Improved interconnect properties for nano-twinned copper: Microstructure and thermal stability

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Outline

• Background and motivation
• Processing and Characterization
• Nanotwin formation mechanism
• Effect of nanotwins on physical properties of Cu
  ◆ Hardness and microstructure
  ◆ Grain growth behavior of nanotwinned Cu
  ◆ Thermal stability of (111) and (112) twins
  ◆ Electromigration behavior

• Summary
Background on Nano-twinned copper

- Nanotwinned Cu shows very high mechanical strength and good electrical conductivity

Lu L. et al, Science 304 (2004), 422-426
In-situ TEM observation of atom diffusion at twin boundaries in Cu

Twin boundaries can effectively block the EM induced atomic migration.

Promising applications in Cu interconnects and other fields

Processing: Pulse electroplating

- **On Time**
  - High current density
  - high volume of nuclei

- **Off-time**
  - Recrystallization
  - Grain Growth
  - Nano twins may form

Cu thin film (1~5 μm thick)  Cu TSV (10~50 μm diameter)  Cu lines (100nm~3 μm wide)
# Nanotwin Characterization

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<tr>
<th>Method</th>
<th>Advantage</th>
<th>Disadvantage</th>
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| X-ray diffraction | crystallinity, preferred orientation  
Non-destructive, large penetration depth | No microstructure imaging, cannot show twin boundaries |
| SEM          | Morphology information, easy access                | small penetration depth, low contrast for twinned grains |
| TEM          | Accurate identification of twin, high resolution   | Time consuming sample preparation process |
| EBSD         | Simple sample preparation, Grain and boundary info over large surface area | Only surface information (~50 nm depth) |
| FIB          | Cross section microstructure, TEM sample preparation | Destructive, Ga contamination |
Stoney’s equation:

\[ F_w = \frac{E_s \cdot t_s^2}{6R} = f\left(\frac{N}{m}, \frac{J}{m^2}\right) \]

\[ F_w = \int_0^{t_f} \sigma(t) \, dt \quad \text{(film growth)} \]

\[ \sigma_{avg} = \frac{F_w}{t_f} \quad \sigma_{inc} = \frac{d\left(F_w\right)}{dt_f} \]

Stress relaxation occurs at pulse off time during pulse electrodeposition.
Nanotwin formation mechanism

- Recrystallization occurs during pulse off time
- Effect of biaxial stress on nanotwin formation by **First principles calculations**

When the strain is high enough (either compressive or tensile) in Cu, it’s easy to form twinning structure during stress relaxation

In-situ stress measurements

The energy (per atom) of a system with \( m \) layers separating twin boundaries can be given by:

\[
E(m) = E_{\text{FCC}} + \frac{\gamma_{\text{twin}} A}{m} \leq E(\varepsilon = 0.2\%)
\]

400 MPa stress Twin spacing about 28 nm
Comparison with twin in Al [strain in (111) plane]

It's much easier to form twinning structure in Cu than in Al
Microstructure investigation by FIB

Microstructure studies on nano-twinned Cu

- Nano-indentation study
- Nanotwin effect on Grain growth of Cu
- Thermal stability of (211) incoherent twin
- Electromigration study
Nanotwin effect on hardness

L.Xu, K.N. Tu et al., Applied Physics Letters, 90, 033111 2007
Nanotwin effect on hardness

Combination of EBSD & nanoindentation:
To study effect of twin boundaries on hardness of Cu at different locations

Twin effects on mechanical strength:
• The density of nanotwins
• The twin spacing
• Twin intersection with grain boundaries
Current studies on nano-twinned Cu

- Nano-indentation study
- Nanotwin effect on grain growth of Cu
  - Grain growth at 200°C for 1 hr
  - Self annealing at RT for 1 year
- Thermal stability of (211) incoherent twin
- Electromigration study
Grain growth and abnormal grain growth

DC electroplated samples with few twins after deposition

Abnormal grain growth
1 year at RT

Grain growth at 200°C

Xu D., Sriram V., Tu K.N. et al Microelectronics Engineering. 85(2008), 2155
Grain growth and abnormal grain growth

Pulse electroplated samples with many twins after deposition

No Abnormal grain growth

1 year at RT

Little Grain growth at 200 C
Thermal stability of (111) and (112) twin boundary

Temperature=473K

The distance of the observed two 111 twin boundary is 2.72 nm, or about 13{111} spacing

Move of 112 twin boundary
(112) Incoherent twin boundaries
Possible (111) twin nucleation mechanism

Stress at grain boundaries

Twin grows

Twin disappears
Current studies on nano-twinned Cu

- Nano-indentation study
- Nanotwin effect on grain growth of Cu
- Thermal stability of (211) incoherent twin
- Electromigration study
  - Electromigration test on IBM samples
  - In situ TEM observation of 112 boundary motion under EM
Higher yield stress could give longer critical length.
Nanotwin effect on Electromigration (sample from IBM, Dr. C. K. Hu)
Possible effect of twins on electromigration

(a)

(b)

(c)

(d)

Twin boundaries!
Summary

- Nanotwinned Cu thin films and interconnects have been produced by pulse electroplating and illustrated by various characterization techniques.

- Effect of stress on nanotwin boundary formation has been investigated by first principles calculations, in situ stress measurements and microstructure characterization.

- Effect of twin boundaries on hardness, grain growth and electromigration behavior have been studied by various measurement methods combined with microstructure characterization techniques.

- Cu with high density of nanotwins can improve the mechanical properties and electromigration reliability of metal interconnects.
Thank you for your attention!