ULSI Applications of Rapid X-Ray Reflectometry (XRR)

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Veeco-CVC
Outline

- ULSI metrology challenges
- Introduction to the Meta-Probe X and XRR
- Applications
  - Cu seed/Ta barrier stacks for Cu metallization
  - Ultra-thin MOCVD barrier development
  - Low-K dielectric materials
- Summary and future applications
Interconnect Metrology Challenges

- Cu Damascene production process
  - Thin metal film stacks for seed/barrier

- Process development
  - Ultra-thin MOCVD barriers
  - CVD Cu
  - Low-K dielectric materials
  - Hybrid (CVD/PVD) metal stacks
  - Thin metal stacks for silicide formation
Production Cu Metallization Metrology

- Current Cu production (Damascene process)
  - Cu seed (1,000Å-1,500Å) on Ta or TaN barrier (200Å-400Å) deposited by advanced PVD techniques
  - Cu filled with ECD process (1µm-1.5µm)
  - Cu removed by CMP

- Cu production metrology requirements
  - Cu seed/barrier thickness and uniformity
  - ECD-Cu thickness
  - CMP dishing & erosion control
The Dual-Damascene Process

1. Deposit Barrier and Seed (PVD Cluster Tool)
2. Deposit Thick ECD Cu (Electro-Chemical Deposition)
3. Remove Cu to Etch Stop (CMP Tool)

- Cu Seed
- Ta (TaN) Barrier
- Etch Stop
- ILD
- ECD Cu
- Cu Wire and Interconnect
The Meta-Probe X

The Meta-Probe X is a fab-compatible metrology tool based on X-ray reflectometry (XRR):

- XRR measures the intensity of reflected monochromatic X-rays incident on a surface at near grazing incidence as a function of angle.
- XRR analysis of a surface provides independent measurements of thin film thickness, density, and surface/interface roughness.
- Value of XRR has been well recognized for R&D, but conventional technique is too slow for metrology.
Basis of the XRR Technique

Monochromatic X-rays

Below the Critical Angle: Total External Reflection

Above the Critical Angle: Reflection & Transmission

Much Greater than the Critical Angle: Transmission Only

The critical angle $\theta_C$ is a function of $\lambda \cdot (\rho)^{1/2}$

\[ \sin^2 \theta_{\text{max}} = \sin^2 \theta_C + \left[ i + \frac{1}{2} \right]^2 \cdot \left[ \lambda / 2 \cdot T \right]^2 \] for \( i = 1, 2, \ldots \)

\[ \text{... use fringe spacing to determine thickness} \]

\[ R = R_{\text{ideal}} \cdot \exp\left( -\frac{4\pi}{\lambda} \sin \sigma \phi / \lambda \right)^2 \]

\[ \text{... use slope of curve and attenuation of fringes to determine interface roughness} \]

Sample: 358Å Cobalt Thin Film
How to Fit Data for Thin-Film Properties

Step 1: Fit Thickness and Density
- Ta on SiO₂
  - Thickness: 268 Å
  - Density: 16.6 gm/cm³

Step 2: Fit Surface Roughness
- Surface Roughness: 17 Å-rms

Step 3: Fit Interface Roughness
- Interface Roughness: 15 Å-rms
Meta-Probe $X$ Method for Rapid XRR

- **Rapid Data Collection** ...*measurements in seconds*
- **No Moving Parts or Complex Lasers** ...*simple and robust*

**U.S. PATENT NO. 5,619,548**
Meta-Probe X
Cu-Seed/Ta-Barrier Stacks

- Measure Cu-seed/Ta barrier stack
- Typical Uniformity
- Repeatability measurements
- Measurement accuracy
  - Correlation with RBS
  - Sematech standard wafer set
### Cu/Ta Thin Film Stacks

<table>
<thead>
<tr>
<th>Cu/Ta Film</th>
<th>Target Cu</th>
<th>Ta</th>
<th>RXRR Cu</th>
<th>Ta</th>
<th>Cu-σ</th>
<th>Cu/Ta-σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuTa-1</td>
<td>500Å</td>
<td>250Å</td>
<td>524Å</td>
<td>250Å</td>
<td>14Å-rms</td>
<td>4Å-rms</td>
</tr>
<tr>
<td>CuTa-2</td>
<td>1,000Å</td>
<td>250Å</td>
<td>969Å</td>
<td>250Å</td>
<td>16Å-rms</td>
<td>5Å-rms</td>
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<tr>
<td>CuTa-3</td>
<td>1,500Å</td>
<td>250Å</td>
<td>1,734Å</td>
<td>249Å</td>
<td>14Å-rms</td>
<td>0Å-rms</td>
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<tr>
<td>CuTa-5</td>
<td>2,000Å</td>
<td>250Å</td>
<td>1,874Å</td>
<td>255Å</td>
<td>15Å-rms</td>
<td>0Å-rms</td>
</tr>
</tbody>
</table>

The graph shows the angle (degrees) vs. reflectivity for various Cu/Ta thin film stacks, with Cu and Ta fringes indicated.
Cu Seed/Barrier Uniformity Control

Average$_{\text{Cu}}$ = 1,367Å
Max$_{\text{Cu}}$-Min$_{\text{Cu}}$ / (Average$_{\text{Cu}}$) = 6.0%

Average$_{\text{Ta}}$ = 172Å
Max$_{\text{Ta}}$-Min$_{\text{Ta}}$ / (Average$_{\text{Ta}}$) = 15.2%
Repeatability on Blanket Wafers

5 Measurements Over Same Area on Blanket Wafer (Cu Seed/Ta Barrier)

Reflectivity vs. Angle (degrees)
Repeatability on Patterned Wafers

5 Measurements Over Same Area on Patterned Wafer (Cu Seed/Ta Barrier)
# Repeatability Summary

5 Measurements on a Blanket Wafer and 5 Measurements on a Product Wafer
(Sister Wafers with PVD Cu Seed/Ta Barrier)

<table>
<thead>
<tr>
<th></th>
<th>Patterned Wafer</th>
<th></th>
<th>Blanket Wafer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cu Seed</td>
<td>Ta Barrier</td>
<td>Cu Seed</td>
<td>Ta Barrier</td>
</tr>
<tr>
<td>Mean</td>
<td>829.4 Å</td>
<td>233.2 Å</td>
<td>826.0 Å</td>
<td>232.8 Å</td>
</tr>
<tr>
<td>Range</td>
<td>2 Å</td>
<td>1 Å</td>
<td>3 Å</td>
<td>1 Å</td>
</tr>
<tr>
<td>$1\sigma$</td>
<td>0.80 Å</td>
<td>0.40 Å</td>
<td>1.10 Å</td>
<td>0.40 Å</td>
</tr>
<tr>
<td>$1\sigma(%)$</td>
<td>0.10%</td>
<td>0.17%</td>
<td>0.13%</td>
<td>0.17%</td>
</tr>
</tbody>
</table>
Cu/Ta Stack RBS Accuracy Correlation

Cu Thickness Measurements

<table>
<thead>
<tr>
<th>Wafer</th>
<th>MPX</th>
<th>RBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>104-03</td>
<td>617Å</td>
<td>600Å</td>
</tr>
<tr>
<td>104-04</td>
<td>1,063Å</td>
<td>1,070Å</td>
</tr>
<tr>
<td>104-05</td>
<td>1,271Å</td>
<td>1,290Å</td>
</tr>
<tr>
<td>104-06</td>
<td>804Å</td>
<td>790Å</td>
</tr>
<tr>
<td>104-07</td>
<td>446Å</td>
<td>420Å</td>
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Cu/Ta Stack RBS Accuracy Correlation (continued)

Ta Thickness Measurements (corrected)

<table>
<thead>
<tr>
<th>Wafer</th>
<th>MPX (Å)</th>
<th>RBS (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>104-03</td>
<td>346Å</td>
<td>353Å</td>
</tr>
<tr>
<td>104-04</td>
<td>348Å</td>
<td>353Å</td>
</tr>
<tr>
<td>104-05</td>
<td>351Å</td>
<td>353Å</td>
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<tr>
<td>104-06</td>
<td>227Å</td>
<td>235Å</td>
</tr>
<tr>
<td>104-07</td>
<td>466Å</td>
<td>460Å</td>
</tr>
</tbody>
</table>
Ta Thickness Measurements (Ta Only Wafers)

<table>
<thead>
<tr>
<th>Slot</th>
<th>Target</th>
<th>TWI</th>
<th>NIST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50Å</td>
<td>57Å</td>
<td>59Å</td>
</tr>
<tr>
<td>2</td>
<td>100Å</td>
<td>97Å</td>
<td>102Å</td>
</tr>
<tr>
<td>3</td>
<td>200Å</td>
<td>168Å</td>
<td>176Å</td>
</tr>
<tr>
<td>4</td>
<td>300Å</td>
<td>259Å</td>
<td>262Å</td>
</tr>
<tr>
<td>6</td>
<td>400Å</td>
<td>415Å</td>
<td>435Å</td>
</tr>
<tr>
<td>7</td>
<td>500Å</td>
<td>490Å</td>
<td>510Å</td>
</tr>
<tr>
<td>8</td>
<td>1,000Å</td>
<td>821Å</td>
<td>839Å</td>
</tr>
</tbody>
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Meta-Probe X Results (TWI)

NIST Results
### SEMATECH Standard Cu/Ta Correlation (continued)

#### Ta Thickness Measurements (Cu/Ta Wafers)

<table>
<thead>
<tr>
<th>Slot</th>
<th>Target</th>
<th>TWI</th>
<th>NIST</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>200Å</td>
<td>183Å</td>
<td>191Å</td>
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<tr>
<td>10</td>
<td>200Å</td>
<td>185Å</td>
<td>193Å</td>
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<tr>
<td>11</td>
<td>200Å</td>
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<td>12</td>
<td>200Å</td>
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<tr>
<td>13</td>
<td>200Å</td>
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<td>14</td>
<td>100Å</td>
<td>530Å</td>
<td>561Å</td>
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<tr>
<td>16</td>
<td>250Å</td>
<td>224Å</td>
<td>234Å</td>
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<tr>
<td>17</td>
<td>300Å</td>
<td>264Å</td>
<td>275Å</td>
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<tr>
<td>18</td>
<td>200Å</td>
<td>192Å</td>
<td>200Å</td>
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</table>
SEMATECH Standard Cu/Ta Correlation (continued)

Cu Thickness Measurements (Cu/Ta Wafers)

<table>
<thead>
<tr>
<th>Slot</th>
<th>Target</th>
<th>TWI</th>
<th>NIST</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>200Å</td>
<td>283Å</td>
<td>299Å</td>
</tr>
<tr>
<td>10</td>
<td>400Å</td>
<td>533Å</td>
<td>556Å</td>
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<tr>
<td>11</td>
<td>600Å</td>
<td>783Å</td>
<td>821Å</td>
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<tr>
<td>12</td>
<td>800Å</td>
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<td>1,060Å</td>
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<tr>
<td>13</td>
<td>1,000Å</td>
<td>1,281Å</td>
<td>1,334Å</td>
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<tr>
<td>14</td>
<td>600Å</td>
<td>754Å</td>
<td>784Å</td>
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<tr>
<td>16</td>
<td>600Å</td>
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</tr>
<tr>
<td>17</td>
<td>600Å</td>
<td>778Å</td>
<td>809Å</td>
</tr>
<tr>
<td>18</td>
<td>1,000Å</td>
<td>1,818Å</td>
<td>1,830Å</td>
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Comparison of NIST and TWI Results for Sematech Slot-3

<table>
<thead>
<tr>
<th></th>
<th>Ta₂O₅</th>
<th>Ta</th>
</tr>
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<tbody>
<tr>
<td>Nominal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>-</td>
<td>200Å</td>
</tr>
<tr>
<td>ρ</td>
<td>-</td>
<td>16.60g/cc</td>
</tr>
<tr>
<td>σ</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TWI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>23Å</td>
<td>168Å</td>
</tr>
<tr>
<td>ρ</td>
<td>8.59g/cc</td>
<td>16.60g/cc</td>
</tr>
<tr>
<td>σ</td>
<td>6Å</td>
<td>5Å</td>
</tr>
<tr>
<td>NIST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>23.7Å</td>
<td>175.7Å</td>
</tr>
<tr>
<td>ρ</td>
<td>8.28g/cc</td>
<td>16.27g/cc</td>
</tr>
<tr>
<td>σ</td>
<td>4.8Å</td>
<td>4Å</td>
</tr>
</tbody>
</table>
Seed/Barrier Production Monitoring

Use rapid XRR in Meta-Probe X to monitor Cu seed and Ta barrier thickness in production stacks on test or product wafers

- Cu seed thickness from <50Å to >1,500Å with repeatability <0.5% (1σ)
- Ta/TaN barrier thickness from <30Å to >500Å under Cu seed with repeatability <0.5% (1σ)
- Insignificant (<1 rad) gate oxide radiation exposure from 1st Cu measurement (no exposure for metal>2)
Critical Process Development Challenges

- Thin CVD Cu seed and compound barriers
  - Thickness of <100Å films in stacks
  - Stoichiometry and purity of MOCVD films
  - Surface and interface roughness of CVD films
- Low-k dielectric density and thickness
- RTP-processed silicides from thin film stacks
  - Ti/Co, Ti/Ni, etc.
  - Thickness and roughness and density
- Rapid measurement turn-around for rapid process iteration - *no time for metrology R&D*
Ultra-Thin CVD TaN Barrier Films

Samples supplied by CVC, Inc.

Sample A
43Å (ρ=9.1 gm/cm³)
σ_{surface}=3Å rms
σ_{interface}=9Å rms

Sample C
83Å (ρ=8.1 gm/cm³)
σ_{surface}=3Å rms
σ_{interface}=7Å rms

Sample D
76Å (ρ=8.0 gm/cm³)
σ_{surface}=3Å rms
σ_{interface}=9Å rms

Sample B
56Å (ρ=8.0 gm/cm³)
σ_{surface}=3Å rms
σ_{interface}=7Å rms

Sample E
70Å (ρ=8.3 gm/cm³)
σ_{surface}=3Å rms
σ_{interface}=6Å rms
Ultra-Thin CVD TaN Barrier Films

Sample F
99Å (ρ=8.3 gm/cm³)
σ_{surface}=8Å rms
σ_{interface}=12Å rms

Sample G
78Å (ρ=11.7 gm/cm³)
σ_{surface}=6Å rms
σ_{interface}=10Å rms

Sample H
68Å (ρ=12.2 gm/cm³)
σ_{surface}=7Å rms
σ_{interface}=7Å rms

Samples supplied by CVC, Inc.
Low-K Dielectric Films

- 20Å SiO₂ (ρ=1.48 gm/cm³)
  - 3,530Å SiO₂ (ρ=0.95 gm/cm³)
  - Average Porosity = 58%

- 41Å SiO₂ (ρ=1.79 gm/cm³)
  - 2,372Å SiO₂ (ρ=1.52 gm/cm³)
  - Average Porosity = 33%

- (ρ=1.66 gm/cm³)
  - Average Porosity = 27%
Summary

- Rapid XRR in the Meta-Probe X is a promising metal metrology tool
- Can be used to monitor Cu-seed/Ta-barrier stack thickness in production
- Thickness, density, and roughness capability promising for process development
  - Ultra-thin MOCVD film stacks
  - Low-K dielectric density
  - Other thin film applications