CORRECTION OF SYSTEMATIC ERRORS IN THE STEP-HEIGHT MEASUREMENT WITH OPTICAL SURFACE PROFILERS

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Abstract:

Optical instruments are frequently used for surface topography measurement. In general their working principles can be divided into interferometric (e.g. white-light interferometers) and focus sensing (e.g. confocal microscopy) techniques. For both groups a number of systematic error sources are well known. In this paper we will concentrate on step-height measurement and take a closer look at those errors that are caused by the material properties of the workpiece, as there are: material-dependent phase-jumps on reflection, phase- and focus-shift caused by transparent layers and the effects of volume scattering. We describe these effects and give suggestions for procedures to correct these errors. Based on the results of this work the standardization organization DIN in Germany is currently preparing a draft standard DIN 32567.

Keywords:
Optical surface profilers, error correction, step height measurement

1 INTRODUCTION

The interaction of optical waves with the surface of a workpiece can be exploited in different ways to get information about the microprofile of the surface. In general these techniques can be subdivided into coherent and noncoherent ones. Interferometric and conoscopic sensors are based on the wave-properties of light and therefore to be considered as coherent techniques, while triangulation sensors, autofocus sensors and confocal sensors can be modeled by geometrical optics and belong to the incoherent techniques. It is well known that because of the different physical interaction measurement data of optical sensors are not necessarily consistent with tactile measurements. Even measurements of the same surface made with different optical sensors might show considerable deviations. The reason for this is that quite a number of properties of the surface topography (e.g. slope, curvature), the measurement instrument (e.g. wavelength spectrum, numerical aperture) and the material (e.g. complex refraction index, volume scattering properties) have an influence on the result. Because of the systematic nature of these influences they can in principle be corrected numerically, but only if a model with sufficient accuracy is available and the related parameters are known precisely enough. This is in general not a trivial task.

In this paper we report on recent research work done with the aim to supply users with reference materials and a procedure to determine material and instrument parameters. We have focused this work on step height measurements in microproduction. Only flat horizontal surface elements are measured, slope and curvature effects can be neglected therefore. Additionally, transparent polymers are used frequently in microtechnology. Therefore we investigated the influence of refraction on layer thickness measurement. We used a confocal chromatic sensor (incoherent) and a scanning white light interferometer (coherent) for experimental investigations. Reference measurement were performed at the Physikalisch Technische Bundesanstalt PTB with calibrated tactile profilers.

2 EXPERIMENTAL DETAILS

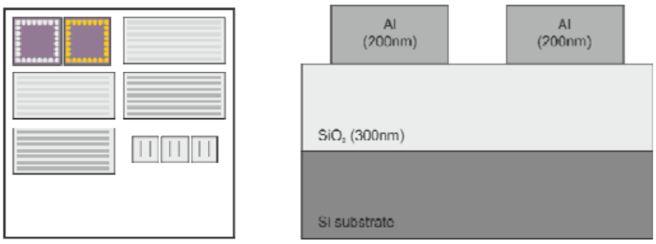

Figure 1: Measurement object used in this investigation (left), schematic of test object #1 (right)

We used a measurement object specially designed and fabricated at Physikalisch Technische Bundesanstalt PTB for round robin tests (Fig. 1). It is a flat glass plate that contains six test objects (Si or SiO_2 substrates) with layer stripes of different materials frequently used in microtechnology. In addition three reference objects with precisely defined step heights are glued to the glass plate. These are used to calibrate the profiler before measuring one of the test objects.

Test object #1 shall be described exemplarily: a silicon wafer is covered with a SiO_2 layer with a thickness of 300±30nm. On top of this SiO_2 layer structures from aluminum with a thickness of 200nm are vapor-deposited. Other test objects are prepared by structuring a transparent SU8 layer (photoresist) with a thickness of 20µm on top of the silicon wafer.

2.1 Measuring instruments

A scanning white light interferometer (Fogale Nanotech Microsurf 3D) and a 2D scanning surface profiler with a chromatic confocal sensor (FRT CWL600) were used for the experimental investigations.

Scanning white light interferometry exploits the interference signals of broadband light with short coherence length. Most of the commercially available instruments are based on a microscope with special interference objective lenses. A beam splitter separates the measurement beam from the reference beam. After reflection from the probe surface and the reference surface, respectively, both beams are recombined. The resulting intensity distribution is acquired by a digital camera. In case of local path differences of the order of the coherence length (typically several µm) interference structures occur.

The workpiece is moved along the optical axis of the objective length with steps smaller than half the center-wavelength of the broadband spectrum. At each step position an image of the camera is taken and stored in computer memory. For each pixel of the camera the intensity is analyzed as a function of distance, giving the autocorrelation function or correlogram of the spectrum of the light. The local height of the workpiece at a given pixel position is calculated either from the position of the maximum of the envelope-function of the correlogram or – more precisely – by evaluation of its phase.

A chromatic confocal sensor makes use of the property of dispersive optics to focus the light of a broadband point light source (illuminated pinhole) not in a single point but spectrally separated at different distances from the lens. Short wavelength components are focused closer to the lens than long wavelength ones. Only for a small spectral fraction of the light the focus lies on the surface of the workpiece.

The light reflected by the measurement object is imaged using the same optics that is used for focusing. Via a beamsplitter this reflected light is again focused onto a so called confocal pinhole. Only that spectral fraction of the light that is focused on the surface of the workpiece is efficiently coupled through the confocal pinhole. A spectrometer behind the confocal pinhole is used to identify the efficiently transmitted wavelength and this is used to determine the local distance to the surface.

3 MEASUREMENT OF TRANSPARENT LAYERS WITH OPTICAL INSTRUMENTS

3.1 Scanning white light interferometer

Using a scanning white light interferometer both the reflection of the light from the top surface of the transparent layer and that from the surface of the substrate can be evaluated. The thickness of the layer can be calculated from the difference of the two determined distances, taking into account the refractive index n of the transparent material. If d is the geometric layer thickness, the measured thickness is nd.

The phase of the light is not only affected by the different velocity characterized by the refractive index (causing a phase shift δ_1) but also by a phase jump δ_2 at the reflection from an optically denser medium:

$$\delta_1 = \frac{2nd}{\lambda}, \qquad \delta_2 = \arctan\left(\frac{2\kappa}{1-n^2-\kappa^2}\right) \tag{1}$$

κ is the imaginary part of the complex refractive index, describing the absorption of the medium.

Some instruments allow a correction of the phase jump on reflection, but in general this is only feasible for a single wavelength. Though the spectral distribution of the light can be derived from the measured correlogram and its center wavelength can be used for correction of the phase jump, this can only imperfectly correct the effect because the wavelength-dependency of the phase jump is not considered.

3.2 Focus sensing methods

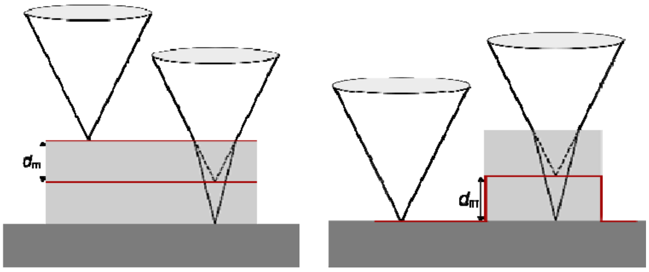

Figure 2: Focus sensing methods: influence of refraction in case of transparent films, either during film thickness measurement (left) or step height measurement (right).

With focus sensing methods the surface of the workpiece is probed by the focused light cone of a microscope lens. When this light cone enters a transparent layer refraction has to be considered. According to Fig. 2 (left) the measured surface distance in this case is smaller than real. If the layer thickness is measured by probing both the top surface and the substrate and calculating the distance difference d_m, the corrected layer thickness results to:

$$d = d_m\sqrt{\frac{n^2 - A_N^2}{1 - A_N^2}} \tag{2}$$

A_N is the numerical aperture of the focusing lens.

A different case may occur when the thickness of the transparent layer is measured at a step where on one side the substrate surface is probed directly, while on the other side it is probed through the transparent layer (Fig. 2 (right)). If the difference between these two distances is called $d_{m,topo}$, then the corrected layer thickness d can be calculated as:

$$d = \frac{d_{m,topo}}{1 - \frac{1 - A_N^2}{n^2 - A_N^2}} \tag{3}$$

3.3 Special test objects

Especially for using the corrections mentioned above some parameters have to be known, like the numerical aperture A_N of the measuring instrument or the phase jump on reflection. In some cases these parameters can be obtained from literature of the instrument’s data sheets. In the case of the numerical aperture it might be delimited by further apertures in the optical path and so differ from the technical data.

Therefore we propose test objects to determine missing parameters as follows:

The effective numerical aperture can be obtained by measuring a defined step in some transparent material with well-known optical parameters. For cover glasses according DIN ISO 8255 the refractive index and dispersion parameters are well known. Thus, the refractive index for each wavelength can be calculated easily.

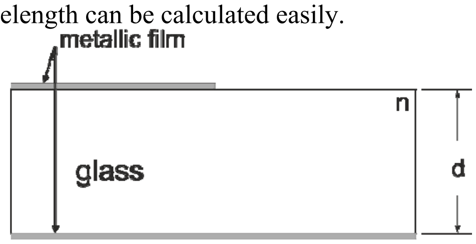

Figure 3: Test object for determining the effective numerical aperture of a focus sensing instrument

The cover glass is covered partly with a thin metallic film in such a way, that a step height between the upper and lower surface of the cover glass can be measured (Fig. 3). By this the effective numerical aperture can be calculated by using Eq. (2) accordingly.

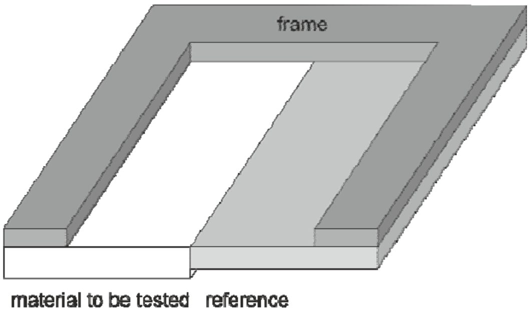

Figure 4: Test object to determine the phase jump on reflection (also the electromagnetic surface of volume scattering materials)

Another test object is depicted in Fig. 4: It can be used to determine the phase jump of a given material. The material to be tested is glued to a stable frame as well as a reference material with a known phase jump, ideally δ=180°. If there remains a step between the material to be tested and the reference it has to be measured using another technique, e.g. using a profilometer. If the phase jump on reflection of the material to be tested differs from 180° a step between the two materials will be measured. As the phase jump leads to an equivalent step Δd_{PJ}, the phase jump can be calculated from this by

$$\delta = \left(\frac{2\pi}{\lambda}\right)\Delta d_{PJ}. \qquad (4)$$

The same setup can also be used the obtain the electromagnetic surface of a volume scattering material. In these materials the interaction between the probing light and the material does not occur directly at the interface between the material and its surrounding environment, but in a certain depth inside the material. This penetration depth depends on the material used, its opacity and the wavelength of the light. Using a test object similar to that in Fig. 4 one will measure a step between the volume scattering material and a surface scattering reference. This step can be used to estimate the electromagnetic surface of the material.

4 RESULTS

The step height measured on test object 1 (aluminum structure on top of a SiO_2 layer on Si) with the scanning white light interferometer is d_m=735nm. This step height is calculated from the measured distance difference between a beam reflected from the aluminum surface and adjacent beam travelling through the transparent SiO_2 layer and reflected at the Si surface. The center wavelength of the spectral distribution of the light source is λ_{WLI}=600nm. For this wavelength the refractive index of aluminum is n=1.1414 and its extinction coefficient is κ=6.9256 [1]. According to eq(3) this results in a phase jump δ_{Al}=-163.99° on reflection from the aluminum surface. The corresponding phase jump for the reflection from Si is in good approximation δ_{Ref}=-180°. The geometrical thickness of the SiO_2 layer is d_{SiO2}=300±30nm. This results in a phase shift according to the optical thickness $n_{SiO2}d_{SiO2}$=1.4772·300±30nm [2]. For the step height of the aluminum structure we get $d_{Al}=d_m- n_{SiO2}d_{SiO2} - \lambda_{WLI}/2\pi(\delta_{Ref} - \delta_{Al})$=735 nm – (443±44) nm - 27 nm=(265±44) nm

This corresponds to some degree with the reference value of $d_{Al,tactile}$=204nm, measured with a tactile profilometer.

The step height of a SU8 structure on a Si wafer was measured to d_m=8,236µm using a chromatic confocal sensor. Using Eq. (3) and setting the refractive index of SU8 to n_{SU8}=1.601 and the numerical aperture of the focusing lens to A_N=0.5 (according to the supplier) the corrected step height is calculated to d_{SU8}=19.13µm, in good accordance to the reference value of $d_{SU8,tactile}$=19.08µm measured with a tactile profilometer.

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