Application of digital image sensors in microscopy for traceable measurements of 2-dimensional structures: Problems and potential solutions

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Digital image sensors are used in microscopy for quantitative measurements of the two-dimensional geometry of microstructures. Traceable measurements with uncertainties in the some 10 nm range require detailed knowledge of important instrument data like magnification, pixel size, and imaging transfer properties of the image sensor.

1 Introduction

Digital image sensors are commonly used in microscopy for measurements of the lateral (i.e. two-dimensional) geometry of microstructures. In general, measurements of lateral dimensions can be performed with very high precision [1], but their traceability to the SI unit 'meter' with uncertainties of a few 10 nm is still insufficient [2]. For accurate measurements it is necessary to have information about the instrument, the relevant optical and geometrical properties of the object, and the optical interaction of light with the object [2]. In this contribution, we discuss especially the calibration of the pixel distance of the digital image sensor. An experimental set-up has been realised to measure circles with sizes in the micrometer range.

2 Principle of measurement

Fig. 1 outlines the principle of a measurement of the lateral dimensions of microstructures.

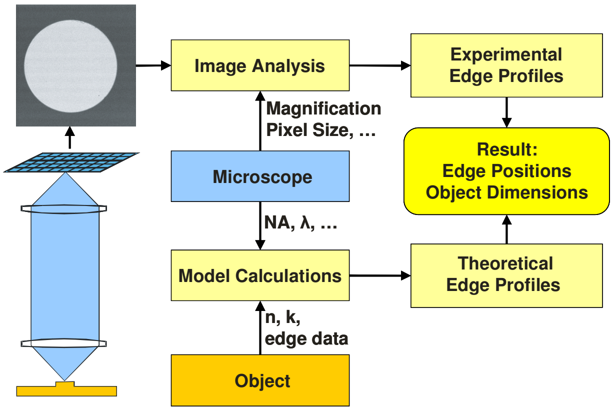

Fig. 1 *Measurement scheme to determine the lateral dimension of microstructures*

From the digital image, optical intensity profiles across the edge ('experimental edge profiles') are determined using appropriate image analysis methods. For this purpose, the microscope magnification and the pixel distance of the image sensor are used to express the lateral positions in the SI-unit 'µm'. If the characteristic curve of the image sensor is nonlinear, the experimental edge profiles need to be linearised. Relevant data of the object (e.g. edge height, optical constants), and of the microscope (NAs, wavelength, spatial resolution of the image sensor) are used to calculate theoretical edge profiles. The comparison of measured and theoretical edge profiles then yields the desired information about the edge positions and thus the object dimensions.

3 Calibration of pixel distance

The calibration of the pixel distance in object space is an important issue. Two different approaches can be applied. The simpler one is to use a calibrated 2-dimensional grating structure, e.g. an array of circles realised as Cr structures on glass. From the positions of each grating element in the digital image the mean pixel distance and the distortion of the image forming process can be assessed. Fig. 2 shows a (bad) example of image distortions obtained for a low-end camera, which is thus not suited for high accuracy measurements.

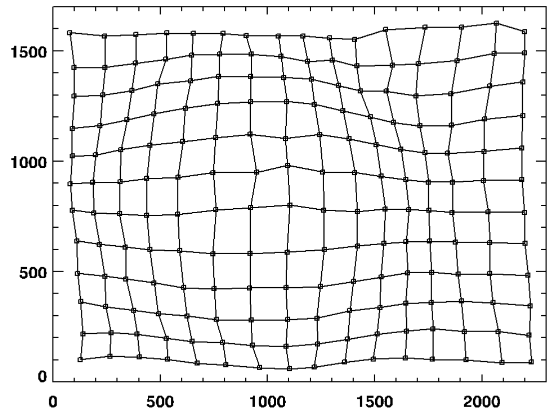

Fig. 2 *Example of image distortions using a low-end digital camera. Deviations from a regular grid indicate the magnitude of the distortions. The deviations are greatly enhanced to be visible.*

The other method exploits object scan techniques. In their simplest form, two images of the same object are taken, and between the two exposures the object is laterally shifted by a certain amount which is measured e.g. by an interferometer. In the two digital images the two positions of the object are determined and the difference is directly linked with the known object shift. These calibration techniques do not rely on a perfect grating standard, and are thus commonly known as ‘self-calibration’ methods [3].

4 Demonstration experiment

A demonstration experiment has been set-up using a commercial Zeiss microscope equipped with a digital camera. Fig. 3 shows, as an example, the microscope image of a 30 µm diaphragm obtained using a low NA objective. An exemplary edge profile (determined for the sector marked in Fig. 3) is presented in Fig. 4.

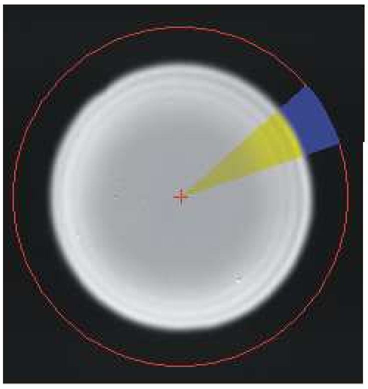

Fig. 3 *Example measurement: Microscope image of a circular diaphragm. The marked area denotes one of the evaluated sectors.*

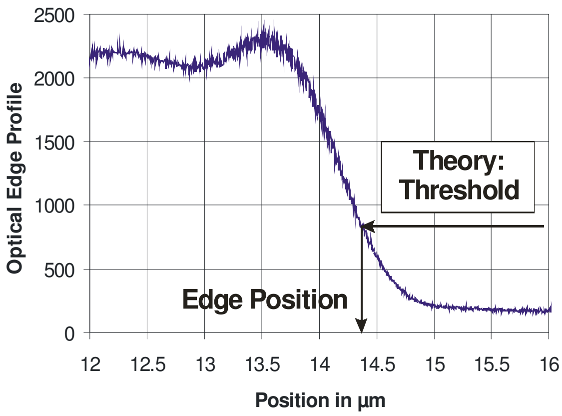

Fig. 4 *Edge profile obtained from the marked sector in Fig. 3. The edge position is determined using the threshold level obtained from model calculations.*

The position of the edge is determined for each sector by comparison with model calculations. The obtained object shape (shown in Fig. 5) can be described by a function r(φ) which is for each polar angle φ the distance of the edge position from the object centre. The function r(φ) is periodic in φ and can thus be represented in a Fourier series (see Fig. 6). The object centre has been determined iteratively; the criterion was that the amplitude of the first harmonic of the Fourier series is zero.

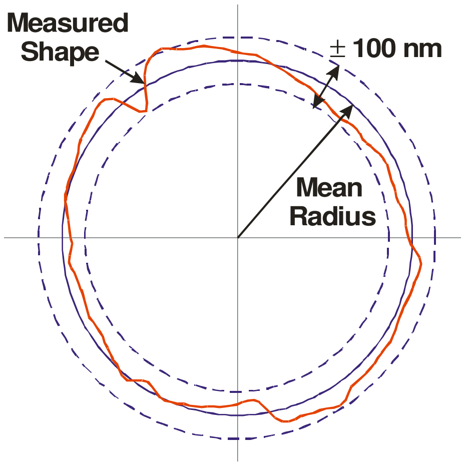

Fig. 5 *Shape (red curve) of the circle shown in Fig. 3. The deviations from a perfect circle have been enhanced for better visibility.*

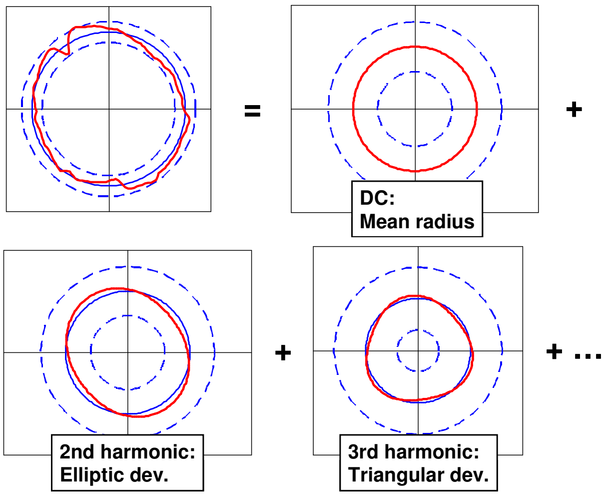

Fig. 6 *Representation of circle shape in a Fourier series. The deviations of the shape from a perfect circle can be classified according to the corresponding harmonic.*

5 Conclusions

Properly calibrated digital image sensors can be used for traceable measurements of the lateral dimensions and shape of microstructures. Important is the calibration of the pixel coordinates and a proper knowledge of the signal transfer properties of the sensor. The measurements are especially applied for the calibration of standards used in semiconductor industry and precision engineering.

References

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[3] J. Ye et al: “An exact algorithm for self-calibration of two-dimensional precision metrology stages“, Prec. Eng. 20, 16-32 (1997)