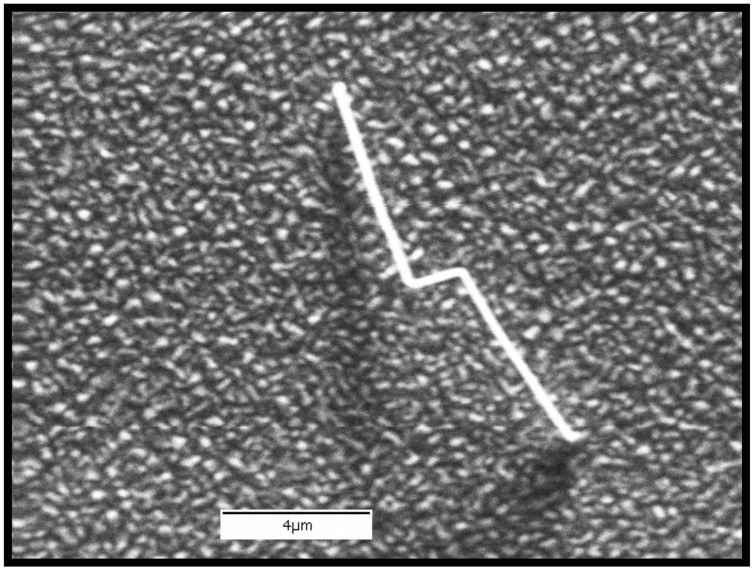
Influence of Surface Composition and Substrate Roughness on Tin Whisker Growth

Sn Whisker Telecon

May 26, 2010



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Research Areas

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- Chip-Level Interconnects Flip-Chip and Underfills
- Component Reliability Prognostic Health Management Systems
- Connectors, and System-Level Interconnects Degradation and Wear Mechanisms
- Harsh Electronics Systems and Manufacturing
- Lead-Free Solder Alloys Constitutive and Wetting Behavior

CAVE Resources

CAPABILITIES

Accelerated Testing
Thermal Cycling
Drop-Testing
Vibration
THB, SIR
Temp-Vibration

Failure Analysis
SEM, AES, XPS, ISS
EDX
FTIR
STEM
RBS

Modeling and Simulation
ANSYS, ABAQUS,
Hypermesh, LS-DYNA
Solid Edge, Meshfree
Nastran, Matlab
Peridynamics
Pro-Engineer

Surface Mount Assembly
MPM Printer
Agilent SP1 Inspection
Asymtek Flux Jetting
Siemens SIPLACE
VISCOM VPS 6053
Heller 1800

Website: cave.auburn.edu

Outline of Talk

Implementation of Pb-free electronics has resulted in the use of pure tin (Sn) surface finishes which are known to pose reliability issues due to the spontaneous growth of Sn whiskers. In this talk, we focus on four aspects of whisker growth:

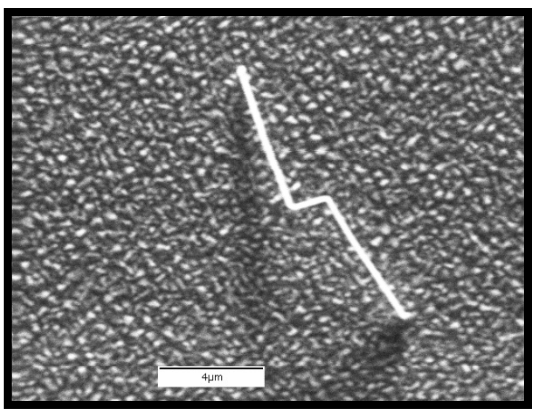
- Whisker basics.
- Surface composition of Sn whiskers.
- Influence of substrate surface roughness on whisker growth.
- Growth of Sn whiskers on semiconductor and insulator surfaces.

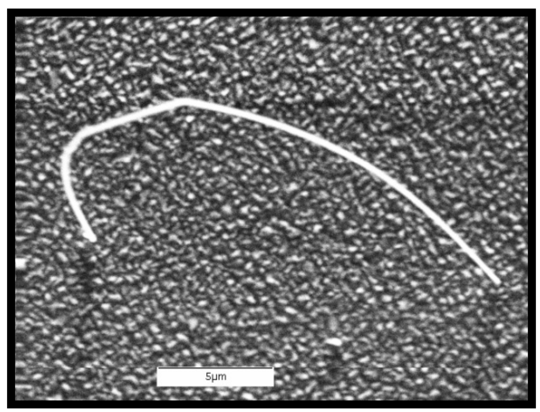
What are Tin (Sn) Whiskers?

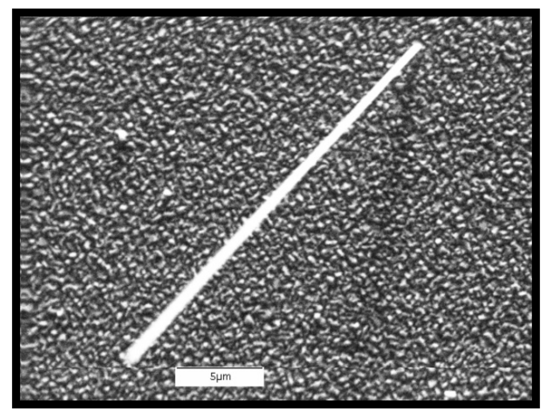
Sn whiskers are single crystal Sn eruptions that grow from deposited tin films.

- They are electrically conductive with lengths varying from microns to millimeters and thicknesses from 0.5-10 microns.
- Whisker densities (whiskers/cm^2) can vary from a few to thousands.
- Unpredictable incubation period (hours, days, years).

Cause: No current consensus. Thin film stress (usually compressive) thought to drive Sn atoms to the whisker base by long-range diffusion along surfaces, interfaces, and grain boundaries.







Tin Whiskers Formation on an Electronic Product: A Case Study

Nausha Asrar · Oliver Vancauwenberghe ·
Sebastien Prangere

Submitted: 31 January 2007 / Published online: 20 June 2007

Background

During qualification testing, a printed circuit board (PCB) of an electronic device from a drilling tool failed. The circuit board did not fail during the 120 h aging at 180°C. However, during the subsequent thermal cycles, in the temperature range of –40 to 180°C, it failed after 10 cycles (each cycle was of 2 h). During the inspection numerous white whiskers were observed over the Sn96 solder joint surfaces of components. In addition, fracture of the wire-bonds of a PCB-mounted chip were observed, which caused the failure of the circuit board. In this paper likely causes of tin whisker formation are discussed.

- Product being tested for "Down Hole Oil" Application. Uses Sn96 High Temp Solder

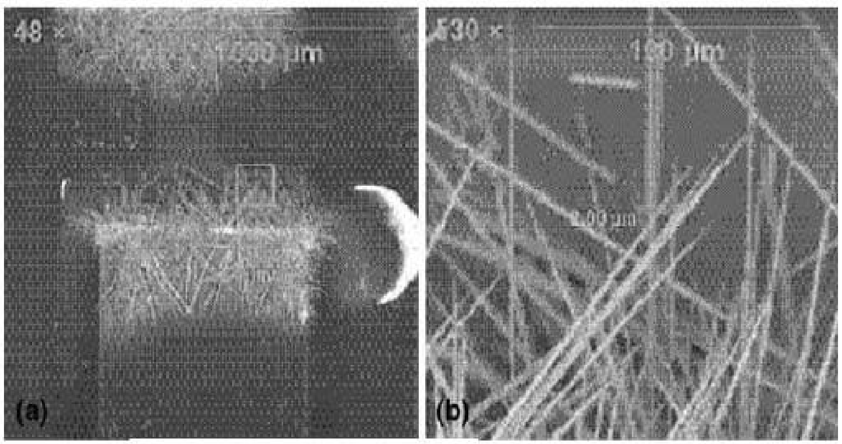


Fig. 4 (a) SEM picture showing the length of the tin whisker (0.344 mm, formed in 140 h). (b) Thickness of the tin whisker (0.002 mm)

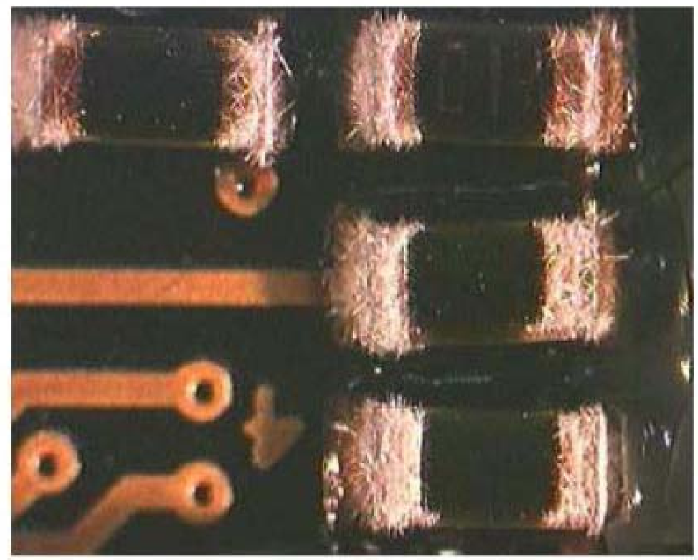


Fig. 3 Close-up showing tin whiskers on the solder joints. 40×

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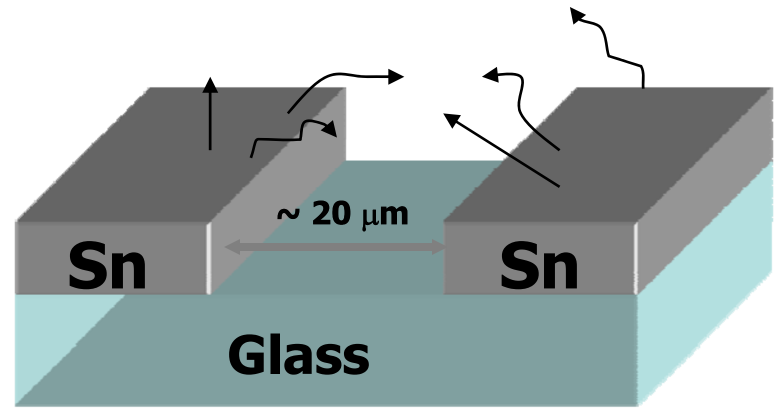
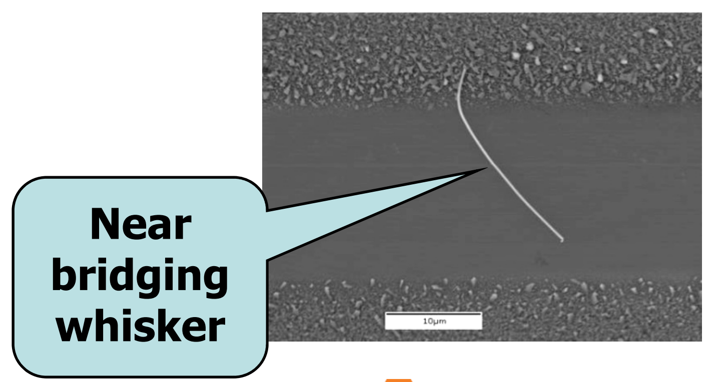
Reliability Concerns

Tin whiskers have become an increasing reliability concern due to the demand for smaller, more compact electronics and continued progress toward lead free electronics.



Failure Modes Caused by Tin Whiskers

- **Electrical Shorts**
  - **Permanent** if current < melting current
  - **Intermittent** if current > melting current
- **Metal Vapor Arcing**
  - High levels of current can cause whiskers to vaporize into a conductive plasma.
  - Plasma subsequently forms an arc capable of sustaining hundreds of amps of current.



History of Documented Metal Whisker Failures: 2000s

Year**	Application	Industry	Failure Cause	Whiskers on?
2000	GALAXY VII (Side 2)	Space (Complete Loss)	Tin Whiskers	Relays
2000	Missile Program "D"	Military	Tin Whiskers	Terminals
2000	Power Mgmt Modules	Industrial	Tin Whiskers	Connectors
2000	SOLIDARIDAD I (Side 2)	Space (Complete Loss)	Tin Whiskers	Relays
2001	GALAXY IIIR (Side 1)	Space	Tin Whiskers	Relays
2001	Hi-Rel	Hi-Rel	Tin Whiskers	Ceramic Chip Caps
2001	Nuclear Power Plant	Power	Tin Whiskers	Relays
2001	Space Ground Test Eqpt	Ground Support	Zinc Whiskers	Bus Rail
2002	DirecTV 3 (Side 1)	Space	Tin Whiskers	Relays
2002	Electric Power Plant	Power	Tin Whiskers	Microcircuit Leads
2002	GPS Receiver	Aeronautical	Tin Whiskers	RF Enclosure
2002	MIL Aerospace	MIL Aerospace	Tin Whiskers	Mounting Hardware (nuts)
2002	Military Aircraft	Military	Tin Whiskers	Relays
2002	Nuclear Power Plant	Power	Tin Whiskers	Potentiometer
2003	Commercial Electronics	Telecom	Tin Whiskers	RF Enclosure
2003	Missile Program "E"	Military	Tin Whiskers	Connectors
2003	Missile Program "F"	Military	Tin Whiskers	Relays
2003	Telecom Equipment	Telecom	Tin Whiskers	Ckt Breaker
2004	Military	Military	Tin Whiskers	Waveguide
2005	Communications	Radio (1960s vintage)	Tin Whiskers	Transitor TO Package
2005	Millstone Nuclear Power Plant	Power	Tin Whiskers	Diode (Axial Leads)
2005	OPTUS B1	Space	Tin Whiskers	Relays
2005	Telecom Equipment	Telecom	Tin Whiskers	RF Enclosure
2006	GALAXY IIIR (Side 2)	Space	Tin Whiskers	Relays

Distinctives of AU/CAVE Approach to Whiskers

- Employ sputtered films exclusively, not electrodeposited films.
- Use **very** thin films (~ 0.2 microns).
- "Dialed in" compressive film stress (we want to grow whiskers).
- Focused research objectives; attempt to answer a limited set of questions.
- "Laboratory" created whisker specimens, as opposed to studies of archival, industrial, and/or sporadic whiskers.

Part I
Surface and Bulk Composition of Sn Whiskers

Background and Objectives:

This work documents high-resolution measurements of several important materials and surface properties of Sn whiskers:

- **surface composition**
- **thickness of whisker oxide**
- **variations in surface composition along the whisker shaft**
- **composition at the blunt end of the whisker shaft**
- **composition as a function of depth into the whisker**
- **whether the growth substrate (in this case, brass) constituents are observed either on the growing whisker surface or in the whisker bulk.**

Materials

Brass (Goodfellow)

Sn (Lesker, sputter target)

1600 Å Sn on Cu/Zn

Techniques

Auger electron spectroscopy (AES)

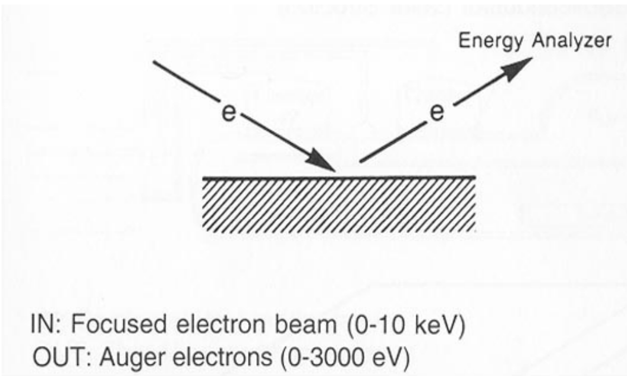
SEM

Sn whiskers have long been presumed to be pure Sn, largely as a result of comparative X-ray diffraction studies on substrates both with and without whiskers. The limitation of conventional diffraction approaches, however, is that it averages data from many individual grains rather than from a single grain.

Basics of Auger Electron Spectroscopy

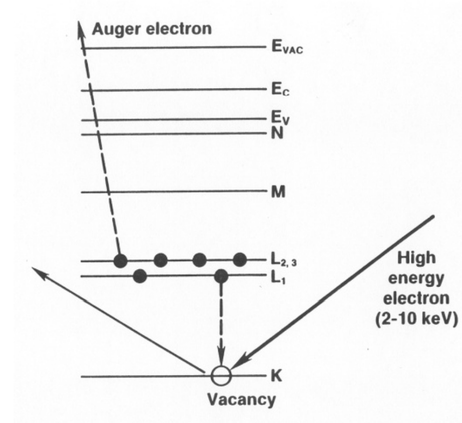
Signal Volume

AES: Electrons IN, Electrons OUT

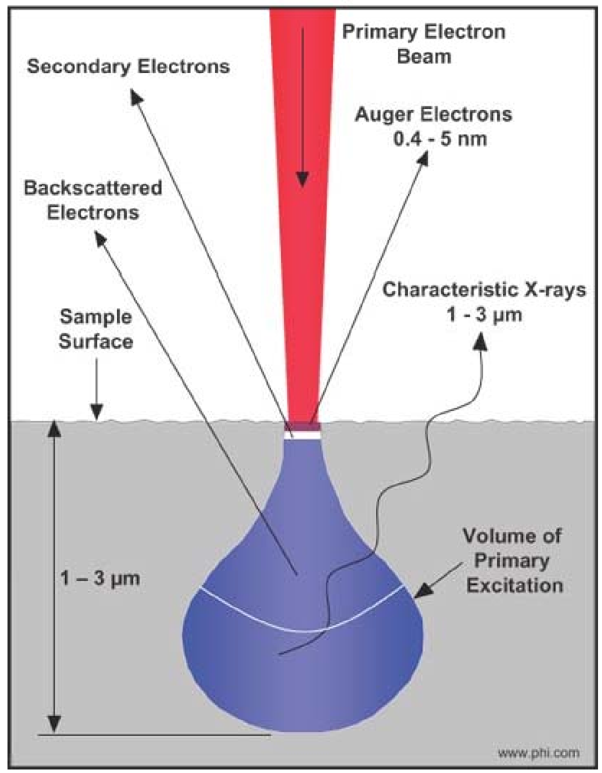


Pierre Auger, The Man

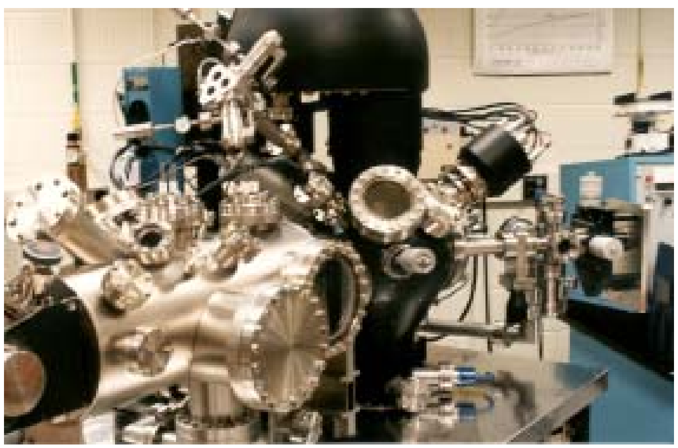
The Auger Process



Electron Beam – Sample Interaction



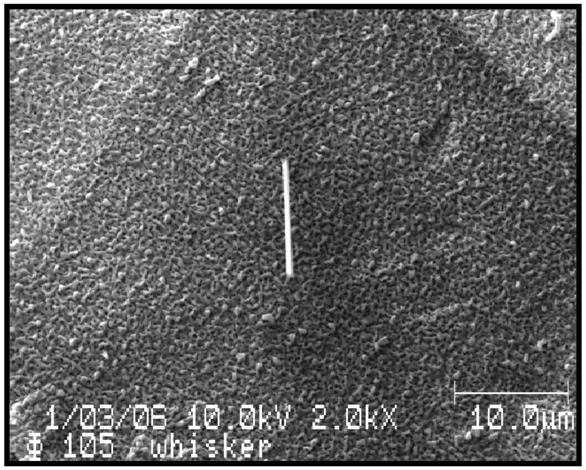
Analysis Volume Comparison AES and EDX



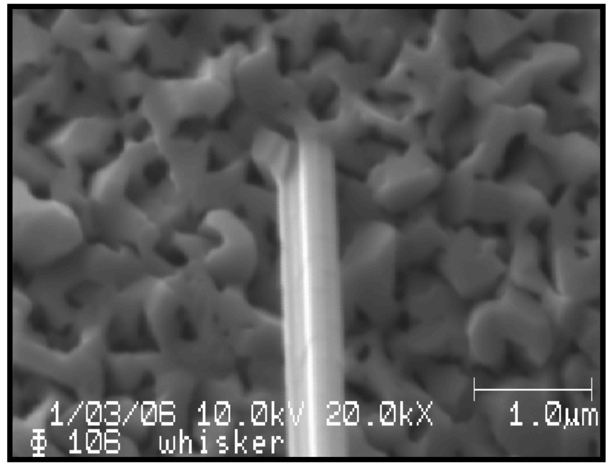
Auger Electron Spectroscopy of a Sn Whisker

Whisker and Analysis Orientation

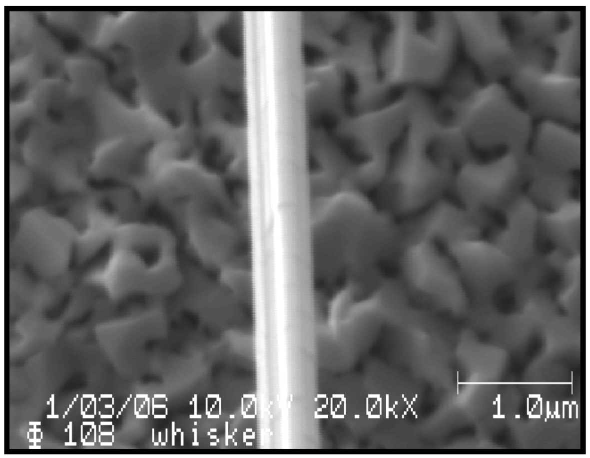
Overall View



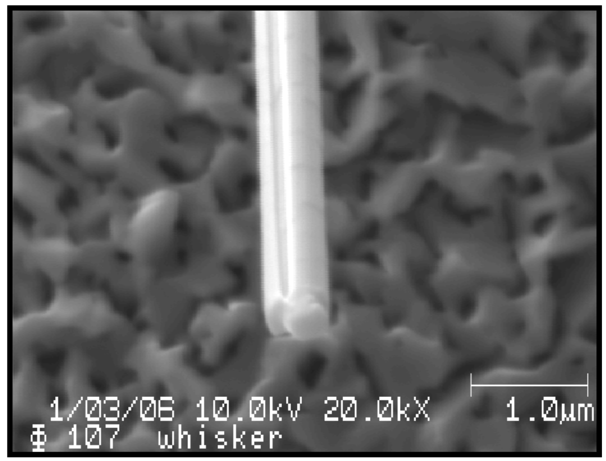
Start of Whisker



Middle of Whisker



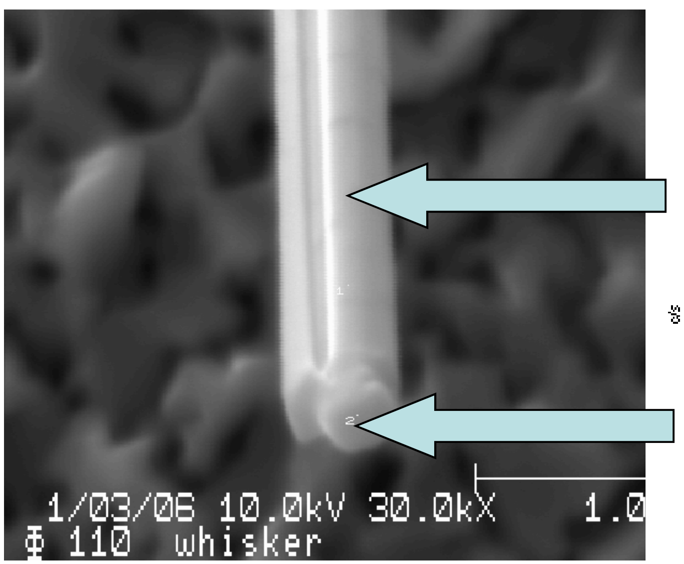
End of Whisker



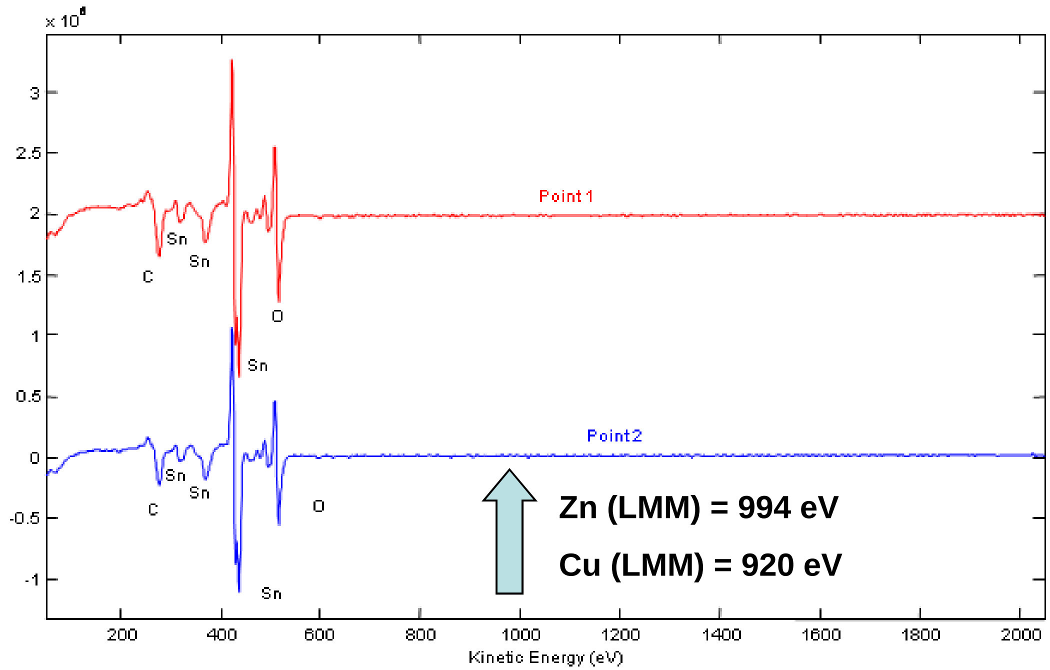
Auger Electron Spectroscopy of a Sn Whisker

As Received Whisker, Representative Result

Conclusion: "As received" surface composition at three locations along whisker shaft shows only Sn (no brass) to the limit of detection (~ 100 ppm; ~ 0.1 at % of analyzed volume) of AES.



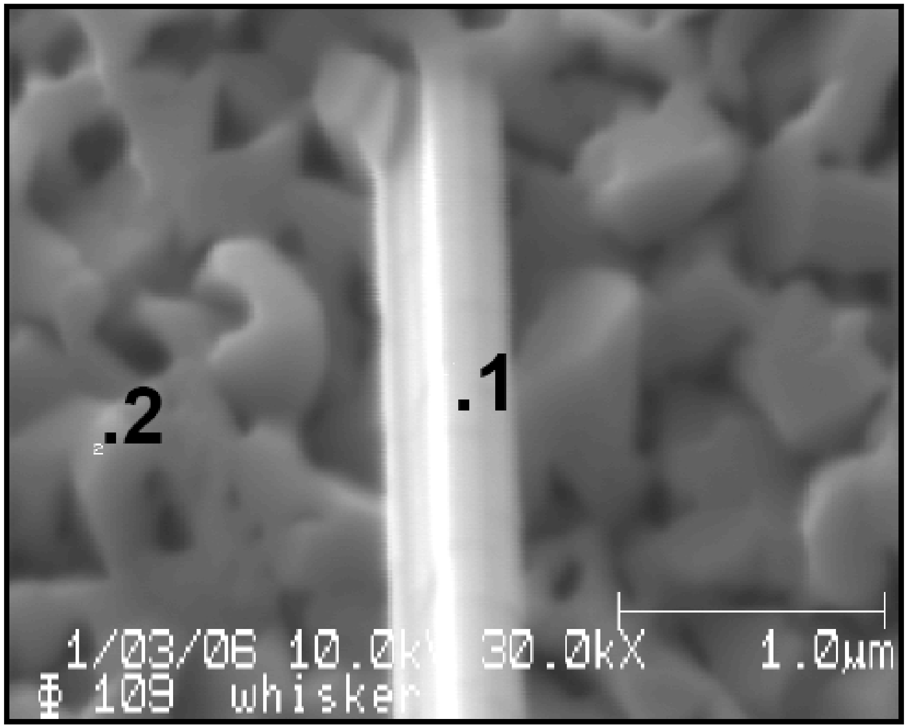
End of Whisker

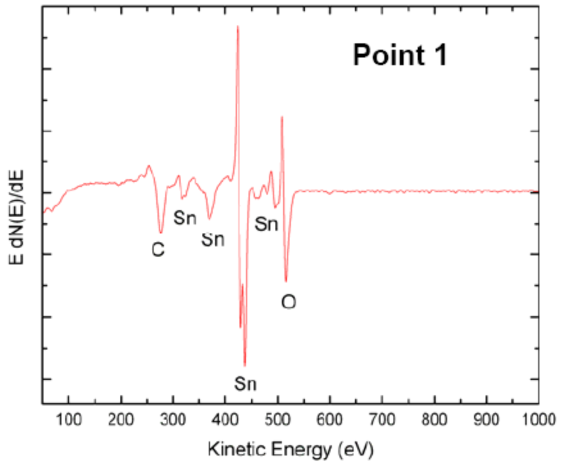


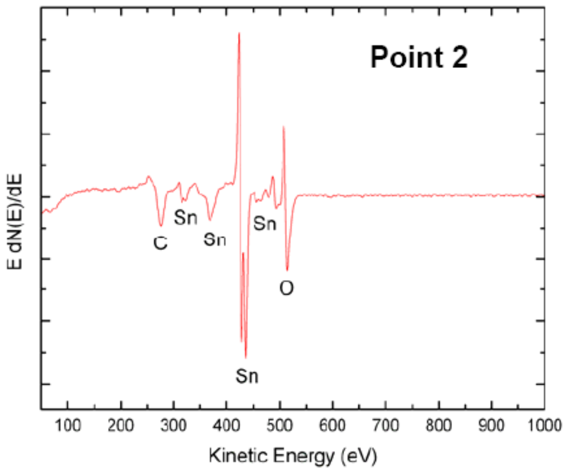
Related Works: 1) T. Woodrow, Proc. SMTA Int'l Conf., Sept, 2006 ("Bible" of whisker diffusion studies); 2) K. Fujiwara and R. Kawanaka, J. Appl. Phys. 51 (1980) 6231 (40 kV incident beam energy !?)

Whisker Surface Composition

Compared to Surrounding Sn Surface

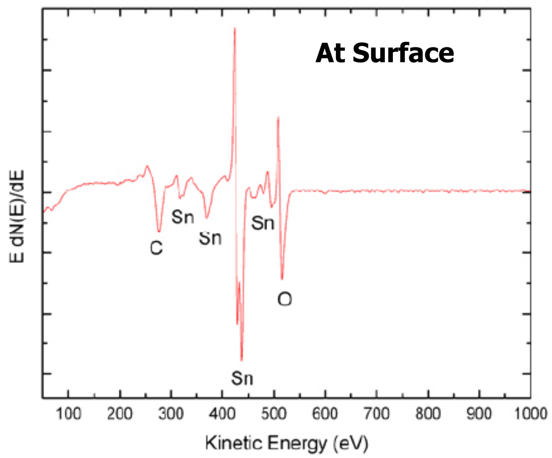


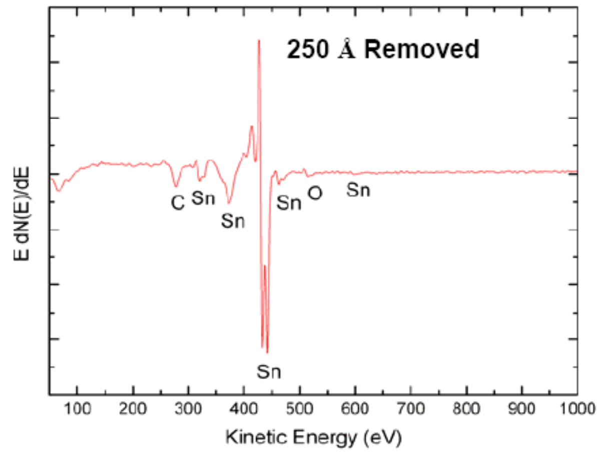




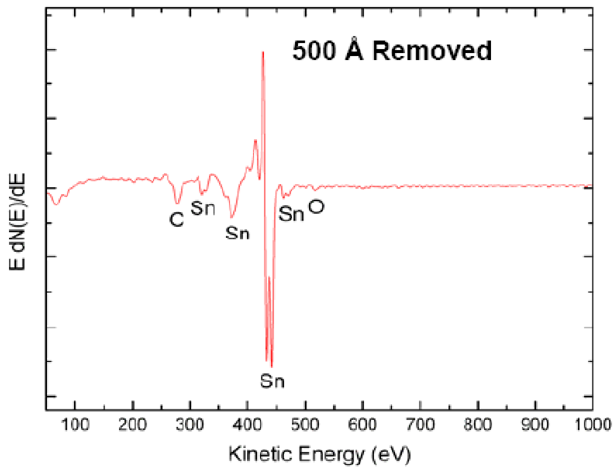
Auger Depth Profile into a Sn Whisker

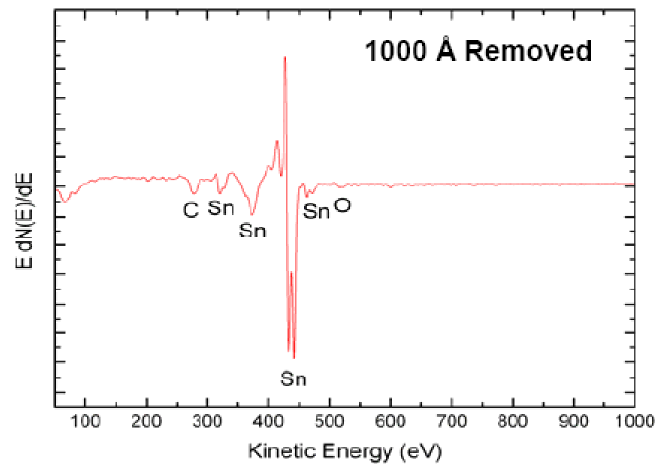
Composition vs. Depth





Surface oxide sputtered away after ~ 250 Å





No evidence of brass in the whisker bulk

Why So Few Direct Analyses of Whiskers?

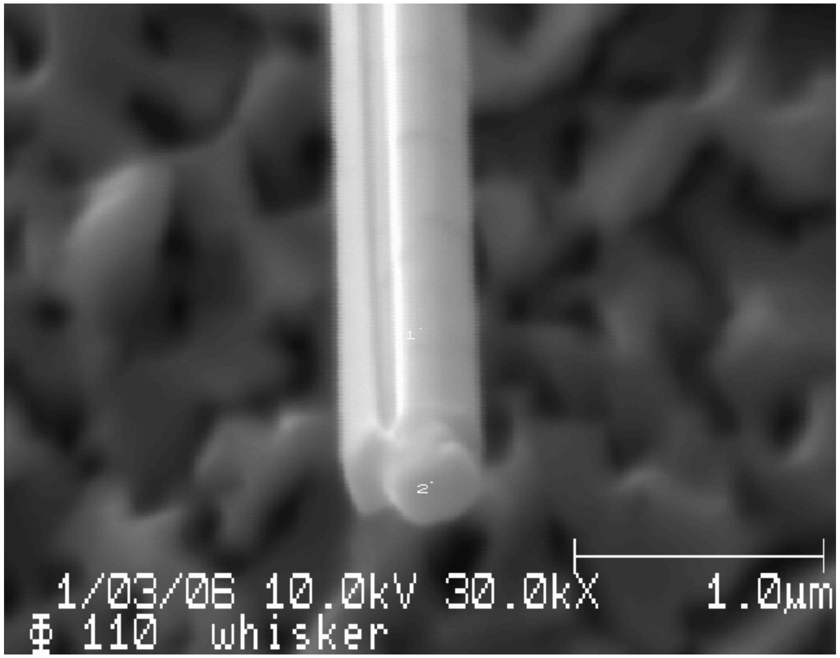
The Analytical Challenge

- The unfavorable aspect ratio of the cylindrical type of Sn whiskers requires submicron imaging and analysis techniques.
- High performance AES, SIMS, FIB instruments are pricey, on the order of ~ $1M.
- Whiskers can be delicate. In the course of this work, we encountered several cases of whiskers that either disappeared during analysis or during overnight parking in our vacuum system. It requires a high degree of experience, luck, and careful handling to achieve successful analysis.
- There is an inverse correlation between lateral resolution vs beam current (S/N) in high-resolution surface spectroscopy.
- As the incident beam current is increased, there is likelihood of discernible electron-beam damage to the analyzed structure due to joule heating during the long analysis times required to acquire sufficient S/N in the Auger spectrum. It is easy to dump enough beam current in a Sn whisker to volatilize it completely.
- The long analysis times required to achieve adequate S/N demands an Auger system that is electrically and mechanically drift-free over a time of ~ 30 minutes. This can be especially difficult for oxide-covered surfaces which can electrically charge during the analysis and cause image-drifting.
- Sixth, sputter profiling for such small and delicate structures is problematic. Automated sputter profiling routines are risky and we instead relied on a series of manual sputtering/spectrum cycles.

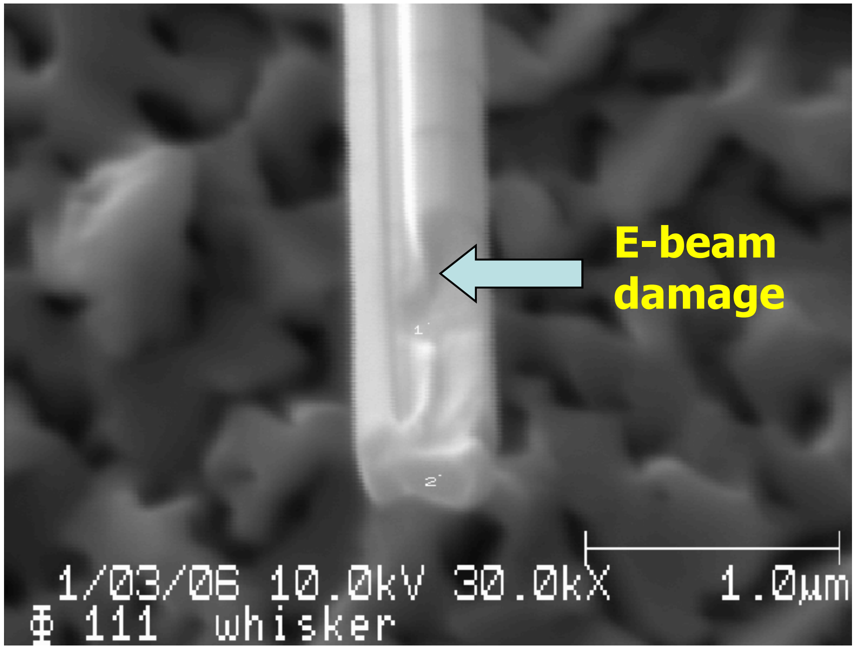
Auger Electron Spectroscopy of a Sn Whisker

Difficulties of Analysis: Electron and Ion Beam Damage

AES Instrument Conditions
Instrument: PHI 680 Field Emission AES Nanoprobe
Electron Beam Conditions: 10kV, 10nA; 30º sample tilt and 5kV, 8nA; 30º sample tilt
Ion Beam Conditions: Ar^+, 2kV, 1µA, 2x2 mm^2 raster; Rate=~ 50 Å/min relative to SiO_2



Before E-beam exposure

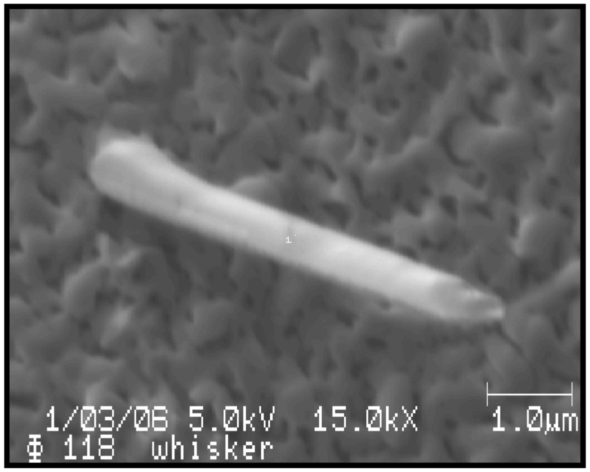


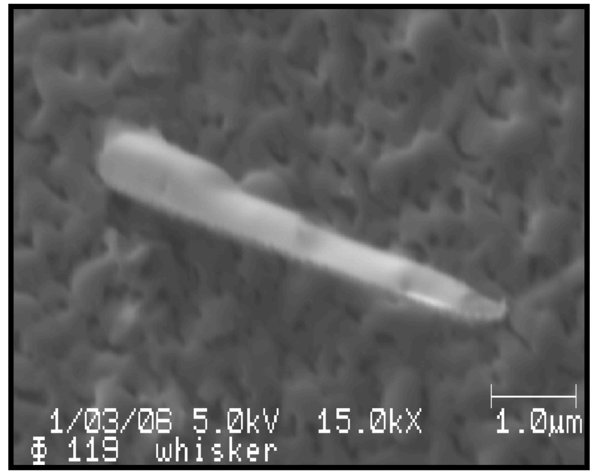
After E-beam exposure

Auger Electron Spectroscopy of a Sn Whisker

Sn Whisker Damage During (2 kV) Ar^+ Sputtering

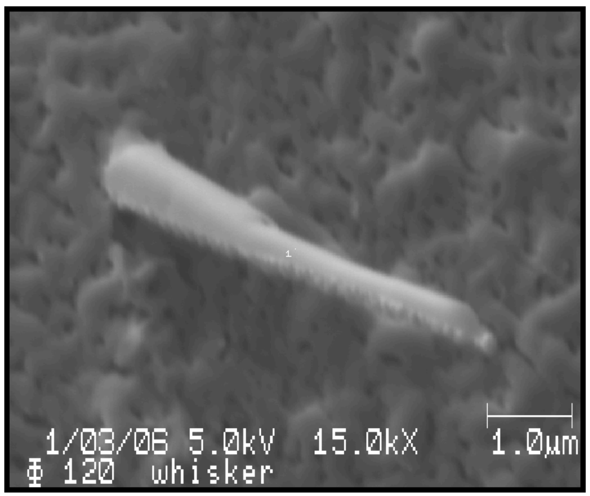
Whisker after 250 Å Sputtering

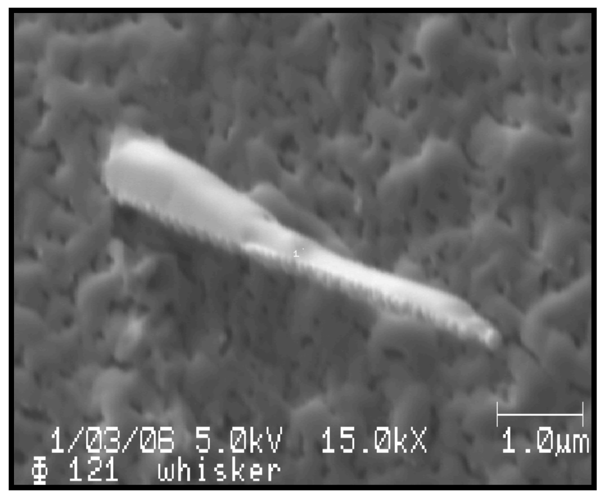




Whisker after 500 Å Sputtering

Whisker after 1000 Å Sputtering





Whisker after 1000 Å sputtering and AES analysis

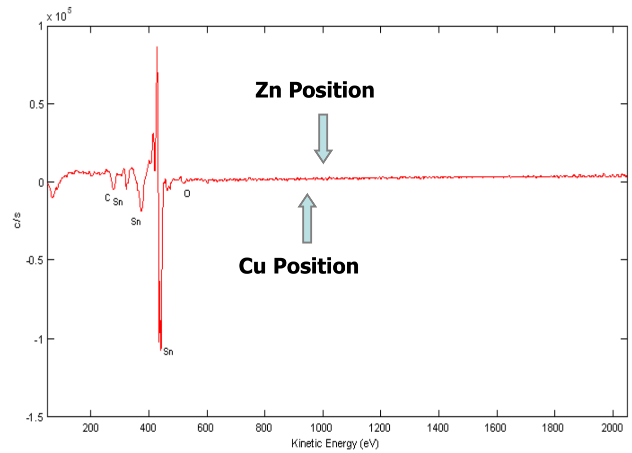
The Feedstock Issue in Whiskering

From Whence the Sn Cometh?

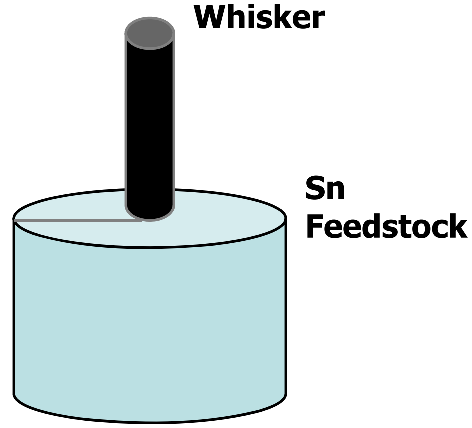
Question: **It is amazing that ≥ 100 μm long whiskers can be generated from such a thin layer of Sn on the brass surface.**

We Ask: **If the entire thin film thickness (1600 Å of Sn) is used to make a Sn whisker, what (feedstock) area possibilities exist around the whisker root?**

No Brass !!

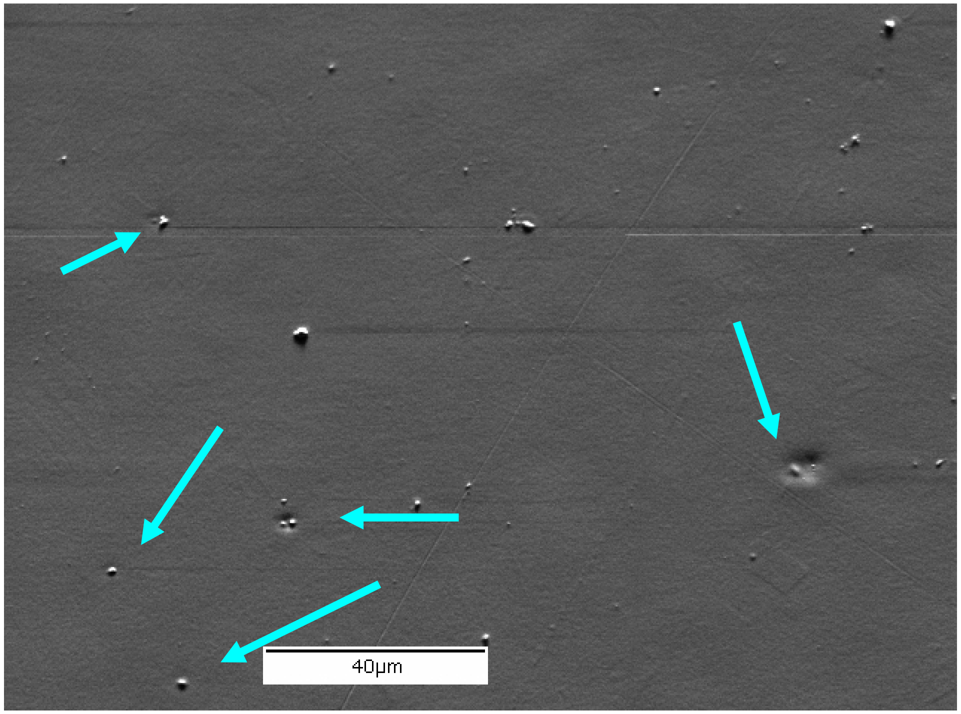


Whisker Length (μm)	Whisker Volume (μm³)	Area of 0.6 μm Sn Thin Film Needed to Synthesize Whisker (μm²)	Radius of Circular Area Around Whisker Base Needed for Whisker Synthesis (μm)
1	0.20	0.33	0.32
10	2.0	3.3	1.0
100	20	33	3.2
1000	200	330	10
Whisker radius 0.25 μm			
Film Thickness 0.6 μm			
Assumption: Density of Sn whisker and surrounding Sn film are identical.			



Evidence for Localized Sn Film Depletion

Ag Whiskers on Brass



Several nub-like Ag whiskers on brass. Areas of potential localized grain subsistence are highlighted with arrows.

Our early work in this area attempted to locate "depletion" areas around fast growing whiskers, indicating a localized Sn feedstock origin.

While we see, in isolated cases, small "depletion" depressions around whiskers, they are rare. More likely is a uniform "draining of the swamp" indicating long-range Sn diffusion, discussed further below.

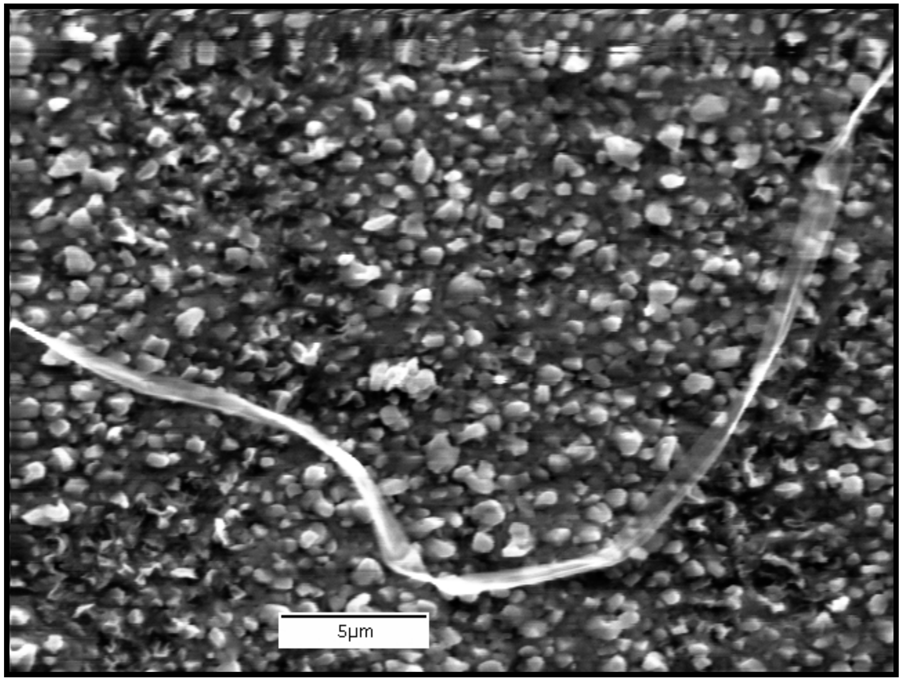
Conclusions

- **High-aspect ratio Sn whiskers on brass grown from sputtered Sn under intrinsic compressive stress consist of ~ 100% Sn covered with a ~ 200 Å layer of native oxide, at least to the limit of detection of Auger spectroscopy (~ 100 ppm or ~ 0.1 at % in the analyzed volume).**
- **There are no variations in the whisker surface composition along the whisker shaft.**
- **The bulk composition of whiskers is pure Sn with no evidence of elemental pull-up from the brass substrate.**
- **The Sn oxide is a garden-variety oxide similar to that found on typical Sn surfaces. More detailed studies using X-ray photoelectron spectroscopy (not reported here) show that the oxide on Sn consists of Sn, SnO, SnO_2, and $O\text{-}H_x$ groups.**
- **That ~ 500 μm pure Sn whiskers are observed to grow from submicron layers of Sn supports the presumption that surface, grain boundary, and interfacial Sn migration supplies the feedstock for whisker growth in Sn.**

Movie

Whisker Exoskeletons as Viewed by Real-Time Scanning Electron Microscopy

(obtain at ftp://131.204.44.20 under title "Death of a Sn Whisker")



Part II
Influence of Surface Roughness on Sn Whisker Growth

Background and Objectives

- **Determine impact of surface smoothness on Sn whisker growth.**
- **Specify and characterize method that produces the smoothest brass substrate and deposited Sn surface.**

Materials

Brass (Goodfellow)

Sn (Lesker, sputter target)

1500 Å Sn on Cu/Zn

Motivation

Can surface roughness alter Sn whisker growth?

Techniques

Atomic Force Microscopy (AFM)

SEM

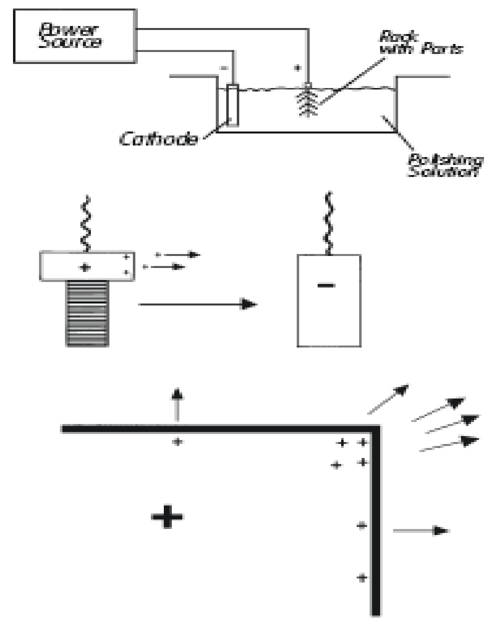
Brass Substrate Preparation Options

1) Unpolished Surface

2) Mechanically Polished Surface

- **Grind in successively smaller increments to 1200 grit**
- **Polish with a 3 mm diamond suspension**
- **Polish with a polishing agent on a polishing cloth**

3) Electrochemically Polished Surface

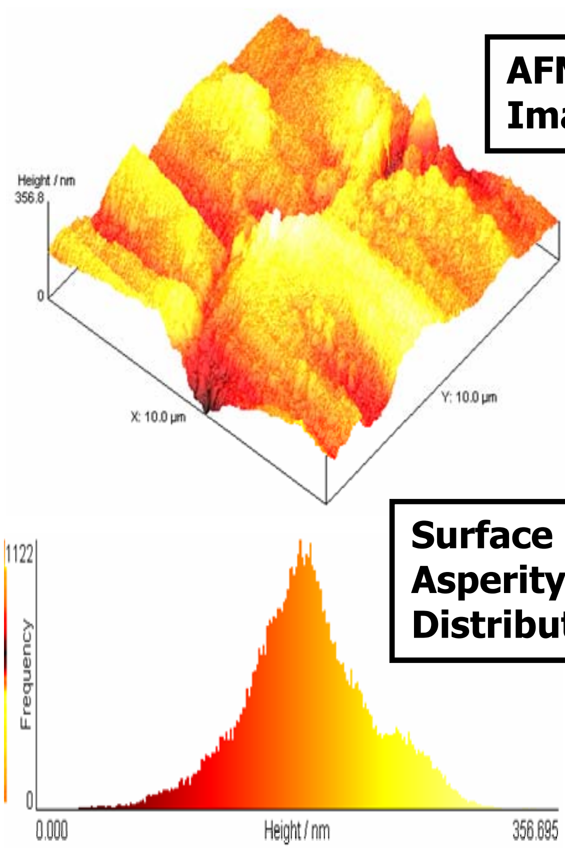


Sn deposited under Ar gas background conditions selected to develop compressive stress in the Sn film.

AFM Characterization of Brass Surface Roughness

RMS roughness values in units of nm/100 μm^2

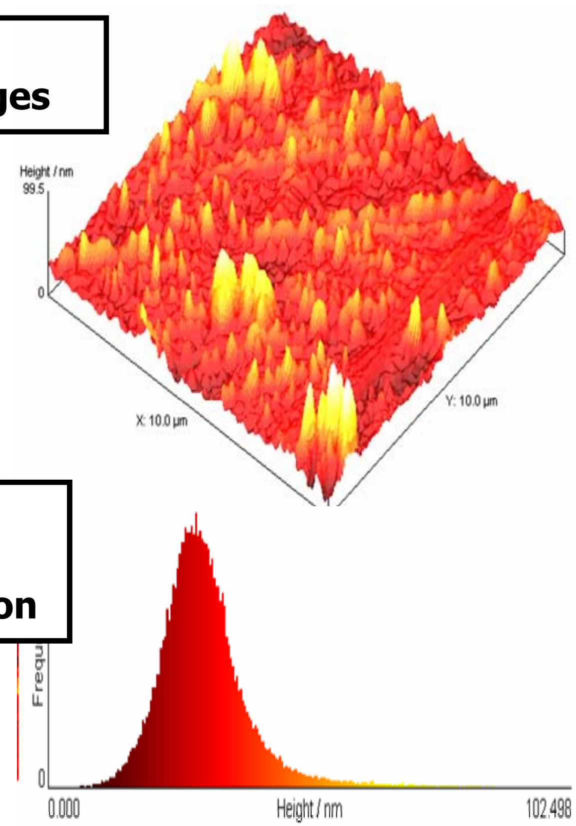
Unpolished
Roughness: 33.9



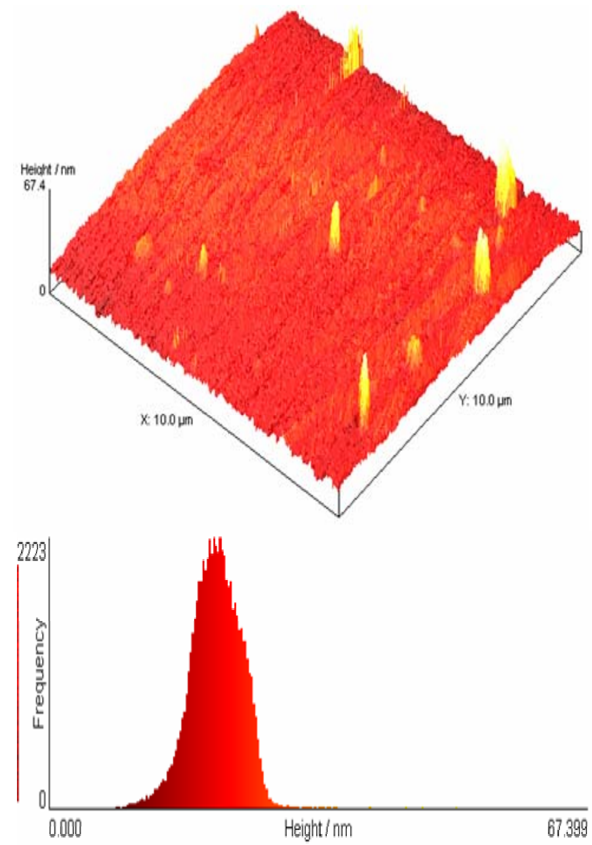
AFM Images

Surface Asperity Distribution

Mechanically Polished
Roughness: 6.4



Electrochemically Polished
Roughness: 2.6



Wider distribution → More roughness

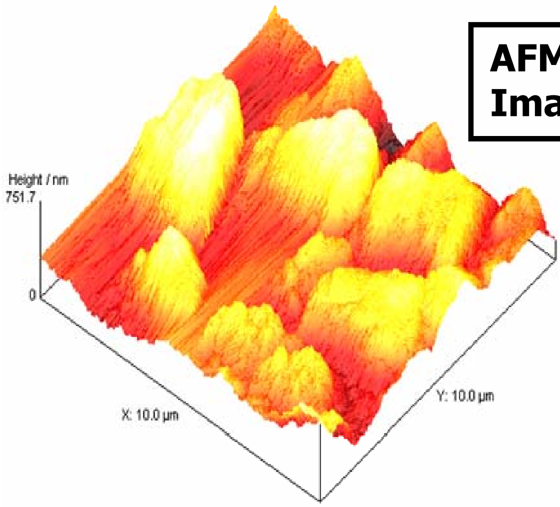
AFM Characterization of Deposited Sn Roughness

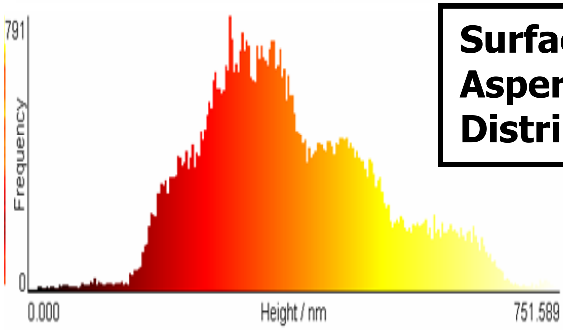
RMS roughness values in units of nm/100 μm^2

AFM Images

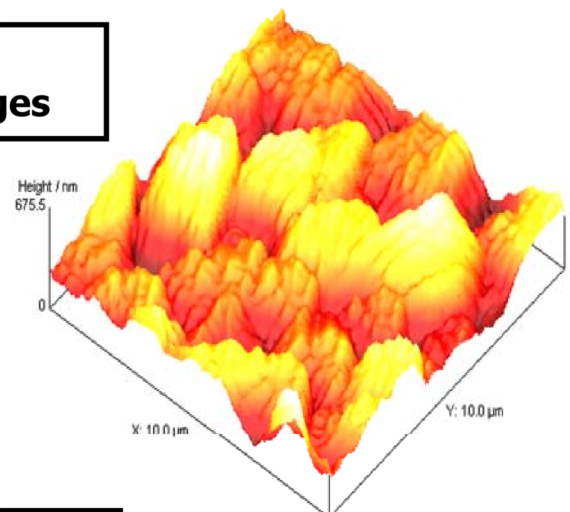
Surface Asperity Distribution

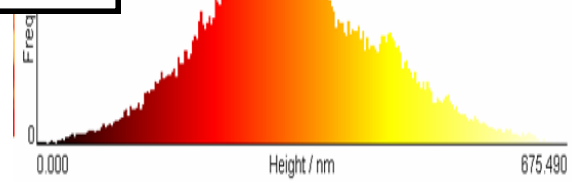
Unpolished
Roughness: 101.7



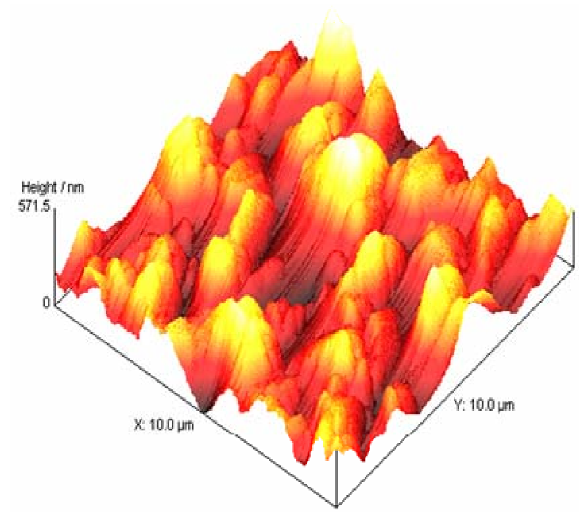


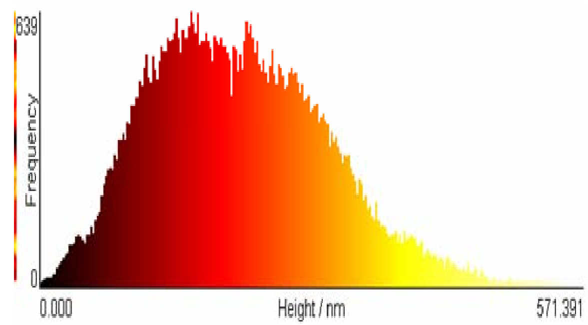
Mechanically Polished
Roughness: 85.5





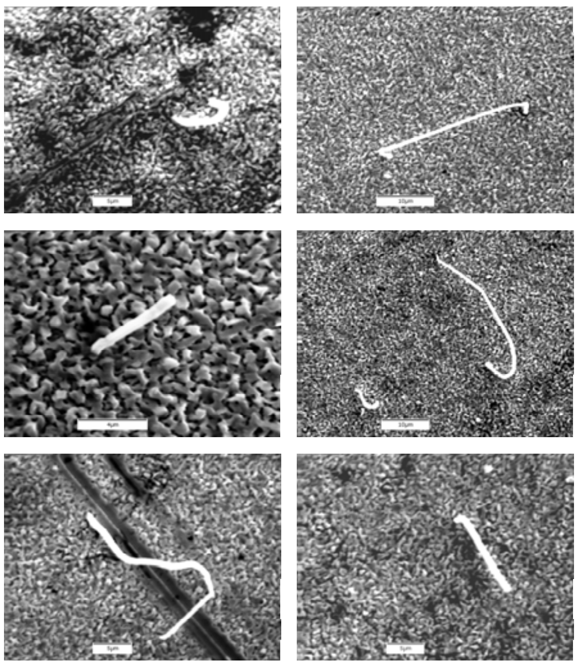
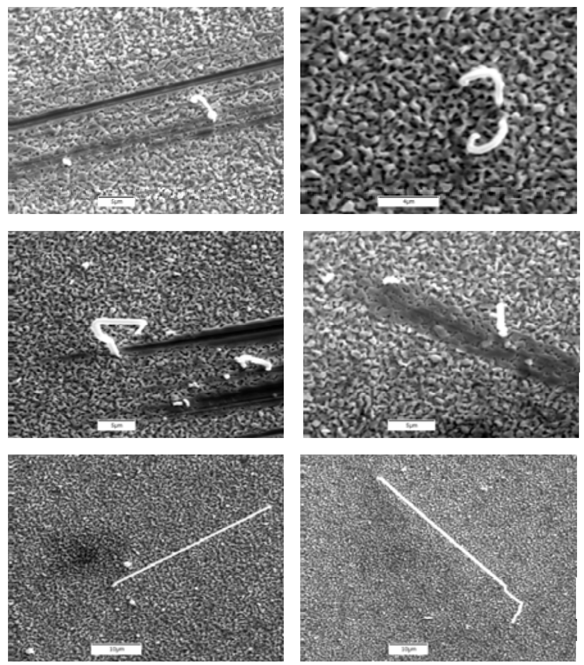
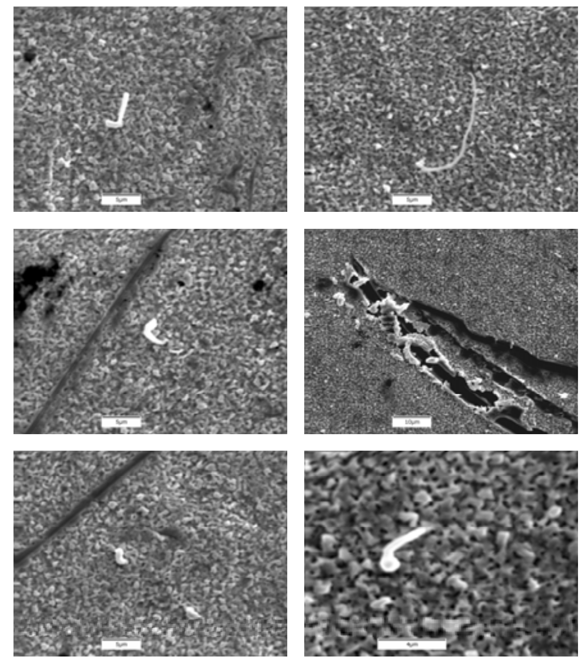
Electrochemically Polished
Roughness: 76.7





Observed Whisker Growth

Four Months at Room Temperature

Electrochemically Polished	Mechanically Polished	Unpolished
		
Hundreds of long whiskers found on a 2 x 2 cm specimen.	**Intermediate** number of whiskers that are well-developed and long.	**Fewest** number of whiskers. Most are small and nub-like in appearance.

Whisker Statistics

120 Days Incubation, RT/RH

Surface Condition	Initial Substrate Roughness (nm/100 μm^2)	Whisker Population Density (cm^{-2})	Average Length (μm)	Longest Whisker Lengths (μm)
Electrochemically Polished	2.62	2265	15-20	80
Mechanically Polished	6.42	598	8	100, 60, 60
As Received	33.87	55	5	14

Conclusions
Number of Whiskers

Results are contrary to conventional wisdom which presumes that rougher surfaces offer more film stress and enhanced whisker growth.

Unpolished		Mechanically Polished		Electropolished
RMS roughness	$\leq$	**RMS roughness**	$\ll$	**RMS roughness**
Brass: 33.9 nm/100μm²		**Brass: 6.4 nm/100μm²**		**Brass: 2.6 nm/100μm²**
Sn: 102 nm/100μm²		**Sn: 86 nm/100μm²**		**Sn: 77 nm/100μm²**

Higher whisker densities on smoother surfaces

Part III
Growth of Sn Whiskers on Semiconductors and Insulators

Background and Objectives:

Previous work has shown growth of Sn whiskers on film systems that form no IMC (e.g., Al, Si, Zn) and therefore offer no contribution to internal film stress. Can this result be generalized to other classes of materials that are not expected to form IMC?

Growing whiskers on semiconductors/insulators will also help us in other ways:

✓ **Most semiconductor surfaces are atomically smooth and allows study of whether whisker growth is even higher than on electro-polished surfaces.**

✓ **Atomically smooth surfaces allows us to measure feedstock depletion in a non-destructive, more accurate way by using RBS and stylus profilometry rather than by AES depth profiling.**

✓ **Corollary is to compare whisker growth for cases where CTE mismatches between substrates and Sn are similar.**

Experimental:

- **Deposit thin films of Sn on Si, GaAs, InAs, InP, Ge, and glass under high compressive stress conditions**
- **SEM characterization of whisker growth and number density**
- **RBS and profilometry as a function of incubation time, to determine film thickness depletion as whiskers grow.**

Experimental Details

Sputter Deposition Conditions

Pure Sn target, Kurt Lesker

Employed background Ar pressure (2 mT) during deposition to produce intrinsic compressive film stress

Sputtering System

Substrates

- **Si**
- **GaAs**
- **InP**
- **InAs**
- **Ge**
- **Glass**

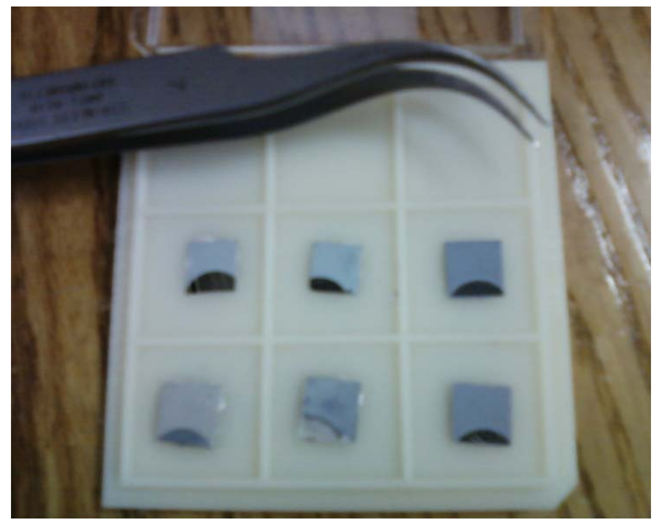
Deposited Film Thicknesses

(measured by profilometry)

1600 Å

Experimental Methodology

- **Incubate ~ 200 days at RT**
- **SEM/image analysis**
- **Count and measure the whiskers**
- **AES/RBS thickness measurements**



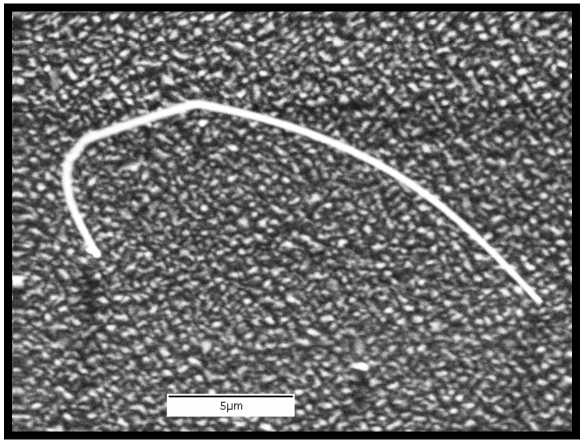
Generated Specimens

Whisker Growth Statistics

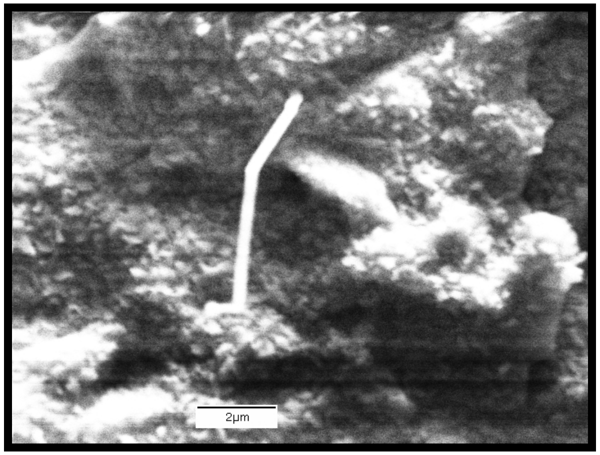
Incubation Period: 54 days

Substrates (1600 Å Sn film)	Whisker Density (cm^{-2})	Average Whisker Length (μm)	Standard Deviation (μm)	Mode* (μm)
Si	15195	6.6	9.1	2
Glass	262	2.5	0.7	N/A
InAs	655	6.0	3.5	N/A
GaAs	7074	4.2	3.8	2
InP	3668	3.3	1.6	2
Ge	19911	7.5	7.6	2

*Mode is defined as the most frequently observed whisker length



Sn on GaAs @ 3760X



Sn on InAs @ 5720X

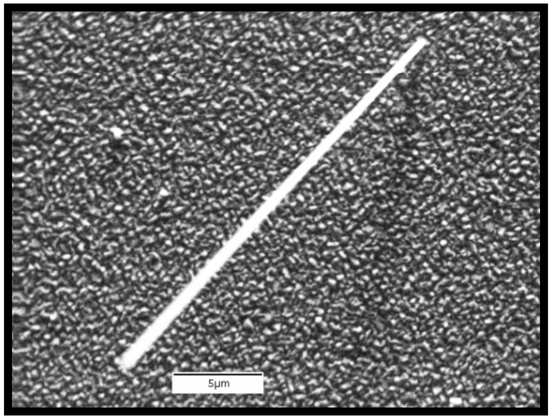
Whisker Growth Statistics

Incubation Period: 116 days

High whisker densities but with relatively shorter whisker lengths compared to other studied materials.

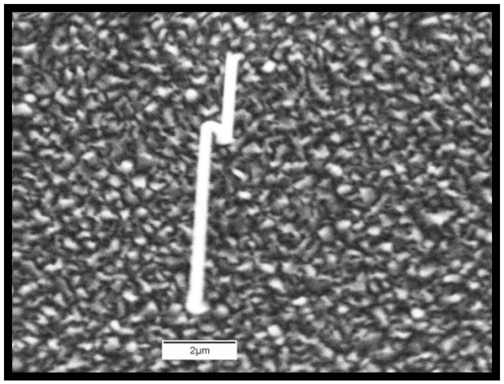
Substrates (1600 Å Sn film)	Whisker Density (cm^{-2})	Average Whisker Length (µm)	Standard Deviation (µm)	Mode* (µm)
Si	38512	6.5	7.9	2
Glass	1703	2.5	0.7	2
InAs	23710	8.3	5.8	6
GaAs	27378	6.9	6.5	2
InP	21221	6.9	6.2	2
Ge	39167	6.6	6.8	2

*Mode is defined as the most frequently observed whisker length

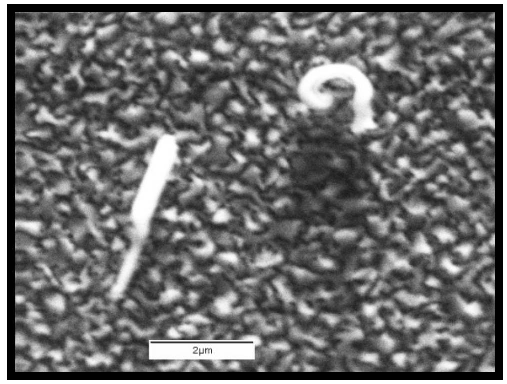


Sn on Ge @ 2820X

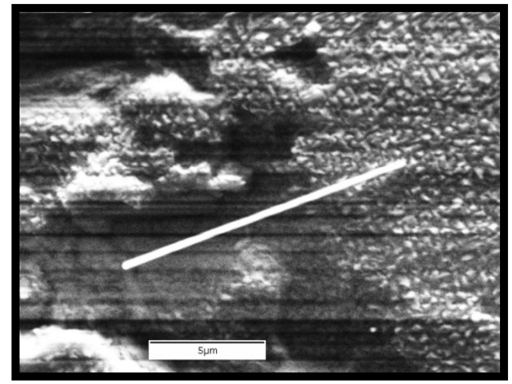
Sn Whiskers on Semiconductor/Insulator Substrates



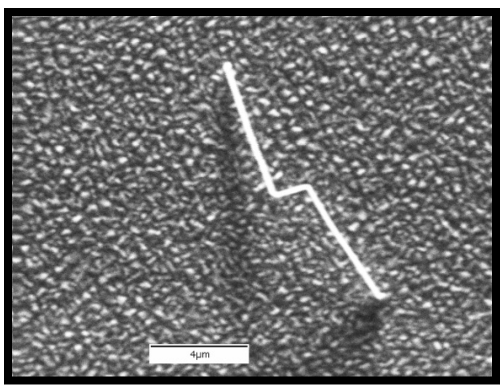
Sn on Si @ 6350X



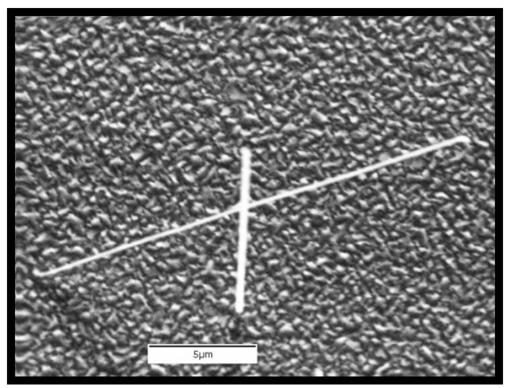
Sn on Glass @ 9050X



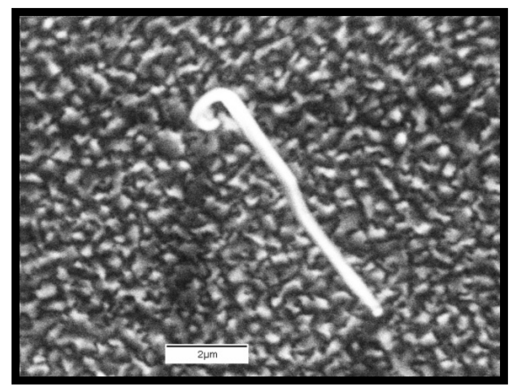
Sn on InAs @ 4020X



Sn on GaAs @ 4270X



Sn on InP @ 3760X



Sn on Ge @ 7100X

Coefficient of Thermal Expansion (CTE) Mismatches

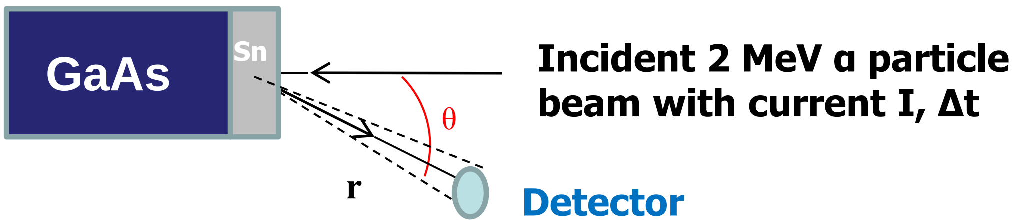
Substrate	CTE (10^{-6}/K)	ΔCTE*	%ΔCTE*
Sn	23.4	0	0
Si	5.1	18.3	78.2
Glass (pyrex)	4.0	19.4	82.9
InP	4.6	18.8	80.3
GaAs	5.7	17.7	75.6
InAs	4.5	18.9	80.8
Ge	6.1	17.3	73.9

***Compared to Sn**

CTE mismatches similar between Sn and the various substrates but widely varying whisker densities observed. Little correlation.

Attempt to Measure Sn Film Thickness after Whisker Growth

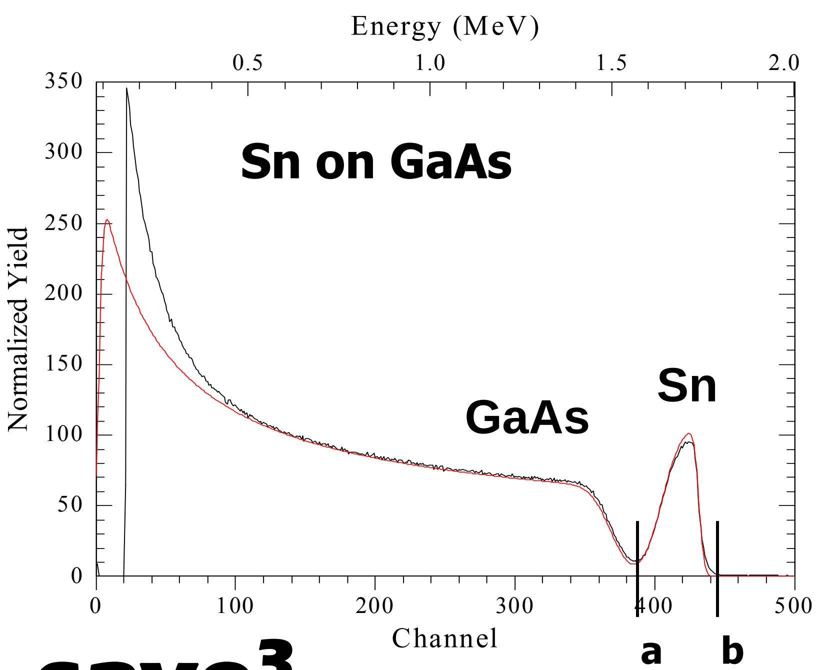
Rutherford Backscattering Spectroscopy (RBS)



$$\Sigma = \int_a^b \left(\frac{\text{counts}}{\text{channel}}\right) d(\text{channel \#}) = \text{total \# of } \alpha\text{'s scattered into detector}$$

$$x = \frac{\Sigma}{N\, n\, d\Omega\, \frac{d\sigma}{d\omega}} \sim \text{film thickness}$$

N = nuclei density of the sample



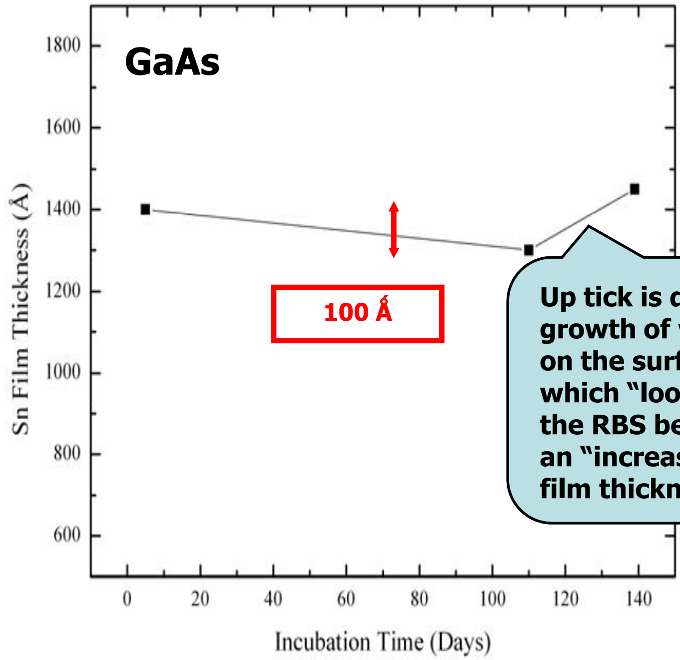
RBS works best when the film stack is laminar and the film thickness.

Energy loss by α-particles as they are scattered from the front and back surface of the Sn film (the a – b distance in the RBS spectra) yields the Sn film thickness.

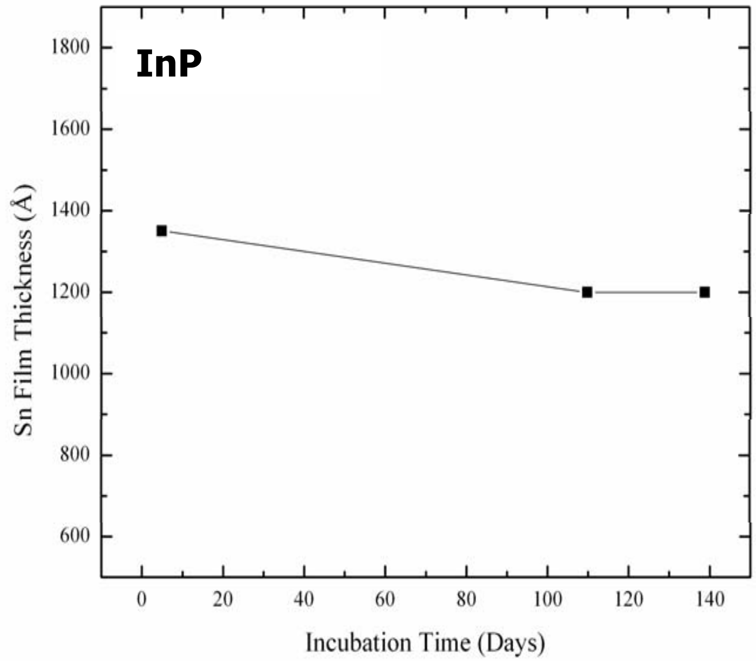
Sn Film Thickness vs Incubation Time

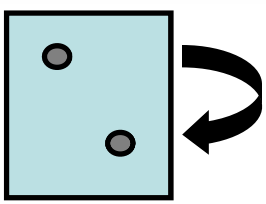
Rutherford Backscattering Spectroscopy

Are we "draining the Sn swamp" during whisker growth ?? YES . . .



Up tick is due to growth of whiskers on the surface, which "looks" to the RBS beam as an "increase" in film thickness.





RBS data was taken at two widely spaced positions on each sample, each position producing similar results.

Sn Film Thickness vs Incubation Time

Sanity Check

Question: Believing the RBS data showing that ~ 100 Å of the Sn film on GaAs has been depleted during whisker growth over ~ 120 days, what possibilities exist for the resulting whisker density and length?

100Å of Sn depletion on GaAs corresponds to . . .	Whisker Density (cm^{-2})	Average Length (μm)
	5000	28.29
	10000	14.15
	15000	9.43
	20000	**7.07**
	27378	5.17
	30000	4.72
	40000	3.54

Measured Sn whisker length on Sn/GaAs

Measured Sn whisker density on Sn/GaAs

Conclusions

- **It is clear that Sn whiskers grow readily on thin, sputter-deposited Sn films on semiconductor and insulator substrates under internal compressive film stress conditions where intermetallic layers are absent.**

- **The fact that Sn on semiconductor surfaces grows copious amounts of whiskers is consistent with our earlier work on surface roughness, which showed that smoother surfaces grow more whiskers. Semiconductor surfaces are the smoothest surfaces that can be technologically manufactured.**

- **RBS studies show evidence of the slight Sn film depletion expected during whisker growth, owing to the mass balance that must occur when forming Sn whiskers. We observe a decrease of ~ 100 Å in the thickness of the deposited Sn film during the incubation period (130 days). The fact that identical RBS results were obtained over two widely separated analysis positions on the film surface support the notion of long-range lateral movement of Sn to the whisker shaft during whisker growth.**

- **No simple correlation due to CTE mismatches was found between the various semiconductor substrates (having similar CTEs) and Sn whisker growth.**

Acknowledgements

We gratefully acknowledge the industrial members of the NSF Center for Advanced Vehicle and Extreme Environment Electronics (CAVE³) for continued support of this work.