Whisker Growth

- Driving Force:

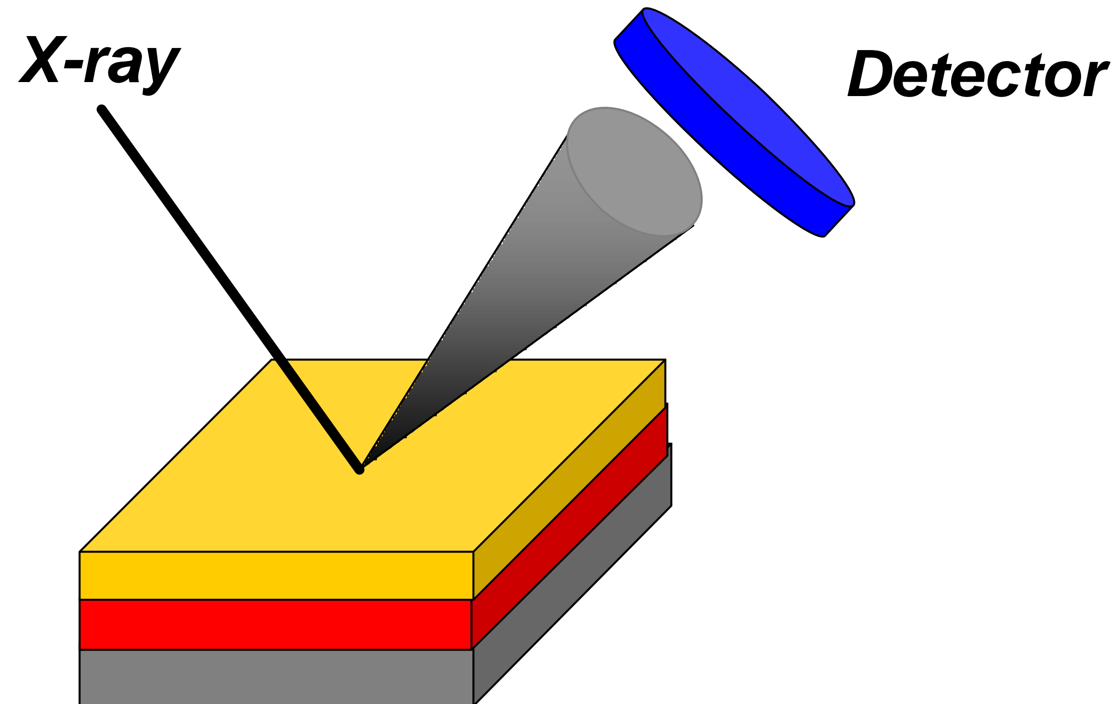
Thermodynamic $DG=DH-TDS$

- Other Factors: Kinetic

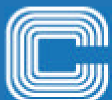
Stress Measurement Based on Mechanical Methods



Why using XRD for the residual stress measurement?



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



Types of Residual Stresses

- **Macroscopic Stress**: Long-range, over several to many grains of materials.

  → *XRD and Mechanical*

- **Structural Microstress**: Over the distance of one grain.

  → *XRD*

- **Microstress**: Over several atomic distances within the grain.

  → *XRD*

Description of Residual Stress

- Tensor: direction and magnitude
- Normal and shear stress

z

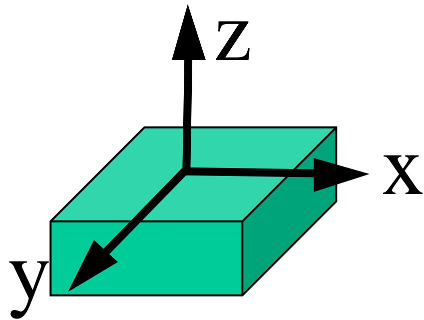
x

y

Normal $\sigma_x, \sigma_y, \sigma_z$

Shear $\sigma_{xy}, \sigma_{xz}, \sigma_{yz}$

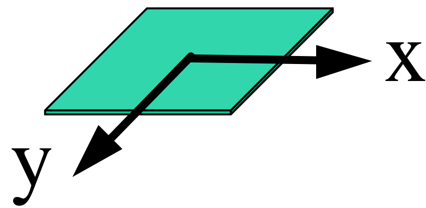
Description of Residual Stress



$\sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{xz}, \sigma_{yz}$

↓ ***Thin Films***

$\sigma_x, \sigma_y, \sigma_{xy}$



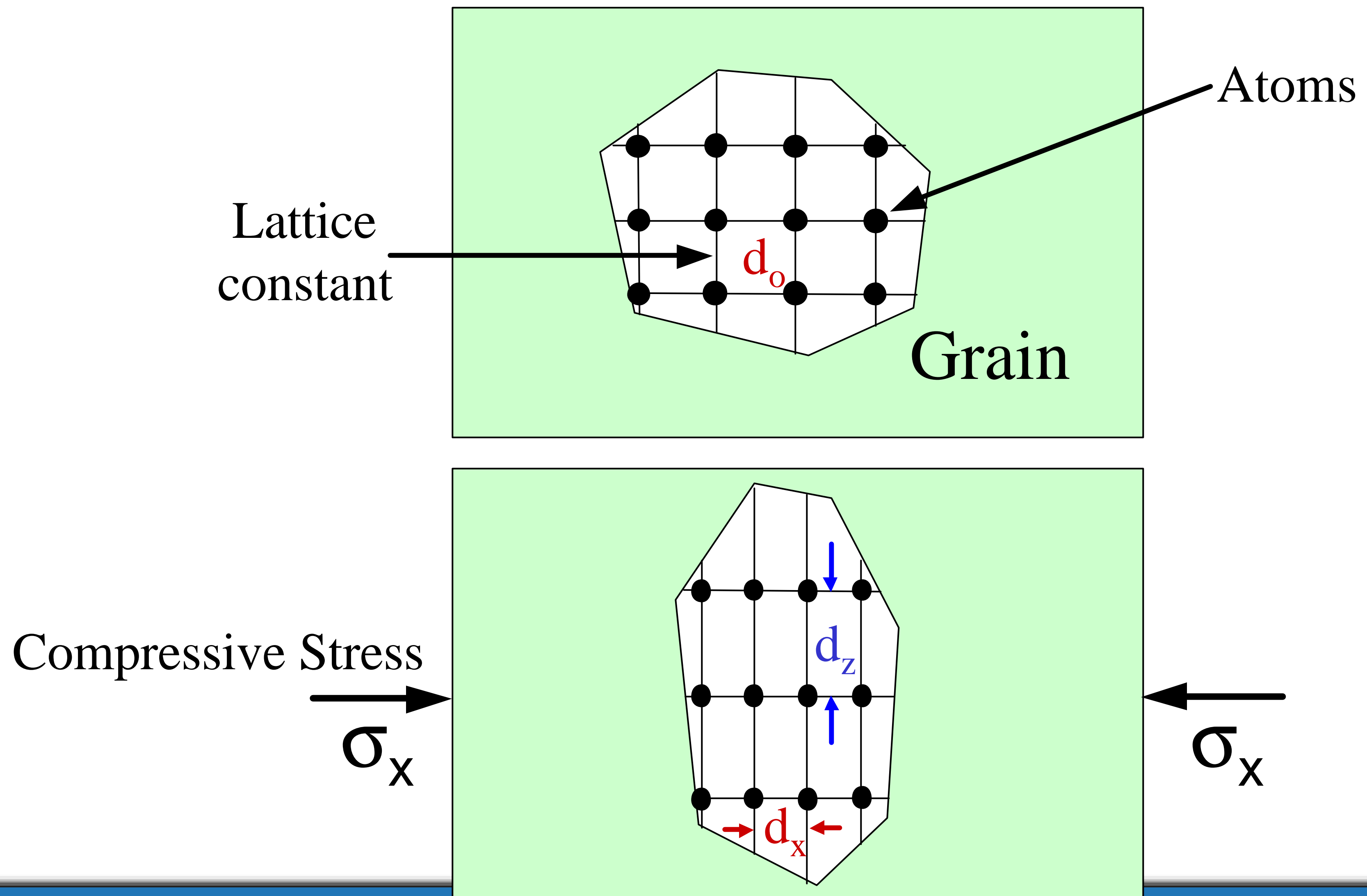
↓ ***No Shear Stress***

σ_x, σ_y

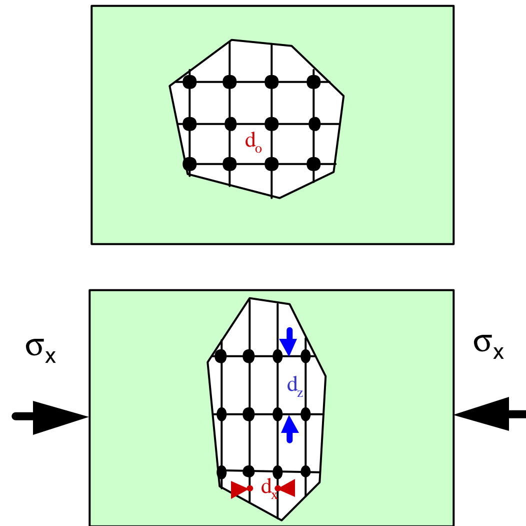
↓ $\boldsymbol{s_x = s_y}$

σ

Stress Measurement using XRD



Stress Measurement using XRD



Strain:

$$e_x=(d_x-d_o)/d_o$$

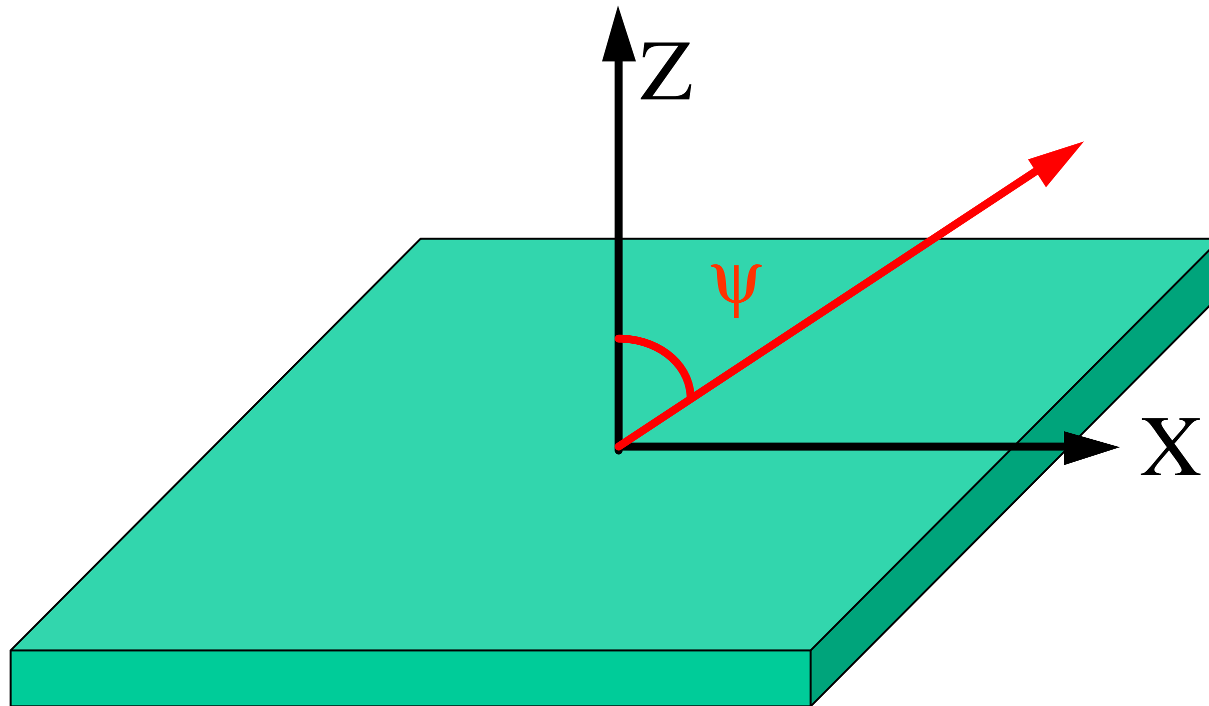
$$e_z=(d_z-d_o)/d_o$$

Hooke's law

$e_x= \sigma_x/E$ E: Young's modulus

$- e_z=u\, \sigma_x/E$ u: Poisson's ratio

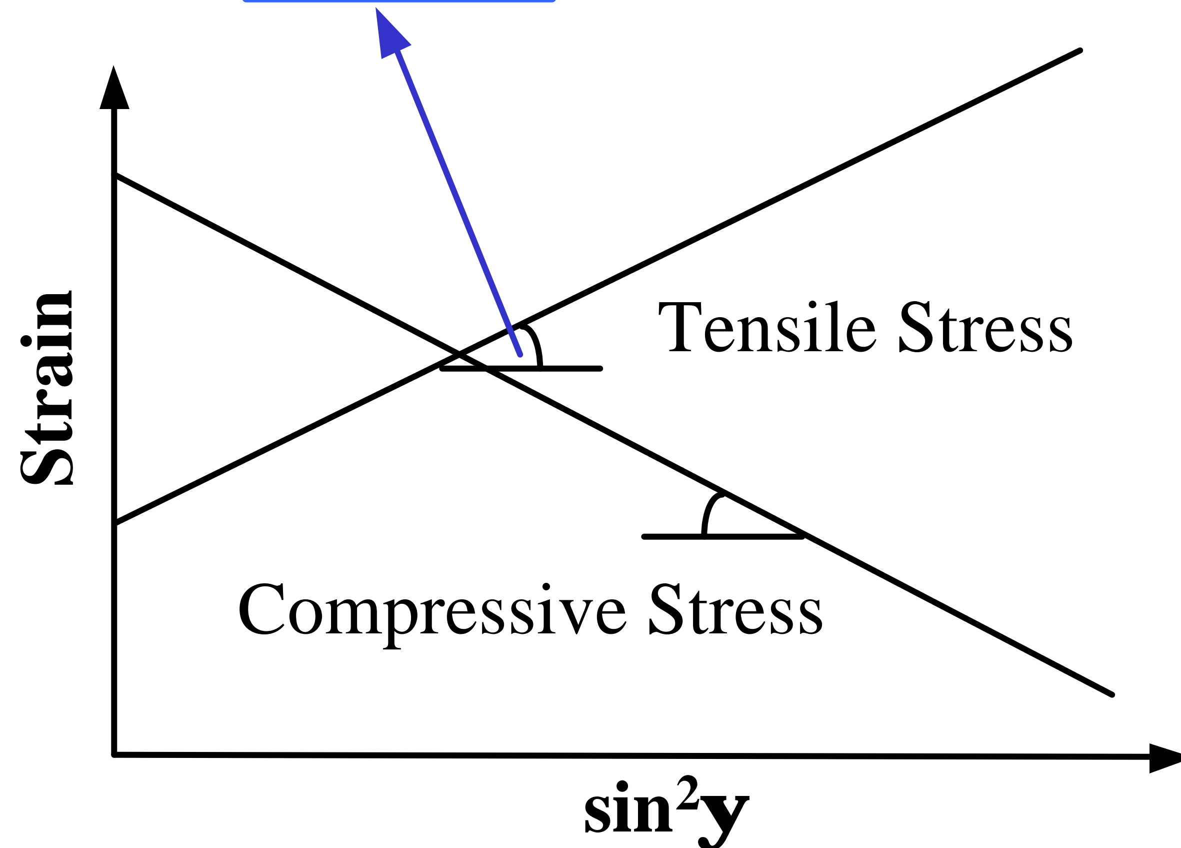
Stress Measurement using XRD



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

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?

Z

ψ ψ

X

Strain

0.0002
0.0000
-0.0002
-0.0004
-0.0006
-0.0008
-0.0010
-0.0012
-0.0014
-0.0016

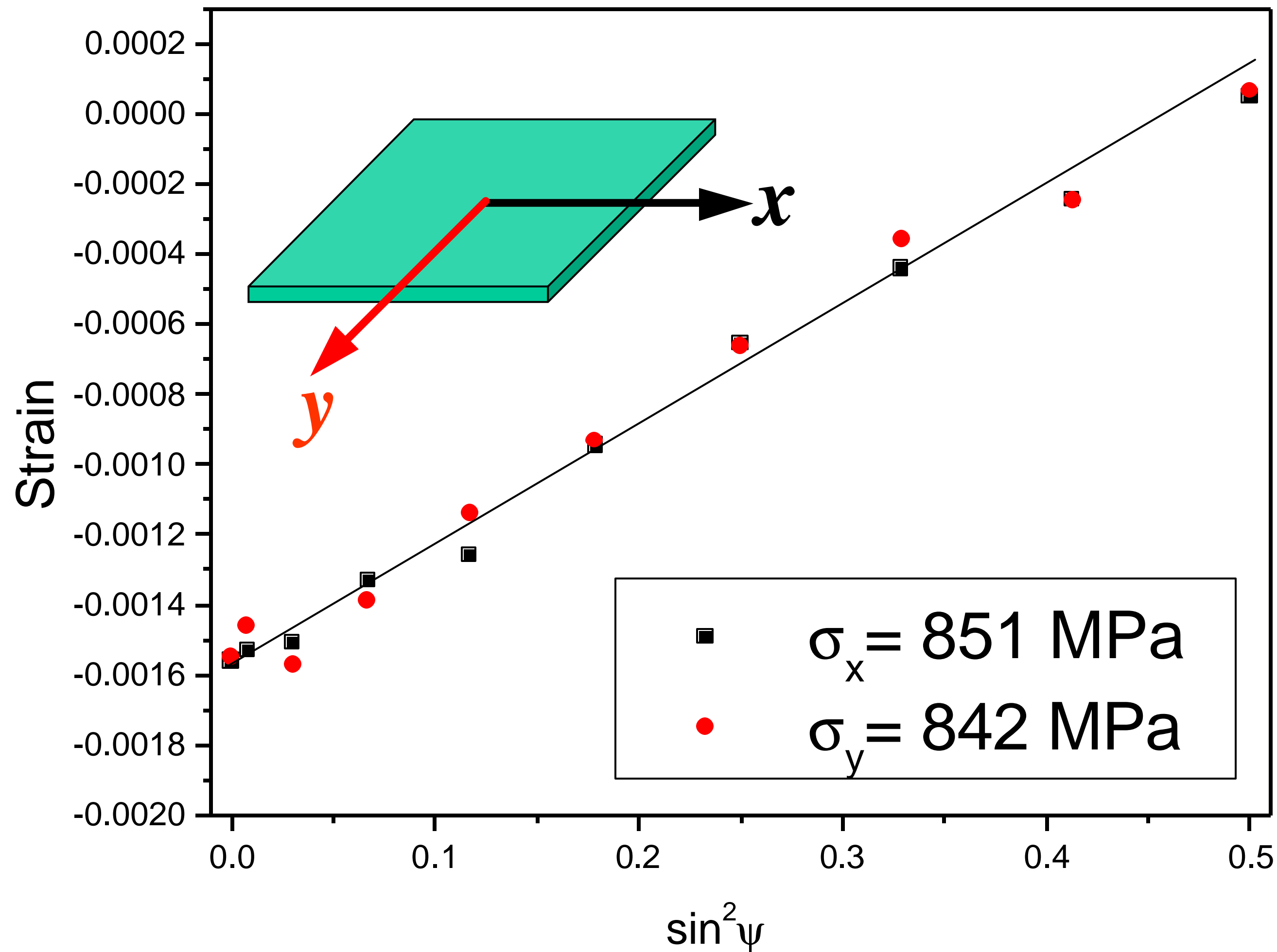
0.0 0.1 0.2 0.3 0.4 0.5 0.6

$\sin^2\psi$

$+\psi$

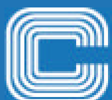
$-\psi$

Biaxial Stress State

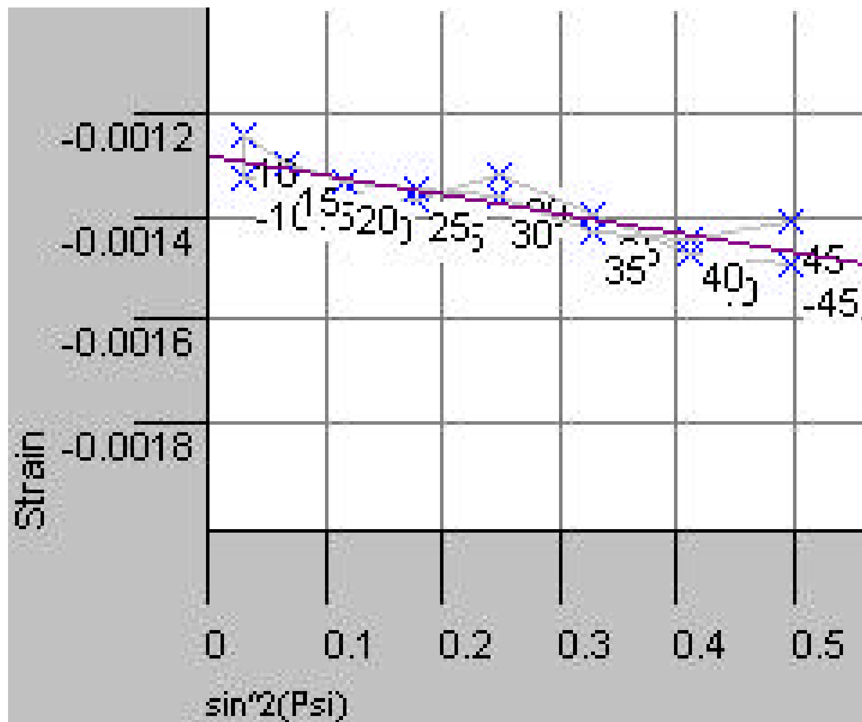


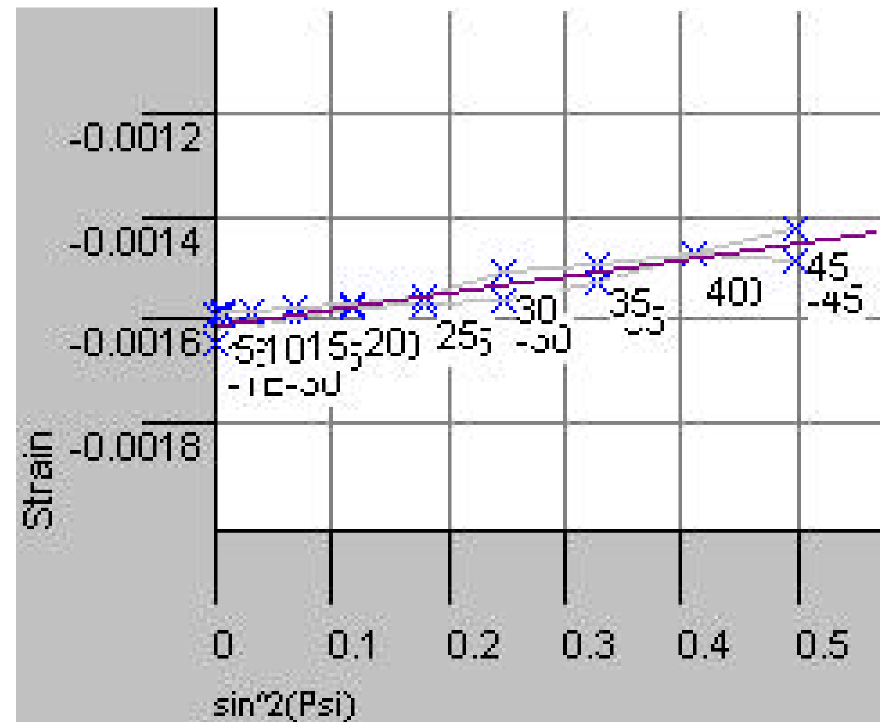
Experimental Setup

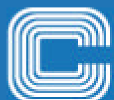
- D8 Discover with GADDS by Bruker.
- Cr-radiation and 0.5mm beam.
- Diffraction peak (312) at $2\theta=143.8^o$.
- The strains were measured at 19 different ψ angles from -45° to 45°.



Stress Measurement Result For Sn Films



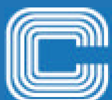




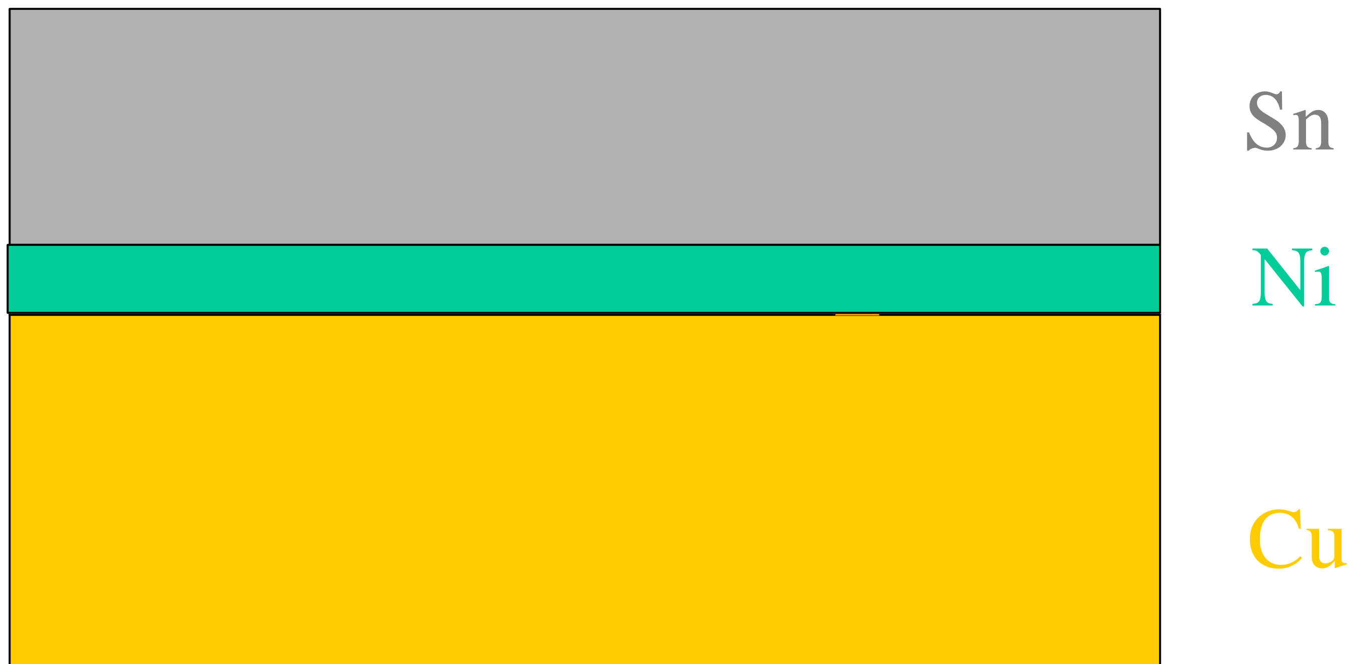
Stress Evolution in Sn Film Plated Directly Over Cu

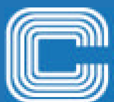
Stress in MPa

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



Stop Cu-Diffusion into Sn

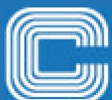




Ni Underlayer on Stress
Samples aged at RT for 4 months

Stress in MPa

	Sn/Cu
Bright	-10±1
SB Sn	-7±1

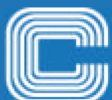


Ni Underlayer on Stress

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

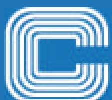


Effect of Ni-Underlayer

Effect of Stress in Ni layers

Stress in Sn after aging at RT for 6M

	No Ni	Ni(-69MPa)	Ni(-14MPa)	Ni(131MPa)
bright Sn	–8?1	11?2	13?1	11?2
matte Sn	–6?1	4?1	5?1	5?1



Whisker Index

Bright Sn

Sn/Cu, aged at 50°C
Ni(-69MPa)
Ni(-14MPa)
Ni(131MPa)

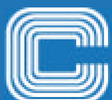
Whisker Index

14000
12000
10000
8000
6000
4000
2000
0

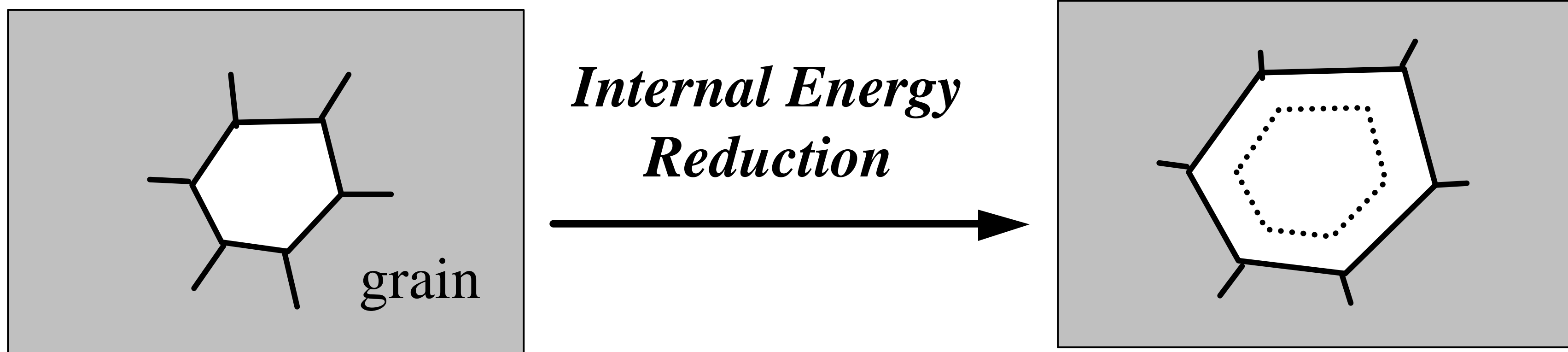
0 1 2 3 4 5 6

Aging Time (months)

Intermetallic Formation
Sn-Cu vs Sn-Ni



Recrystallization and Grain Growth



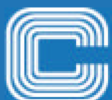
Driving Force:

Residual stress (compressive and tensile)

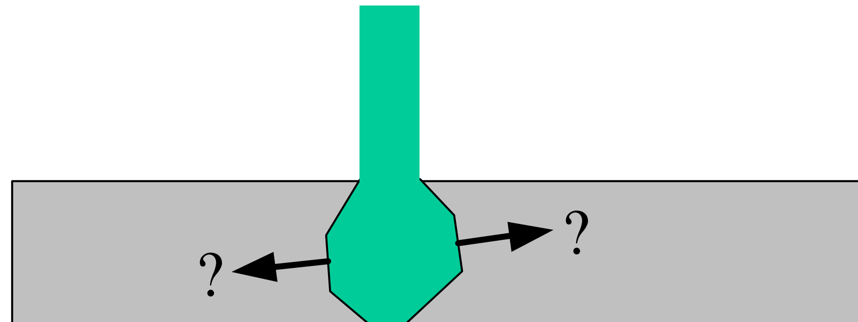
Grain size

Grain shape, orientation and distribution

Organic and hydrogen inclusion



Does whisker grow in the x,y-direction?



Lateral growth	release →	Compressive stress
	release →	Tensile stress
Vertical growth	release →	Compressive stress
	increase →	Tensile stress

Focused Ion Beam (FIB)

Ga^+ Ion Beam

5-200 nm

Detector

Cutting Through a Whisker

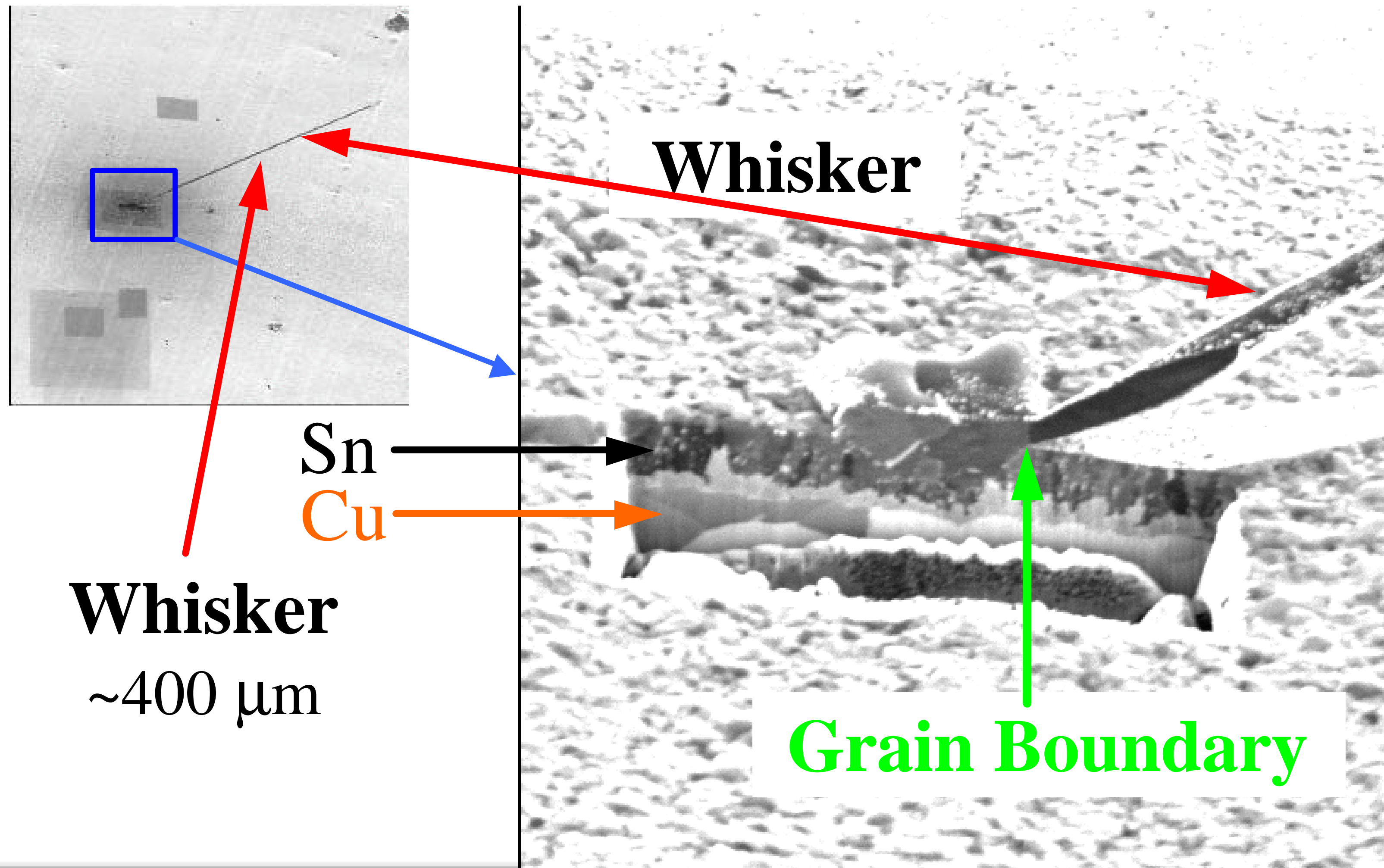
Sn

Cu_6Sn_5

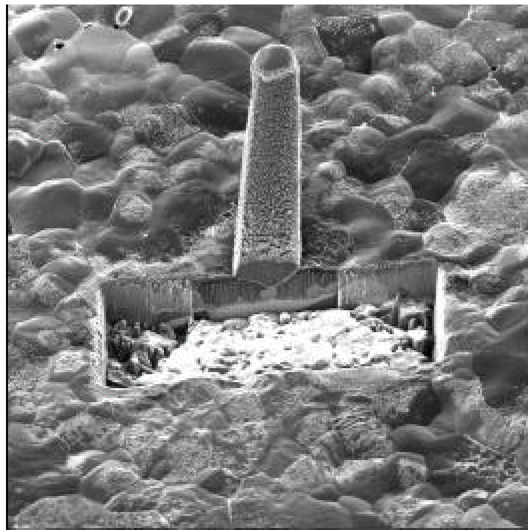
Cu

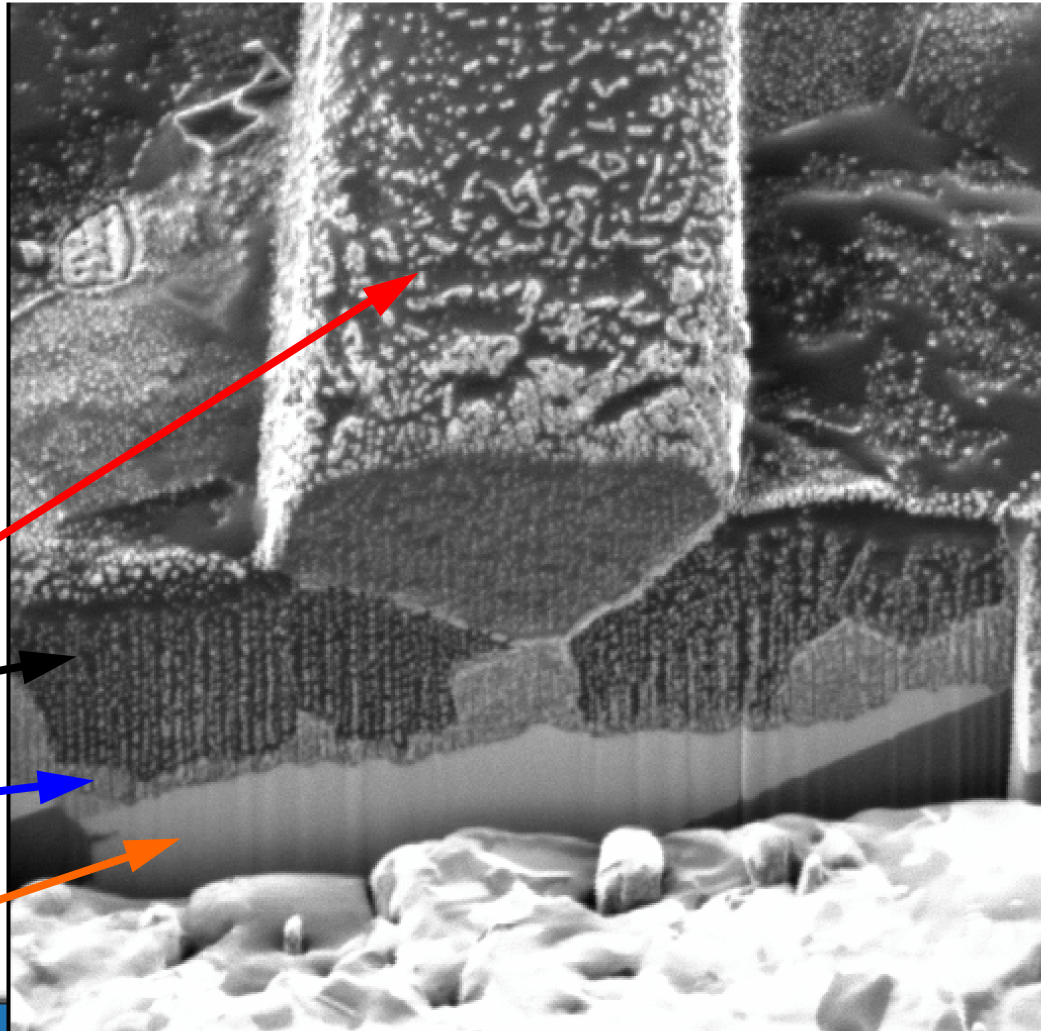
Whisker

Bright Sn/Cu, aged at RT for 18 months



SB Sn/Cu, aged at RT for 18 months





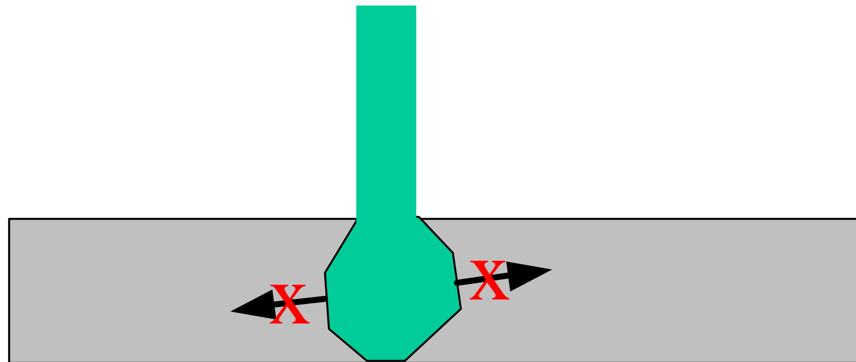
Whisker

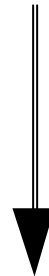
Sn

Cu_6Sn_5

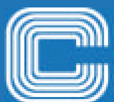
Cu

FIB





Tensile stress hinders whisker growth



Driving Force vs Factors Affecting Whisker Growth

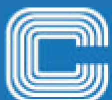
- Driving Force: Thermodynamic

  Compressive Stress : Whisker

  Tensile Stress : No Whisker

- Other Factors: Kinetic

  Grain Structure, Aging Condition, etc.



Conclusion

- Tensile stress hinders whisker growth.

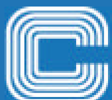
- Ni underlayer generates a tensile stress in the Sn film.

- 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



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