

# Understanding and Minimizing Tin Whiskers

A Review of the Literature

---

Qian Sun and Guna Selvaduray

Chemical & Materials Engineering Department

San Jose State University

June 04, 2003



# Introduction

---

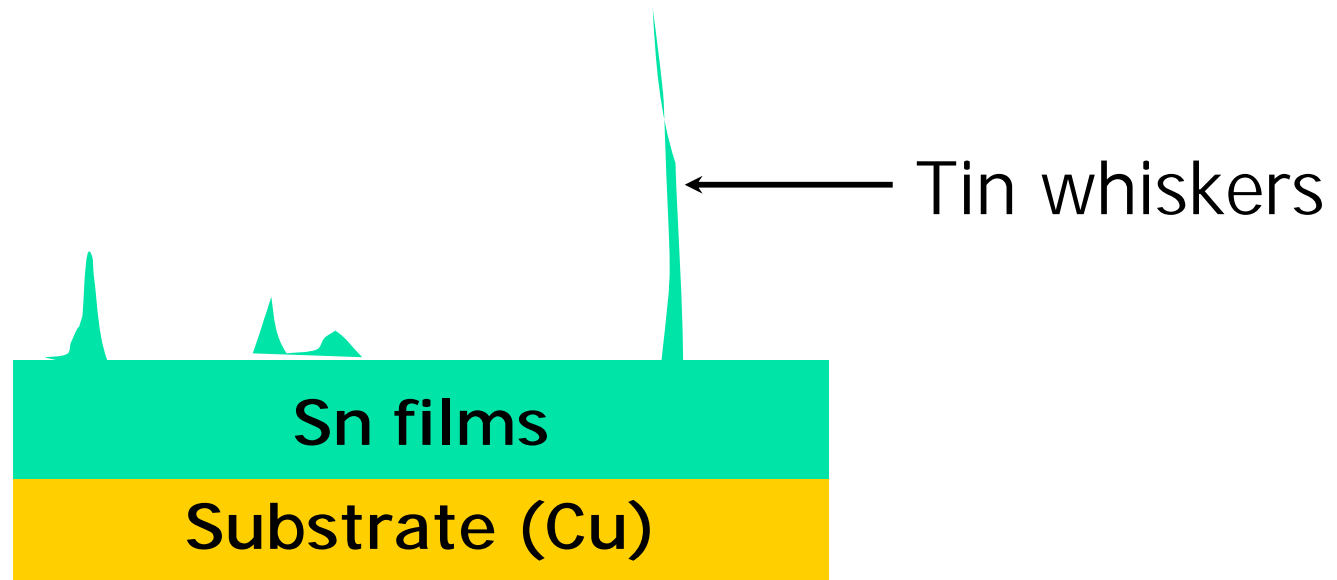
- The move to eliminate Pb from electronics assemblies has resulted in Sn and Sn-rich alloys becoming the alternative
- Pure Sn poses a serious reliability risk due to potential for tin whisker formation and growth
- Tin whiskers are electrically conductive, single crystal structures, spontaneously growing from within pure tin coatings



# Introduction

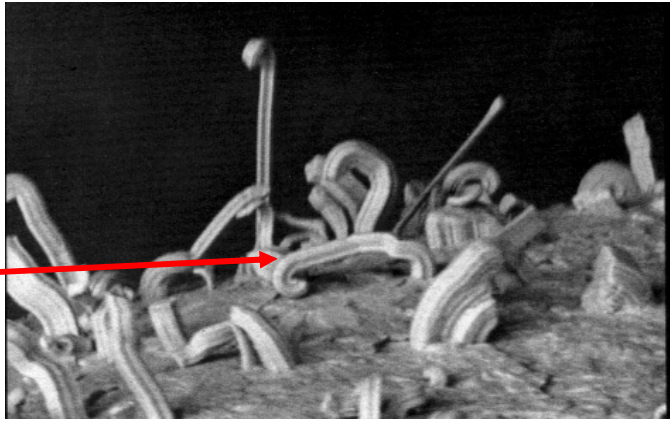
---

## Tin whisker growth on Sn films

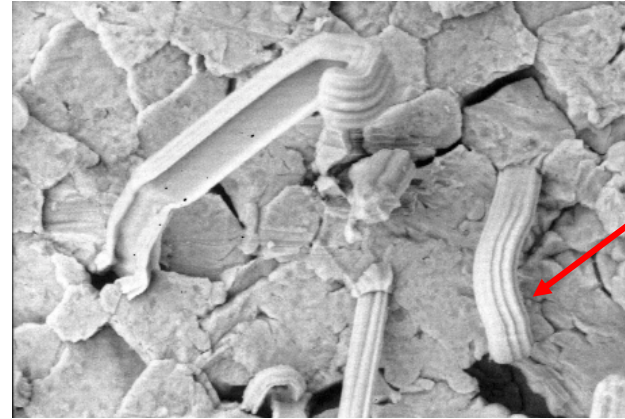


# Sn Whiskers - Micrographs

Kinked



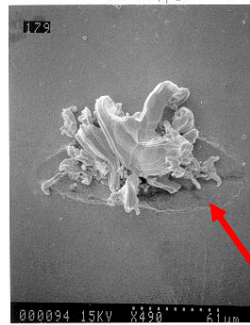
Bent



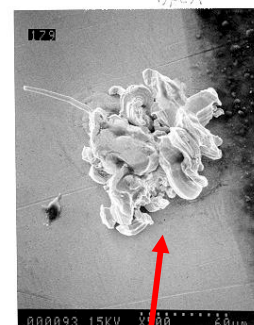
Needle/  
Filament



Striated



Odd-shaped



Needle/Filament



(Pictures from <http://nepp.nasa.gov/whisker/> )



# Introduction

---

Tin whiskers cause two major reliability problems

- **Mechanical problems**

- Generation of debris

- **Electrical shorting**

- Stable short circuits
- Transient short circuits
- Plasma arcing in vacuum

- Complete failure of 3 commercial satellites
- 4 partial losses of commercial satellites
- Tin whisker related problems also reported from medical, military and energy fields



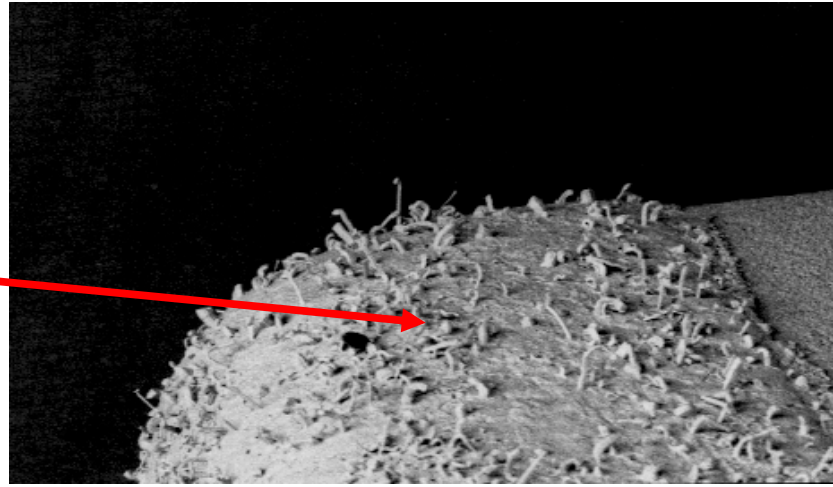
# What are Sn whiskers?

---

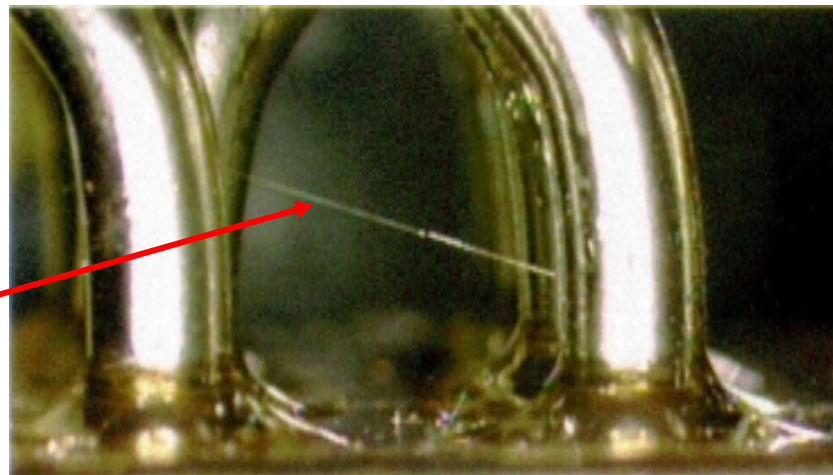
- Single crystals of tin that grow **spontaneously** from plated tin surfaces
- Can grow without electrical field in vacuum and in atmosphere
- **Diameters:** 0.3 ~ 10  $\mu\text{m}$ , typically ~ 1  $\mu\text{m}$  ( 0.04 mils)
- **Lengths:** >1.5 mm (60 mils); some claims of up to 10 mm (0.4 inch)
- Grows best at room **temp** to 75°C (50°C seems optimum)
- **Shape** can be perfectly straight, bent, kinked or forked; some may be hollow

# Sn whisker shapes

Nodules Kinked Bent



Filament



(Pictures from <http://nepp.nasa.gov/whisker/>)



# Sn whiskers

---

- **Growth rates** unknown: may start to grow soon after plating or lie dormant for years
- **Current carrying capacity:** as high as 75 mA before fusing; plasma of tin ions may sustain several HUNDREDS of AMPERES in space
- **Mechanical strength:** strong and stiff



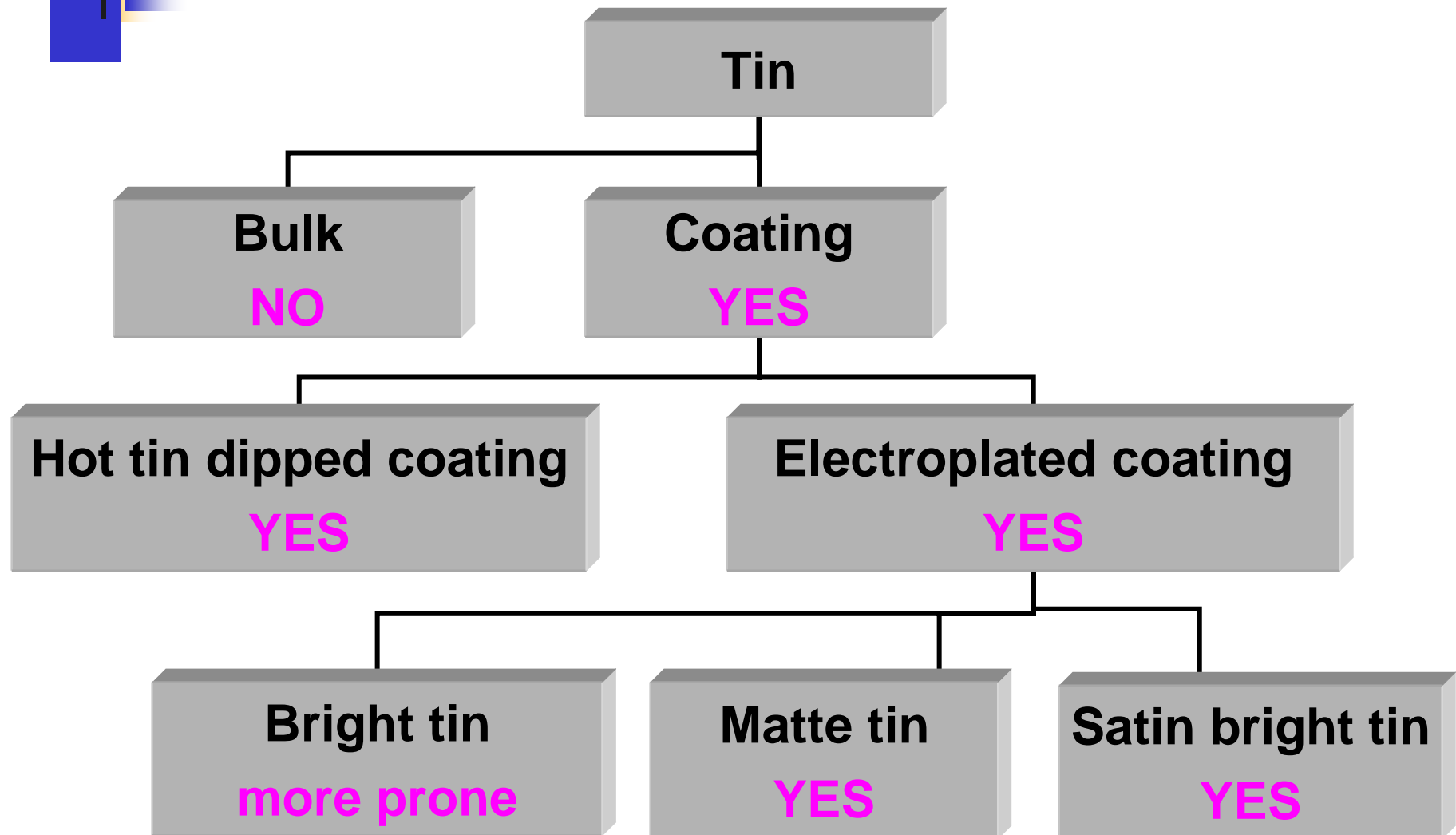


# Tin whiskers: brief history

---

- Reported to be present on electronic hardware in 1946 (there may have been an even earlier report)
- Studied intensively but randomly ever since
- Until 1991, principle concern was effects at atmospheric pressure where whiskers fuse open at  $<10\text{ mA}$  to  $>50\text{mA}$
- First report of “plasma arcing” failure mechanism in 1992

# Where Sn whiskers occur





# Key Issues

## Thermodynamics

- The driving force  $-\Delta G$
- Why tin whiskers grow spontaneously?

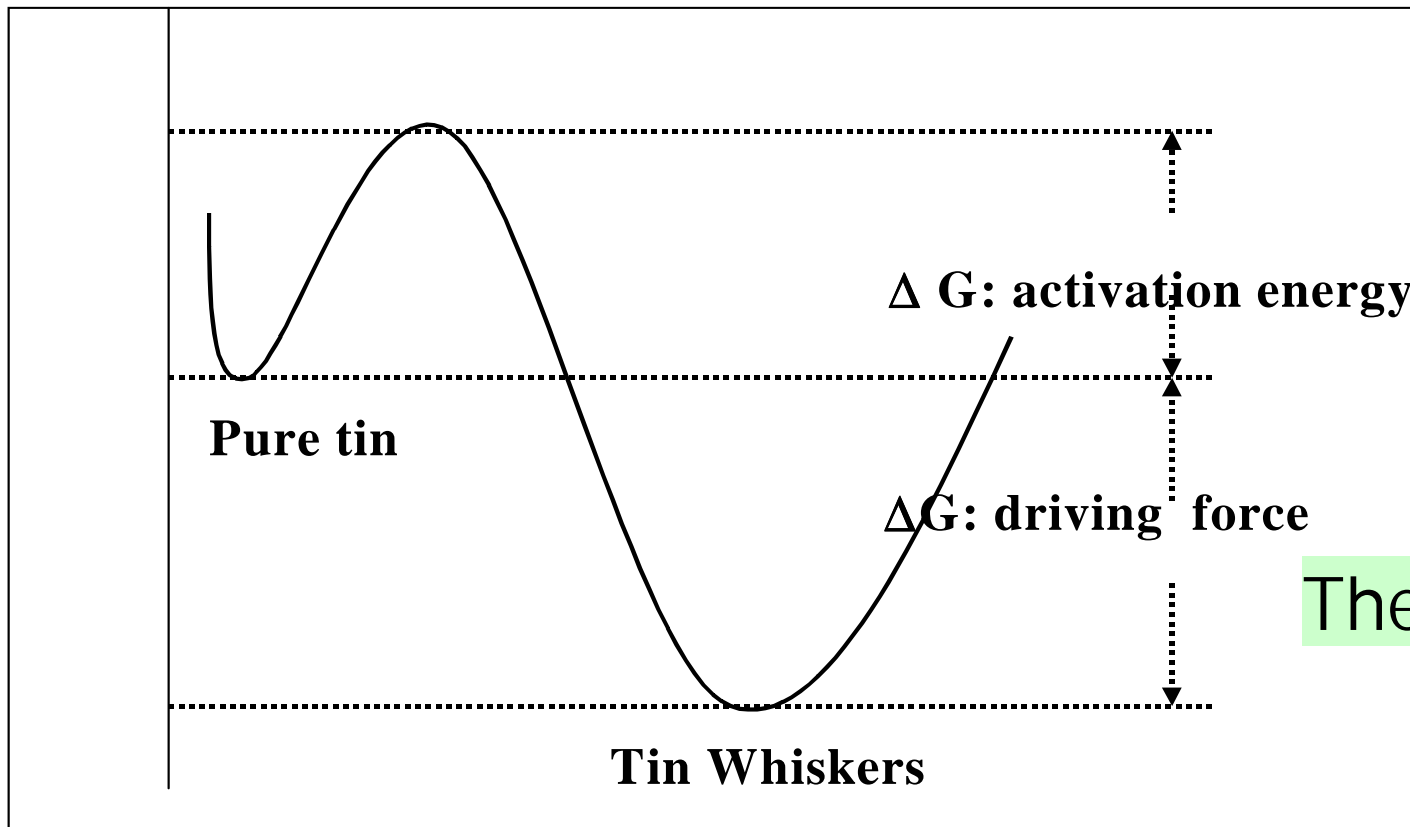
Compressive stress

## Kinetics

- Growth rate  
 $(\text{GrowthRate}) = N \exp\left(\frac{-\Delta G}{RT}\right)$
- How fast do Sn whiskers grow?

Various factors

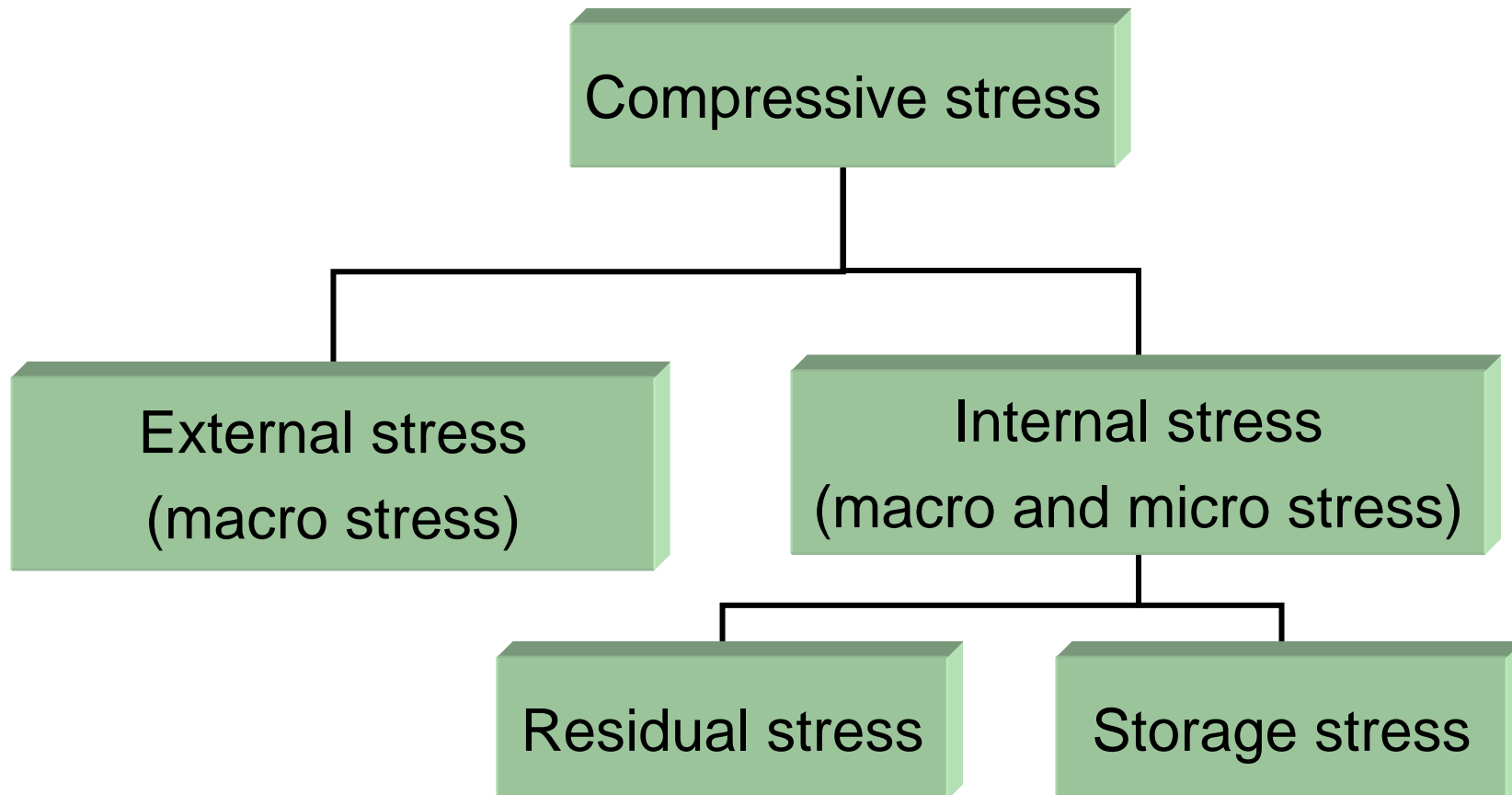
# Key Issues



Kinetics

Thermodynamics

# Thermodynamic factors affecting whiskers growth





# Thermodynamic factors affecting whiskers growth

---

- External stress (in debate)

## **YES**

Influences many aspects of tin whiskers, including nucleation period, density, characteristics, growth rate

## **NO**

No real effects on tin whiskers



# Thermodynamic factors affecting whiskers growth

- Internal stress

## Storage Stress

Diffusion and intermetallic

Diffusion and Surface oxide

## Residual Stress

Grain size and shape

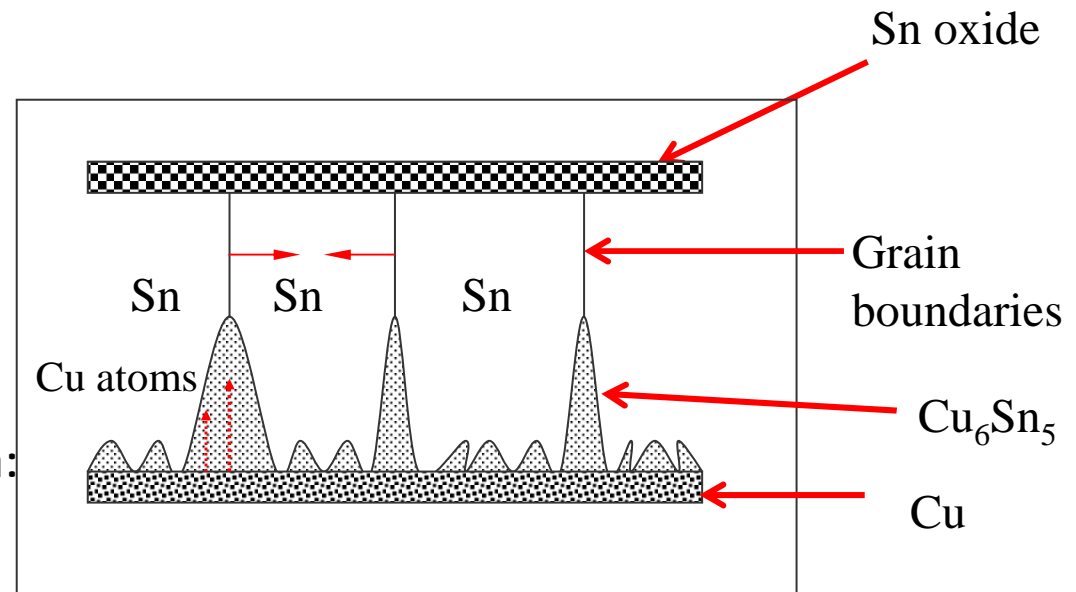
Interfacial and substrate

Electroplating current density

# Thermodynamic factors affecting whiskers growth

## Diffusion and intermetallic compounds

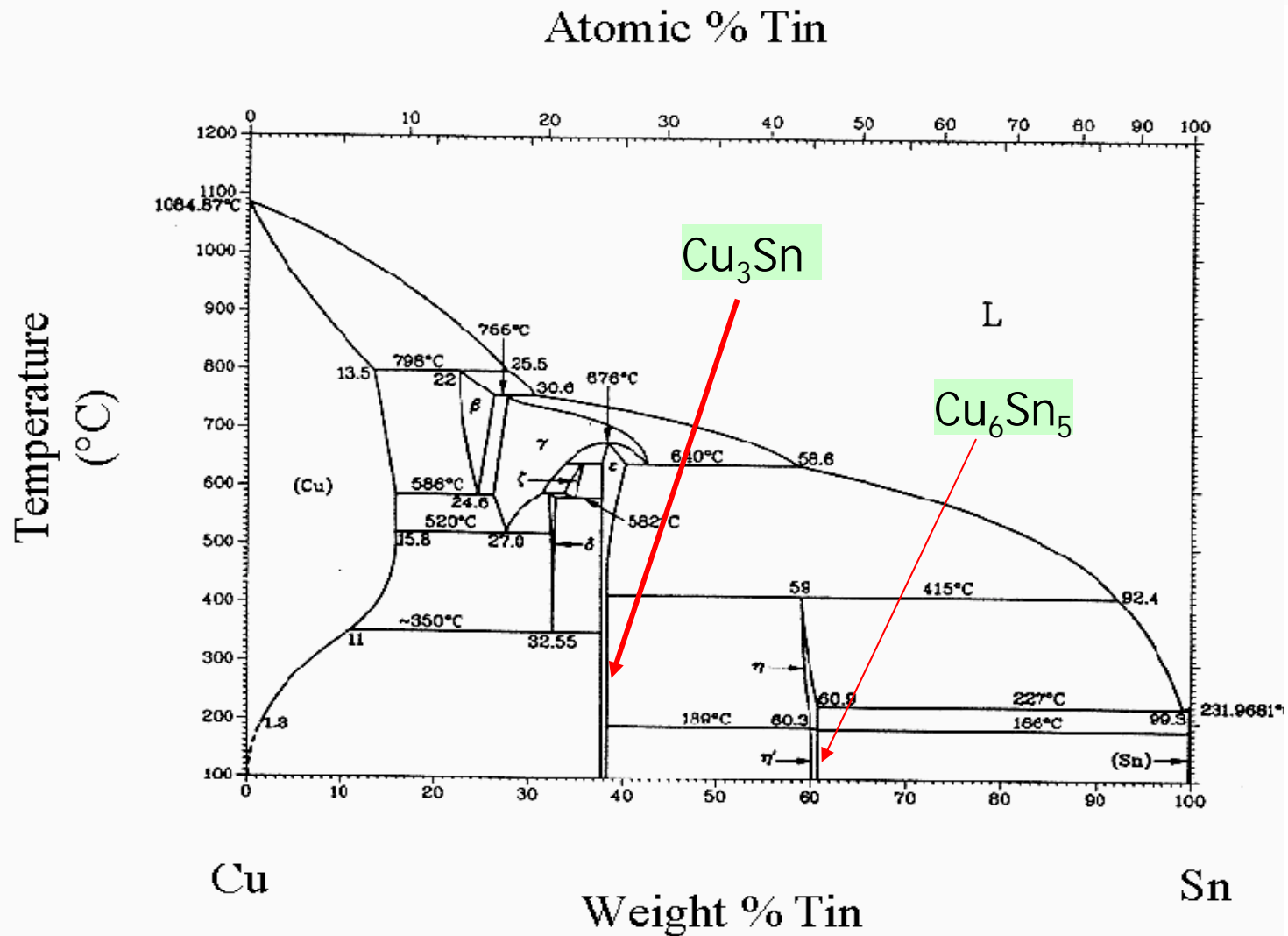
- **Diffusing species:**  
Cu, Zn (from brass substrate)
- **Diffusing direction:**  
from substrate into Sn
- **Diffusion path:**  
Interstitial? Grain boundaries?
- **Diffusion coefficient in Sn:**  
(at room temperature)  
Cu:  $1.2 \times 10^{-6} \text{ cm}^2/\text{s}$   
Zn:  $1.1 \times 10^{-6} \text{ cm}^2/\text{s}$



Diffusion of copper species via grain boundaries



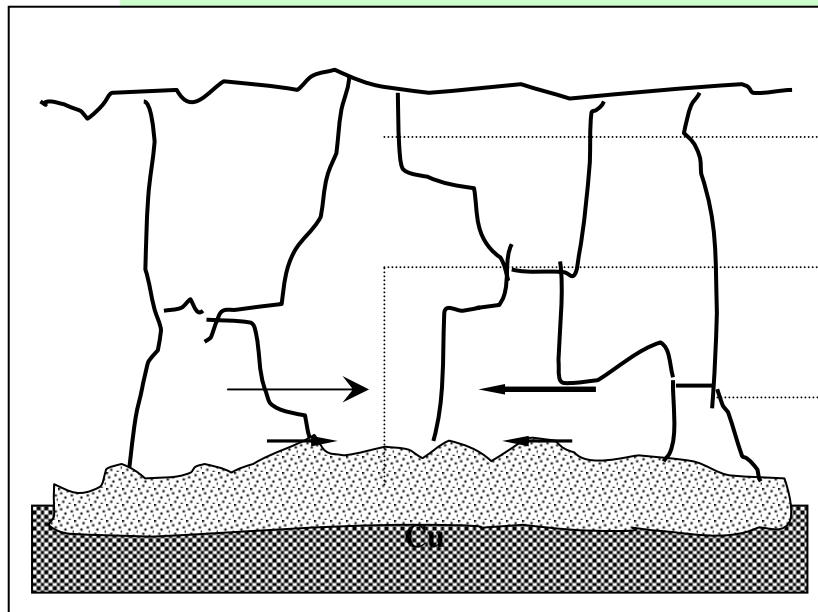
# Thermodynamic factors affecting whiskers growth



Cu-Sn Binary phase diagram

# Thermodynamic factors affecting whiskers growth

## Diffusion and intermetallic compound



**Sn grains**

**Cu<sub>6</sub>Sn<sub>5</sub>**

**Grain boundaries**

■ Tin whiskers initiate only within Sn films

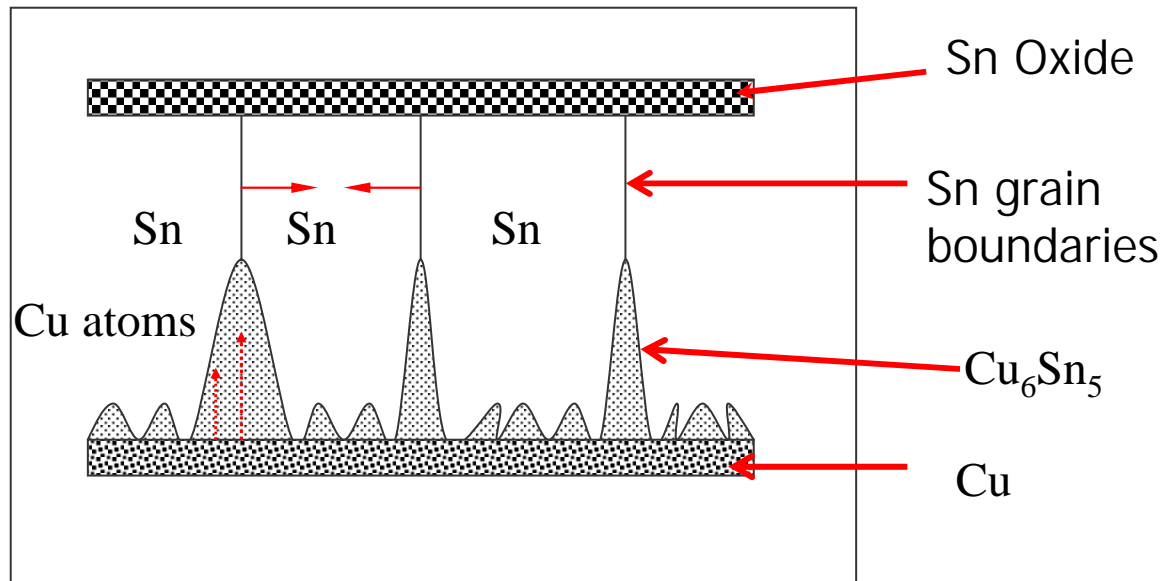
■ Tin whiskers only start at the interfaces

- Density of copper, Sn and Cu<sub>6</sub>Sn<sub>5</sub> are 8.96, 7.28 and 8.27 g/cm<sup>3</sup>, respectively.

- Intermetallic compound formation decreases specific volume and causes compressive stress within Sn film

# Thermodynamic factors affecting whiskers growth

## Grain size and shape



- Sn films with smaller grain size have more grain boundaries and are more prone to tin whisker growth

- Whether high angle or low angle grain boundaries are more favorable for tin whiskers is still in debate

Intermetallic compounds form within grain boundaries



# Thermodynamic factors affecting whiskers growth

---

## Electroplating current density

- Higher current density produces higher residual stress
- Current density vs grain size

## Interfaces and substrate

- Coating vs substrate
- Intermetallic compound vs substrate



# Thermodynamic factors affecting whiskers growth

## **Factors or sources affecting the compressive stress in the Sn layer**

(Ranked by Sn Whisker Fundamentals Modeling Group at NEMI)

- Grain size, shape, orientation
- Carbon, hydrogen, impurities
- Substrate material
- External mechanical stress: bending, scratching, thermal cycling
- Substrate stress
- Irregular, thick, and fast IMC formation



# Kinetic factors affecting whiskers growth

---

## Temperature

Optimum temperature for Sn whisker to form is around 50° C

## Plating thickness

Below 0.5  $\mu\text{m}$  and above 20  $\mu\text{m}$  are the relatively "safe " ranges. Over 8  $\mu\text{m}$  Sn whiskers are more resistant to grow

## Grain size and shape

Tin whisker grows faster within Sn film with small grain size grain angle can also affect the growth rate



# Kinetic factors affecting whiskers growth

## Temperature

$$(\text{Growth Rate}) = N \exp\left(\frac{-\Delta G}{RT}\right)$$

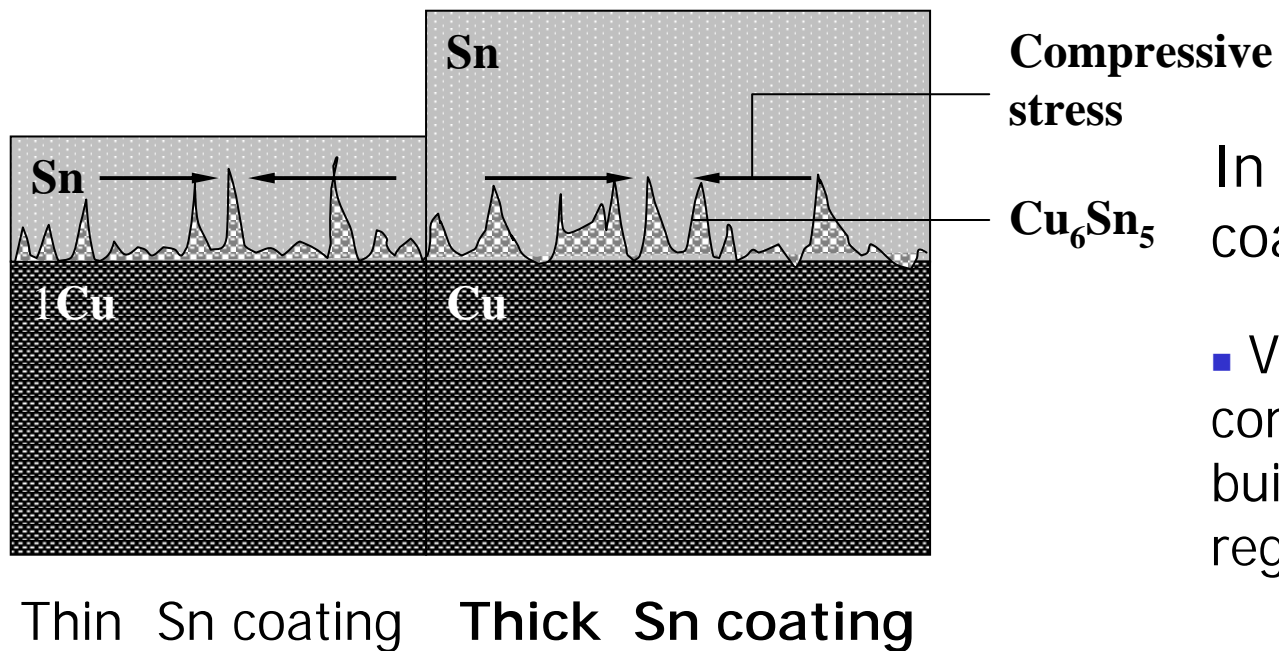
- High temperature helps relief internal stress - decreasing driving force
- Enhancing temperature also accelerates diffusion - increasing driving force

It is believed 50°C is the optimum temperature for Sn whiskers to grow.

It is also reported that 25°C is more favorable than 50°C

# Kinetic factors affecting whiskers growth

## Plating thickness



In the case of thick Sn coatings:

- Very little to no compressive stresses are built up near the surface region
- Intermetallic compound layer retards further diffusion



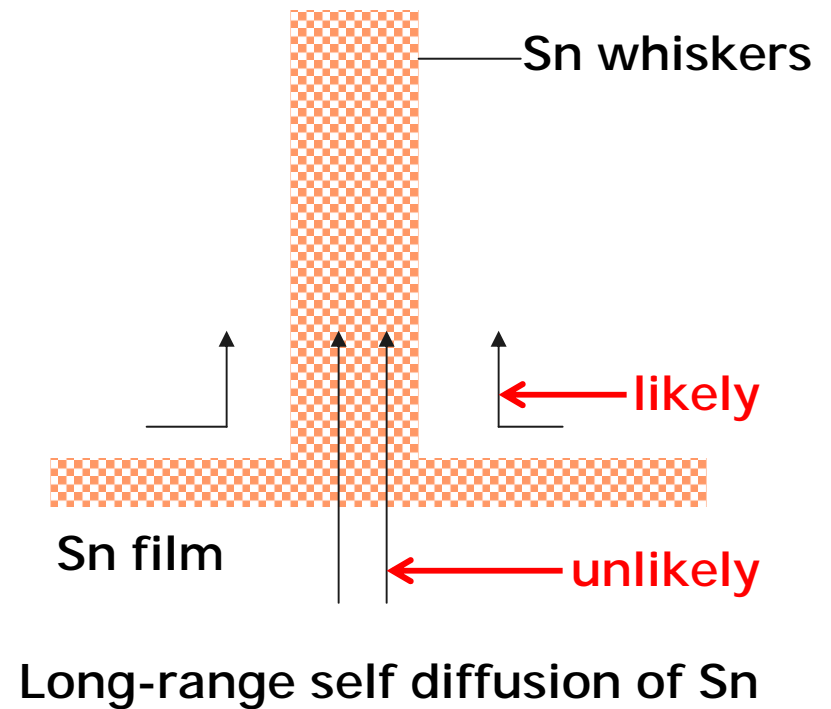
# Outstanding issues

## Self diffusion and Sn whiskers growth

### Sn

- **Melting temperature**  
232°C (relatively low for metals)
- **Recrystallization temperature**  
30°C (around room temperature)
- **Self diffusion coefficient**
- **Diffusion path**  
From center to top (unlikely)  
From outside to top (likely)
- **Driving force**  
Might be small electrical potential bias

$$\mu^{Sn}_{top} < \mu^{Sn}_{bottom}$$





# Outstanding issues

---

Does tensile stress inhibit Sn whisker growth?

- **Intentionally induced tensile stress**

Initially imposed tensile stress seems slow down the built-up process of compressive stress

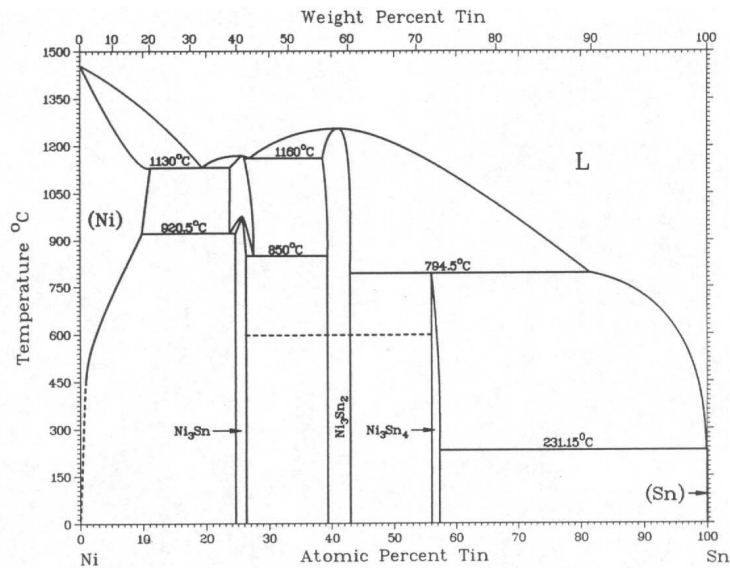
Annealed Sn film developed a thermal tensile stress of 14 Mpa at room temperature and no whisker growth took place afterwards

- **Nickle barrier**

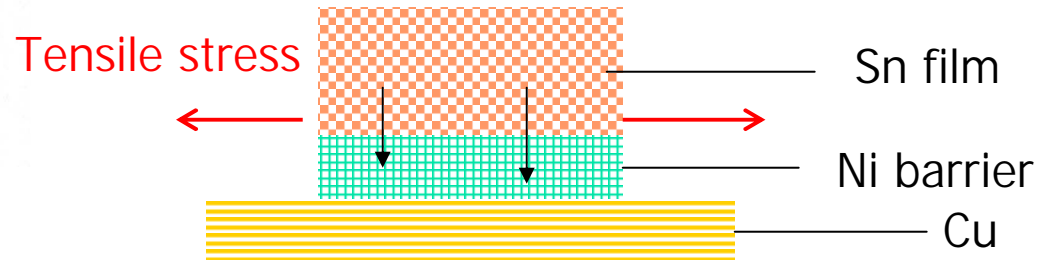
Tin diffuses into nickle barrier resulting in tensile stress within Sn film

# Outstanding issues

## Does tensile stress inhibit tin whisker growth?



Sn atoms diffusing into Ni barrier may result in material deficiency on the Sn film side (Kirkendall effects)



The significant difference of the solubility implies that it is easier for Sn to dissolve into Ni than for Ni to dissolve into Sn.



# Conclusion

---

- Compressive stress is widely accepted as the driving force to form Sn whiskers
- The origination of compressive stress is still under extensive studies
- Kinetically, many factors can affect the growth rate of Sn whiskers. The understanding of the correlations of these factors is the key
- Mitigation practices such as conformal coating, Ni barrier, reflow still can not eliminate whiskers effectively to date
- Many puzzles remain
- Testing and standards are needed