Potential and Limits of Texture Measurement Techniques for Inlaid Copper Process Optimization

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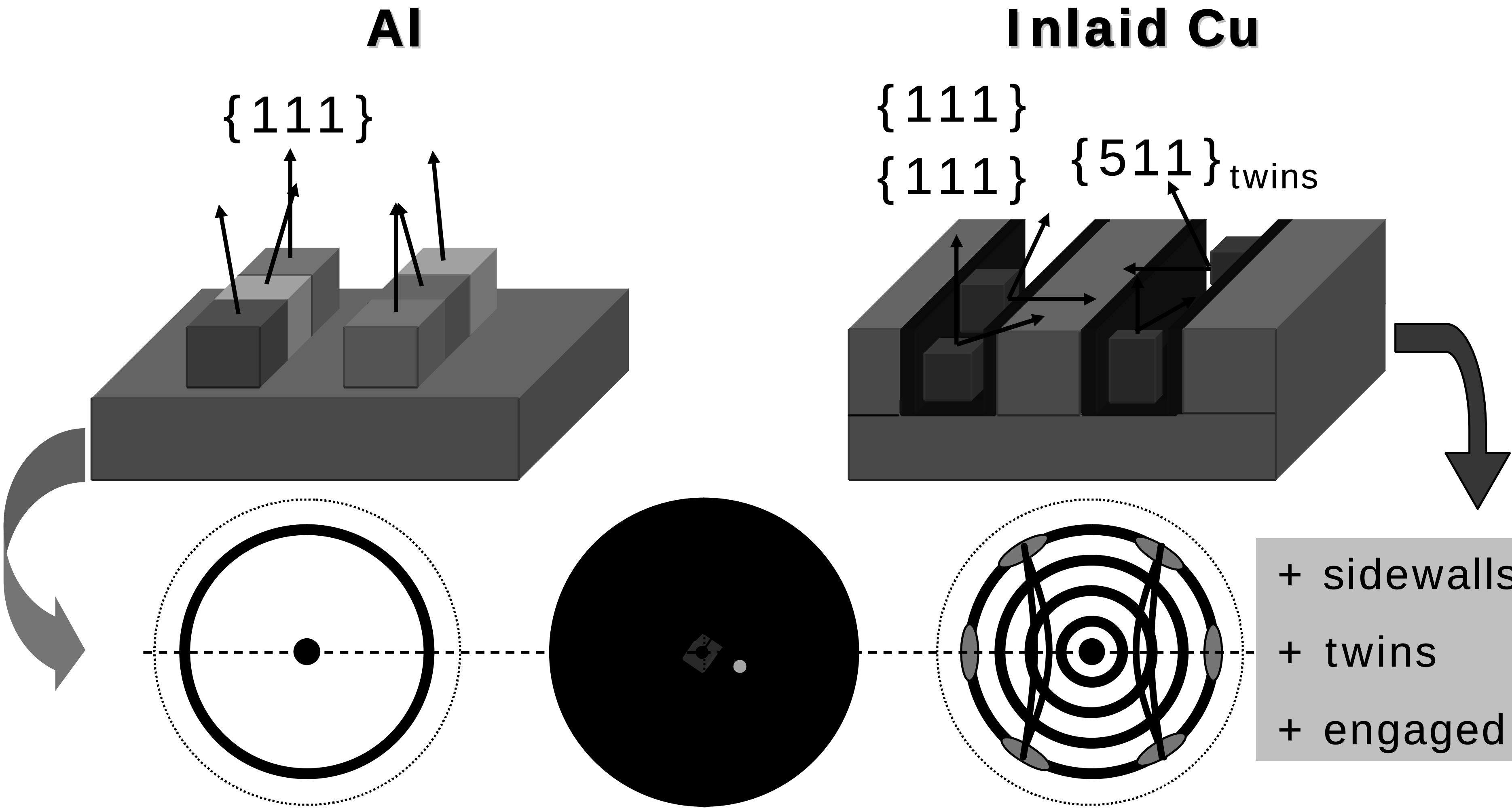
Outline

- Microstructure characterization of inlaid copper interconnects
- Texture measurement techniques
  - X-ray micro-diffraction
  - OIM: EBSD & ACT
- Application
  - Microstructure monitoring
  - ECD-filled inlaid structures with new ILDs, capping layers and barrier layers
  - Texture and stress
  - Orientation stereology, grain size, grain boundary distribution
  - Texture in ECD-filled via chains
  - Texture of barrier and seed layers before ECD filling
- Summary

Microstructure characterization of inlaid copper interconnects

- Aluminum vs. inlaid copper: What is different ?
- Texture, EM & defects
- Microstructure characterization: general concept
- Orientation distribution function (ODF)
- Quantification

Texture Al vs. inlaid Cu



- + sidewalls
- + twins
- + engaged

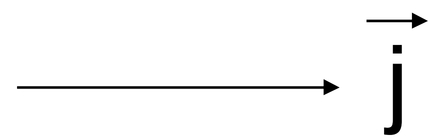
What is different ?

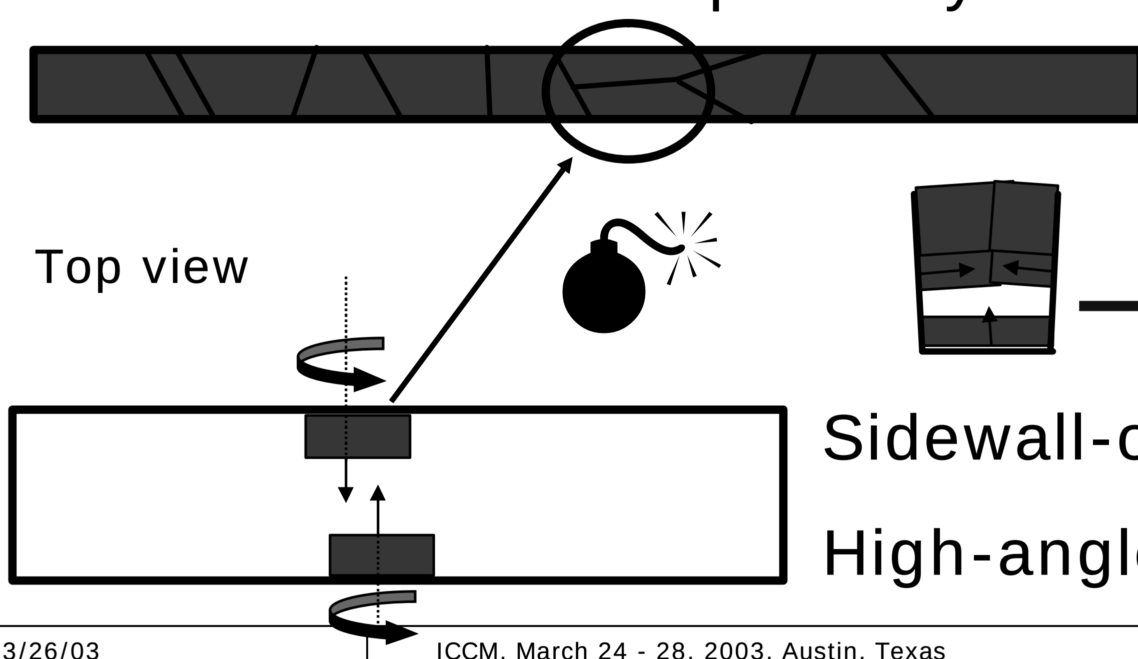
Inlaid Copper Interconnects	Aluminum Interconnects
Twins + Sidewall	Bamboo + Columnar
????	Optimum EM Behaviour
Large Anisotropy **$E\langle 111\rangle$ = 191 GPa** **$E\langle 100\rangle$ = 66.7 GPa**	Small Anisotropy
Electroplating	Vapour Deposition
Cu CMP	Metal etch
....	....

Electromigration:

→ Prevent grain boundaries along the trench direction!

= Fast diffusion pathways





→ void $v_{\rightleftarrows} > v_{\uparrow}$

Sidewall-oriented grains?

High-angle grain boundary?

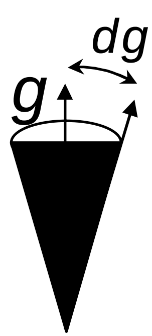
Microstructure Characterization: General Concept

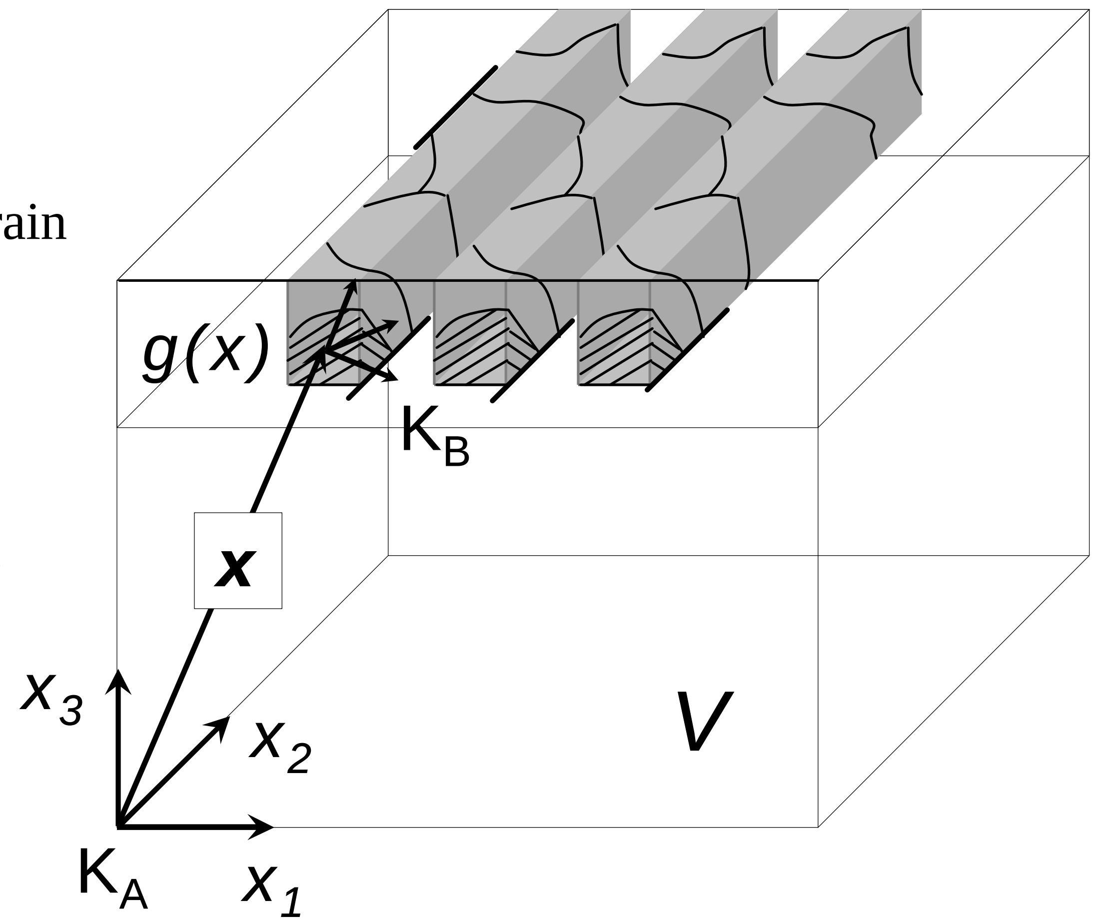
- Microstructure Function:

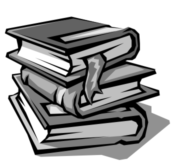
$$G(x)=\begin{cases} i(x) & \text{phase} \\ g(x) & \text{orientation} \\ D(x) & \text{defects, lattice strain} \end{cases}$$

- Orientation Distribution Function:

$$f(g)=\frac{dV_g\,/V}{dg}=f(j_1,\Phi,j_2).$$



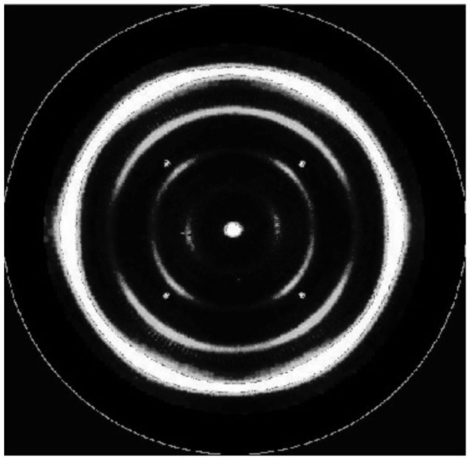




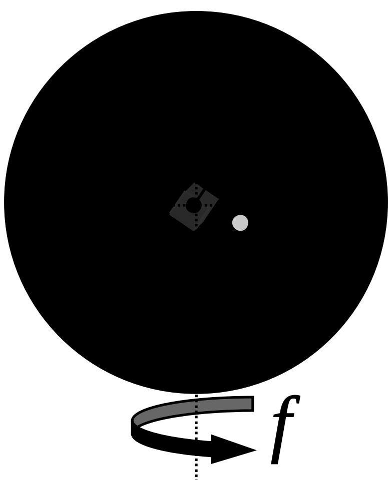
H.J. Bunge (1999, 2001)

Quantification: ODF approximation

[redacted]

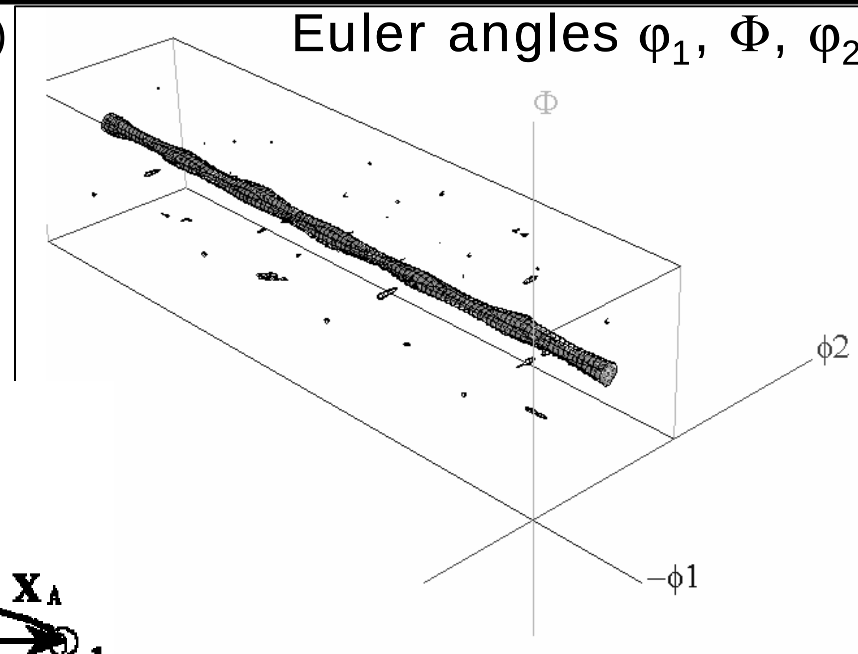


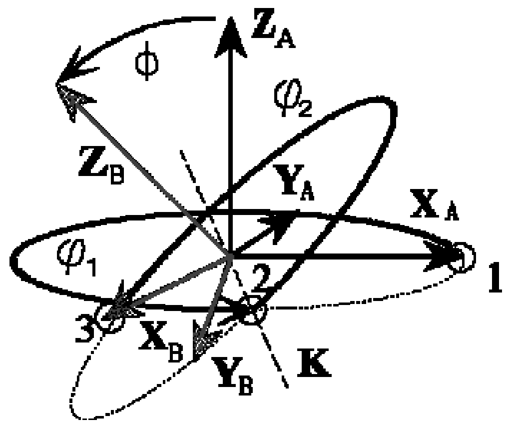
$P(c,f)$



(111)+(200)+(220)

e.g., ADC





$$P_{(hkl)}(c,f) = \frac{1}{2p}\int_0^{2p} f(f_1,\Phi,f_2)dg$$

$$f(g) = \frac{dV_g\,/V}{dg} = f(j_1,\Phi,j_2).$$

K_A: sample coordinates

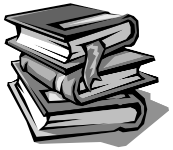
K_B: cryst. coord. system

[K. Helming, http://www.texture.de/]

Evaluation of pole figures

- Computational algorithms for OD analysis
  - Harmonic Methods: computation in Fourier space
  - Discrete (Direct) Methods: computation in orientation space:

$$P_h(c,f) = \frac{1}{N}\sum_{i=1}^{N} f[(c,f) \Leftarrow (f_1,\Phi,f_2)_i]$$



K. Pawlik et al. (1991)

U.F. Kocks et al. (1998)

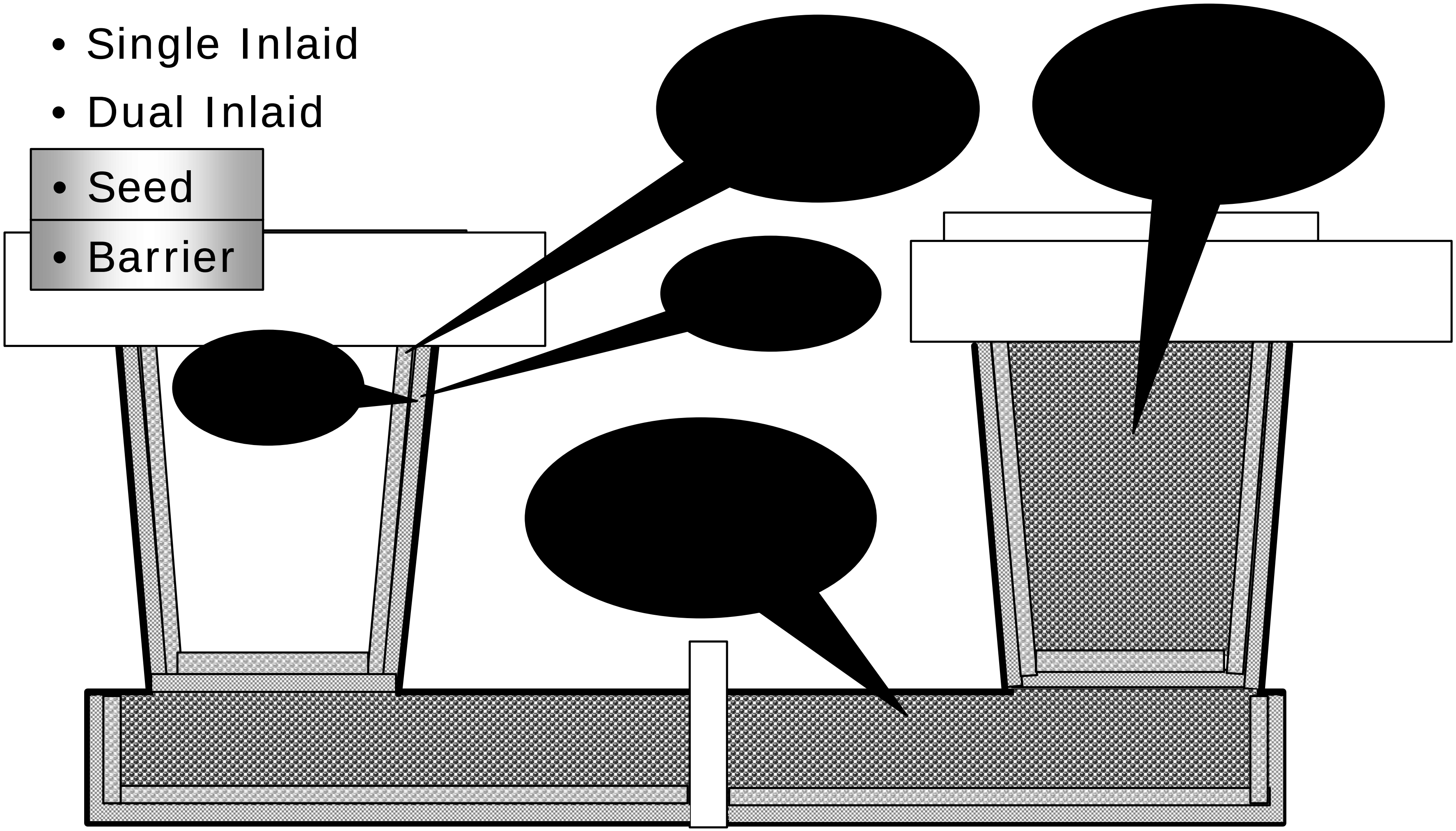
- Commercial software: LaboTex
  - based on ADC (Arbitrarily Defined Cells)
  - direct method, good for sharp textures
  - quantification of
    - **fibers**
    - **engaged fibers**
    - **twins**
  - uncertainty in determination of random texture component (background, low signal-to-noise ratio)

Texture measurement techniques

- Overview
- X-ray micro-diffraction
- OIM (Orientation Imaging Microscopy)
  - EBSD: Electron Backscatter Diffraction
  - ACT: Automated Crystallography for the TEM

Texture measurement techniques for inlaid Cu interconnects: Overview

- Single Inlaid
- Dual Inlaid



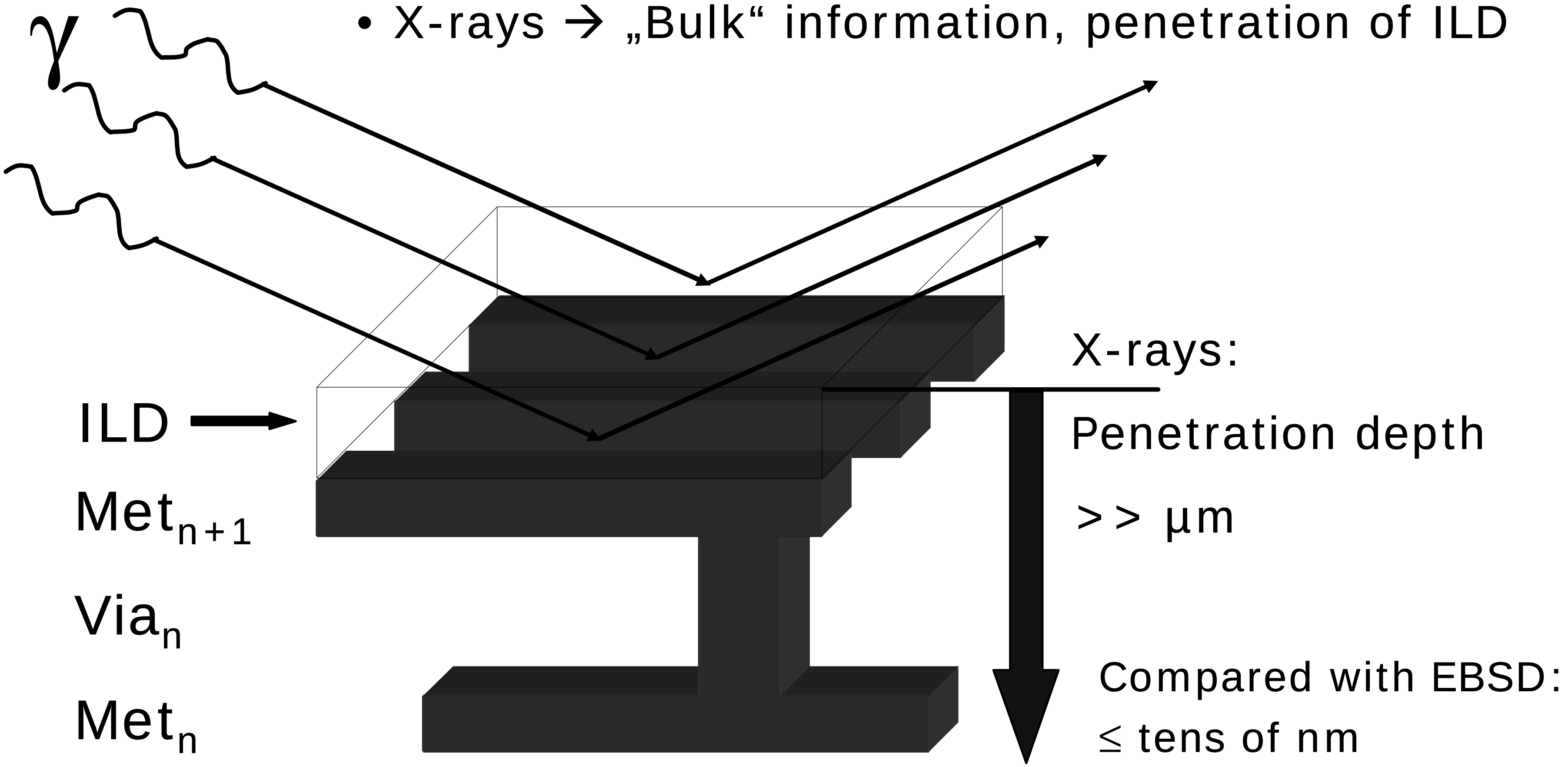
Techniques: comparison

- μ-XRD → Classical Texture, ODF: $f(g) = f(\varphi_1, \Phi, \varphi_2)$
  → Phase: i
  → Strain (Stress): D_s

- OIM → Orientation Stereology: $g(x)$
  → Grain Size
  → Grain-boundary distribution

Probed volume

- Beam diameter between 50µm and several 100µm
  - X-rays → „Bulk“ information, penetration of ILD

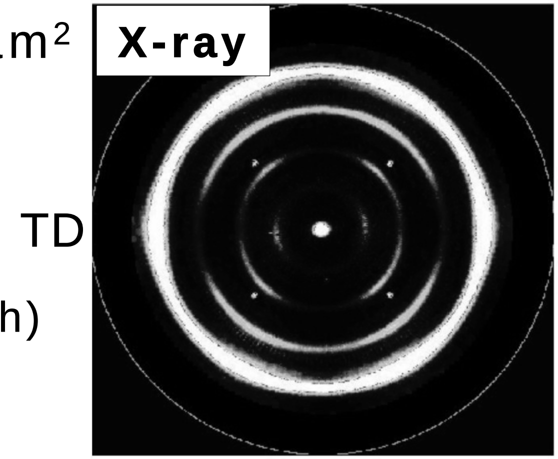


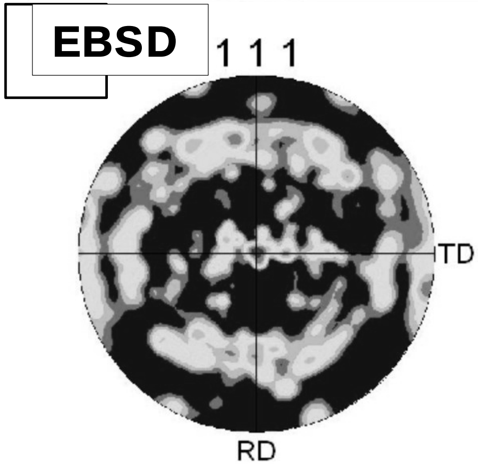
Statistics

- **X-ray micro-diffraction**
  - Beam diameter d = 100µm → $A = \pi r^2 = 7854$ µm²
  - Test pattern: parallel trenches, w = 180nm, p = 360nm
  - Assumption: mean grain diameter = w (one grain extends over the whole line width and depth)
  - $n = (L / w) / (2Lw) = 1 / (2w^2)$
    L: length of the line
  - $n \sim 15$ grains / µm²
  - $N = n A \sim 118000$ grains

- **EBSD**
  - A = 3µm x 10µm = 30 µm²
  - $N = n A \sim 450$ grains

{111} pole figures



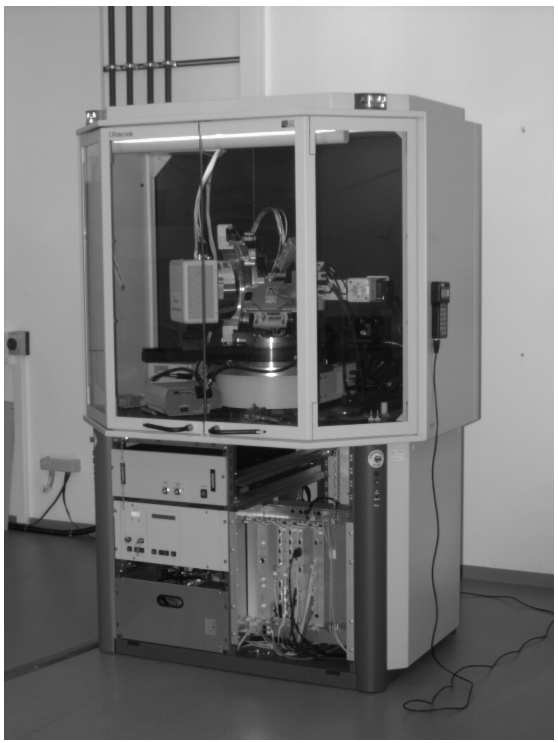


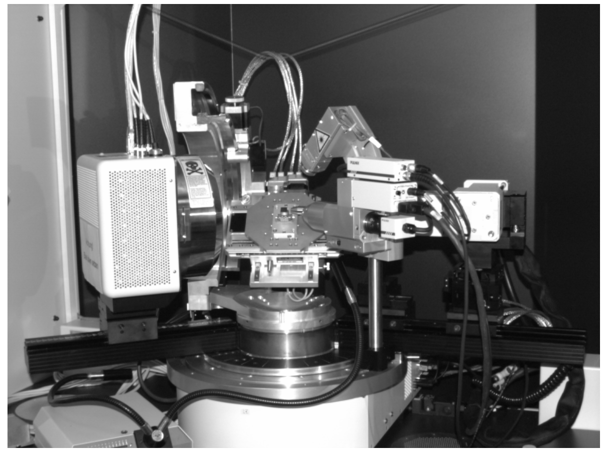
X-ray micro-diffraction

- Arrays of ECD-filled inlaid copper lines
- Arrays of ECD-filled inlaid line segments
- Arrays of ECD-filled vias (?)
- Process monitoring
- In-line application

Texture and stress measurements at inlaid test structures using X-ray micro-diffraction

Bruker AXS D8
micro-diffraction tool



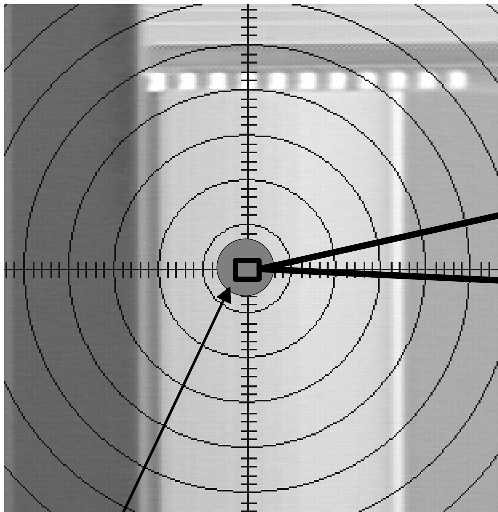


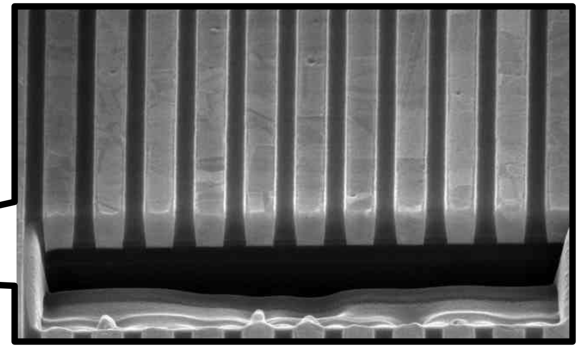
Huber goniometer
with ¼ Eulerian cradle,
PolyCap and
area detector (GADDS)

Video + laser
for accurate height
adjustment

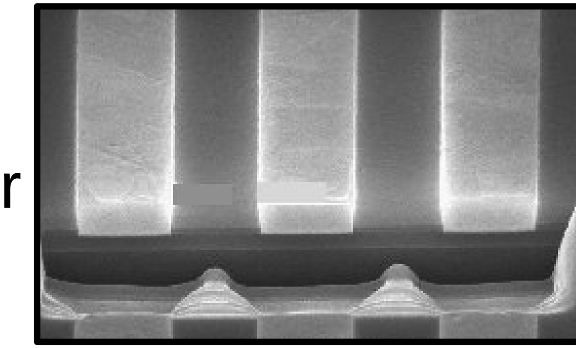
- **Tool performance:**
  - large detector area with high detector sensitivity (80% quantum efficiency)
  - small area beam focus with high intensity
- **Test structures:**
  - blanket or structured thin film samples from 120 x 120 μm^2 up to 10 x 10 mm^2

X-ray micro-diffraction on arrays of inlaid Cu lines





or



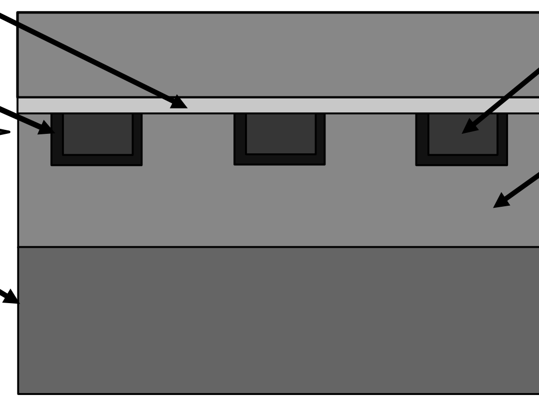
Narrow inlaid Cu lines

Wide inlaid Cu lines

Inlaid structure > 120µm

X-ray beam 80µm Ø

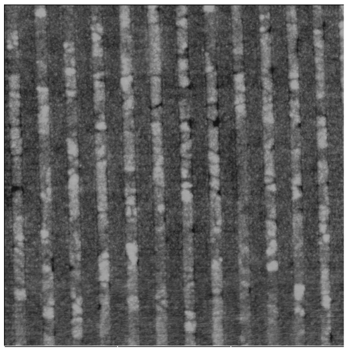
Metal 1



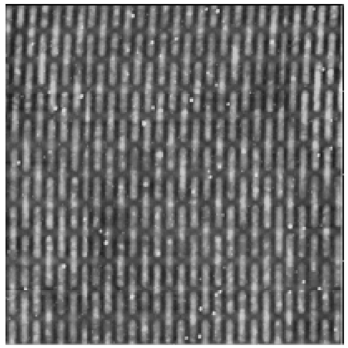
Video camera + laser beam → alignment

X-ray µ-diffraction on arrays of Cu lines and line segments → geometry effects

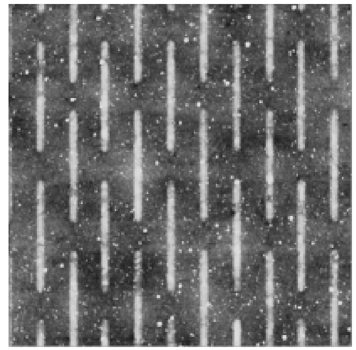
Narrow Cu lines and line segments – width = 180nm



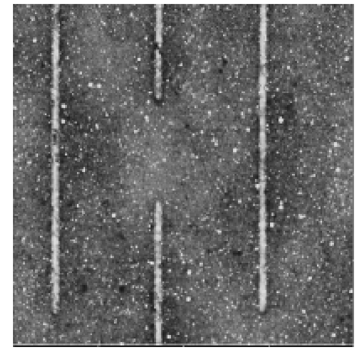
4.3µm x 4.3µm



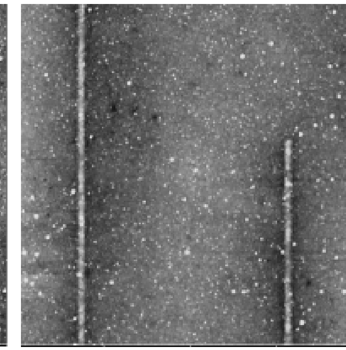
10µm x 10µm



10µm x 10µm



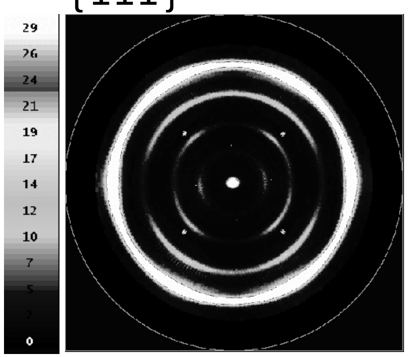
10µm x 10µm



10µm x 10µm

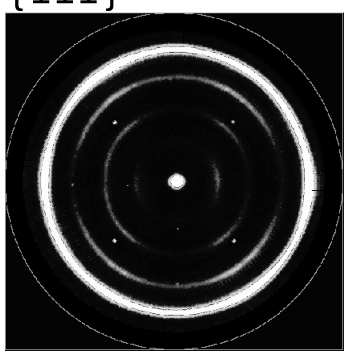
X-ray beam ~ 80 - 100µm Ø

{111}



good

{111}

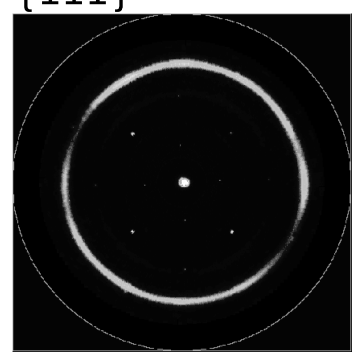


good

....

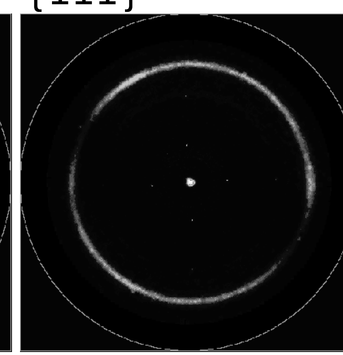
It should work on dense via arrays

{111}



poor

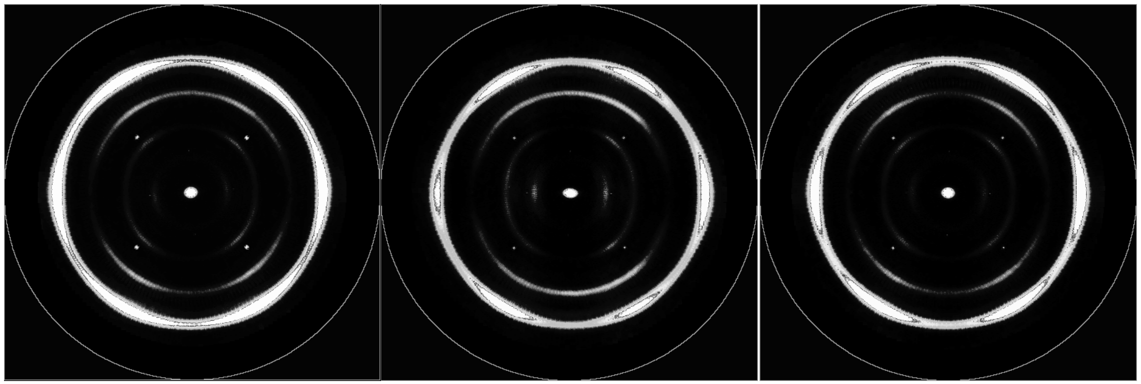
{111}



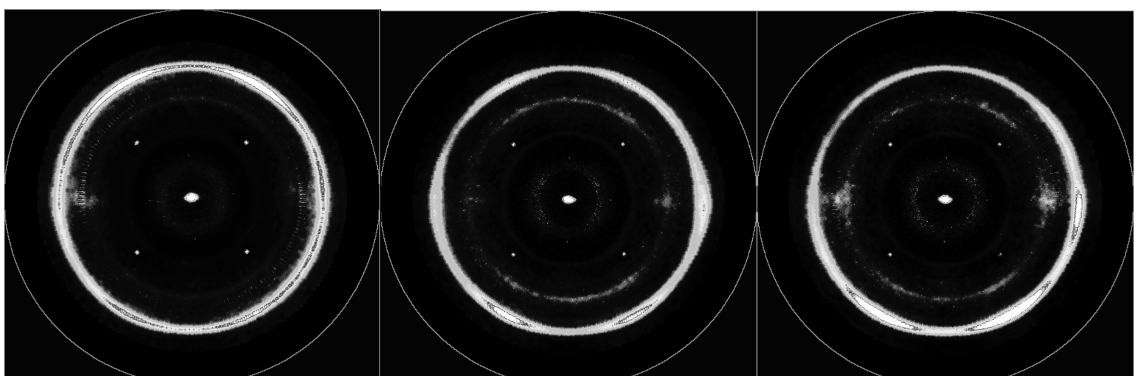
bad

X-ray microstructure monitoring: Arrays of inlaid copper lines

{111} - narrow copper lines (180nm)

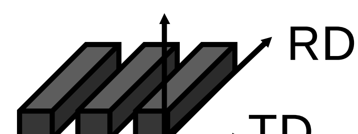


{111} - wide copper lines (1.8µm)



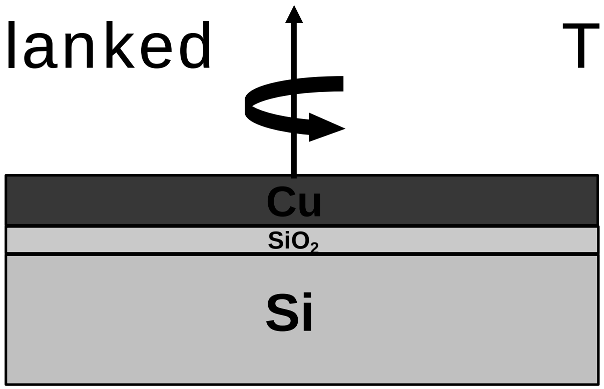
Week

- ILD = Si(F)O
- SiN etch stop
- Metal 1
- sharp {111} fiber
- engaged component
- {511} twins
- sidewall-oriented grains negligible
- Stability of process of record

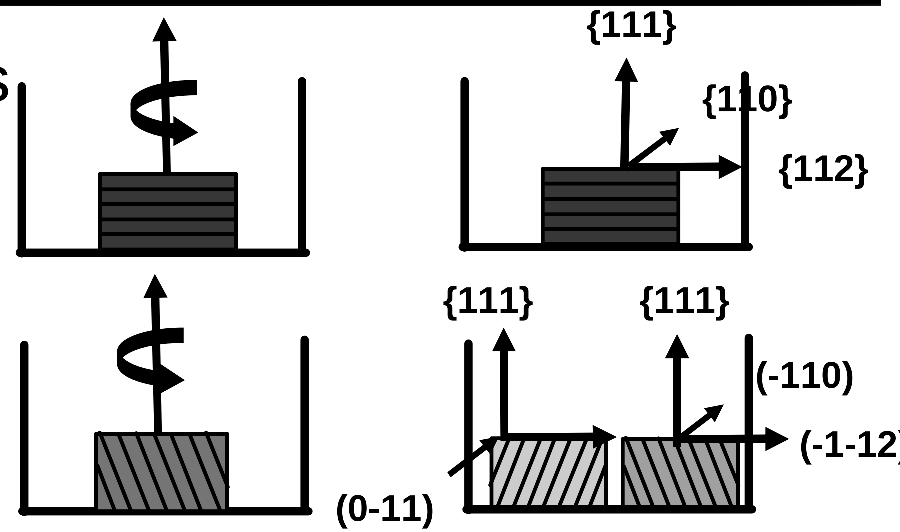


Texture components in Cu lines

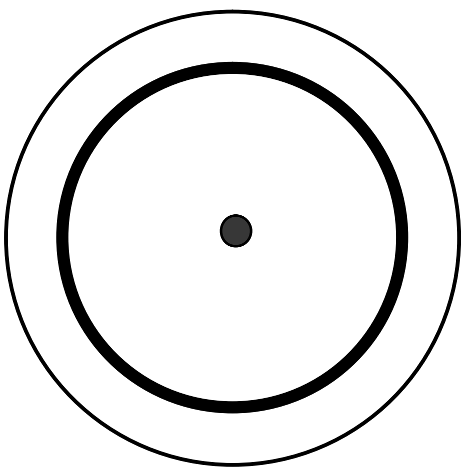
Blanked

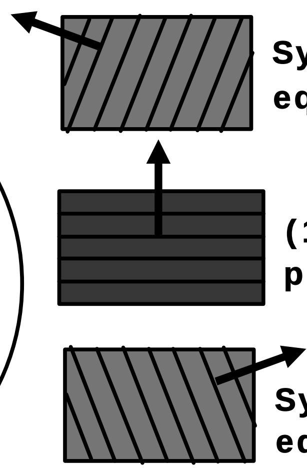


Trenches



Sketch of (111)
Pole Figure

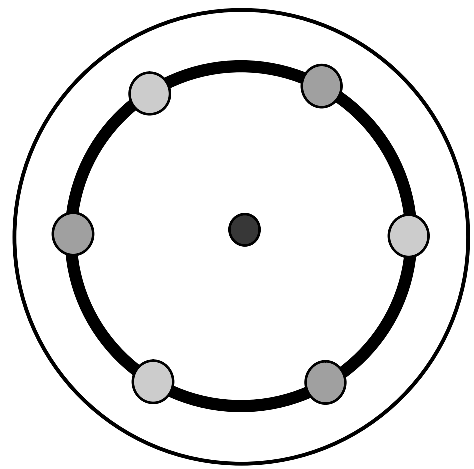




Symmetry equivalent, 70.5°

(111) lattice planes

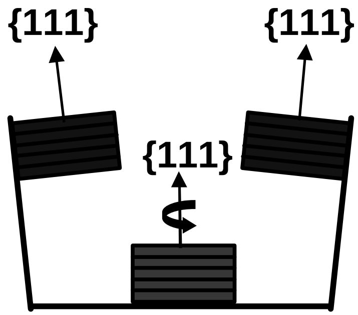
Symmetry equivalent, 70.5°

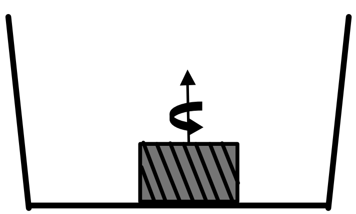


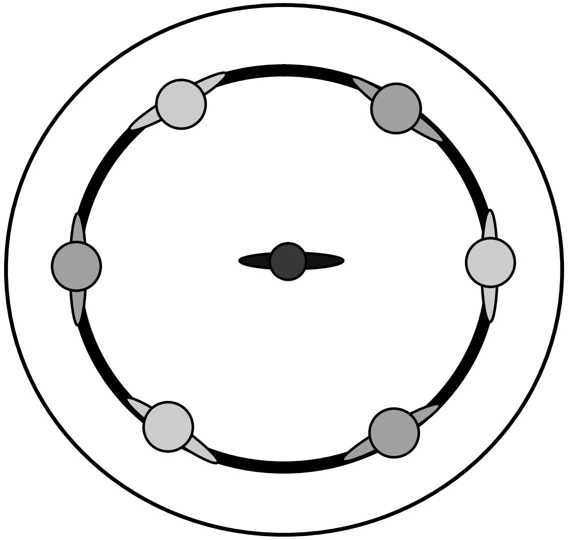
Engaged (111) Fiber Texture

Texture Components in copper lines

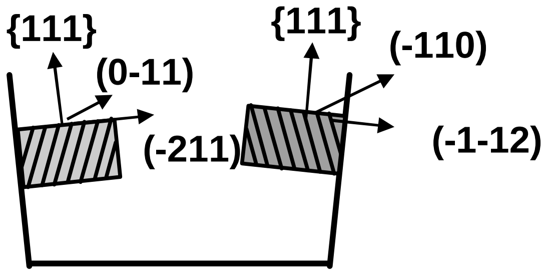
Tilted sidewalls

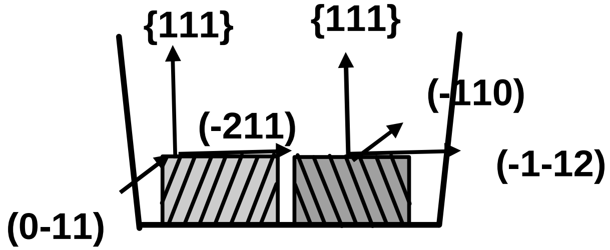




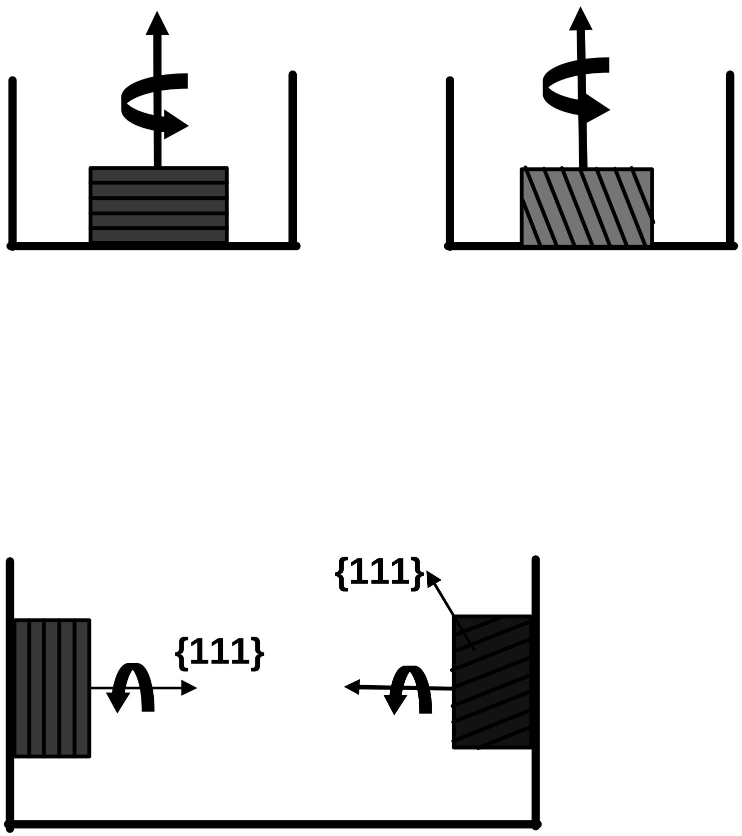


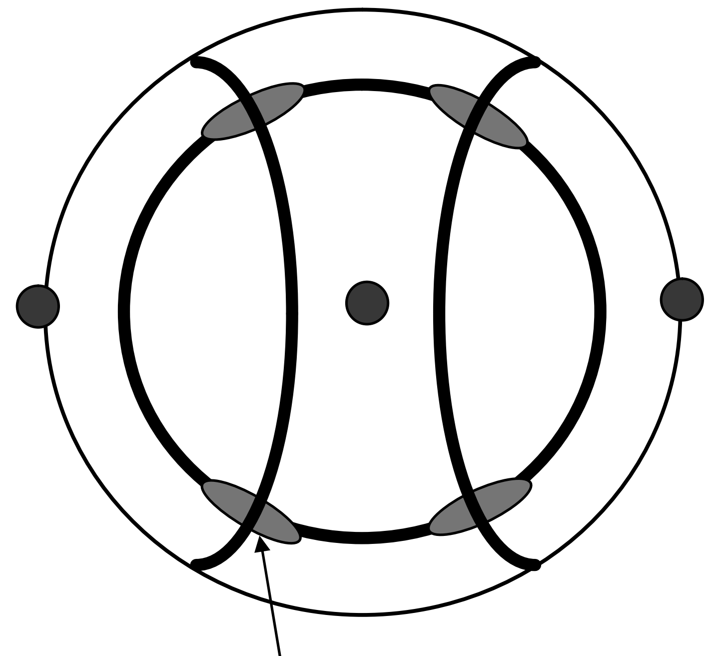
Sketch of
{111} pole figure





Texture Components in copper lines

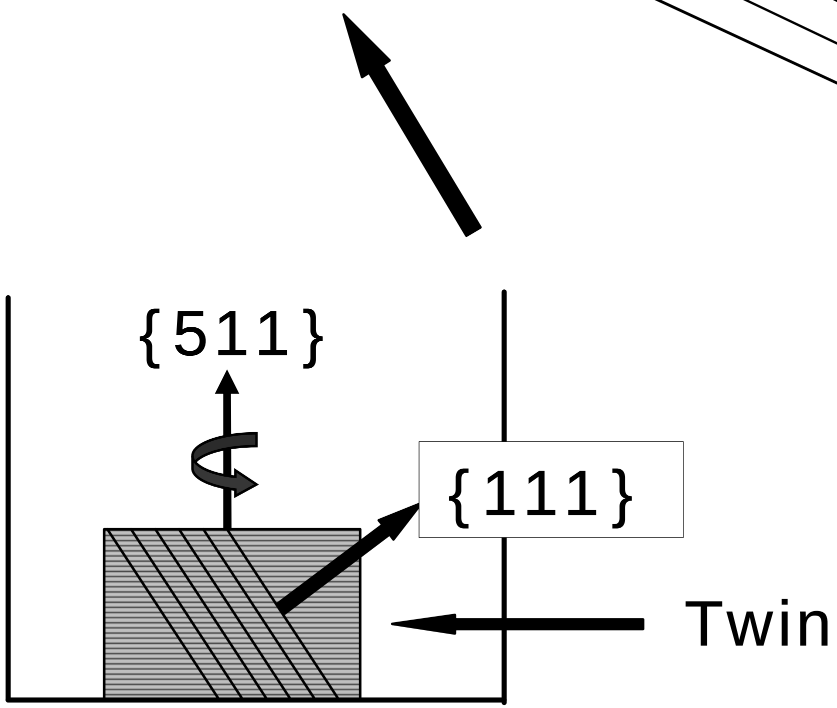




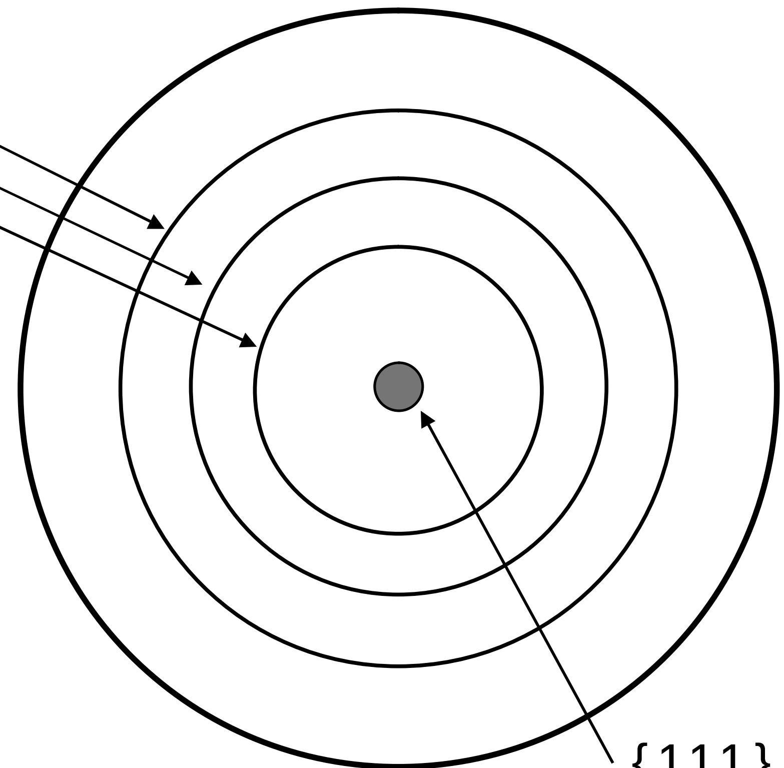
1st generation twins

{511} : 1st generation twins

Additional circles @ 38.9°, 56.2°
and 70.5° in {111} pole figure



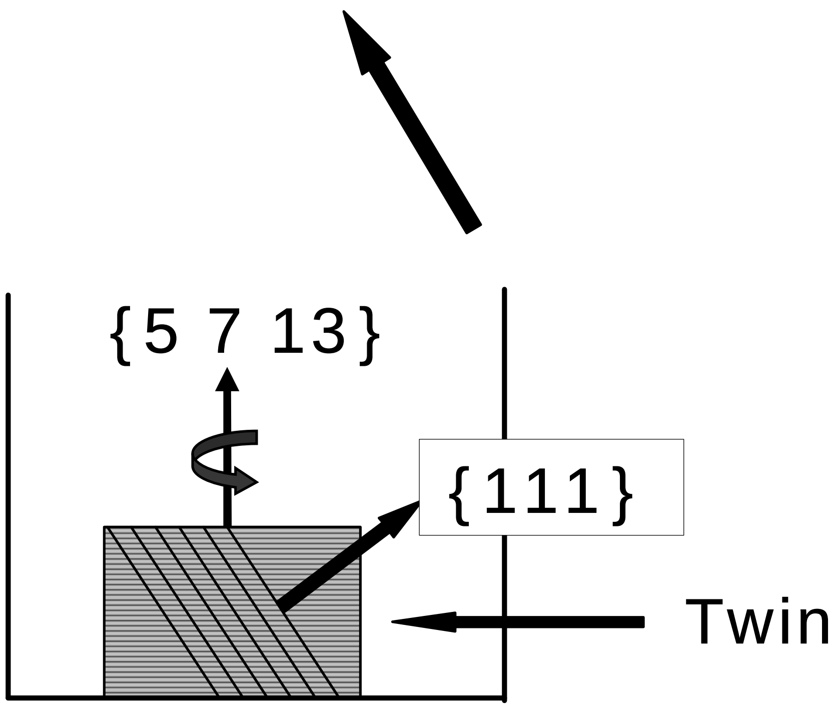
{111} pole figure



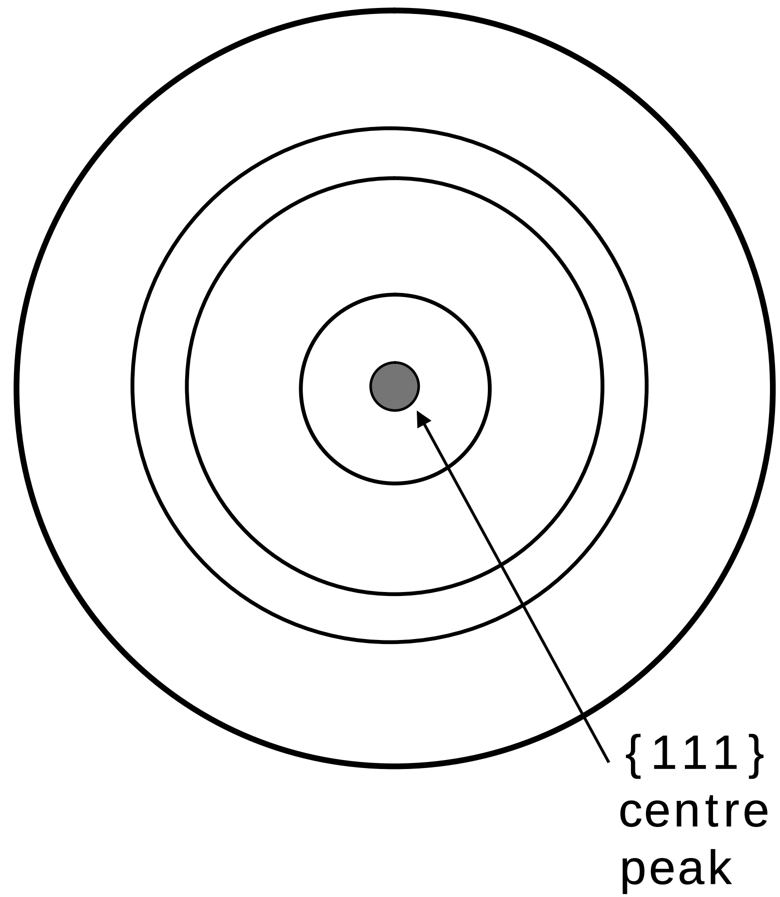
2nd generation twins

{5 7 13} : 2nd generation twins

Additional circles @ 22.19°, 56.25° and 65.95° in {111} pole figure

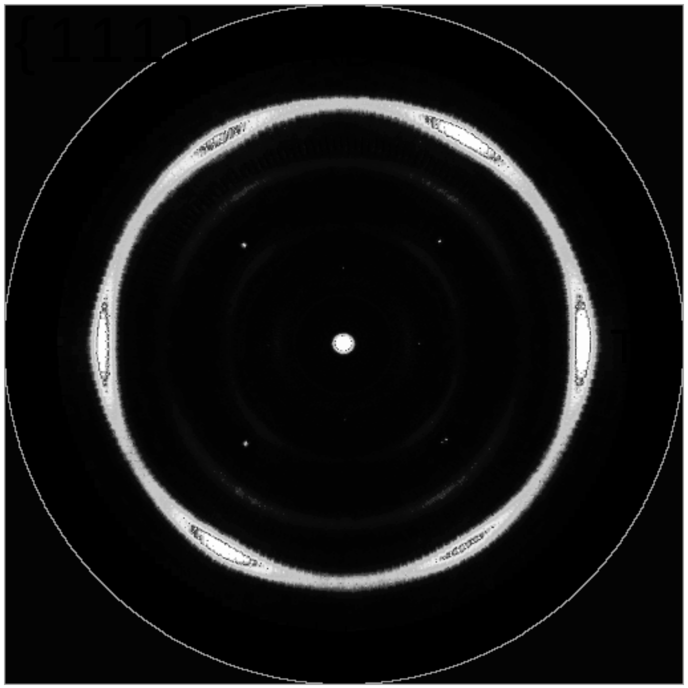


{111} pole figure

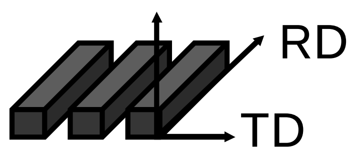


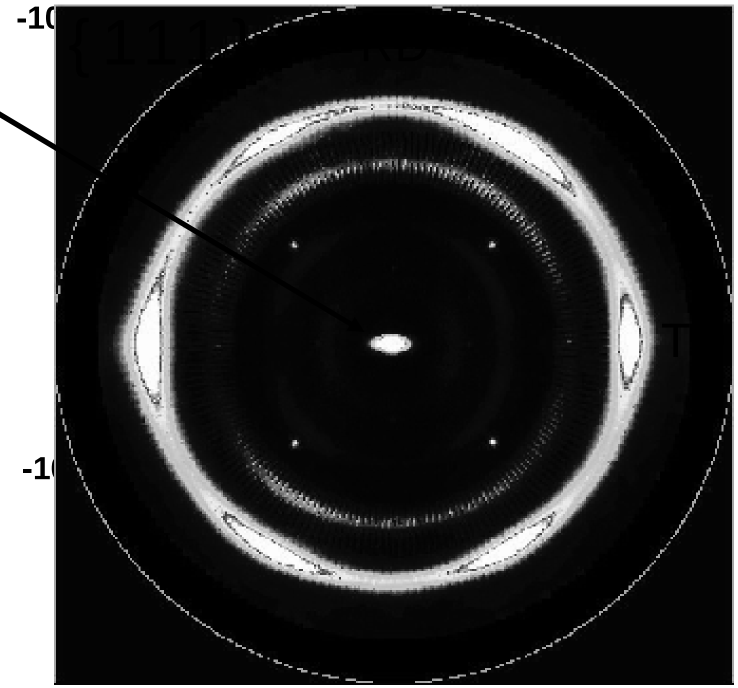
Effect of different ILDs and etch stop layers on texture in copper lines

- Broadening transverse to the metal line direction



Si(F)O + SiN

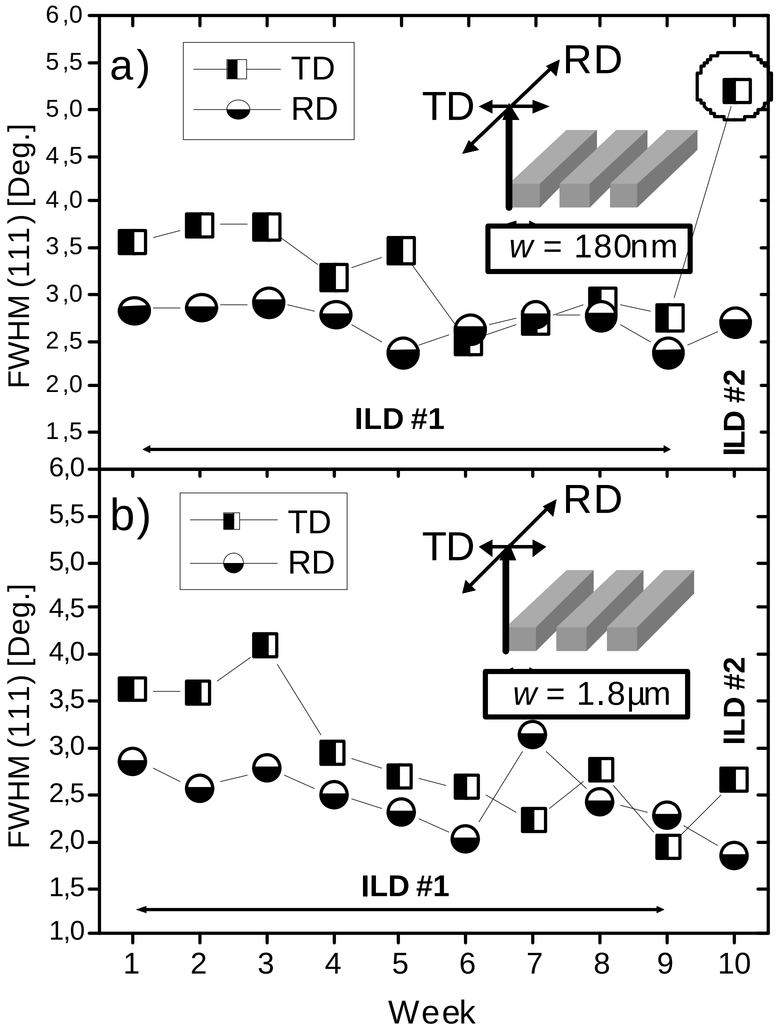




SiCOH + SiCN

- Narrow lines (180nm)

Orientation spread: FWHM



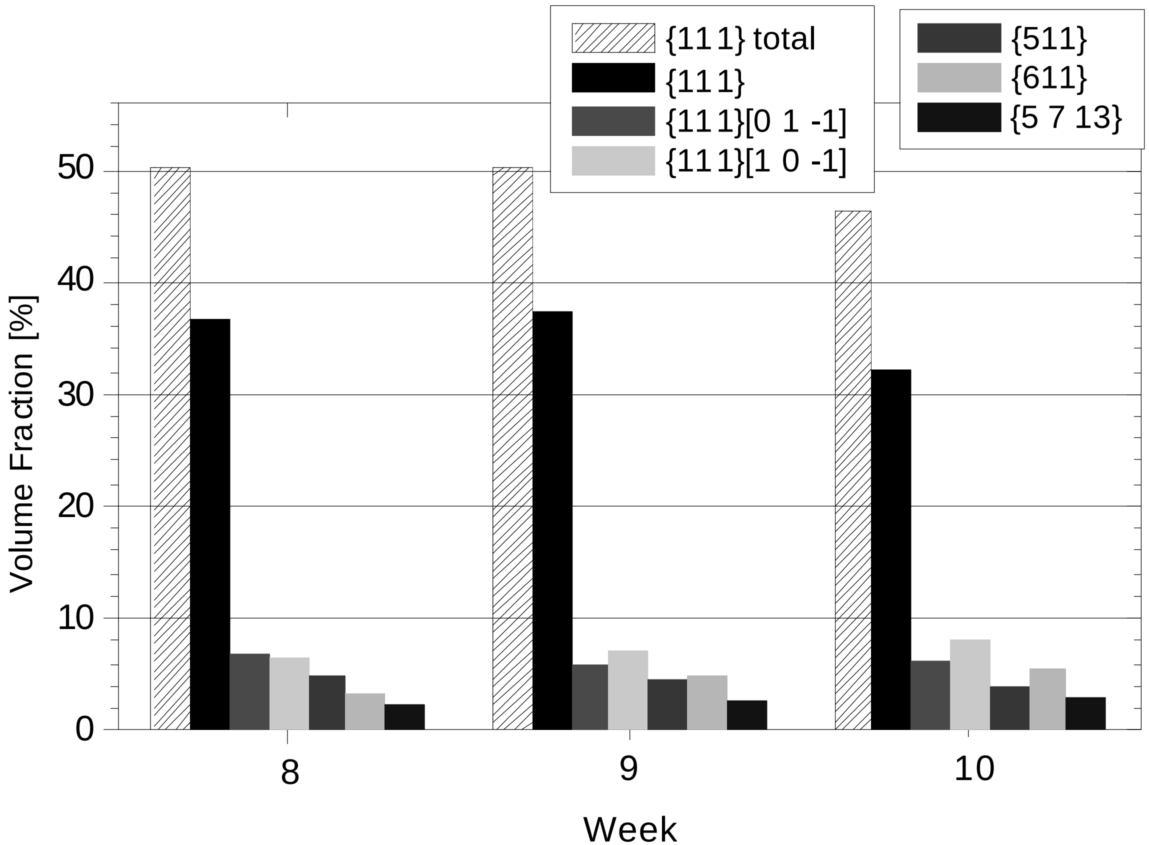
Deviation: changed ILD + capping layer

Process of record stable

Wide lines: no influence

Monitoring: Quantification

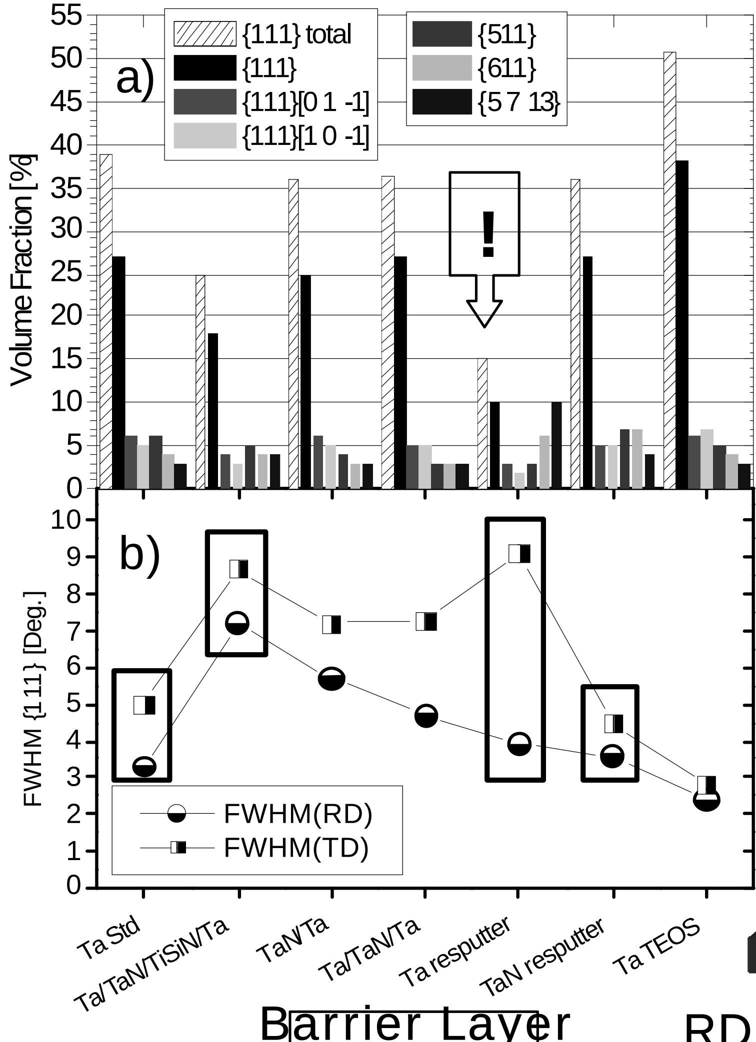
With LaboTex (ADC)



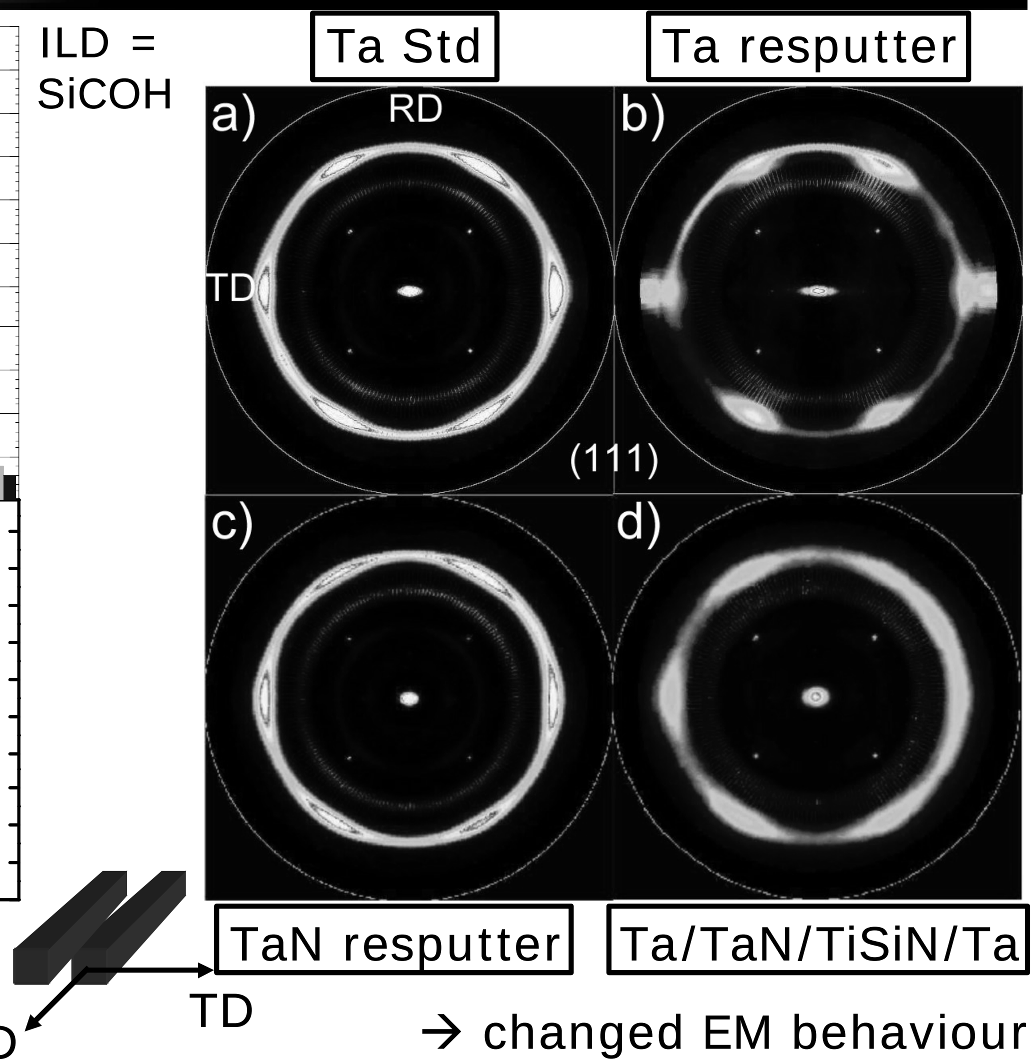
- Narrow lines (180nm)
- Weeks 8-9: Si(F)O / SiN
- Week 10: SiCOH / SiCN

- Uncertainty in volume fraction of random component !

Influence of barrier layers on final Cu texture in inlaid copper lines

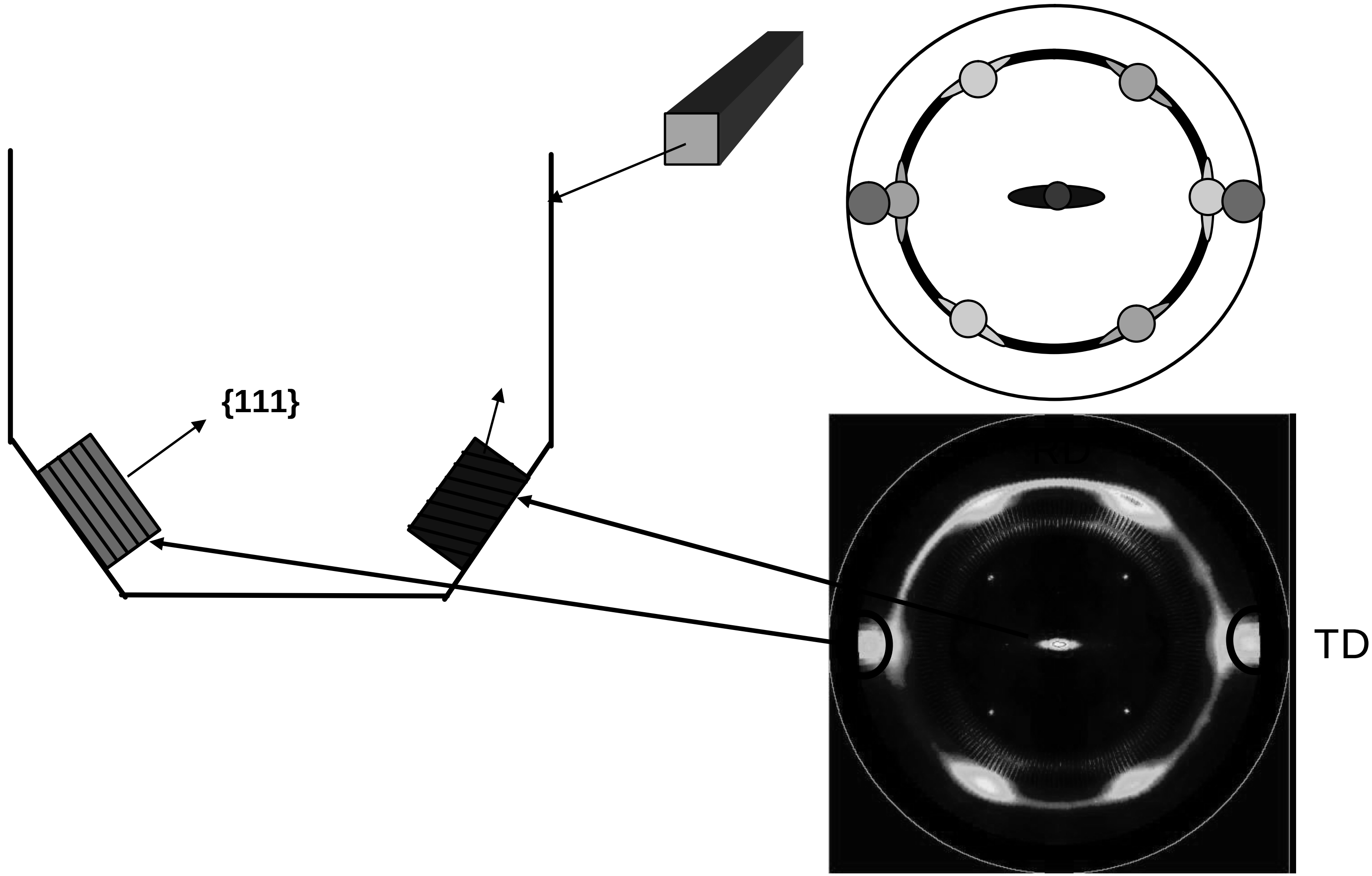


ILD = SiCOH

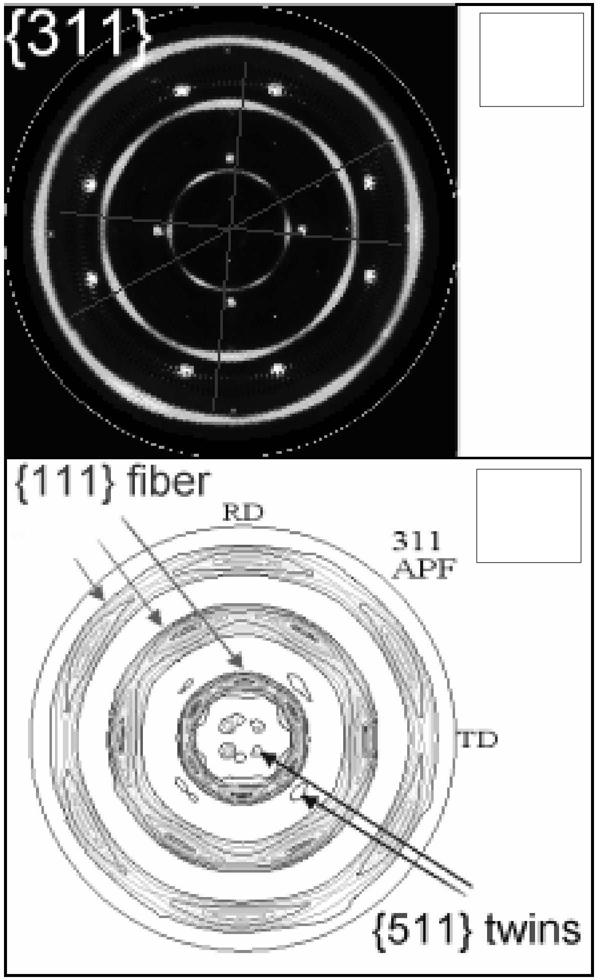


→ changed EM behaviour

Texture: explanation process (b)



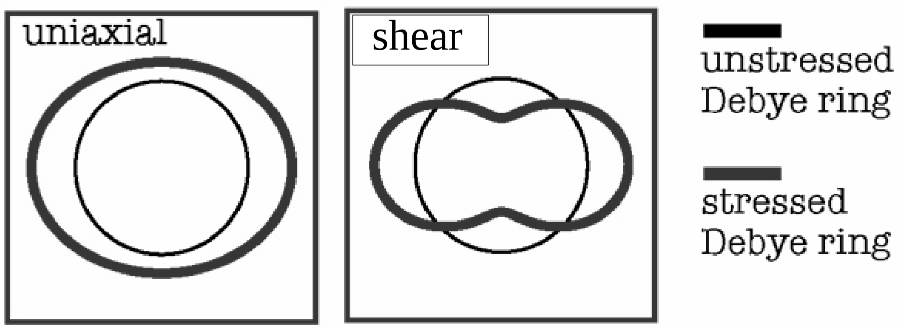
GADDS → Texture & Stress

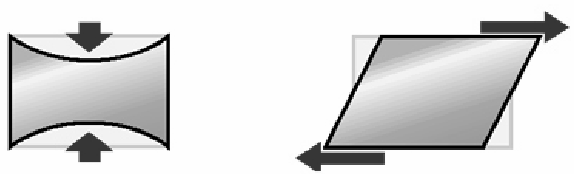


- GADDS + precise ¼ circle Eulerian cradle
- Pole figures + stress on patterned wafers on the same test structures
- Record higher order {hkl}, e.g., {311}
- Study of possible influence of changed texture on stress values
- Choose: (fiber + engaged) or fiber only
- Optimization of $\{\chi;\phi\}$ for stress analysis
- 2D (triaxial) stress data analysis

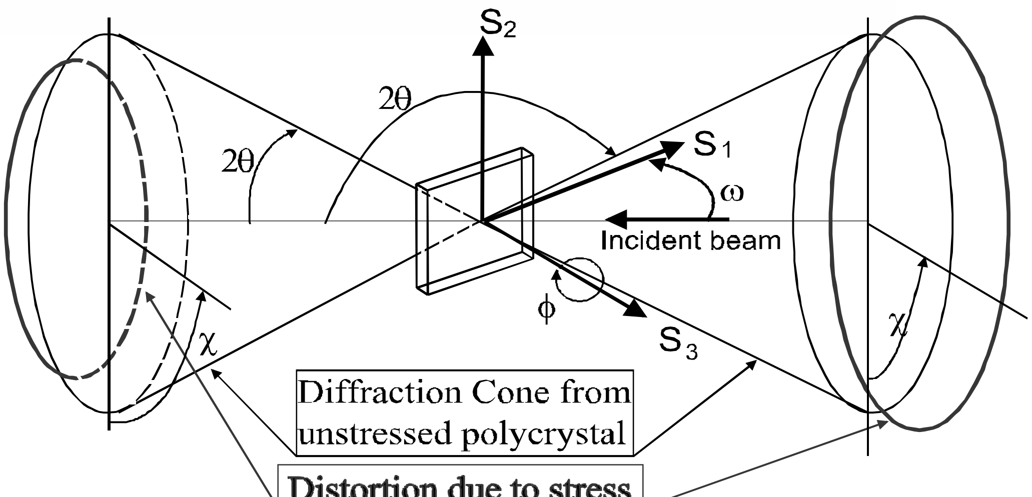
  → Anisotropy & shear stresses
- Limit: intensity

GADDS → 2D stress analysis (triaxial)

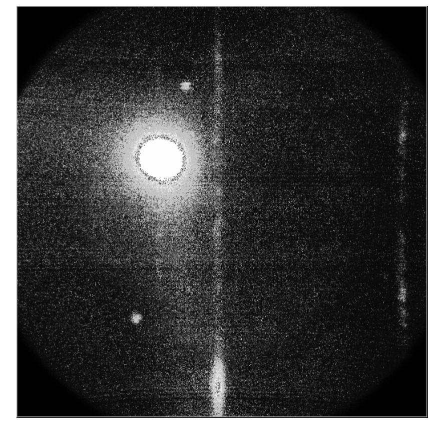




Bruker AXS



GADDS



(311)

180nm inlaid copper lines

X-ray: in-line application

Why? Time critical issues (e.g., recrystallization)

In-line process monitoring (also 300mm)

How? Nondestructive, relatively fast → X-ray

See this conference:

- **WE-10**: „Room Temperature Electroplated Copper Recrystallization: In-Situ Mapping on 200/300mm Patterned Wafers“, K. J. Kozaczek, et al.
- **WE-11**: „Metrology Tool for Microstructure Control on 300mm Wafers During Damascene Copper Processing“, K. J. Kozaczek, et al.
- **WE-17**: „Texture Evolution in Interconnects upon Annealing“, K. Mirpuri, et al.
- **WE-18**: „Microstructure Variations in Annealed Damascene Cu Interconnects“, K. Mirpuri, et al.

X-ray summary:

- X-ray micro-diffraction suitable for texture (and stress) analysis on arrays of ECD-filled inlaid copper lines, line segments, and vias (?)
- Nondestructive (→ also in-line)

X-ray limits:

- Inlaid structures with barrier only or barrier and seed only (intensity!)
- Does not provide $g(x)$, grain-boundary distribution and in-plane grain size

→ OIM: EBSD, ACT

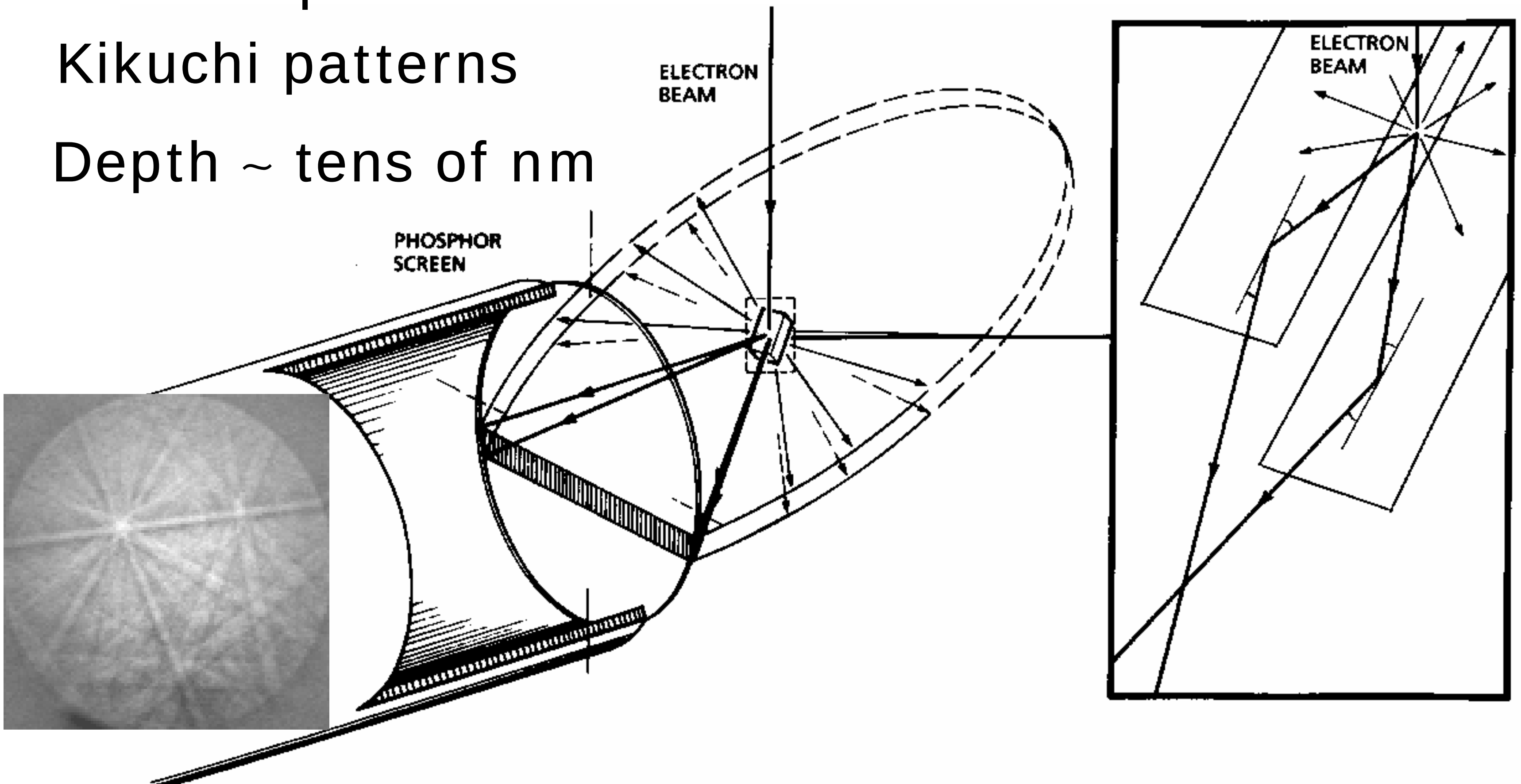
EBSD: principle

70° sample tilt

Kikuchi patterns

Depth ~ tens of nm

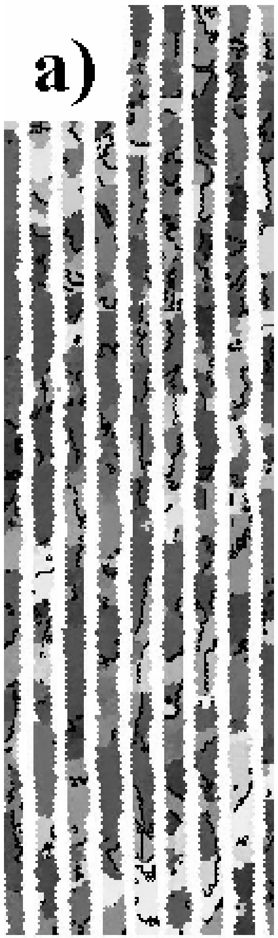
SEM



Here: LEO 1550 + therm. FEG, EBSD: TexSem Lab. (TSL)

EBSD on copper lines & via chains

a)

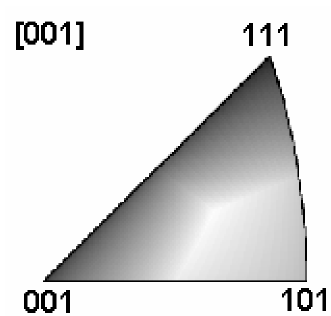


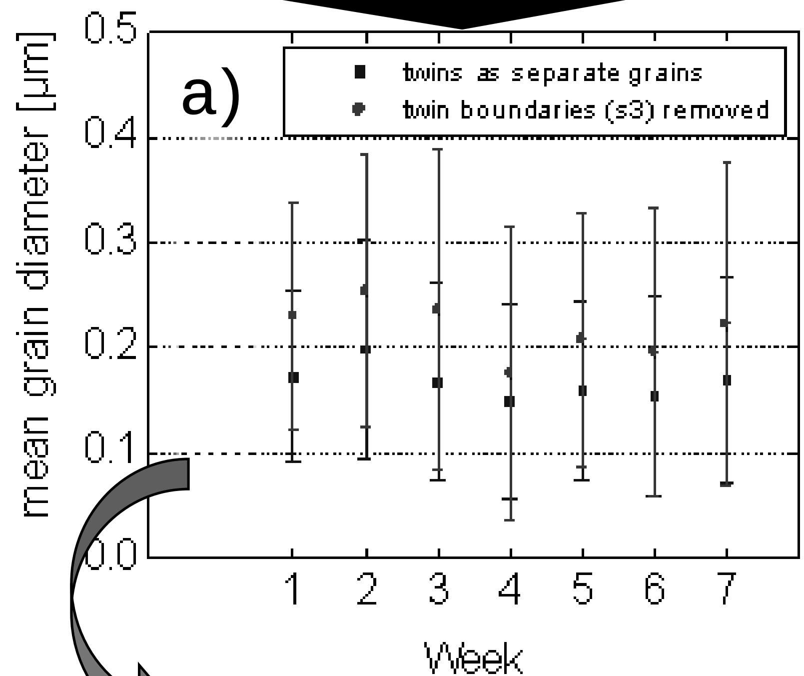
600nm = 15 steps

b)

600nm = 20 steps

→ $g(x)$





Grain size monitoring

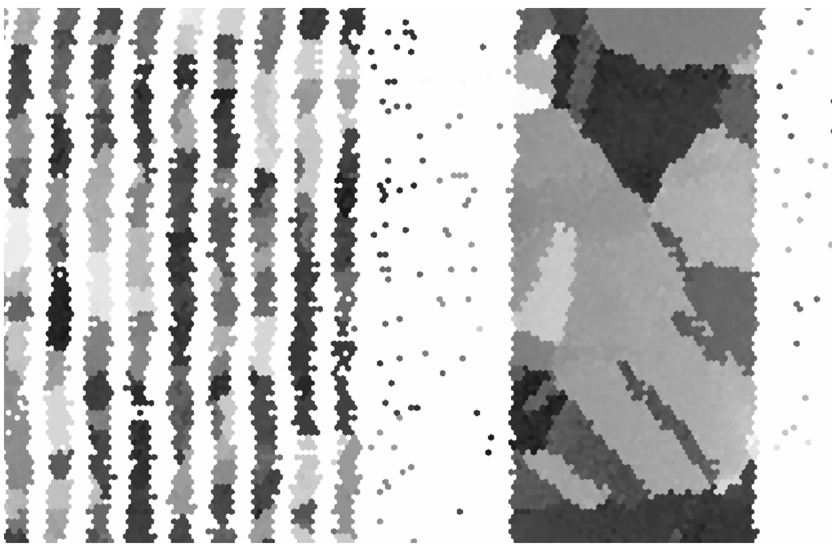
Inverse pole figure maps

(a) 200nm lines

(b) via1, via3, via5

Limits of EBSD: passivation

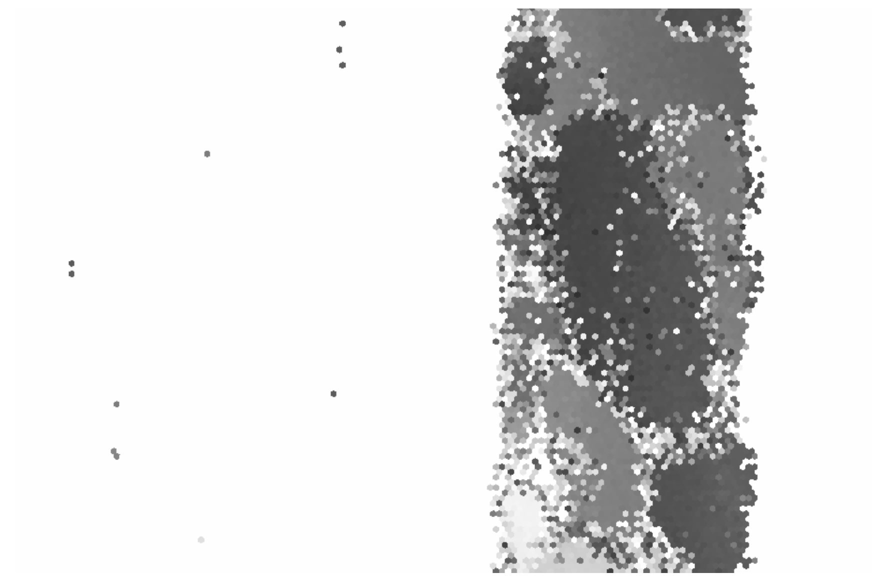
Narrow lines (200nm) | Cu Pad



H=27nm

(Thickness of Passivation)

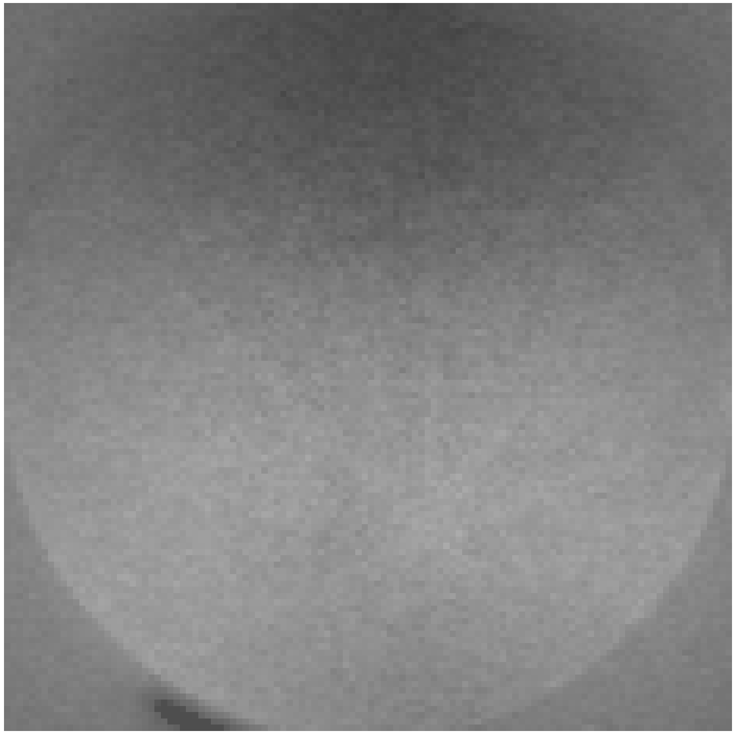
Narrow lines | Cu Pad



H=34nm

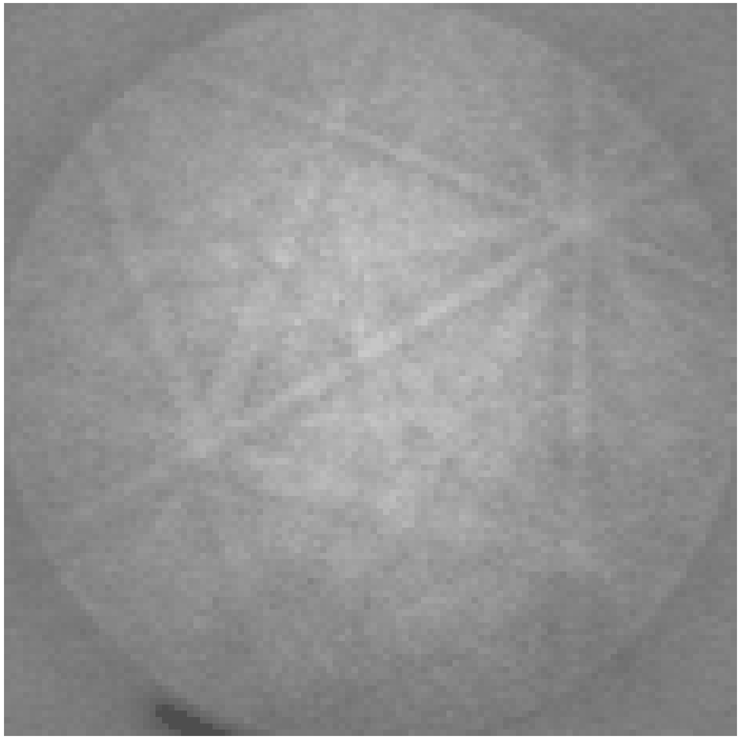
Limits of EBSD: passivation

EBSD Analysis **H=30**



Lines

IQ=93



Cu pad

IQ=143

EBSD: perspectives

- Future perspective

  Sequential FIB + EBSD

  → 3D orientation image (e.g., via cross-section)
- EBSD after EM test (difficult: before EM test !)

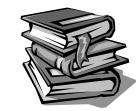
  → which grains & grain boundaries are critical ?

  → locally resolved since $g(x)$ is measured

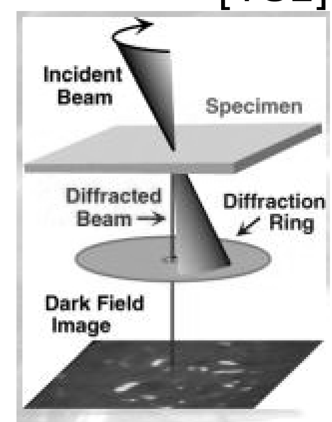
Barrier & Seed: X-ray, EBSD → **ACT**

- Lateral resolution of EBSD is of the order of grain sizes in copper seed layers (~30-50nm)

  → EBSD not possible for nanocrystalline barriers and seed inside inlaid structures



[TSL]



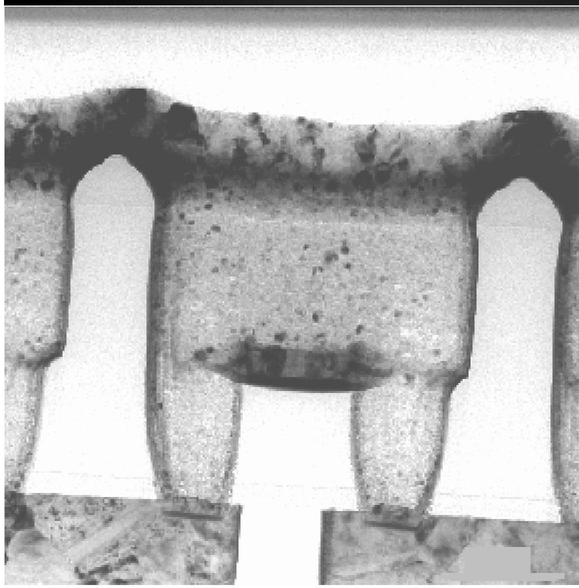
→ **ACT** needed for barriers and seed in inlaid structures

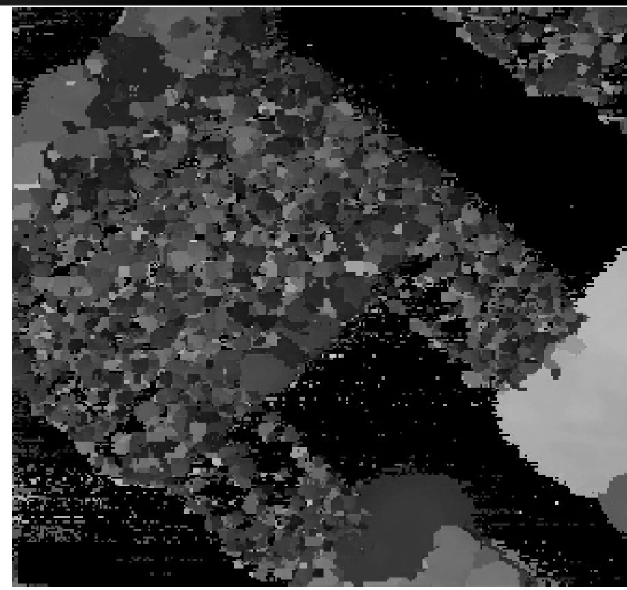
ACT – _A_utomated _C_rystallography for the _T_EM

Multiple dark field images are collected by rotating the beam

- Small, non-planar inlaid structures accessible by ACT
- But: time consuming
- Special sample preparation needed

ACT on Cu seed in inlaid structures





→ Grain size distribution of Cu seed inside inlaid structures

→ Grain orientation map not possible yet in this case

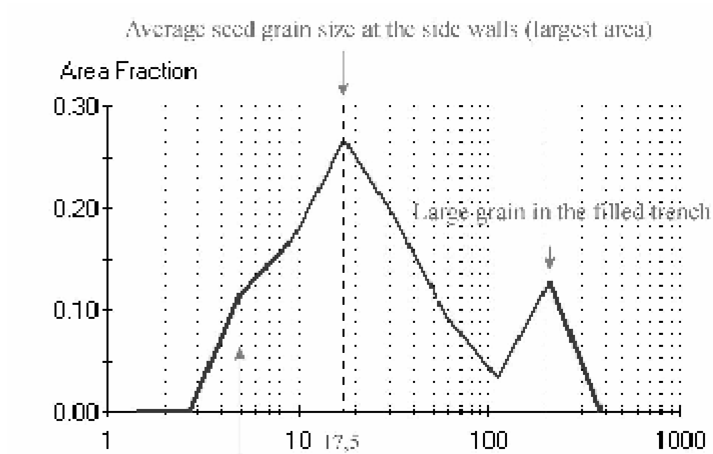
→ Compare seed grain sizes inside the structures with seed grain sizes on top and in the ECD-filled metal layer underneath !!

Courtesy of

Holger Saage,

Hans-Jürgen Engelmann

AMD Saxony, Dresden, Germany



Summary

- ECD-filled inlaid copper structures
  → X-ray micro-diffraction & EBSD
  → process monitoring, texture, grain size, grain boundary distribution, trenches and vias
- Copper seed and nanocrystalline barrier layers in inlaid structures
  → ACT needed

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