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National Institute of Standards and Technology
U.S. Department of Commerce

Three-Dimensional SEM Metrology for Nanoelectronics

András E. Vladár and John S. Villarrubia
National Institute of Standards and Technology Gaithersburg, MD 20899, USA
andras@nist.gov

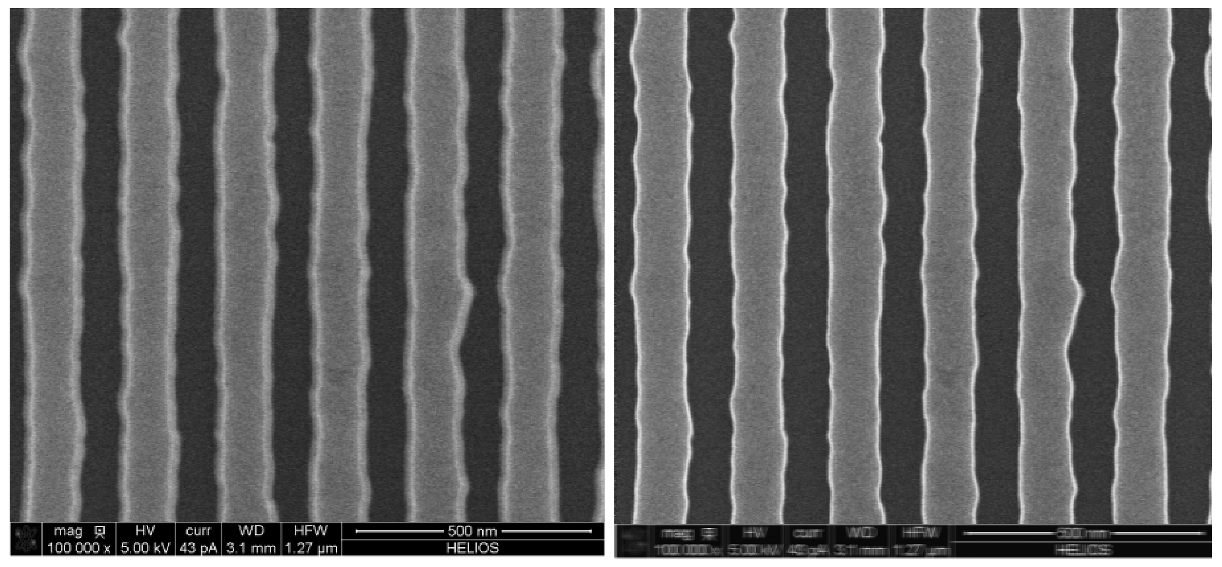
SEM images contain useful 3D information of 10 nm and smaller structures. Model-based interpretation of the image or simple color-coded visualization using image pairs could reveal this 3D information otherwise not recognizable for human vision and comprehension. Further efforts are needed and some are already underway to explore the possibilities and to find production-worthy solutions. Based on the results of the current work at NIST, it likely that some kind of SEM-based 3D metrology will be possible even for all those structures at the very end of the International Technology Roadmap for Semiconductors (ITRS).

The use of mostly arbitrary edge algorithms leads to unpredictable biases, partly due to the neglect of the 3rd dimension, i.e., the shape of the structures[1,2]. Carefully optimized SEM measurements combined with matching the measured images with model-based library results have proven to provide excellent results. The shape cross section determined by this method was compared to transmission electron microscopy (TEM) and critical dimension small angle x-ray scattering (CD-SAXS) measure-ments of the sample with good agreement within a few atoms-worth of exactness[3,4].

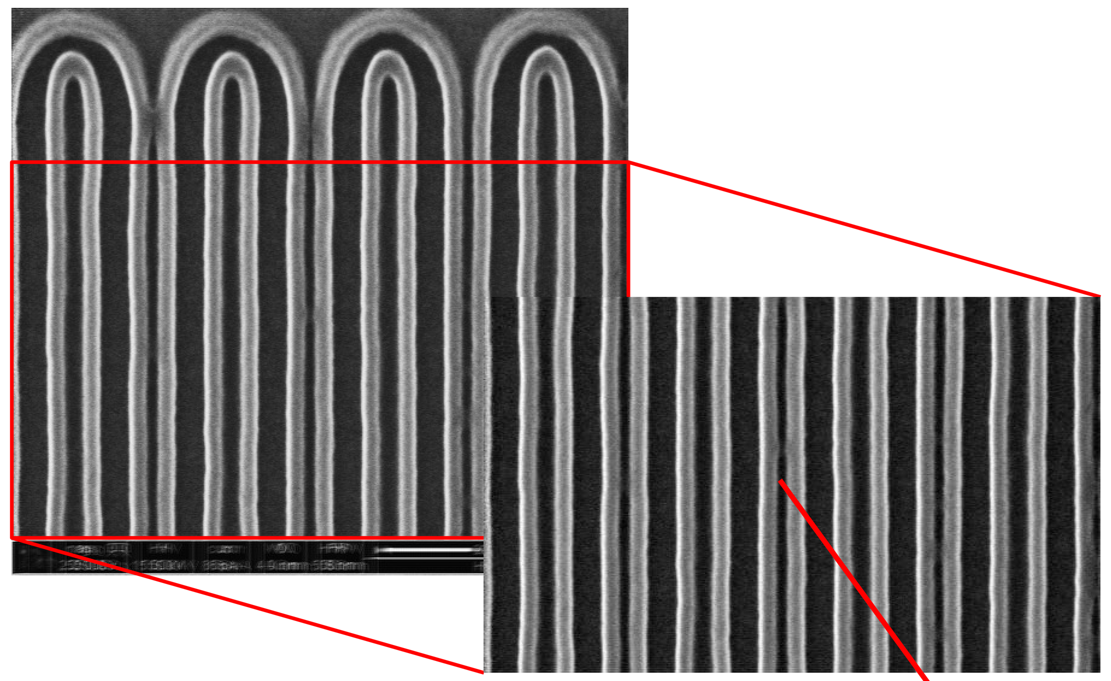
The SEM image contains information related to the 3D shape of the structures, and with suitable, physics-based model, it is possible to find the shape using a single, top-down-view image.

The future of 3D CD metrology is bright and it depends on us to make it as good as it can and must be. Further improvements in size and shape determination in this study are still possible, but likely the values and information reported here are already useful for process development and control.

Drift-Compensated Image Acquisition



The traditional fast imaging results in blurry images (left) The NIST 2D Fourier-transform-based image acquisition method compensates for drift and provides more accurate image (right).



Over 200 fast-scan 512 pixel by 480 pixel, 100 ns dwell time images are added together (averaged) using 2D Fourier transform to compensate for drifts. The resulting raw images were used as input for the model-based 3D evaluation of the lines. Quadruple exposure "fin-FET" structures of approximately 10 nm wide lines (Intel).

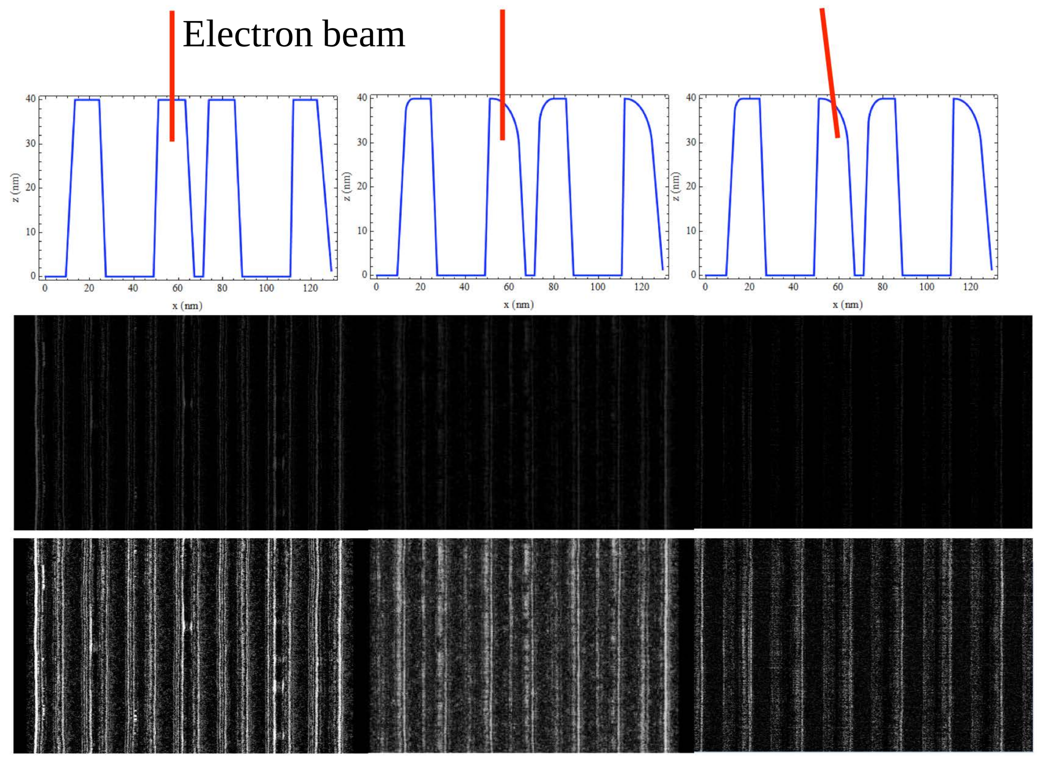
Physics-based Model for 3D Shape

The NIST JMONSEL Monte Carlo modeling software generated a large library of possible video waveforms belonging to a large variety of shapes, which is used to find the best fit, and determine the 3D shape and size of the sample at the nanometer scale.

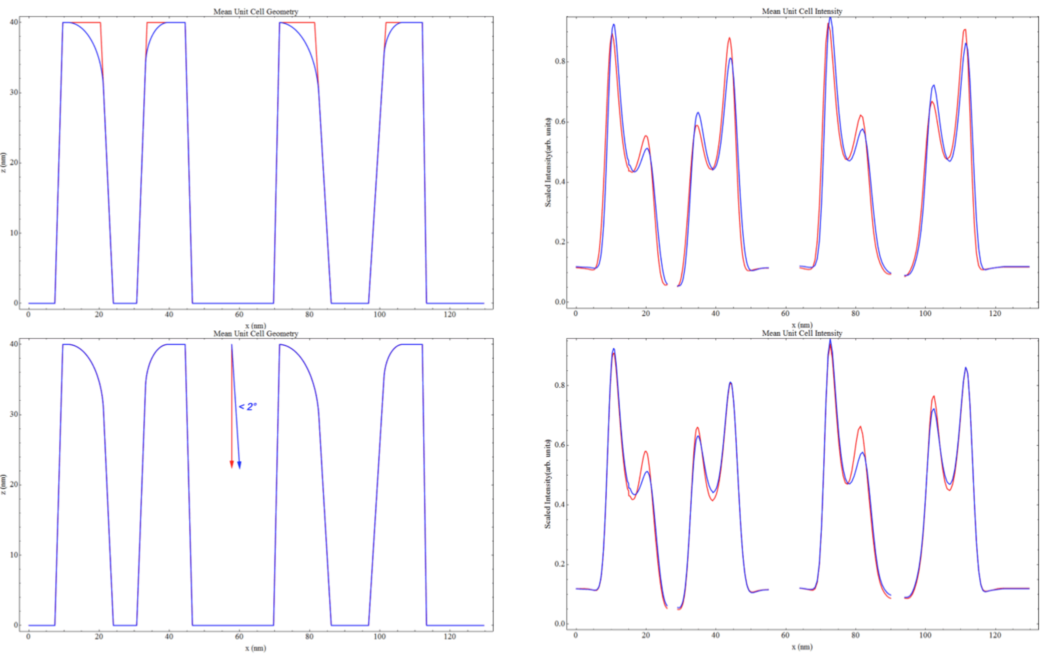
The quality of the library depends on the accuracy of the input data about the composition, thickness, (high energy n&k values), etc. of the sample.

The generation of the library is time-consuming, similarly to the case of scatterometry. Work is underway to speed it up significantly.

Finding the Best Fit of the 3D Shape

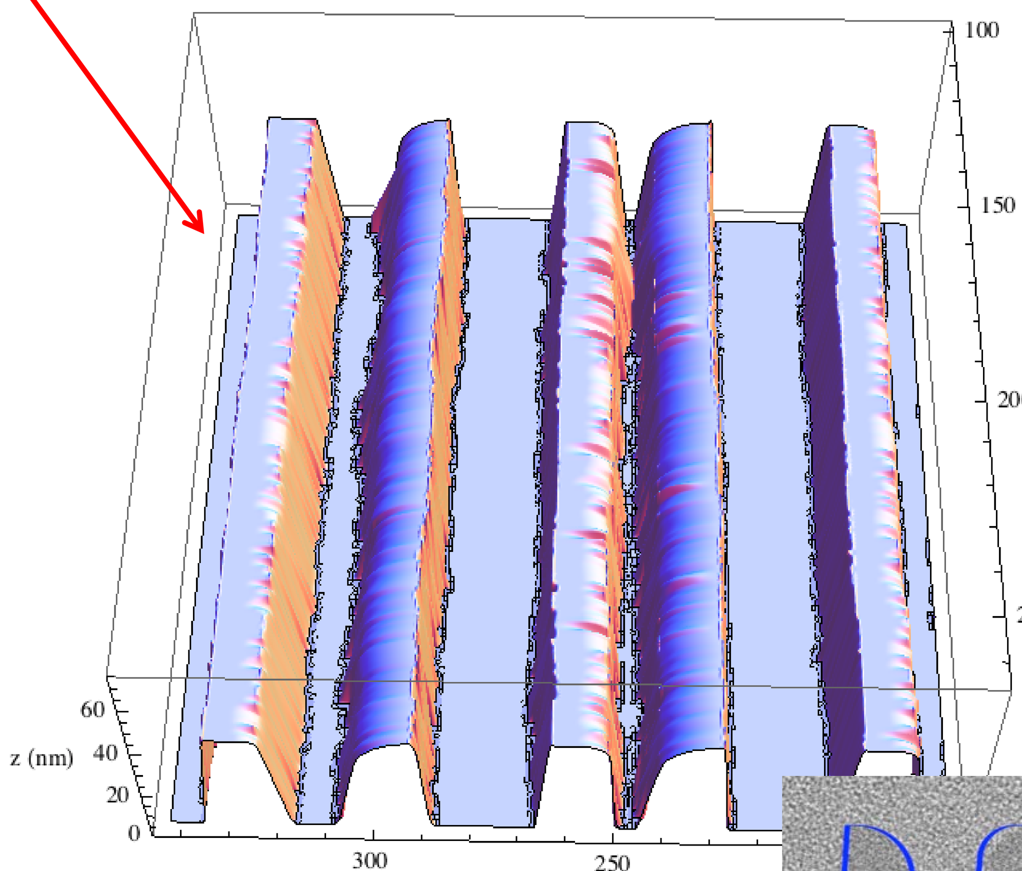


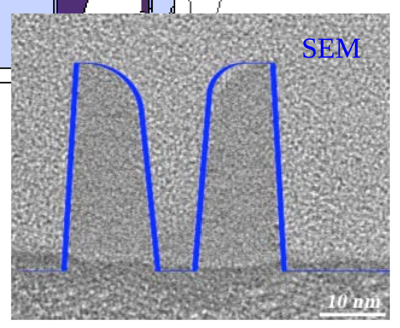
The various shape approximations and their results. The left, middle and right shows these for trapezoidal, "shark fin" and "shark fin" with "stray tilt" respectively at the top, and their corresponding actual differences (at the center) and the differences amplified to show the residues clearer (at the bottom)



The relationship among of the shape and their corresponding waveforms (top); the difference between the waveforms with and without tilted primary electron beam (bottom)

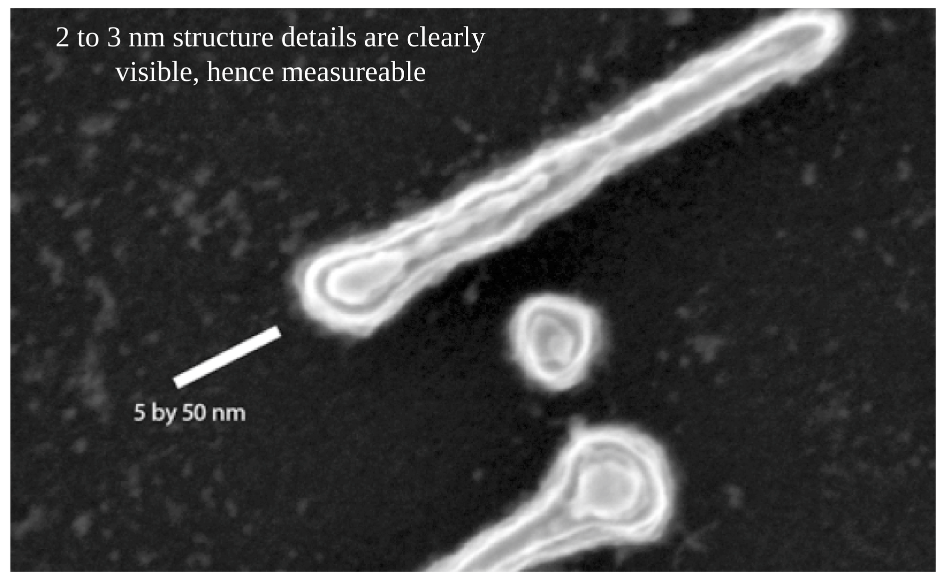
10 nm 3D SEM Measurement Results



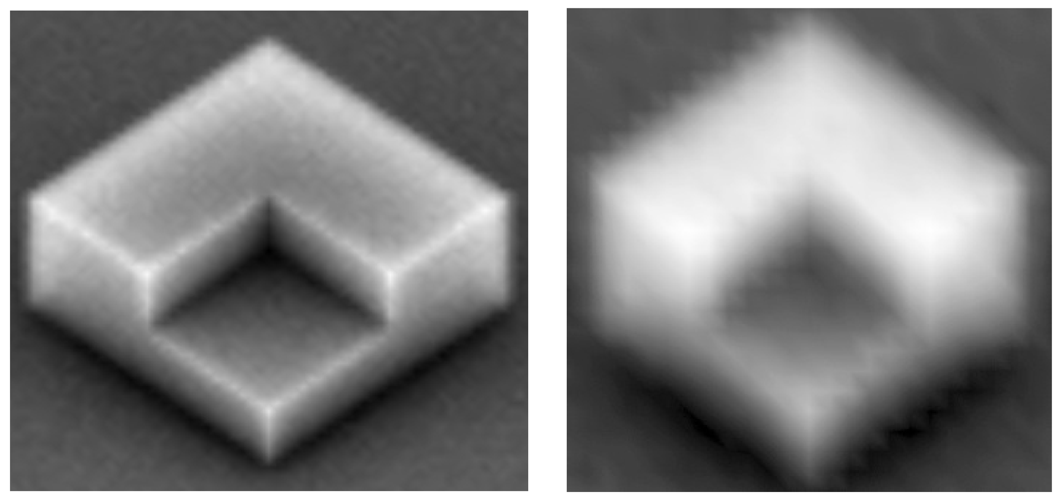


An area rendered into a 3D plot by the NIST model-based measurement method, note the fine details. The average cross sectional shape by the SEM measurement is in good agreement with TEM image (Intel).

3D SEM Measurement of Sub-10 nm Structures

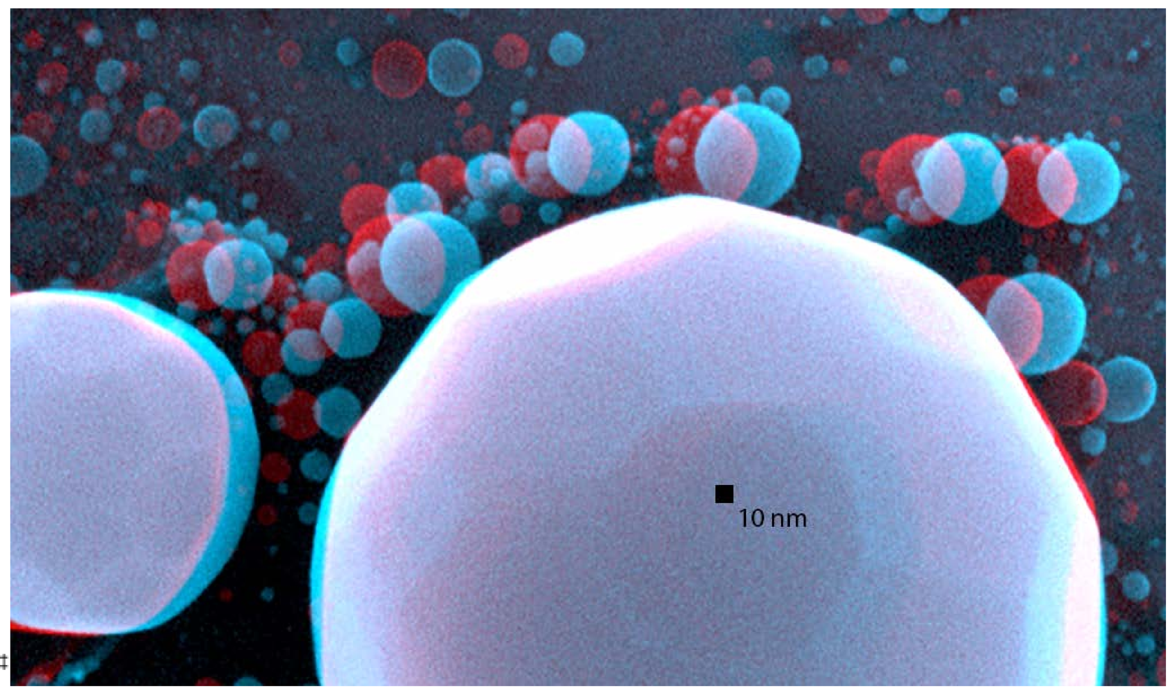


Even top-down images reveal a tremendous amount of 3D information. Here 3D structure is clearly visible, so is the residue on the surface. Top-down view of a resist sample of intentional defect arrays



3D simulation of complex structures for the assessment of likely SEM images. Note the meaningful 2D and 3D edge effects, the lower secondary electron yield at the inner corner and at the edges sitting on the substrate. 1 keV landing energy, 40 nm wide, 20 nm tall, 0.5 nm beam spot size (left) and 6 nm wide, 3 nm tall, 0.3 nm beam (right) structures

3D SEM Measurement of Complex Structures



3D SEM measurements of complex structures is possible by acquiring two or more images from different viewpoints, and by using a suitable rendering software

Model-based SEM measurements are useful for process development and control on 10 nm and 7 nm size IC structures. For smaller size 3D SEM measurements sharper beam, laser-interferometry sample stage in the acquisition of the images, and further advancements in the accuracy of modeling and simulation are needed.

1. J. S. Villarrubia et al., Simulation Study of Repeatability and Bias in the CD-SEM, J. Microlith., Microfab., Microsyst. 4(3) (2005)
2. A. E. Vladár et al., Can we get 3D-CD metrology right? Proc. of SPIE Metrology, Inspection, and Process Control for Microlithography Vol. 8324 832402-1 (2012)
3. A. E. Vladár et al., 10 nm Three-dimensional CD-SEM Metrology, Proc. of SPIE Metrology, Inspection, and Process Control for Microlithography Vol. 9050 90500A-1 (2014)
4. J. S. Villarrubia et al., Scanning electron microscope measurement of width and shape of 10 nm patterned lines using a JMONSEL-modeled library, Ultramicroscopy (2015)

*Certain commercial equipment is identified here to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.