3D ATOMIC FORCE MICROSCOPY OF HIGH ASPECT RATIO STRUCTURES

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› Introduction: why 3D AFM measurements
› Bottlenecks in AFM based 3D metrology for the semiconductor industry
› TNO approach to 3D AFM
› Conclusions
INTRODUCTION: WHY 3D AFM MEASUREMENTS?

- Measuring the full profile of nanostructures such as FinFET, gates, gate all around nanowires are very important.
- Side wall roughness and angle measurements are now process control parameters.
- The next generation of FinFETs will be gate all around nanowires, and the profile parameters are even more challenging to be measured.

To summarize: evolution in nanostructures reflected in required performance and functionality of metrology.
Metrology Evolution

Pre 1990
- Dimensional
- Defect
- Variability

1990s-mid 2000s
- Dimensional
- Compositional
- Defect
- Variability

Mid 2000s-present
- Dimensional
- Compositional

Future
- Property
  - Strain
  - Adhesion/E/H
  - Chemical State
  - Density/Porosity/K
- Defect
- Variability

Resolution/scaling/sensitivity

Circa 1995

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Technology Node

Critical Metrology for Advanced CMOS Manufacturing
**INTRODUCTION: WHY 3D AFM MEASUREMENTS?**

<table>
<thead>
<tr>
<th>Attributes:</th>
<th>OCD</th>
<th>CD-SEM</th>
<th>AFM</th>
<th>TEM/XSEM</th>
<th>X-Ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>What to measure</td>
<td>CD, profile, other</td>
<td>CD</td>
<td>CD, profile</td>
<td>CD, profile, other</td>
<td>Ultrathin films, composition</td>
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<tr>
<td>Where to measure</td>
<td>Periodic grating</td>
<td>Any</td>
<td>Any</td>
<td>Mostly Unpatterned</td>
<td>Mostly Unpatterned</td>
</tr>
<tr>
<td>Time to solution</td>
<td>Days to weeks</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Hours to days</td>
<td>Minutes</td>
</tr>
<tr>
<td>Destructive</td>
<td>Negligible</td>
<td>Minor (resist)</td>
<td>Mostly none</td>
<td>Mostly none</td>
<td>Yes</td>
</tr>
<tr>
<td>Time to measure</td>
<td>Seconds</td>
<td>Seconds</td>
<td>Minutes to hours</td>
<td>Minutes to hours</td>
<td></td>
</tr>
<tr>
<td>Summary: strengths</td>
<td>Fast measure</td>
<td>Most profile info</td>
<td>High Precision</td>
<td>Quick setup and fast measure</td>
<td>Anywhere</td>
</tr>
<tr>
<td>Assumptions and limitations</td>
<td>Model assumptions</td>
<td>Accuracy &amp; precision</td>
<td>Requires grating</td>
<td>Accuracy &amp; precision</td>
<td>Full profile info</td>
</tr>
<tr>
<td>Typical Fab usage</td>
<td>&quot;workhorse&quot; for CD and profile</td>
<td>&quot;workhorse&quot; for CD</td>
<td>Reference, partial in-line</td>
<td>Absolute reference</td>
<td>Composition</td>
</tr>
</tbody>
</table>

**No single best solution: all fill particular needs**

Each single metrology has limitations

-> **Hybrid Metrology** fills in gaps, toolsets become more complex
INTRODUCTION: WHY 3D AFM MEASUREMENTS?

- 3D AFM in a metrology context requires for success:
  - The 3D capability
  - Non destructive measurement → force control
  - High Throughput
  - High accuracy
  - Tomography capability (e.g. mechanical, electrical, sub-surface properties)
INTRODUCTION: WHY 3D AFM MEASUREMENTS?

High throughput
Non destructive
3D capability
High Accuracy
Tomography

20 nm SiN
100 nm SiN
100 nm SiN
Pyrex

Topography
Sub-surface

Parallel AFM system
Mini SPM
Positioning unit

Surface modification

Miniaturized scan head with fiber interferometer.

k=38 N/m, freq=166.7 KHz, A0=45 nm, Yield stress, S=35 GPa
INTRODUCTION: STATE OF THE ART 3D AFM

- Tilting + HAR probes + stitching
INTRODUCTION: STATE OF THE ART 3D-AFM

- Image Acquisition Mode: Peak Force Tapping
- Probe: High Aspect Ratio ScanAsyst Air

Parallel AFM system

Mini SPM

Positioning unit
BOTTLENECKS IN AFM BASED 3D METROLOGY

- Precise control of applied forces
  - Tapping mode: exact forces very difficult to assess
  - Peak-force tapping mode:
    - Open loop sinusoidal cantilever movement
    - Only has point-to-point feedback → no guaranteed control of applied force
  - Using full F-D curves
    - Repeatedly measure F-D curves
    - Control of maximum force lacking (control, stability, noise)

- (Very) narrow HAR trenches
- (Potential for) high throughput (single probe systems only)
- Tomography: observing other parameter than topography
BOTTLENECKS IN AFM BASED 3D METROLOGY

- AFM is fundamentally determined by tip sample interaction
  - Only in contact-mode continuous, most modes short intermittent interaction
- Not knowing and controlling of tip-sample interaction can lead to
  - Sample damage
  - Tip damage
  - Wear-induced metrology errors
  - Force-induced metrology errors
  - Reduced performance

3D Atomic Force Microscopy of High Aspect Ratio structures
TNO APPROACH FOR 3D AFM

Tomography
High throughput
Non destructive
3D capability
High Accuracy
ACHIEVABLE ASPECT RATIO’S: GEOMETRY EFFECT

- $A=20$, $c=2$ nm, $R=5$ nm; $\alpha$ in legend (deg)

Graphs showing reachable depth and reachable depth/width as functions of width for different angles $\alpha$.

- c: clearance on opposite edge = 2 nm
- Tip geometry:
  - A: Aspect ratio (diameter/height) of tip = 1:20
  - R: Tip radius = 5 nm

Diagram illustrating the tip geometry and clearance.
TNO APPROACH FOR 3D AFM

- Mode development
  - Force control
  - Non resonant mode for HAR → 3D-HAR

- Tomography
- High throughput
- High Accuracy
- Non destructive
- 3D capability
Z-trajectory: third order motion profile

Accelerate to required velocity

1 - Retracted

Decelerate to Retract distance break

2 - x,y step

Constant velocity

3 - Approach

Acceleration to High velocity

4 - Measure

Deceleration to Retract distance break

5 - Retract

Lateral trajectory: X,Y stepping
TRAJECTORY PERFORMED PER PIXEL

- No sinus
- Rapid retract
- Stabilization after retract
- Continuous ramp down

leads to maximum performance
3D HAR MODE

- HAR structures: both lateral and vertical tip-sample forces important

- We need force control to minimize force and wear induced measurement errors for this we need to understand (variation of) tip-sample forces.

- Feedback: able to act on attractive and repulsive force → only possible when changes > detection uncertainty
  - Low noise required
  - Low drift / high stability required
3D HAR MODE

- Main problems for reliably acting on force information:
  - Lateral tip deformation
  - Noise budget
  - Available reaction time
- Considerations for 3D-AFM mechatronic design:
  - F-D curves
  - Cantilever properties: stiffness, spike AR, spike stiffness, sharpness/tip radius

3D Atomic Force Microscopy of High Aspect Ratio structures
TNO APPROACH FOR 3D AFM

- High Accuracy through:
  - Mechatronic design
  - Proper choice of instrument settings for the test. E.g.:
    - Probe type
    - Probe angle
    - Control settings
    - Speed
    - Pixel count
    - Image dimensions
    - Etc.
MECHATRONIC DESIGN: POSITION MEASUREMENT

› Separate read-out of deflection and position
  › Linear & absolute measurement of z-position
  › Low-noise & very stable deflection measurement

› Closed loop, low-noise XY
  › Stepped lateral movements (i.e. not continuous scan)

› Stringent requirements for stability of metrology loop

› Accommodate 3D imaging:
  › Rotation of sample
  › Tilting of cantilever w.r.t. sample
  › Stitching measurement results

Laser interferometer for measuring fine stage displacement and OBD for measuring cantilever deflection
INSTRUMENT ACCURACY CHALLENGES

- Lowest noise when tip movement is perpendicular to surface
- Sidewalls:
  - Lowest noise when sample is tilted as little as possible
  - Large tilt → only top of trench reachable
  - Lower in trench → lower sample tilt possible → increased noise

- Single metric for system accuracy and noise not valid anymore
- Performance result of both system and sample
VALIDATING WITH SAMPLES

Planned tests:
- FinFETs and other fin structures
- Nanowires in Trench

Structures by LETI and IMEC
SUMMARY & CONCLUSIONS

TNO develops 3D AFM system that aims for:

- Guaranteed damage-free imaging with controlled force
- 3D contouring
- High accuracy
- Tomography compatible (mechanical, electrical, sub-surface)

3D AFM for high aspect ratio structure has stringent system requirements

- Low noise, high stability, high accuracy of system components
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