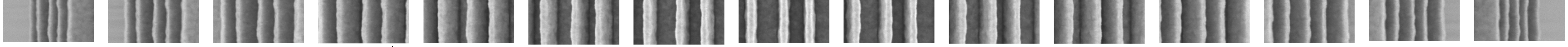

Assessing Scanning Electron Microscopy Stereophotogrammetry Algorithms with Virtual Test Samples

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Overview

The problem:

Non-planar electronic devices have functional dependence on vertical device dimensions in addition to the already existing dependence on in-plane dimensions.

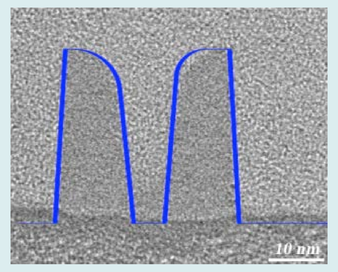
3-D shapes may in principle be reconstructed from multiple images acquired from different viewpoints. Such reconstructions have been done from photographs or other optical images for decades. Commercial software to do the reconstruction is readily available in both paid and free versions. (See, e.g., the Wikipedia article on “Comparison of photogrammetry software.”)

Since SEMs have spatial resolution near 1 nm, it is natural to ask whether SEM-based stereophotogrammetry methods are accurate enough for our 3-D metrology needs. In fact, there already exist software packages intended for SEM stereophotogrammetry. But how should we regard these? Are they merely a way to produce visually pleasing 3-D renderings? Or are they accurate enough to be used for quantitative metrology? Should software developers wish to improve the software for quantitative use, how are even they to know whether their efforts are successful?

What we did:

Test problems are required. These are data sets for which we have all the necessary inputs (e.g., SEM images at known angles) and for which the right answer (the true shape and dimensions of the imaged object) is known. Then we or the software developer can provide the inputs to the photogrammetry software, obtain its reconstruction, and compare it to the known correct answer.

In our approach, the known correct answer is a “virtual sample” a mathematical object in which the position of any point on the boundary can be determined from its definition. We “image” this object at different angles using our JMONSEL SEM simulator. The simulator employs models of electron elastic scattering, secondary electron generation, and scattering at boundaries to compute electron yield vs. position, capabilities that have been used for model-based metrology that agrees with transmission electron microscopy and critical dimensions small angle x-ray scattering measurements to better than 1 nm.



JMONSEL-reconstructed profile (blue) overlaid on TEM profile. [J. S. Villarrubia et al., “Scanning electron microscope measurement of width and shape of 10 nm patterned lines using a JMONSEL-modeled library,” *Ultramicroscopy* **154**, 15-28 (2015)]

For this work we constructed test data sets for 3 virtual samples. All were lines on a substrate. Two were smooth linear forms about which we wrapped a rough skin, with RMS roughness = 1 nm, mean excursion = 0 nm, and correlation length = 15 nm or 30 nm. On the third, surfaces were smooth apart from hemispherical bumps that we placed on line tops, line sides, or substrate. (See details and images at the right.)

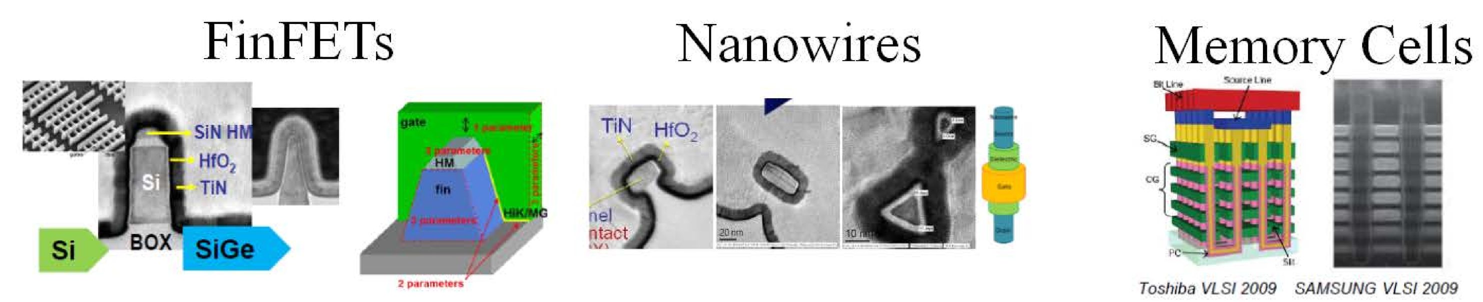
We tested 3 different purchased photogrammetry software packages. The packages take two or three images along with the sample tilt angles as input and they output a 3-D reconstruction. When successful, we generated two such reconstructions for each package, one with a set of images at positive tilts to produce a reconstruction of the right side of the line(s) and a second set at negative tilts to produce a reconstruction of the left side. Some regions, such as the line tops and part of the substrate, were visible in both reconstructions. These were used to stitch the reconstructions together, giving a single combined 3-D model with few hidden parts.

Conclusions:

Detailed results are shown at the right. Conclusions from these:

- Nanometer-scale errors for mean height and width were obtained only for the most densely (and atypically highly) textured sample.
- This is a reflection of the current state of the tested software but likely *not* an inherent limitation of stereophotogrammetry. (We were in some cases able to do better than the software with manual reconstructions.)
- Data sets based on virtual samples are useful for discovering weaknesses in 3-D reconstruction algorithms and should be valuable tools for software developers.

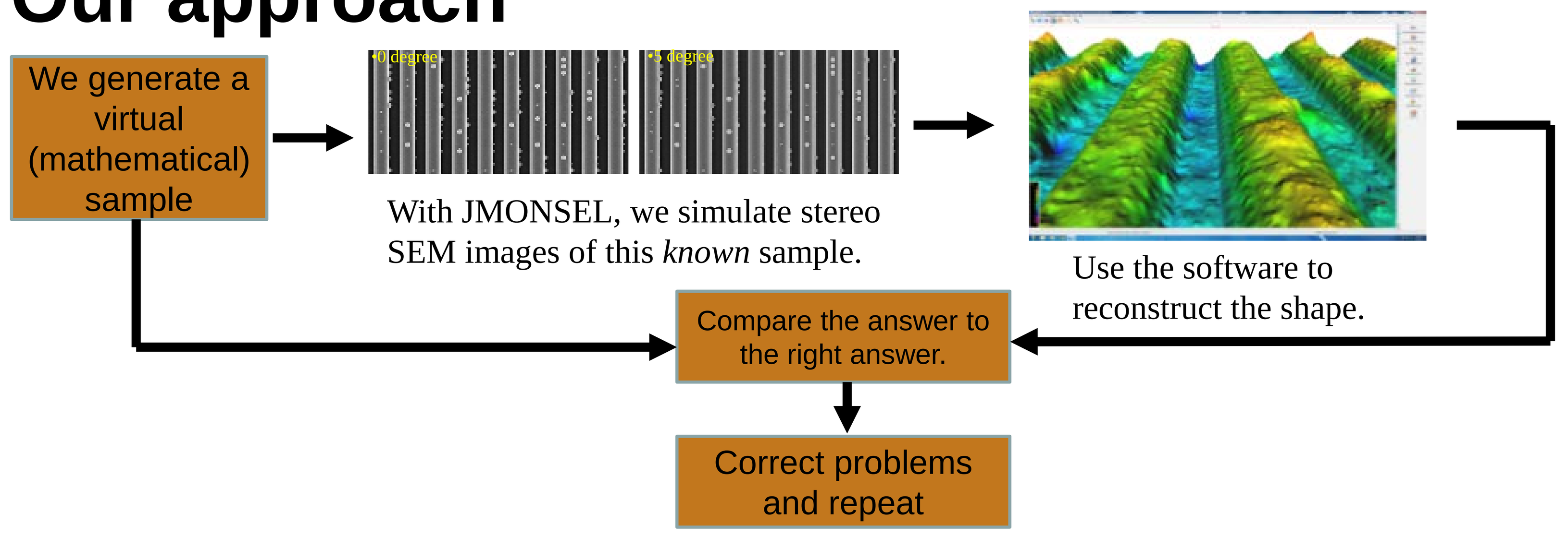
3-D Measurement problem



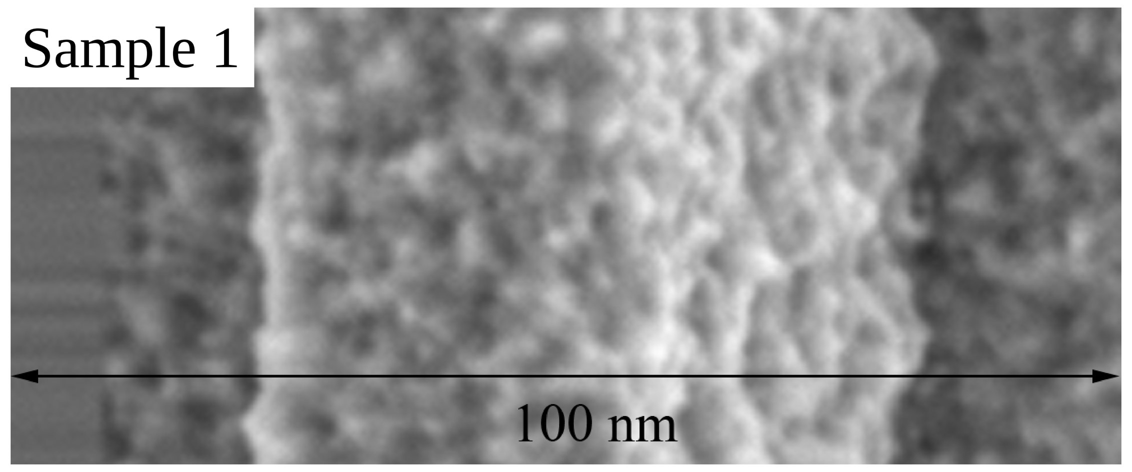
Images from Bunday et al., “Metrology Capabilities & Needs for 7 nm and 5 nm Logic Nodes, presentation at SPIE Adv. Lithography, San Jose, CA 2017

Logic and memory components are 3-D with sizes at the few-nanometer scale. Critical dimensions include some in the vertical direction. The scanning electron microscope (SEM) has enough resolution, but the images have only two spatial dimensions. How to get 3-D information? One possibility is 3-D reconstruction from multiple views at different angles: stereophotogrammetry. There is even already software to do such reconstruction, some for purchase and even some for free—and some explicitly for use with SEM images. But is it any good? How are even developers to know, unless they have test problems for which the right answer is known? We can do that! Here’s how it works:

Our approach



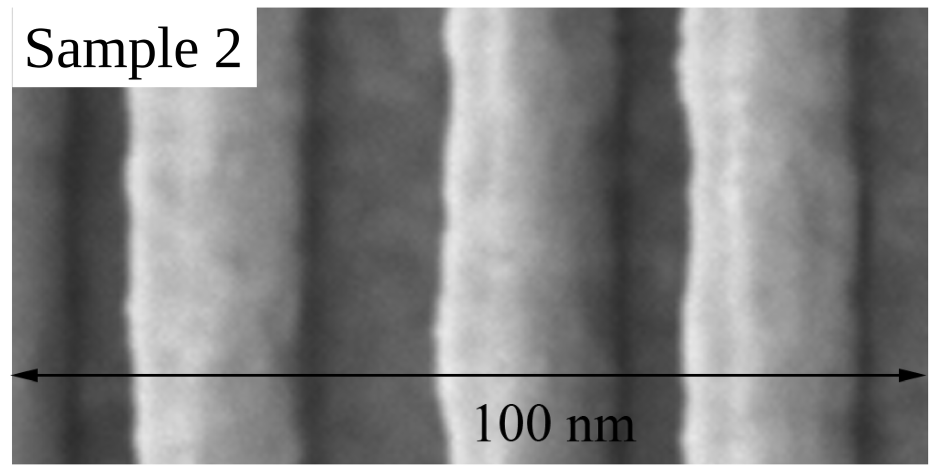
Our virtual samples



Sample 1 is 80 nm high, 50 nm wide at mid-height, with sidewalls 3° from the vertical and 10 nm top corner radii wrapped with 1 nm RMS roughness with 15 nm correlation length.

Advantage: The size and isolation of the line and the high spatial frequency of the roughness should make this a relatively easy reconstruction problem. Each pixel is in a unique neighborhood.

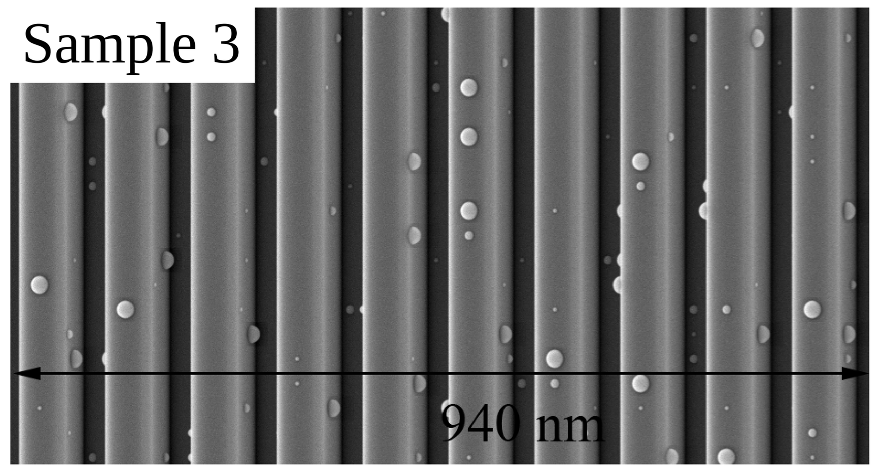
Disadvantage: This feature is unrealistically large and rough.



Sample 2 is an intermediately rough sample: 30 nm high, 10 nm wide at mid-height, sidewalls 2° from vertical and 2 nm top corner radii, wrapped with 1 nm RMS roughness with 30 nm correlation length.

Advantage: The dimensions, roughness, and presence of neighboring lines is more representative of fin-like structures in modern electronics.

Disadvantage: Though pixel neighborhoods remain in principle unique, the longer correlation length makes it more difficult to match homologous points. Presence of neighboring lines limits the range of angles useful for reconstruction.

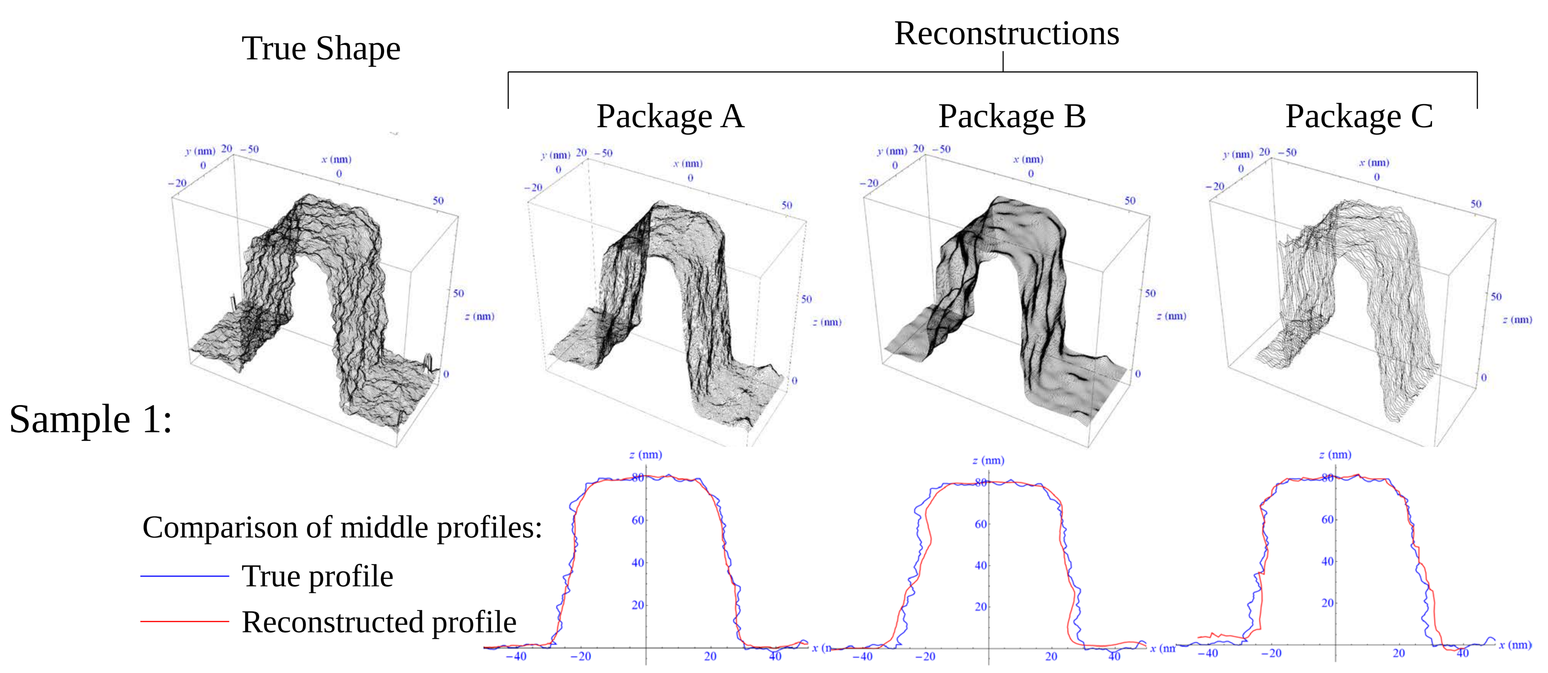


Sample 3: Smooth lines, hemispherical bumps on tops, valleys, and sides. Lines are 60 nm high, 60 nm wide at mid-height, with sidewalls 3° from vertical and 10 nm top corner radii.

Advantage of this shape: Relatively short simulation time constructs building blocks that can be tiled to make large images with random patterns. The hemispheres provide homologous point identification with excellent signal-to-noise.

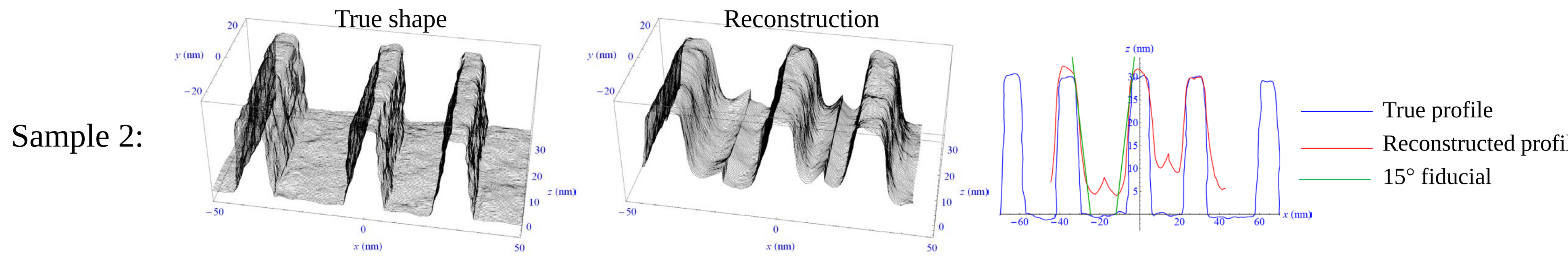
Disadvantage: Surfaces between hemispheres are smooth, so identifiable homologous points are sparse.

Performance of photogrammetry software on our virtual samples

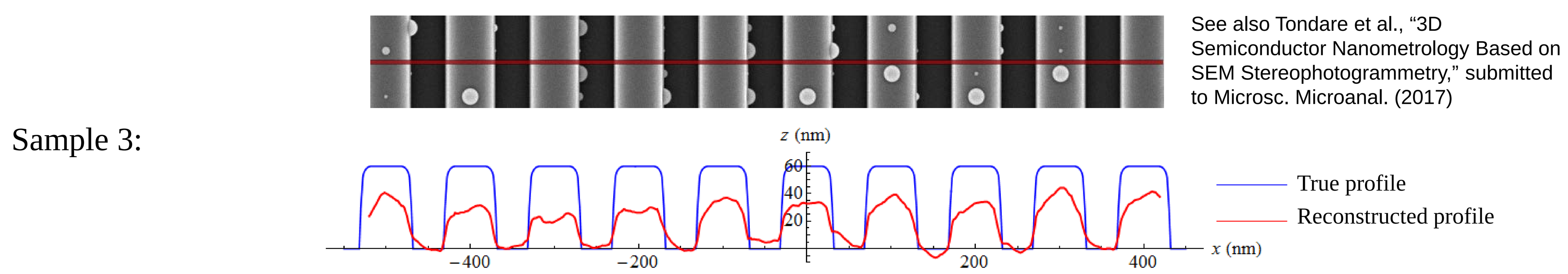


All 3 software packages produced reconstructions for Sample #1. Results are shown above, 3-D renderings in the upper row and comparison of profiles in the lower one. Mean widths and heights and their errors are below:

	width (nm)	w Error (nm)	height (nm)	h Error (nm)
True	49.5	0.0	79.7	0.0
Package A	48.2	-1.3	79.3	-0.4
Package B	46.8	-2.8	79.6	-0.1
Package C	49.4	-0.1	80.0	0.2



See also Tondare et al., “3D Semiconductor Nanometrology Based on SEM Stereophotogrammetry,” submitted to Microsc. Microanal. (2017)



Package A produced the above reconstructions for Sample 2 and Sample 3. The heights and widths have large errors. The other packages were worse, often producing results not even qualitatively recognizable as lines on a substrate. A likely issue is insufficient density of homologous pairs (in Sample 3) or insufficient contrast to identify them (in Sample 2), yet in this respect these virtual samples are similar to what is expected in real measurement problems.