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Off-Line Metrology on SEM Images Using Gray Scale Morphology

Elias N. Zois[1,*], **Ioannis Raptis**[2], and **Vassilis Anastassopoulos**[3]

[1] Electronics Eng. Dept., Technological Educational Institution of Athens, Ag. Spiridonos 12, Athens 12210, Greece
[2] Inst. of Microelectronics NCSR "DEMOKRITOS", Ag. Paraskevi, Athens 15310, Greece
[3] Electronics Lab., Physics Dept., University of Patras, Patras 26500, Greece

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Abstract. Discrimination and metrology results of microlithographic patterns from top-down SEM images are explored by means of morphological image analysis. The method relies on the use of various morphological filters on a top down SEM image. The resulted images are segmented in order to derive a quality factor which discriminates the candidate images as under- or fully-developed. Furthermore, the fully developed images are processed in order to extract useful measurements. The proposed image analysis methodology achieves for first time, to the authors' knowledge, successful off-line discrimination between under-developed and fully-developed cases. For the latter case, the measuring method relies upon the evaluation of the connected regions in the SEM image after segmentation. This is expressed by the Useful Threshold Range (UTR), which corresponds to that specific value of connected regions obtained for the wider range of the threshold. The method is experimentally demonstrated by employing 72 test images from high resolution patterns. The evaluated critical pattern parameters are found in good agreement to those derived from on-line procedures.

Key words: Lithography; SEM metrology; morphology; image segmentation.

High accuracy estimation of pattern dimensions is particularly important for manufacturing high performance integrated circuits, since even a small change in the pattern dimensions could cause severe degradation to circuit performance. The most representative approaches for the measurement of pattern dimensions is based on cross-section Scanning Electron Microscopy (SEM) images, which is a destructive method since it employs sample cleavage. A number of non-destructive methods based on processing top-down SEM images have been developed and published so far [1–10]. Recently, image processing techniques have gained greater attention towards measuring several technologically important parameters such as the mean patternwidth and the corresponding variation [2–5].

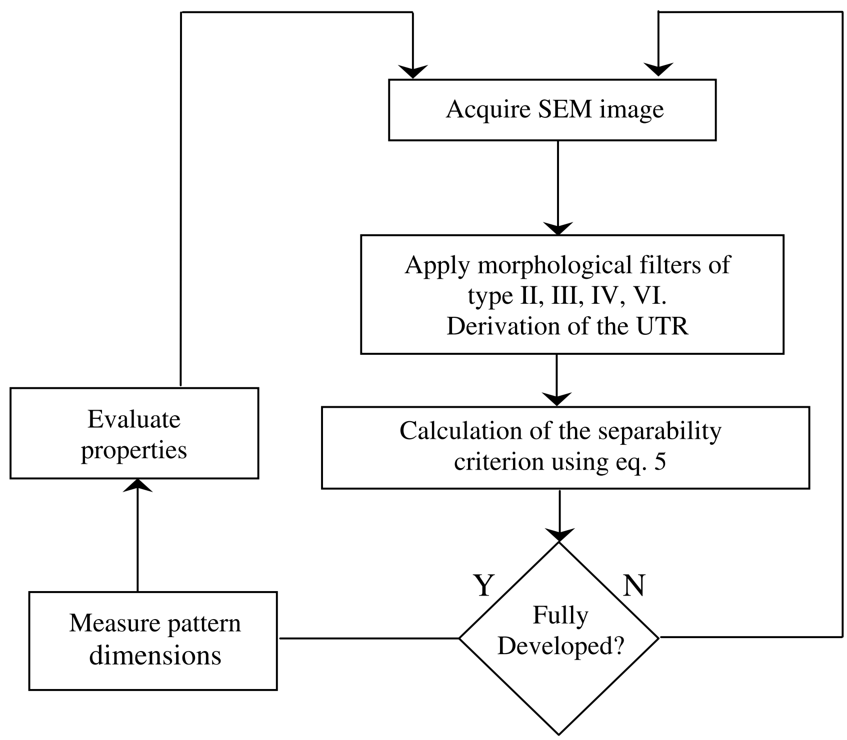
In the present work we propose the use of morphological filters in order to assess the above-mentioned parameters from top-down SEM images of high resolution patterns prepared by electron beam lithography. The basic operations in mathematical morphology are erosion and dilation [11, 12]. For a digitally scanned SEM image $z = f_D(x, y)$, the above operations can be performed on the umbra U of the function f_D defined as:

$$U(f_D(x, y)) = \{(x, y, z) \in R^2 \times R : f_D(x, y) \leq z\} \quad (1)$$

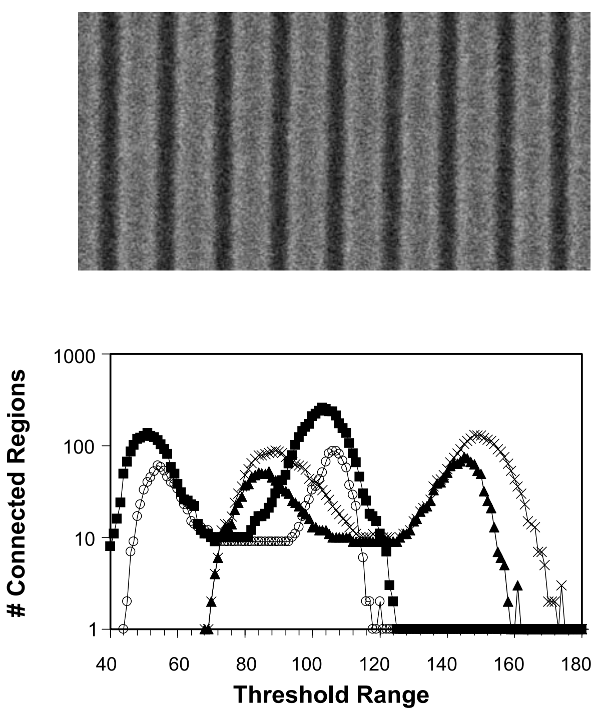
The function $f_D(x, y)$ can be reconstructed from its umbra as

$$f_D(x, y) = \sup\{z \in R : x, y \in U(f_D)\} = S(U(f_D)) \quad (2)$$

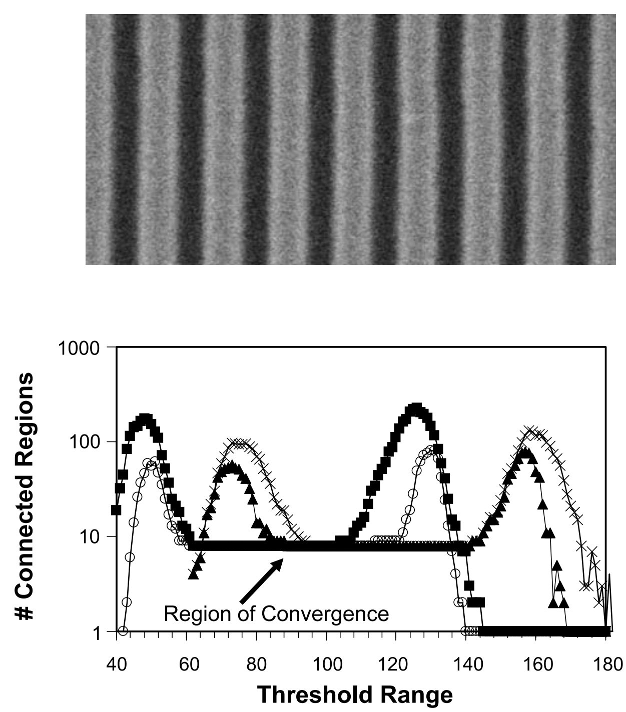
* Author for correspondence. E-mail: elias@ee.teiath.gr



(a)



(b)



(c)

Fig. 1. (a) Flowchart of the proposed experimental procedure. (b) Original SEM image and corresponding plots of connected regions vs. threshold after filtering. Case of under-developed pattern. (c) Case of fully-developed pattern. —×— Type II, —▲— Type III, —■— Type IV, —○— Type VI

Accordingly, the erosion and dilation of a function f_D by the function g, which is considered as a probing structuring element (S.E.), are defined accordingly as [11, 12]

$$f \ominus g = S[U[f] \ominus U[g]] \tag{3}$$

$$f \oplus g = S[U[f] \oplus U[g]] \tag{4}$$

Furthermore, an erosion followed by a dilation defines the opening operation (Type I filter) while the inverse sequence provides the closing operation (Type II). In addition, other filters can be formed using various combinations of the above described Type I and Type II filters. In particular, Type III filtering provides the mean value of the individual opening and closing operations. Type IV filtering is the output of the opening on the initial image and subsequent closing the opened image. Type V filtering is the output of the closing on the initial image and subsequent opening the closed image. Type VI is the mean value of the individual type IV and V filters. The form of the output image depends both on the selection of the morphological transformation as well as the S.E. structure. The statistics of the output of these types of filters have been extensively studied [12]. In this work, a pyramidal-like S.E. was selected to be applied in order to maintain the pattern edges and achieve adequate noise level rejection [13].

Experimental Results

The e-beam exposures were carried out at 50 KeV (EBPG-3, Leica) with 0.5 nA beam current and 50 nm beam diameter. The layout configuration used for the present study consists of long, dense, high resolution structures of 100 nm lines/300 nm spaces and 250 nm lines/250 nm spaces, exposed on 400 nm thick poly (methyl methacrylate) resist (positive tone) film over bulk Si substrate in the 150–700 $\mu C\,cm^{-2}$ exposure dose range. This range corresponds both to under- and fully-developed patterns for the development conditions applied. The SEM images were obtained with a calibrated LEO440 with LaB_6 filament.

The six morphological filters, mentioned in the previous section, are applied to the original SEM images by using a pyramidal type S.E. with window dimensions of 7×11 pixels. The S.E. height matrix is set according to *a-priori* examination of the original image histogram. The morphologically filtered images are segmented using a variable threshold covering the entire histogram dynamic range. For each specific threshold, indexing is performed [14] and the function of the evaluated connected regions is plotted vs. the threshold value. Extensive measurements on the available images with all six filters strongly indicate that type II, III, IV and VI filters perform satisfactorily on the specific experimental samples by means of reducing the images overall signal to noise ratio. Further experimentation on the type of these preprocessing filters requires analysis of the background noise which is out of the scope of this paper. The segmentation procedure is assumed to be successful for those values of the threshold where the previous graph presents a flat region named the Useful Threshold Range (UTR). The separability criterion, which will be used for discriminating the candidate images as under- or fully-developed, is expressed by evaluating the mean of the normalized UTRs:

$$Q = \frac{1}{4} \sum_{\text{All Filters}} \frac{\text{UTR size}}{\text{Original Image Dynamic Range}} \tag{5}$$

The proposed discrimination algorithm (Fig. 1a) was applied to 72 SEM images. In Fig. 1b and c the results from the application of the proposed methodology are presented for under-developed and fully developed patterns accordingly. The exposure dose for the under-developed example was 300 $\mu C\,cm^{-2}$ and the corresponding discrimination factor Q was evaluated equal to 0.11. The exposure dose used for the fully developed case was 400 $\mu C\,cm^{-2}$ while the discrimination factor Q was found equal to 0.37. In all examined cases the discrimination factor values for fully developed patterns are significantly greater than the corresponding values in the cases of under-developed patterns.

When the above factor exceeds a predetermined discrimination threshold, the corresponding number of regions coincides with the actual number of trenches, as can been seen in Fig. 1c. In this case, the procedure for measuring the pattern dimensions is performed. It is obvious that the derived measurements strongly depend on the applied threshold value. In most approaches published so far, the threshold value used is fixed. In this work, the median value of each derived set of measurements has been selected to provide the final trenchwidth evaluation. The global values, using the final four filters and for various cases, are listed in Table 1 for different exposure doses and patterns. In addition to the off-line measurements performed on the examined samples, the last column presents the on-line measurements. It has been observed that the type VI filter provides the most accurate results when compared to all others. This is justified by examining the results provided by all four processes against the on-line measurements. Commenting on the results we can state that type VI filter provides an enhanced output image when compared to others, in terms of a) preserving the information content onto the edges of the lithographic structures and b) smoothing the acquisition noise to the resist surface. The whole process was implemented using MATLAB. Typical execution times of the proposed algorithm for an image of 200×200 pixels were measured at

Table 1. Metrology results for the two types of fully developed patterns and for various exposure doses

Pattern type	Dose ($\mu C\,cm^{-2}$)	Type II (nm)	Type III (nm)	Type IV (nm)	Type VI (nm)	On-line (nm)
100 nmL/300 nmS	400	166.6	147.5	164.8	153.1	152.7
100 nmL/300 nmS	500	177.9	159.3	173.2	166.4	165.6
250 nmL/250 nmS	300	354.1	341.1	347.3	335.1	313.2
250 nmL/250 nmS	350	381.5	361.7	379.7	360.5	341.5

20 seconds, on a Pentium 1.8 GHz, in case of under developed images and 40 seconds for the case of fully developed patterns.

Conclusions

A novel, off-line image processing method for measuring characteristic features from top-down SEM image is proposed. It is based on the transformation of the SEM images using morphological operations, whereas at the same time it provides powerful discriminative results and accurate pattern dimension measurements when compared to the cross-section techniques. Further research is directed towards discrimination in the case of complex non-periodical layouts and the application of pattern segmentation algorithms with different structuring elements.

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