Evaluation of scanning electron microscope resolution

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A contribution to the evaluation of scanning electron microscope resolution

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ABSTRACT

The evaluation of Scanning Electron Microscopes (SEM) resolution through Two Dimensions Fast Fourier Transform (2D FFT) image analysis is becoming a standard[1,2,3]. We propose an improvement of these methods with a patented technique[4].

This new image processing is designed to extract the transfer function of the SEM from the picture and then to realize the analysis of this function.

A first algorithm extracts an "ideal" image of the sample from the "raw" image obtained on the equipment. Then a second algorithm extracts the SEM transfer function through a comparison between the two images ("ideal" and "raw"). Finally a third algorithm modelizes the transfer function as a two dimensions Normal function and draws out the result.

The representation of the transfer function of the SEM with a Normal function allows to define the shape of an Equivalent of the Electron Beam (EEB). This EEB represents the primary electron beam altered by the interactions with the sample and the losses in the acquisition loop. It is important to outline these alterations as they limit the sharpness of the images obtained from the tool.

This way of doing lessens the influence of sample parameters on the final results and thus represent more precisely the SEM Transfer Function.

Key words : Scanning Electron Microscope (SEM), Transfer function, Resolution, Microporous Silicon, Two Dimensions Fast Fourier Transform (2D FFT).

1. INTRODUCTION

The evaluation of Scanning Electron Microscopes (SEM) resolution through two Dimensions Fast Fourier Transform (2D FFT) image analysis is a way to get an operator free and global evaluation of the resolution increasing the reliability of the results. Human eye check of the resolution is tricky and subjective, on the other hand, image processing with frequency space transforms allows more objective determination[5]. This technique has a broad spectrum of applications from : the tool development, its installation as well as equipment monitoring by the customer[2]. Moreover it is now possible to find a tool designed for this application[1].

One of the limitation of this technique is to dissociate in the analyzed image, the contribution of the sample from the tool's one. For SEM engineers, the interesting information is preferentially the one depicting the ability of the tool to generate a precise image of the sample whichever it is. The goal is to quantify only the "filtration" effect of the tool on the images rather than the structure of the sample.

A second and minor limitation of our precedent method is the use of a threshold to determine the Cut Off Frequencies (COF) in the Fourier Domain (FD). Although, efficient and simple, this method is not perfect and cannot stand too large differences in the sample without loosing in repeatability.

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In this paper, we propose an improvement of the FFT image analysis methods with a new patented technique.
This new image processing is designed to extract the transfer function of the SEM out of the picture and then to realize the analysis of this function. The final result will be a more precise control of the tool, increasing the confidence of the users in the equipment as well as in the results of the controls realized on it. We perform this extraction through successive steps. The first one is the determination of an "ideal" image that represents the sample like a perfect SEM will do. The second is to compare this "ideal" image to the real one and to estimate the transfer function of the SEM. Finally it is fitted with an appropriate function and relevant parameters values are calculated.

2. ENVIRONMENT OF THE WORK

This work was realized during a student training for SGS Thomson Microelectronics. The limited time frame of a training did not allow a complete resolution of the numerous problems of the method development. For the same reason the software used in this work was based on previous work[2]. We decided to modify the existing "home made" macros written with Optimas 5* and with Excel**.

2.1 Scanning Electron Microscopes :

The first SEM used in this work is from Hitachi, model S-7280H. We mainly perform on this instrument the lithography or etch process evaluations and occasionally CD measurements (200 nm to 400 nm contact holes). The electron beam source is a cold field emission gun. The maximum emission current is 20 μA and the addressable accelerating voltage is from 0.7 kV to 2.0 kV.
The second SEM used in this work is from Applied Materials - Opal, model 7830i. We mainly perform on this instrument the after development or after etch CD measurements (180 nm to 400 nm features) and occasionally process evaluations. The electron beam source is a Schottky emission gun. The nominal probe current is around 6 pA and the nominal accelerating voltage is 0.6 kV.

2.2 Acquisition system :

The acquisition on Hitachi is made via a personal computer on a frame grabber board including the synchronization extraction from the image and its digitalization. This card may be fine tuned with the associated software (Winscan PC)*** allowing an easy adaptation to standard video signals from cameras or non standard ones from SEM. Image acquisition, processing and management are performed with the same software. The acquisition of images on the Opal system is integrated in its workstation.

2.3 Sample material choice :

For the advantages described in a previous work [2], and because this method has an increased need for high aspect ratio features, we choose the porous silicon as the test sample. (see next section)

3. IDEAL IMAGE DETERMINATION

3.1 Definition and attributes of an ideal image

In the step of the SEM verification we wish to extract from the images the information concerning the SEM itself rather than the sample description. To do so we first determine with the "raw" image obtained from the equipment what could be the image of the sample coming from a perfect tool. Then comparing this "ideal" image with the original ("raw") one, we can

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* Optimas 5 is a software from Optimas Corporation, 18911 North Creek Parkway, Suite 101, Bothell, WA-98011.

** Excel is a software from Microsoft Corporation.

*** Winscan PC software and the acquisition board are products of Newtec, 1028 chemin du carreau de Lanes, F-30900 NIMES, France.

evaluate the transfer function of the equipment.
The "ideal" image as described in the previous lines should have the following characteristics :
Sharpness : When using a higher resolution tool the first improvement we can see on the image is the better contrast and the better description of the small details of the sample. This is the sharpness.
Precision : The "ideal" image should be a precise picture of the sample. Any alteration of this image will affect the precision of the final result. If not all the sample information is in this image, these missing details of the sample will be added to the transfer function. On the contrary if there is more than the sample details in the "ideal" image, the transfer function will be incompletely estimated.
To ease this operation the sample used for the image acquisition must satisfy requirements in terms of aspect ratio and in term of population of the structures (morphological criterion). The sizes and positions must be random all across the sample to prevent artifacts in the FD. This sample must represent a spatial white noise, in that case the pictures of different locations of the sample gives the same spectrum in the FD.
We found that microporous silicon, with a random distribution of the diameter and location of the pores was well suited. Deep pores, of diameters ranging from 10 to 100 nm, almost perpendicular to the wafer surface with thin walls lead to high contrast images. This material is formed during an anodization of silicon in an hydrofluoric acid electrolyte[6]. This material is studied for capacitor or light-emitting devices[6,7,8].

3.2 Different ways to obtain the ideal image

To extract the "ideal" image out of the "raw" picture we identified several ways. Each of them has strong and weak points. The three main ones are the binarization of the image, the use of "golden" image, or the calculation through complex algorithms.

3.2.1 Binarization

In this approach we focus on the contrast of the image. All the pixels are converted either in black or in white. The technique looks simple but we have to determine the gray level that will be the frontier separating the light gray pixels that will be converted in white from the darker that will be turned into black ones.
The Plus and Minus of this technique are the following :
+ Simplicity
+ Speed
- Fidelity : we have a high contrast image but the smallest details are lost with this mode.

3.2.2 High resolution SEM "Golden Image"

If the sample fulfills the morphological criterion defined before (spatial white noise), it is possible to use one reference image of this sample or a similar one obtained on a higher resolution SEM. Each and every region having the same spectrum in the FD, this unique reference will be representative of the sample. Our porous silicon sample has these properties and we could use a golden image acquired on a high resolution SEM at the same magnification as the control.
The Plus and Minus of this technique are the following :
+ Simplicity
+ Speed
- Fidelity : We need two simplifications in this mode. The first one is the assumption of equivalence between any location of the sample and the second is the hypothesis that a higher resolution SEM generates pictures of the sample with negligible errors.
- One golden image for each working magnification.
- The working sample must be very similar to the reference sample who generates the golden image.
- Usually the reference sample is destroyed because higher resolution SEM have a small chamber !

3.2.3 Multi-acquisition of the image or multi-iteration function

Some workers[9] has obtained better resolution on images through a multi-acquisition mode with small object displacements and rebuilt of a higher resolution image.
It may be possible to refine the ideal image after the calculation and modelization of an imperfect transfer function that is fed back at the beginning of the loop and so on...
The Plus and Minus of these techniques are the following :
+ All types of sample are accepted
+ Precise if the rebuild algorithm is robust enough or if there is a convergence in the iterations for the ideal image calculation.
- The software development phase is time consuming, complex and requires a more adapted software package.
- The calculation phase is time consuming as well.

3.3 Our choice

We have chosen the binarization technique for this work to test this method because of the limited software package we have and because we wished to have a fast calculation. The more complex iterating solution needed an image generation software to close the feed back loop, such a software was not available within the time frame of this work. Moreover, the tests we conducted on partial routines of this kind of technique indicated that the treatment time may be a quarter of a minute to realize one loop, this will exclude the "real time" use of the method until Personal Computers get higher operating speed. The golden image method needed to associate to this technique and to manage an image base, this is not convenient.
We tried to overcome the limitation noticed in a previous section with the binarization technique, working on the determination of the best transition limit in the gray levels. Through the different ways to delimit the separation between black and white pixels we did not consider the 128 threshold. This fixed level would introduce a sensitivity of this step to the brightness of the image. In order to reduce the impact of these image to image brightness variations we choose the level that is at the maximum value of the gray level histogram of each image.

4. CALCULATION OF THE TRANSFER FUNCTION

4.1 Principle

Through the 2D FFT we benefit of interesting properties. The first one is the ability of a global calculation over the entire image a or major part of it. The second is the conversion of the small dimensions in high frequencies, this is attractive because for the determination of the resolution we have to look for the small size features. Another powerful property of the Fourier transforms (FT) is the potentiality for the deconvolution of the different components of a function.
Let h, g and f be three functions.
If h is the convolution of g and f :

$$h = f \otimes g \tag{1}$$

If g and f are linear functions
Let â be the Fourier transform of the function a.

$$\hat{h} = f \hat{\otimes} g \tag{2}$$

$$\hat{h} = \hat{f} \times \hat{g} \tag{3}$$

Now let s be the function representing the SEM image. This function associate to each pixel (coordinates x and y) of the image a value ranging from 0 to 255 equal to its gray level. The lower (respectively higher) is the value the darker (respectively clearer) is the pixel (0 = black and 255 = white). The clear pixels depict the silicon and the black pixels depict

the pores in a porous silicon image.
Let i be the function associated to the "ideal" image. Following the choice we have described in the previous section, for each pixel this function will take either the value 0 or the value 255.
Let t be the SEM transfer function.
The SEM image is the result of the convolution of the "ideal" image and of the transfer function. Using equations (1) to (3) and assuming in first approximation that the SEM response is linear we obtain :

$$\hat{s} = \hat{i} \times \hat{t} \tag{4}$$

Or for the transfer function :

$$\hat{t} = \frac{\hat{s}}{\hat{i}} \tag{5}$$

When dividing the FT of the SEM image by the FT of the "ideal" image we obtain an approximation of the FT of transfer function of the SEM.

4.2 Realization

After extraction of the "ideal" image from the SEM image we process them through 2D FFT then we realize the division of the two FT. If not all the image area is used for the calculation the same pixels must be processed in the two images. Then this FT is smoothed by a convolution with a "two dimensions door function". This give the same result as a moving average of the pixels in each direction of the FD.
At this point it is possible to process a reverse FT that will represent the EEB. We choose not to do it because of the small size of this EEB (few pixels on the image), thus any calculation would induce very large relative error.

5. MODELIZATION OF THE TRANSFER FUNCTION

5.1 Model choice

When generating an image through a SEM, we have a combination of several process. One is the size of the incident electron beam and most precisely its shape. Another is the emission of the secondary electrons in different modes after the interaction with the sample. We assume that all these different steps increase the size of the secondary beam as collected by the detectors while maintaining a shape close to the one of the incident beam. As a result we consider that the transfer function as extracted may represent the Equivalent of the Electron Beam (EEB) that will gave the same image with a perfect SEM and without sample interaction.
E. Vicario[10] suggest to describe the incident beam of a SEM with a Lorentzian function or in a first approximation with a Normal or Gaussian function. We propose to modelize the EEB with a Normal function. At this step we benefit of an other property of the FT, the FT of a Normal function is an other Normal Function. As a consequence we can modelize the result of the division described in section 4.2 (the FT of the EEB) with a Normal function and so, there is no use to recover the EEB through a forward Fourier Transform.

5.2 Tuning of parameters

At this step the method is very close to the ones described earlier by H. Martin or G. Fanget [11,2]. A predefined number of directions (usually 60) of the FD are checked. The contrast profile of each direction is modelized with a Gaussian law whose equation is :

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-m)^2}{2\sigma^2}\right) \qquad (6)$$

Where : $f(x)$ are the gray levels of the profile.

x are the frequencies along the profile.

σ is the standard deviation of those frequencies.

m is their mean value.

Considering the profiles, the mean value m is zero as they are symetrical in reference to the null frequency. On each of them a Normal function is fitted and the Cut Off Frequency (COF) is estimated at :

$$COF \approx 3\sigma$$

We choose this number because, for a Normal function, 99.7 % of the data are within the interval $]m - 3\sigma; m + 3\sigma[$. This mean that our description of the FT of the EEB is precise enough, knowing that some approximations have been made previously (see sections 4.1 and 5.1) to simplify this method. This way to determine the COF is automatically adjusted at the mean contrast level, it was not the case with the arbitrary threshold used in our previous method[2].

5.3 Formatting of the results

The mean, maximum and minimum values over the 60 COF are extracted. After what the "Eccentricity", Max COF over min COF ratio and the "Tilt", Max COF direction angle are determined. A "Resolution Contour Map" (fig. 1) may be issued and mean COF, min COF, Max COF, Eccentricity and Tilt may be printed as a "Resolution Parameters Sheet"(fig. 2).

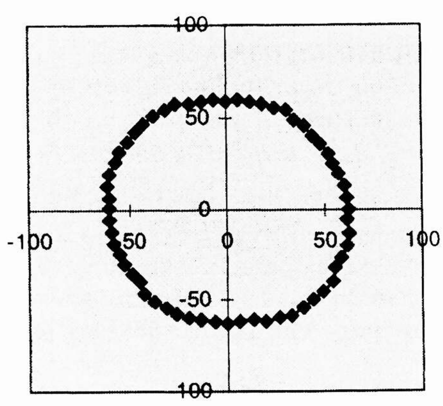


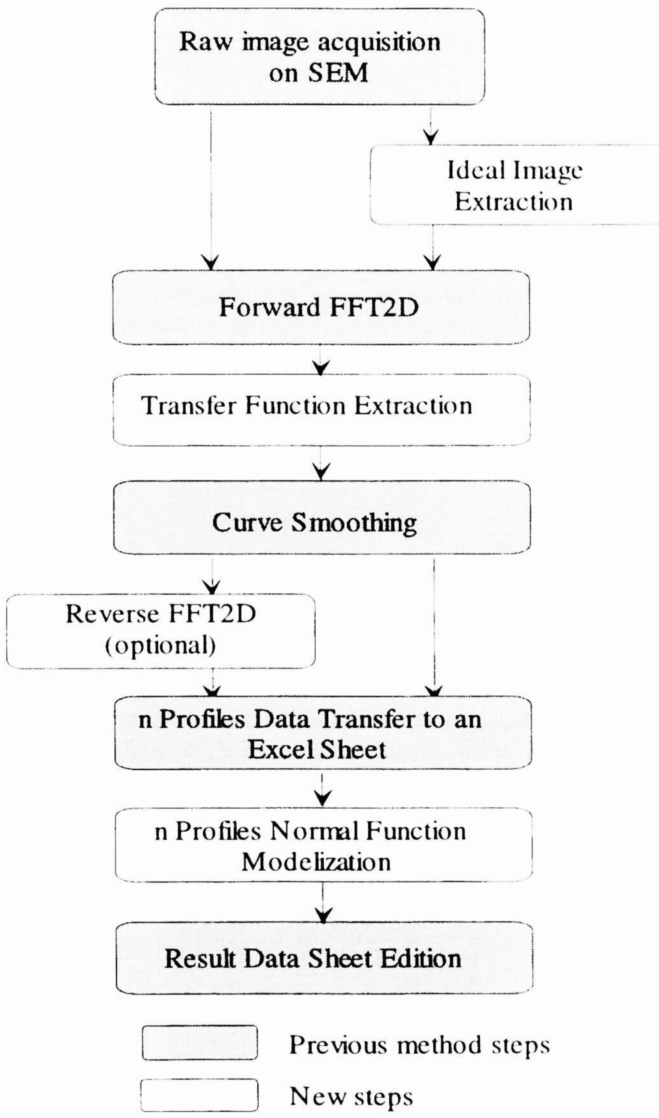
Fig. 1 : Resolution Contour Map.

Resolution Parameter Sheet			
	Date	: 29/12/1997 @ 6:35	
SEM		: S 7280H	
Acceleration Voltage		: 1 kV	
Emission Current		: 10 µA	
Magnification		: 100 kX	
Acquisition Mode		: 32 scans	
Calibration		: K1007280	
Image Reference		: C:/IMAGES/LITHO/METRO/RESOL/IMAGES/c3630a10.TIF	
Comments		: Ok	
Measurement Conditions			
Angle Pitch		: 6°	
Area Size		: 256 x 256 Pixels	
Digitalisation Pitch		: 1.749 nm // 571.89 µm-1	
RESULTS			
Mean COF		: 62.2 µm-1	
Max COF		: 67 µm-1 @ 324°	
min COF		: 58.1 µm-1 @ 90°	
Eccentricity		: 0.87	("shape factor")
Tilt		: 144°	("Oval Tilt")

Fig. 2 : Resolution Parameter Sheet.

6. RESULTS

6.1 Flow chart of the method :



6.2 Ideal image

As expected the binarization was a too simple technique and we demonstrate that some information coming from the acquisition defects are still present in the "ideal" image (see fig. 3a and 3b). We tried to tune the technique moving the black to white limit at different percentage below or above the maximum of the brightness histogram selected first, without overcoming this limitation.

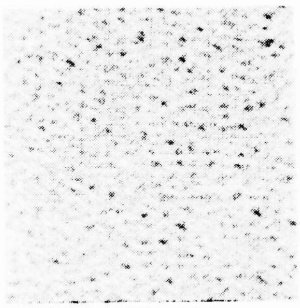


Fig. 3a : "Real" image

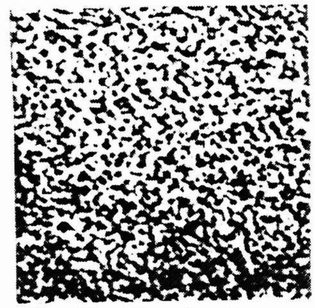


Fig. 3b : Binarized image

We propose to improve this technique following two ways :
In the real world of images, even the sharpest ones have not this extreme contrast we obtain with the binarization . The real images are not made of two dimensions door functions but there are progressive transitions between black and white pixels areas. For a better extraction we have to increase the speed of the gray transitions between the pixels rather than convert this transition into steep steps from black to white. Some analysis on high resolution pictures of samples similar to the ones used will indicate what is this transition speed to apply in the real image determination. This analysis may indicate as well if a wavelet transform processing could improve the extraction through a noise reduction.
A second possibility may improve the result of this step, there is a large panel of filtering techniques that could complement the method improving the "real" images quality. All these filters are available in most of the image analysis software.

6.3 Transfer function

As a consequence of the limited quality of the "ideal" image we have obtained through the binarization step, we get unexpected artifacts in the transfer function. The best demonstration of the limit of the binarization we performed is that the reverse FFT of this theoretical transfer function gives an image where the sample structure information is still present (see fig. 4a to 4c).
On the other end we have a strong amplification of the high frequencies in the Fourier Domain. This is very positive because it unveils the small imperfections of the acquisition chain as well as it increases all the larger ones. This phenomenon is the consequence of the division of the images, because the contrast levels in the high frequencies areas is close to zero. It is interesting because it could ease the tuning of the equipment during its development step or during its installation or servicing

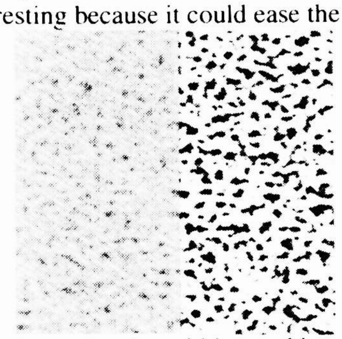


Fig. 4a : "Real" and binarzed images

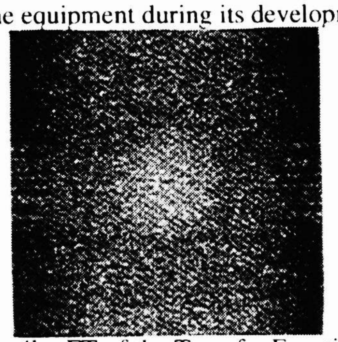


Fig. 4b : FT of the Transfer Function

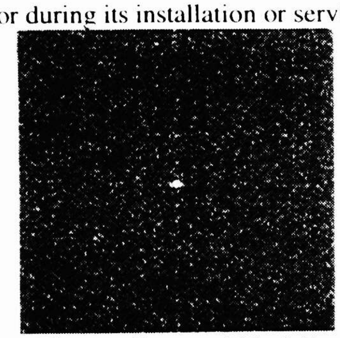


Fig. 4c : Reverse FT of 4b (Transfer Function)

In the standard use of the method, the high frequencies amplification effect may be ignored by screening out of the Fourier Domain of both the "raw" and "ideal" images the frequencies above 110 to120 % of the upper specification limit of the maximum COF.
A second improvement may be possible through the use of a wavelet transform rather than a Fourier transform in the image analysis process. Fourier transform decomposes the analyzed function in an equivalent sum of cosine functions. The most universal wavelet transform allows to use any other type of periodic function in the function analysis. This may give an other degree of freedom that allows a better description of the image and, as a consequence, a more precise transfer function extraction.

6.4 Modelization

Despite the actual imperfections of the first two steps of the method, the final results after modelization are interesting. We found an improvement on the static repeatability of the maximum COF (on different areas within one image), that goes down from 15 µm-1 with our previous method to 2 µm-1 with the new one. The image to image repeatability of the maximum COF is not as good, it increases from 7.5 µm-1 with our previous method to > 20 µm-1 with the new one.
The two main causes of this result are firstly the software unsuitability for the modelization and secondly the need to screen the highest frequencies out of the FD as mentioned in the previous section.
We observe that the modelization is not efficient on some types of curves leading to large errors. We have observed ratios up to 1.5 between the modelized COF and the one that one can estimate with a direct reading on the curve (see fig. 5). This comes essentially from the contrast that is time to time first increasing up to a maximum and then "normally" decreasing.

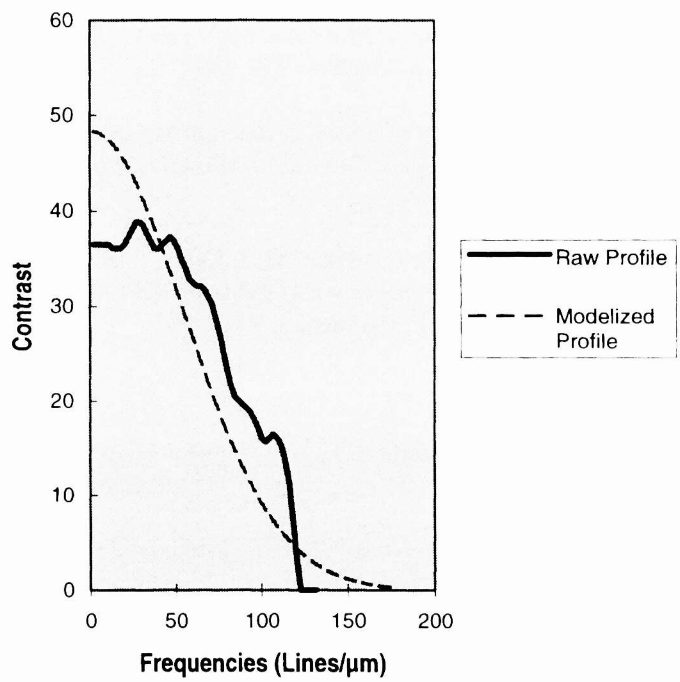


Fig. 5 : Inaccurate Modelization

This part of the curves in the lower frequencies is influenced mainly by the contrast of the original image, and is not representative of the SEM resolution. As explained in the previous section we believe that the screening of the amplified highest frequencies will allow a better accomplishment of this last step of the method. These two parts of the FD should be screened and the fit must be done only on the medium frequencies that are typical of the SEM filtering effect[11]. This outline the necessity to have a powerful mathematical software for this application.

7. CONCLUSION

In this paper, we propose a new method for the evaluation of SEM resolution, this technique is designed to reduce or suppress the sample influence on the results.
This new approach has to be improved to overcome the limits outlined by this work. These limits are an insufficient sample influence reduction and a poor dynamic repeatability. The origins of these problems are identified, first one is the imperfect "ideal" image determination and the second is the incorrect modelization.
In order to solve them we propose some directions to correct or to modify this technique. Firstly we propose to develop a

more refined "ideal" image extraction introducing a more complex algorithm and using customized filters. Secondly we propose to employ an other software package being best suited for the modelization.

8. ACKNOWLEDGMENTS

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S. Tedesco reviewed this article we appreciate his relevant remarks.

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