Automated Geometric SEM Calibration

Innovative Standards Enable Fast and Easy-to-Handle Calibration

A new calibration approach allows a fast and easy-to-handle geometric calibration of Scanning Electron Microscopes (SEM). This article outlines the application of 3D calibration standards with spatially distributed circular reference markers. The underlying marker-based calibration concept determines scale and shear factors of the coordinate axes and facilitates the analysis of image distortions and other remaining image errors. We present the application of 3D calibration standards, both for 2D and for 3D measurements, and show its contribution to achieving a higher measurement accuracy.

Fig.1: 3D SEM calibration standard MMC-80-4BSD. 3D view of SPM measurement data set (units in µm). The hemisphere allows the adjustment of BSE detectors.

Introduction

Several SEM applications (e.g. measurement of the layer thickness in solar cells or dielectric optical layers, determination of pore and grain sizes) require well calibrated instruments for the accurate measurement of distances. For some applications (e.g. wave guides), a precise determination of angles is needed in addition. In general, reference samples with line features are used to calibrate the scale of SEM images in x- and y-direction. Due to the more or less manual measurement of the line features and the reduction of calibration parameters to a single distance, this procedure is not very accurate and can be a time-consuming process. Moreover, it might not provide information about the shear factors between x and y and it cannot be used to calibrate the angles. Although SEMs are mostly used for 2D imaging and analysis, they are utilized more and more for 3D measurements [1-3]. 3D calibration standards are required for this purpose. A sophisticated
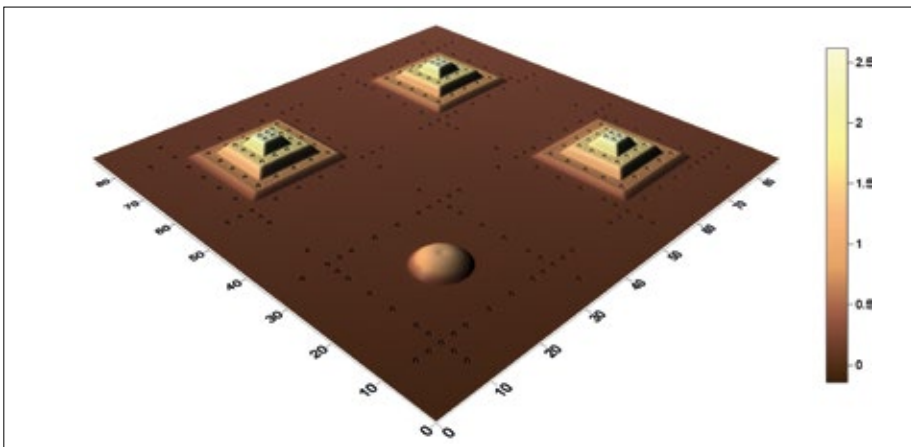
solution for 3D calibration are samples with pyramidal structures and circular reference markers, already applied for SPM calibration [4]. In this article, both the application of such calibration structures for automated geometrical SEM calibration and how this can improve accuracy are presented.

3D Calibration Standards

3D SEM calibration standards consist of three multi-level pyramids for geometric calibration and a spherical element (fig. 1). The spherical element enables the detector adjustment, i.e. tuning the offset and gain of backscatter electron detectors (BSD), which is necessary for 3D data generation [5]. The design of the calibration structures includes spatially distributed, circular reference markers with known centre coordinates (reference information). The necessary reference measurement of the calibration structure is performed at the PTB with the Metrological Large-Range SPM (MetLR-SPM, based on a NanoMeasuringMachine by SIOS). The position of all three translation axes of the MetLR-SPM are monitored by laser interferometers and thus direct traceability to the SI unit meter is guaranteed [6]. 3D calibration standards are available in different sizes, starting from single pyramids with a base area of 5 µm x 5 µm up to arrays of 80 µm x 80 µm with heights from about 0.5 µm to 3 µm. The spherical element has a base diameter of 10 µm and a height of about 1 µm. The complete structure consists of platinum composite, providing long term stability.

Marker-Based Calibration

The marker-based 3D calibration strategy uses circular reference markers that are applied on the pyramid-shaped reference structures. The coordinates of the reference markers are automatically detected and measured in the SEM data and compared to the reference coordinates. Depending on the application, the registration is done with a 2D or 3D transformation. In both cases, all scale and shear factors are calculated. While the 2D application allows the determination of scaling and shearing of the x- and y-axis, in 3D, there are additional parameters for z-scaling and shearing between the lateral and the vertical axes.

For marker-based calibration, especially the automated detection of the position of circular markers and uncertainty estimation, the software microCal was developed by m2c. This software automatically detects and measures all markers with sub-pixel accuracy by image processing methods. This includes the detection of the sample orientation by using coded targets. The calibration procedure determines all linear geometrical parameters (scaling and shearing), as well as the sample orientation (rotation and translation). The algorithmic approach is based on LSM (least-squares methods) and allows a statistical analysis of the results, including data snooping for outlier detection. Graphical output of the remaining non-linear residuals makes further analysis of the accuracy of the used system possible. All results can be saved as reports, and the calibration parameters are always stored in external files. These parameter files enable an automated SEM image correction (rectification) when using dedicated image correction software. Alternatively, if the SEM has an appropriate interface, the calibration parameters can be transferred to the SEM control software in order to obtain calibrated images.

Application and Results

2D Calibration

For a successful calibration, the operator has to select appropriate SEM parameters (detector type, magnification, beam voltage, working distance). After the image acquisition of the standard, calibration is performed by the calibration software in an easy way. Due to the varying imaging features of the applied detector type, only an appropriate setup has to be selected in the calibration software. For documentation or later use, all settings and results are saved in a project file.

Figure 2 shows the 2D calibration results of a SEM Hitachi S520. A MMC-40-4BSD calibration standard has been used. It has a size of about 40 µm x 40 µm x 1.5 µm, the base edge length of every pyramid is 10 µm, allowing fields of view (FOV) of 15 µm to 50 µm. The determined x-scale correction factor is 1.010, scale correction factor in y is 1.026, and the shearing factor between both coordinate axes is -0.002. Compared to non-calibrated image data, the maximum remaining deviations between the measured and the reference marker coordinates are reduced from 268 to 27 nm in x-direction and from 534 to 56 nm in y-direction when applying shear corrections (2D Affine). The results indicate that the application of a single scale factor (2D Similar) or even the application of two scale factors (2D Non-isotropic) is not sufficient to get the highest accuracy.

3D Calibration

There are various approaches for the non-destructive generation of 3D data from SEM images. An advanced solu-

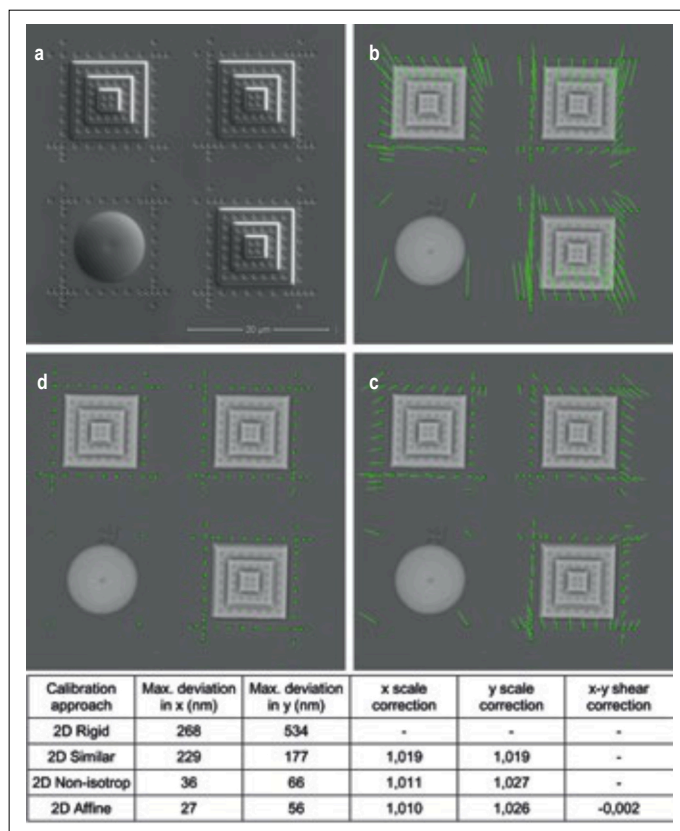| Calibration approach	Max. deviation in x (nm)	Max. deviation in y (nm)	x scale correction	y scale correction	x-y shear correction
2D Rigid	268	534	-	-	-
2D Similar	229	177	1,019	1,019	-
2D Non-isotrop	36	66	1,011	1,027	-
2D Affine	27	56	1,010	1,026	-0,002

Fig. 2: Results of 2D calibration of a SEM Hitachi S520. Without calibration, comparison of the marker coordinates in the SEM image with the reference coordinates shows large deviations. With calibration, the remaining deviations are reduced to a minimum. In clockwise order: (a) SE image of calibration standard MMC-40-4BSD. (b) Coordinate deviations against reference data (error vectors 10x enlarged). (c) Remaining deviations after scale calibration (2D Similar). (d) Remaining deviations after complete linear 2D calibration (2D Affine). (e) Resulting calibration factors.

Calibration approach	Mean point error (nm)	x scale correction	y scale correction	z scale correction	x-y shear correction
3D Rigid	264	-	-	-	-
3D Similar	132	1,012	1,012	1,012	-
3D Non-isotrop	110	1,010	1,013	1,148	-
3D Non-isotrop with 2D Affine	81	1,010	1,013	1,152	-0,008

Fig. 3: Results of 3D calibration of SEM Jeol 840 A with 4Q BSE Detector. Overlay of the remaining coordinate deviations after 3D non-isotropic calibration over surface topography data (error vectors 10x enlarged). Left (a): Lateral deviations are reduced to a minimum. Right (b): Vertical deviations show a systematic non-linear error. This is subject of further data correction. (c) Resulting calibration parameters. Estimation of separate scale and shear factors yields to a smaller remaining mean point error.

tion is the application of a four-quadrant (4Q) back-scatter electron (BSE) detector. However, without calibration of the detector system, the height information of the resulting 3D-model of the sample surface has only qualitative character. In order to turn a 4Q BSE system into a quantitative measurement device, a true 3D calibration is necessary. Figure 3 shows the 3D calibration of a SEM Jeol 840 A, which is equipped with a 4Q BSE detector (by point electronic) and 3D reconstruction software microShape by m2c. After the selection of the appropriate SEM parameters and the detector adjustment, a data set containing all four BSE images was acquired and used for 3D data reconstruction. These data are imported into the calibration software, automatically analysed and compared to the reference data. By applying separate scale factors for each coordinate axis and a lateral shear factor, the mean point error of all markers was reduced from 264 nm to 81 nm.

Conclusions

With marker-based standards, SEM calibration is performed in a fast and automated way. The comparison of the coordinates of the circular reference markers to existing reference coordinates enables the scale and shear factor determination of all coordinate axes of a measurement system. Dedicated software allows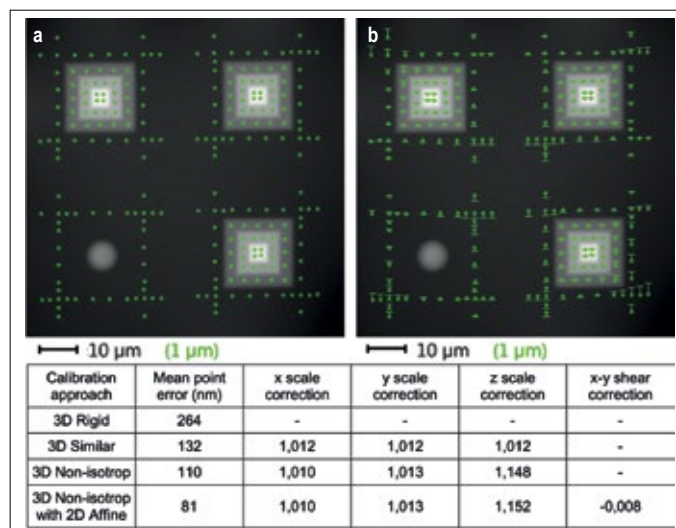 not only a widely automated calibration, but also the analysis of SEM image distortions, as well as an estimation of the accuracy and reliability of the calibration results. With the application of the resulting calibration parameters for data correction, or, by directly using them in the SEM control software, a higher accuracy is achieved. The new calibration standards presented here are designed for versatile use with SEM, as well as with SPM (Scanning Probe Microscopy) and CLSM (Confocal Laser Scanning Microscopy). Therefore, they may also be applied to improve accuracy in correlative microscopy.

Acknowledgements

References

[1] W. Drzazga et al.: Meas. Sci. Technol., 17, 28–31 (2006)

[2] J. Paluszynski and W. Slowko: Journal of Microscopy, 233/1, 10–17 (2009)

[3] D. Berger and M. Hemmleb: MC 2009, 1, 99–100 (2009)

[4] M. Ritter et al. : Meas. Sci. Technol. 18, 404–414 (2007)

[5] D. Berger et al. : EMC 2008, 1, 533–534 (2008)

[6] G. Dai et al.: Rev. Sci. Instr., 75/4, 962–969 (2004)

Contact
Dr.-Ing. Matthias Hemmleb
m2c calibration
Potsdam, Germany
matthias.hemmleb@m2c-calibration.com
www.m2c-calibration.com

Dr.-Ing. Dirk Berger
Technische Universität Berlin
Center for Electron Microscopy (ZELMI)
Berlin, Germany
www.zelmi.tu-berlin.de

Dr.-Ing. Martin Ritter
Hamburg University of Technology (TUHH)
Electron Microscopy Unit (BeEM)
Hamburg, Germany
www.tuhh.de/beem/

Read more about calibration in microscopy: http://bit.ly/calimic

More information on SEM metrology: http://bit.ly/semetrology