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Experimental investigation on the influence of instrument settings on pixel size and nonlinearity in SEM image formation

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Abstract

The work deals with an experimental investigation on the influence of three Scanning Electron Microscope (SEM) instrument settings, accelerating voltage, spot size and magnification, on the image formation process. Pixel size and nonlinearity were chosen as output parameters related to image quality and resolution. A silicon grating calibrated artifact was employed to investigate qualitatively and quantitatively, through a designed experiment approach, the parameters relevance. SEM magnification was found to account by far for the largest contribution on both parameters under consideration. Optimal instrument settings were also identified.

1 Introduction

Image quality is a crucial issue to be addressed when traceable SEM measurements are required. An experimental investigation was carried out concerning the influence of SEM instrument settings on the image formation process considering pixel size and nonlinearity, related to image quality and resolution, as output parameters. Qualitative and quantitative contributions of three main influencing factors, accelerating voltage *HV*, spot size *SS* and magnification *M*, were investigated using a silicon grating as calibrated artifact. A factorial experiment was adopted accounting for typical working conditions, and seek estimates of effects of major parameters under consideration. Data analysis exploited two well established techniques, i.e. *Best Subset Regression* ([1]) and an extension of classic *Yates algorithm* ([2], [3]).

2 Theoretical basis of image formation

SEM's electron beam is thermionically emitted from a heated filament with an energy typically ranging from a few hundreds to forty thousands electron volt and focused to a few nanometers diameter spot. The beam is then deflected in the *x* and *y* axes scanning in a raster mode over a rectangular area on the sample. Thus, SEM image quality and resolution depend on the scanning area, related to the magnification, and on beam characteristics linked to the spot size and the accelerating voltage. A high accelerating voltage leads to a better image resolution, but also to more unclear surface structures and more sample damage. A decrease in the spot size results in higher image resolution although more grainy and noisy images are obtained. The magnification is also strictly related to the resolution, since the higher the former the smaller is the pixel size, even if this setting results in a smaller field of view [4]. A proper parameter adjustment is therefore crucial to perform traceable 2D SEM measurements, as well as when stereophotogrammetry techniques are employed to perform 3D SEM reconstructions [5].

3 Exploitation of a calibrated artifact

An ultrasharp silicon grating TGT1 from NT-MDT, intended for SPM calibration, was chosen as calibrated artifact. It consists of an array of sharp tips with a period of 3.00±0.05 µm and a diagonal period of 2.12 µm as stated in the calibration certificate. The period can be calculated from SEM images using software SPIP (Scanning Probe Image Processor) and the related routine Unit Cell Detection, allowing also nonlinearity evaluation [6]. Figure 1 shows two SEM images of the artifact, acquired under different conditions. The effect of accelerating voltage and spot size at a constant magnification are seen to agree with the theoretical description (section 2).

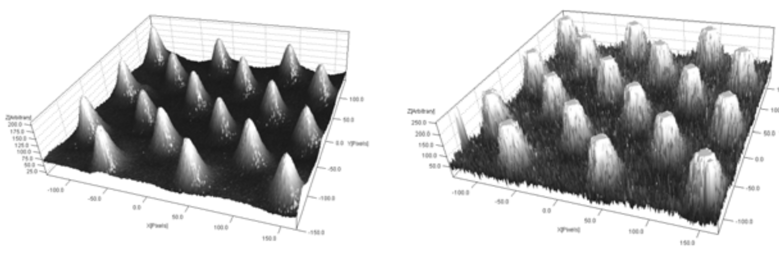

Figure 1: 3D rendering of the calibrated artifact from SEM images with *HV*=5.0 kV and *SS*=7.0 nm (left) and *HV*=10 kV and *SS*=4.0 nm (right) both at *M*=10000x. Qualitatively, the optimum parameters setting results *HV*=10.0 kV and *SS*=4.0 nm.

4 Designed experiment approach and specific problems

Accelerating voltage (*HV*), spot size (*SS*) and magnification (*M*) were selected as factors to investigate their effects on SEM image formation process. Pixel size and nonlinearity were identified as the main parameters related to image quality and resolution and accordingly considered as response variables. The factors under consideration are liable to have nonlinear effects on both responses, therefore three levels were chosen for each factor. These levels were selected equally spaced (on a logarithmic scale in case of *M*) covering as much as possible the sample space. A 3^3 factorial plane was then produced as described in table 1.

Table 1: DoE factors and levels.

Factors and Levels	**0**	**1**	**2**
HV/kV	5.0	7.5	10.0
SS/nm	4.0	5.5	7.0
M/times	2500	5000	10000

No replications were performed since repeated changes in the accelerating voltage may cause filament blow up and severe damage of the calibrated artifact. However, the experimental design caters for "hidden replications", as the presence of non significant effects leads to replications in estimating the remaining ones. Analysis of variance for both pixel size and nonlinearity reveals a high significance of magnification, while accelerating voltage and spot size are barely significant only for nonlinearity. Best Subset Regression further clarifies results by identifying the best-fitting empirical regression models up to second order, among all possible combinations of predictor variables. Yates algorithm estimates all the 26 factorial effects, evaluating their levels of significance. Best Subset Regression identifies parsimonious models, while Yates algorithm yields a detailed picture of all effects, offering jointly a comprehensive appraisal. Accordingly, for pixel size a second order model including *M* and M^2, accounting for almost the whole variability, is identified; log *M* covers 96% of total sum of squares, and (log M)^2 the remaining 4%, other effects being negligible. For nonlinearity, Best Subset Regression identifies a second order model including *SS*, HV^2, SS^2, M^2 and the interaction *HV-SS*, accounting for 58% of variability. And, Yates' algorithm shows log *M* to cover 27% of total sum of squares, followed by SS^2 (11%), interaction *HV*-*SS*-log *M* (10%) and interaction SS^2–log *M* (10%). These effects cover 58% of total sum of squares, others accounting for less than 10% each. Differences between results provided by the two methods are explained by Yates' algorithm considering log *M* and effects up to the sixth order, while Best Subset Regression is performed in terms of magnification and limited to second order. Finally, exploiting response surface methodology, an optimal instrument setting was identified in terms of minimum nonlinearity, i.e. *HV*=10.0 kV, *SS*=4.0 nm and *M*=2500x.

5 Conclusions

In this work the influence of Scanning Electron Microscope (SEM) instrument settings on the image formation process was investigated. The qualitative analysis of SEM images showed an agreement with the theoretical description of the different effects. A factorial experiment was adopted considering pixel size and nonlinearity as quantitative outputs to be optimized. Magnification was found to account by far for the largest contribution, both on pixel size and nonlinearity, followed by accelerating voltage and spot size for the latter response only. Optimal instrument setting was found to be HV=10.0 kV, SS=4.0 nm and M=2500x to minimize the nonlinearity, while optimal image quality and resolution are obtained at M=10000x.

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