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Influence of line edge roughness on scatter signatures for CD-metrology

B. Bilski, K. Frenner, W. Osten

Line Edge Roughness (LER) is a random deviation of a feature edge from its smooth, ideal shape.

It is stated that LER will become the most significant source of process control problems for features smaller than 50nm. This means that with every next lithography generation critical dimensions (CD) deviations are becoming its increasing fraction. Seen in this light, CD control will more and more converge to LER control.

In our previous research we determined that scatterometry can be used for LER metrology if we print the CD in a dense line-grating pattern and conduct two scatterometric measurements upon it, in two distinct setups, in which the plane of incidence of light used for the measurement is either perpendicular or parallel to the grating’s lines, respectively [1]. After applying a realistic roughness to the edges of the given grating, the obtained results showed that the impact of the roughness can be quantified in terms of a so-called effective CD. However, due to the limitations of the applied simulation method (RCWA), the roughness was modeled using only one layer of staircase approximation.

In our recent study we used our in-house implementation of the Differential Method for solving the light-grating interaction problem. With its help we are free to create a complex model of a rough grating, with all the previously not included parameters, see Fig. 1. The creation of 2D roughness is an extension of modelling of 1D rough profiles. One only needs to start with a two-dimensional Power Spectrum Density (PSD) resembling a low-pass filter. Such a roughness is much more close to realistic features.

In Fig. 2 we investigated the impact of side-wall angle and roundings in two cases: when the side-wall angle is 90° and the same when the side-wall angle is 85°. There are two interesting observations one can make. First and foremost we see a remarkable similarity between the 90° and 85° case. We observe that also the impact of roundings preserves the impact of LER.

Based on our investigations we conclude that the effective CD is valid in general case, with side-wall and top- and bottom-roundings. As a side-note, it is interesting to observe that the case when the two roundings exist simultaneously is a combination of cases when these roundings exist individually. This may support the statement that the more complex case could be composed of simple cases.

![Fig. 1: Modeling of a realistically rough line, now including side-wall angle and roundings.](image1)

![Fig. 2: The impact of roundings and LER on reflectivity Rs.](image2)

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References:
Model-based reconstruction of periodic sub-wavelength structures by white light interference Fourier scatterometry

V. Ferreras Paz, S. Peterhänsel, K. Frenner, W. Osten

The white light interference Fourier scatterometry setup is based on a typical Fourier scatterometer. Instead of monochromatic illumination, the sample is illuminated using a broadband white light source. Additionally, a reference branch including a reference mirror for white light interference is introduced. The interfering pupil images from the object and reference branch are imaged with a Bertrand lens on a CCD camera. The schematic setup is depicted in Fig. 1. For reconstruction of the structure profile, a comparison between measured and simulated pupil images for each z-position of the scanned reference mirror is performed until the best match is found.

As part of the DFG priority program SPP 1327 “Optically Generated sub-100-nm Structures for Biomedical and Technical Applications” we already presented in the ITO annual report 2009–2010 a simulation based analysis comparing the sensitivity of the white light Fourier scatterometry method to other scatterometric configurations. To verify the promising results obtained from simulation we now built up the experimental setup and compared the resulting structure reconstruction of a sub-lambda silicon line grating to measurements with an atomic force microscope (AFM) as well as with a scanning electron microscope (SEM).

The comparison between measured and simulated pupil images can be found in Fig. 2. Performing a library search the structure parameters can be reconstructed. The values obtained are compared to the AFM and SEM.
reference measurements. The results can be found in Tab. 1. The reconstructed values are in good agreement, although the height is at the upper limit. One should keep in mind that scatterometry always integrates over the complete illuminated area (multiple periods of the line grating), while SEM and AFM always yield results at the chosen measurement site. Especially when the structure suffers from line edge roughness (LER), there can be differences in the values obtained by direct measurement methods compared with the integrated values obtained from our model-based measurement technique, which at the moment does not take into account LER effects.

The method is well suited for the model-based profile reconstruction (Fig. 3) of periodic line gratings of silicon, which are often used in the semiconductor industry. The measurements performed were reproduced satisfactorily by simulations. A library search inside the precomputed library identifies the best agreement and gives us the possibility to easily obtain the profile parameters of the analyzed structure.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Mid-CD [nm]</td>
<td>182 ± 7</td>
<td>–</td>
<td>182 nm</td>
</tr>
<tr>
<td>Pitch [nm]</td>
<td>400 ± 2</td>
<td>400 ± 2 nm</td>
<td>–</td>
</tr>
<tr>
<td>Height [nm]</td>
<td>76 ± 9</td>
<td>72 ± 7 nm</td>
<td>85 nm</td>
</tr>
<tr>
<td>SWA [°]</td>
<td>77 ± 3</td>
<td>–</td>
<td>77.5 °</td>
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</tbody>
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Tab. 1: Profile parameter ranges for the silicon grating (CD=200nm) measured with AFM, SEM and the reconstructed values obtained from the white light Fourier Scatterometry measurement.

Fig. 3: Schematic flowchart of the reconstruction strategy in general model-based metrology.

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References:


Design of microlenses using plasmonic stacks

L. Fu, K. Frenner, W. Osten

Plasmonics is a flourishing new field of science and technology due to its capability to confine light into a subwavelength volume, which induces strong light matter interactions at nanometer scales. Novel optical elements for light harvesting, plasmonic antennas, super-lenses and resonators have been developed in the last decade [1]. In the framework of a project with Bundesdruckerei GmbH, a novel type of plasmonic microlens using metal/dielectric stacks has been designed and simulated. The developed structure is of great importance for security elements, laser cavity reflectors or CD/DVD read/write heads with controlled focus size and length [2].

Fig. 1 shows a schematic of a periodic plasmonic structure embedded in polycarbonate (PC) with two unit cells. The metal is Silver and its dielectric constant is described by a Drude model. The dielectric is assumed to be PC having a refractive index of 1.58 at a wavelength of 630 nm. Our inhouse developed software package Microsim based on Rigorous Coupled Wave Analysis was used to simulate the structure. To obtain a parabolic phase front of the reflected beam, we treat the stacks as an effective medium and its effective index was approximated using the following equation, which is only valid when the thickness of the layers is much smaller than the wavelength:

\[
\frac{1}{\varepsilon_{\text{eff}}} = \frac{h}{\varepsilon_d} + \frac{1-h}{\varepsilon_m},
\]

in which, \(\varepsilon_m\) and \(\varepsilon_d\) is the permittivity of metal and dielectric, respectively, and \(h\) is the filling factor of the dielectric determined by \(\frac{d_d}{d_m+d_d}\), in which \(d_m, d_d\) is the corresponding thickness of the metal or dielectric.

The results of a plasmonic lens designed for 630 nm wavelength are shown in Fig. 2. To obtain a reflected focused field at \(z = -150 \mu\text{m}\) (the top surface of the structure locates at \(z = 0 \mu\text{m}\)), a parabolic wavefront of the reflected waves is desired. To achieve this, three pair of Ag/PC layers with thicknesses of 30/107 nm and widths of 25, 20, and 15 \(\mu\text{m}\) from bottom to top as shown in Fig. 1 were derived based on Eq.(1). Fig. 2(a) shows the intensity of the electric field above the stacks under the illumination of a p-polarized plane wave. It was also found that the focusing characteristics was kept under a tilted illumination of 30° and was robust in a larger wavelength and structure parameter range. Future work will focus on developing and fabricating plasmonic lens with a stronger focus capability and smaller size.

This work was cooperated with Bundesdruckerei GmbH in the framework of the BMBF-Project UMBABASA [3]. We thank the support from the Federal Ministry of Education and Research.

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Improved speckle simulator for rough surfaces using surface integral equations

L. Fu, K. Frenner, W. Osten

Any real surfaces, both those occurring naturally, and those fabricated artificially, are rough to some degree. It is of great interest and importance to know how this roughness affects physical properties of a surface. The scattering of electromagnetic waves from rough surfaces has been studied actively for more than a century now. More than thirty analytical approximation methods have been developed [1], among which the often used ones are small amplitude perturbation theory, Rayleigh-Rice and the Beckmann-Kirchhoff theory. In the last two decades, great advances in analytic approaches have been made by incorporating multiple scattering effects into the approaches. However, analytic models are all valid only in some specific application ranges [1].

In order to gain a fundamental understanding of how light interacts with a broad variety of rough surfaces, we aim to develop a rigorous numerical simulator for penetrable metals with a surface roughness in a large variation range. For this aim the full Maxwell equations have to be solved and surface integral equations with boundary element method were most often used. Based on Stratton-Chu's formulation and the associated boundary conditions on the tangential field components, a generalized formulation is obtained (PMCHW [2]):

\[ E_{\text{inc}}(r)_{\text{tan}} = (L_1 + L_2)J(r)_{\text{tan}} - (K_1 + K_2)M(r)_{\text{tan}}, \] \hspace{1cm} (1)

\[ H_{\text{inc}}(r)_{\text{tan}} = (K_1 + K_2)J(r)_{\text{tan}} - \left( \frac{L_1}{\eta_1} + \frac{L_2}{\eta_2} \right)M(r)_{\text{tan}}, \] \hspace{1cm} (2)

in which \( M \) and \( J \) are equivalent magnetic and electric surface currents induced by the incident fields \( E_{\text{inc}}(r) \) and \( H_{\text{inc}}(r) \), respectively. \( K_{0,2} \) and \( L_{0,2} \) are linear integrodifferential operators and \( \eta_1 \) and \( \eta_2 \) are the impedances of the two media above and below the surface.

To solve the two coupled equations, the rough surface, which is modeled using Monte Carlo methods, is discretized using isoparametric elements (boundary element method). In this work, the element takes a curvilinear quadrilateral shape as shown in Fig. 1, which is more accurate compared to planar elements [3]. The approximated field in each element is calculated through a linear combination of the 10 edges:

\[ J_{\text{tan}} = \sum_{i=1}^{10} N_i(\eta, \xi)S_{Hi}, \] \hspace{1cm} (1)

in which \( N_i = f_i v_i \) is vector element function along each edge, \( v_i \) is the gradient of \( \eta \) or \( \xi \) of the edge \( i \), and \( S_{Hi} \) denotes the line-integral of \( J \) along the edge \( i \) \((i = 1, \ldots, 10)\) [3]. A similar equation exits for \( M \).

By using Galerkin method, the integration equations can be transformed into linear matrix equations. Once the unknown coefficients \( f_i \) for the effective current density in each element are solved, the \( E \) (or \( H \)) field everywhere in space can be calculated correspondingly [2]. Especially, one of the advantages with this method is that both near and far field can be calculated accurately.

Fast multiple method combined with an iterative solver can accelerate the solution of the matrix equations.

Fig. 1: Numbering scheme of the edges of a curvilinear quadrilateral shape element.

References:
Reconstruction of dynamical perturbations in optical systems

H. Gilbergs, K. Frenner

High-performance optics pose strict limitations on errors present in the system. External mechanical influences can induce structural vibrations in such a system, causing the optical components inside the objective to deviate from their designated positions. This can have an impact on the imaging performance, leading to blurred images or broadened structures in lithography processes.

A method to detect and predict the motion of the components of such an optical system by means of opto-mechanical simulation in combination inverse problem theory has been demonstrated. Such a method is the first step towards a control loop that corrects the lens positions with mechanical manipulators.

On the optical side of the simulation, ray-tracing is used for the generation of wavefront data of the system in its current state. A high speed Shack-Hartmann wavefront sensor is therefore implemented to gather the data needed for the reconstruction of the motion. The mechanical properties of the system are simulated using multibody dynamics, where the system is modelled as a set of rigid bodies (lenses, mounts, barrel), represented by rigid masses connected by springs that represent the coupling between the individual parts. External excitations cause the objective to vibrate. This motion can be represented by the eigenmodes and eigenfrequencies of the system.

The reconstruction of the system geometry as a function of time from the wavefront data is an inverse problem. Tikhonov regularization is used in the process in order to achieve accurate reconstruction results. This method relies on a certain amount of a-priori information on the system. The mechanical properties of the system are a great source of such information. It is taken into account by performing the calculation in the coordinate system spanned by the eigen-modes of the objective and using information on the spectrum of frequencies present in the current vibration as a-priori data. The positions of the individual lenses as a function of time is then reconstructed from several frames of the wavefront data and extrapolated to future timesteps in order to give a prediction on the system behaviour. This can be useful for applying and controlling countermeasures against the vibrations of the objective or for designing new systems that are less influenced by vibrations.

The results of this study have been published and presented in [1]. The next steps in this project are the extension of the reconstruction process to lens deformations and thermal expansion as well as experimental verification of the results.

Fig. 1: Visualization of the four eigenmodes used to represent system vibrations. The red line is the optical axis. The eigenmodes correspond to the eigenfrequencies $f_1 = 0.70 \text{ s}^{-1}$ (top left), $f_2 = 1.10 \text{ s}^{-1}$ (top right), $f_3 = 2.07 \text{ s}^{-1}$ (bottom left), $f_4 = 4.11 \text{ s}^{-1}$ (bottom right).

Fig. 2: Comparison of the quality of the position prediction based on Tikhonov regularization (red) and least squares fit (dashed blue) vs. the number of evaluated timesteps. The results are improved greatly, especially for a lower number of evaluated timesteps. The smallest achievable mean position error is achieved for the Tikhonov based method.

References:
Sub-wavelength imaging with metallic meander structures

P. Schau, L. Fu, K. Frenner, H. Schweizer, H. Giessen, W. Osten

In semiconductor manufacturing and nanotechnology, high-resolution metrology is crucial for process and quality control. At this point there are specialized tools available, which enable high-resolution imaging or metrology for individual process steps but no universal device. While demands of the industry have driven technology to the limits, none of the presented solutions is capable to image arbitrary sub-lambda structures directly in a contactless, fast and non-destructive way.

This is where the new research field of metamaterials comes into play. Metamaterials consist of periodic structures with dimensions smaller than the wavelength and can be designed to create particular electromagnetic responses that cannot be found in nature. Particularly interesting is the Veselago material, which exhibits a negative refractive index and can be used for superlensing as investigated by Pendry in 2000. Although a simple slab of silver already creates a perfect image of a sub-wavelength source, the image is still in the near-field and not magnified. Hence, all sub-wavelength information will still decay exponentially and vanish in the far field. Our research goal is to design a superlens capable of transforming evanescent waves to propagating modes, which then can be imaged via conventional microscopy (see below).

It has been shown that surface plasmon polaritons (SPPs) propagating on the metal/dielectric interfaces of a bulk negative index material (NIM) have a dominant influence on the unique properties of these materials. Consequently, one could replace bulk NIMs by resonantly coupled metallic surfaces that allow the propagation of SPPs.

A metallic meander structure (Fig. 2) is perfectly suited as such a resonant surface due to the tunability of the short range SPP (SRSPP) and long range SPP (LRSPP) frequencies by means of geometrical variation.

We have already demonstrated numerically how a stack consisting of two meander structures can mimic perfect imaging known from Pendry’s lens. To observe sub-wavelength features in the far-field, however, we extended this principle towards a stack made up of meander structures with varying periodicities. A numerical simulation of this device is shown in Fig. 3.

In the course of the project, we have developed different ways to manufacture single and stacked meander structures preferably with e-beam lithography but also using other techniques such as interference lithography.
or focused ion beam milling. We have shown experimentally that the transmission spectra of these meander structures agree well with our numerical simulations. Furthermore, we demonstrated negative refraction occurring in meander structures using dispersion measurements and have high hopes to realize a proof of principle superlens in the near future.

![Fig. 3: Stack consisting of four meander structures that magnifies two sub-wavelength holes by a factor of 8.](image)

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References:


Polarization scrambling with plasmonic meander-type metamaterials for space applications

P. Schau, L. Fu, K. Frenner, H. Schweizer. H. Giessen, W. Osten

The polarization state of light is one of the most important properties for many optical applications. However, in some instances, such as earth observation from space, any exhibited polarization of the light is undesirable and depolarization of the light is critical for a good optical performance of a space-based instrument. One approach towards depolarizers are so called polarization scramblers or pseudodepolarizers, which divide the incident light beam into a large number of varying and intermixed polarization angles instead of truly depolarizing the light. Currently and historically, most pseudodepolarizers in space instruments utilize different arrangements of birefringent wedges. Major drawbacks of these designs are their bulkiness, heavy weight and limitation in size due to the anisotropy of the thermal expansion coefficient of birefringent materials.

Especially for space instruments, large-area and low-weight optical elements are desirable. So-called metamaterials could advantageously replace bulky standard optical components with thin layers of the same functionality but lower mass and volume. Depolarization effects in metamaterials have been discussed frequently in literature whereas metamaterial pseudodepolarizers have not been investigated yet.

The device proposed by ITO and the 4th Physics Institute is based on metallic meander structures (see OPTIM project report), which behave not only like an almost ideal linear polarizer, but also demonstrate a large phase retardation and polarization conversion capability between two orthogonal polarization states. The main idea of our approach consists of meander structures that are spatially distributed on a surface. Each meander structure within such a tile is rotated by a random angle (Fig. 1).

For perpendicularly incident light (θ = 0), we have described the behaviour of a single meander structure using Jones calculus. Because the meander structure itself is not depolarizing, it is valid to transform the Jones matrix to a Mueller matrix, which is dependent on the azimuth angle ϕ of the incident polarized light. The random orientation and distribution of the meander tiles effectively averages the azimuth angles and, hence, ϕ can be integrated from 0 to 2π. Then, within the pass band of the meander structure, the off-diagonal elements of the averaged Mueller matrix are zero and the diagonal elements around 0.5 or smaller. This makes the device already a good partial pseudodepolarizer.

To investigate the behaviour for oblique incidence, we used our in-house software tool Microsim to calculate the Mueller matrix rigorously. We found out that we can enhance the depolarization by stacking two meander sheets onto each other. With this scheme we achieve preliminary depolarization rates of >50% linearly polarized light and even 95% for circularly polarized light.

The presented polarization scrambler might be a good alternative to existing approaches and would be especially desirable for space applications due to its low weight and large-scale manufacturability using nano-imprint lithography.

Fig. 1: Working principle of the proposed polarization scrambler consisting of meander-type metamaterials.

References:

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Optical coherence tomography (OCT) is an important technology for non-invasive, in-vivo medical diagnostics. It enables the high-resolution recording of two-dimensional tomograms or three-dimensional volumes of biological tissue. Two mechanisms help separating the signal from the scattering background. First, reflected or backscattered light from outside the focal spot is suppressed by confocal discrimination. Additionally, the signal modulation is enhanced due to identical optical path lengths of both branches of the white light interferometry setup. Since the OCT relies on the interference between reference light and scattered light, this method cannot be readily extended for fluorescence measurements.

An alternative approach is the confocal fluorescence microscopy, which uses confocal microscopy to suppress the fluorescent light from outside the focal spot. Hence, only the fluorescent light in the focal plane, which is three to four magnitudes lower in intensity than the excitation light, is detected. However, the surrounding area is illuminated with full intensity, which might cause photobleaching. There are also other promising approaches such as the two-photon excitation microscopy or fluorescence lifetime microscopy.

However, for depth-sensitive fluorescence measurements of strongly-scattering samples such as biological tissue but also for technical surfaces, these methods are not well-suited. To enhance fluorescent depth-sensitive measurements, we cooperate with Institut für Lasertechnologien in der Medizin und Meßtechnik (ILM), Ulm and propose a combination of a structured white-light illumination and shearing interferometry (Fig. 1).

For this purpose, a structured illumination limits the area of interest on a rough scale. The exact lateral and axial position of the fluorescent molecules is then determined by a shearing interferometer. Using Fourier analysis, the curvature of the incident wave fronts can be calculated via the density and orientation of the interference fringes. Finally, the axial distance can be determined, which corresponds to the exact location of the particular molecule emitting fluorescence.

In a first step towards the realization of the whole system, we investigate and optimize the structured illumination. In a setup similar to a white-light interferometer, the light from the two branches is obliquely incident and interferes within the strongly scattering sample. Due to the short coherence length of the white light source, the light superposes only coherently for the exact same optical path length of both branches. Scattered or reflected light interferes only marginally or not at all. Hence, there is a ‘plane’ or ‘sheet’ within the strongly scattering sample that is illuminated with a higher intensity than the surrounding volume. The shape and intensity of the interferogram making up this plane can be manipulated with the bandwidth of the white light source and the angle of incidence, respectively. To what extent the scattering within the sample influences the measuring process will be investigated numerically by the ILM.

Fig. 1: Principle setup of the measurement system consisting of the structured white-light illumination part and the shearing interferometer for detection of fluorescent light.

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