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Improving Tin Whisker Testing through Quantitative Measurements of Plated Film Properties

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Biography:

Aaron Pedigo received his B.S. in Materials Engineering from Purdue in 2006. He continued his education at Purdue by enrolling as a PhD student in Materials Engineering, researching the growth of tin whiskers. In 2009, Aaron began working for NSWC Crane while continuing his graduate studies.

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Improving Tin Whiskers through Quantitative Measurements of Plated Film Properties

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September 29th, 2010

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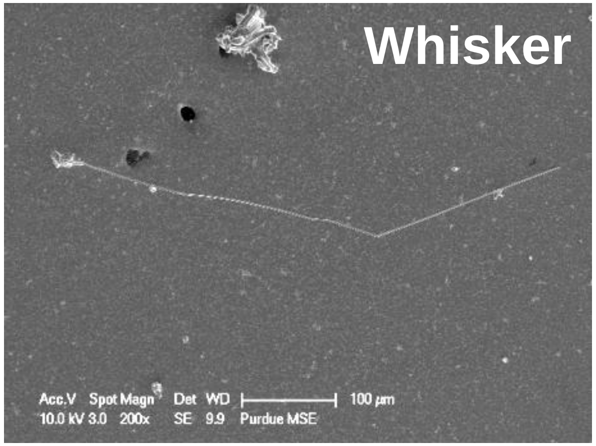
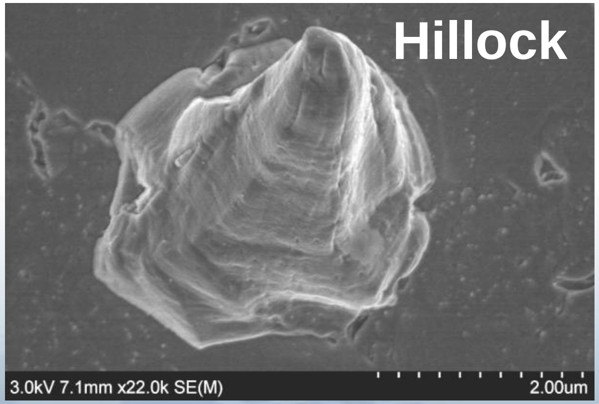
Introduction:

Whiskers and Hillocks

- Tin whiskers grow spontaneously from Sn based finishes
  - Conductive
  - Grow to be millimeters in length
  - **Represents a significant electric reliability risk**
- Mechanisms responsible for whisker growth not well understood
  - Multiple surface growths including hillocks and whiskers
  - **Hinders successful mitigation strategies**



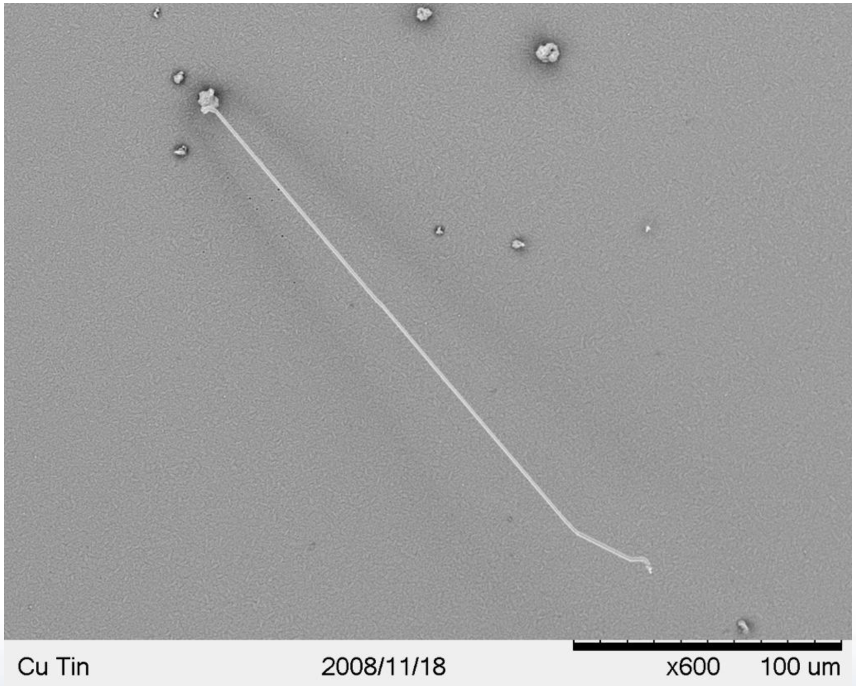


Introduction:

The Pb-Free Manhattan Project

http://www.navyb2pcoe.org/b2p_news_lfmp2.html

- Team of experts from both industry and academia
- Addresses particular concerns of the Aerospace and Defense industries with Pb-Free electronics
- Tin whiskers identified as one of the "**greatest reliability risks associated with lead-free electronics.**"



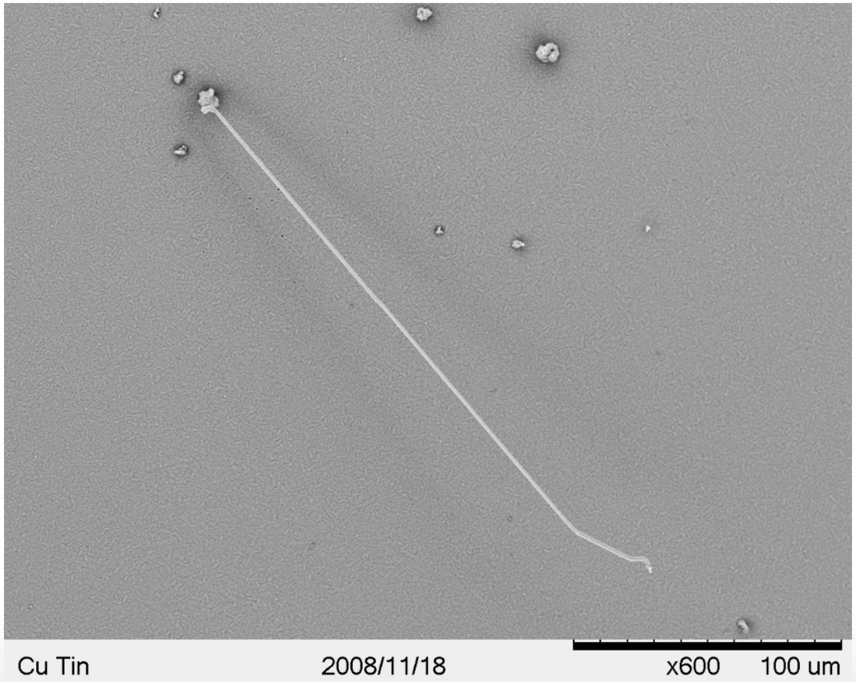
SEM micrograph showing a a 300mm whisker growing from a electroplated Sn finish containing <2% Cu after 1 year.

Introduction:

The Pb-Free Manhattan Project

http://www.navyb2pcoe.org/b2p_news_lfmp2.html

- From Pb-Free Manhattan Project Phase 2 Report:
  - “**Current tin whisker testing methods** cannot predict whether a finish or solder will grow tin whiskers, nor can they identify what additional whisker mitigation strategies are needed for a particular part or assembly.”



SEM micrograph showing a a 300mm whisker growing from a electroplated Sn finish containing <2% Cu after 1 year.

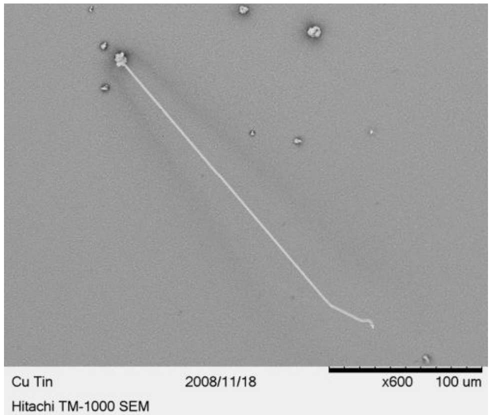
Introduction:

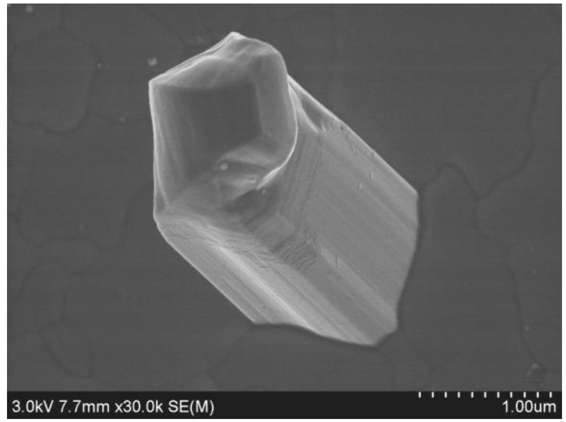
JEDEC standard JESD22A121

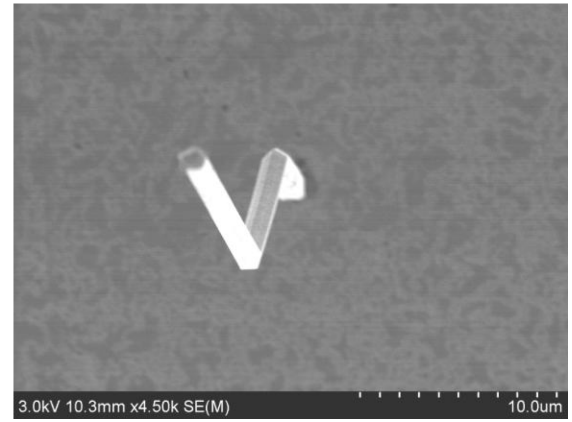
- Sn whisker testing standard
  - Variety of of storage conditions
    - Ambient, thermal hold, and thermal cycling
  - Time consuming
    - 3000hrs (125days)
  - Must be repeated if there are changes in the process
    - Electrolyte additive, processing parameters, reflow profile
  - Binary result
    - The finish is or is not prone to whiskering
  - **From JEDEC standard JESD22A121**
    - "[T]here is at present no way to quantitatively predict whisker lengths over long time periods based on the lengths measured in the short-term tests described in this document. At the time of writing, the **fundamental mechanisms** of tin whisker growth are not fully understood and acceleration factors have not been established" - May 2005

Motivation:

Understanding Fundamental Whisker Growth Mechanisms







- Developing successful mitigation strategies
  - Perform experiments to determine film properties related to whisker growth to **develop a comprehensive whisker growth model**

Motivation:

Comprehensive Whisker Growth Model

- A comprehensive whisker growth model is composed of the fundamental mechanisms responsible for whisker growth and should be able to explain empirical observations related to whisker growth

- Empirical Observations
  - Compressive stress driving whisker growth[1]
  - Straight whiskers, kinked whiskers, and hillocks all growing on the same sample
  - Surface contamination influencing the propensity to whisker[2]
  - Bright Sn more susceptible than matte Sn
  - Co-depositing Cu and Sn increases propensity to whisker[3,4,5,6,7]

Methods:

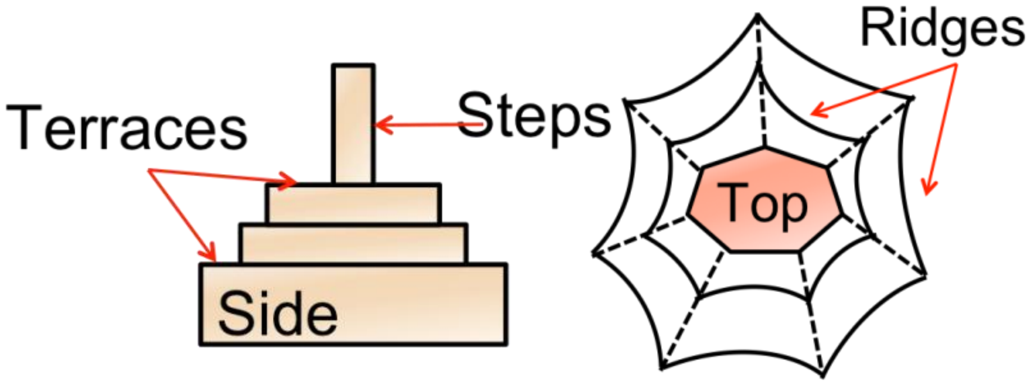
Measurements of Plated Film Properties

- Hillock and Whisker Growth
  - Presence of whiskers and hillocks
  - Morphology of hillocks
- Film Stress Evolution
  - Deposition stress
  - Film stress as a function of time
- Microstructure
  - Crystallographic texture
  - Grain size
  - Grain morphology

Methods:

Hillock and Whisker Growth

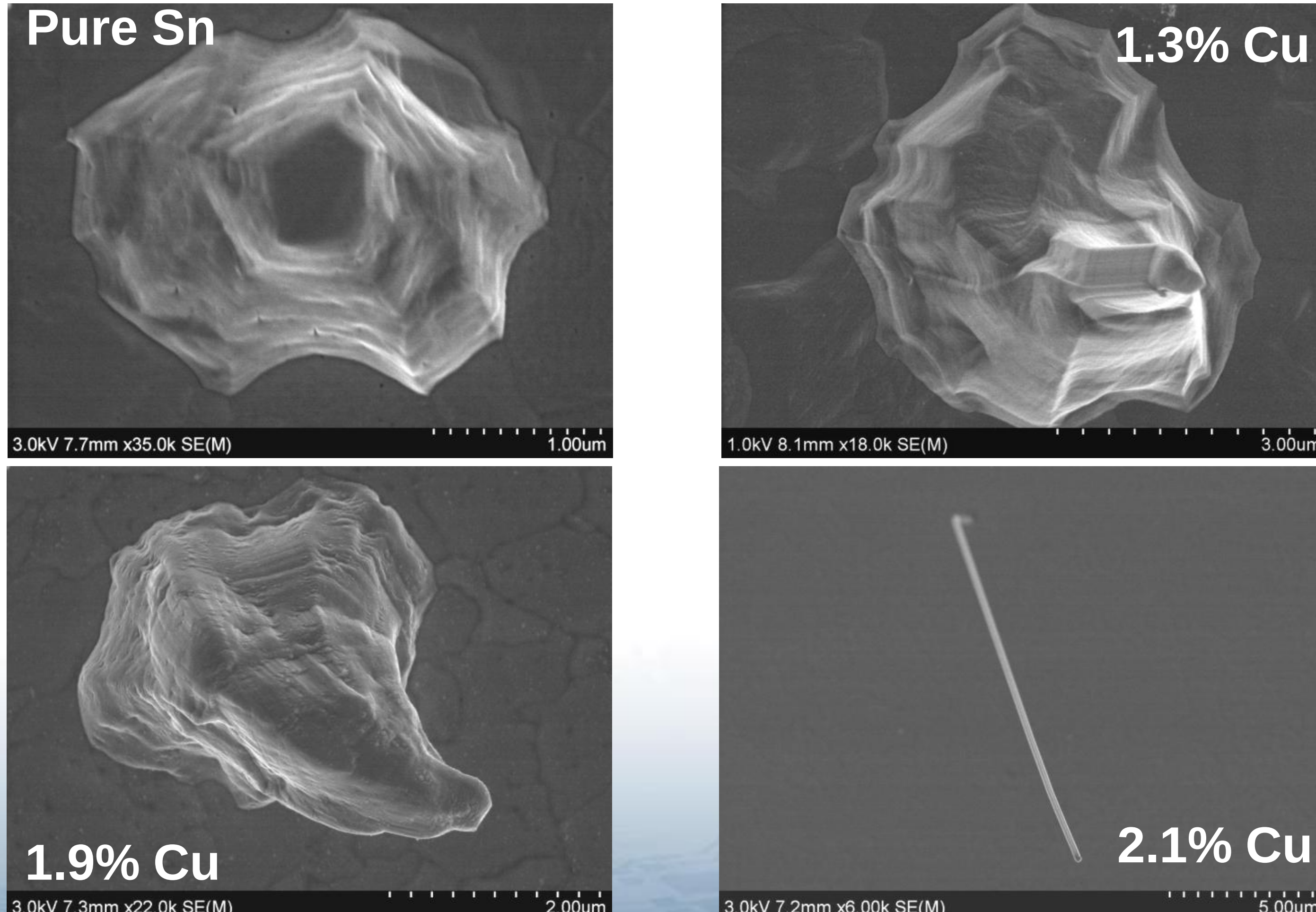
- Electrodeposition of Sn and SnCu films[5]
  - Film ranging in composition from pure Sn to 2.1wt% Cu, Sn
  - Hillock and whisker growth observed a short time after deposition
  - A range in hillock morphologies as a function of Cu content in the film



Schematic of a proposed hillock growth model created from hillock morphology observations.

Results:

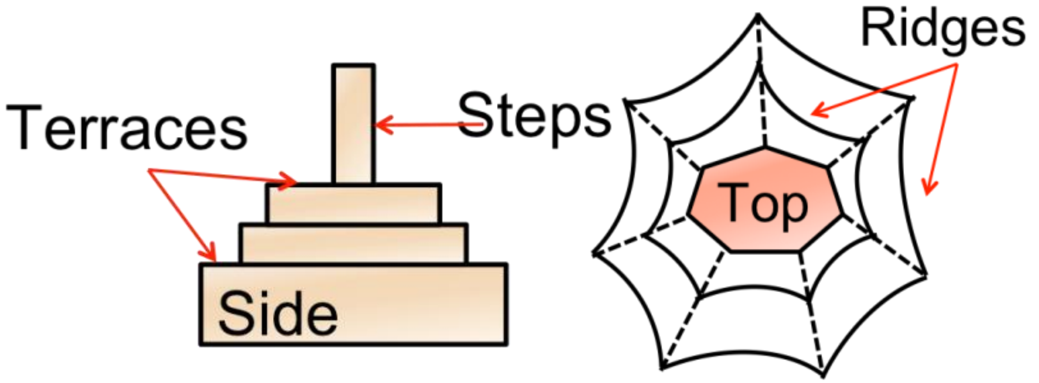
Hillock and Whisker Growth



Results:

Hillock and Whisker Growth

- Increasing Cu concentration resulted in
  - Transition from hillock only to hillock and whisker growth
    - Agrees with previous studies[1,2]
  - Hillock growth where the rate of uplift increased compared to the rate of lateral growth
  - Hillocks with whisker-like tops



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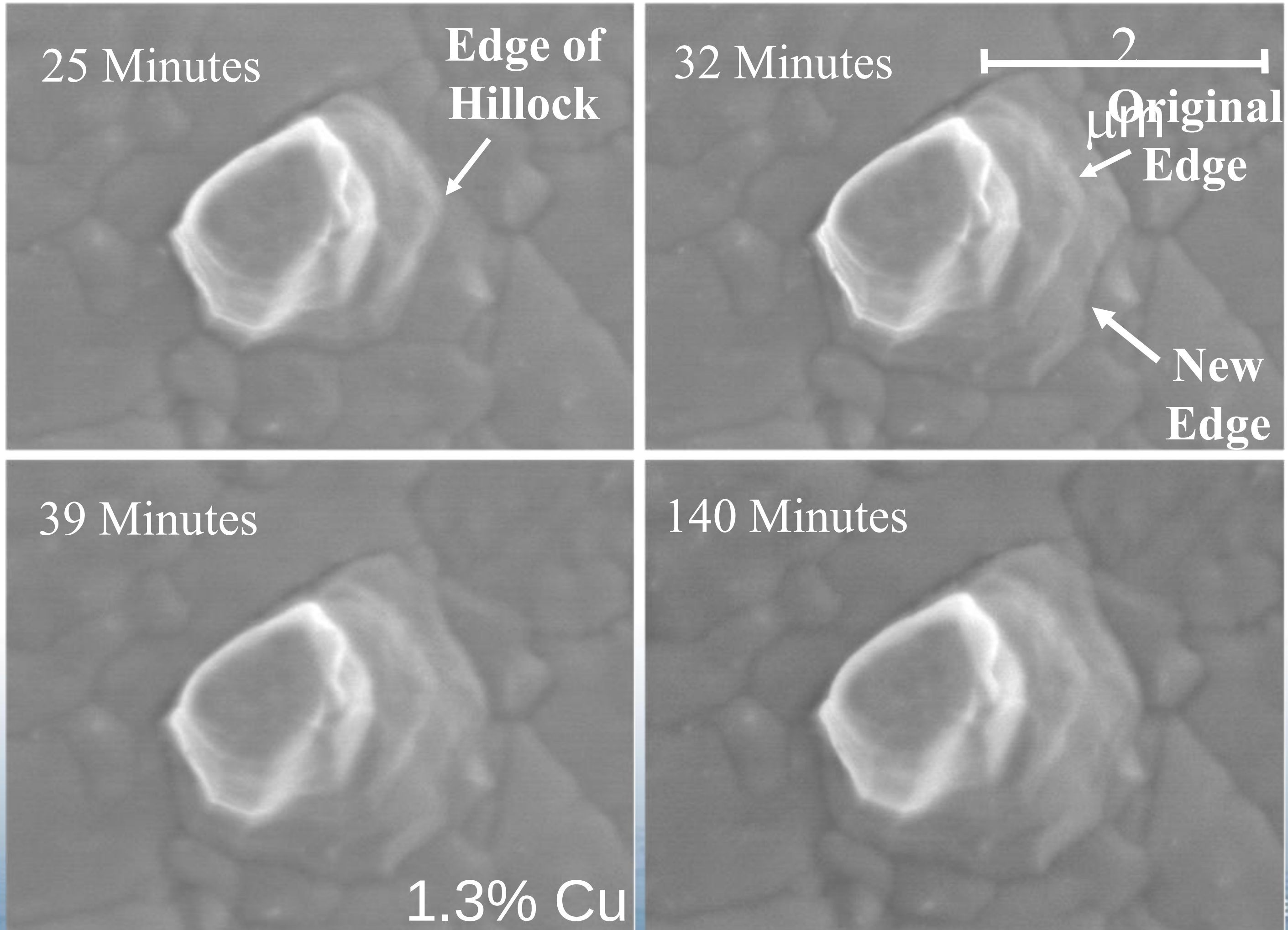

Results:

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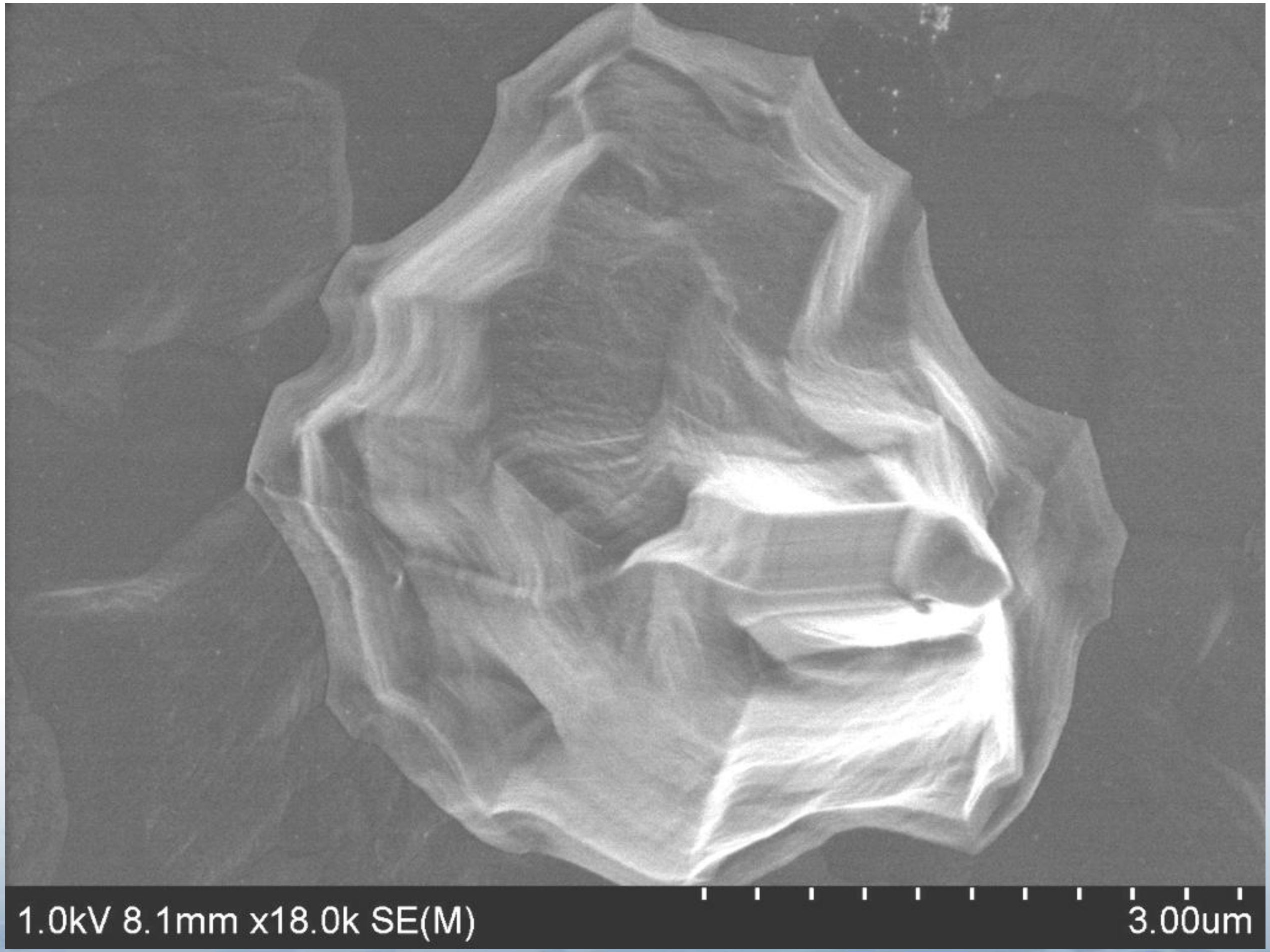
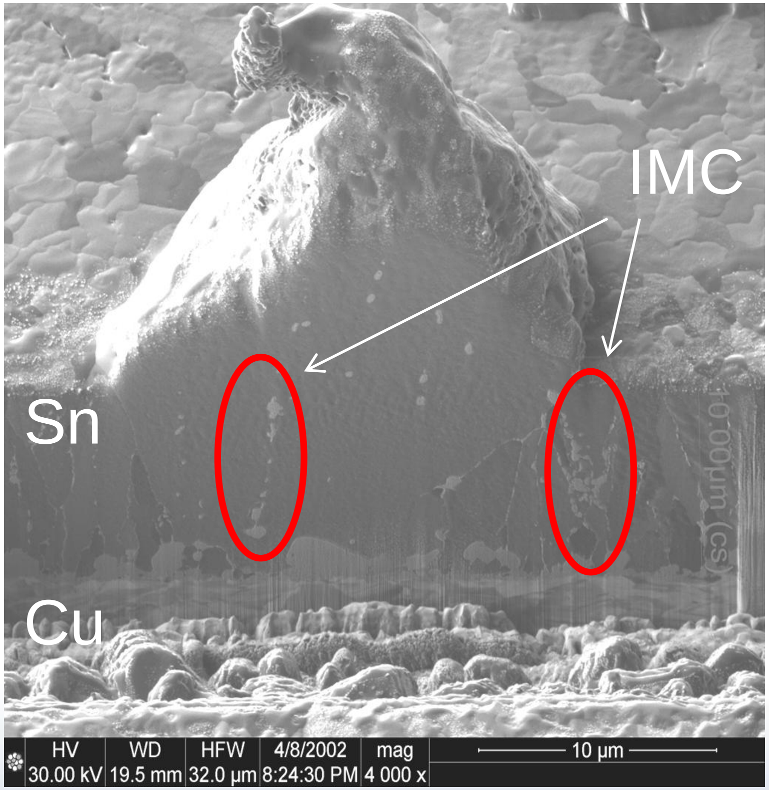


Results:

Hillock and Whisker Growth

- Mechanism: Grain boundary pinning
  - Co-deposition of Cu and Sn results in Cu_6Sn_5 IMC along grain boundaries (GB). These IMC can decrease GB mobility or completely pin the GB.
  - What is pinning the GB in “pure” Sn deposits?



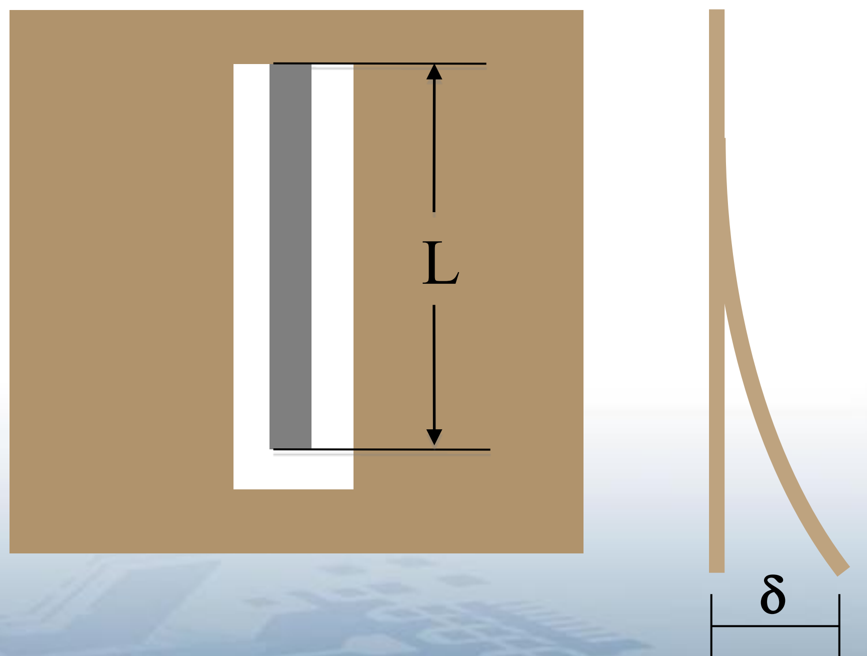
FIB milled cross-section through a hillock showing lines of IMC marking previous locations of GBs.

Methods:

Film Stress Evolution

- Same compositions evaluated for hillocks and whisker observations deposited on flexible cantilever beams
- Deflection of the cantilever beam is related to the film stress(σ_f)[8]
- Measurements made as a function of time

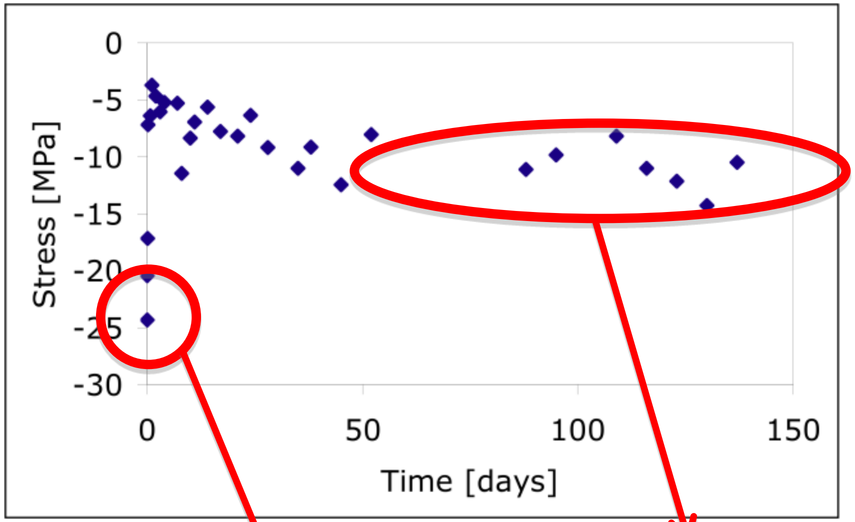
$$\sigma_f = \frac{Modulus_{Substrate}}{6(1 - poisson's_{substrate})} \times \frac{thickness_{substrate}^{\;2}}{thickness_{film}} \times \frac{2\delta}{L^2}$$



Results:

Film Stress Evolution

- Same general trends in stress evolution regardless of Cu concentration
- Increasing Cu concentration resulted in
  - Increased compressive plating stress
  - Increased compressive long-term residual stress
- Results agree with previous studies

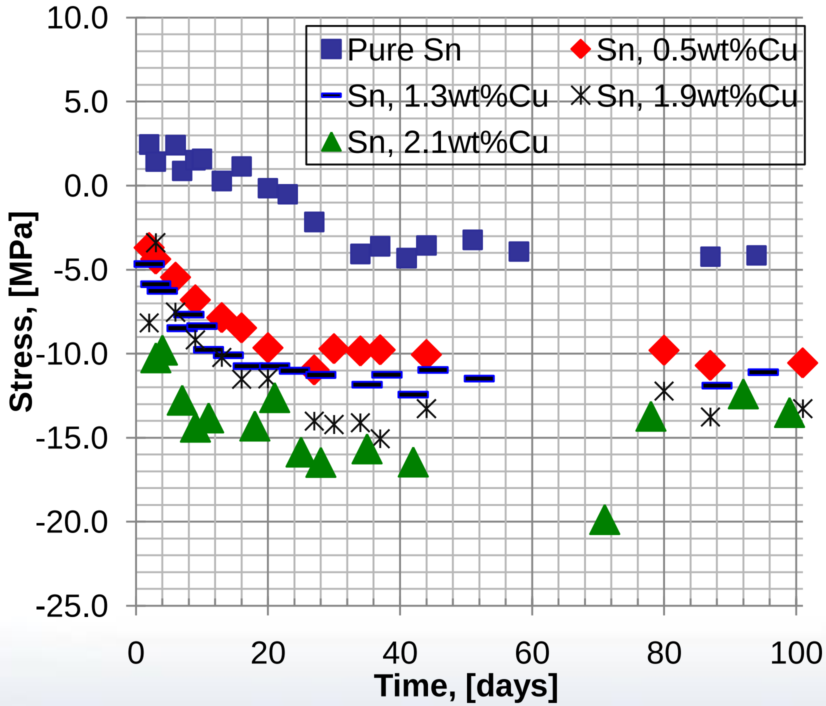


Copper Conc. [%]	Plating Stress [MPa]	30-150 Day Average Stress [MPa]
0.0	-17 (+/- 4)	-7 (+/- 3)
0.5	-17 (+/- 8)	-12 (+/- 5)
1.3	-31 (+/- 6)	-14 (+/- 9)
1.9	-26 (+/- 3)	-15 (+/- 4)
2.1	-28 (+/- 19)	-16 (+/- 10)

Results:

Film Stress Evolution and Whisker Growth

- Increasing film stress correlates with an increased propensity to whisker
- Increased film stress correlates with decreased GB mobility
- What are the active stress relief mechanisms?

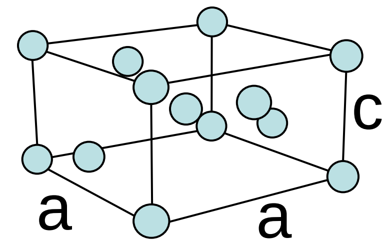


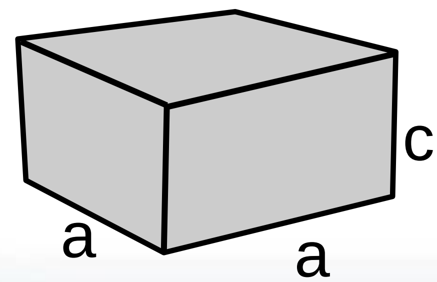
Film stress as a function of time for Sn and SnCu electroplated films.

Methods:

Microstructure - Crystallographic Texture

- Crystal Structure
  - Building block of atomic arrangements
- Sn Crystal Structure
  - Body-centered tetragonal (BCT)
    - a = 0.583nm
    - c = 0.318nm
- Crystallographic Texture
  - Distribution of crystallographic orientations

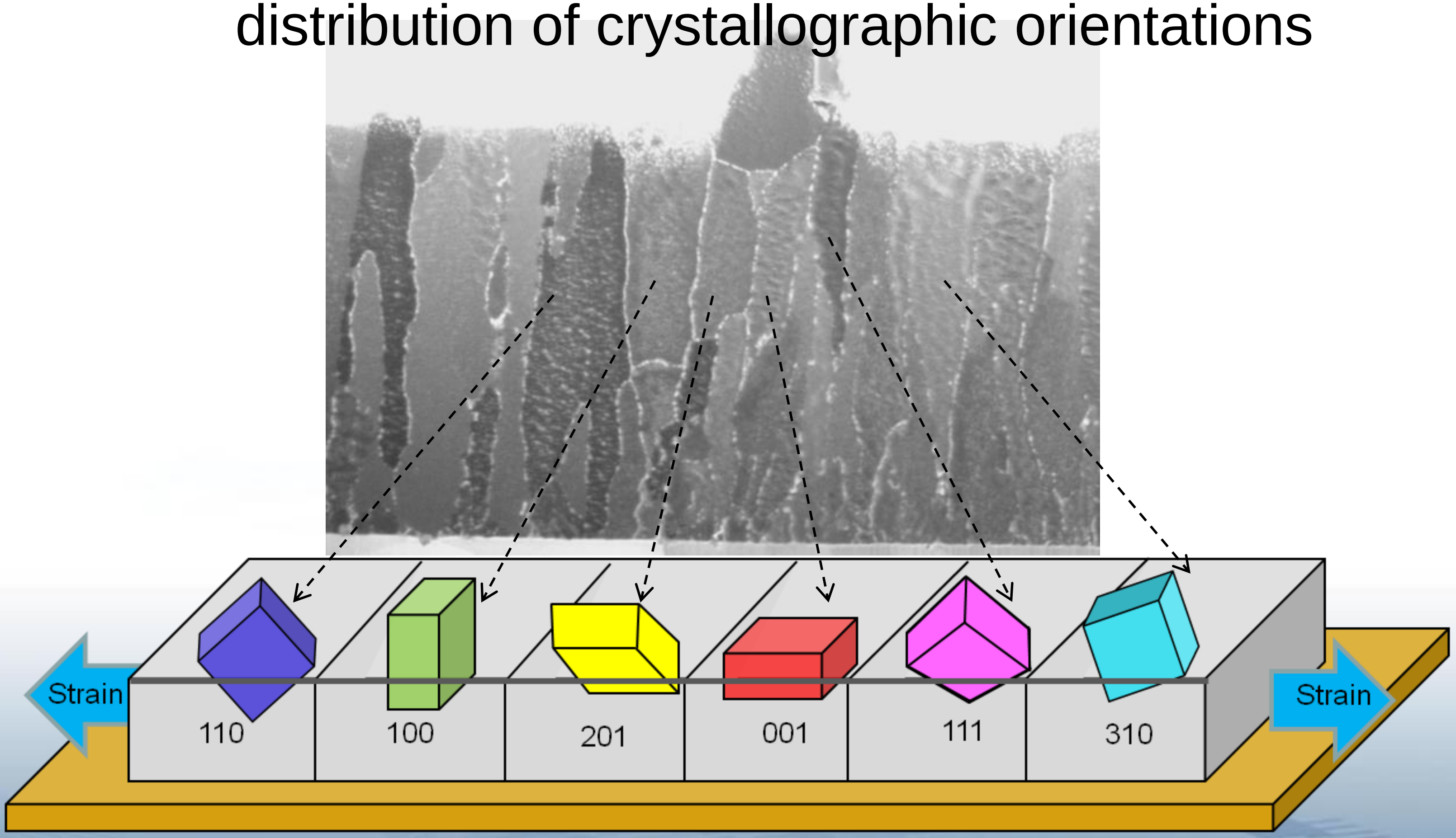




Methods:

Microstructure – Crystallographic Texture

Crystallographic texture describe the distribution of crystallographic orientations



Method:

Microstructure – Crystallographic Texture

- Observations by Arnold[9]
  - Observed that basic processing parameters influenced the propensity of an electroplated film to whisker
    - Current density
    - Electrolyte additives
    - Plating thickness
- These factors also influence crystallographic texture[4]

- Observations from Lee and Lee[8]
  - Focused on the mechanically anisotropic nature of Sn
  - For a stress of 8MPa, the expected strain could vary by 300%
  - Reaction to a strain affects the local stress state of a grain
    - Local stress gradient affects mass transport

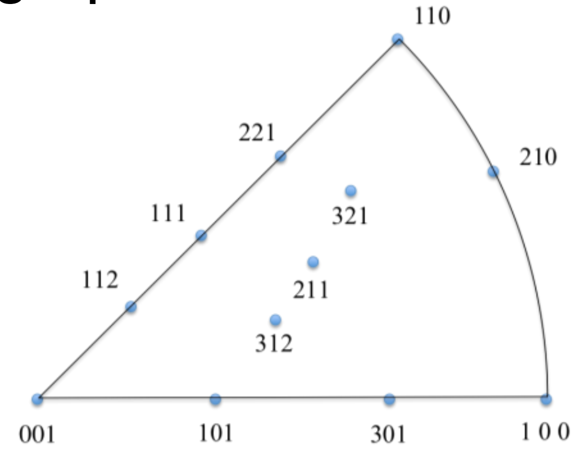
Method:

Microstructure – Crystallographic Texture

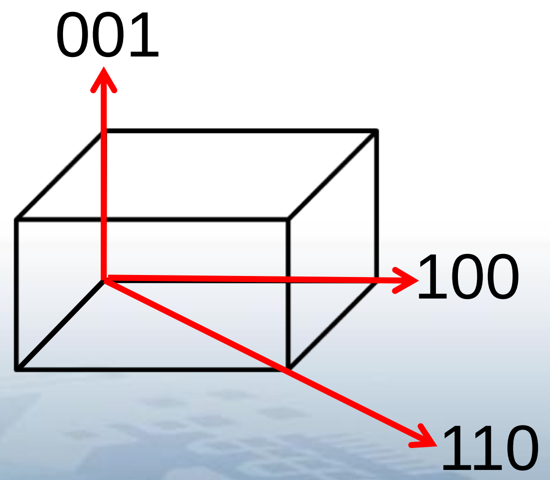
- Two commercial Sn electrolytes
  - Electrolyte 'A'
    - Reported to be whisker resistant
  - Electrolyte 'B'
    - Reported to be whisker prone
- Range in thickness
  - 1, 2, 4, 8, 12μm
- 40 or 80 mA/cm^2 deposition current density
- Measured texture the day after and 30 days after plating using XRD

Method:

Microstructure – Crystallographic Texture



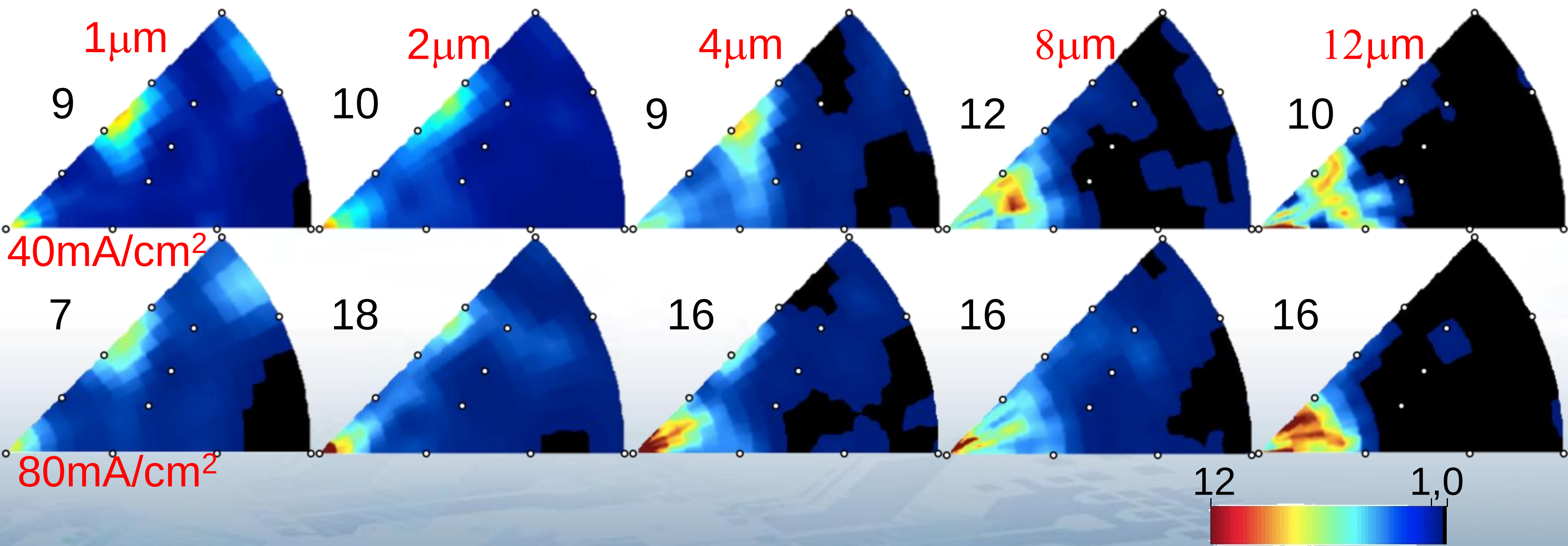
- Texture results presented as inverse pole figures
  - Topographical maps were the color represents the degree of texture in **multiple of random distribution (MRD)**
    - <1 is less probable
    - 1 = same as random distribution
    - >1 is more probable



Results:

Crystallographic Texture for ‘A’

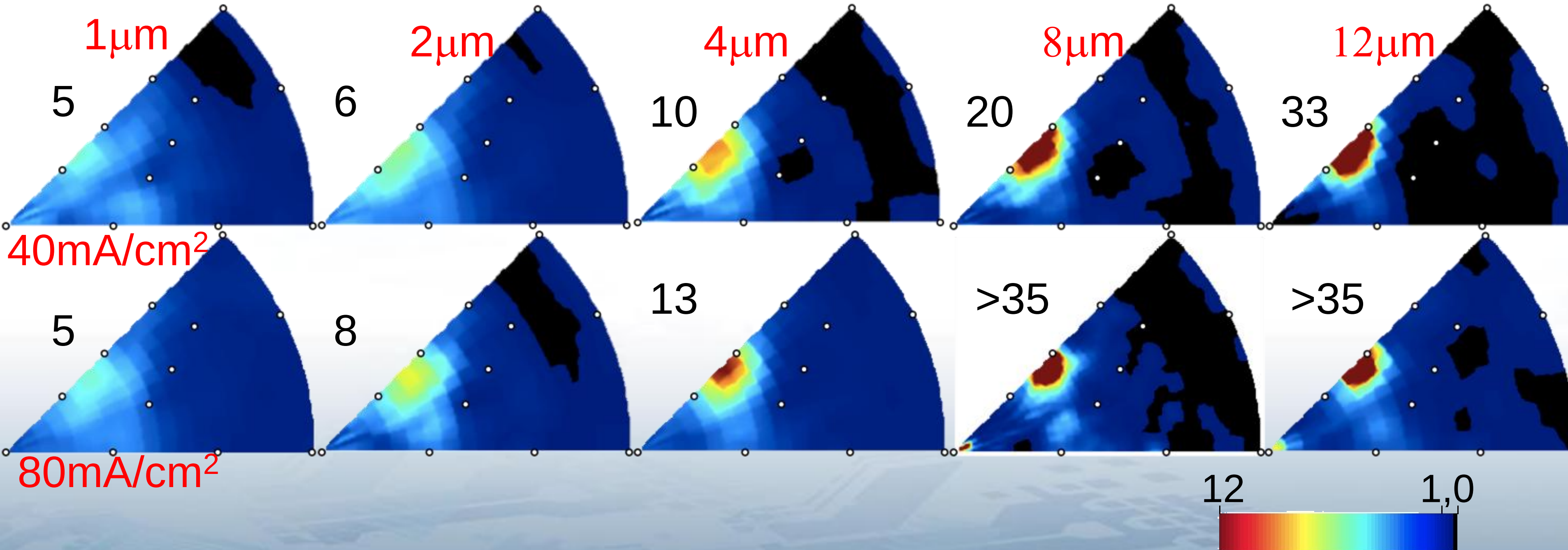
- Texture changes due to film thickness and deposition current density



Results:

Crystallographic Texture for ‘B’

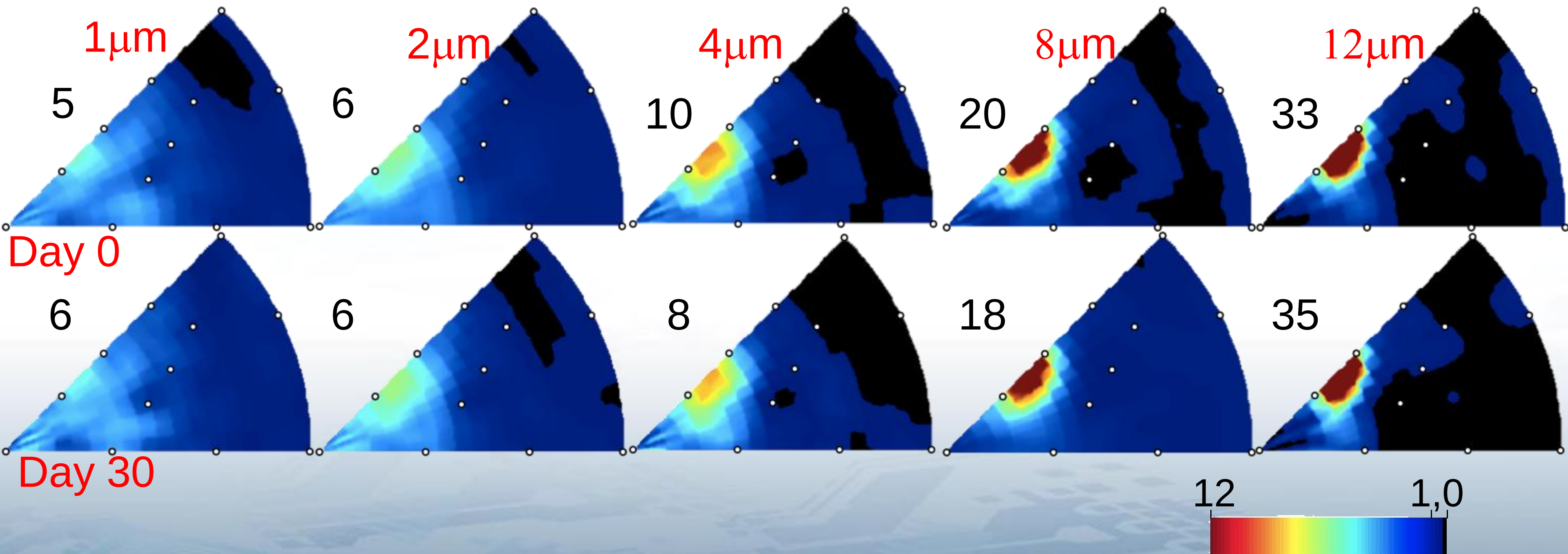
- Texture changes due to film thickness and deposition current density



Results:

Crystallographic Texture for 'B'; Day 30

- No hillock and whisker growth after 30 days
- No change in crystallographic texture



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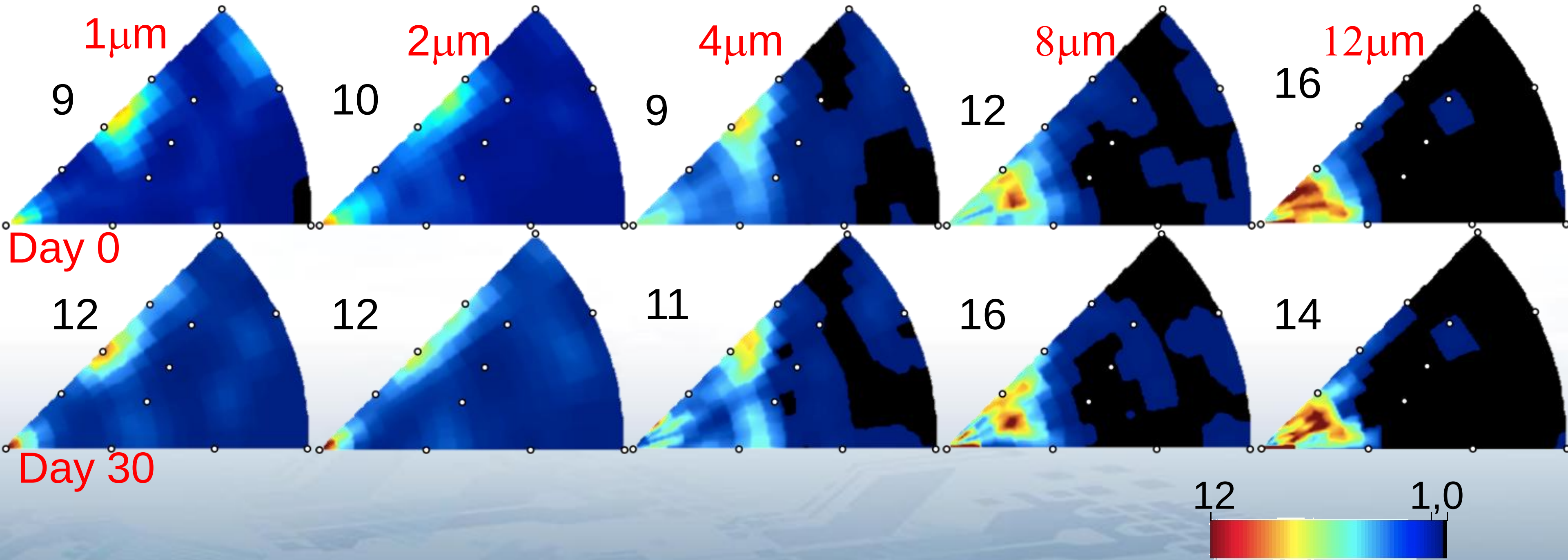
Results:

Crystallographic Texture for ‘A’; Day 30

- Hillock growth after 30 days on films 8 and 12μm thick
- Changes in crystallographic texture for all films



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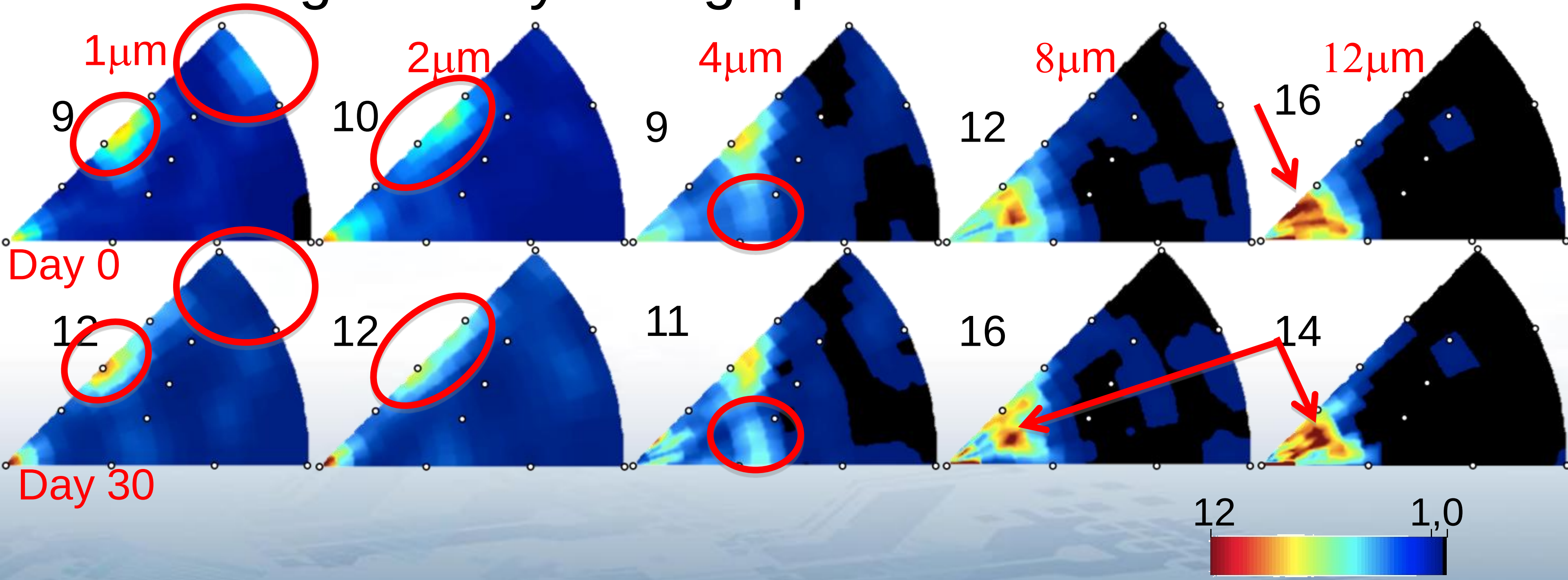
Results:

Crystallographic Texture for ‘A’; Day 30

- Hillock growth after 30 days on films 8 and 12μm thick
- Changes in crystallographic texture for all films



Results:

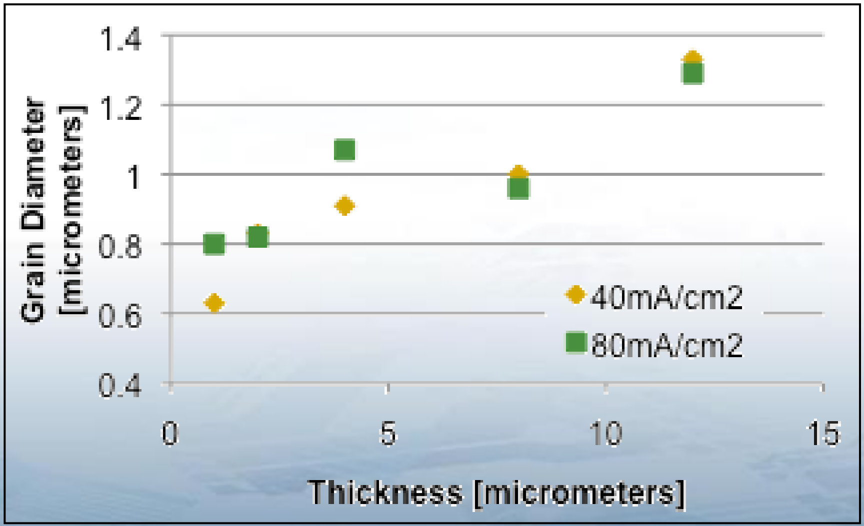
Crystallographic Texture Summary

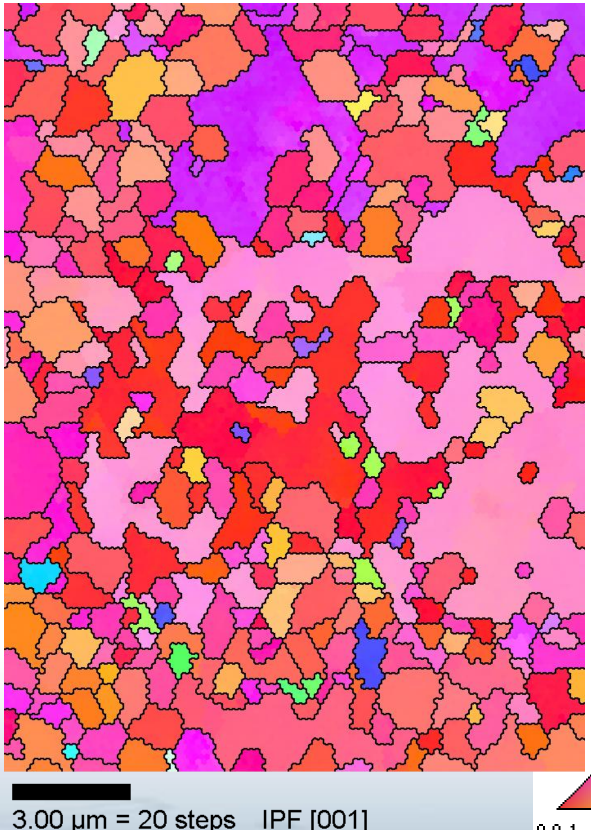
- All processing parameters results in differences in crystallographic texture
  - Electrolyte type
  - Deposition current density
  - Film thickness
- Change in texture after 30 days for films deposited from electrolyte ‘A’ but not from electrolyte ‘B’
- Evidence of recrystallization and/or grain growth with changing texture
  - Possible stress relief mechanism
- Increase in particular orientation correlated to hillock growth
  - Possible orientation dependence
    - Role of active slip systems (mechanism)

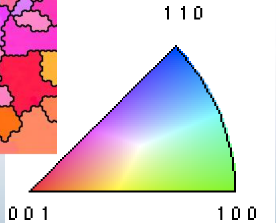
Results:

Grain Size Development – Electrolyte ‘A’

- Increasing grain diameter with thickness
  - Grain diameter between 0.6 and 1.4μm
- Bimodal distribution of grain size
- No clear effect due to current density





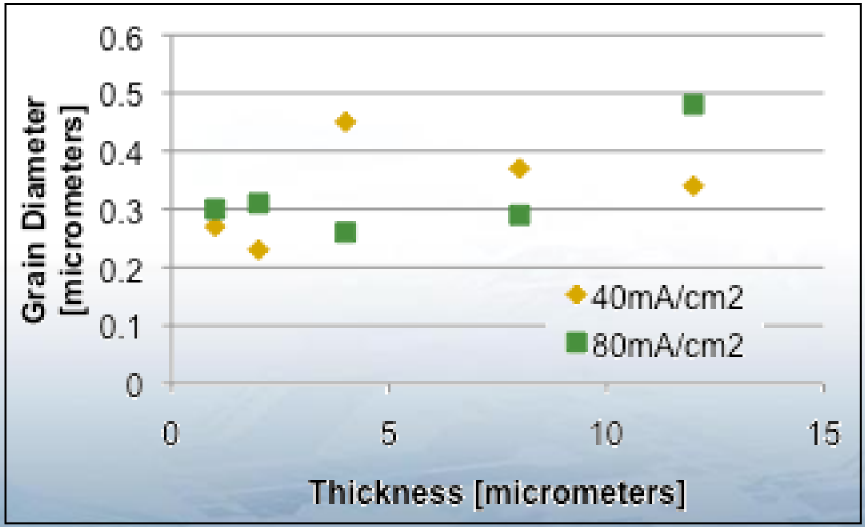


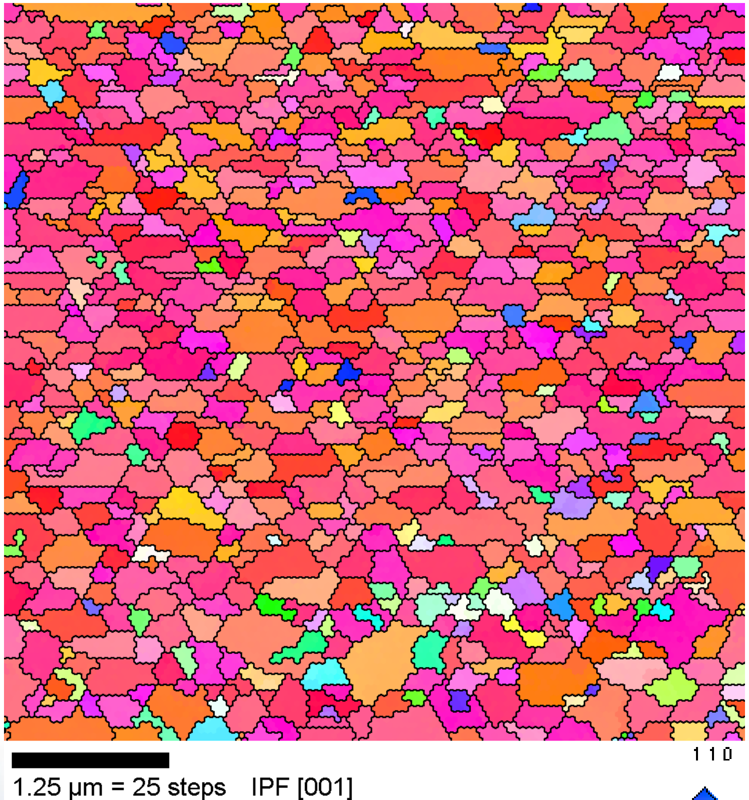
EBSD grain map in inverse pole figure colors for a 4μm film deposited from electrolyte ‘A’

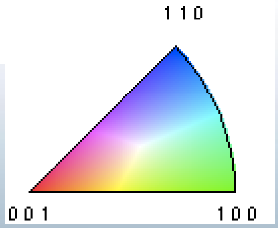
Results:

Grain Size Development – Electrolyte ‘B’

- Grain diameter between 0.2 to 0.5μm
- No clear effect due to current density







EBSD grain map in inverse pole figure colors for a 4μm film deposited from electrolyte ‘A’

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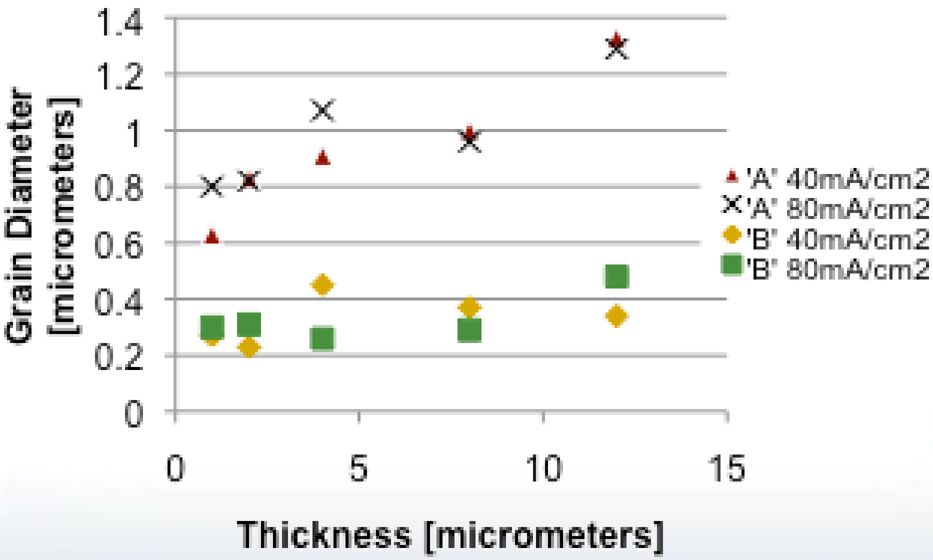
Results:

Grain Size Summary

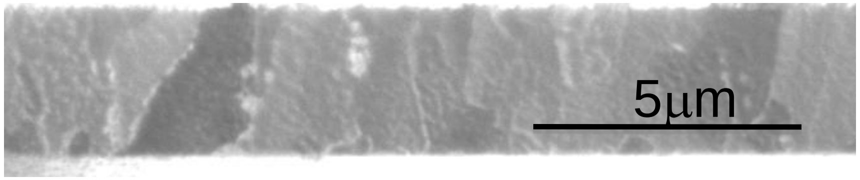
- Films deposited from electrolyte 'B' have a finer grain structure
- The grain size of films deposited from electrolyte 'A' increase with thickness but there is no clear effect with films from electrolyte 'B'
- Films from electrolyte 'A' have a bimodal distribution of grain diameters



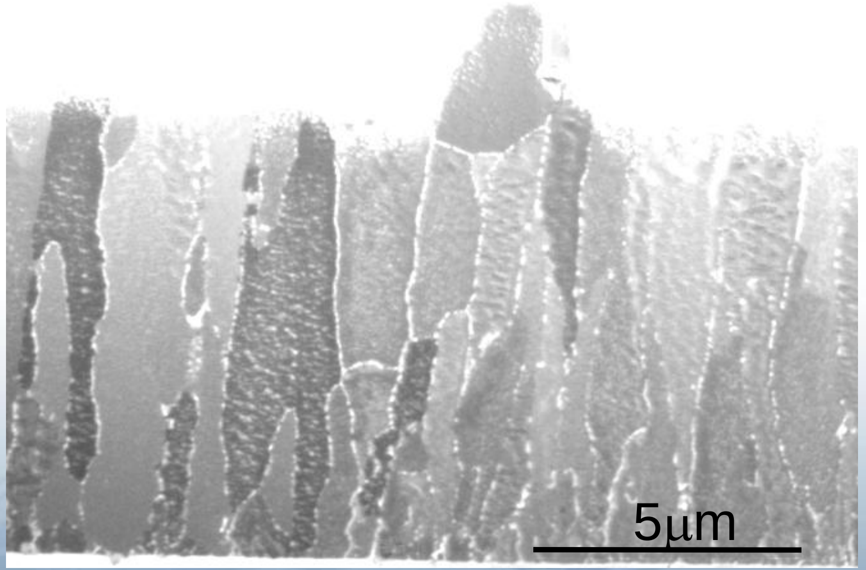
Results:

Microstructure – Grain Morphology – Electrolyte 'A'

- Columnar grain growth observed at all thicknesses evaluated
- Existing grains terminate and new grains form throughout the thickness of film



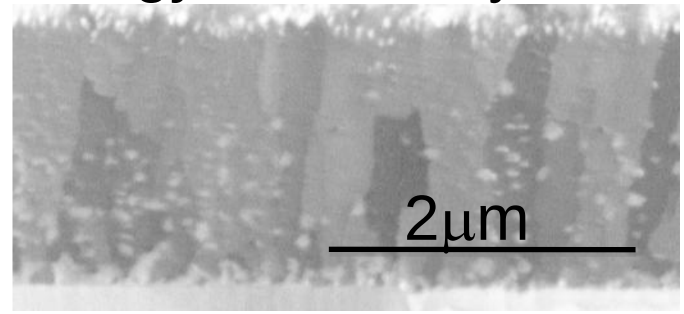
FIB cross section 4μm(above) and 12μm (below) thick film deposited from electrolyte 'A'



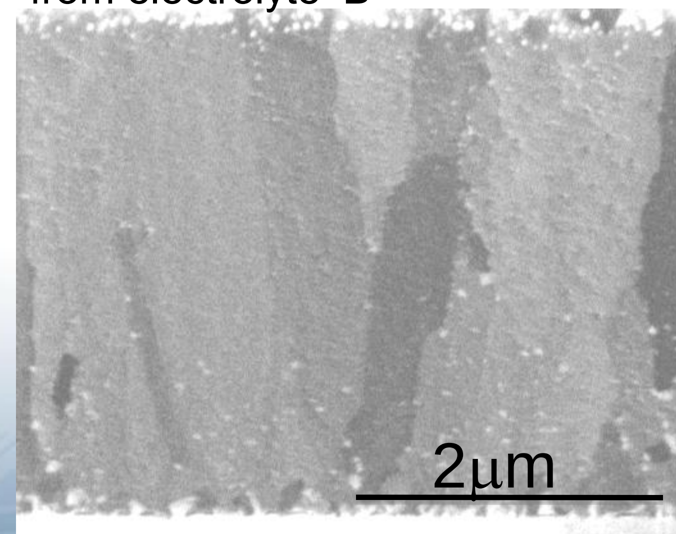
Results:

Microstructure – Grain Morphology – Electrolyte ‘B’

- Columnar grain growth observed at all thicknesses evaluated
- Existing grains terminate and new grains form throughout the thickness of film



FIB cross section 2μm(above) and 4μm (below) thick film deposited from electrolyte ‘B’



Concluding Remarks

Correlating film properties to the propensity to whisker will lead to the development of a comprehensive whisker growth model and create successful mitigation strategies.

- Hillock and whisker growth have been correlated to measureable film properties
  - Film stress evolution
  - Grain boundary mobility
  - Crystallographic texture evolution
- Film properties are influenced by basic processing parameters
  - Electrolyte type
  - Electrolyte additives
  - Deposition current density
  - Film thickness

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Questions

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