DIGITAL MICROPHOTOGRAMMETRY WITH THE SCANNING ELECTRON MICROSCOPE

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ABSTRACT:

This paper presents the application of photogrammetric methods for the three-dimensional reconstruction of microstructures. The image acquisition is realized with an Scanning Electron Microscope (SEM), which is connected with either a Personal Computer or a Workstation. To enable a photogrammetric evaluation, it is necessary to take a series of SEM images under small tilting angles. The multi-photo evaluation takes place on the base of a parallel block adjustment, which is a bundle adjustment under the restrictions of parallel geometry. The microstructures, used in this project, have very different types of surfaces and shape. For that reason it is necessary to select different ways of extraction of relevant image information, as like as image matching and presentation. To explain the special demands on the digital processing way two very different micro structures will be presented. They have been reconstructed automatically, using feature-based matching methods as well as area-based matching methods.

1. INTRODUCTION

The three-dimensional evaluation of surfaces in microrange plays an important role in microstructure technology or material research. Technological development and quality control of microprobes require a non-destructive and easy-to-use method for high resolution 3D-measurements.

The combination of digital photogrammetric methods with image acquisition through Scanning Electron Microscopes (SEM) offers some advantages. Images from SEM have an excellent depth of focus and can be acquired over a wide range of magnification. Digital photogrammetry and image processing techniques provide new approaches for 3D-measurements in microranges.

The developed photogrammetric processing software takes special properties of electron microscope imaging into consideration, i.e. nearly parallel projection and changing imaging conditions. The software offers also the possibility of photogrammetric calibration of SEM, in order to increase the accuracy of three-dimensional point determination.

A further advantage is the flexibility of photogrammetric methods in combination with digital image processing techniques. In microsciences there are probes with very different surface structures and texture features. In order to achieve a largely automated determination of the surface geometry it is necessary to apply different processing approaches. On the one hand there are microprobes with nearly continuous surfaces, which can be described in Digital Elevation Models (DEM), using area-based matching methods for the determination of homologue points. On the other hand there is a growing number of complex microstructures and microdevices, which are manufactured according to CAD-models, with strong edges and undercutting areas.

The 3D-evaluation of the surface of such probes may require interactive operations. For instance for high precision measurement, it is possible to create local markers at interesting sample regions by the SEM electron beam. This method has been demonstrated in connection with the determination of the bending of a micro cantilever for atomic force microscopy (Hemmleb et. al., 1995). For further automation, it is necessary to combine different image processing operations like edge-extraction, vectorization and feature-based matching methods.

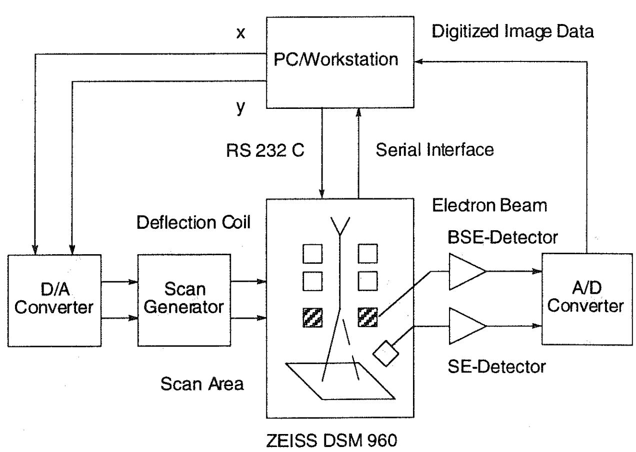

Figure 1: Connection between SEM and PC for computer-controlled acquisition of image data

2. IMAGE DATA ACQUISITION

In order to make use of the advantages of digital photogrammetry it is necessary to acquire the image data directly from the SEM without any non-defined signal preprocessing. This fact is of importance because of the high requirements in accuracy of 3D-measurement. Beside this, a direct connection enables the operator to choose a suited area for photogrammetric surface determination and offers an image acquisition with optimal conditions concerning to image quality.

A digital interface connecting a personal computer (PC) and SEM was developed in a joint project between the Technical University of Berlin (TUB) and the Institute for Physical High Technology (IPHT) Jena (Fig. 1). The connection consists of a AD/DA-converter for raster control and image data acquisition, and a serial interface for controlling and saving pickup parameters (for instance working distance or magnification). Therewith it is possible to take tilting series of images – necessary for photogrammetric 3D-evaluation – directly from a PC.

This interface offers also new potentials for the improvement of image quality. By controlling the scan of the electron beam in dependence on the signal level (which means the grey value in image data) the images have a higher contrast – even in dark and shading areas of the scanned microprobe.

3. PHOTOGRAMMETRIC PROCESSING

The photogrammetric evaluation requires two or more SEM-pictures of a probe under different tilting angles. Photogrammetric processing takes place successively in different steps. Besides this the selection of the appropriate approach for an automated 3D-determination of the surface depends – as already mentioned – on the characteristics of the microprobe.

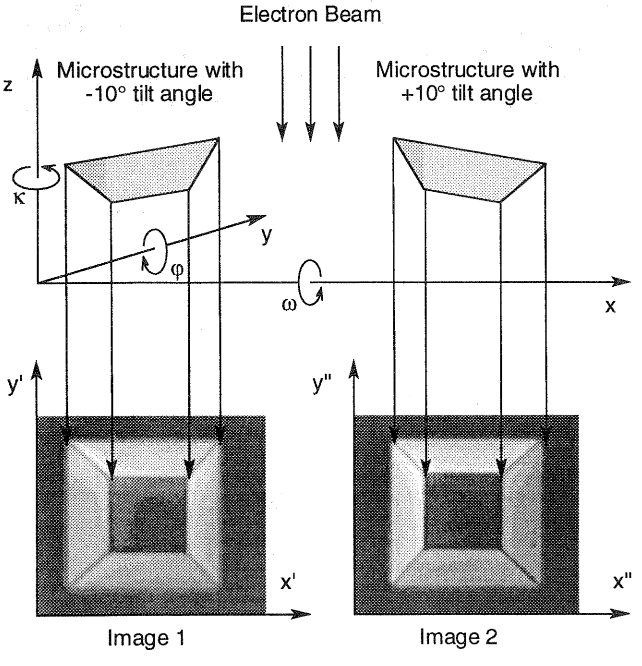

Figure 2: Principle of Parallel Imaging with the SEM

3.1 Parallel-Block-Adjustment

The basis of the photogrammetric processing is the estimation of the orientation parameters. In general a mathematical description is used, which allows six degrees of freedom for every image: three rotations and three translations. Because of the applied geometrical model, which is a parallel projection, the number of degrees of freedom is reduced to five. Additionally there are parameters for image distortion and scale available (different in x and y direction), because the conditions of image acquisition do not remain constant in the SEM.

The block adjustment requires homologue image points in all pictures involved. According to the used microprobe it is necessary to select the appropriate procedure for this task. The easiest method is to measure the required points interactively in each image. Correlation techniques simplify this procedure by determining and measuring image points in corresponding images with subpixel accuracy. In order to achieve a higher degree of automation in photogrammetric processing it is possible to use feature or edge extraction operators in relation with feature matching methods. The results of the automatic measurement of homologue image points will be presented below.

Because of the changing imaging conditions of the SEM it is necessary to determine the scale factor for each image. Additionally, imaging with the SEM allows no definition of control points. Hence, the parallel-block adjustment takes place in form of a self calibration. In order to enable self calibration it was necessary to use least-squares methods for free bundle adjustment. In this case the spatial distribution of the tie points plays an important role for the solution and accuracy of the block adjustment.

The orientation process runs in two steps. The first step is the estimation of approximate values. Given are the corresponding image coordinates of the tie points and approximate values for the tilting angle and the scale factor. On the assumption that the images are only tilted, it is possible to determine approximate coordinates for the used points in object space (Burkhardt, 1981):

$$x = \frac{x_i}{m_x} \quad y = \frac{y_i}{m_y} \quad z = \frac{\frac{x_i - x_{i+1}}{\sin\beta} - x_i \cdot \tan\frac{\beta}{2}}{m_x} \qquad (1), (2), (3)$$

x, y, z object coordinates
x_i, y_i image coordinates in image i
x_{i+1}, y_{i+1} image coordinates in image i+1
β tilt angle of image i
m_x, m_y scale factor in x- and y-direction

Following, it is possible to define a coordinate system in object space, necessary for instance for the definition of a reference plane for a Digital Surface Model (DSM).

The second step is the determination of the orientation parameters and the scale factor for each image. The orientation process is performed in analogy to central projection in form of a parallel block adjustment, because of the parallel imaging equations:

$$x_i = m_x \cdot (b_{11} \cdot (x - x_0) + b_{12} \cdot (y - y_0) + b_{13} \cdot z) \quad (4)$$

$$y_i = m_y \cdot (b_{21} \cdot (x - x_0) + b_{22} \cdot (y - y_0) + b_{23} \cdot z) \quad (5)$$

x_0, y_0 coordinate origin
b_{11}-b_{23} elements of rotation matrix (Rüger et al., 1987)

In order to define an accurate scaling factor and to increase the stability of the orientation process, it is possible to measure a horizontal distance with the SEM and to use it in the block adjustment.

In addition to the orientation and scaling parameters the affine factor and distortion parameters can be estimated through this procedure (El Ghazali, 1984), (Gleichmann et al., 1994). Using a known reference probe, it is possible to perform a calibration of the SEM. Usually a calibration is performed before the surface measurement of a microprobe. The resulting parameters can be used in the following steps of orientation and point determination. Under constant imaging conditions it is even possible to get the scaling factor from the magnification of the SEM.

3.2 Area-based Matching by Image Correlation

Homologue image coordinates of microprobes with nearly continuous surfaces and good texture features are measured with an area-based matching method.

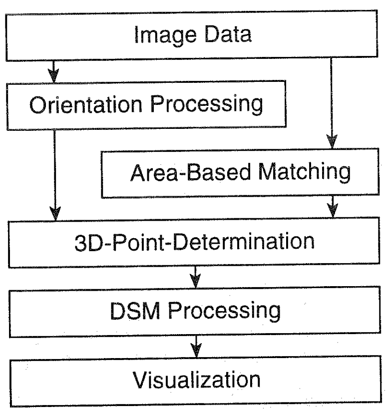

Figure 3: Processing Surface Models

The applied method of image correlation is widely used, yielding reliable results with objects presenting a good texture (König et al., 1987). It is useful to divide this method in two steps:

a) Normalised Cross-Correlation
b) Least-Squares Matching

In case of the normalised cross-correlation, a pattern matrix is shifted pixel by pixel across the search matrix of a corresponding image, and the cross correlation coefficient is calculated each time. The maximum correlation coefficient indicates the best match and defines the homologue point.

The results of the normalised cross-correlation represent the approximation values for the least-squares matching. This method uses a geometric and a radiometric transformation on the basis of a least squares estimation in order to compensate both distortions of the image information and differences in brightness and contrast. Resolving a system of equations containing all geometrical and radiometric coefficients yields results in the subpixel range. To facilitate the availability of approximate values an image pyramid approach is used, which is executed systematically from the top down to the original image.

Fig. 3 shows the processing steps of microprobes with nearly continuous surfaces and good texture features. Assuming successful results from the matching process, the obtained data can be used for a Digital Surface Model (DSM) after the 3D-Point Determination (see chapter 3.4).

3.3 Feature Extraction and Feature-Based Matching

Because of the characteristic edge structure in relation with poor texture features of the surfaces, the evaluation of corresponding features in images, taken from microstructures and microdevices, represent the greatest challenge for the automatic processing of 3D-models.

There exists a lot of feature-based matching methods, but there is no algorithm available, which is suitable for all different kinds of objects and the great demands required for the automatical three-dimensional reconstruction of these objects. But it is possible to select suitable methods for different tasks.

Interest operators are used to get pairs of homologue image points for the orientation process. The function of interest operators is to extract features from digital image data, which differ significantly from their environment. If, however, oriented image data are already available, then the image features detected can be verified without any problems on the basis of the known imaging equations. In other cases when the orientation of the images is not known, the image matching is much more complicated because the results obtained during the processing of the image data by means of an interest operator differ from each other. The consistent application of statistic test methods in connection with the robust least-squares estimation of an affine transformation between the detected features (Förstner, 1986) serves this purpose just as the verification of the matched pairs of images by means of the least-squares matching.

Edge matching methods serve suitable conditions for the three-dimensional reconstruction of structures with edges and poor texture. One approach is the method of dynamic programming (Li, 1990). The basic idea is to match not only pairs of edges with each other, but to include the edges as a whole by their intersection points with the epipolar lines.

The aim of the three-dimensional reconstruction of microstructures is a 3D-model, which is to compare with the design data of this microobject in order to make conclusions for the technological process. To solve this problem, nodes and edges of the object have to be extracted from an image by edge extraction algorithms and vectorization tools. After that the extracted nodes will be set in relation and verified with the nodes in the other images. Usually it is necessary to know the approximate orientation of the images to match nodes. Because of the similarity of the different images, taken with small tilting angles, the matching process can take place without orientation data with a least-squares matching. Robust statistical methods and the use of multi-image matching methods guarantee that only precise and reliable nodes will be used for the estimation of the orientation parameter. After the determination of the three-dimensional coordinates of all matched nodes (see next chapter) edges have to be merged. During this process the previously extracted edges will be merged with the three-dimensional node points. Besides, the merging algorithm has to connect edges, which lost their nodes because of errors in the matching process or because of less accuracy. The result is a 3D-model of the microstructure. Fig. 4 shows the described processing steps.

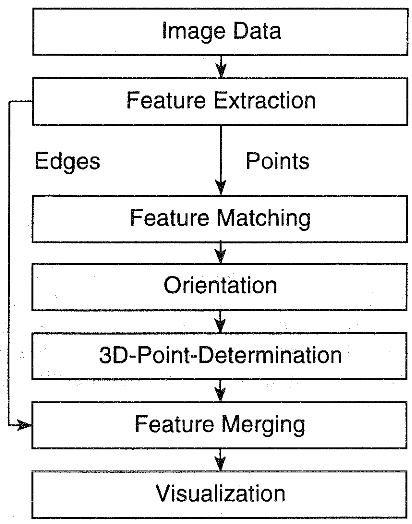

Figure 4: Processing 3D-Models

3.4 3D-Point-Determination and DEM-Estimation

The next step is the determination of the 3D point coordinates. If there exists only a small number of points it is advantageous to determine this points within the block adjustment, because of the highest accuracy of this method. The estimation of a large number of points, for instance required to reconstruct a whole surface, is performed as a spatial intersection on the basis of the parallel imaging equations (4), (5) using orientation parameters from the parallel-block adjustment. Additionally it is possible to use the known distortion parameters, which are known from a previous calibration of the used SEM. By applying robust statistical methods, it is possible to eliminate gross errors from the image matching process.

The 3D-Point-Determination takes place in two steps. The first step is the evaluation of approximate values with participation of all used images:

$$x = x_0 + \frac{b_{11}' \cdot x_i}{m_x} + \frac{b_{12}' \cdot y_i}{m_y} \qquad (6)$$

$$y = y_0 + \frac{b_{21}' \cdot x_i}{m_x} + \frac{b_{22}' \cdot y_i}{m_y} \qquad (7)$$

$$z = \frac{b_{31}' \cdot x_i}{m_x} + \frac{b_{32}' \cdot y_i}{m_y} \qquad (8)$$

b_{11}' ..... b_{32}' elements of the inverse rotation matrix

After the evaluation of approximate values the point coordinates will be estimated through spatial intersections. This estimation uses least-squares methods under application of all available images to achieve a high accuracy and to detect gross errors.

In case of the reconstruction of a nearly continuous surface with a large number of object points it is useful to generate a regular grid of height points. For that purpose a commercial DEM-Software is used (DEM = Digital Elevation Model, in microsciences also called Digital Surface Model = DSM). This DEM-Software provides standard methods for the derivation of a regular digital elevation grid from three-dimensional point clusters. It also enables the derivation of further products, like profiles, perspective views or shading maps. For further details, see Ebner et al. (1980).

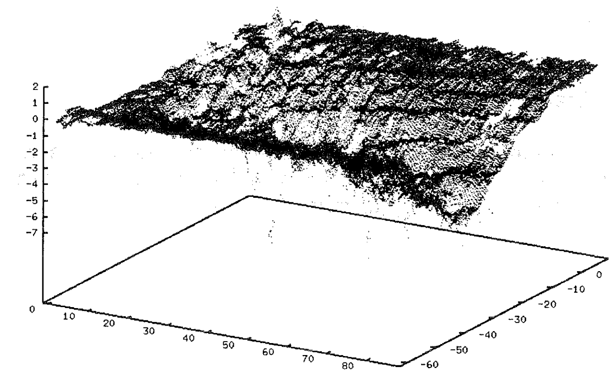

Figure 5: Three-Dimensional Point Cluster of a Microprobe (Dimensions in µm)

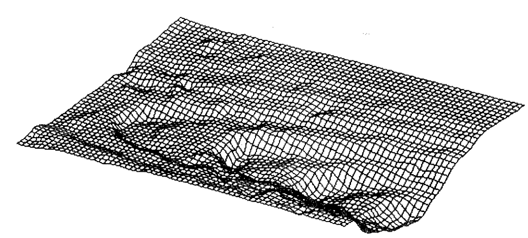

Figure 6: Digital Surface Model of the Microprobe

A common problem are incorrectly estimated point coordinates, which are represented in DEM as peaks. The reason for that failures are mostly incorrect matching results, because of the texture, which is not suitable for every grid point. There are several methods to remove these failures: First we define a threshold value for the correlation coefficient. The next step is a statistical control of the three-dimensional point determination with Data Snooping and a threshold for the mean error of the coordinates. The last step is the definition of a working area, especially in the z-axis. Due to this restrictions failures in the DEM can nearly completely removed from the original data.

In case of the feature-based processing approach, the derived nodes and edges have to be converted into a CAD data format with the basis elements of points and lines. This converted data are available for the visualization and further processing with CAD systems.

4. EVALUATION SAMPLES

4.1 Reconstruction of the Surface of a Copper Sample

The aim of this investigation was the determination of the topography of dissipative chemical patterns spontaneously developed during etching procedure of thin copper films. The copper sample shown in Fig. 7 has been used in a SEM (Zeiss DSM 960) for the acquisition of an image series with tilt angle steps of 5°, at an acceleration voltage of 30 kV and a magnification of 3000.

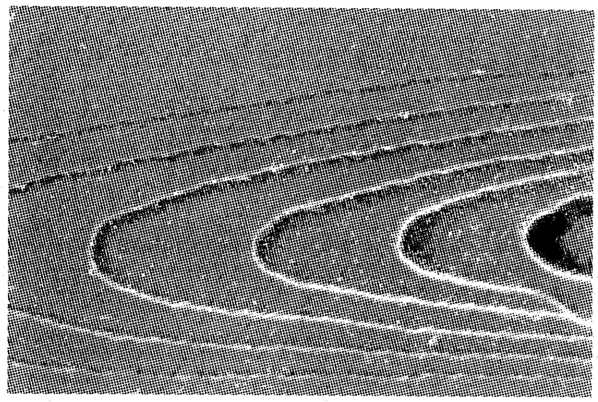

Figure 7: Copper Sample
(SEM Image with a Magnification of 3000:1)

For the subsequent processing of the images, realized on a SGI-Workstation, two images with tilt angles of - 5° and + 5° were selected. Ten points were measured in an interactive way in both images for the orientation process. The difference between the scales in x- and y-direction has been determined by a previous calibration of the system.

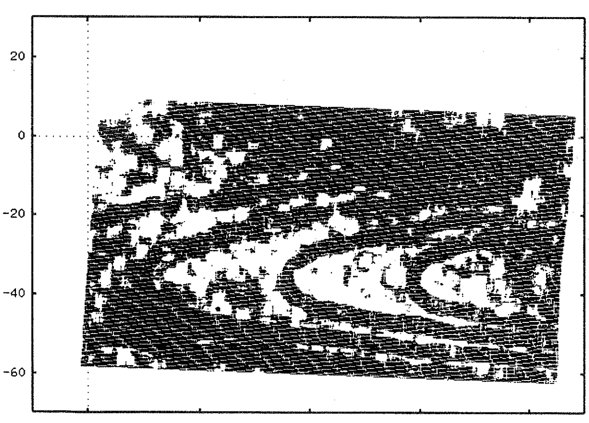

Figure 8: Surface Points in x/y-Plane estimated with Least-Squares Matching (Dimensions in μm)

After the successful estimation of the orientation parameters follows the automatic correlation process. The area-based least-squares matching yields a success rate of nearly 80%. Fig. 8 shows the results of the matching process with a threshold for the correlation coefficient at 0,8.

The next step is the estimation of coordinates in object space. The obtained three-dimensional cluster with nearly 75000 points (Fig. 5) was used for the generation of a Digital Surface Model and for all following operations and visualization. Fig. 6 shows a perspective view of the DSM data. Finally – as seen in Fig. 9 – a shading map, generated with the DEM software, has been mapped over a perspective grid model.

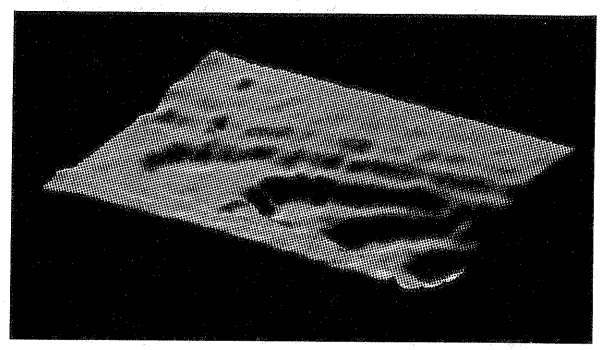

Figure 9: Shading Model of Copper Microprobe

4.2 Geometrical Reconstruction of a Silicon Sample

The micromechanical structured silicon sample (see Fig. 10) is provided with typical features of microstructures: Strong edges and surfaces with poor texture. For this reason we chose this sample to test the possibilities of a widely automated reconstruction of the geometrical shape of such probes.

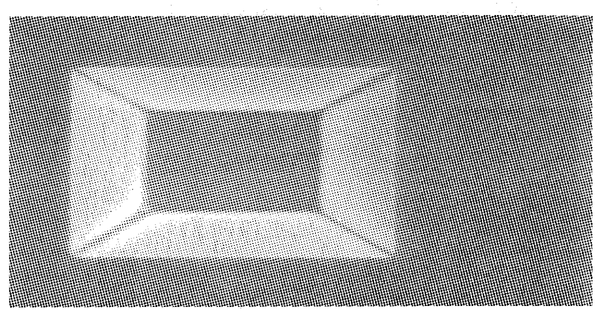

Figure 10: Silicon Sample
(SEM Image with a Magnification of 500:1)

As already described, the automatic feature-based processing approach includes a number of operations. The first step is the detection of edges in one reference image. For this purpose we compare four different approaches:

- Canny-Operator
- Deriche-Operator
- VDRF-Operator (from Khoros)
- SUSAN (Smallest Univalue Segment Assimilating Nucleus)

The best results, achieved by the Canny-Operator, are shown in Fig. 11. For more information about this special operator see Canny (1986). The result of the edge extraction is a binary image with extracted edge pixels. To obtain edges and nodes, a vectorization is necessary (Fig. 12).

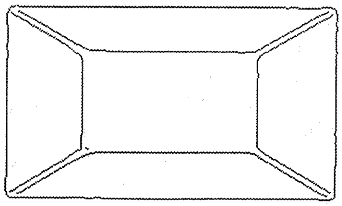

Figure 11: Detected Edges (Canny-Operator)

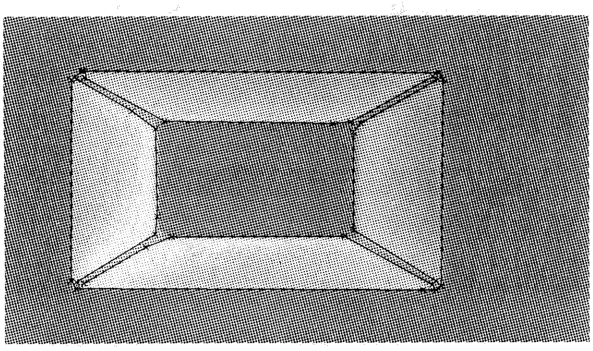

Figure 12: Vectorized Edges and Nodes

The next step was the feature-based matching. For this task we chose three images with tilt angles of - 5°, 0° and + 5°. As the result of the matching process over 90% of the features, both nodes and edges, were matched successfully. The matched nodes were used as tie points for the following estimation of the orientation parameters. After the evaluation of the three-dimensional coordinates of the edge points, the reconstructed microsample has been visualized, as seen in Fig. 13.

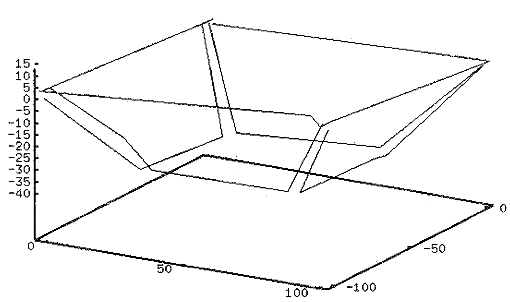

Figure 13: Automatically Reconstructed Silicon Sample (Dimensions in μm)

5. OUTLOOK

It is possible to analyse surfaces in microranges with the described photogrammetric methods. This enables the comparison of quantitative differences, for example between the nominal and the actual dimensions influenced by the technological process.

Further improvements are necessary to develop the presented photogrammetric system to a robust automatic method in three-dimensional microsciences. With help of a detailed calibration of SEM it is possible, to simplify the orientation process with the aim of a higher stability and accuracy. In order to further automation the number of threshold values and control parameters should be reduced. Other correspondence algorithms will be investigated in the future, for instance relational matching methods. In some cases, the difficult process of feature matching can be supported by a knowledge-base from evaluated data from the CAD-model of the microstructure.

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