Enhancing SEM image metrology with SMILE: Advances, features, and portability

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ABSTRACT

SMILE is a free software for the analysis of line/space and contact/hole pattern images. The software is specifically designed to investigate SEM images of test structures for photoresist screening and to extract relevant metrics to assess the quality of the patterns. These metrics include the average critical dimension, the unbiased line edge roughness and the eventual presence of defects. This paper reviews the latest functionalities of SMILE, discusses the plans for future upgrades and includes a step by step workflow guide to use the software.

Keywords: Metrology, Open Source, SEM, Image Analysis

1. INTRODUCTION

The SEM Image Lines Estimator (SMILE), is a free and open-source software tool for scanning electron microscopy (SEM) image metrology. It was initially conceived to support EUV resist screening programs conducted in collaboration with various resist manufacturers at the Paul Scherrer Institute. SMILE offers essential core functionalities, encompassing critical dimension (CD) measurements, unbiased line edge and line width roughness (LER and LWR) analysis, and local CD uniformity assessments for lines and space patterns.[1] Additionally, SMILE can perform a simple analysis of contact patterns, enabling measurements of average radius, ellipticity, and local CD uniformity.[2]

Over the years, SMILE was updated to incorporate new functionalities addressing the needs of an increasing pool of users. Most notably, users have now the option to use an edge detection mode for images with strong pattern edge effects and a new method to obtain a more robust estimate of the LWR and LER bias. These two new functionalities are described in sections 2 and 3.

SMILE is developed using the MATLAB App Designer, an interactive development environment for designing graphic user interface applications in MATLAB®. SMILE is distributed as a Windows or MacOS executable which will automatically download and install the required free MATLAB runtime libraries. The source code is also available upon request, but for a user to further develop the application, a valid MATLAB license is required. Recognizing the need for greater accessibility and usability, efforts have been initiated to translate SMILE to Python. This transition aims to empower potential users to build upon the current code and evolve the software further.

Finally, the workflow describing how to use SMILE to analyze line/space and contact/hole patterns are presented in appendices A and B respectively.

2. EDGE DETECTION METHODS

The detection of the image feature edges is a fundamental step in the image analysis process. SMILE has several methods to perform this task, depending the type of features and the results the user wants to achieve. The generic approach to identify the edge location for line and space patterns has been discussed in a previous publication.[1] In short, after a pre-processing step, the software proceeds to identify the general location of each edge and then performs an edge search row by row using a customizable threshold value. The edge search is

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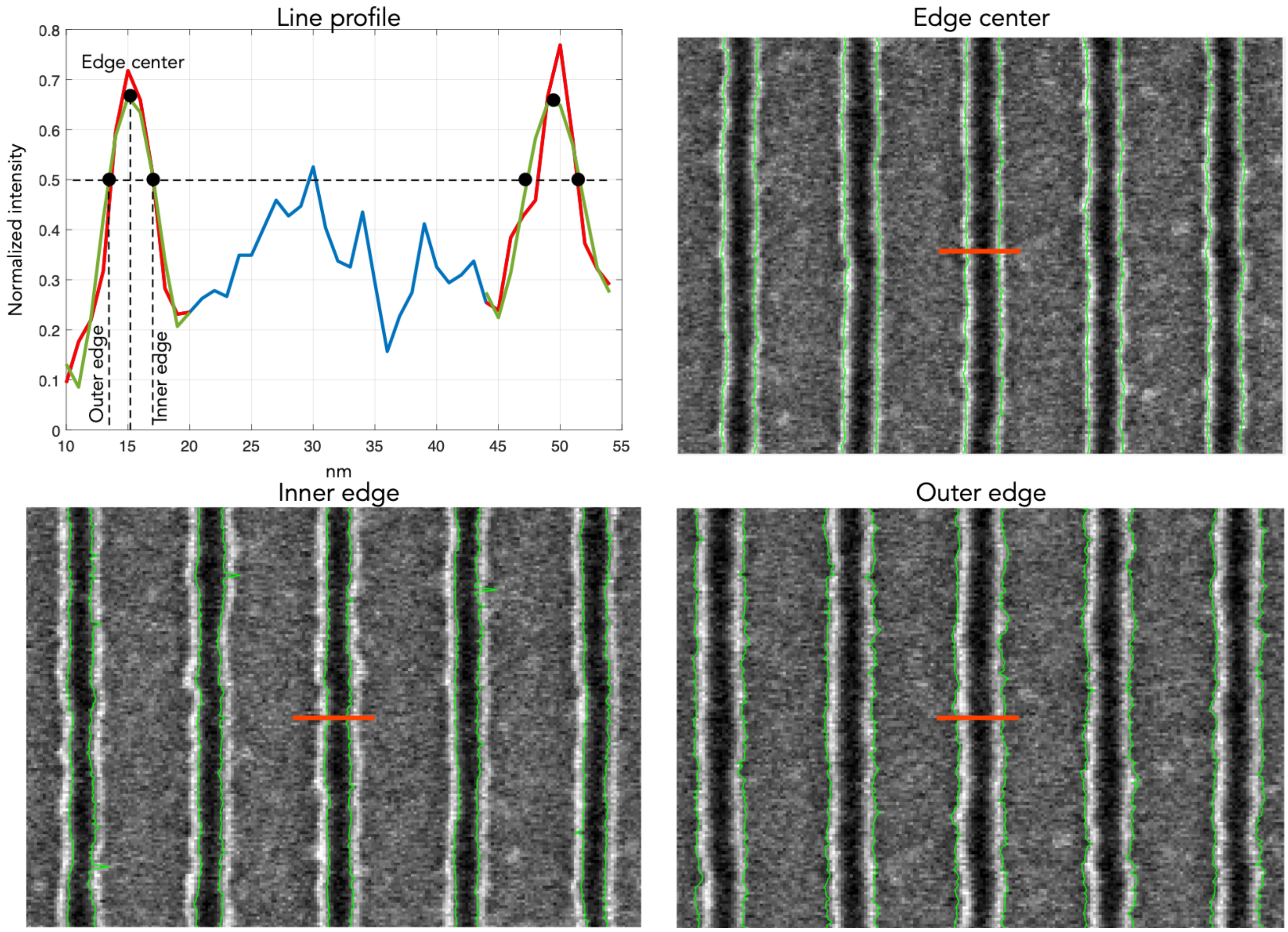


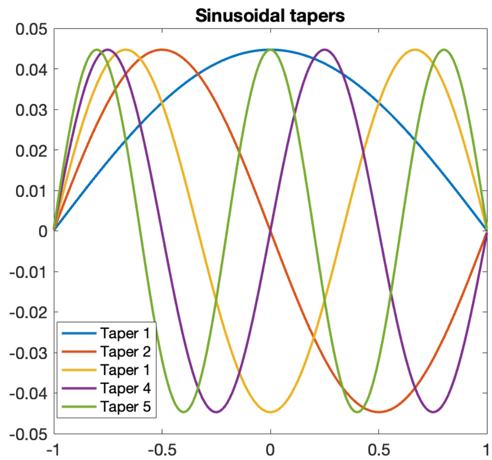
Figure 1. Bright edge detection example. The top left panels shows the intensity profile of a line with visible edge effect. The green curves are the 4-degree polynomials fitted to the red portions of the line's profile. The other three panels show the edges detected by smile corresponding to different parameter selections.

normally performed by fitting a profile function to the image intensity distribution along a given row and finding the position corresponding to the specified threshold.

This approach is suitable for line profiles that do not exhibit a strong edge effect. In some cases however, the edge profiles in SEM image have a higher intensity. This can be due, for instance, to topography-dependent secondary electron emission.[3] SMILE allows to select a specific edge detection method, where the bright edge profiles are extracted by fitting a 4 degree polynomial to the image intensity distribution as shown in Figure 1. The user can decide to select the inner or outer profile of the bright edge and use the specified threshold value to find the edge position. It is also possible to ignore the threshold and select the central part of the edge by looking for the maximum intensity value. The top left panel in Figure 1 shows a line intensity profile with a visible edge effect. The profile corresponds to the red line in the image shown on the top right panel. When using the *Bright edge selection* option, SMILE assigns the edge position according to the user's selection.

3. MULTI TAPER PSD ANALYSIS

Line edge roughness and line width roughness are two important metrics to evaluate the performance of EUV resist materials. LER and LWR are calculated from the profiles extracted from SEM images which contain a certain amount of noise derived from the imaging process. This noise introduces a bias in the evaluation of LER and LWR. To evaluate these metric accurately is therefore necessary to estimate this bias and remove it. The unbiasing procedure concept is described in the IMEC roughness protocol for line and space metrology.[4]



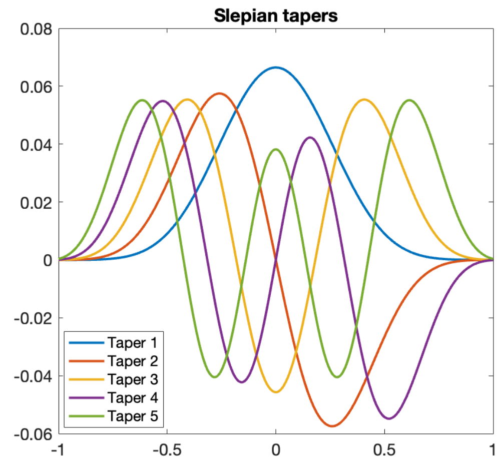


Figure 2. Left: Sinusoidal taper functions. Right: Prolate spheroidal functions.

This procedure, in a nutshell, consist in estimating the average power spectral density of the detected profiles, identifying and removing the spectral contribution of uncorrelated noise and integrating the PSD to determine the unbiased standard deviation. In SMILE, this is done by fitting a customizable model to the measured PSD data.

The robustness of the fit and the accuracy of the bias estimate depend on the quality of the PSD data. the power spectral density is calculated as the average PSD of all the detected profiles. In general, the PSD signal to noise ratio improves with the number of the detected profiles. For this reason, when possible, multiple L/S images collected on the same sample at different positions can be used to achieve better statistics. Unfortunately, this is a time consuming process and it is not always a viable option as it requires a sample with multiple test fields.

SMILE is equipped with a multitaper analysis option which allows to effectively denoise the PSD function and obtain a more robust fit and a more accurate unbiasing of LER and LWR.[5] This approach consist in projecting each detected profile onto a basis of orthonormal functions called tapers[6] and calculating the PSD of each projection. This makes it possible to increase the number of averaged PSD distributions by a factor equal to the dimension of the chosen taper basis. In SMILE, the user can choose between two taper basis, sinusoidal and prolate spheroidal functions, or Slepian sequences,[7] and define the size of the taper basis. Figure 2 shows the first 5 tapers of the two types. A single image with a low signal to noise ratio as the one shown in figure 3C, can have a rather noisy PSD (figure 3A). The conventional approach to reduce the signal to noise ratio in the PSD is to collect features (lines) from multiple images and get a larger set to average. Using a multitaper approach, it is possible to drastically reduce the noise in the PSD using fewer images. In this case, a basis of 50 Slepian sequences was used to obtain the result shown in figure 3B).

4. CONCLUSION AND FUTURE DEVELOPMENTS

SMILE is a free software designed for the analysis of SEM images with periodic line/space and contact/hole pattern. It was originally developed to support the EUV resist metrology program run at the Paul Scherrer Institute, but it has been adopted by an expanding pool of users who contributed to improve and expand the capabilities of the software. One of the latest upgrade consists in the capability to perform multitaper PSD estimate to improve the robustness and accuracy of the unbiased LWR and LER.

Although SMILE has been released to the public for free, it has been developed with MATLAB App Designer. This limits the ability of interested users to further develop the code autonomously. For this reason, an effort to create a Python-based version of SMILE is currently undergoing. The new GUI is being developed using the Qt framework and the PyQt6 Python bindings and will be kept as similar as possible to the current one. A screenshot of the new interface is shown in Figure 4.

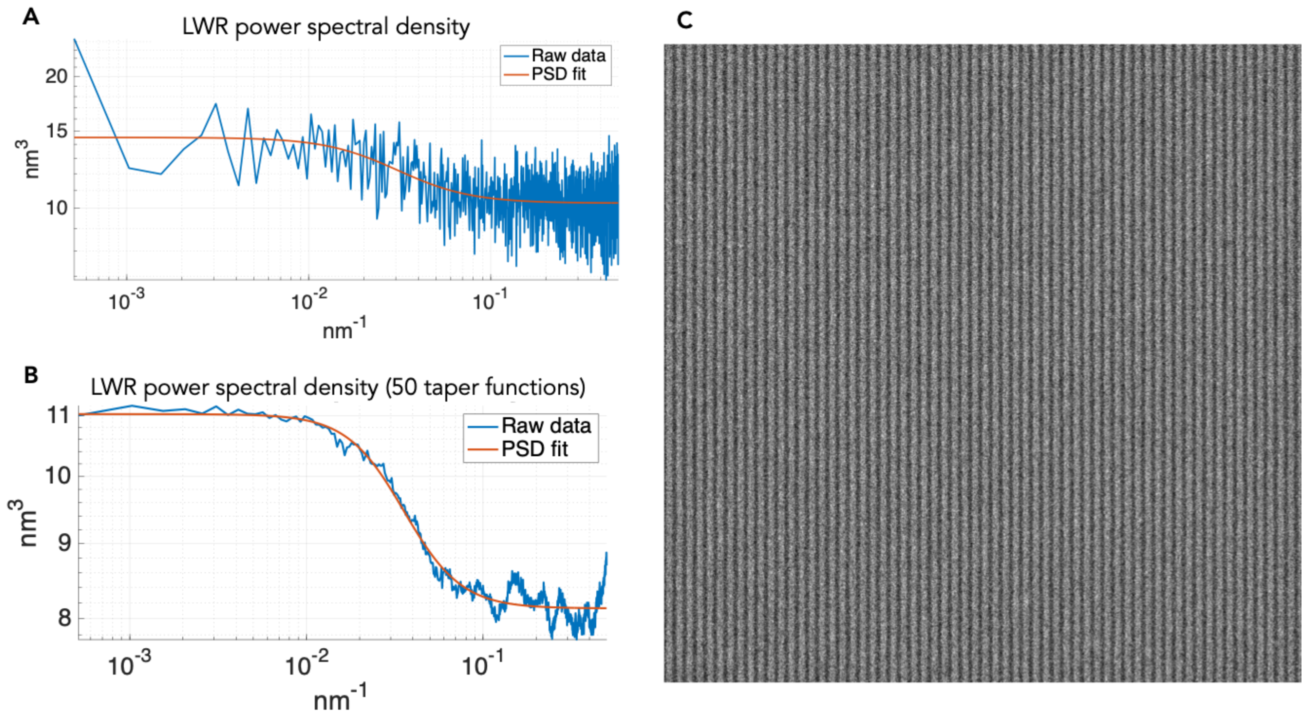


Figure 3. **A**: Average LWR power spectral density calculated from the lines in the image on the right. **B**: Average LWR power spectral density calculated using 50 Slepian sequences. **C**: SEM image of a line space pattern with 59 lines, with a pitch of 26 nm and a CD of 13 nm.

In addition to the current features, the new version of the software will include other functionalities like the ability to customize the look of the interface and the possibility to evaluate the image intensity distribution of each image and determine the line scan error.[8]

APPENDIX A. LINE AND SPACES ANALYSIS WORKFLOW

At startup, SMILE displays the *Images* tab window (Figure 5). The top right part of this window (figure 6) includes most of the controls the user needs to run the data analysis.

A.1 Image selection

The first step consist in loading the images to be analyzed. This is done by pressing the *Images Folder* button. The software will display a dialogue window where the user can select the folder containing the images. SMILE will then proceed to load all the images in the selected folder. SMILE 2.3 recognizes images in *tif*, *png* and *jpg* format.

By default, the toggle button above the table is labelled *Automatic feature recognition*. In this state, SMILE will try to automatically discriminate between lines and contact images. The former will be listed in the topmost table and the latter will be listed in the bottom table. Note that this function requires the Neural Network Toolbox if the software is run from within MATLAB. In case SMILE assigns an image to the wrong group, the user can correct it by selecting the corresponding row in the table and pressing the "t" key to move it in the correct table. Alternatively, before choosing the images folder, the user can toggle the *Automatic feature recognition* button. In this case, SMILE will assign all the images to the top table considering them as lines. The user can then use the "t" key to move the contacts images in the bottom table. SMILE will perform the image analysis according to their classification. The images in the topmost table will be analyzed as lines and space patterns while the ones in the bottom table will be treated as contact/holes patterns.

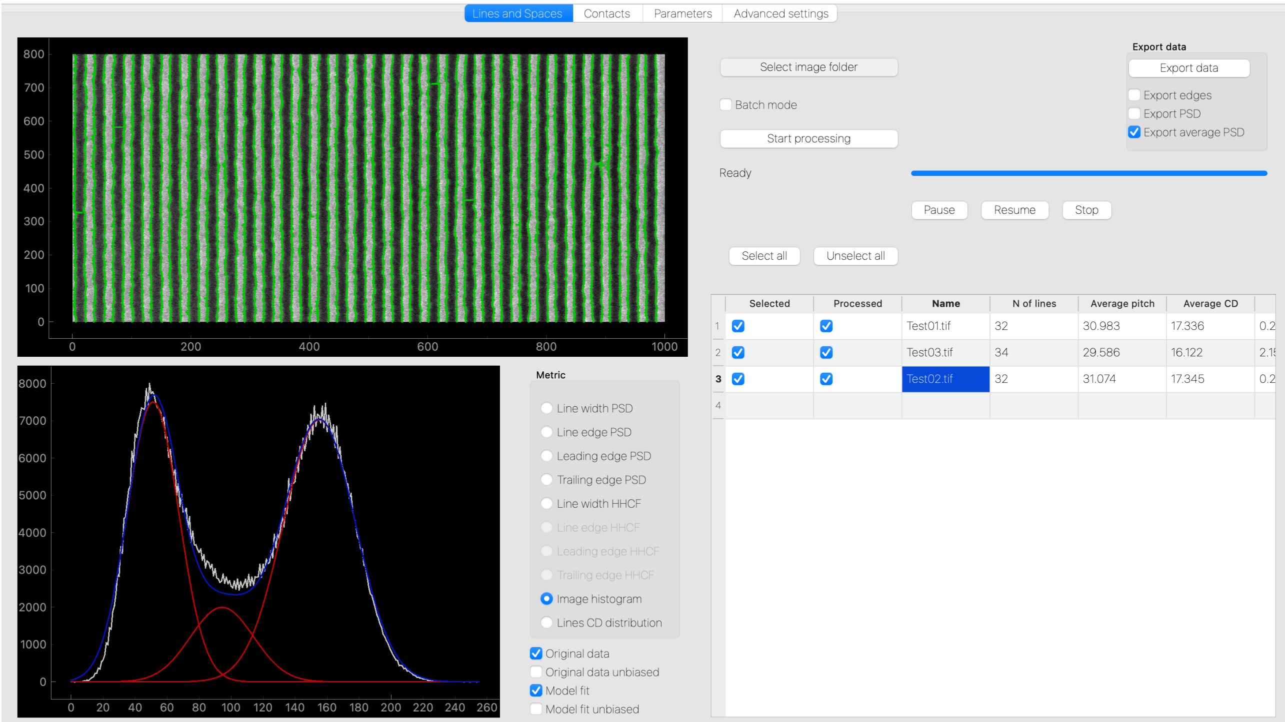


Figure 4. Python version of SMILE. The graphical user interface is similar to the current one. The plot in the bottom left shows the selected image histogram.

A.2 Setting up the parameters

The second step requires the user to move to the *parameters* tab window. This window is divided into several panels where the user can adjust the relevant parameters for the analysis.

A.2.1 Image pre processing

This panel, shown in figure 7, includes all the parameters defining the image pre-processing step. Here the user must specify the region of interest of the image. This can be done by clicking the *Set ROI* button and drawing a rectangle in the image displayed above it, or simply by specifying the minimum and maximum limits (in pixel) along the x and y axes in the text boxes below.

The *Auto rotation alignment* check box option instructs the software to correct small angle rotations of the pattern. Note that the software will use a near neighbor approach only as bilinear and bicubic interpolations can sometimes introduce a suppression of the high frequency components of the edges profiles.

The *Auto rotation alignment* check box option instructs the software to calculate the average profile of all the edges in the image and subtract it from every profile. This option can be used to correct systematic distortions in the lines due to scanning artifacts.

The *Manual rotation adjustment* slider can be use to change the orientation of the image. This can be used to convert an image with horizontal lines into a vertical pattern, or to correct large rotation errors.

The *AP Smoothing* textbox specifies the kernel size of a median filter applied to the image before trying to detect the general location of the edges. Note that the actual edge detection is performed on the unfiltered image.

The *Gradient correction* box gives the user the option to correct an eventual field intensity gradient by fitting a planar, quadratic or cubic surface to the image and remove it before proceeding with the analysis.

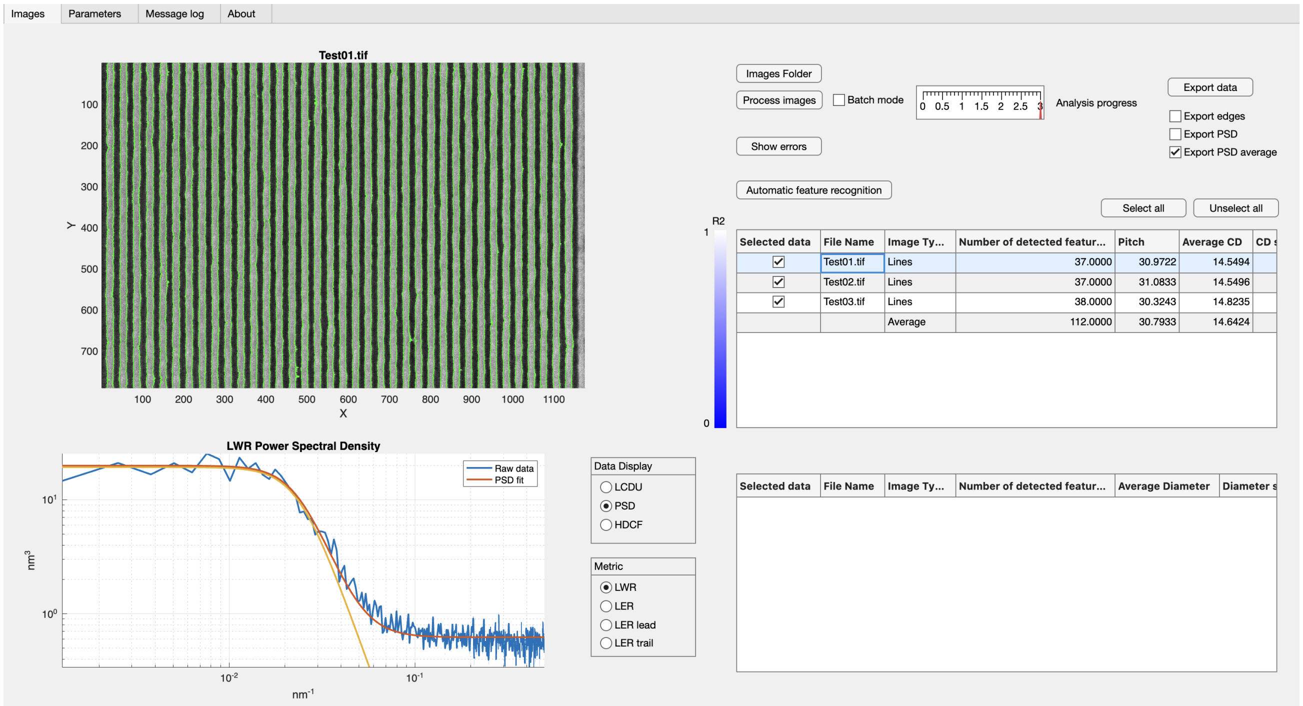


Figure 5. SMILE startup window. Upon startup, SMILE will display a main window with 4 tabs. The *Images* tab is displayed in this picture.

A.2.2 Edge detection

The *Edge detection* panel includes the paramters that SMILE uses to determine the actual position of the edges. The *image tone* box allows the user to select the tone of the lines. In SMILE, a line is defined as the space between a leading edge (left) and a trailing edge (right). When the *Positive* radiobutton is selected, the software will identify lines where the intensity is above a specific threshold, When the *Negative* radiobutton is selected, the detected lines will be the "dark" ones. In some cases, when the lines show a strong edge effect (see section 2), it may happen that the intensities of the areas corresponding to the lines and the spaces are comparatively close. If this happens, SMILE could fail to discriminate the lines from the spaces. To overcome this problem, the user can select the *Undefined* tone radio button. The software will then consider the leftmost edge as a leading edge.

The *Threshold* text box allows the user to specify the edge detection threshold. Note that the threshold refers to the normalized image intensity, and should therefore be larger than 0 and smaller than 1.

The *Bridging threshold* and the *Pinching threshold* parameters are used to specify the distance between the edges beyond which SMILE considers a location in the image as a bridge or a gap defect respectively. Both parameters are expressed in pixels.

The *Max spike* parameter, expressed in pixel is the maximum allowed difference between two contiguous points in the detected profiles. If this threshold is exceeded SMILE substitutes the offending point with the median value of the profile. Reducing this parameter below the default value of 10, may induce some unwanted filtering which is usually detectable as a sudden drop in the PSD high frequency range.

The *Edge detection range* and the *CD fraction* parameters are two mutually exclusive values used to determine the search range for the edge. SMILE looks for the line edge position along each row in a certain range around the average edge location. This range can be specified as a number of pixels ($\pm$ *Edge detection range*) or as a fraction of the pattern half pitch (*CD fraction*).

The *Min peak distance* parameter, expressed in pixel, sets a threshold on the minimum distance between the edges. This parameter can be kept low (10 or less) in case of high-contrast images with little or no edge

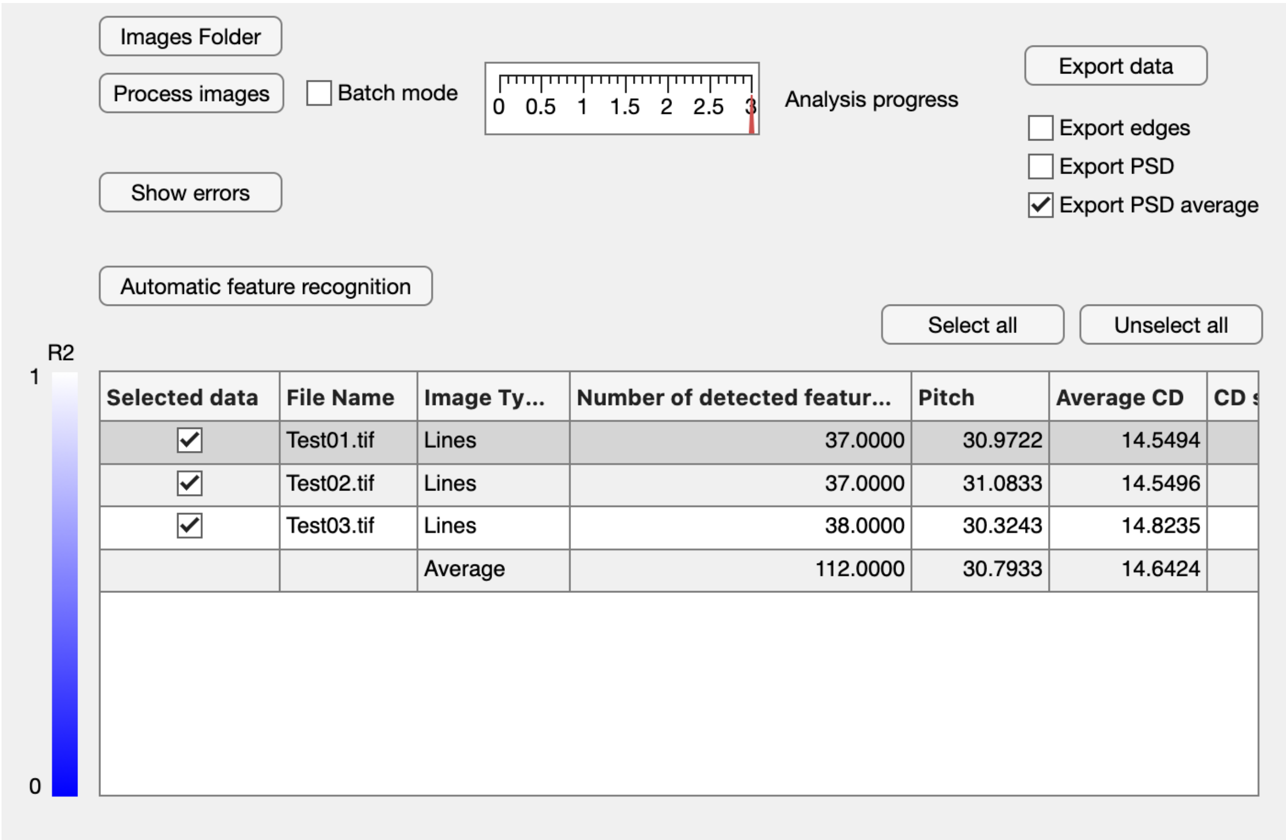


Figure 6. The *Images* tab is displayed at startup.

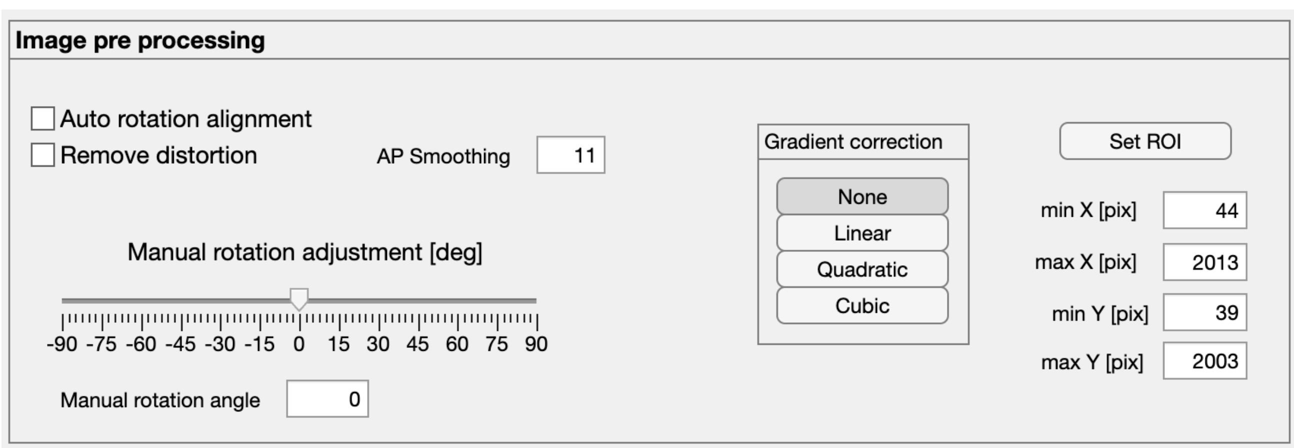


Figure 7. Image pre processing panel in the *Parameters* tab.

effect or can be increased to remove spurious edges that may be detected in images with artifacts or with low signal-to-noise ratio.

The *Min peak prominence* parameter can be used to increase the sensitivity of the edge identification algorithm in images with low contrast. A lower value will increase the sensitivity, but will increase the risk of detecting false edges.

The *SEM model* selection widget offers three options: *Generic*, *Zeiss* and *Hitachi*. When *Generic* is selected, the software reads the user-specified image pixel size, in nanometers, from the text box on the left. When either

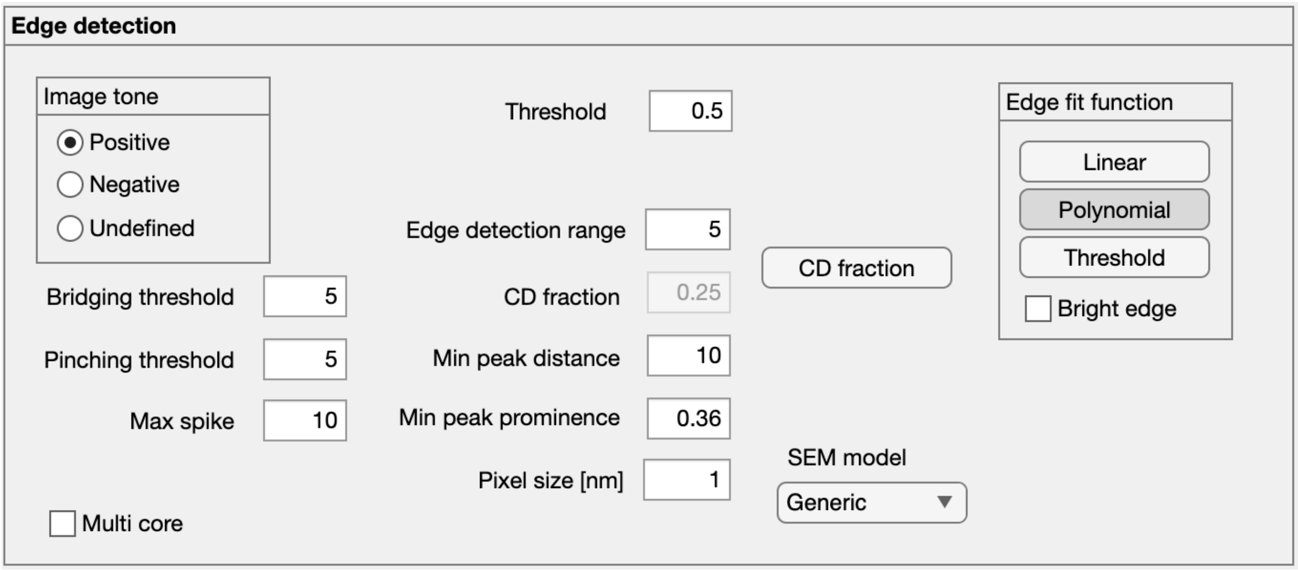


Figure 8. Edge selection panel in the *Parameters* tab.

of the other two options is selected, SMILE will try to read the image file header and extract the pixel size value. These options have been designed for the SEM models in use in the PSI cleanroom, (Zeiss SUPRA 55VP and Hitachi Regulus 8230).

In the *Edge fit function* selection box, the user can specify the method to fit the intensity profile as explained in section 2. In most cases, the most accurate results are obtained with the *Polynomial* fit function.

A.2.3 Roughness Power Spectral Density fit

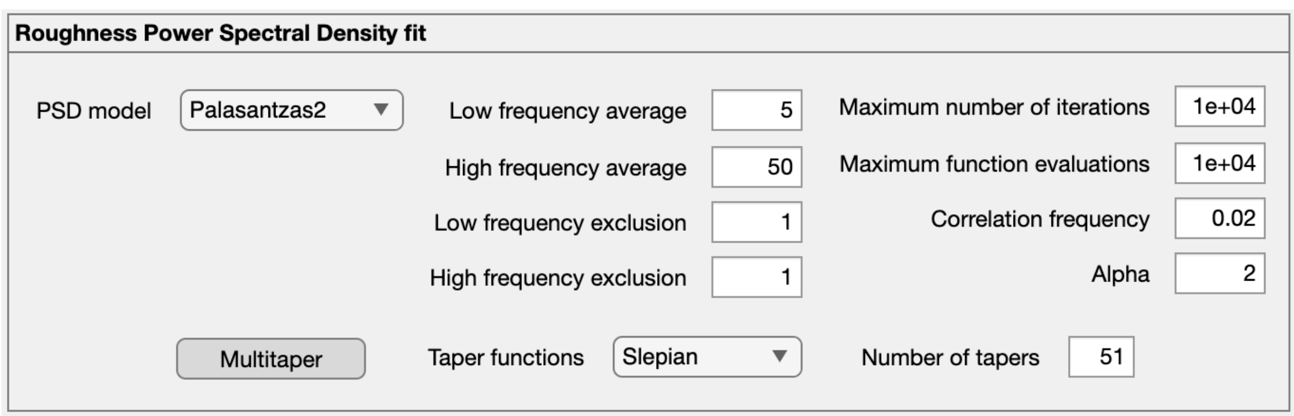


Figure 9. Roughness Power Spectral Density fit panel in the *Parameters* tab.

The parameters in this panel are used to select the appropriate method to estimate the power spectral density of the edges. The *PSD model* drop-down list includes five models to fit the average PSD of the edges in the image. The *Palasantzas2* model,[9] which is the default option, is described by the following expression:

$$PSD(\nu) = \frac{\xi\sigma^2}{(1+\xi^2\nu^2)^{0.5+\alpha}} + Nl \tag{1}$$

To fit this model to the measured PSD curve, the software needs an initial guess of the model parameters. The initial guesses for the parameters α and ξ are specified directly by the user in the *Alpha* and *Correlation frequency* text boxes. The initial guesses for the noise level Nl and for σ are calculated averaging an interval of the PSD in the high frequency range and low frequency range respectively. The user can specify a number of the PSD array terms to exclude and the size of the averaging range for both parameters as shown in Figure 10. When

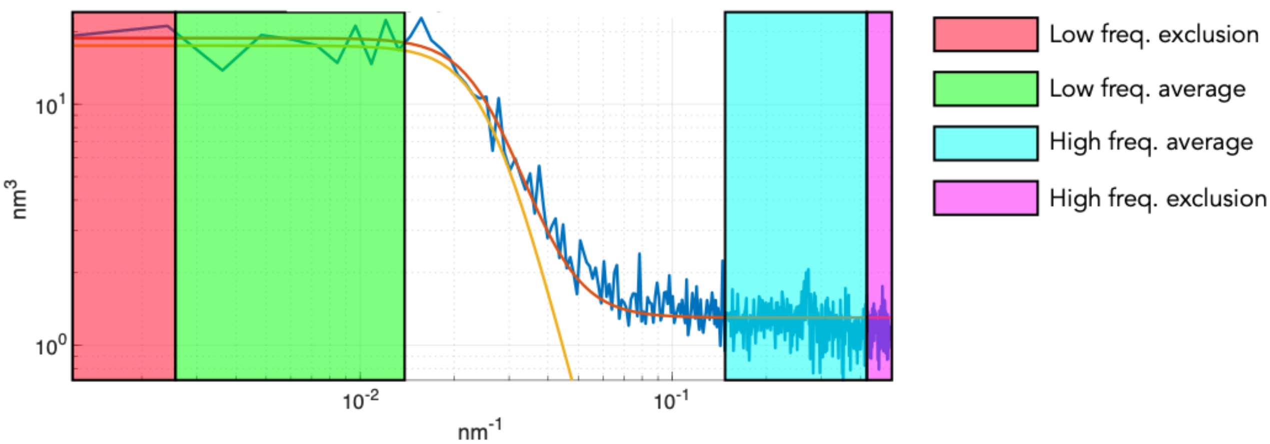


Figure 10. Estimate of the parameters for the PSD fit. The user can specify the intervals where to calculate the averages of the PSD to get an initial guess of the model parameters.

the *Multitaper* toggle button is selected, as shown in Figure]9, the software performs a multitaper analysis of each detected edge using either Slepian or sinusoidal tapers as described in section 3.

A.3 Image processing

The final step in the workflow is the image processing. The analysis can be started from the *Images* tab (Figure 6) by pressing the *Process images* button. The software will start processing the images and fill the measured values in the table below. SMILE will use the same set of parameters for all the images. To use different parameter sets for different images, a user can manually select the files for the analysis with the tick boxes in the first column, and process the selected images with a specific parameters set.

When the analysis is completed, the results can be exported pressing the *Export data* button. The software will display a dialog to specify the path and the file name. If the file name extension is *.xlsx*, SMILE will save a Microsoft Excel spreadsheet with the results of the analysis, otherwise the results will be written in text format as comma separated values.

If the file is saved in spreadsheet format, the user has the option to include the PSD for each image and the array of the detected edges. It is recommended to use these options only for a small number of images though (1 or 2), as it can be a very long operation. The default option is to export only the average PSD of all the images.

The *Batch mode* tick box is used to process images arranged in multiple sub folders automatically. If this option is selected, SMILE will scan the folder tree under the selected folder, process all the sub folders containing images and export an xlsx file for each subfolder.

APPENDIX B. CONTACT ANALYSIS WORKFLOW

The workflow to process images containing contact/holes arrays is substantially identical to the one for line/space patterns. SMILE will interpret as contact images all the files listed in the lower table in the *Images* tab window. In this case, the user must specify some additional parameters.

B.1 Contact-specific parameters

To identify the general location of the contact profiles in an image, SMILE applies a Gaussian filter to reduce the image noise. The filter strength along the x and y axes is controlled by parameters *Denoise X* and *Denoise Y* respectively. A higher value will increase the strength of the filter in case the software detects spurious contours. If the contour detection method is set to *Filtered image*, the software will use the contours detected directly from

Figure 11. Contact-specific parameters.

the filtered image. If *Edge fit function* is selected, the contours will be detected using the same edge detection algorithm specified in the *Edge fit function* box in the Edge detection panel. The latter is generally the most accurate method of the two.

The *Contact sub-image size* parameter is expressed as a fraction of the diameter of the contact and indicates the size of the image subdomain SMILE attributes to the contact.

The *Radius fraction* parameter indicates the size of the radial interval where the software looks for the each point of the contact's contour.

If the *Exclude edges* box is checked, SMILE will remove the contacts at the edge of the image.

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