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# Interferometer -based Technology for Optical Nanoscale Inspection

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**We demonstrate the interferometer-based approach for nanoscale grating Critical Dimension (CD) measurements and prove the possibility to achieve no worse than 10 nm accuracy of measurements for 100 nm pitch gratings. The approach is based on phase shift measurement of light fields specularly reflected from periodical pattern and adjacent substrate with subsequent comparison between experimental and simulation results. RCWA algorithm is used to fit the measured results and extract the CD value. It is shown that accuracy of CD value measurement depends rather on the grating's CD/pitch ratio than its CD value.**

**Keywords: Critical dimension, nanoscale inspection, nanoscale measurements, interferometry.**

## 1. INTRODUCTION

NOWADAYS, semiconductor industry requires highly precise, reliable and fast methods for inspection of structures with different topology, which are composed of materials with different refractive indices. There exist several technologies which are considered as potential candidates for solving this problem. To mention of few, there are scatterometry [1], ellipsometry [2] and Optical Critical Dimension (OCD) [3]. Though the last one, which provides accuracy about 1 nm for inspection of periodical structures with Critical Dimension (CD) value as low as 22 nm, is most commonly used today, a more accurate and flexible technology for future industry standards is required [4].

Usually the value of grating's CD is not the only parameter to be measured. Height, sidewall slope angle and CD distribution uniformity are also of interest for the manufacturer. OCD technology partially solves these problems by analyzing intensities of scattered light fields in broad spectral range. However, phase information in this case is usually ignored.

Phase of the scattered light can be taken into account during inspection of the nanostructured surface by means of interference microscopy [5] which allows one to reconstruct a phase portrait of an object under investigation. Generally, the structure of this phase portrait depends on many parameters of the object, both optical and geometrical; therefore, special processing algorithms are required to restore the real form of a surface. In case of uniform distribution of the refractive index interference microscopy reconstructs the geometrical surface profile with the vertical resolution up to $\lambda/1000$ and lateral resolution up to $\lambda/10$ [6]. The main feature of this approach is reconstruction of the phase profile with resolution well below the resolution limit of the optical system by precise measurement of light intensity. Such accuracy of intensity measurements and phase profile reconstruction became possible during the last 20-30 years due to the development of highly sensitive detectors and methods for fast processing of large amounts of data.

In the given work we demonstrate an optical method of measurement of the periodical grating CD value. The proposed method, similar to OCD, does not assume grating imaging or grating relief reconstruction with nanoscale resolution but, unlike OCD, analyzes the phase information of scattered light field. The approach is based on measurement of phase shift between light fields specularly reflected from grating and substrate, which is performed with the use of Linnik microinterferometer, with subsequent comparison between experimental and RCWA-based simulation results. In contrast to interference microscopy, the proposed approach does not require highly sensitive detectors or complicated data processing algorithms.

## 2. SUBJECT & METHODS

In our work we use optical scheme of the Linnik microinterferometer (Fig.1.) with two 20x Olympus microobjectives (NA=0.4) in interferometric arms. The setup is placed on a vibration-isolated optical table, and measurements are performed under stable laboratory conditions. Illumination part consists of LED ($\lambda$=660 nm, spectral width $\Delta\lambda$=20 nm (FWHM)) coupled to multimode optical fiber (400 µm core diameter) imaged to the microobjectives' back focal planes by relay optics composed of L1 and L2 lenses with 50 mm focal distances and a polarizer.

This scheme provides Kohler [7] illumination of nanoscale grating and mirror placed in object and reference arms of the interferometer, correspondingly. Nanopositioning XYZ piezo-stage provides movement of the grating under investigation with 10 nm step. To register the light scattered from the grating and reference mirror a 12-bit CCD camera (Spiricon, Ophir) is used.

In our work we investigated two sets of calibrated silicon rectangular gratings (800 and 100 nm pitch, 50 nm depth, CD values lie within range 250-700 and 30-70 nm respectively, gratings aperture size 100x100 µm$^2$) with periods corresponding to spatial frequencies of diffracted light well above limit frequency – $(NA_{ill} + NA)/\lambda$ which can still pass through objective lenses, where $NA_{ill}$ and NA are numerical aperture of illumination and microobjectives' aperture, correspondingly. In this case only specularly reflected light is registered. The schemes of the gratings are presented in Fig.2.

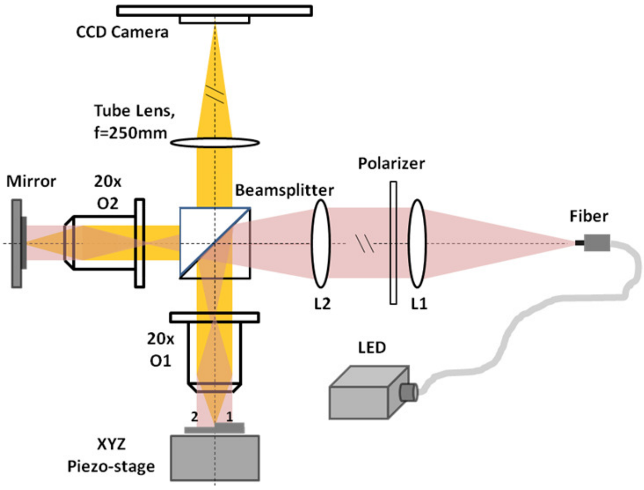
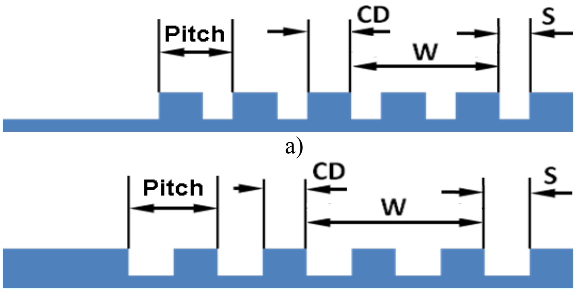


Fig.1. Linnik microinterferometer scheme. L1 and L2 – 50 mm lenses, O1 and O2 – objective lenses.



a)

b)

Fig.2. Schemes of the gratings: a – pitch 100 nm (A1-A9); b - 800 nm (G1-G10), with width (W), (CD) and space (S).

The phase difference between light reflected from grating surface and silicon substrate can be measured as a function of the grating's CD by two ways.

The first one assumes registration of interferograms with fringes of equal inclination in plane of the grating–substrate region image corresponding to the field of view with the size of about 100x100 μm$^2$ (Fig.3.) with their subsequent processing.

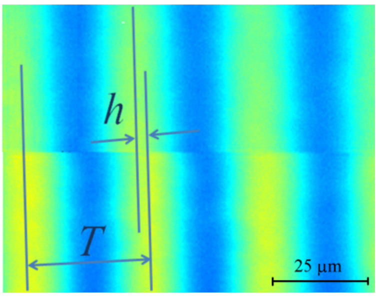


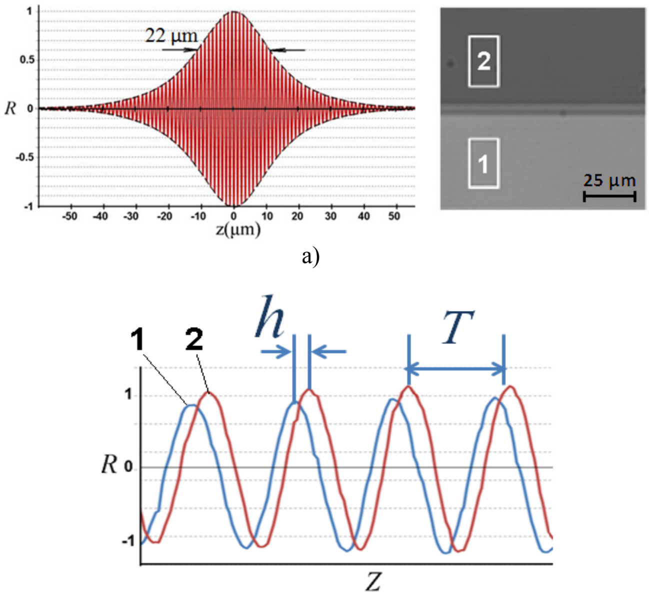
Fig.3. Interferogram with fringes of equal inclination for the grating with 100 nm pitch, 50 nm CD, TE polarization. Upper and lower parts represent grating and substrate regions correspondingly.

To extract the phase difference we use the following expression:

$$\Delta\varphi = 2\pi h / T \qquad (1)$$

where $h$ - is the fringe shift on the edge of the grating and substrate, $T$ – is a period of the interference fringes. Both $h$ and $T$ are measured in different parts of interferograms with their subsequent averaging to minimize measurement errors.

The second approach is based on measurement of the autocorrelation function of detector's signal from the grating region and the silicon substrate region during object scanning along the optical axes in the direction to the objective lens, and further data processing to extract shift of the responses (Fig.4.).



a)

b)

Fig.4. Autocorrelation functions shift measurement: a, left – autocorrelation function of detector's signal, right – microphotograph of the grating and substrate areas with the size about 100x100 μm$^2$; b – phase shift measurements based on autocorrelation functions displacement.

It is known that both the period of the fringes and the autocorrelation function envelope depend on the spectrum of a light source as well as on its angular size, so precise phase measurements require calibration, especially in case of use of wide-aperture interferometer [8]. In our case, due to the small angular size of light source, the period of the fringes is almost equal to λ/2 and envelope width predominantly depends on light source spectral width as $\lambda^2/\Delta\lambda$ which is approximately 22 μm (Fig.4.a).

To measure phase delay between two autocorrelation function responses we select equal regions in the image of nanoscale grating – region 2 and silicon substrate – region 1 (Fig.4.a, right and b) and measure total pixel counts over chosen regions as functions of the object's position along the optical axes (Fig.4.b) during the object's scanning. Fig.4.b illustrates the principle of the phase shift measurement. Phase shift calculation is based on (2), which, as one can see, looks similar to (1):

$$\Delta\varphi' = 2\pi h' / T' \tag{2}$$

where $h'$ - is the displacement of autocorrelation functions, and $T'$ – is a distance between maxima of autocorrelation function responses.

To enhance accuracy of phase shift measurement the intervals between corresponding maxima and minima of two shifted autocorrelation functions were averaged over several periods of fringes. It is necessary to emphasize that in our experiments we use an optical imaging system only for spatial localization of grating and substrate regions meant for measurement, and we do not try to improve the resolution.

The environmental conditions, such as ambient temperature, humidity, etc. can affect the phase difference measurement accuracy. However, we did not notice any significant phase difference change during the 5 days period of measurements. Also, at the semiconductor production line, where such inspection is required, the attention is paid to support constant environmental conditions required for the manufacturing process.

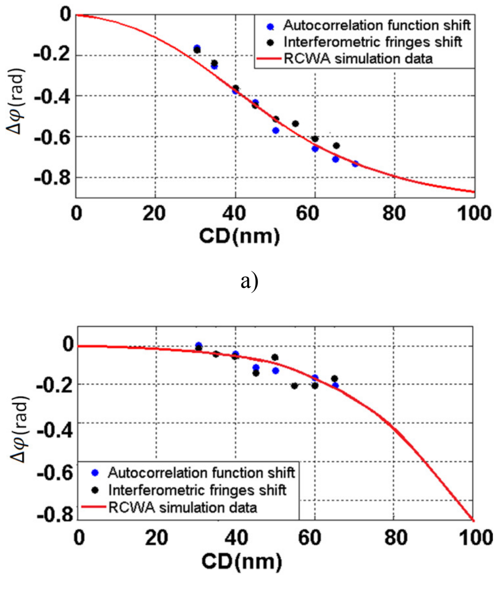
For simulation of the phase shift of specularly reflected light fields the RCWA algorithm is used [9]. As a result, we obtain a set of plane waves with complex amplitudes corresponding to different spatial frequencies. The intensity and relative phase values of each component can be extracted easily. We simulate illumination as a single plane wave incidenting normally upon grating and silicon substrate. This assumption seems reasonable, because 400 µm diameter of fiber light source corresponds to approximately ±0.4° of angular size of illumination light field for 20x objective lens and results in $10^{-4}$ rad of reflected wave phase difference, which is much less than phase shift values to be measured. The effect of sample inclination with respect to optical axis is also negligible, because its alignment accuracy is better than ±1°.

In order to get the best match between measurement and simulation results in our mathematical model we use sample parameters provided by the manufacturer and vary them in the accuracy range (±3 nm for height and CD values for 100 nm pitch gratings) guaranteed by manufacturer until the best match is reached.

## 3. RESULTS

The results of simulation for TE and TM polarization as well as results of comparison between simulated and experimental data for different CD values are presented in Fig.5. One can see that relative phase shift between light specularly reflected from nanoscale grating and silicon substrate is quite sensitive to CD variations. By using methods for accurate measurement of phase difference as small as 0.01 radians, it is possible to resolve CD with accuracy better than 1 nm.

Both approaches for experimental phase shift extraction provide accuracy of CD measurement no worse than 10 nm. However, in our case phase shift measurements based upon detection of autocorrelation function delay seem to be more accurate. There are two major reasons that may explain the discrepancy between simulation and experimental results. Firstly, in both approaches procedure of phase shift extraction is not too accurate due to noise of the CCD camera, vibrations, etc. There exist methods for more accurate phase measurement, such as modulation interferometry [10]. Secondly, the real samples under study are not uniform. CD, height and other structure parameters may vary due to pattern noise, therefore, the measured phase shift is determined by not nominal but some effective or averaged CD value.



a)

b)

Fig.5. Simulated relative phase shifts of specularly reflected light from nanoscale grating with respect to silicon substrate as a function of CD value for 100 nm pitch grating: a – TM polarization, b – TE polarization.

Comparison between experimental and simulation results obtained for 800 nm pitch gratings with CD values in the range 100 – 550 nm is shown in Fig.6.

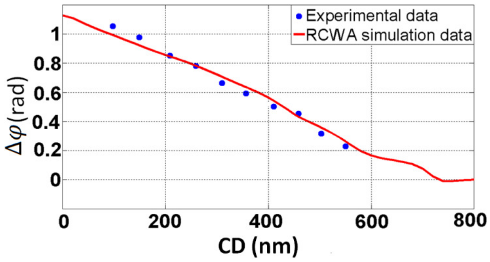


Fig.6. Relative phase shifts of specularly reflected light from silicon grating on silicon substrate as a function of CD value for 800 nm pitch and TM polarization of illumination.

The witnessed difference between phase shift dependency measured for 100 and 800 nm pitch gratings reflects basically the difference in grating structure (Fig.2.). One can notice that the phase shift for 100 nm pitch gratings (Fig.5.) is negative, while it is positive for 800 nm pitch grating (Fig.6.). This difference is due to the fabrication process. In the case of 800 nm pitch, the grating pattern was etched in substrate, while in case of 100 nm pitch, outside area was etched and the grating level was lower than the substrate area. Taking into account experimental and simulated results for gratings with 100 nm and 800 nm pitch, one can make an important conclusion that phase shift depends rather on grating's CD/pitch ratio than its CD value. So, gratings with smaller pitches are available for inspection with the same relative accuracy.

Marginal values for simulation results in the case of 100 nm pitch grating for 0 nm and 100 nm CD value correspond to the phase shift from the single substrate and step with 50 nm height. The same marginal values are for 800 nm pitch grating.

The demonstrated interferometer-based approach, similarly to the OCD technology, has advantages when several unknown parameters of grating are measured simultaneously, which is important for higher throughput. The OCD technology in this case employs a light source of a broad spectral range (several spectral light components measured simultaneously). In case of interferometer-based technology the dependency of phase shift of light fields specularly reflected from grating and substrate regions on the angle of incidence can be used to measure several grating parameters at the same time. To change the sample illumination angle, just a shift of the small light source, placed at the plane conjugated to the back focal plane of the objective lens in the direction perpendicular to the optical axis, will be required. There is a simple relation between source shift $\Delta x$, angle of incidence $\Theta$ and focal distance of objective lens $f$:

$$\Theta = \Delta x / f \qquad (3)$$

The simulation curves of the dependency of phase shift on light incidence angle for 100 nm pitch gratings are presented in Fig.7.

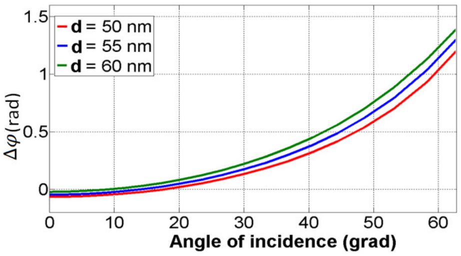


Fig.7. Angular dependence of the phase shift calculated for silicon grating with 100 nm pitch, CD = 50 nm, heights 50, 55, and 60 nm ($\lambda$ = 660nm, TE polarization).

Fig.7. shows that the phase shift change is high enough to be precisely measured in 0°-60° angle range, which corresponds to objective lens numerical aperture NA = 0.9. That makes inspection of grating height in addition to CD value possible.

## 4. DISCUSSION / CONCLUSIONS

It has been demonstrated that sensitivity of phase shift between light specularly reflected from nanoscale grating and silicon substrate to grating's Critical Dimension is high enough for accurate CD inspection. Accuracy of CD value measurements for gratings with 100 nm pitch, achieved in experiments with the use of Linnik interferometer, is no worse than 10 nm and can be significantly improved by application of special phase extraction algorithms. It was shown that value of phase shift and, hence, accuracy of CD measurement depend rather on grating's CD/pitch ratio than on its CD value, thus gratings with smaller pitches can be inspected with the proposed method without loss of relative accuracy. Further development of the demonstrated interferometer-based technology for measurement of several unknown grating parameters (CD, height, sidewall slope angle, etc.) using dependency of scattered light phase on angle of light incidence is suggested.

Relying on the results obtained, we consider the interferometer-based technology as a promising tool for optical metrology in semiconductor manufacturing industry, which can be used either stand-alone or in combination with current OCD technique in order to acquire a more powerful measurement technology based on complete analysis of both amplitude and phase information on scattered light field.

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