Understanding and Minimizing Tin Whiskers

A Review of the Literature

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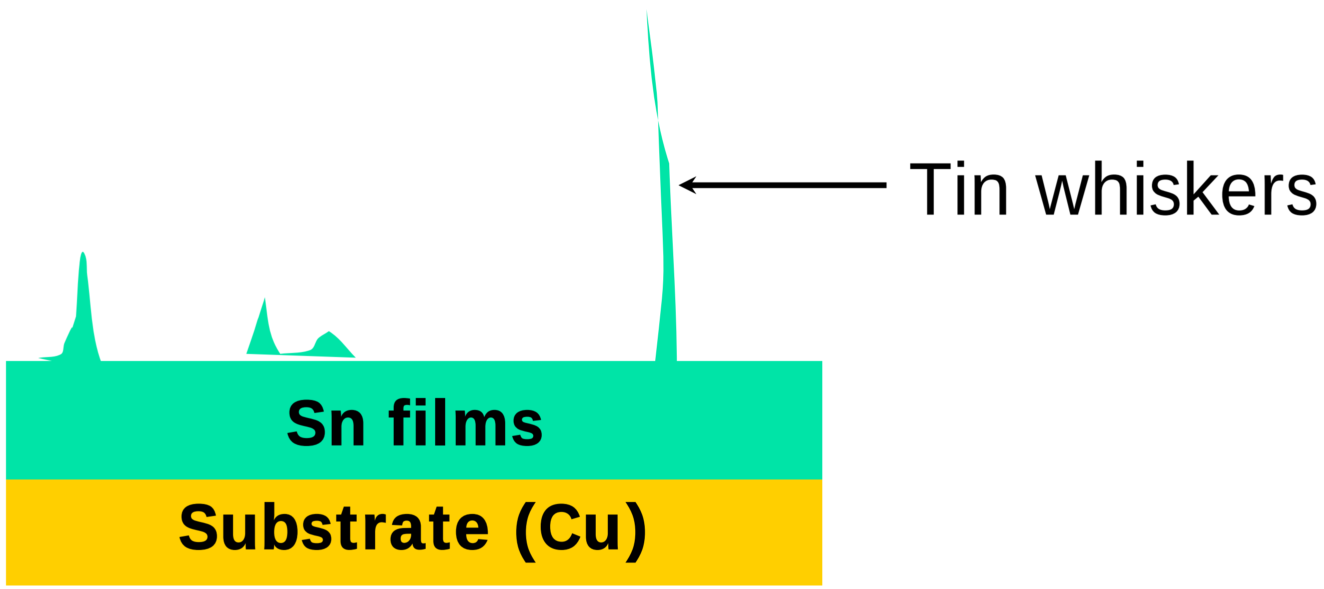
Introduction

- 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

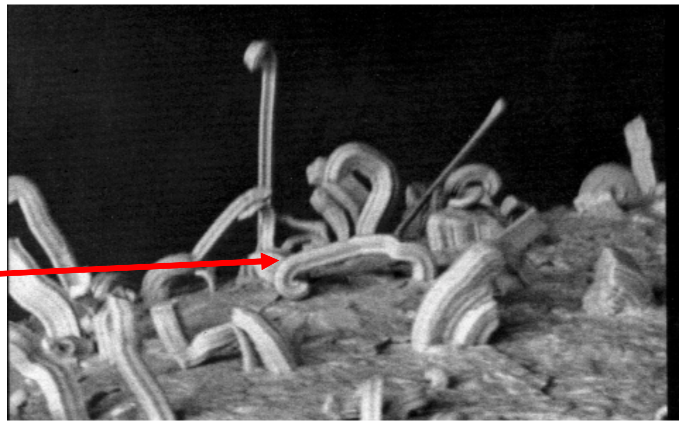
Introduction

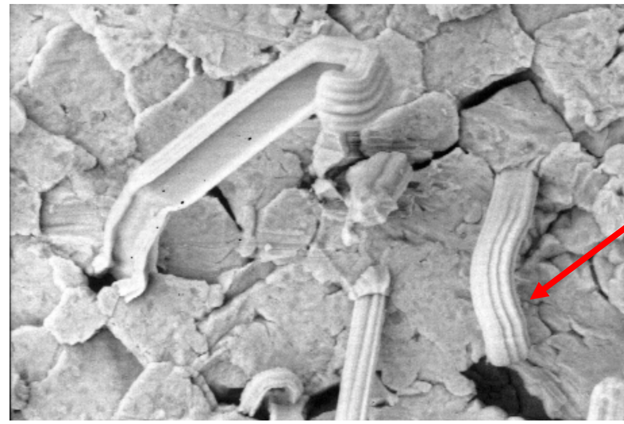
Tin whisker growth on Sn films



Sn Whiskers - Micrographs

Kinked

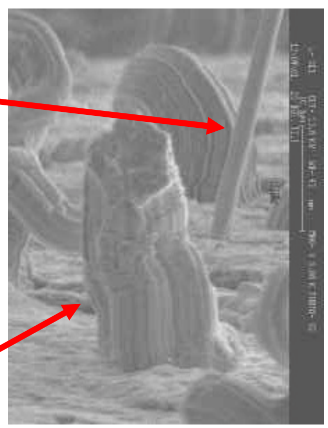




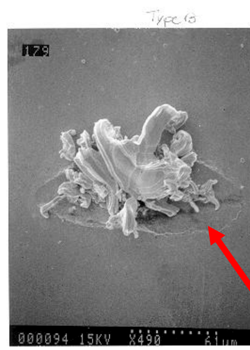
Bent

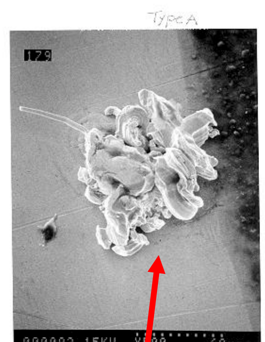
Needle/

Filament

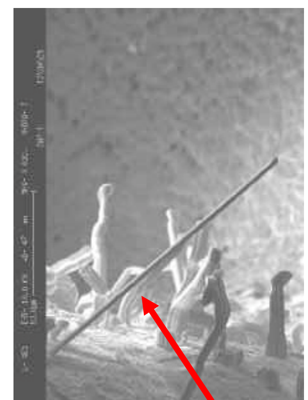


Striated





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

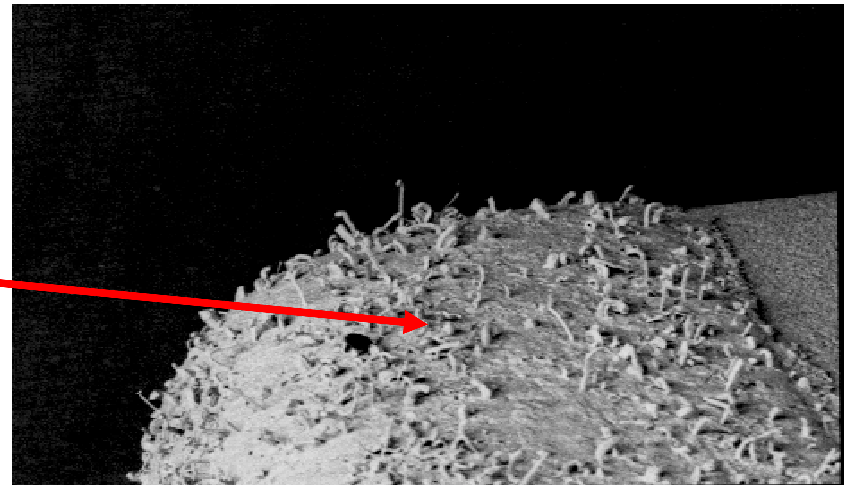
- Complete failure of 3 commercial satellites
- 4 partial losses of commercial satellites
- Tin whisker related problems also reported from medical, military and energy fields

What are Sn whiskers?

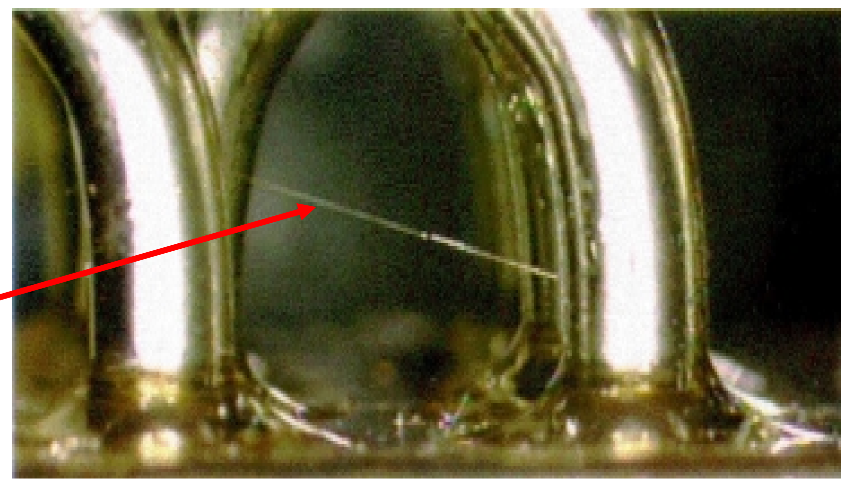
- Single crystals of tin that grow **spontaneously** from plated tin surfaces
- Can grow without electrical field in vacuum and in atmosphere
- **Diameters:** 0.3 ~ 10 µm, typically ~ 1 µm (0.04 mils)
- **Lengths:** >1.5 mm (60 mils); some claims of up to 10 mm (0.4 inch)
- Grows best at room **temp** 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/)

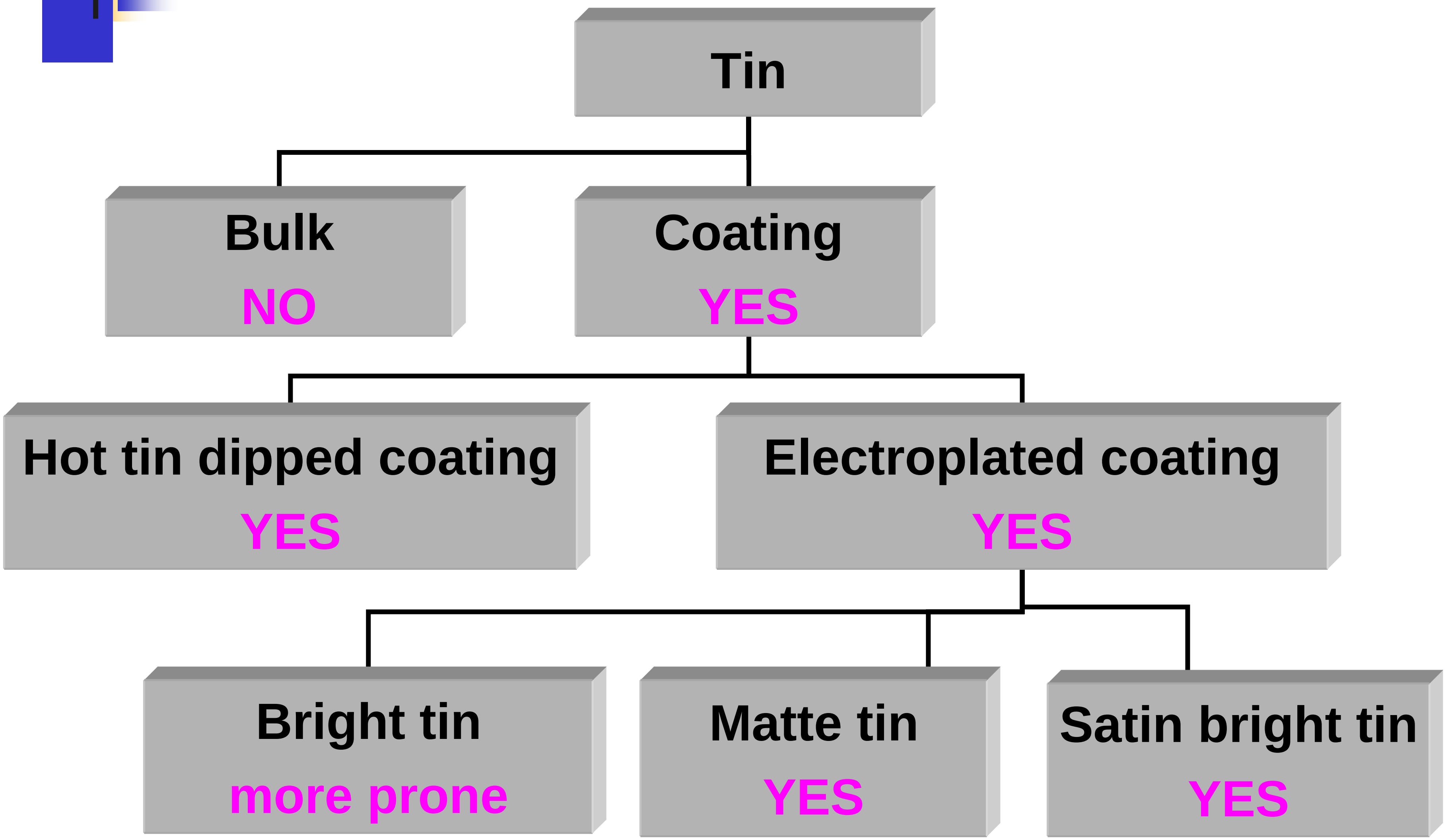
Sn whiskers

- **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 mA to >50mA
- 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

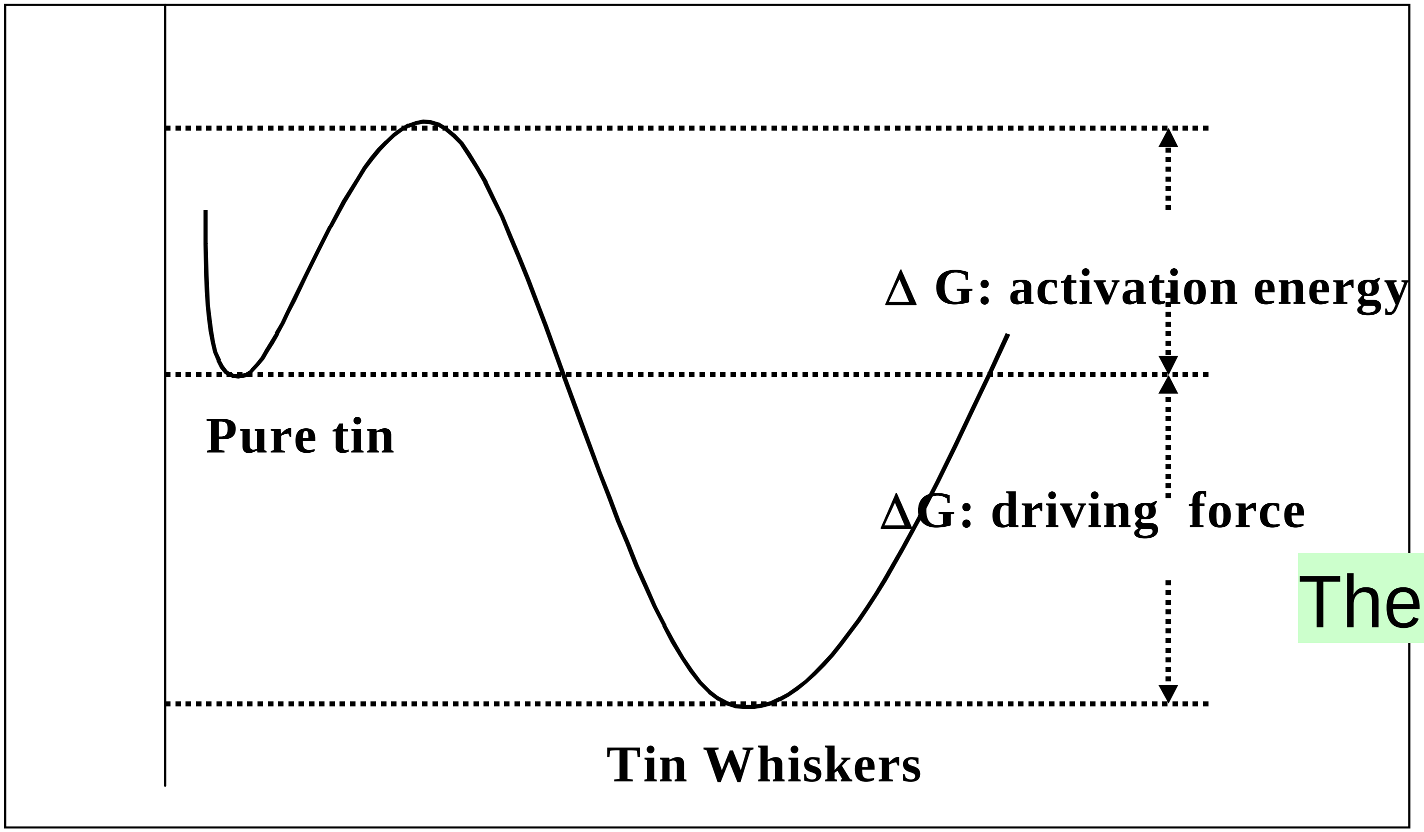
- Growth rate

$$(\text{GrowthRate}) = N\exp(\frac{-\Delta G}{RT})$$

- How fast do Sn whiskers grow?

Various factors

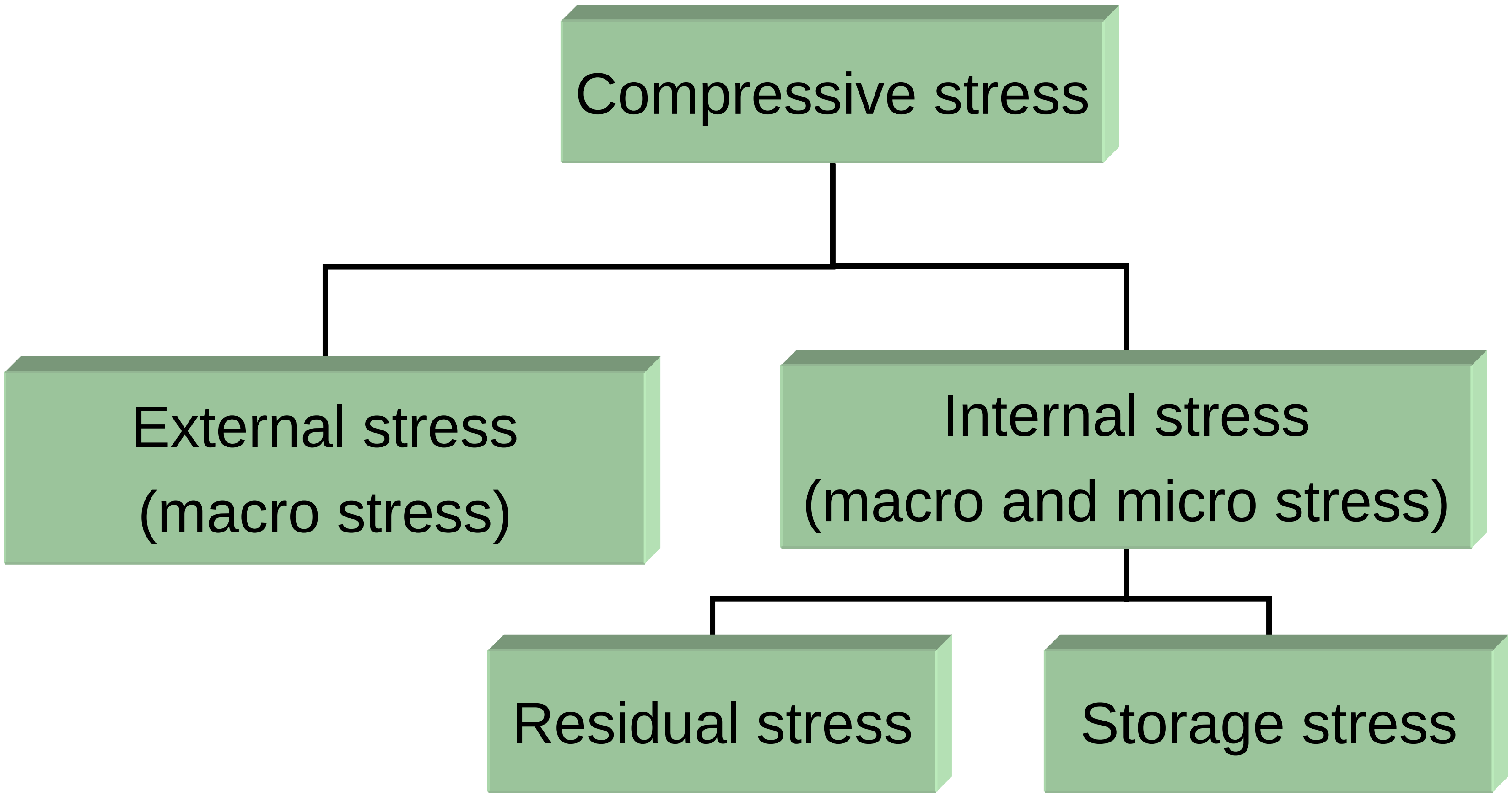
Key Issues



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**:

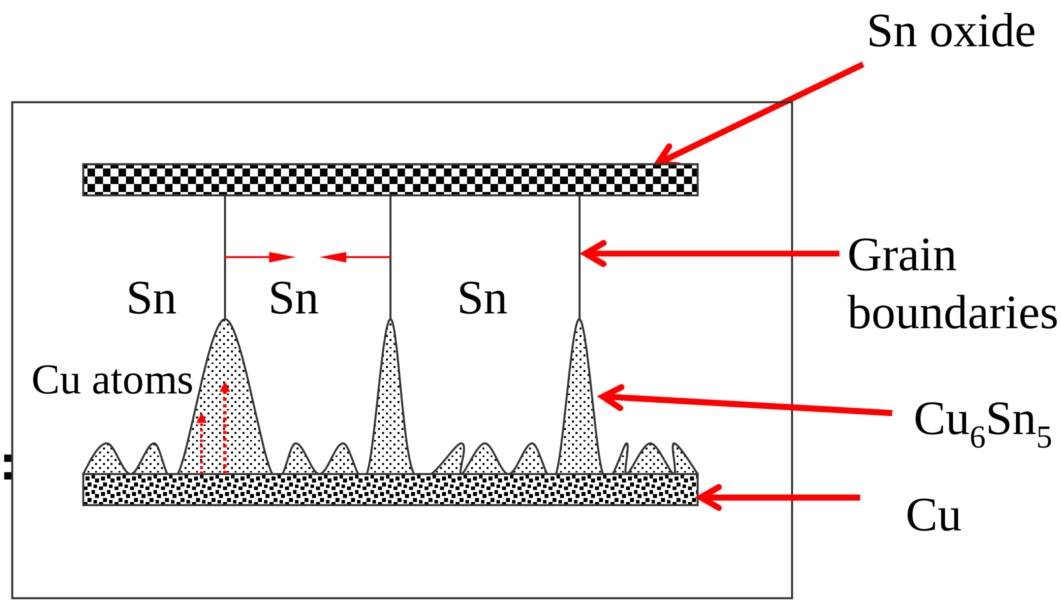
Interstitial**?** Grain boundaries?

- **Diffusion coefficient in Sn:**

(at room temperature)

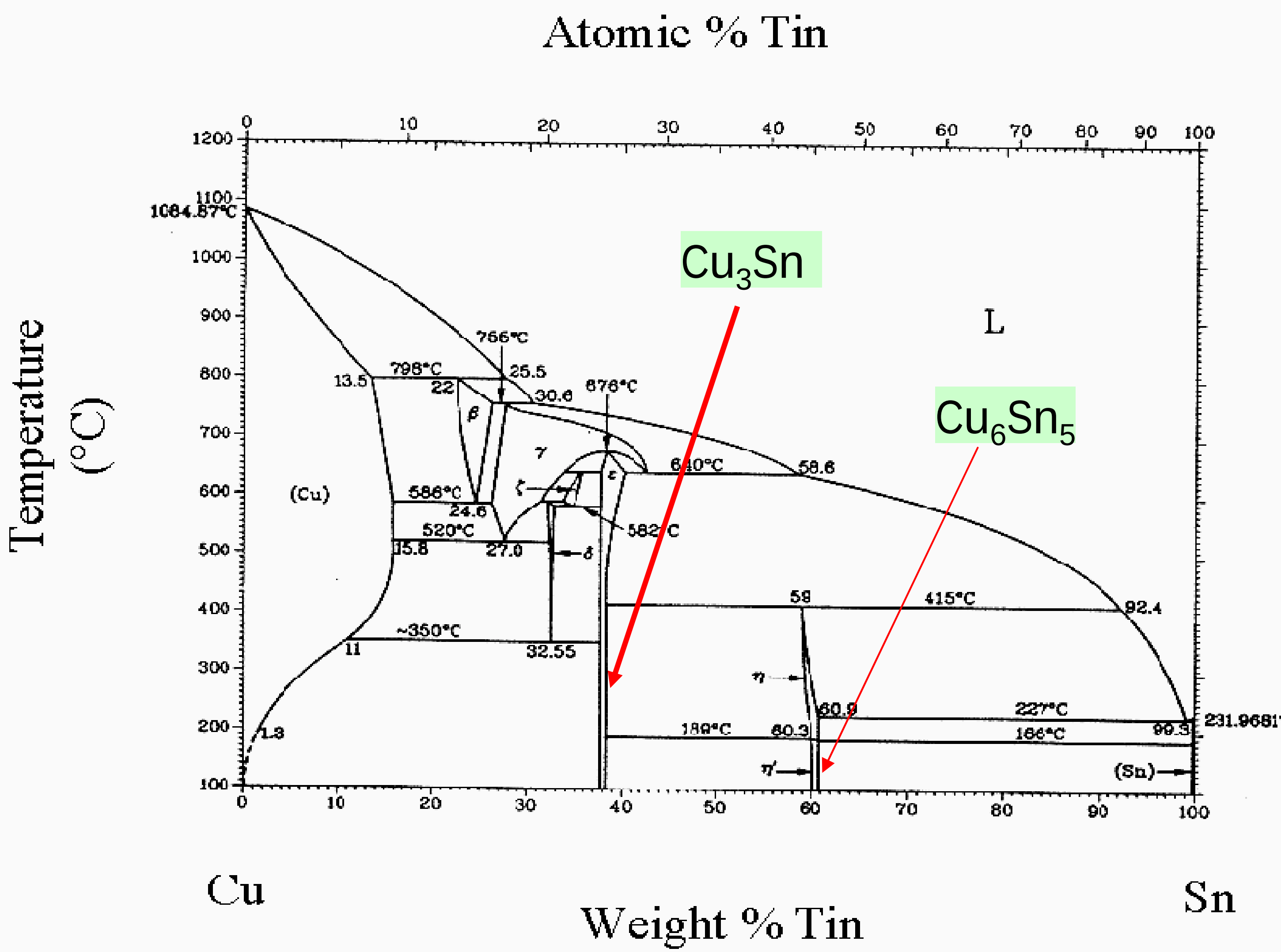
Cu:1.2x10^{-6} cm^2/s

Zn:1.1x10^{-6} cm^2/s



Diffusion of copper species via grain boundaries

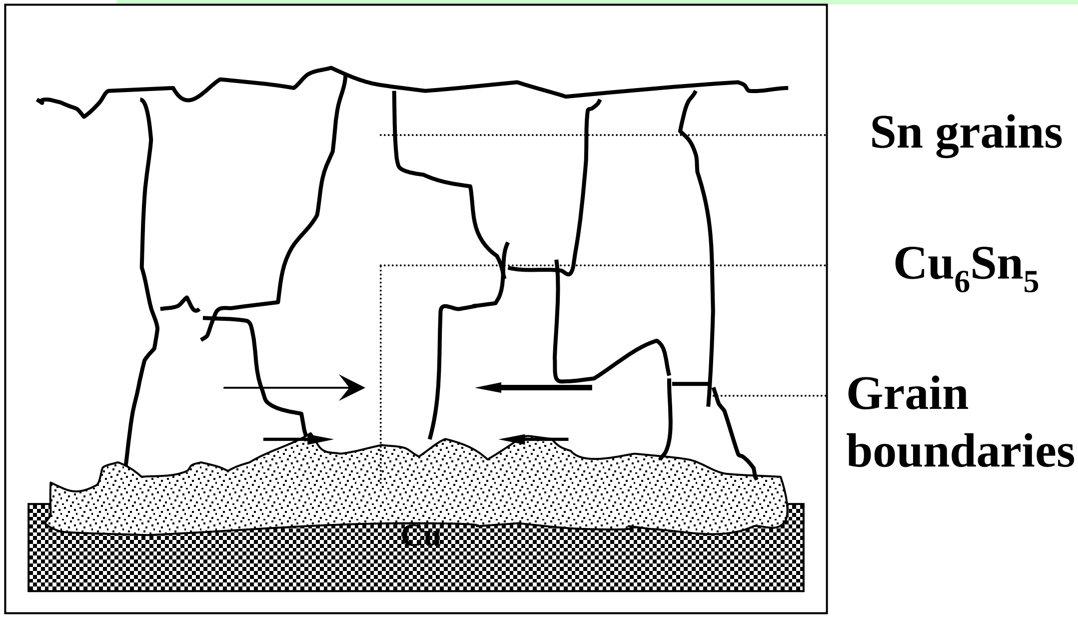
Thermodynamic factors affecting whiskers growth



Cu-Sn Binary phase diagram

Thermodynamic factors affecting whiskers growth

Diffusion and intermetallic compound



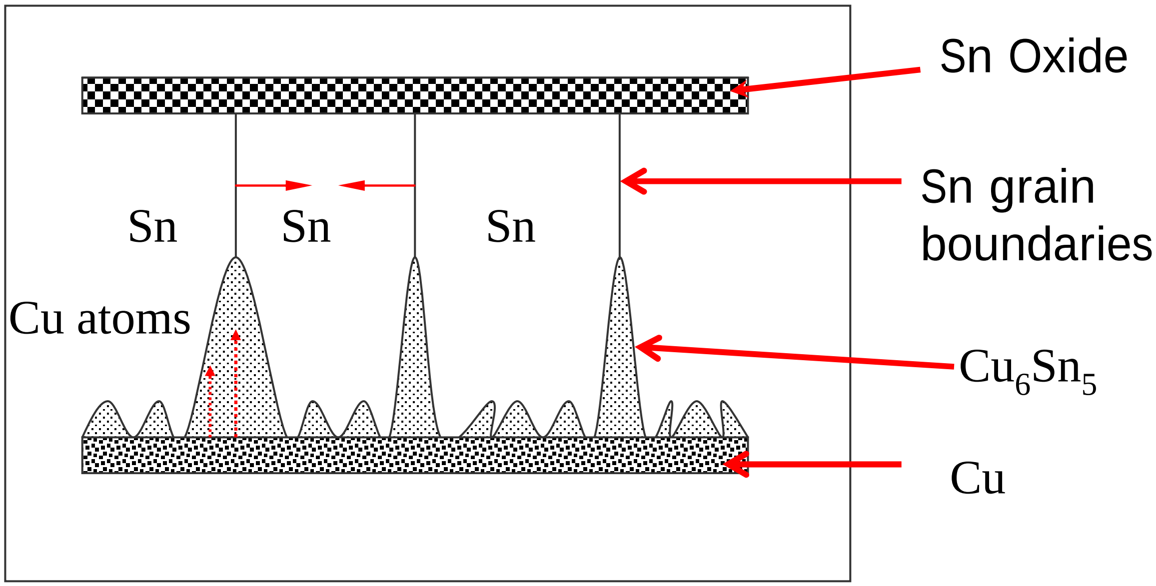
- Tin whiskers initiate only within Sn films
- Tin whiskers only start at the interfaces

• Density of copper, Sn and Cu_6Sn_5 are 8.96, 7.28 and 8.27 g/cm^3 , 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 µm and above 20 µm are the relatively "safe " ranges. Over 8 µm 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

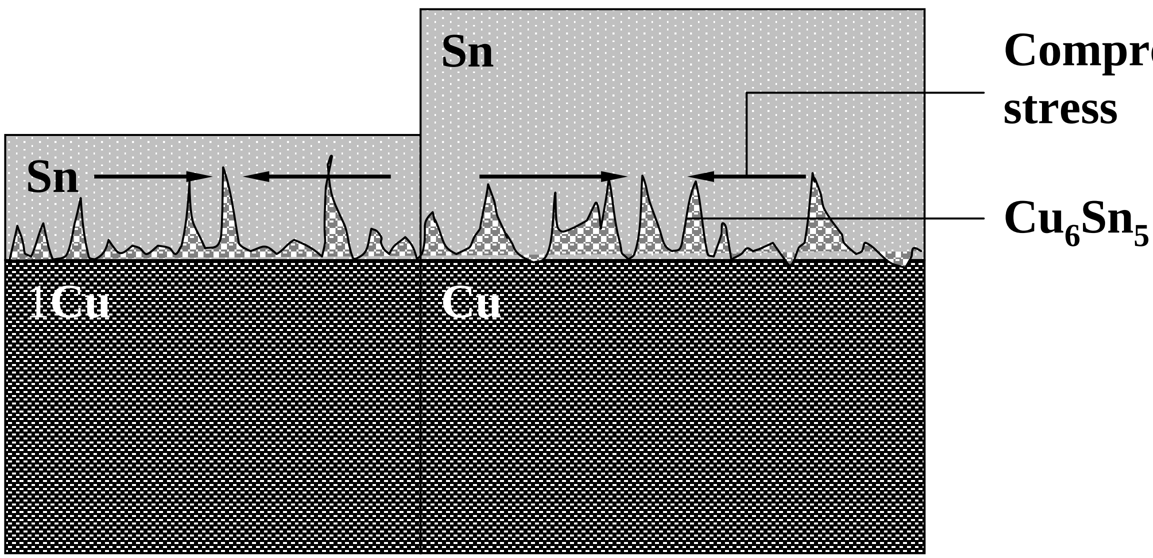
$$(\text{Growth Rate}) = N\exp\left(\frac{-\Delta G}{RT}\right)$$

- 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



Thin Sn coating **Thick Sn coating**

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**

232ºC (relatively low for metals)

- **Recrystallization temperature**

30ºC (around room temperature)

- **Self diffusion coefficient**
- **Diffusion path**

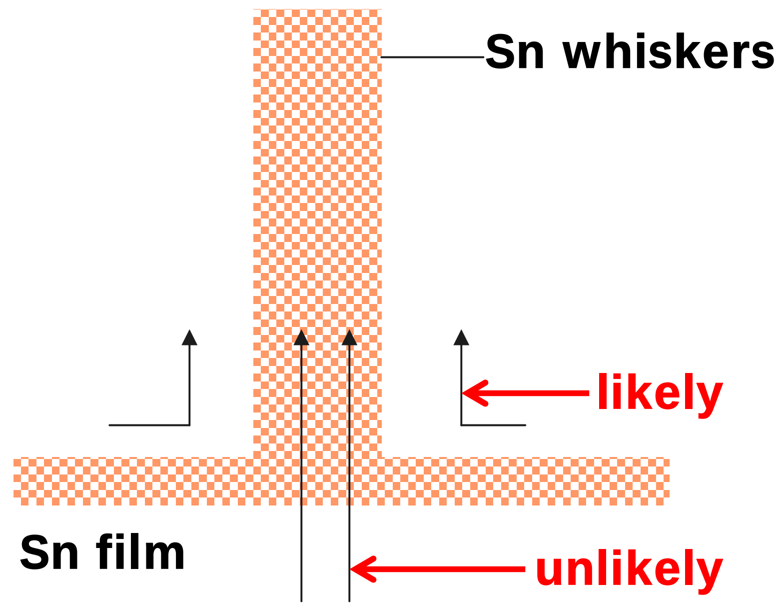
From center to top (unlikely)

From outside to top (likely)

- **Driving force**

Might be small electrical potential bias

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



Long-range self diffusion of Sn

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

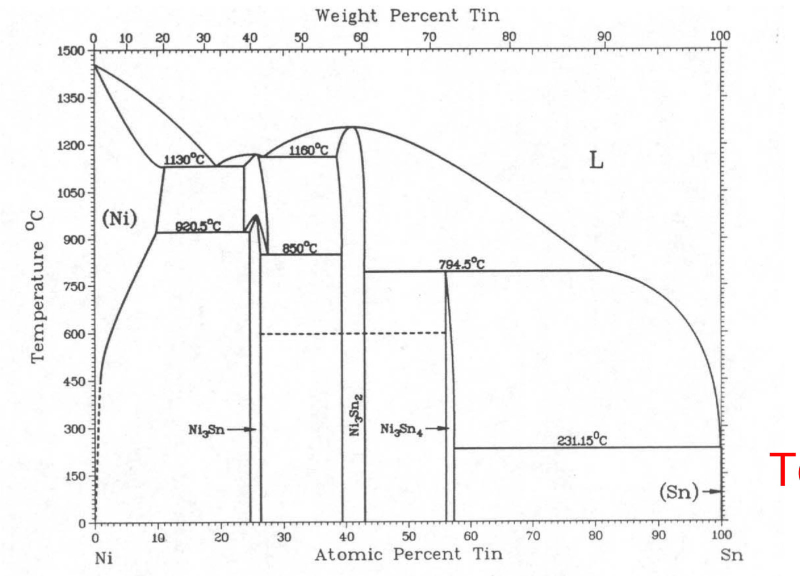
  Annealed Sn film developed a thermal tensile stress of 14 Mpa at room temperature and no whisker growth took place afterwards

- **Nickle barrier**

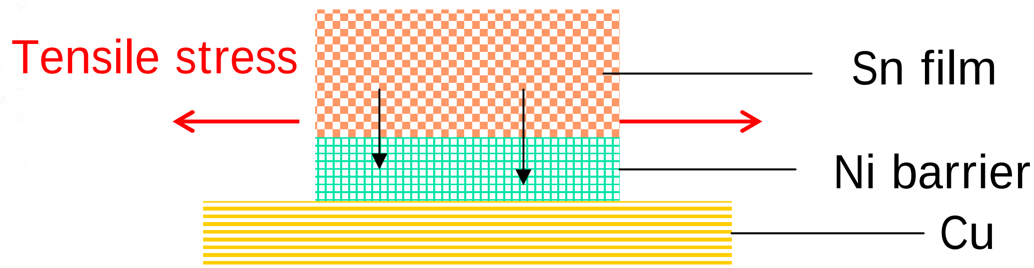
  Tin diffuses into nickle barrier resulting in tensile stress within Sn film

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