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Challenges for scanning electron microscopy and inspection on the nanometer scale for non-IC application – and how to tackle them using computational techniques

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ABSTRACT

In this paper key challenges posed on metrology by feature dimensions of 20nm and below are discussed. In detail, the need for software-based tools for SEM image acquisition and image analysis in environments where CD-SEMs are not available and/or not flexible enough to cover all inspection tasks is outlined. These environments include research at universities as well as industrial R&D environments focused on non-IC applications. The benefits of combining automated image acquisition and analysis with computational techniques to simulate image generation in a conventional analytical SEM with respect to the overall reliability, precision and speed of inspection will be demonstrated using real-life inspection tasks as demonstrators.

Keywords: Scanning Electron Microscopy; SEM; Inspection; Metrology; Nanofabrication; Nanodevices; Simulation

1. INTRODUCTION

   In the decades that followed its invention by Manfred von Ardenne in 1937 the scanning electron microscope (SEM) became an additional set of eyes for scientists in almost every field of research, including biology, medicine, physics, mechanical engineering, construction engineering, material science and electronics. SEM-based inspections are routinely used in laboratories around the world as a key method in nanoscale devices fabrication. With the ever-decreasing dimensions of such devices, approaching a few nanometers and a few atomic layers, composed of conductive and non-conductive materials in complex 3D topographies, and increasingly demanding requirements regarding inspection accuracy, novel nanoelectronic and nanophotonic devices pose considerable challenges for this type of inspections. In standard production environments for integrated circuits (ICs), highly dedicated and automated critical dimension SEMs (CD-SEMs) are the work-horses for high resolution inspection and metrology. However, such systems fall short to meet the needs and requirements of both R&D environments as well as custom nano-scale applications with regards to flexibility and cost. Thus, most nano-fabrication centers, University laboratories as well as industrial R&D and prototyping departments still rely on manually operated classic analytical SEMs. Typically, the operator has to acquire and analyze an SEM picture and extract the required information manually without the support of automated image acquisition or algorithm-based image analysis. Therefore, it is a major challenge to obtain reproducible and consistent data, as measurement results may significantly depend on both the operator and the specific tool settings used during the inspection. In this paper, we introduce a methodology to cope with these challenges.

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2. SOFTWARE-SUPPORTED IMAGE ACQUISITION

While careful tool operation can guarantee that key parameters such as acceleration voltage or working distance are chosen consistently throughout inspections. However, many other SEM inspection parameters with potential effects on the actual inspection result, including image brightness and contrast or internal settings affecting signal detection, are much harder to control by a user as modern SEMs often automatically optimize these settings in favor of high contrast images. Furthermore, depending on the inspection history, e.g. previously used magnification settings, images obtained at the same nominal magnification are often recorded using different amplifier stages and/or DACs. As those electronic components will always have slight nonlinearities in their effective characteristics this will lead to small differences with respect to the actual area covered by an image or its distortion. Therefore, an automated image acquisition, which not only guarantees that images are obtained from exact pre-defined positions on a sample or wafer but also can circumvent many of the above-mentioned issues by setting the SEM tool to well-defined conditions is crucial to achieve reproducible imaging results if feature with CDs on the nanometer scale are investigated. While CD-SEMs heavily rely on such techniques they are rarely used in combination with classic analytical SEMs. At the same time, most state of the art SEMs provide build-in features such as macro recording functionality which can easily be used to implement an flexible image acquisition automation. By exploiting the syntax of the recorded macros and/or the macro language of a tool it is even possible to establish a programmable fully automated image acquisition featuring user-friendly GUIs. An early example for in-house solution towards macro language based image acquisition automation is AMO's *SEMacroDesigner* [1] tool shown in Figure 1a. It allows the SEM operator to create a macro file controlling the recording of SEM images at pre-defined positions of a die or wafer. Such a macro can then be used to automatically record hundreds of SEM images using a pre-defined tool parameter set without the need of any additional operator-tool interaction.

As feature sizes shrink such simple but still highly effective methods of making CD-SEM technology available for conventional SEMs will become standard in R&D SEM inspection, enabling the reproducible acquisition of SEM images with identical tool parameter sets and quality needed for a precise image analysis on nanometer scale.
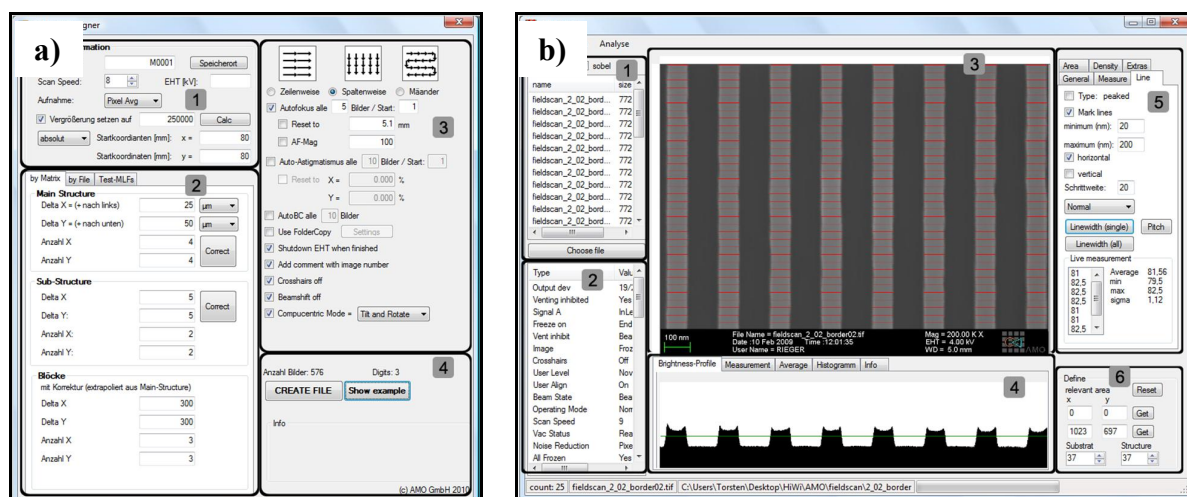

Figure 1. In-house solutions for a) automated SEM image acquisition and b) analysis at AMO by the *SEMacroDesigner* and *SEMalyser* tools. [1]

3. IMAGE DATA ANALYSIS

With the problem of an automated image acquisition for classical SEMs being solved by a combination of the tools' build-in macro capabilities and/or programming in their macro language, the next major challenge is image analysis. Particularly the task to extract data from an SEM image and calculate key figures of merit (FoM) such as CD or line width and line edge roughness (LER) values becomes more demanding as the number of images which need to be processed can be significantly increased by the extensive use of image acquisition automation.

Build-in image analysis capabilities of most state of the art conventional SEMs are very limited. The measurement of CDs is usually only supported for a very small number of measurement points per image and is highly operator-

dependent means to measure LER and other FoM needed to judge the quality of a nanoscale feature are often completely missing.

Again, a first step towards a solution for this problem can be the development of a basic in-house software tool for SEM image data analysis such as AMO's *SEMalyser* tool shown in Figure 1b. As an alternative, software packages such as Olympus´ *analySIS*, originally developed to analyze images acquired by optical microscopy, can be adapted to the field of SEM image analysis. Such tools provide means for a fast and reliable measurement of basic data such as CD values at many measurements sites per image and for the many images provided by an automated image acquisition. At the same time, they also offer options to extract data such as LER from the images. To fully utilize the potential of an automated analysis of SEM images, dedicated software packages such as GenISys' *ProSEM* can be used, encompassing most of the data acquisition and analysis features of CD-SEMs. The combination of automated image acquisition and sophisticated image data analysis can help to maintain a high degree of flexibility, which is crucial for an R&D environment, while at the same time providing the measurement accuracy and reliability needed for scientific research.

A basic example for the benefit of using such dedicated software tools for SEM image analysis is given in Figure 2. In a manual micrograph analysis, only a limited amount of data, e.g. CD values, can be measured within a reasonable inspection time. In a software-based analysis, in contrast, much larger datasets can be extracted and evaluated. For the micrograph shown in Figure 2a, five line width and pitch values were measured by hand. Note that the amount of CD measurements carried out in this example already represents the maximum number of measurements supported by the *Zeiss Supra 60 VP* SEM tool used here for this lines & spaces scenario. An automated analysis of the same image contains data from hundreds of line width and pitch measurements (Figure 2b). Furthermore, additional information, such LER data or data regarding the image orientation relative to the features, can easily be extracted (see inset of Figure 2b), significantly improving the overall quality of the inspection.
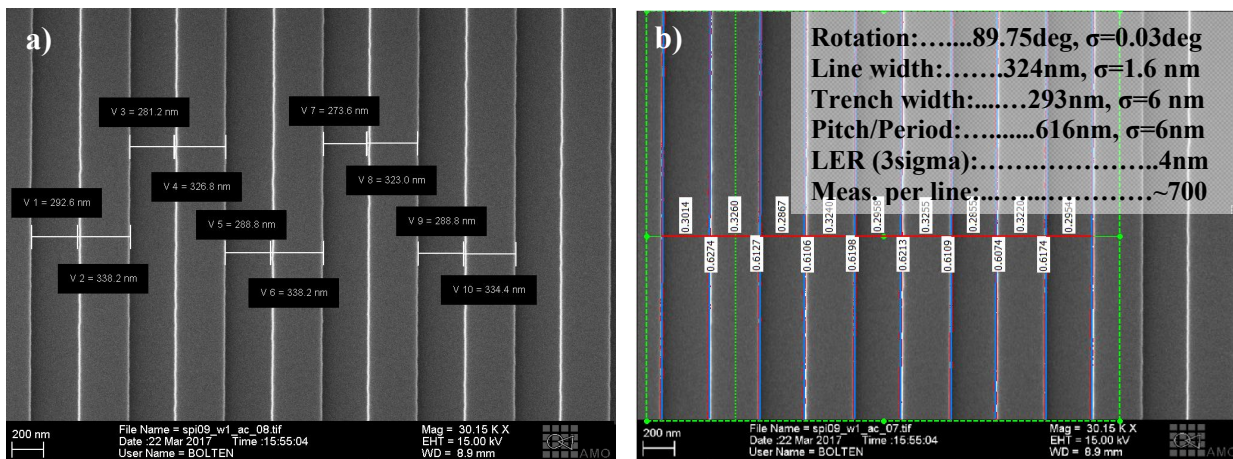

Figure 2. SEM micrograph of a grating structure, evaluated by a) hand and b) *ProSEM*. Inset: details of data automatically extracted from the micrograph. Note that the automated measurement by *ProSEM* analyses data along the whole lines while the measurement by hand only measures data at a specific position in each line.

The image analysis capabilities of CD-SEMs are strongly focused on IC-related inspection task and hence almost exclusively refer to Manhattan-type features. For many non-IC applications such as photonics inspection tasks also include non-Manhattan features like curvatures or circles which often form crucial parts of a device. Here, the analytical means of CD-SEMs are too limited to cope with all inspection tasks. Software packages like *analySIS* or *ProSEM* also include algorithms to analyze non-Manhattan structures, proving their users with the tools needed for an accurate metrology of such features. An example is given in Figure 3, featuring an SEM image of a 1D photonic crystal resonator. The complete resonator structure with four measurement boxes is shown in Figure 3a. In Figure 3b a detailed view of the forth measurement is depicted. The data extracted by the four measurements are summarized in Table 1. Note that such data can easily be saved as a spreadsheet using the above-mentioned tools while in a manual image analysis using an SEM's build-in functionality the user often has to take care of collecting such data for further evaluation and analysis.
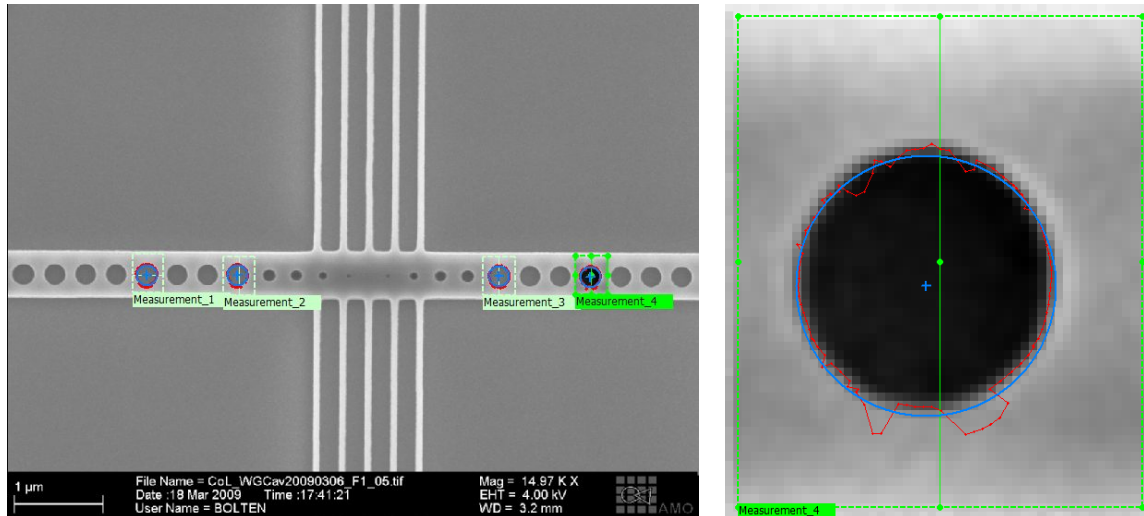
Figure 3. SEM micrograph of a 1D photonic crystal resonator structure. A) Overview including four measurement boxes and b) detailed view of the fourth measurement box. Measurements have been carried out using *ProSEM*.

Table 1. Data extracted from circle measurements

# of Meas.	Diameter [μm]	Area [μm²]	Fit error mean [μm]	Fit error std. dev. [μm]
1	0.246	0.474	0.006	0.004
2	0.241	0.455	0.006	0.004
3	0.239	0.450	0.005	0.004
4	0.236	0.438	0.006	0.005

4. SIMULATION OF SEM IMAGE GENERATION

While this approach is sufficient for many inspection challenges, the inspection of even more aggressively scaled and nano-patterned features can only be tackled by applying different, much more sophisticate and complex techniques of SEM image data analysis. For a wide range of novel applications both in the area of conventional nanoelectroics as well as in non-IC fields such as optics, sensing or energy features with CDs of 20 nm and well below provide additional challenges for SEM inspection. On this size scale tool-related effects such as charging or the beam blur, leading to image distortions, can significantly alter the image recorded by the tool. As a result SEM images no longer represent the inspected features themselves but a convolution of the feature and the imaging process [2].

To demonstrate this effect, we derived a design for several 20 nm wide sidewall modulated nanowire features. These consisted of a straight line, a chain of circles and chains of up- and downward facing triangles as depicted in Figure 4a. The design was used to expose a 40 nm layer of Hydrogen Silsesquioxane (HSQ) resist on a silicon sample using a Raith EBPG 5200 electron beam lithography system operated at an acceleration voltage of 100kV. The exposed resist has been developed using a high contrast development process based on highly concentrated Tetramethylammonium hydroxide (TMAH) [3] and the resulting features have been inspected using the *Zeiss Supra 60 VP* SEM tool. The resulting SEM micrograph for the chains of up- and downward facing triangles, features *C* and *D*, is presented in Figure 4b. The SEM image reveals a significant deviation from the design to the visualization of the features in the SEM image.
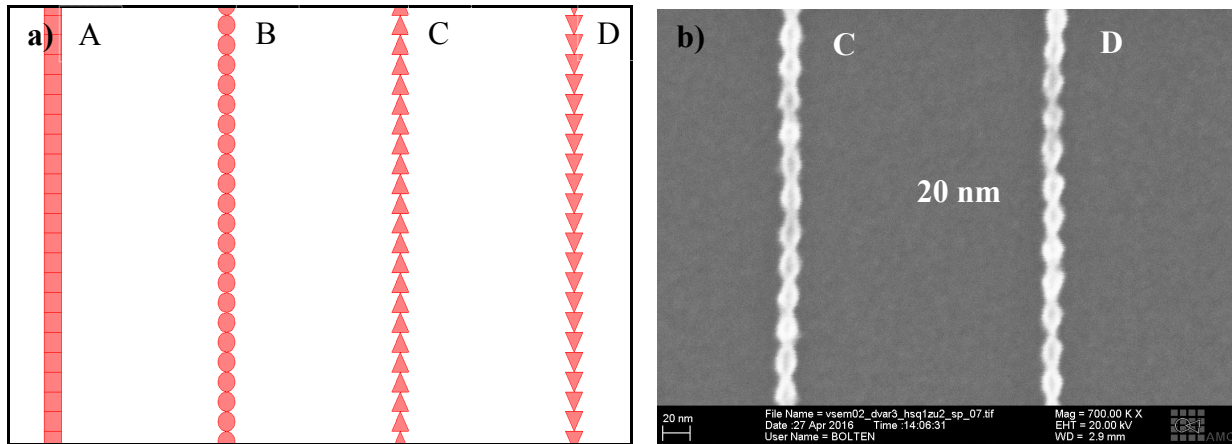
Figure 4. Sidewall modulated nanowires. a) Design and b) HSQ resist features after development

We have used *virtualSEM*, a Monte-Carlo based SEM simulation software package currently under development by GenISys, to investigate the reason for these deviations. In particular, the electron beam shape, the interaction of the electrons with the sample in 3D including electron scattering, sample charging, electric fields, tracing of emitted electrons in the field and the resulting detector signal were simulated. The simulation results are summarized in Figure 5. The simulation only matches the design accurately if the charging simulation feature is turned off and if a highly focused beam with a diameter of only 1 nm is assumed as shown in Figure 5a. When a more realistic beam diameter of 3 nm is assumed in the simulations, blurring is predicted, caused by the larger beam (Figure 5b). Finally, when charging effects are also considered for the simulation (Figure 5c), the simulated image shows distortions and deviations from the design very similar to the actual SEM image. Hence, a substantial part of the deviation between design and actual SEM image can be attributed to beam blur and charging effects. The actual features thus probably resemble the design much better than their SEM images suggest.
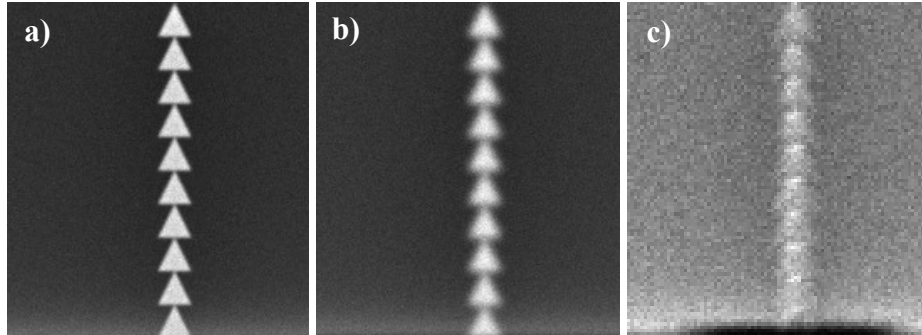

Figure 5. Chain of triangular features formed in a 40 nm HSQ layer simulated using *virtualSEM*. a) 1 nm beam diameter, no charging effects; b) 3 nm beam diameter, no charging effects and c) 3 nm beam diameter, charging effects considered.

Hence, by accurate simulation of the image acquisition process of an SEM effects such as charging or beam blur as suggested in Figure 5 can be precisely predicted. The image can then be de-convoluted into the tool-related distortion and the actual features and the latter can be reconstructed from the SEM image data, providing the operator with a more accurate image of the inspected features.

A process flow for such simulation-based image correction could be as follows:
a) SEM image acquisition based on a well-defined set of tool parameters;
b) Simulation of image acquisition based on the design;
c) Feature reconstruction based on the actual image and the simulation.

For the reconstruction of the actual features two basic options are available: The faster but less accurate one is to assume a perfect replication of the design. In this case the actual feature will be reconstructed by using subtracting the distortion effects predicted by the simulation from the actual SEM image data. A much slower but more

accurate approach is to repeatedly simulate the image acquisition with modified versions of the design until simulated and actual SEM image are in good agreement.

Another promising application for simulation-based computational SEM image analysis is the top-down imaging of topographic features. Here, such algorithms can help to derive three-dimensional information (step heights, sidewall angle, and buried defects). For both these and many other SEM-based inspection tasks algorithmic support by means of sophisticated simulation tools and accompanying modelling will be key to maintain the high level of data quality extracted from SEM images of features with ever-decreasing dimensions.

5. CONCLUSION

The use of both software tools for automated image acquisition and analysis as well as for the simulation of the image generation by a conventional analytical SEM has been motivated in this work. It has been outlined why such tools can significantly improve the overall quality of SEM inspections with respect to speed, precision and reliability.

Automated image acquisition and image analysis are standard techniques in semiconductor industry, usually provided by CD-SEMs. The same functionality can also be realized in more R&D oriented environments by extensive usage of macro and scripting capabilities offered by many state of the art analytical SEMs in combination with novel dedicated SEM image analysis solutions . At the same time, such tools often provide additional analytical capabilities, e.g. functionality to evaluate non-Manhattan features such as circles, not available in CD-SEMs.

Furthermore, the novel concept of using simulation to precisely predict the influence of charging effects or beam blur on the actual SEM image presented here offers both additional analytical capabilities as well as improved inspection reliability. Such techniques may develop into the metrology counterparts of proximity effect correction and other computational techniques which helped to extend lithography into the sub-20nm CD regime.

6. ACKNOWLEDGMENTS

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