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1.5 nm fabrication of test patterns for characterization of metrological systems

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ABSTRACT

The semiconductor industry is moving toward a half-pitch of 7 nm. The required metrology equipment should be one order of magnitude more accurate than that. Any metrology tool is only as good as it is calibrated. The characterization of metrology systems requires test patterns that are one order of magnitude smaller than the measured features. The test sample was designed in such a way that the distribution of linewidths appears to be random at any location and any magnification. The power spectral density of such pseudo-random test pattern is inherently flat, down to the minimum size of lines. Metrology systems add a cut-off of the spectra at high frequencies; the shape of the cut-off characterizes the system in its entire dynamic range. This method is widely used in optics, and has allowed optical systems to be perfected down to their diffraction limit. There were attempts to use the spectral method to characterize nanometrology systems such as SEMs, but the absence of natural samples with known spatial frequencies was a common problem. Pseudo-random test patterns with linewidths down to 1.5 nm were fabricated. The system characterization includes the imaging of a pseudo-random test sample and image analysis by a developed software to automatically extract the power spectral density and the contrast transfer function of the nano-imaging system.

Keywords: metrology, nanometrology, SEM, CD-SEM, system characterization, pseudo-random, power spectral density, contrast transfer function

1. INTRODUCTION

Any metrology tool is only as good as it is calibrated. The semiconductor industry is moving towards the 7 nm integrated circuit processing nodes and below. The dimensional metrology equipment required for these feature sizes should be at least a few times more accurate than that[1-2]. The characterization of metrology systems requires test patterns at a scale about ten times smaller than the measured features. Characterization of electron microscopy and atomic force microscopy imaging systems at the nanoscale is of special interest, and is no easy task. Companies use vague definitions of "resolution" or "beam size" to describe the performance of their systems; definitions vary. These definitions are often biased in a way to show competitive advantage; however, they do not describe the system objectively. NIST suggested to use image sharpness, which is a step forward but still far from comprehensive.

For example, definition of "resolution" is often based on a capability to resolve a single line; without consideration of the contrast of imaging. In this way, a single line can be resolved with a good contrast and contrast-to-noise ratio in a good tool, and with lower contrast in a tool with "not-so-good" performance; however, by reducing brightness and increasing contrast, a similar "resolution" can be demonstrated for a single line, see Figure 1a. The difference in tool performance, however, is significant: a good tool can

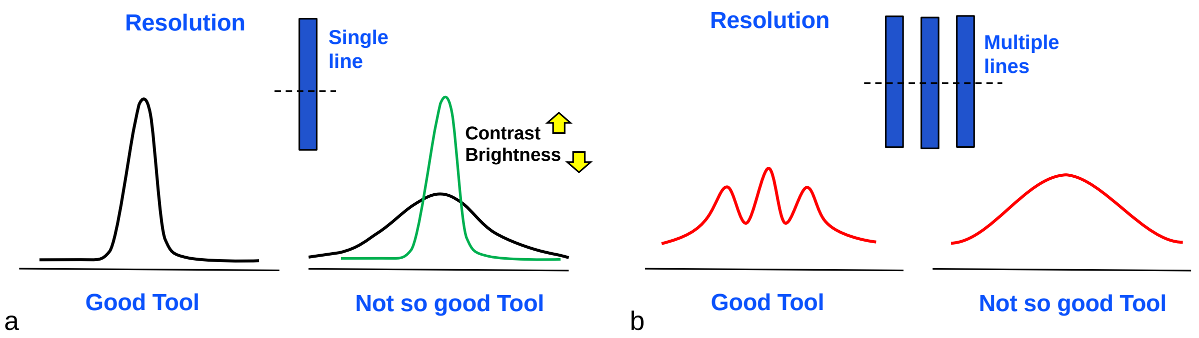

Figure 1. a) Resolution measurement based on a single line is not an objective characterization of a system; b) gratings could be used, but they are not available at any desired pitch.

resolve a grating made of such lines, while the second tool cannot, see Figure 1b. Gratings with any desired pitch at nanoscale are not available for resolution measurements.

Beam size is a more objective characteristic of imaging system, and the metrics of Full Width at Half Magnitude (FWHM) is well established. However, system vendors use company-specific definitions in attempt to compete on the smallest possible number of "beam size" as shown in Figure 2. Performance comparisons between systems becomes difficult. A vendor independent test sample with software called BEAMETR is used to automatically measure beam size; it uses FWHM definition in measurements.[3]

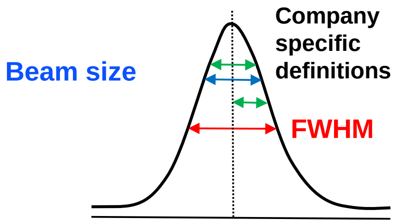

Figure 2. Beam size is more objective characteristic of a system than "resolution". FWHM beam size is a straight forward definition, however, equipment makers often use company specific definitions of the beam size, which makes comparison of systems difficult.

In contrast, visible-light optical instrumentation performance is much better measureable down to the diffraction limit; mainly because performance is measured using a comprehensive characterization metric called the modulation transfer function (MTF) or the contrast transfer function (CTF). As shown in Figure 3, an object with the feature size distribution according to Figure 3.a will have a reduced contrast at smaller dimensions in an imaging system, see Figure 3.b; this loss of contrast is described by the CTF shown in Figure 1.c. CTF describes system performance objectively and also characterizes the system throughout its entire range of spatial frequencies.[4,5]

There were attempts to use CTF to characterize nano-metrology systems such as scanning electron microscope (SEMs),[6] but the lack of suitable samples with known spatial frequencies in the required dimensional range resulted in limited efficacy.

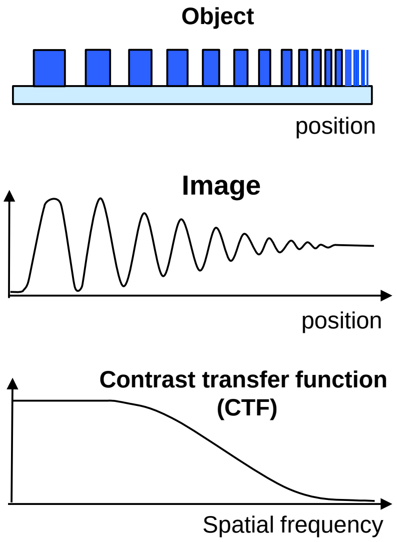

Figure 3. a) An object with variable pitch; b) Its contrast in imaging system depends on feature sizes; c) The loss of contrast as a function of spatial frequency is the contrast transfer function, which characterizes imaging system in its entire dynamic range.

In this paper, we describe the design and the fabrication of "ideal" test samples for the characterization of metrology systems at nanoscale by measurement their contrast transfer function. Test samples with minimum feature sizes down to 1.5 nm were fabricated. The quality of the test samples was investigated using transmission electron microscope (TEM). Images of the test samples were taken with SEM and atomic force microscope (AFM) systems; example of the measured power spectral density (PSD) is presented.

2. PRINCIPLE AND DESIGN OF PSEUDO-RANDOM TEST PATTERN

The ideal pattern to measure CTF is a random pattern having even number of lines with any linewidth; its power spectra is flat. The random pattern is mathematically strongly deterministic. Researchers from Lawrence Berkeley National Laboratory and Brookhaven National Laboratory suggested the use of binary pseudo random arrays to measure CTF of dimensional metrology systems[7]. The power spectral density of an ideal random array is flat, as shown in Figure 4.a. Metrology systems change this PSD to a curve with a resolution-limited cut-off at high frequencies; the deviation from the PSD provided by the random array characterizes the system performance, see Figure 4.b. It describes the loss of system's sensitivity over the full range of feature sizes that are present in a test sample.

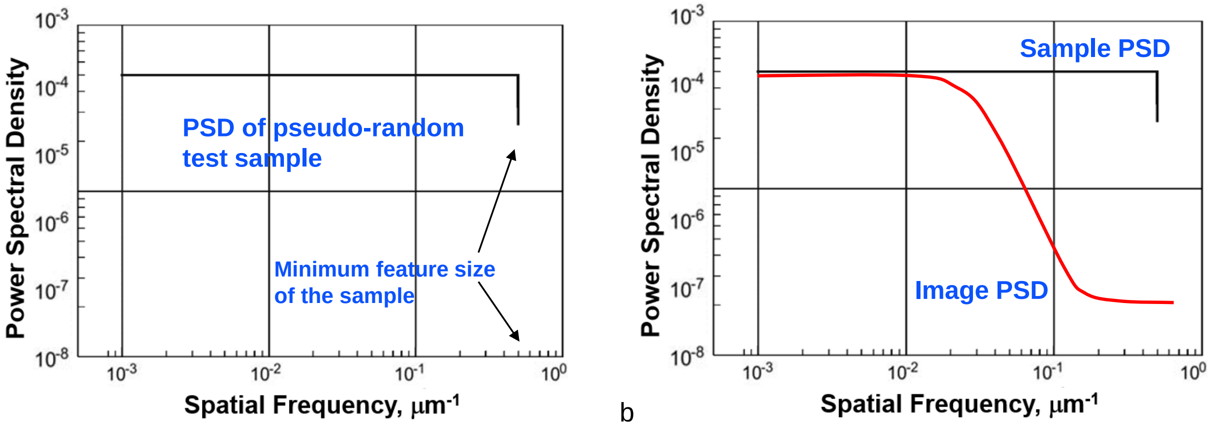

Figure 4. a) Power spectral density of an "ideal" pseudo-random test sample is flat down to the minimum feature sizes of the sample; b) Metrology systems cut-off PSD at high frequencies; the difference of PSDs characterizes the system performance.

One-dimensional and two-dimensional pseudo-random test patterns have been designed. They involve lines with assigned linewidths at specific positions; the number of lines with each linewidth is evenly distributed over the test sample. The distribution of linewidths appears to be random at any location over a wide range of magnifications.[7,8] Parts of the designs are shown in Figure 5, a, b.

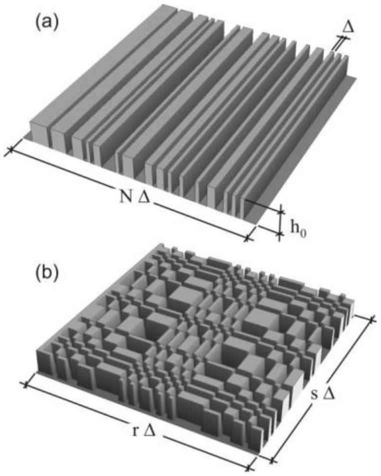

Figure 5. Parts of the designed pseudo-random test samples: a) 1D pseudo-random sample, b) 2D sample.

3. REQUIREMENTS TO THE TEST SAMPLE, ITS FABRICATION AND VERIFICATION

3.1 Requirements to the test sample at nanoscale

The minimum feature size of the pseudo random test sample determines the inherently flat portion of the sample's PSD. For nanometrology systems, the minimum feature size should be as small as possible. The test sample requirements are:

- The best possible resolution, under 2 nm minimum feature size
- Materials should provide good contrast in imaging tools (including electron microscopes)
- Materials should be conductive to avoid charging
- Size: a few micrometers (larger than the field of view)
- Line edge roughness significantly less than line width
- Fabrication technology should be reproducible

Test samples meeting these requirements cannot be fabricated using modern electron-beam lithography techniques. Directed self-assembly, nanoimprint lithography, and helium ion microscopy methods are widely used to fabricate small features, however, they cannot be used for the fabrication of pseudo-random test samples.

3.2 Fabrication

In order to circumvent limitations found with other fabrication techniques, the pseudo-random structure was produced by depositing a multilayer of two alternating materials using magnetron sputter deposition and then sectioning the stack. The sectioned side of the multilayer is used for subsequent metrology instrumentation characterization. In addition to high electrical conductivity, the material and deposition process requirements are:

- Low surface and interfacial mixing roughness
- Significant difference in mass density
- Low stress

The multilayer material system utilized for the sample, silicon and tungsten silicide, have been used extensively for fabrication of other types of thick multilayer structures[9] and the 1.5 nm smallest layer thickness is still significantly larger than the minimum requirement for good layer contrast.

A custom magnetron sputtering system with multiple targets[10] was used for deposition. The targets were 75 mm diameter by 6.25 mm thick disks. The tungsten silicide target was hot-pressed, and the silicon target was boron-doped in order to facilitate DC sputtering. The system was controlled by a computer with the thicknesses of the deposited layers corresponding to the designed values of pseudo-random pattern. 4095 unit layers were deposited to form the multilayer coating with the designed pseudo-randomly distributed thicknesses on a thick, polished silicon wafer.

After that, a focused ion beam (FIB) of a dual beam FEI system was used to remove a vertical slice off the top of the wafer. The slice was platinum-welded by the FIB to a piece of silicon wafer. A SEM image of the welded test sample is shown in Figure 6. The sample is comprised of alternating lines, each according to its designed linewidth. A part of the silicon wafer is also seen on the left. The selected materials exhibited good contrast in the image set. The total size of the test sample was approximately 8 micrometers by 6 micrometers.

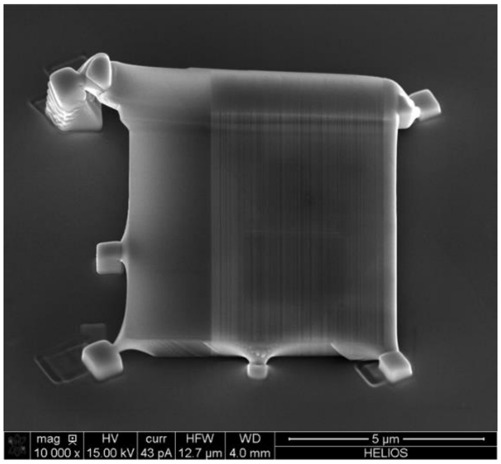

Figure 6. Fabricated pseudo-random test sample with 1.5 nm minimum feature size was welded to a silicon wafer.

3.2 TEM verification of sample quality

The lamellae of the test samples were imaged using TEM. TEM images of the test sample at two magnifications are shown in Figure 7. The scale bars are 100 nm in the Figure 7,a and 50 nm in Figure 7,b. Lines with minimum feature sizes are present; their contrast is lower than the contrast of “large” lines of about 7 nm.

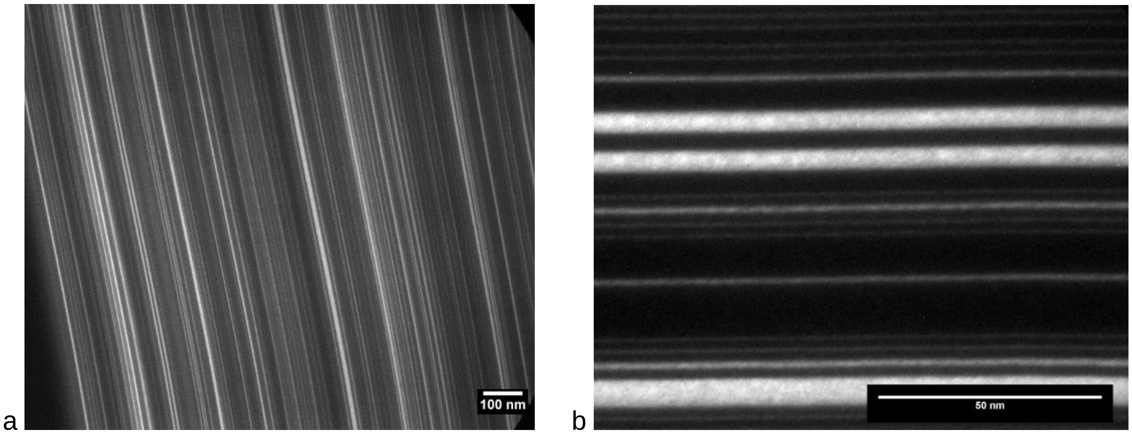

Fig. 7. TEM images of the lamella at various magnifications.
The mark on the image (a) is 100 nm, the mark on (b) is 50 nm.

In order to see the sample at a sufficient spatial resolution but span the entire length, multiple TEM images were taken across the lamellae and then stitched. A part of the images overlapping region over roughly one micrometer are shown in Figure 8.

The stitched images were overlapped with the design as shown in Figure 8,a. The design is shown in the background at the top and bottom of TEM images. By a detailed visual inspection, it was confirmed that all lines are present in the test sample according to the design. In Figure 8,b stitched TEM images over the entire length of the test sample is shown.

TEM images at high magnification confirmed that there is no intermixing of layers at their boundaries that would effect measurements.

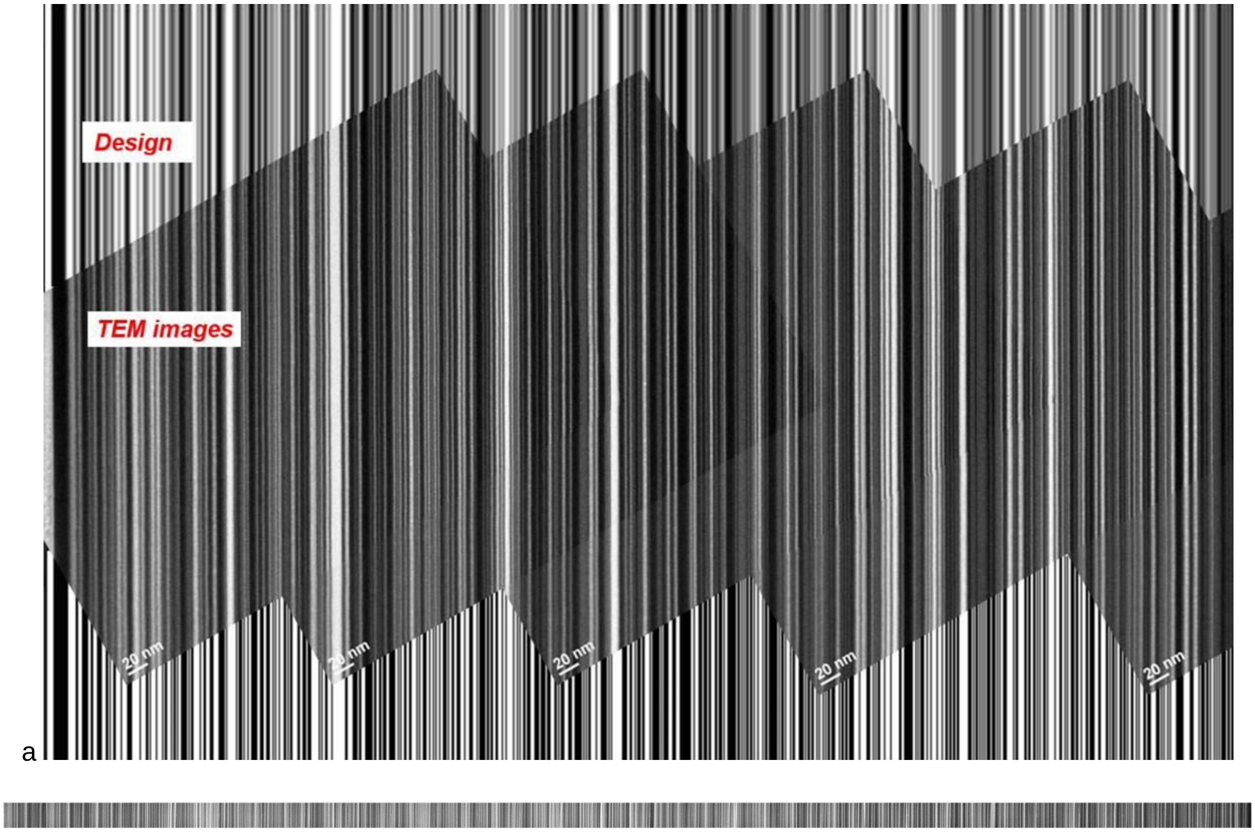

Fig. 8. a) Stitched TEM images overlapping the design of the pseudo-random test sample. A good correspondence and a low defect density were confirmed. The mark on the TEM images is 20 nm, the length of the displayed area is about 1 micrometer; b) stitched TEM images over the entire length of the test sample.

As can be seen on Figures 7 and 8, the high quality of the test sample is evidenced by all lines being present according to the design and the absence of defects. Multiple test samples were fabricated; the fabrication process resulted in a 100% yield.

4. SPECTRAL MEASUREMENTS USIGN FABRICATED TEST SAMPLES

Multiple imaging tools were used to image pseudo-random test samples: SEM, AFM, and a soft x-ray microscope. Similar samples with scaled up designs were also fabricated; they are used for optical interferometers, confocal microscopes and optical microscopes. Fabrication of scaled up test samples involved electron beam lithography and nanoimprint lithography.

AFM images of the pseudo-random test sample were taken using phase contrast with an Asylum AFM, seen in Figure 9. The material contrast is not high but well visible.

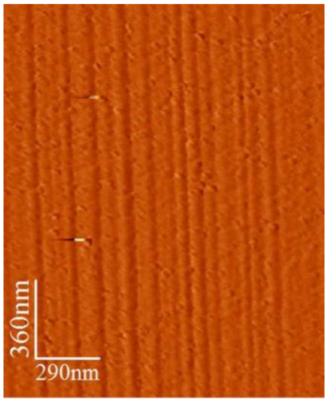

Fig. 9. AFM image of the test sample over a 0.1 μm^2 area, using phase contrast.

Images were taken using a FEI Helios SEM at various electron energies. Images taken at 15 kV and 5 kV are shown in Figure 10.

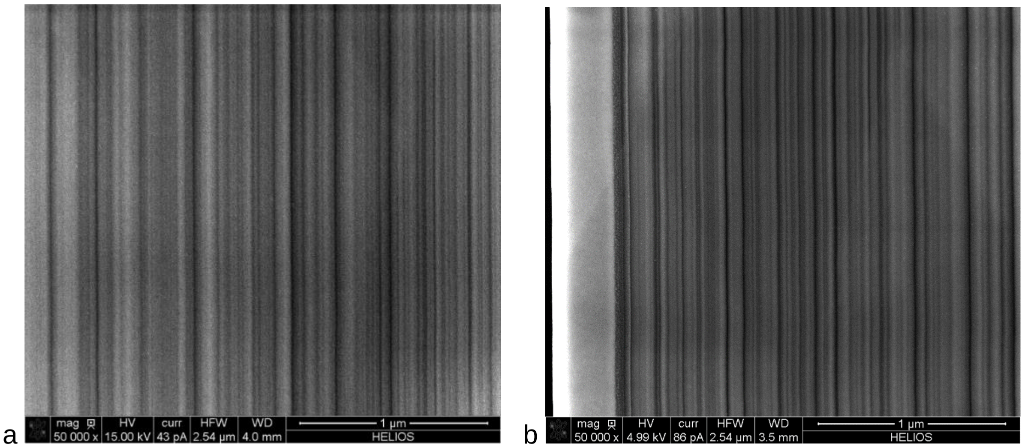

Figure 10. SEM images of the test sample taken at a) 15 kV electron energy; b) 5 kV electrons.

A software called P-Spectra (Power Spectra) has been developed to automatically measure power spectral density of the image and extract contrast transfer function of the imaging tool. The software takes into account field distortions and corrects for them before extracting PSDs. The PSD of image noise is measured separately and is deducted from the PSD of image in order to extract system PSD. The software also compares PSD of the image with the PSD of the design for this same specific area of the test sample in order to highly reduce the statistical noise. As a result, a PSD and CTF of the system are extracted. In Figure 11, an example of a PSD is displayed for the SEM image shown in Figure 10,a.

It is noteworthy that the statistics of lines in the imaged area may not be perfect – a variation of the PSD at lower frequencies is noticeable on the power spectra. Nevertheless, this statistical problem was corrected: the design of the test pattern is exactly known and, therefore, can be identified in the corresponding imaged area. The PSD of the part of the test sample was calculated and used for the correction of PSD of the system.

In this method, using the pseudo-random test pattern, nano-metrology systems can be characterized over their entire range of spatial frequencies. The evaluation of the power spectra from images produces the CTF of the microscope and reliably describes the loss of contrast as the linewidth decreases.

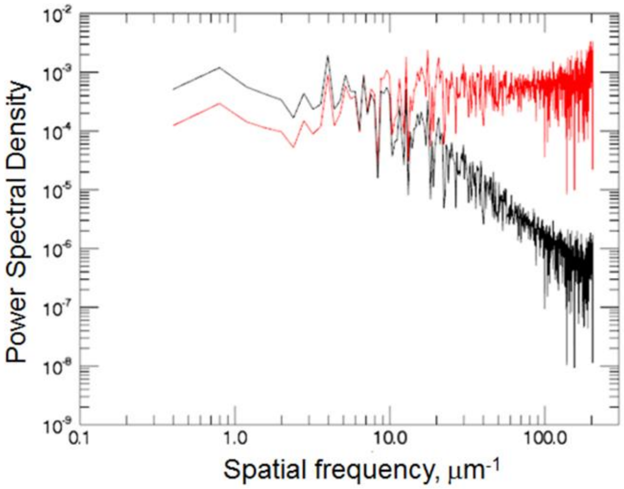

Figure 11. Power spectral density extracted from SEM image; the shape of the curve at high frequencies characterizes the SEM's ability to measure smaller and smaller sample features. Insufficient statistics of specific sample area can be compensated by the knowledge of the designed pattern; the PSD of this same area of the designed pattern is also displayed (top line).

5. CONCLUSION

Comprehensive characterization of imaging systems at nanoscale is possible based on Contrast Transfer Function with pseudo-random test samples. Such samples have been designed and fabricated with the minimum feature size of 1.5 nm. The materials used in fabrication were silicon and tungsten silicide. The resulting test pattern produces alternating lines of these materials with the linewidths corresponding to the design. The fabrication process resulted in good quality with sufficient reproducibility of test patterns; the yield was 100%.

The verification was done using TEM. By overlapping TEM images with the design over the full length of the test pattern, it was confirmed that there were no missing lines or noticeable defects.

The samples were investigated using TEM, AFM and SEM. An example of the extraction of the power spectral density is presented. In the case of insufficient statistics in the imaged area, the advantage of the designed pattern can be used: the corresponding area of the design can be found and its PSD can be used for the correction of the contrast transfer function of the imaging system. A software P-Spectra was developed to automatically extract PSD and CTF of a system under characterization.

6. ACKNOWLEDGEMENTS

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