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Automated STEM and TEM Metrology of Advanced Semiconductor Devices

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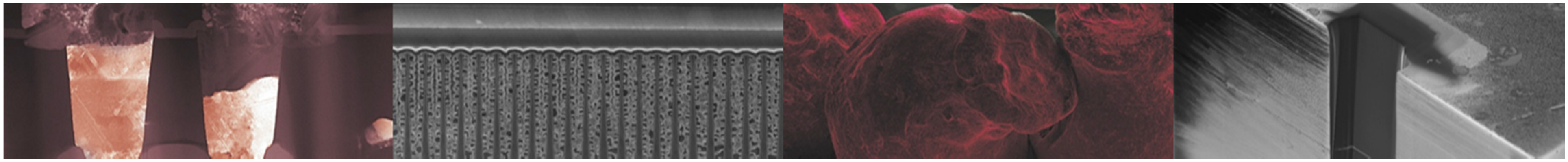
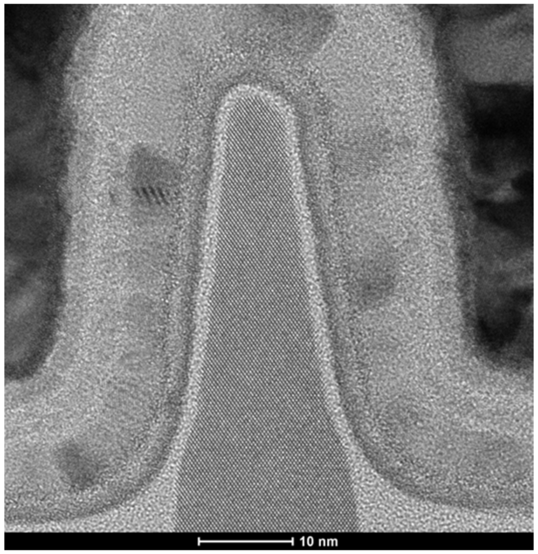


Introduction



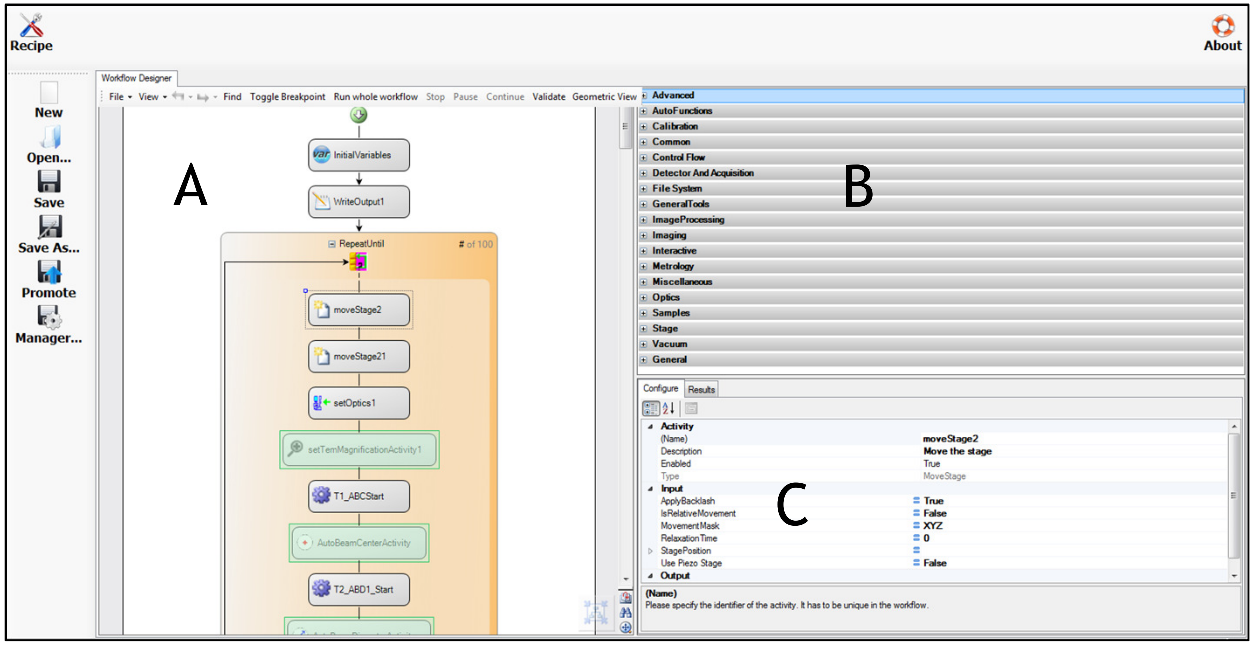
FEI is extending their automated scanning transmission electron microscopy (STEM) to conventional transmission electron microscopy (TEM) to bring higher throughput and repeatability of measurements in increasingly complex advanced semiconductor structures. These structures of interest include 3D transistors (e.g. FinFET or Tri-gate), various shrinking line widths, thin films, and etch profiles, that require metrology techniques beyond those currently offered by conventional CD-SEM or scatterometry. These established metrology solutions offer excellent repeatability and throughput, but they each have limitations for investigating advanced three-dimensional integration schemes, such as those defined in the 2011 metrology roadmap presented at the ITRS Winter 2011 meeting. For example, scatterometry does not offer the capability for line edge roughness analysis, and it is not possible to undertake sub-surface analysis using CD-SEM.

Scanning and transmission electron microscope based dimensional metrology (CD-STEM and CD-TEM) are candidates to overcome these limitations and extend metrology capabilities into the most advanced technology nodes. Recently, we have shown STEM and TEM based dimensional metrology provide good repeatability and robustness.

This poster summarizes the progress to date on such TEM based metrology and offers an outlook on possibilities for fully automating the whole process from sample navigation and alignment, through image acquisition, to the metrology itself. Sensitivity and repeatability data are presented for key autofunctions as well as repeatability data for metrology measurements of a simple device.

Recipe Designer

FEI has developed a recipe designer to facilitate automating routine TEM and STEM functions and allowing them to be put together to create automated work flows for both imaging and metrology. Recipes can be run as stand alone applications or executed through a simplified S/TEM user interface. The UI is aimed at providing less experienced microscope users with repeatable and reliable data.

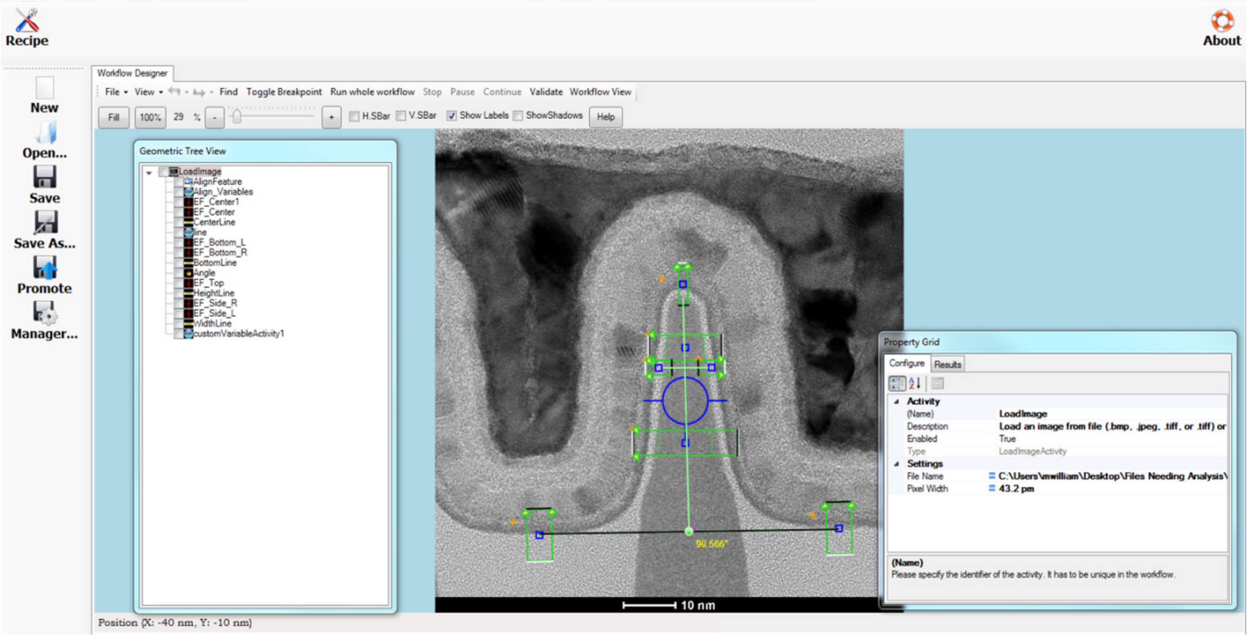


Activity	
(Name)	**moveStage2**
Description	**Move the stage**
Enabled	True
Type	MoveStage
Input	
ApplyBacklash	**True**
IsRelativeMovement	**False**
MovementMask	**XYZ**
RelaxationTime	**0**
StagePosition	
Use Piezo Stage	**False**
Output	

(Name)
Please specify the identifier of the activity. It has to be unique in the workflow.

The recipe designer contains 3 primary areas for editing recipes: (A) shows a recipe being created which is done by dragging activities shown in (B). The pane shown in (C) allows for editing parameters relevant to the activities.

Geometric View



Activity

(Name)	LoadImage
Description	Load an image from file (.bmp, .jpeg, .tiff, or .tiff) or
Enabled	True
Type	LoadImageActivity

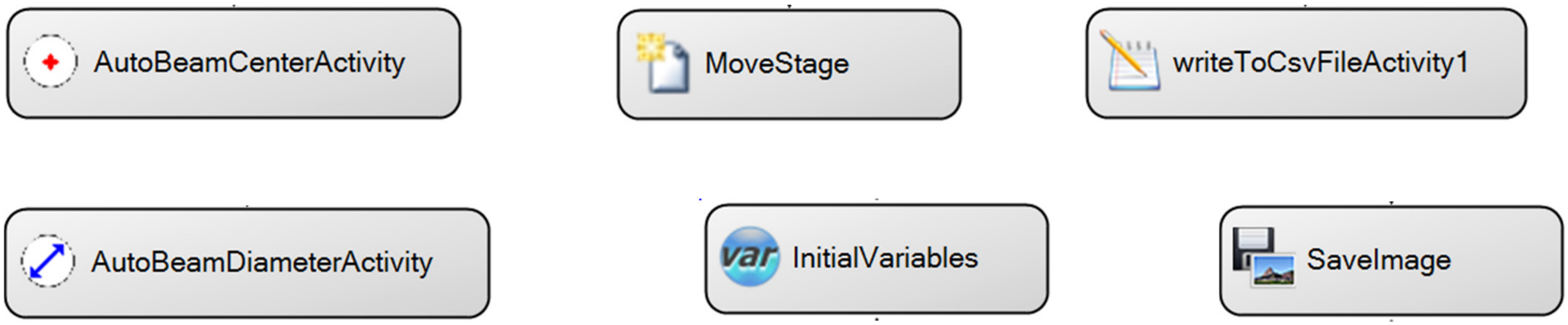
Settings

File Name	C:\Users\mwilliam\Desktop\Files Needing Analysis\
Pixel Width	43.2 pm

(Name)
Please specify the identifier of the activity. It has to be unique in the workflow.

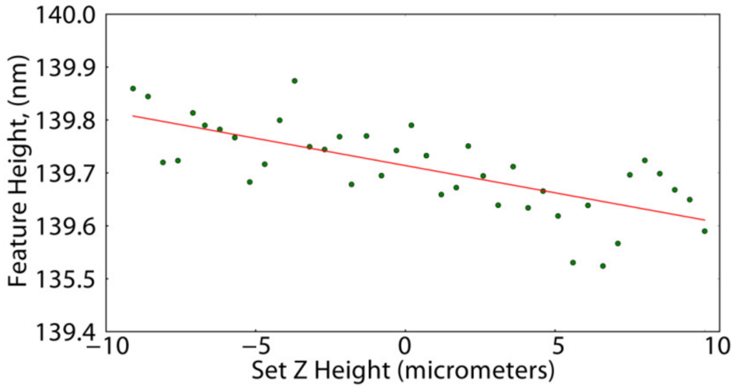
The recipe designer also contains a geometric view with separate windows related to A, B, and C above (A and B not shown). The geometric view allows one to visually place metrology activities on to a relevant image (A). This view also provides the ability to run metrology recipes offline with a rerun images function. In addition to offline metrology this functionality is useful for optimizing metrology recipes.

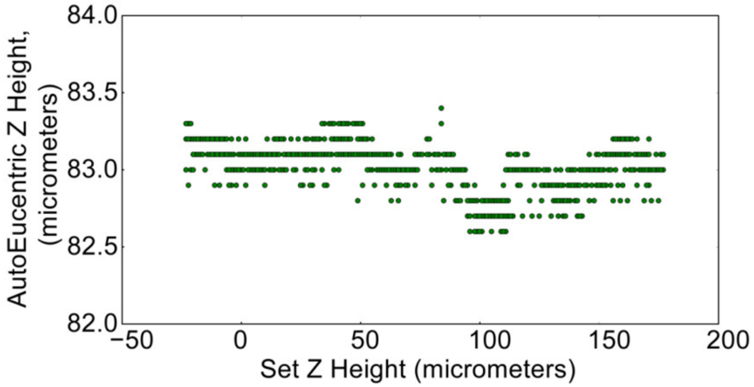
AutoFunctions



In a typical automated workflow many activities are required to record high resolution images for defect inspection or metrology. Currently over 100 functions are available for controlling the microscope, recording images, manipulating images, and performing metrology. A few key functions are shown above while others are described below.

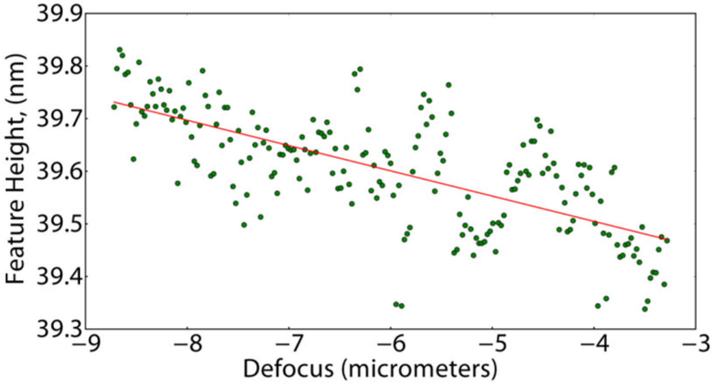
Eucentric Height

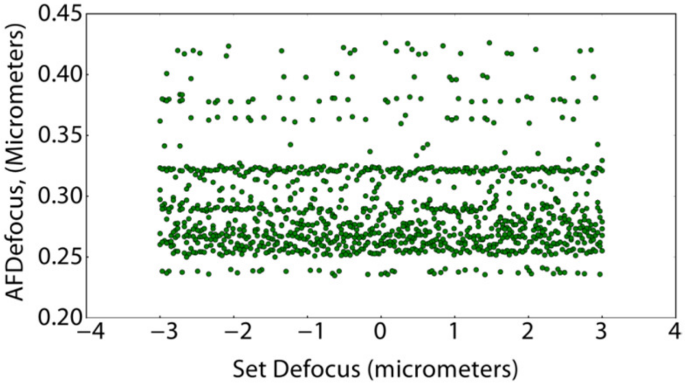




The top figure to the left shows a plot of sample feature height as a function of the Z height of the sample within the microscope for a range of 20 micrometers, (±10 µm from manually determined eucentric height). The feature used was a cross-sectional view of a MetroCal™ wafer, which consists of lines of amorphous silicon ~110 nm in width and ~140 nm in height. The slope of the best fit line to the data is 0.01 nm/µm (0.01nm dimension change per 1 µm Z change) suggesting that a 100 nm deviation in Z-height results in a 0.001 nm change in the metrology. The image on the bottom shows repeatability of the TEM auto eucentric function. The sample Z-height is set to randomly ordered values in a range ± 100 µm from the actual sample eucentric height and the auto function was used to find the eucentric height. The test shown has an average eucentric value of 83 µm over 1350 cycles with a standard deviation of 145 nm. This results in a 3σ value for the repeatability of the autofunction of 435nm which corresponds to a change in metrology measurement of 0.04 nm on the Metrocal height measurement.

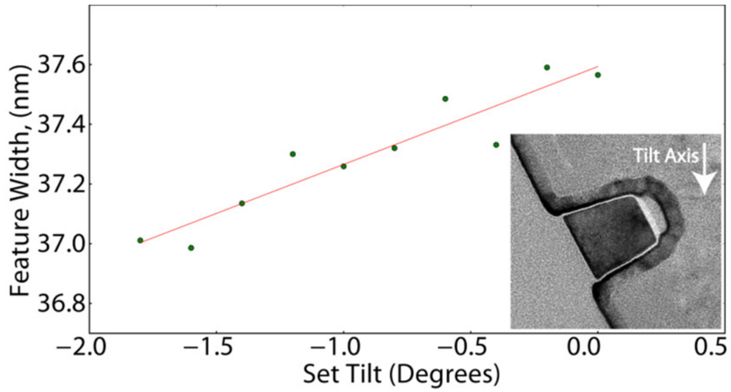
Focus

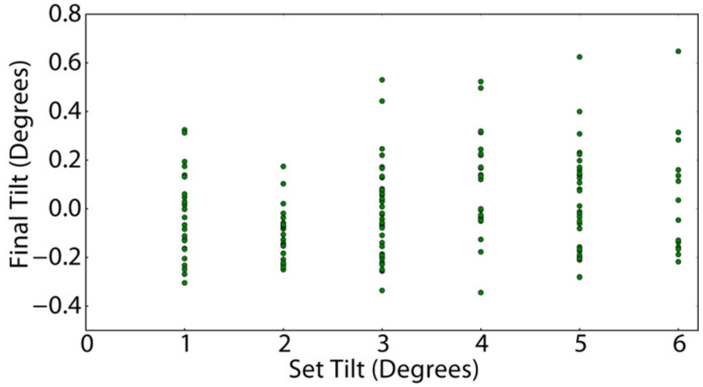




The top figure on the left shows a sensitivity plot for focus. The plot displays feature height in nanometers as a function of defocus in micrometers. The slope of the best fit line is 0.048nm/µm. This results in a possible 0.025 nm measurement change due to a 50 nm change in focus. To determine the repeatability of the TEM auto focus routine a recipe was created in the recipe designer to set the focus value to random values ±3 µm from the manually determined focus value. The figure on the bottom shows results of this test. The test shows an average focus value of 291 nm with a standard deviation of 39 nm, (3σ = 117 nm).

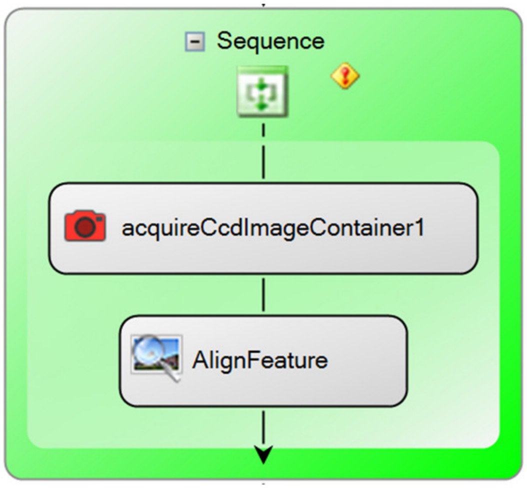
Zone Axis

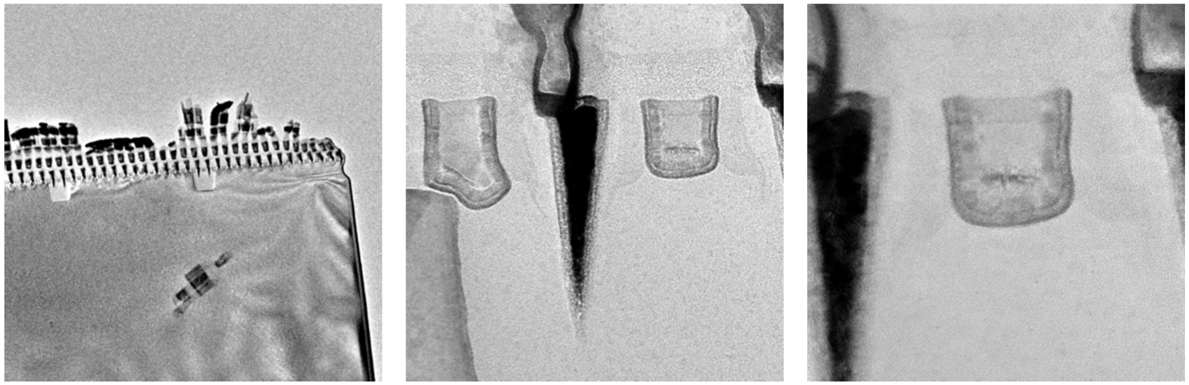




Sensitivity of the AutoZoneAxis autofunction is shown in the figure on the right above. This plot shows the feature width measurement as a function of sample tilt. The best fit line to the data shows a slope of 0.33 nm/degree tilt. The repeatability and accuracy of the AutoZoneAxis autofunction was tested by applying a tilt offset from the manually found zone axis, running the AutoZoneAxis autofunction, and comparing the found tilt of the autofunction to the true zone axis, (right figure). The tilt offsets applied were in one degree steps in the range of one to six degrees total offset. The robustness of the AutoZoneAxis autofunction was 94% over 177 runs. After removal of the failed runs, the average found tilt was 0.4° from the manually found zone axis. The 3σ standard deviation of the autofunction results was 0.6°.

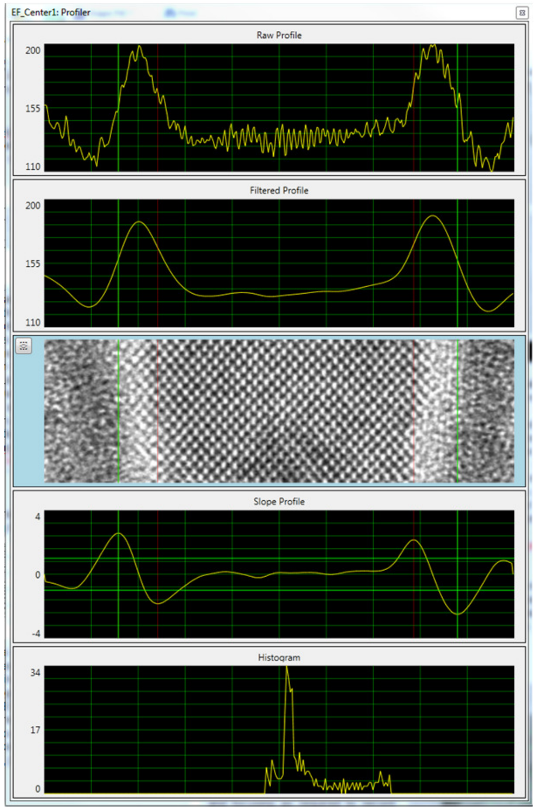
Aligning Features





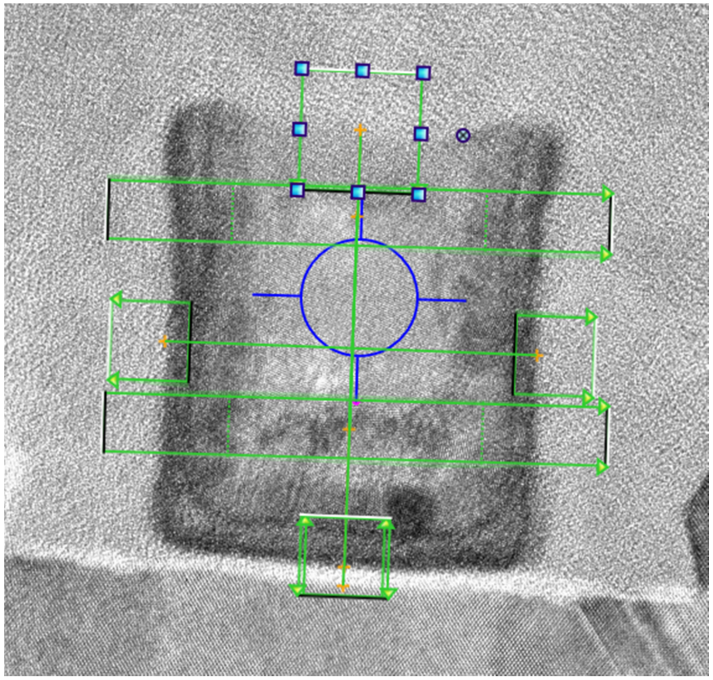
Feature alignment and tracking is very important in automated microscopy. It is often necessary to identify a feature and track it through increasing magnifications. This is accomplished by providing training images for the software to match features in real time in the process flow. The sequence above shows the microscope starting at a field of view of 4.6 µm magnifying to a field of view of 200 nm and finally 115 nm. At each step the feature is found and aligned. Typically this alignment requires 4 to 7 seconds.

Metrology



Many parameters are available for optimizing metrology recipes. The image on the left shows a profiler associated with a double edge finder. Algorithms are available to determine edge placement based on intensity values or the slopes of those intensity values. It is also possible to adjust the smoothing of the raw profiles and to add weighting to the probable region within the edgefinder where the edge will be found.

Metrology



TEM recipes are being created to understand the dynamic precision of metrology recorded with automated microscope functions and metrology.

The image on the left shows a simple metrology recipe designed to measure the height, width, and bottom oxide thickness of the feature. In each of 8 iterations this recipe ran the stage was reset in X, Y, and Z, followed by finding the feature, running AutoEucentric height and moving through the magnifications and focusing as required to record images similar to those on the right. Over the 8 images 3 sigma values were 0.35, 0.24, and 0.22 nm for the width, height and oxide thickness respectively, (See table below).

	Height	Width	Oxide
Average (nm)	43.0	39.0	01.5
3 Sigma (nm)	0.24	0.35	0.22
3Sig/Avg	0.54%	0.90%	14.8%

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Conclusions

FEI has developed a set of microscope autofunctions and a recipe environment that enables automatic image acquisition and metrology analysis using a TEM. Sensitivity and repeatability data for automated eucentric height, zone axis, and focus demonstrate sub-angstrom effects on metrology for measurements where the associated height, tilt, or focus is within three standard deviations as defined by the repeatability.

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Thank You

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