3D-microscopy with large depth of field

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We present an incoherent, non-interferometric 3D sensor for micro topography measurements with microscopic lateral resolution and nm height resolution. The object height can exceed the Rayleigh depth of focus to a large extent and the surface can be rough or smooth. We discuss the physical limits of the method and present measurement examples with a noise level less than 10 nm.

1 Introduction

The increasing complexity and miniaturization of technical components such as microcircuits and MEMs pose ever increasing demands on the inspection process. As these microstructures are generally not planar only a three dimensional inspection allows complete production control. The sensor that we present in this paper meets the requirements of high lateral resolution and highly resolved height measurements. It is a full-field sensor and can easily be implemented into a common incident light microscope.

2 Principle

Microscopical images of samples with height variations of more than the depth of field contain both focused and blurred areas. The basic idea is to identify focused areas and to use this knowledge to infer the topography of the surface.

For that purpose, different techniques making use of context information (i.e. high spatial frequencies in focused areas) are available [1]. These techniques require surface structures. Thus, they are of limited use on optically smooth surfaces. Instead we follow a context independent approach to identify focused areas using structured illumination as in [2], enhanced by controlled variation of this structured illumination as suggested by Neil et al. [3].

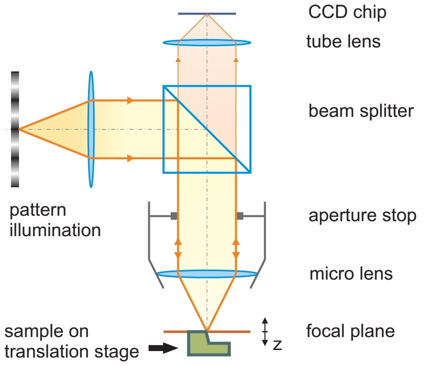

Fig. 1 *Setup for structured illumination.*

We project a sinusoidal fringe pattern at the focal plane of the micro objective (Fig. 1). Thus, the object and the fringe pattern are in focus or blurred at the same time. Blurring of the fringe pattern entails a loss in fringe contrast C (MTF of unfocused systems). We use C to identify surface areas that are in focus.

To measure C locally, we apply standard phase shifting to the fringe pattern. C is evaluated from the resulting image sequence. The object then is moved through a number of different z positions and the contrast is evaluated in each position. The result is a stack of contrast maps.

3 Signal evaluation

In Fig. 2 a typical contrast signal at one pixel along z is shown. With the telecentric setup, one camera pixel always corresponds to the same area on the surface. The contrast signal is very low out of focus while it shows a peak when the surface is moved through the focal plane. With the rough estimate that the signal close to the maximum is gaussian-shaped, we can use Three-Point-Gauss-interpolation to determine the maximum along z with subsample accuracy. Thus, we generate a height map of the object.

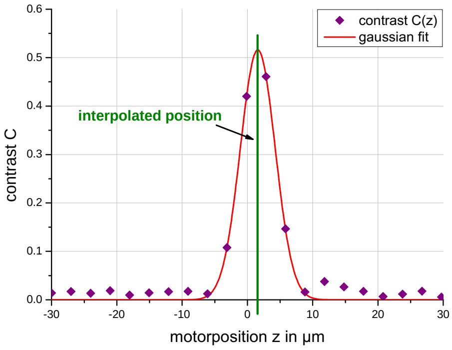

Fig. 2 *Measured and interpolated contrast signal at one pixel for a NA = 0.45.*

4 Limits

Since the applied focus search is based on triangulation, we assume that the measuring uncertainty on *rough surfaces* is limited by speckle noise as was shown by Dorsch and Häusler [4]. For a speckle contrast of $C_{speckle} = 1$ and an appropriate compensation for surface roughness the theoretically expected noise on the measured heights is plotted in Fig. 4 (solid line).

The results of the following experiment correspond to the expected uncertainties: We measured the topography of a planar surface with a known roughness of 800 nm. We repeated this with different NAs and evaluated the standard deviation σ_z of the measured heights for each NA (Fig. 3). For high NA σ_z is almost equal to the surface roughness whereas σ_z increases for low numerical apertures.

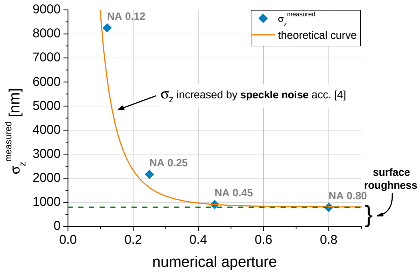

Fig. 3 *σ_z of measured height on rough (800 nm) surface.*

For *optically smooth* objects, the major source of noise is not anymore coherence, but camera noise. Since the camera noise is much smaller than the coherent noise, we expect an accordingly much smaller measuring uncertainty σ_z. As displayed in Fig. 4, we achieved an uncertainty of 10 nm, with an NA = 0.80.

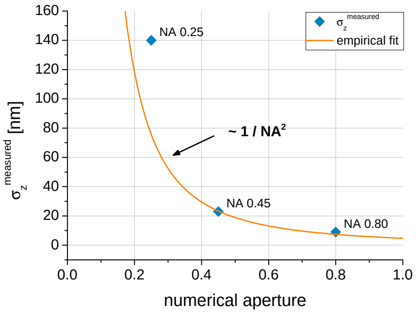

Fig. 4 *Standard deviation of measured height on a planar optically smooth surface for different NAs.*

5 Summary

The suggested sensor based on "structured illumination" has some intriguing features:

• It is incoherent, it is not based on interferometry and it works at rough and smooth surfaces.

• The sensor does not suffer from depth of field limitations, so we can use very high aperture imaging, to achieve the highest possible lateral resolution. With high aperture, steep slopes can be measured.

• The depth uncertainty at smooth surfaces is only limited by camera noise, and can without effort be smaller than 10 nm.

• Combining the high depth of field together with the low noise and the high lateral resolution, we can create intriguing images with SEM like features, as displayed in Fig. 5.

• As a further option we can combine the basic principle with deflectometry [5] and generate texture images with expanded depth of field.

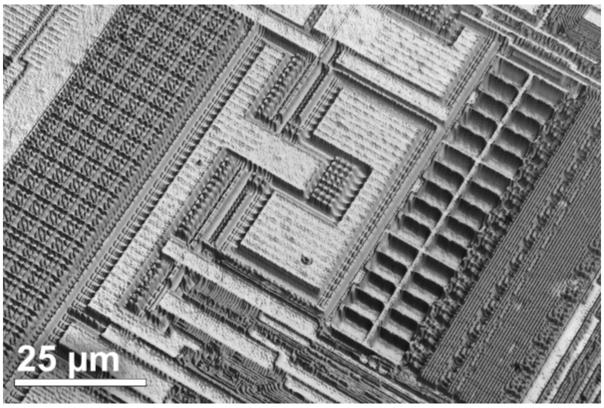

Fig. 5 *SEM-like image of a wafer generated by our sensor.*

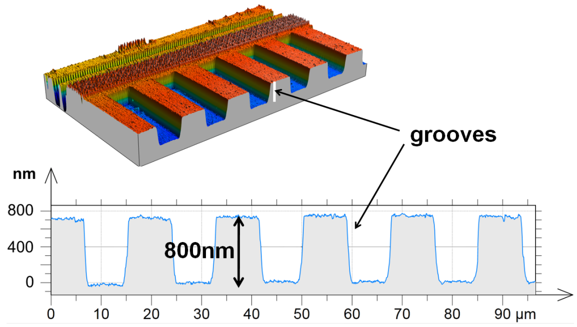

Fig. 6 *Quantitative measurement of a wafer surface.*

References

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