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

Holm Geisler, Inka Zienert, Hartmut Prinz, Moritz-Andreas Meyer, Ehrenfried Zschech

AMD Saxony LLC & Co. KG, Dresden, Germany
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

Al

\{111\}

Inlaid Cu

\{111\}

\{111\}

\{511\}_{\text{twins}}

+ sidewalls
+ twins
+ engaged
What is different?

<table>
<thead>
<tr>
<th>Inlaid Copper Interconnects</th>
<th>Aluminum Interconnects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twins + Sidewall</td>
<td>Bamboo + Columnar</td>
</tr>
<tr>
<td>????</td>
<td>Optimum EM Behaviour</td>
</tr>
<tr>
<td>Large Anisotropy</td>
<td>Small Anisotropy</td>
</tr>
<tr>
<td>$E(111) = 191$ GPa</td>
<td></td>
</tr>
<tr>
<td>$E(100) = 66.7$ GPa</td>
<td></td>
</tr>
<tr>
<td>Electroplating</td>
<td>Vapour Deposition</td>
</tr>
<tr>
<td>Cu CMP</td>
<td>Metal etch</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Texture, EM & defects

Electromigration:

→ Prevent grain boundaries along the trench direction!

= Fast diffusion pathways

Top view

Sidewall-oriented grains?

High-angle grain boundary?

void 😞 v⟮ > v↑
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:

\[
f(g) = \frac{dV_g}{dg} = f(\varphi_1, \Phi, \varphi_2).
\]

H.J. Bunge (1999, 2001)
Quantification: ODF approximation

\[ P(\chi, \phi) \]

K_A: sample coordinates
K_B: cryst. coord. system

Evaluation of pole figures

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

  \[ P_h(\chi, \phi) = \frac{1}{N} \sum_{i=1}^{N} f[(\chi, \phi) \leftrightarrow (\phi_1, \Phi, \phi_2)_i] \]

• 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)

K. Pawlik et al. (1991)
U.F. Kocks et al. (1998)
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

- Seed
- Barrier

ACT
µ-XRD
EBSD

EBSD
µ-XRD?
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

X-rays:
Penetration depth
>> µm

Compared with EBSD:
≤ tens of nm
Statistics

- **X-ray micro-diffraction**
  - Beam diameter $d = 100\mu m \rightarrow A = \pi r^2 = 7854 \mu m^2$
  - Test pattern: parallel trenches,
    $w = 180\text{nm}$, $p = 360\text{nm}$
  - 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 / $\mu m^2$
  - $N = n A \sim 118000$ grains

- **EBSD**
  - $A = 3\mu m \times 10\mu m = 30 \mu m^2$
  - $N = n A \sim 450$ grains
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

**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

Inlaid structure > 120µm

X-ray beam . 80µm Ø

Video camera + laser beam → alignment

Narrow inlaid Cu lines

Wide inlaid Cu lines

SiN, SiCN

Barrier

Silicon

Copper lines

Si(F)O, SiCOH

Metal 1
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
4.3µm x 4.3µm
10µm x 10µm
10µm x 10µm
10µm x 10µm
10µm x 10µm

X-ray beam ~ 80 - 100µm Ø

It should work on dense via arrays

good 😊 good 😊 poor 😞 bad 😞
X-ray microstructure monitoring: Arrays of inlaid copper lines

\{111\} - narrow copper lines (180nm)
- 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

\{111\} - wide copper lines (1.8µm)

Week
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

Superposition sidewall + fiber
$\{511\} : 1^{st} \text{ generation twins}$

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

$\{111\}$ pole figure

Additional circles @ 38.9°, 56.2° and 70.5° in $\{111\}$ pole figure.
2\textsuperscript{nd} generation twins

\{5\ 7\ 13\} : 2\textsuperscript{nd} generation twins

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

\{111\} pole figure

2\textsuperscript{nd} generation twins

\{5\ 7\ 13\}

\{111\}

Twin

\{111\} centre peak
Effect of different ILDs and etch stop layers on texture in copper lines

- Broadening transverse to the metal line direction

- 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

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

ILD = SiCOH

Barrier Layer

\[ \text{ILD} = \text{SiCOH} \]

Volume Fraction [%]

 barrier layer

\[ \text{Volume Fraction [%]} \]

FWHM (111) [Deg.]

\[ \text{FWHM (111) [Deg.]} \]

FWHM (RD)

\[ \text{FWHM (RD)} \]

FWHM (TD)

\[ \text{FWHM (TD)} \]

\[ \text{a) } \]

\[ \text{b) } \]

\[ \text{c) } \]

\[ \text{d) } \]

\[ \text{Ta Std} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]

\[ \text{Ta/TaN/Ta} \]

\[ \text{TaN resputter} \]

\[ \text{Ta TEOS} \]

\[ \text{Ta Std} \]

\[ \text{Ta/TaN/TiSiN/Ta} \]

\[ \text{TaN/Ta} \]

\[ \text{Ta resputter} \]
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 $\rightarrow$ 2D stress analysis (triaxial)

Bruker AXS

Diffraction Cone from unstressed polycrystal

Distortion due to stress

(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.
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 \sim tens of nm

Here: LEO 1550 + therm. FEG, EBSD: TexSem Lab. (TSL)
EBSD on copper lines & via chains

Inverse pole figure maps
(a) 200nm lines
(b) via1, via3, via5

Grain size monitoring
\[ g(x) \]
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 $\rightarrow$ ACT

- Lateral resolution of EBSD is of the order of grain sizes in copper seed layers ($\sim$30-50nm).
  - EBSD not possible for nanocrystalline barriers and seed inside inlaid structures.

$\rightarrow$ ACT needed for barriers and seed in inlaid structures.

ACT – Automated Crystallography for the TEM

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

Courtesy of

Holger Saage,
Hans-Jürgen Engelmann
AMD Saxony, Dresden, Germany

→ 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 !!
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
Trademark Attribution

AMD, the AMD Arrow Logo and combinations thereof are trademarks of Advanced Micro Devices, Inc. Other product names used in this presentation are for identification purposes only and may be trademarks of their respective companies.