Description of the program LWR_Demokritos for LWR extraction and characterization

- ## Introduction

The program LWR_Demokritos aims at:

a) The detection of the edges of resist lines by analyzing their top-down SEM images.

b) The characterization of the roughness of the obtained line widths (LWR) providing appropriate parameters and functions.

In this version the signal-threshold algorithm is used to determine the edges of the resist lines from the bright zones of the SEM image (which are produced from the secondary electron emission) and elements of scaling and fractal theory are applied for the quantification and characterization of the extracted LWR.

In order to use the program, first one has to open the input.txt file and determine the needed parameters for the LWR analysis of the images (for instructions see below). Then one can perform the LWR analysis and get the results by running the executable file of the program LWR_Demokritos.exe by double clicking on it.

- ## A short description of the methodology (more details can be found in the papers)

The program is based on a LWR measurement and characterization methodology that has been developed in our Institute. This consists of two steps. First, an image analysis algorithm is applied to the SEM image of the resist lines, so that the coordinates of the edge points can be obtained and the line edges are detected. Each pixel in a given SEM image is characterized by its (x,y) coordinates (in pixels) and an integer in the range (0-255) representing a shade of gray. The basic assumption in the algorithm is that this discrete spectrum of the image gray scale values corresponds to the continuous signal intensity values of the scattered electron beam of SEM. However, real world signals contain noise (usually Gaussian type) and the first task of the algorithm is to reduce it by using a noise-smoothing filter. The parameters involved in this filter (length and width) have to be specified. The smoothed image can be analyzed by using the direct signal or its derivative. We use the direct signal since it has been shown that it gives results closer to those of on-line analysis. After removing the noise, one proceeds to the detection of the edge. In fact, one can obtain three profiles from each edge bright zone in an image: the outer and the inner border of the zone, and the "middle" profile consisting of the pixels of maximum intensity at each row. The outer (inner) border of a particular edge is determined by keeping as an edge point the first pixel along an image pixel row, where the threshold criterion is satisfied, i.e. the normalized intensity becomes greater (smaller) than the specified threshold. The middle profile is obtained when the normalized intensity threshold is taken equal to 1. We prefer to work with the outer or middle edges. Before the statistical analysis and characterization of the edge, a tilt correction is performed. In contrast to the first versions of the software where the borders in the image for the edge detection were given manually, now they are calculated automatically. Thus the process is accelerated and we get the "skeleton" of the image with the detected line edges immediately. After determining the edges of the resist features from the SEM image, the linewidths of the resist lines can be found. Fig. 1 summarizes the main stages of the edge detection algorithm.

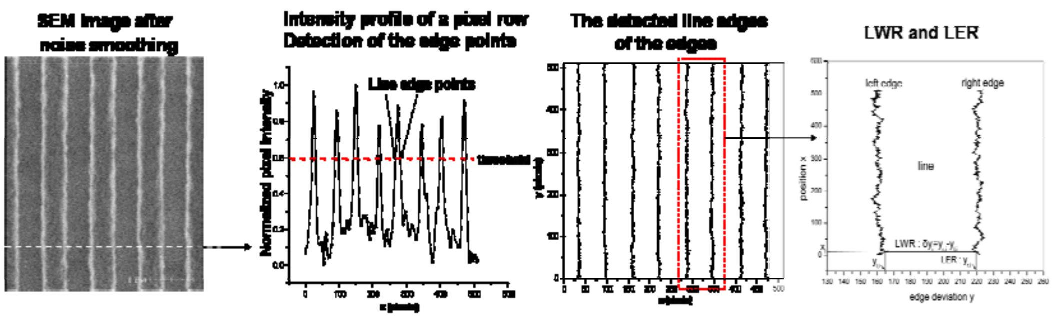

Figure 1

Then the analysis and characterization of the linewidth roughness (LWR) follows. The most widely used parameter for this task is the rms value of the edge points (sigma_LER) or the rms value of the linewidths (sigma_LWR). For uncorrelated edges, it holds that in average : $\mathrm{sigma}_{LWR}(L)=\sqrt{2}\ \mathrm{sigma}_{LER}(L)$ (1).

However, this parameter does not provide a complete description of LWR, since it neglects the spatial distribution of roughness along the edge. Furthermore, it depends upon the length of the measured edge especially for small lengths. In the case of self affine fractal edges (edges which are invariant under anisotropic scaling), both the spatial complexity of roughness and the dependence of sigma on edge length can be determined by two parameters: *the roughness exponent α and the correlation length ξ*. A method for calculating these spatial roughness parameters is based on the study of the correlations among the heights y_i (distances from a reference axis) of the edge points. Assuming that the number of the edge points is N with coordinates (y_i,x_i) i=1,…,N, and taking $d=x_{i+1}-x_i$, the height-height correlation function G(r=md) defined as

$$G(md) = [\frac{1}{N-m}\sum_{i=1}^{N-m}(y_{i+m}-y_i)^2]^{1/2} \qquad (2)$$

quantifies the edge points correlations and therefore gives information about the spatial aspects of LWR. A typical behavior of the G(r=md) function is shown in Fig.2, where one can see that a power law behavior for small r ,$G(r)\sim r^{\alpha}$, is followed by saturation at (or random oscillations about) the value $\sqrt{2}$sigma. Statistically persistent regular oscillations in G(r) reveal the existence of a periodicity in line edge, whose wavelength can be extracted by the position of the first minimum of the oscillations. The spatial aspects of LWR is also reflected on the sigma(L) curve i.e. the dependence of the rms value sigma on the measured edge length L. Typically, the sigma(L) rises as a power law, sigma(L)~L^{α}, and then saturates to its final value sigma(inf). The exponent α of the power laws is called *roughness (or Hurst) exponent α* and it can be shown that it is connected to the fractal dimension D_F through a relation, which for lines is $\alpha=2-D_F$. In fact, it gives the relative importance of high frequency fluctuations on LWR and thus determines how fast the sigma drops off as the measured line length (gate width) decreases. The distance after which the sigma saturates is related to the *correlation length ξ*, which is defined as the value of the distance r at which the autocorrelation function drops to 1/e of its value at r=0 or equivalently the height-height correlation function increases at the $\sqrt{1-\frac{1}{e}}$ of its maximum value $\sqrt{2}$sigma, i.e. $G(\xi) = \sqrt{1-\frac{1}{e}}\ \sqrt{2}$ sigma.

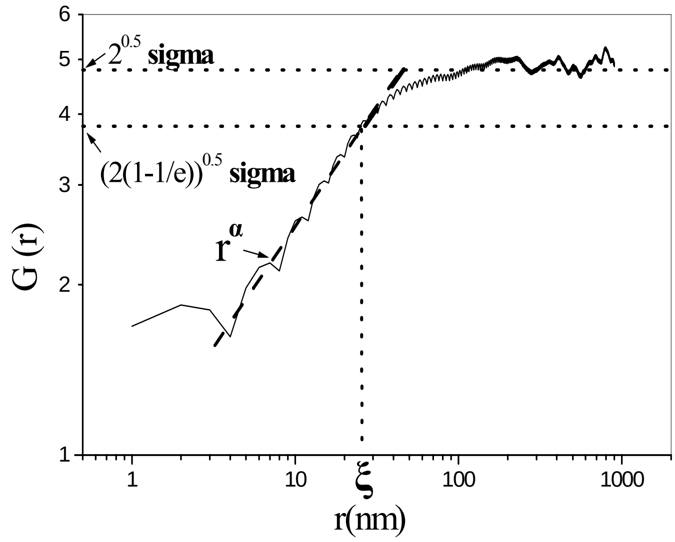

Figure 2

The saturation value sigma(inf) can be estimated using a relationship between the sigma(L) curve and the dependence of the CD variation on L. The $CD_{variation}$ is the linewidth difference between multiple lines available within the SEM image.This relationship refers to the $sigma_{LWR}$, and it has been demonstrated both experimentally and theoretically. It has a Pythagorean form:

$$sigma_{LWR}^2(inf) = sigma_{LWR}^2(L) + CD_{variation}^2(L) \quad (3)$$

and through (1) it is transformed into :

$$sigma_{LER}^2(inf) = sigma_{LER}^2(L) + 0.5 * CD_{variation}^2(L) \quad (4)$$

giving thus the $sigma_{LER}(inf)$ assuming lines with uncorrelated edges.

This way, one can calculate the $sigma_{LER}(inf)$ and $sigma_{LWR}(inf)$ using any part of the resist lines. Actually, the algorithm takes for L the total line length included in the analyzed SEM image ($L=L_{total}$) .

In conclusion, the LWR descriptors calculated by LWR_Demokritos are: a) the line length independent sigma value 3***$sigma_{LWR}(inf)$*** calculated through relationship (3), b) ***the correlation length ξ*** after which the edge looks flat and the sigma does not depend strongly on the length of the measurement box, and c) ***the roughness exponent α*** which gives the relative importance of high frequency fluctuations on LER and thus determines how fast the sigma drops off as the measured length of the line edge decreases.

Furthermore, LWR_Demokritos outputs the functions: a) **the height-height correlation function G(r)**, b) **the sigma(L) curve**, c) **the dependence of the CD variation on L** and d) **the uncertainty of LWR measurements** and its dependence on L. The latter parameter is calculated as the ratio of the rms of sigma values to the mean sigma.

- ## Explanation of the parameters contained in the input file: input.txt

ANALYSIS_PROCEDURE

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THRESHOLD This parameter determines the normalized signal intensity of the image at which the edge is detected. Usually 0.5<THRESHOLD≤1. When THRESHOLD approaches 1, the estimations of the critical dimension (CD_average) lower, since the edges are detected nearer to the top of the line.

NOISE_SMOOTHING

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NSF y (recommended) if noise-smoothing filter is going to be applied to the image before edge detection, n if it isn't

The following three parameters are the parameters for a 2-D rotationally symmetric Gaussian noise smoothing function. Their values depend on the pixel size and the quality of the image. A successful choice leads to a reliable detection of the edges.

NSF_HEIGHT It gives the number of rows participating in the smoothing.

NSF_WIDTH It gives the number of columns in the smoothing.

NSF_STD It gives the standard deviation of the Gaussian filter in both directions.

STATISTICS

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SHOW_FIGURES y (recommended) if you want to see the obtained figures (the SEM image with the detected edges, the heigh-height correlation function and the dependence of sigma on the edge length), n if you don’t.

NUM_IMAGES It refers to the number of images you want to analyze in a batch job

IMAGE_PARAMETERS

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PIX2NM The image pixel size in nm

LWOVER2_PIX A rough estimation of the nominal line width in pixels

OFFSET The distance from the bright edge regions at which the detection algorithm starts. A good choice is the half of the nominal line width (LWOVER2_PIX), when the line and space widths are the same.

image_name.jpg l (or s)

The name(s) of the SEM image(s) you want to analyze with a letter indicating whether the image starts at its left within a line (type letter l) or within a space (type letter s). In the case that the SEM image starts within a line, the program automatically skips the first single edge.

- **Example run of LWR_Demokritos**

The contents of the input.txt file:

ANALYSIS_PROCEDURE

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THRESHOLD 0.9

NOISE_SMOOTHING

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NSF y

NSF_HEIGHT 5

NSF_WIDTH 7

NSF_STD 1

STATISTICS

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SHOW_FIGURES y

NUM_IMAGES 2

IMAGE_PARAMETERS

===================

PIX2NM 2.0

LWOVER2_PIX 50

OFFSET 30

test_image_1.jpg l

test_image_2.jpg s

(please note that only ONE image can be analyzed with the LWR_Demo Version, while many images can be analyzed simultaneously with the full version LWR_Demokritos)

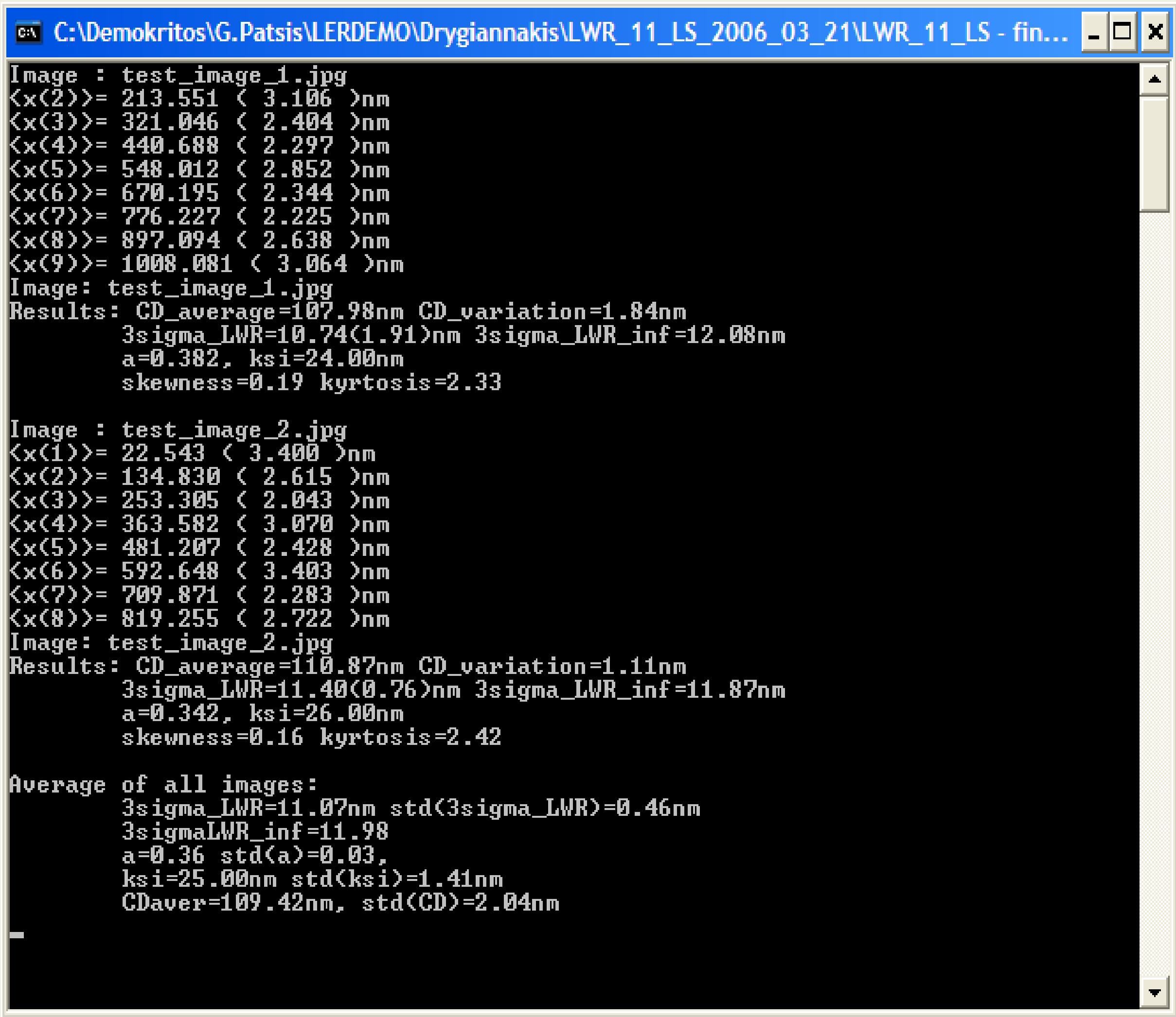
The program LWR_Demo outputs:

a) a window with the LWR parameters

b) a window with figures showing the detected edges and the dependence of LWR metrics on the line length and

c) three txt files containing the values of the LWR parameters and their dependence on the line length **(txt files are not generated by the LWR_Demo Version)**

a) The window with the LWR parameters :



```
C:\Demokritos\G.Patsis\LERDEMO\Drygiannakis\LWR_11_LS_2006_03_21\LWR_11_LS - fin...
Image : test_image_1.jpg
<x(2)>= 213.551 ( 3.106 )nm
<x(3)>= 321.046 ( 2.404 )nm
<x(4)>= 440.688 ( 2.297 )nm
<x(5)>= 548.012 ( 2.852 )nm
<x(6)>= 670.195 ( 2.344 )nm
<x(7)>= 776.227 ( 2.225 )nm
<x(8)>= 897.094 ( 2.638 )nm
<x(9)>= 1008.081 ( 3.064 )nm
Image: test_image_1.jpg
Results: CD_average=107.98nm CD_variation=1.84nm
         3sigma_LWR=10.74(1.91)nm 3sigma_LWR_inf=12.08nm
         a=0.382, ksi=24.00nm
         skewness=0.19 kyrtosis=2.33

Image : test_image_2.jpg
<x(1)>= 22.543 ( 3.400 )nm
<x(2)>= 134.830 ( 2.615 )nm
<x(3)>= 253.305 ( 2.043 )nm
<x(4)>= 363.582 ( 3.070 )nm
<x(5)>= 481.207 ( 2.428 )nm
<x(6)>= 592.648 ( 3.403 )nm
<x(7)>= 709.871 ( 2.283 )nm
<x(8)>= 819.255 ( 2.722 )nm
Image: test_image_2.jpg
Results: CD_average=110.87nm CD_variation=1.11nm
         3sigma_LWR=11.40(0.76)nm 3sigma_LWR_inf=11.87nm
         a=0.342, ksi=26.00nm
         skewness=0.16 kyrtosis=2.42

Average of all images:
         3sigma_LWR=11.07nm std(3sigma_LWR)=0.46nm
         3sigmaLWR_inf=11.98
         a=0.36 std(a)=0.03,
         ksi=25.00nm std(ksi)=1.41nm
         CDaver=109.42nm, std(CD)=2.04nm
```

Explanation of the output parameters shown in the window:

1. Output parameters from the analysis of each image:

- **<x(n)> :** The average value of the abscissas of the edge points of the n-th edge included in the image. In parenthesis, the corresponding standard deviation of these points from their average value is given.
- **CD_average.** The average of the CD values of the lines contained in the image(s). The CD value of each line is the average of its line widths
- **CD_variation.** The standard deviation of the CD values of the lines contained in the image.

- **3sigma_LWR.** The average of the 3sigma values of all lines contained in the image. The 3sigma value of the linewidths of each line is calculated for the total line length included in the image. In parenthesis, the standard deviation of these 3sigma values is recorded.
- **3sigma_LWR_inf.** The average 3sigma of the linewidths for infinite line length. This value is found by the relationship (3) with L the maximum line length contained in the image
- **skewness.** When 0, the distribution of the line widths is symmetric about their mean.
- **kyrtosis.** .When 3, the distribution of the line widths is Gaussian. (Gaussian LWR)
- **a.** It is the roughness exponent which gives the relative importance of high frequency fluctuations on LWR and thus determines how fast the sigma drops off as the measured length decreases. It relates to the fractal dimension D, since D=2-α.
- **ksi.** It is the correlation length of the lines. Its meaning is that for lengths larger than a multiple (~10 times) of it, the line looks almost flat and the sigma saturates to its final value sigma_inf. At present, it is calculated through the height-height correlation function HHCF(r).

2. Average output parameters from the analysis of all images:

- **3sigma_LWR :** The average of the 3sigma values of all images
- **std(3sigma_LWR) :** The standard deviation of the 3sigma values of all images
- **3sigmaLWR_inf :** The average of the 3sigmaLWR_inf values of all images
- **a :** The average of the roughness exponents of all images
- **std(a) :** The standard deviation of the roughness exponents of all images
- **ksi :** The average of the correlation lengths of all images
- **std(ksi) :** The standard deviation of the correlation lengths of all images
- **CDaver :** The average CD of the CD values of all images
- **std(CD) :** The standard deviation of the CD values of all images

b) The window with the output figures:

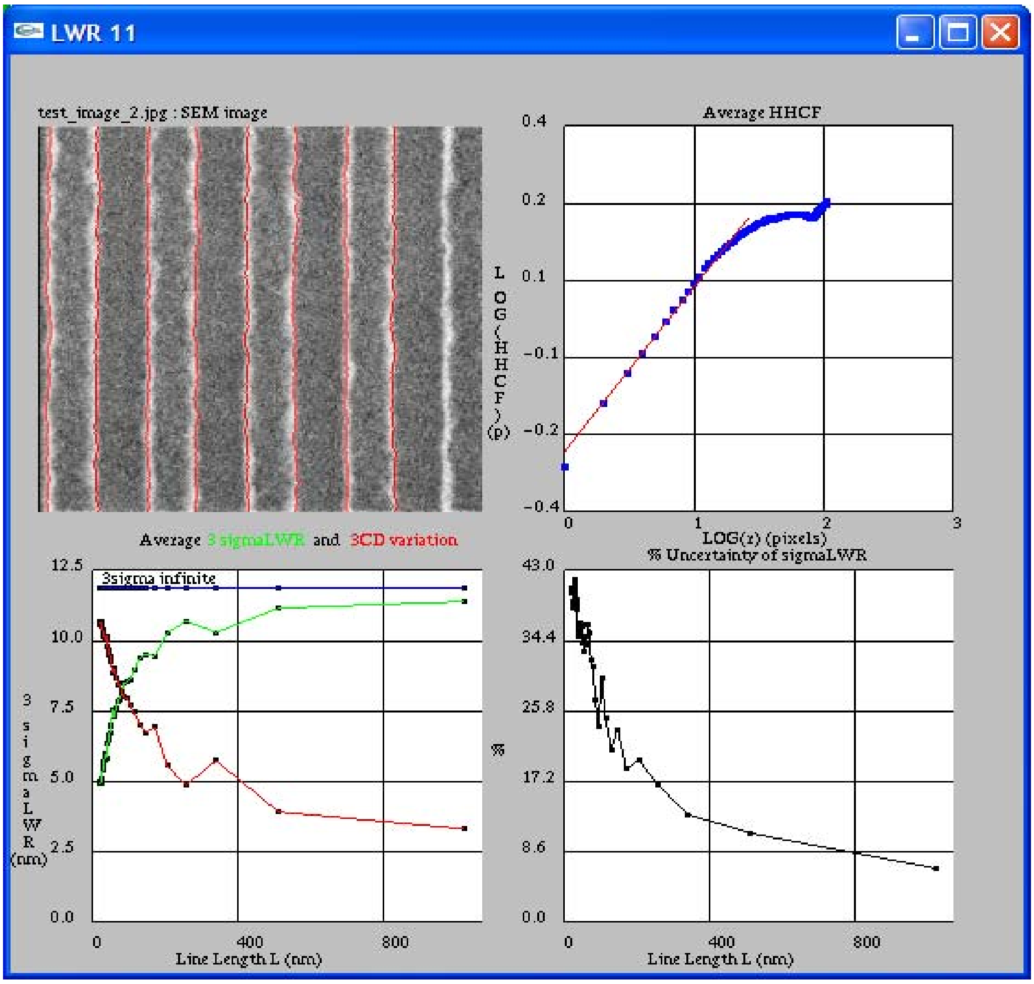


Figure 4

a) The first (upper left) diagram in fig. 4 depicts the top down SEM image to be analyzed with the detected through the software edges on it. You have to inspect it so that you confirm that the detected edges follow the line edge variations.

b) The second (upper right) graph depicts the height height correlation function HHCF(r) in logarithmic axes averaged over all lines included in the image. As well, it shows the linear fit (red line) of its power law portion through which the roughness exponent value is calculated.

c) The third (lower left) figure shows two curves; the 3sigma(L) curve (in green) and the 3CD variation curve (in red). As one can easily deduce from the relationship (2) these curves have inverse behavior: when the first increases the second decreases. The sum of their squares is constant for all lines lengths and it is equal to 3sigmaLWR_inf. It is shown in the figure with the horizontal blue line.

d) The fourth (lower right) graph in fig. 4 depicts the relative standard deviation of the 3sigma_LWR values (percentage uncertainty of 3sigma_LWR measurements) and its dependence on line length L.

c) The output files (please note that the output files are NOT available with the LWR_Demo Version but only with the full LWR_Demokritos version):

- **Total_Results.txt** : It contains the average values of the parameters explained above with the date of obtaining them.
- **Image_name.jpg_AvgHHCF** : It contains the values of the average height-height correlation function vs distance (in pixels) whose diagram is shown in the upper right output figure (see below).
- **Image_name.jpg_3sigma_CD_var** : It includes the values of the 3sigmaLWR, CD variation and uncertainty of the sigmaLWR vs the line length (in nm) at which they are calculated. The graphical representation of these parameters are depicted in the lower left and right output figures.

References

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7. Patsis, G.P., et al., *Quantification of line-edge roughness of photoresists. I. A comparison between off-line and on-line analysis of top-down scanning electron microscopy images.* Journal of Vacuum Science and Technology B: Microelectronics and Nanometer Structures, 2003. **21**(3): p. 1008.
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