

Enhanced stereo SEM measurement of sub-micrometer structures

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Summary

In this paper results of a modified photometric 3D-reconstruction method of scanning electron microscope (SEM) images are presented. It retrieves more accurate data of sub-micrometer substructures like diffractive optical elements (DOE) due to an increased lateral resolution and works more efficiently than common techniques.

Introduction

Since almost 30 years attempts have been made to change the SEM in the sub-micron range into a 3D measuring device. There exist different approaches, among them the “shape from shading” method, which reconstructs the surface by exploiting the emission yield dependency on the local slope angle and the cosine form of the angle distribution of the emitted electrons [1].

Due to qualitative knowledge of the emission process in the SEM, several models of the signal generation and therefore different reconstruction algorithms exist. In this paper the experimental reconstruction results are presented, which have been achieved by the algorithm, introduced in the article „3D-Measurement with Stereo SEM“. The advantage of this model over former methods is, that it takes into account the efficiency of the detector system as well as it improves assumptions concerning properties of the emitted electrons.

The conventional SEM was additionally equipped with two vis-à-vis positioned Everhardt-Thornley (ET) detectors and a Z-rotation unit, see Figure 1.

The rotation of the sample allows to position the ET detectors first along the x-axis and then along the y-axis to record the I_{1x} -, I_{2x} -, I_{1y} - and I_{2y} -signals. These signals are functionally connected with the partial derivatives of the sample surface which provide the basis of the surface reconstruction:

$$\frac{I_{1x} - I_{2x}}{I_{1x} + I_{2x}} = F_x \left(z(x, y), \frac{\partial z}{\partial x}, \frac{\partial z}{\partial y} \right), \frac{I_{1y} - I_{2y}}{I_{1y} + I_{2y}} = F_y \left(z(x, y), \frac{\partial z}{\partial x}, \frac{\partial z}{\partial y} \right) \quad (1.1)$$

Discussion

To examine the accuracy of measurement a steel ball of 1.2 mm diameter was used. As Figure 2 shows, for small slope angles the 3D reconstruction fits a nearly perfect spherical shape. After reaching a slope angle of approximately 45°, the deviation in the height increases strongly.

This circumstance can be explained by the non unique correspondence between the signal relation $k_x = (I_{2x} - I_{1x}) \cdot (I_{2x} + I_{1x})^{-1}$ and the local slope angle, as it is shown in Figure 3. Here the ball is positioned in the centre of the image, so the inclination decreases monotonically along the marked lines. In contrast to the inclination, the

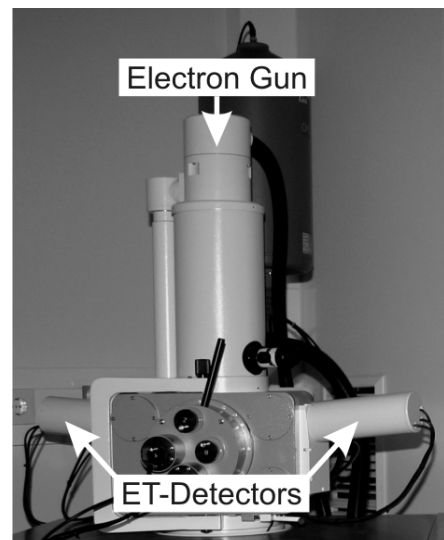


Figure 1. SEM with 2 ET-detectors

signal relation k_x can be distinguished as a monotonically decreasing function only for small slope angles.

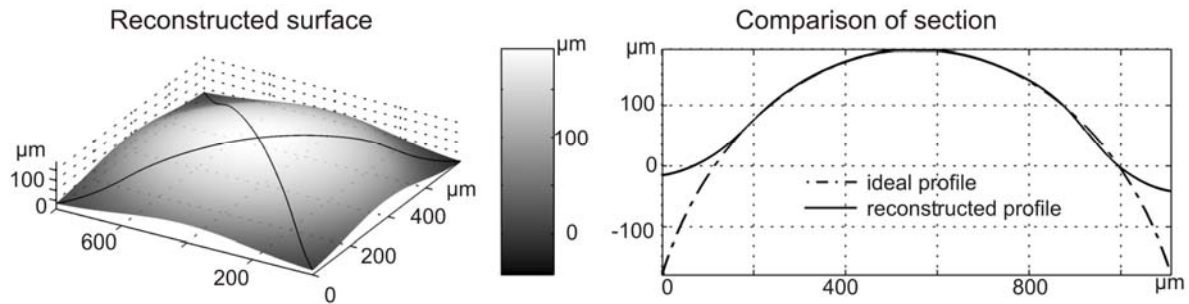


Figure 2. 3D-reconstruction of a steel ball: total reconstruction result (left), marked diagonal profile and corresponding profile (right)

After reaching the turning point at around 45° the signal relation k_x changes its orientation. The angle of this turning point depends on the SEM and can be increased significantly by taking proper precautions like shielding the electron gun [2]. While reconstructing, the slope is derived out of the signal relation where an ambiguity of the determination of the surface gradient occurs and smallest possible slope will be chosen.

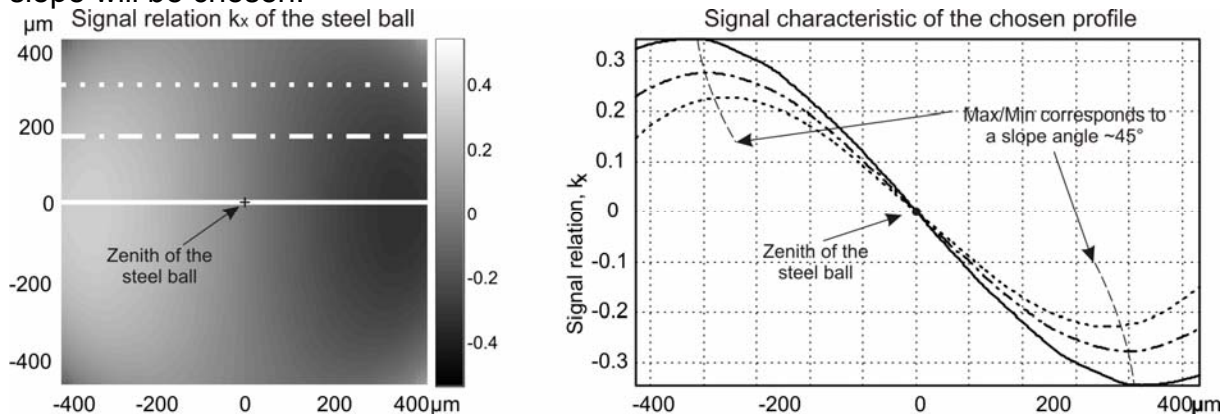


Figure 3. Calculated signal relation k_x of the steel ball

For slope angles between 0 and 45° degrees the deviation is less than $5 \mu\text{m}$. Though the deviation of the measuring results is relatively large, it is crucial that the reconstruction algorithm is only connected to the slope and therefore linearly dependent on the dimension of the sample. If, for example, a steel ball of $10 \mu\text{m}$ diameter is measured an accuracy of approximately 50 nm can be expected.

The advantages of the SEM over optical measuring methods will be highlighted with a holographic diffractive grating of 830 nm . Because of the physical resolution restriction of about 200 nm , the optical measuring devices are at their limit although the grating period length is relatively large. While the sine wave is identifiable with $100\times$ magnification, it can't be measured with $50\times$ magnification due to poor lateral resolution of 300 nm per pixel, see Figure 4.

Since tactile measuring methods might damage the surface they also cannot be used for collecting topography data. Though the atomic force microscope (AFM) in non-contact mode is able to fulfil the measuring task, the time effort is so tremendous that measuring objects with higher complexity like holograms is not feasible in a reasonable amount of time.

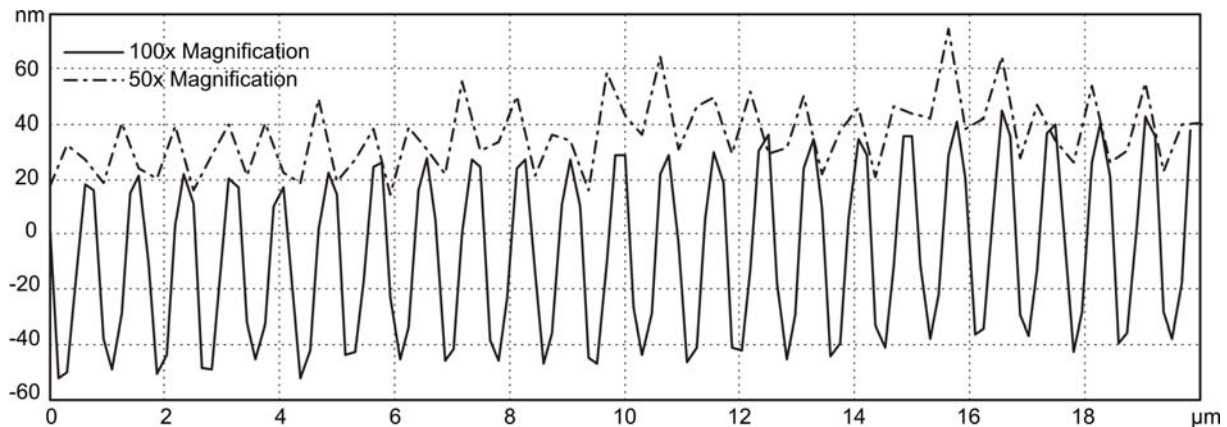


Figure 4. Measurement of a holographic diffractive with a confocal microscope

Figure 5 shows the SEM and AFM measurement results. Due to the homogeneous character of the grating surface, an exact localization of the measuring position and therefore the comparison between the two different methods is barely possible. Nonetheless a structural height of 60-80 nm is noticeable in both, the SEM and the AFM, measurements. While it took the SEM about 10 minutes, the AFM required 6 hours. In addition the SEM can be operated interactively, while it is nearly impossible to do repetitive measurements with the AFM after changing the sample's position.

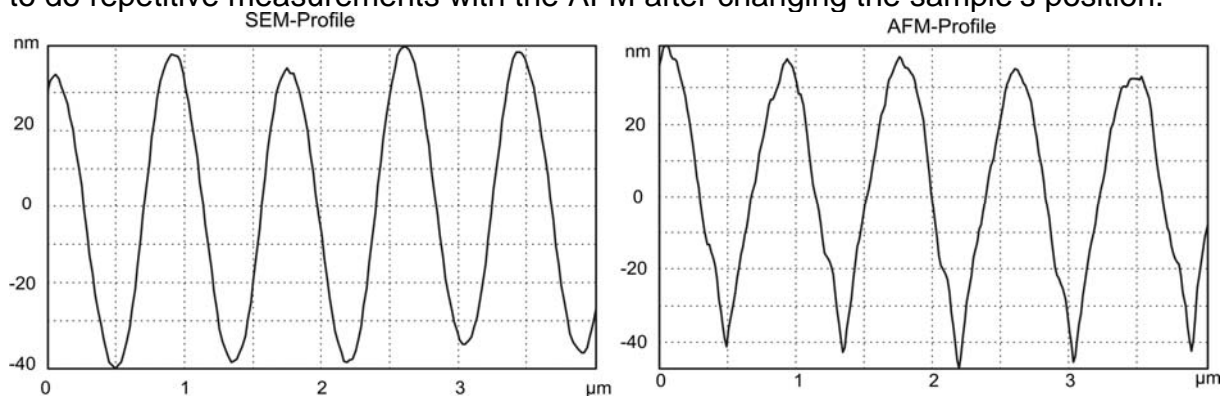


Figure 5. Comparison between SEM and AFM measurement results

Conclusions

The presented results prove that the modified SEM method is suitable to use for investigations of flat structures to obtain high lateral resolution data (30 nm). This method gives the possibility to measure DOEs with a reasonable effort of time, where optical and tactile measuring devices fail. For the measurement of structures with a slope angle above 45° an improvement of the setup is needed. This can be fulfilled by optimizing the field distribution near the sample and by reducing the influence of the electron gun.

References

- [1] Reimer, L., *Image Formation in Low-Voltage Scanning Electron Microscopy*, (SPIE Press Book, 1993)
- [2] Kässens, M.; Reimer L., Contrast effects using a two-detector system in low voltage scanning electron microscopy; *Journal of Microscopy*, **Vol. 181**, pp. 277-285, 1996