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TCG - XIV

# Validation of the Dynamic Recrystallization (DRX) Mechanism for Whisker and Hillock Growth in Thin Films

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# Fundamental Mechanisms

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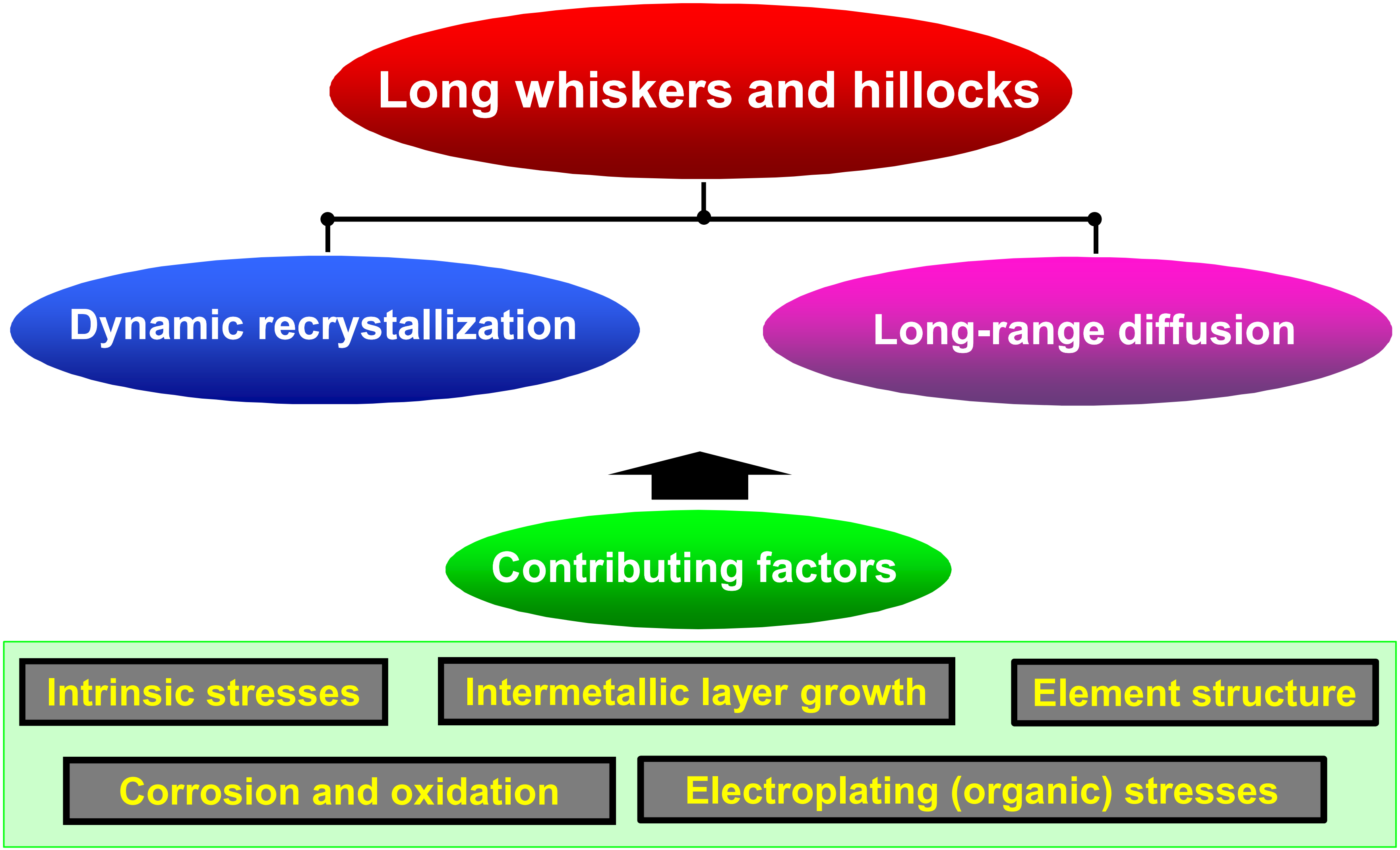

# Introduction

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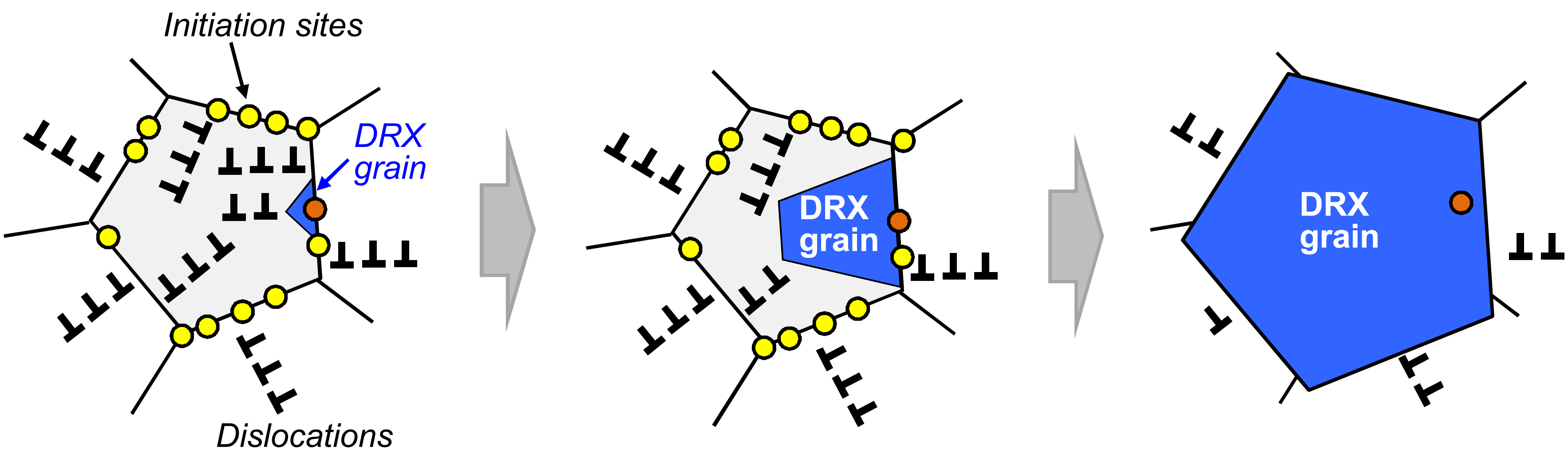
- **Dynamic recrystallization (DRX):**
  - **New grain formation-plus-grain growth accelerated by the additional driving force provided by the strain energy.**




**Grain initiation**

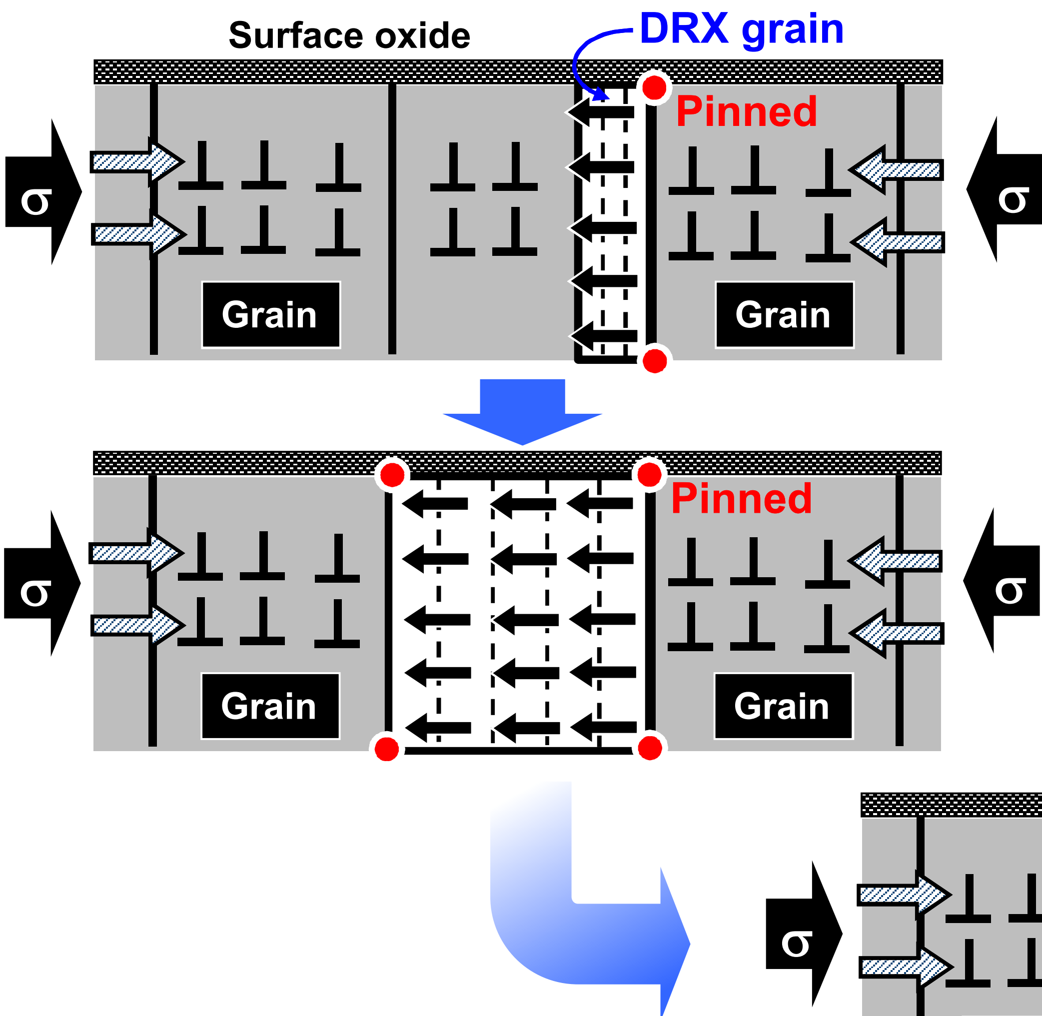
**Grain growth.**

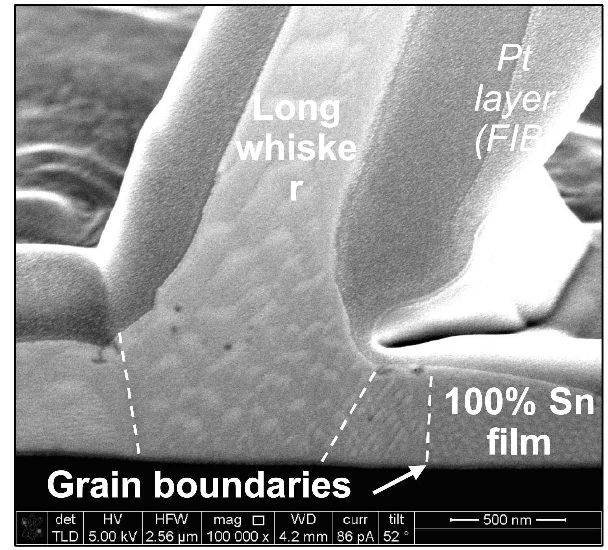
**DRX stops when the strain energy is lost.**

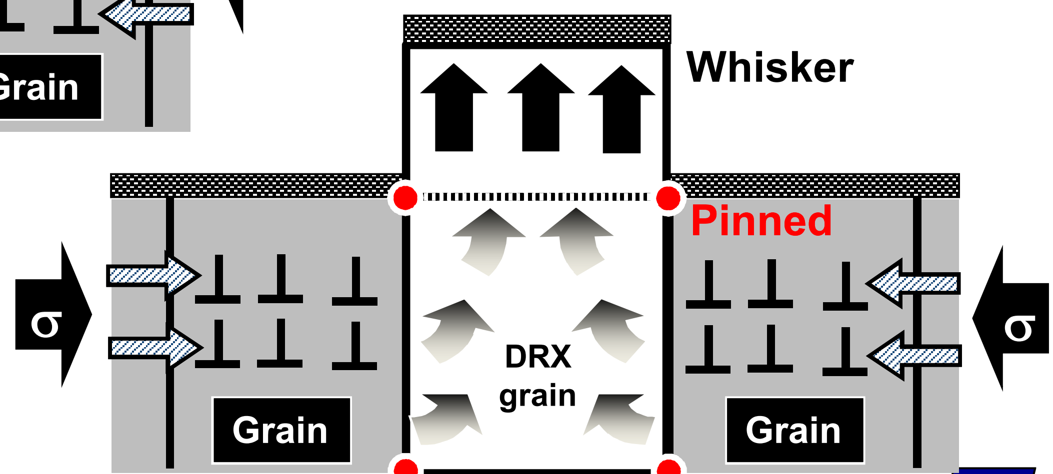
# Introduction



- **Diagram shows DRX applied to long whisker development:**



# Creep Data of Sn: Hollow Cylinder

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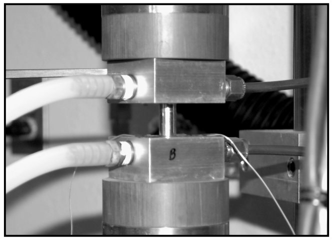
**Creep behavior** → **Strain energy and DRX** → **Whiskers and hillock**

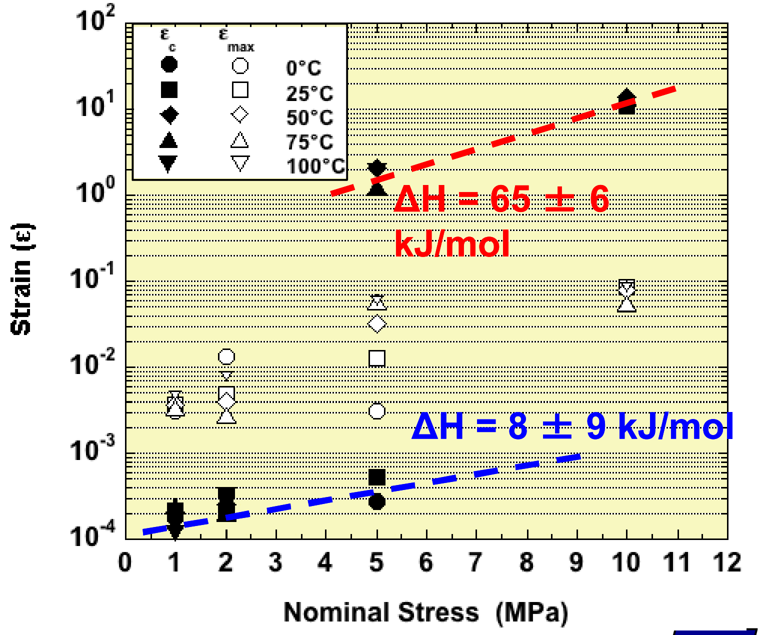
- **The strain energy from creep relaxation provides the driving force for DRX.**
- **Literature data and the present study, indicate that long-range diffusion is *generally* not a controlling factor.**
- **Critical finding: There are two creep deformation regimes in Sn:**
  - **$d\varepsilon/dt < 10^{-7}\ s^{-1}$ …**

    **$\Delta H = 8 \pm 9$ kJ/mol**
  - **$d\varepsilon/dt > 10^{-7}\ s^{-1}$ …**

    **$\Delta H = 65 \pm 6$ kJ/mol**

*Compression creep testing*

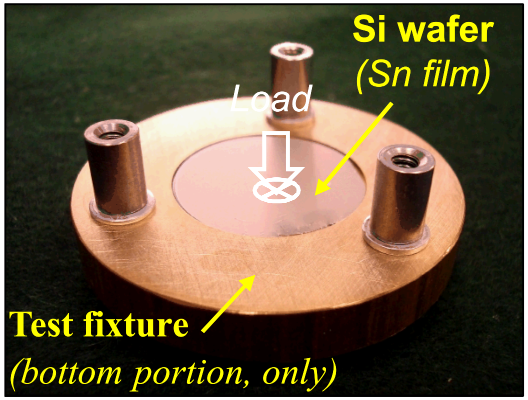




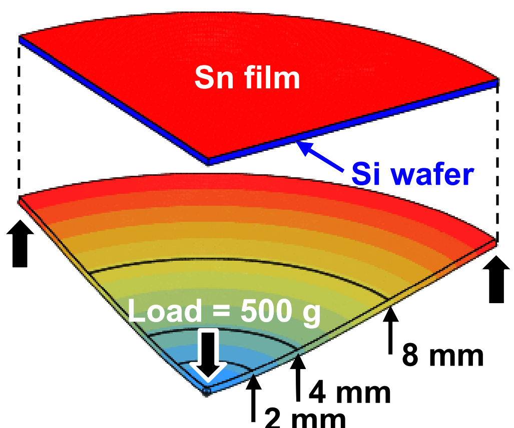
# Creep Data of Sn – Sn on Si Wafers



- Evaporated Sn on Si wafer removes "contributing factors."
- Test variables encourage to whisker growth:
  - Si wafers … 2.54 mm diameter
    … 0.275 mm thick
  - Adhesion layer … 20 nm Cr
  - Sn thicknesses …
    0.25, 0.50, 1.0, 2.0, and 4.9 µm
  - Temperatures (nine days) … 35, 60, 100, 120, and 150°C
  - Load … 500g (C), 500 (T), and No Load




- Computational modeling predicted the anelastic strains and strain rates in the Sn films caused by:
  - Applied load (500g): $10^{-4} – 10^{-3}$
    - Mismatch of coefficient of thermal expansion (CTE), *Sn vs. Si*: $10^{-3} – 10^{-2}$



# Thin Film Phenomena

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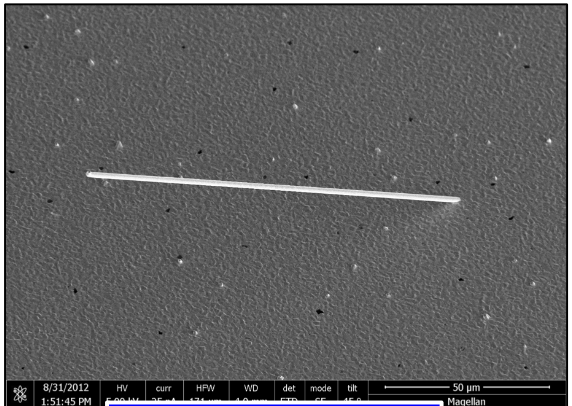
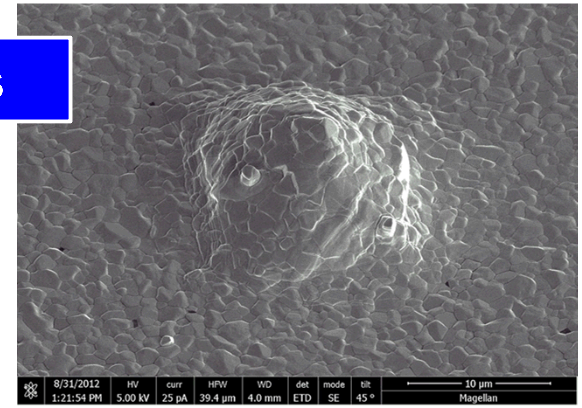
- Three phenomena were documented in these experiments:

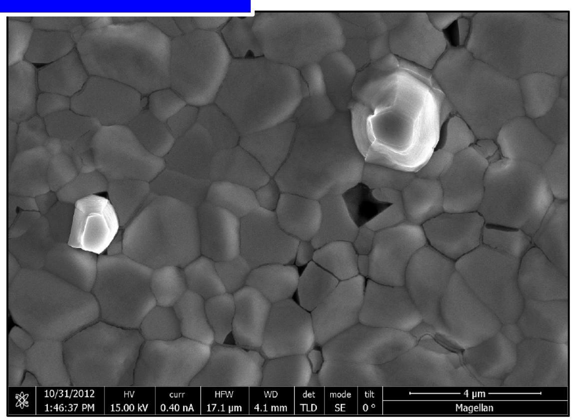



*Long*

**Hillocks**

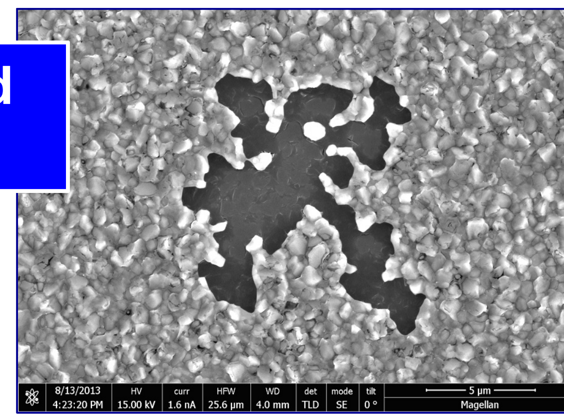



**Whiskers**




*Short, stubby*

**Depleted zones**



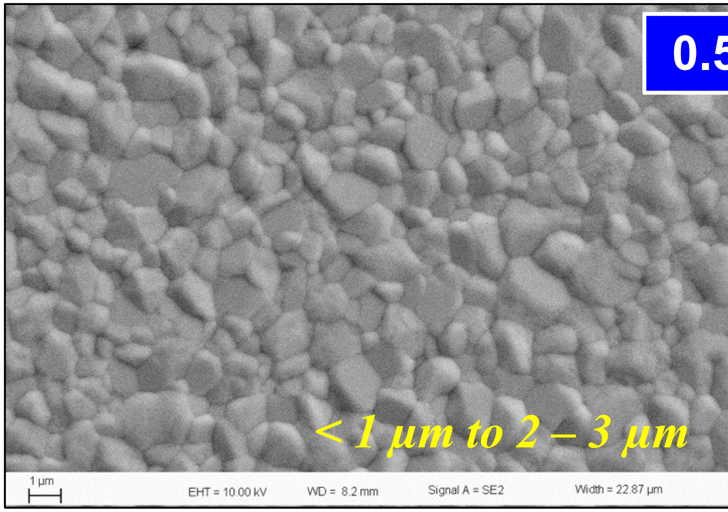

- Required measurement granularity: **Present** or **Not-present**

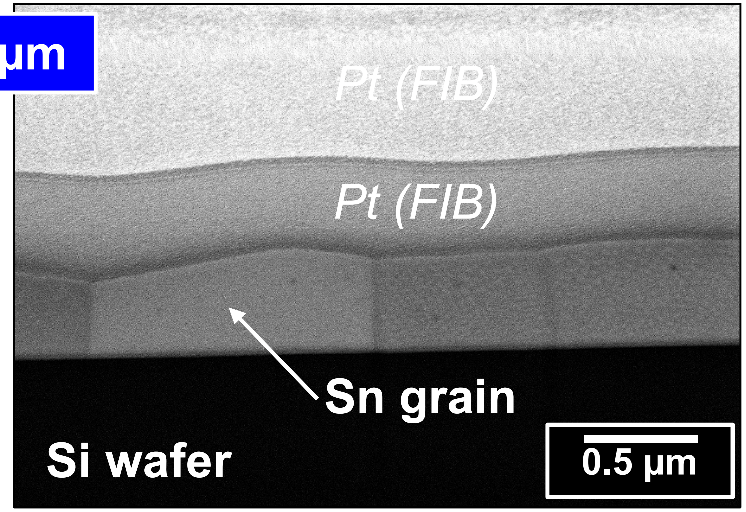
# Sn Film Microstructures



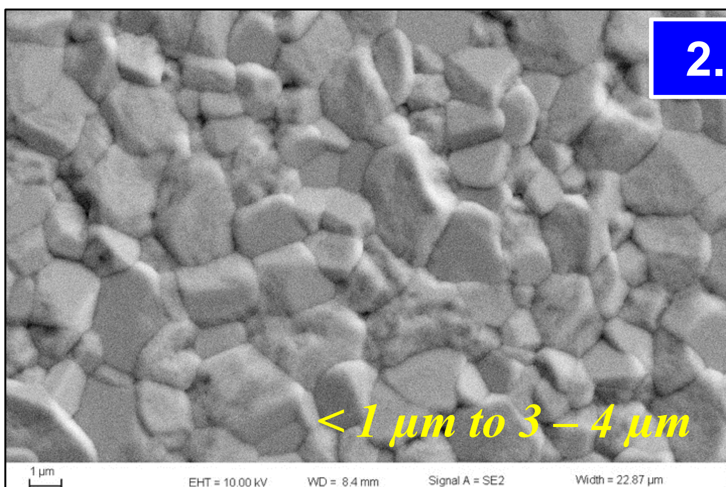
- **Certainly, the film microstructures affect DRX mechanism …**

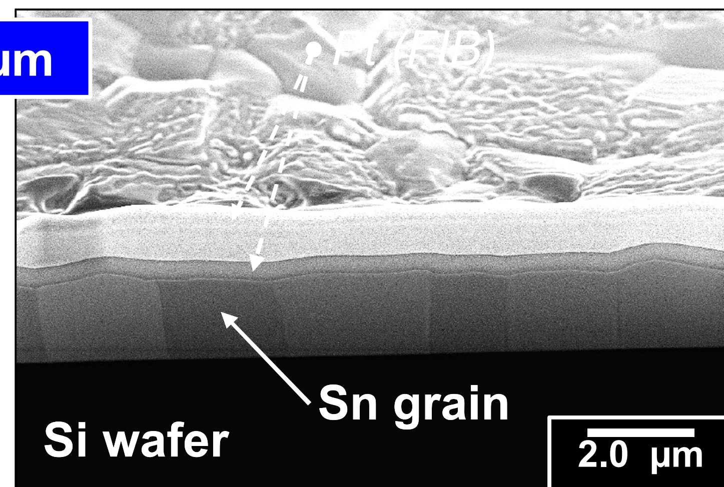
**0.50 µm**




**2.0 µm**



# DRX Mechanism and Thin Films



- More so, it is the *synergy* between the DRX mechanism and thin film properties that determine whisker and hillock growth.

Long whiskers and hillocks

Long-range diffusion

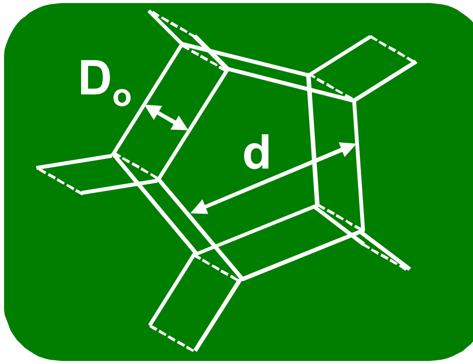
Dynamic recrystallization

Thin film (layer) effect

$$\varepsilon_c = A\, D_o^{m}\, Z^{n}$$

*and*

$$D_o < 2D_r$$



# Critical Strain versus Actual Strain

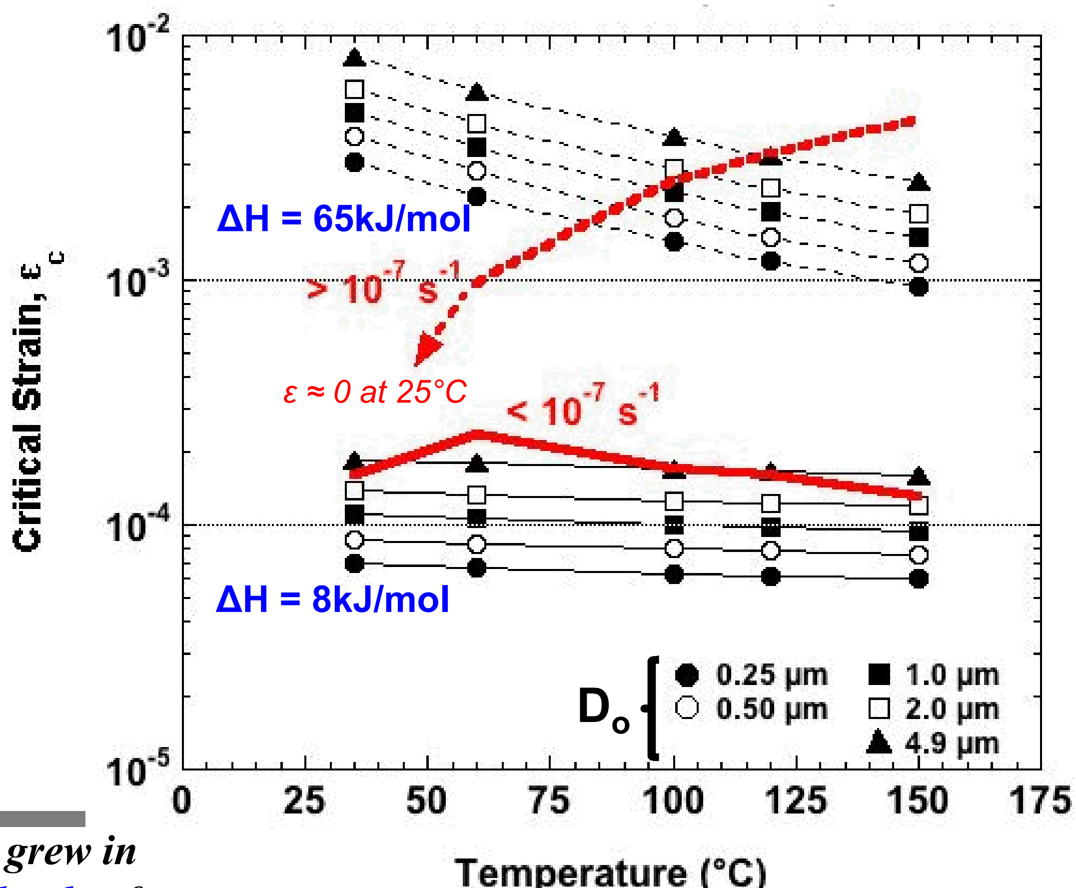


- The critical strain contours, $\varepsilon_c$, were calculated from $A\,D_o^m Z^n$, based upon the the two $\Delta H$ values and strain rate, $d\varepsilon/dt = 10^{-7}\ s^{-1}$.

- The computational model predicted strain, $\varepsilon$, versus temperature for all $D_o$ thicknesses*:

  The computed $\varepsilon$ was partitioned into the strain accumulated under:
  $d\varepsilon/dt > 10^{-7}\ s^{-1}$ …

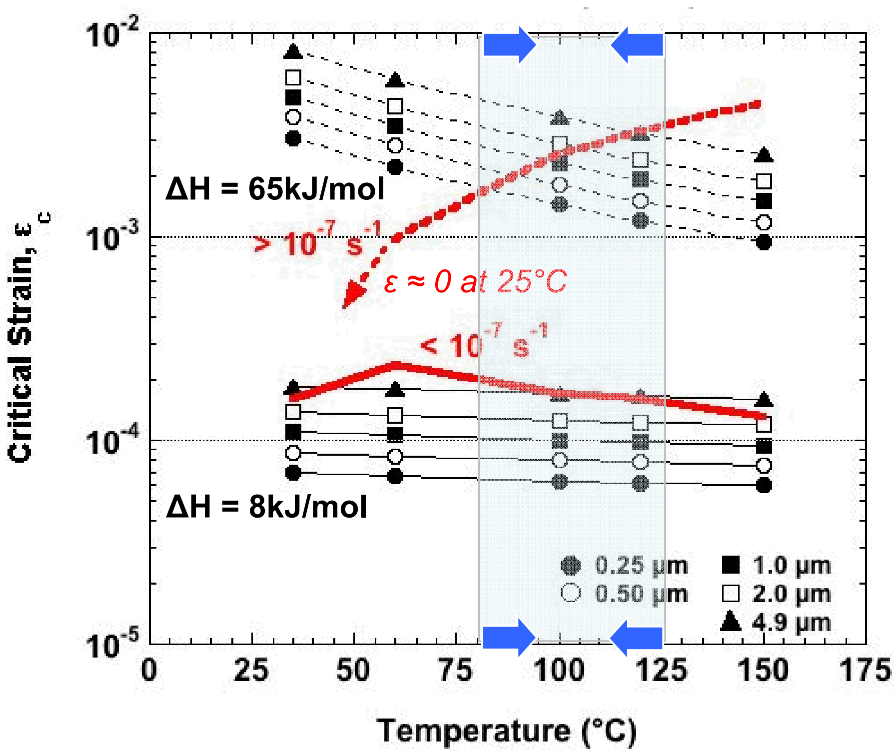
  … and the portion of $\varepsilon$ that accumulated under:
  $d\varepsilon/dt < 10^{-7}\ s^{-1}$.




**It was assumed that the strain that grew in the > $10^{-7}\ s^{-1}$ regime did so independently of the strain that grew in the < $10^{-7}\ s^{-1}$ regime.*

# Validation

| Film Thickness | Temperature (C) | | | | |
|---|---|---|---|---|---|
| | 35 | 60 | 100 | 120 | 150 |
| 0.25 | | | | | |
| 0.5 | | | | | |
| 1.0 | | | | | |
| 2.0 | | | | | |
| 4.9 | | | | | |




- Validation compared the experimental data with the DRX model.

**80°C < T < 125°C**

- **$d\varepsilon/dt > 10^{-7}$ $s^{-1}$ …**
  - **$\varepsilon > \varepsilon_c$, 0.25 – 1.0 µm**
    Driving force for DRX.
    - *$\varepsilon <> \varepsilon_c$, for 2.0 µm*
      *DRX … borderline*
  - **$\varepsilon < \varepsilon_c$, 4.9 µm**
    *No driving force for DRX.*
- **$d\varepsilon/dt < 10^{-7}$ $s^{-1}$ …**
  - **$\varepsilon < \varepsilon_c$, for 0.25 – 2.0 µm**
    *Driving force for DRX.*
  - **$\varepsilon \approx \varepsilon_c$, 4.9 µm**
    *No driving force for DRX.*

# Validation



**80°C < T < 125°C**

- **The analysis, $\varepsilon_c = A\,D_o^m\,Z^n$, predicted that there was a nominal driving force for DRX in 2.0 µm films.**
- **But, only short-stubby whiskers were observed, indicating that DRX was limited to the continuous variant rather than cyclic DRX.**
  - **Long-whisker had diameters of 1.0 – 1.5 µm.**
  - **$2D_r$ = 2.0 – 3.0 µm**
  - **$D_o$ < 2.0 – 3.0 µm**
    - **Therefore, the 2.0 µm films have too large of a grain size to experience the degree of cyclic DRX required to produce long whiskers.**
      - **Rather, under the driving force, the 2.0 µm films exhibit the limited, continuous DRX that leads to short, stubby whiskers.**

**Dynamic recrystallization**

$$\varepsilon_c = A\,D_o^m\,Z^n$$

*and*

$$D_o < 2D_r$$

- **The 4.9 µm films are predicted to not show DRX. The presence of a few, isolate, short, stubby whiskers indicates a small degree of continuous DRX – *and the relative sensitivity of this analysis*.**

# Validation



**80°C < T < 125°C**

- **Hillocks were not observed on 2.0 µm films.**
  - **Hillocks had diameters of 7.0 – 10 µm.**
  - **$2D_r$ = 14 – 20 µm**
  - **$D_o$ < 14 – 20 µm**
    - **The 2.0 µm films have a $D_o$ < 14 – 20 µm so hillocks would be expected on the surface.**
  - ***Why aren't there any hillocks ?***
  - **Thin film effect:**
    - 2.0 µm … *versus* … < 1 to 3 – 4 µm
      ($D_o$ = 2.0 µm; d = < 1 to 3 – 4 µm)
    - **$D_o$ ≈ *or* < d, grain boundaries are more likely to be pinned.**
    - **Grain boundary pinning discourages hillocks.**

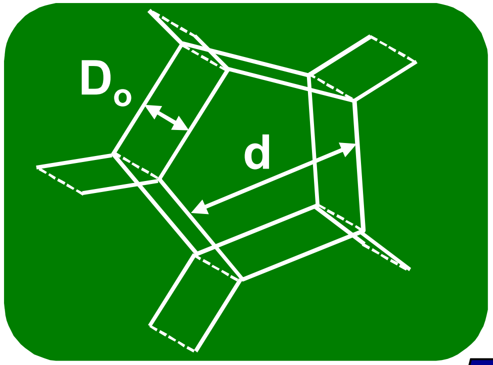
**Dynamic recrystallization**

$$\varepsilon_c = A\, D_o^{\,m}\, Z^n$$

*and*

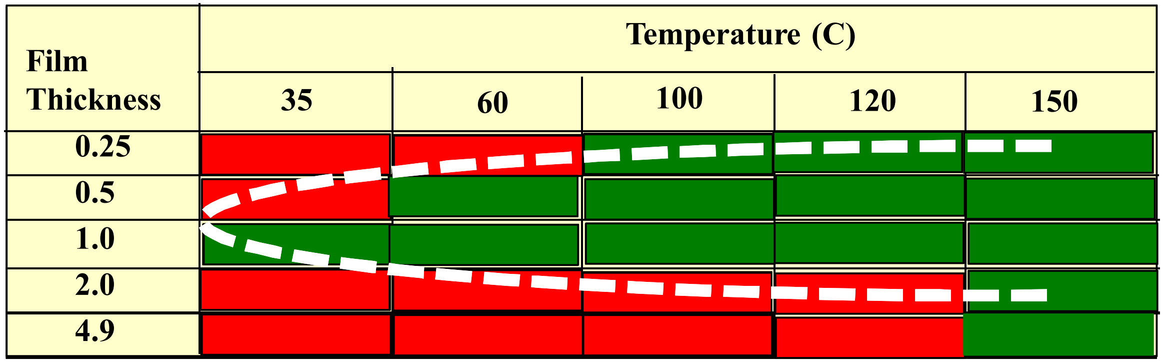
$$D_o < 2D_r$$

**Thin film (layer) effect**



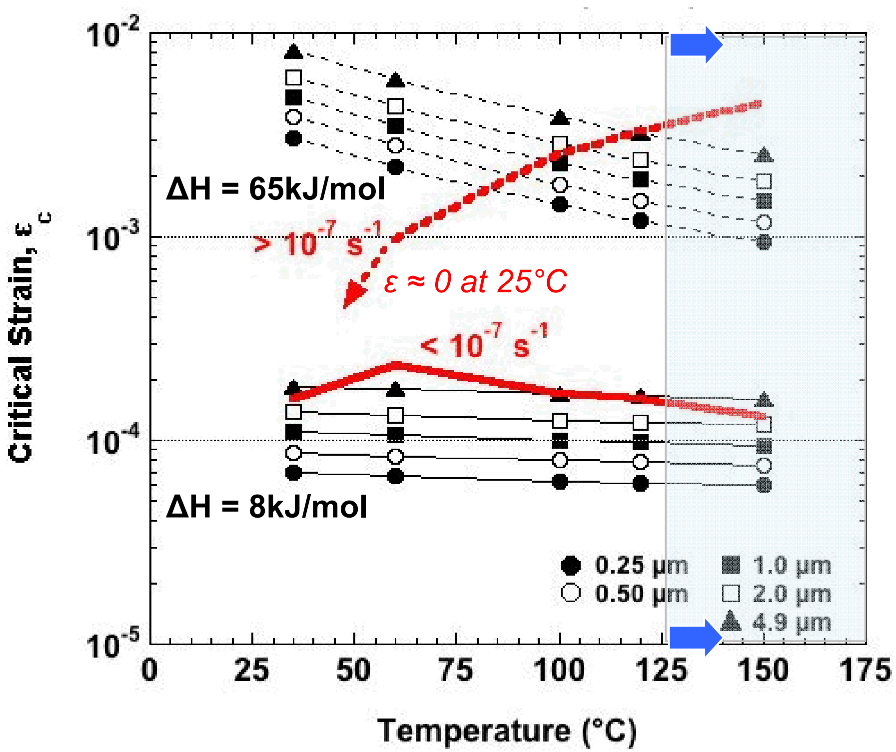
# Validation






- ◆ **Thin film properties had a greater role in the formation of whiskers or hillocks.**

**T > 125°C**




- **dε/dt > $10^{-7}$ $s^{-1}$ …**
  - **$\varepsilon < \varepsilon_c$, 0.25 – 4.9 mm**
    *Driving force for DRX.*
- **dε/dt < $10^{-7}$ $s^{-1}$ …**
  - **$\varepsilon < \varepsilon_c$, for 0.25 – 1.0 µm**
    *Driving force for DRX.*
    - *$\varepsilon$ < > $\varepsilon_c$, for 2.0 µm*
      *DRX … borderline*
  - **$\varepsilon < \varepsilon_c$, 4.9 µm**
    *No driving force for DRX.*

# Validation



**T > 125°C**

**Dynamic recrystallization**

$\varepsilon_c = A\,D_o^m\,Z^n$

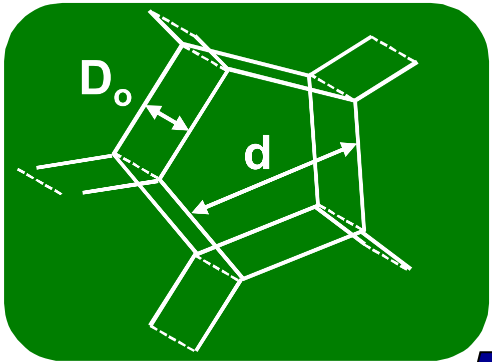
*and*

$D_o < 2D_r$

- **The analysis, $\varepsilon_c = A\,D_o^m\,Z^n$, predicted a driving force for DRX in 4.9 µm films (due to > $10^{-7}$ $s^{-1}$).**
  - **$D_o$ < 2.0 – 3.0 µm for long whiskers**
    - **Therefore, the 4.9 µm grain size was too large to support the cyclic DRX required for long whiskers. (*There were a few, short, stubby whiskers formed by continuous DRX.)***
  - **$D_o$ < 14 – 20 µm for hillocks**
    - **Therefore, the 4.9 µm films can potentially experience hillock growth.**
  - **Thin film effect:**
    - **4.9 µm** … *versus* … **1 – 5 µm**

      ($D_o$) … (d)
    - **$D_o$ ≈ *or* > d, grain boundary pinning is less likely.**
    - **Reduced grain boundary pinning encourages the formation of hillocks.**

**Thin film (layer) effect**



# Summary

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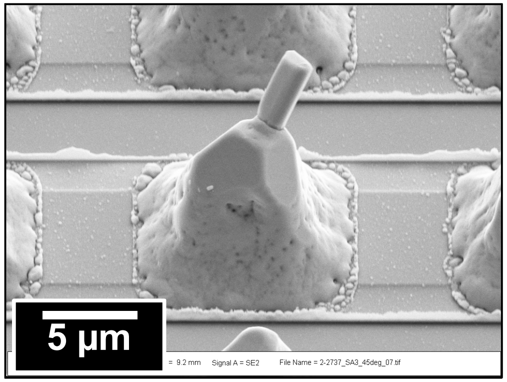
- This study validated **cyclic dynamic recrystallization (DRX)** as the controlling mechanism responsible for the development of **long whiskers** and **hillocks**.
- **Continuous DRX** appeared in the form of short, stubby whiskers.
- The supporting mechanism is **long-range diffusion.**




*100In*

- The thin film nature of the layer has a vital role in whisker development – the **specimen thickness effect**.
- Although **depleted zones** do not require DRX, the trends provided insight into the film **stress state** and **diffusion kinetics**.

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- The particular susceptibility of **Sn** to long whiskers and hillocks is because there are **two creep mechanisms *supporting the DRX mechanism*** over the relevant stress and temperature conditions.