Characterization Methods for Shape and Length Nanoscale Metrology

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Projects

Nanotechnology Standardization: Form of Nano structure

- The goal was to collaborate on the development and standardization of nanoscale probe characterizers.

- As part of this collaboration, we evaluated the use of the comb characterizer for critical dimension AFM (CD-AFM) probes.

Nanotechnology Standardization: Size of Nano Structure

- The goal of the project was to collaborate in developing traceable physical standards for height and lateral dimensions.

- This will serve as part of a body of data in support of standardizing these samples for AFM vertical scale calibration.
One of the motivations of this work is the need to meet industry specifications for nanoscale length measurements. The international technology roadmap for semiconductors (ITRS) uncertainty specification for fin height and gate overhang are currently either in yellow or red, indicating that values are not currently being met. The work is also applicable to a wide range of nanoscale characterization.
3D –AFM Application

The CD-AFM uses flared tips, sub-resonant lateral dithering of the tip in addition to the near-resonant vertical oscillation of the cantilever, and a bidirectional servo and feedback system. This combination allows the imaging of vertical and even reentrant sidewalls, which are crucial to quantifying 3D features. To obtain shape information, some of the tip parameters listed below must be known.

Schematic diagram of CD-AFM operation. The tip vibrates in the Z direction and dithers in the lateral direction. The tip tracks both the vertical and lateral surfaces by adjusting the servo direction when a change in slope is detected by the sensor.

Flared 3D-AFM tip shape parameters

Image from G. Dahlen et al. J. Vac. Sci. Technol. B 23, 2297 (2005);
The features include the size of the tip!

Probe shape characteristic determination using the narrow ride structure.

This example shows probe shape estimation using cylindrical tips. The technique can also be applied to flared tips, but does not yield tip reentrant parameters.
For flared CD tips, the width and edge height can be determined.
Comparison with Other Techniques

<table>
<thead>
<tr>
<th>Characterizer</th>
<th>Intrinsic Accuracy</th>
<th>Important Metrology Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relative Traceability Route</td>
<td>Undercut Features</td>
</tr>
<tr>
<td>IFSR</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>IVPS</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>NanoCD</td>
<td>Yes</td>
<td>TEM*</td>
</tr>
<tr>
<td>‘Comb’</td>
<td>Yes</td>
<td>TEM</td>
</tr>
<tr>
<td>SCODRM</td>
<td>Yes</td>
<td>TEM</td>
</tr>
</tbody>
</table>

Linewidth values are within 0.5 nm from results based on calibration from other methods.
Nanoscale Grating Characterization

Scale Calibration Gratings

- Although the feature widths are known from TEM, if the AFM scale calibration is not correct, the tip widths will be wrong.
- The sample includes gratings that could be used as traceable lateral scale for the whole evaluation process.
- The gratings are calibrated using the NIST T-AFM.

<table>
<thead>
<tr>
<th>(nm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>28.03 This is the mean value obtained from the displacement interferometry data.</td>
</tr>
<tr>
<td>Sample Uniformity</td>
<td>0.21 This is the standard deviation of the grating from a single measurement rather than from repeated measurements, and represents the sample quality.</td>
</tr>
<tr>
<td>1 Standard deviation</td>
<td>0.09 10 repeated measurements</td>
</tr>
</tbody>
</table>
Simulation

- When considering using a characterizer, it would be helpful to know if a particular characterizer is suitable for the task.
- To do this we simulated the AFM scanning process using a range of tip parameters.

- The goal is to
  - Be able to specify what types of tips could be used on a specific characterizer. This information will enable users to select appropriate characterizers for their needs.
  - Develop a tool for designing specialized characterizers.

\[
A \oplus B = \bigcup_{b \in B} (A + b)
\]

\[
sim(x, y) = \max\{A(x', y') + B(x - x', y - y')\}
\]

\[
z(x, y) = \max\{s(x', y') - t(x' - x, y' - y)\} = \max\{s(x', y') + p(x - x', y - y')\}
\]
Other Applications

Although our focus has been on semiconductor metrology, probe shape characterization is applicable to a wide range of nano-structures.

John Dagata at NIST used the comb characterizer to evaluate AFM tips for nanoparticle measurements, with a focus on drug delivery systems for nanomedicine. A key part of the work was validating the consistency of individual particle measurements, which requires a detailed knowledge of the probe shape. This was then used to develop models of particle-tip deformation and particle-substrate deformation.

Three manuscripts describing key metrological aspects of this work have been submitted to the journal Measurement Science and Technology.

J. A. Dagata et al, Deformation of polystyrene reference spheres in atomic force microscopy

I. Use of a tip characterizer for correlated height and width measurements
II. Particle-tip deformation
III. Particle-substrate deformation

AFM images of different sizes of polystyrene latex reference material used in the study
Evaluation of Al₂O₃ (Sapphire) Stepped Surfaces

Analysis Procedure

- One sided step height algorithm
- Linear fits to the middle portion of the terraces
- The height values fits are extrapolated and determined at the edge.
- The step values from each file are averaged.

\[ H_{\text{meas}} = (a_1 x_T + b_1) - (a_2 x_T + b_2) \]
Instrument: Traceable Atomic Force Microscope

- Metrology AFM with Displacement Interferometry in three axes.
  - Traceable to the SI meter through 633nm He-Ne laser wavelength
- Fiber optic cantilever detection
- Independent x, y, z scanning stage actuators
- Z noise resolution of less than 0.05 nm
- Stage linearity of less than 0.01%
- Abbe offset of less than 5 mm in x and y axe and 0.5 mm in z axis.
- Stage drift of less than 10 nm per hour
- Scan range: 100 µm x 100 µm x 6 µm
r Plane (1¯102) Nominal Height: 0.35 nm

Qualitative Observations:

- Well defined edges
- Most terraces are more than 150 nm, allowing for adequate area for data fitting.
- Relatively low roughness on the terraces.
- Short terrace transition region relative to the length of terrace size.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean (nm)</th>
<th>1 SD (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.348</td>
<td>0.008</td>
</tr>
<tr>
<td>B</td>
<td>0.359</td>
<td>0.014</td>
</tr>
<tr>
<td>C</td>
<td>0.353</td>
<td>0.010</td>
</tr>
<tr>
<td>D</td>
<td>0.361</td>
<td>0.008</td>
</tr>
<tr>
<td>E</td>
<td>0.357</td>
<td>0.004</td>
</tr>
<tr>
<td>F</td>
<td>0.359</td>
<td>0.003</td>
</tr>
<tr>
<td>G</td>
<td>0.355</td>
<td>0.008</td>
</tr>
<tr>
<td>H</td>
<td>0.356</td>
<td>0.007</td>
</tr>
<tr>
<td>I</td>
<td>0.355</td>
<td>0.010</td>
</tr>
</tbody>
</table>

| Mean     | 0.356     | 0.004     |
c-Plane (0001) Nominal Height : 0.22 nm

Qualitative Observations:
- Well defined edges
- Most terraces are more than 350 nm, allowing for adequate area for data fitting.
- Relative low roughness on the terraces.
- Short terrace transition region relative to the length of terrace size.

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<tr>
<th>Location</th>
<th>Mean (nm)</th>
<th>1 SD (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.220</td>
<td>0.006</td>
</tr>
<tr>
<td>B</td>
<td>0.227</td>
<td>0.016</td>
</tr>
<tr>
<td>C</td>
<td>0.231</td>
<td>0.012</td>
</tr>
<tr>
<td>D</td>
<td>0.230</td>
<td>0.003</td>
</tr>
<tr>
<td>E</td>
<td>0.232</td>
<td>0.009</td>
</tr>
<tr>
<td>F</td>
<td>0.236</td>
<td>0.005</td>
</tr>
<tr>
<td>G</td>
<td>0.218</td>
<td>0.010</td>
</tr>
<tr>
<td>H</td>
<td>0.239</td>
<td>0.008</td>
</tr>
<tr>
<td>I</td>
<td>0.221</td>
<td>0.008</td>
</tr>
<tr>
<td>Mean</td>
<td>0.228</td>
<td>0.007</td>
</tr>
</tbody>
</table>
Summary

- We evaluated the comb characterizer for CD-AFMs and compared the results with existing techniques.

- We report feature size results that are within 1 nm compared with existing methods.

- An evaluation of a length standard built into the multi-feature characterizer show an uniformity of less than 0.75 %, indicating that the characterizer could be used as nanoscale SI traceable length artifacts.

- We evaluated sub-nm sapphire steps in preparation for ISO standardization and round robin test.
Publications


J. A. Dagata et al, Deformation of polystyrene reference spheres in atomic force microscopy to be Measurement Science and Technology

3. Use of a tip characterizer for correlated height and width measurements
4. Particle-tip deformation
5. Particle-substrate deformation
Continuing Work

• Continue work on different applications of the tip characterizer in semiconductor dimensional measurements.

• Continue collaboration on nano-roughness applications.

• Assist in developing a guideline for round robin test of Al3o2 steps

• Prepare a proposal to set up a study group for scanning probe based techniques for 3D Nanometrology.
  
  *Shape Characterization*
  
  *Instrument Calibration and Linearity*
Special Thanks To AIST/NMIJ