Smoothing layers for EUV substrate defectivity mitigation

R. Teki, A. John, M. House, J. Harris-Jones, A. Ma, F. Goodwin

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Current EUV substrates: Quality & Issues

QTZ: quartz material (undoped fused silica)
LTEM: Low thermal expansion material (titania doped fused silica)
Multilayer (ML) blank defectivity

ML blank defect data on both supplier substrates:

Number of pits/scratches increases exponentially as we go to smaller defect sizes
**Substrate defectivity**

Majority of the small sized pits, bumps and scratches do not show up on substrate inspection post cleaning, but show up on the multilayer (ML) after being “decorated” by ML deposition.

<table>
<thead>
<tr>
<th>Defectivity</th>
<th>Pits</th>
<th>Scratches</th>
<th>Particles</th>
<th>Pit+Scr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate @ 40 nm SiO$_2$ size</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>ML blank @ 43 nm SiO$_2$ size</td>
<td>56</td>
<td>43</td>
<td>21</td>
<td>99</td>
</tr>
</tbody>
</table>
### QTZ defectivity and roughness

#### Impact of surface roughness:

<table>
<thead>
<tr>
<th></th>
<th>Average RMS roughness</th>
<th>Cleaning recipe used</th>
<th>ML Defectivity @ 50 nm (scaled)</th>
<th>Avg. increase in (pit+scratch) count after ML deposition @ 50 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Substrate</td>
<td>ML blank</td>
<td></td>
<td>Scratch</td>
</tr>
<tr>
<td>QTZ: A</td>
<td>0.10 nm</td>
<td>0.16 nm</td>
<td>1 MHz*</td>
<td>1y</td>
</tr>
<tr>
<td>QTZ: B</td>
<td>0.07 nm</td>
<td>0.13 nm</td>
<td>1 MHz*</td>
<td>1.3y</td>
</tr>
</tbody>
</table>

- Lower the surface roughness, greater the substrate defectivity
- CMP is currently unable to meet both roughness and defectivity specifications

#### Surface roughness requirements:

<table>
<thead>
<tr>
<th>Roughness Specification</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure tool</td>
<td>0.15 nm RMS</td>
</tr>
<tr>
<td>Inspection tool</td>
<td>( \leq 0.05 , \text{nm RMS} ) for 33 nm sensitivity</td>
</tr>
<tr>
<td>LER target</td>
<td>( \leq 0.05 , \text{nm} ) for 22/16-nm nodes per ITRS, (ref. P. Naulleau, LBNL)</td>
</tr>
</tbody>
</table>

- Need lower roughness for greater inspection sensitivity (especially on substrates)
- Need lower roughness for smaller line-edge roughness (LER)
Substrate quality: LTEM vs. QTZ

All the numbers are scaled to LTEM value of 1

Harder to CMP LTEM substrates: doped, harder, rougher, lower RR, more defects, more SSD
Alternative Methodologies
Methodologies being evaluated

Smoothing options

Substrate based
- LTEM/QTZ substrates
  - Dressed photon nano-polishing
  - CO₂ laser polishing
  - Magneto-rheological fluid polishing

Silicon based
- a/poly-Si thin films
  - Non-abrasive CMP
  - Annealing induced surface migration

Coating based
- Inpria ‘resist’ layer
  - Spin coating
  - Capillary coating
  - Template smoothing

Process alternative or improvement technique

Defect mitigation or repair technique
Smoothing metrics

Evaluation metrics:
1. Defectivity
2. Surface roughness
3. Smoothing power

Aspect ratio (A.R.) = \(\frac{\text{full width at half maxima}}{\text{depth or height}}\)

Smoothing power (S.P.) = \(\frac{AR_{\text{post}}}{AR_{\text{pre}}}\)

PRE
Depth = 9.4 nm
FWHM = 154 nm
A.R. = 16.4
S.P. = 155/16.4 = 9.45

POST
Depth = 1.4 nm
FWHM = 217 nm
A.R. = 155
Individual techniques
Inpria spin coating (Sematech)

Inpria inorganic metal oxide thin films:
• Vacuum quality films from solution
• Fully dense and atomically smooth post baking
• Passes scanner outgassing requirements

Results:
• Obtained S.P. of 5.5 with AlO based spin coating
• Typical S.P. with ML deposition is 2.3

Plan further experiments to determine correlation between thickness, roughness and smoothing power

<table>
<thead>
<tr>
<th>Coating thickness</th>
<th>RMS surface roughness</th>
<th>Smoothing power (avg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~8 nm</td>
<td>0.156 nm</td>
<td>1.6</td>
</tr>
<tr>
<td>~50 nm</td>
<td>-</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Pit defect dimensions (pre/post)
Inpria capillary coating (Hirano)

Principle of capillary coating:
• Based on capillary effect and surface wettability
• Advantages: utilization, uniformity, defectivity

RMS roughness [nm]

0.141 nm
0.078 nm

Chart showing defect depth/height before and after cap coating

Avg. smoothing power = 8.2

Coating ~ 83 nm

Courtesy: SUSS Microtech, Germany
Inpria defectivity (Inpria, Sematech)

As prepared concentrated solution in diluted form

Using as prepared diluted solution

Baseline DI water

See a ~30-fold drop in defectivity

- Defectivity likely arising from precursor chemicals used
- Defectivity appears to depend on dilution and shelf life
- Plan further experiments with filtration of solution
Polymeric CMP of a-Si (Clarkson U.)

Principle:
- Pits/scratches are mainly caused by abrasive slurry particles
- Deposit a-Si thin film and perform CMP without using slurry particles
- Si thin film can be deposited in current IBD tool & cleaned like ML blanks

\[ E(\text{-Si-Si}-) < E(\text{Bridging}) < E(\text{-Si-O-} \& \text{-Si-N-}) \]

Experimental conditions:
- a-Si coated 8” Si wafers
- Polymer: PEI, ORN
- Pad: IC-1000, Politex
- Pad Pressure: 0.25 – 1 psi
- Polish time: 1 - 5 min
- Rotation speed: 15/15, 60/60 rpm

Plan to transfer the process to a-Si coated EUV substrates and check for pit/scratch defects
Dressed photon nano-polishing (NPEO)

**Principle:**
- Based on non-adiabatic photochemical dissociation of reactive Cl$_2$ gas at 523 nm exposure (Abs. $\lambda_{Cl} = 400$ nm)
- Surface protrusions generate steep optical near-field spatial gradient
- Etching stops when gradient (roughness) disappears
- Can be used for localized etching of particle type defects on substrates

![Graphs showing height and length before and after treatment](image)

- $Ra = 0.22$ nm
- $Ra = 0.17$ nm

- Smoothened particle from 4 nm to <1 nm height

*Courtesy: Prof. Ohtsu & Prof. Yatsui, NPEO, Japan*
MRF polishing (QED Technologies)
Magneto-rheological fluid

Principle:
• MRF fluid - properties (e.g. viscosity) change with magnetic field
• Removal relies on shearing mechanism
• No normal load eliminates SSD
• Can be used in combination with CMP

Initial testing:
• M1350 inspection shows characteristic grooves of MRF (Fig. B) as compared to un-polished surface (Fig. A)
• Plan to measure roughness/hardness
• Plan cleaning experiments to evaluate pit adders (~SSD) on MRF polished substrates
CO₂ laser polishing (Fraunhofer ILT)

Principle:
• Laser radiation is absorbed in a thin layer
• Surface temp. rises & viscosity is lowered
• Roughness flows due to surface tension

Preliminary evaluation on LTEM/QTZ:
• Micro-roughness ($\lambda_{\text{spatial}} < 100 \, \mu m$) was not effected
• Waviness ($\lambda_{\text{spatial}} > 100 \, \mu m$) increased

Plan further tests with lower processing temperatures

Courtesy: A. Richmann, Fraunhofer Institute, Germany
Si migration on annealing (Stanford U.)

Principle:
- Silicon surface migration under H$_2$ annealing conditions acts to lower the chemical potential associated with the curvature of a surface.
- Deposit a-Si thin film in the IBD tool and anneal the substrate under reducing conditions
- Annealing temperatures tested: 850 – 1100 C
- Annealing times tested: 4 – 64 min

Plan to further refine the process window and evaluate surface roughness
Summary

- CMP is currently unable to reach the roughness and defectivity levels required for commercialization of EUV lithography.
- CMP and cleaning of LTEM substrates is more challenging than QTZ substrates.
- Alternative techniques based on substrate, silicon, inorganic coating are currently being investigated to evaluate substrate smoothing.
- CMP is still the best mainstream method currently available with respect to overall process integration, but it could use some support from some of the alternative techniques.
- For e.g. it can be used in combination with MRF polishing to reduce the extent of sub-surface damage, or it can be used in combination with DPNP to etch embedded or hard to remove particles so that we don’t need aggressive cleaning (which adds more pits).
- Further work is required to refine the current techniques, evaluate their defectivity, roughness and smoothing, and verify final proof of concept by getting printability data on the Actinic Inspection Tool (AIT).
# Selected methodologies summary

<table>
<thead>
<tr>
<th>Category</th>
<th>Material</th>
<th>Technology</th>
<th>Main Pros &amp; Cons</th>
<th>Future work</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Substrate based options</strong></td>
<td>Fused silica, LTEM</td>
<td>Dressed-photon nano-polishing</td>
<td>✓ Non-contact (dry) etching, ✓ Self-limiting, x Defectivity</td>
<td>▪ Verify smoothing of pits and metal/oxide particles, ▪ Evaluate etching on ML surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magneto-rheological fluid polishing</td>
<td>✓ No normal forces, only shear, ✓ No sub-surface damage, x Final surface quality (roughness)</td>
<td>▪ Measure roughness, hardness, M7360 inspectability, ▪ Try cleaning experiments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ laser polishing</td>
<td>✓ Low surface damage, x Narrow process window, x Final surface quality (flatness)</td>
<td>▪ Refine process window, ▪ Evaluate smoothing power, change in roughness</td>
</tr>
<tr>
<td><strong>Silicon based options</strong></td>
<td>a-Si, poly-Si thin films</td>
<td>Non-abrasive polymeric CMP</td>
<td>✓ No abrasive slurry particles, ✓ Less likely to create pits/scratches, x Cleaning of a-Si layer</td>
<td>▪ Transfer process to a-Si coated EUV substrates, ▪ Evaluate defectivity, cleaning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annealing induced Si migration</td>
<td>✓ Low surface damage, x Narrow process window, x Final surface quality (flatness)</td>
<td>▪ Refine process window, ▪ Evaluate smoothing power, change in roughness</td>
</tr>
<tr>
<td><strong>Coating based options</strong></td>
<td>Inpria resist Smoothing layer</td>
<td>Spin coating</td>
<td>✓ Potential to smooth pits, x Defectivity</td>
<td>▪ Reduce defectivity by filtration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capillary coating</td>
<td>✓ Potential to smooth pits &amp; particles, x Defectivity</td>
<td>▪ Determine relation between thickness, smoothing &amp; roughness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Template smoothing</td>
<td>✓ Replication of defect map, ✓ Champion ML can be the template, x Uniformity, defectivity</td>
<td>▪ Experiment using ML blanks as template, ▪ Evaluate roughness &amp; smoothing</td>
</tr>
</tbody>
</table>
Thank you for your attention

Questions?
Issues with CMP:

- Defects – pits, scratches, embedded particles
- Sub-surface damage
- Defectivity yield
- Poor control, narrow process latitude

Embedded particle removal leaves a pit

Flattened particle

Scratch
CMP scratches