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DOI

[10.1117/12.2544156](https://doi.org/10.1117/12.2544156)

Publication date

2020

Document Version

Final published version

Published in

Proceedings of SPIE

Citation (APA)

Siaudinyte, L., & Pereira, S. F. (2020). Wavelength influence on the determination of subwavelength grating parameters by using optical scatterometry. In O. Adan, & J. C. Robinson (Eds.), *Proceedings of SPIE: Metrology, Inspection, and Process Control for Microlithography XXXIV* (Vol. 11325). [113252M] (METROLOGY, INSPECTION, AND PROCESS CONTROL FOR MICROLITHOGRAPHY XXXIV). SPIE. <https://doi.org/10.1117/12.2544156>

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Lauryna Siaudinyte, Sylvania F. Pereira, "Wavelength influence on the determination of subwavelength grating parameters by using optical scatterometry," Proc. SPIE 11325, Metrology, Inspection, and Process Control for Microlithography XXXIV, 113252M (20 March 2020); doi: 10.1117/12.2544156

SPIE.

Event: SPIE Advanced Lithography, 2020, San Jose, California, United States

Wavelength influence on the determination of subwavelength grating parameters by using optical scatterometry

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ABSTRACT

The paper represents a comparison of simulated light scattering of the near and far fields of subwavelength grating at various wavelengths. By quantifying and comparing the scattered near and far fields of multiple grating parameters to the nominal parameter based scattered field, the sensitivity to the change of grating parameters is determined. The wavelength influence on the near field is analyzed by applying a plane wave at certain angle of incidence and the far field diffraction patterns are simulated by applying coherent focused light (conical incidence). The paper analyses how each wavelength affects the sensitivity to the change of the height and the sidewall angle of a subwavelength grating.

Keywords: Coherent Fourier scatterometry, optical scatterometry, coherent light, far field, near field, subwavelength grating, grating parameters, sensitivity

1. INTRODUCTION

In the semiconductor industry, optical scatterometry is a widely used technique as it is non-destructive and therefore suitable for parameter reconstruction of printed structures. This technique is precise, useful for inspection of periodic structures and, moreover, it is not limited by diffraction. The latter is an important issue due to the continuously shrinking critical dimensions of the nanostructures [1, 2]. Subwavelength silicon structures play an important role in integrated photonics due to their multi-purpose application in the industry [3, 4]. Therefore, this research focuses on a subwavelength grating regime when the wavelength of light is longer than a grating period. The literature [5-7], suggests that deep sub-wavelength and near-subwavelength regimes should be separated due to different optical effects. Depending on the sample material, different wavelengths may have a big influence on the results. Although in different fields of research, there are approaches on combining a few wavelengths at once [8-11], it is still useful to analyse the impact of each wavelength separately.

The silicon grating commonly used in semiconductor industry was chosen as a scatterer for this research due to the well known silicon sensitivity to the wavelength of light. In this paper, we compare simulated near and far fields of both near-subwavelength and sub-wavelength grating regimes in order to find out if the wavelength has an influence on the sensitivity to the change of grating parameters.

2. SENSITIVITY DETERMINATION IN OPTICAL SCATTEROMETRY

Scatterometry is a non-contact method and its main principle lies in parameter retrieval by comparison of measured and simulated diffraction patterns. The nominal parameters are used as a priori knowledge of the sample and as a reference to generate far and near field simulations based on the combinations of the parameters close to the provided information. Also, after interaction with the sample, the diffraction pattern within the numerical aperture is captured by the CCD camera. Later, the simulated data is compared with the measured data and the smallest difference indicates the best match of grating parameters. Scatterometry and its variations are widely used not only in geometrical parameter determination but also in overlay metrology in semiconductor industry [12].

For our numerical simulations, we used silicon on silicon periodic grating with nominal parameters: height (h) = 130 nm, grating pitch (d) = 500 nm, sidewall angle (SWA) = 90°, middle linewidth of critical dimension (midCD) = 216 nm. In order to analyse near-subwavelength, sub-wavelength and deep subwavelength grating regimes, the wavelength of the incoming light was chosen in relation to the nominal grating height ($h = \lambda/4$, $h = \lambda/4.5$, $h = \lambda/5$, $h = \lambda/5.5$, $h = \lambda/6$, $h = \lambda/6.5$, $h = \lambda/7.5$ and

$h=\lambda/8$) expecting higher sensitivity to the change of one of the parameters (grating height or sidewall angle) because when grating height gets closer to $h=\lambda/4$, it creates a π phase shift in the reflection. For the near-subwavelength regime analysis, the chosen wavelength was 520 nm and for deep subwavelength 1040 nm, corresponding to a π and $\pi/4$ phase shift in the reflection, respectively. For this research it was decided to determine sensitivity to the change of two grating parameters – grating height and sidewall angle.

Sensitivity to the change of grating parameters is one of the main characteristics describing the precision of the grating parameter retrieval. The bigger the change of electromagnetic field while varying one of the parameters, the more precisely retrieved parameters could be found. Increasing the sensitivity to the parameter change is an important topic in the field of scatterometry [13, 14].

To analyse the sensitivity, far field and near field numerical simulations were computed with different wavelengths ($\lambda = 520$ nm, $\lambda = 585$ nm, $\lambda = 633$ nm, $\lambda = 715$ nm, $\lambda = 780$ nm, $\lambda = 845$ nm, $\lambda = 975$ nm and $\lambda = 1040$ nm) by using Rigorous Coupled Wave Analysis (RCWA) [15]. As shown in Figure 1, the best way to determine the sensitivity to the change of simulated parameters is to analyse the difference between the electromagnetic field simulated based on nominal parameters and other parameter combinations [16]. The electromagnetic fields are computed by varying probable parameters and their combinations in a certain range around the values of the nominal parameters. Then, every difference is quantified and inserted in the sensitivity map in order to analyse if one of the parameters has a higher impact or is more dominant.

Figure 1. Process of creating the far field sensitivity maps ($\lambda = 975$ nm).

The far field shown in the inset of Fig. 1 (right) was obtained by focusing the coherent light onto the grating and recording the scattered far field within the numerical aperture of the focusing system. This 2D distribution represents the far field within the numerical aperture of a microscope objective (NA=0.4) and each pixel in the matrix represents one scattered angle within the numerical aperture. More details on how the data was obtained can be found in [17]. The sensitivity map displayed in Fig.1. was created to visualize the scattered far field after the coherent focused light interacted with the 1D silicon grating. The example in Fig.1 shows the sensitivity map for the far field generated using amplitude of the input field, wavelength $\lambda = 975$ nm, varying grating height $120 \text{ nm} \leq h \leq 140 \text{ nm}$ and sidewall angle $70^\circ \leq \text{SWA} \leq 90^\circ$. Cases as presented in Fig. 1 require further investigation to determine the dominant parameter. However, usually the tendency is visible in the sensitivity map. Far field sensitivity maps generated with multiple wavelengths are presented further in this paper. The sensitivity was quantified for each parameter combination as a deviation from the nominal parameter based far field and normalized with the respect to it as follows:

$$\Delta = \frac{\int \sqrt{|A_{\text{est}}(x, y) - A_{\text{nom}}(x, y)|^2} dx dy}{\int \sqrt{|A_{\text{nom}}(x, y)|^2} dx dy} \quad (1)$$

where: A_{est} - simulated scattered far field matrix (estimated matrix) generated by changing one or both parameters (grating height and sidewall angle); A_{nom} - simulated scattered far field matrix generated with nominal grating parameters.

Eq. 1 lets us quantify and evaluate amplitude or phase input based pattern in the far field pixel by pixel. In this way we can determine, visualize and quantify overall sensitivity, as a difference from the nominal parameter based electromagnetic field, for each desired combination of grating parameters. The above described model for determination of the sensitivity to the change of grating parameters can be applied for both the near and the far fields and was used for the numerical simulations presented further in this paper.

3. OPTICAL MODELLING OF NEAR AND FAR FIELDS

3.1 Wavelength influence on the sensitivity in the near field

In the near field, evanescent waves carry helpful information for the parameter retrieval, but they decay within a wavelength and it is very complex challenge to measure (and image) the electromagnetic near field [18, 19]. Although there are methods dealing with the near field problems [20], it is still complicated to realize the full procedure of optical scatterometry for parameter retrieval by using only the near field data. However, in order to analyse certain optical phenomena, it is useful to simulate the near field. For the visual representation of the electromagnetic near field and the grating containing aforementioned nominal parameters, simulations presented in Fig. 2 were computed by the finite element method (FEM) based solver JCM wave which considers the details of the grating shape such as corner roundings of the grating line [21]. As shown in Fig. 2, TM-polarized plane waves of different wavelengths with a normal angle of incidence ($\alpha=0^\circ$) have different effect on the subwavelength periodic structure and create different patterns in the near field. Decaying evanescent waves are also visible. Each near field in Fig. 2 is computed up to 1300 nm above the surface of the same silicon-on-silicon grating.

Figure 2. Schematic view of the simulated near fields in near-subwavelength ($\lambda = 520$ nm), subwavelength ($\lambda = 633$ nm) and deep-subwavelength ($\lambda = 1040$ nm) regimes containing decaying evanescent waves.

As mentioned in a prior research, the reflectivity of the grating containing silicon layers is dependent on the angle of incidence [22, 23]. Therefore, shining the light at different incident angles in subwavelength regime might affect the near field sensitivity to the change of grating parameters. In order to analyse if there is a sensitivity to the change of the grating height while changing the angle of incidence, the sensitivity map was created for the near field similarly as described in sec.2. After quantifying the simulated near fields for each combination of the grating height and the angle of incidence, it was determined that the sensitivity to the change of grating height is relatively low compared to the incident angle. Fig. 3. shows the differences between the normal angle of incidence ($\alpha=0^\circ$) and all other possible incident angles ($0^\circ \leq \alpha \leq 90^\circ$, step size 1°) at the nominal grating height ($h=130$ nm) for each wavelength.

Figure 3. The change of the angle of incidence in the near field for multiple wavelengths when $h=130$ nm, and $swa=90^\circ$.

It is noticeable from Fig. 3, that the incident angle with the biggest difference increases with the longer wavelengths. It turned out that each wavelength had its own one angle of incidence with the highest difference from normal angle of incidence ($\alpha=0^\circ$). Therefore, it was decided to analyse the sensitivity to the change of the grating height and sidewall angle under this specific (possibly the most sensitive) angle of incidence.

For this purpose, two sets of near field numerical simulations were generated. In one of them, the angle of incidence and the grating height were fixed, but the sidewall angle was varied ($70^\circ \leq \text{swa} \leq 90^\circ$, step size 1°). In another one, angle of incidence and sidewall angle were fixed but the grating height was varied ($120 \text{ nm} \leq h \leq 140 \text{ nm}$, step size 1 nm).

After quantifying the differences between the near field based on nominal parameters and near fields based on aforementioned parameter combinations, the derivatives showed that for every wavelength the magnitude of the change to one of parameters is different. The mean values of the derivatives of the sensitivity to the change of grating height and the sidewall angle are presented in Table 1.

Table 1. The derivatives of the sensitivity to the change of the grating height (h') and the sidewall angle (swa') for multiple wavelengths at their best angles of incidence.

Wavelength, λ (nm)	Angle of incidence ($^\circ$)	$\frac{1}{n} \sum_i^n h'_i$, arb. units	$\frac{1}{n} \sum_i^n \text{swa}'_i$, arb. units
520	31	$1.011 \cdot 10^{-4}$	$1.7455 \cdot 10^{-5}$
585	35	$4.8129 \cdot 10^{-5}$	$7.0768 \cdot 10^{-5}$
633	37	$2.9841 \cdot 10^{-4}$	$5.4873 \cdot 10^{-5}$
715	40	$3.8892 \cdot 10^{-4}$	$-1.9749 \cdot 10^{-4}$
780	44	$7.0058 \cdot 10^{-4}$	$-2.7844 \cdot 10^{-4}$
845	40	$8.3472 \cdot 10^{-4}$	$-6.4018 \cdot 10^{-4}$
975	46	0.0012	$-5.1388 \cdot 10^{-4}$
1040	46	0.0011	$-4.3457 \cdot 10^{-4}$

Table 1 shows that the sensitivity to the change of the grating height is highest when the wavelength is $\lambda = 975 \text{ nm}$ (it corresponds to $\pi/3.625$ phase shift) and is very close to the average sensitivity of wavelength $\lambda = 1040 \text{ nm}$ which corresponds to $\pi/4$ phase shift in the reflection. The highest sensitivity to the change of the sidewall angle was reached with the wavelength $\lambda = 585 \text{ nm}$ which corresponds to $\pi/1.375$ phase shift.

In the following section we analyse the sensitivity of multiple wavelengths in the far field in order to see if the wavelengths have the same impact as in the near field.

3.2 Wavelength influence on the sensitivity in the far field

For the far field simulations, it was chosen to analyse the TMTM case, when both incoming and outgoing light has a transverse-magnetic polarization, because the far field in this case is richer than other polarisation combinations. The numerical aperture of the system was 0.4. Far fields were computed based on coherent Fourier scatterometry method with the conical incidence [24]. In order to visualize the sensitivity to the change of grating parameters, each simulated far field for every parameter combination and for every wavelength was quantified and after determining the difference from the nominal parameter based far field, inserted into the overall sensitivity map.

All the sensitivity maps were created and quantified as described in Fig.1. by varying grating height ($120 \text{ nm} \leq h \leq 140 \text{ nm}$, step size 1 nm) and the sidewall angle ($0^\circ \leq \alpha \leq 90^\circ$, step size 1°). For a deeper investigation, two different cases were analysed – the sensitivity of the amplitude (Figure 4) and the phase (Figure 5) in the far field. The amplitude based sensitivity maps showed more noticeable changes to the sidewall angle while phase base sensitivity maps were more related to the grating height.

Figure 4. Far field sensitivity maps for the amplitude of the TM polarized input field of multiple wavelengths.

As it is shown in Fig. 4 and Fig.5 each wavelength has a noticeably significant impact on sensitivity to the parameter change of the same sample. The pattern in the sensitivity maps helps to determine if there is a higher sensitivity to the change of one parameter and the magnitude of each quantified far field difference shows the change between the neighbouring parameter combinations. Since these characteristics differ for each wavelength, the sensitivity maps are presented in difference scales.

Figure 5. Far field sensitivity maps for the phase of the TM polarized input field of multiple wavelengths.

As a result of the sensitivity analysis in the far field, the highest sensitivity to the change of the sidewall angle was achieved with wavelength $\lambda = 585$ nm (amplitude input). The biggest sensitivity to the change of the grating height was determined when the wavelength $\lambda = 975$ nm (phase input) was used. Both wavelengths agree with the results obtained from the near field.

4. CONCLUSIONS

In this research we presented the analysis of how different wavelengths influence the sensitivity to the change of different grating parameters. The sensitivity can predict the precision of parameter retrieval in scatterometry. However, to perform a full scatterometry procedure and retrieve grating parameters it is necessary to compare the simulated diffraction pattern

of electromagnetic field with directly imaged diffraction pattern. Since it is very challenging to perform such measurements in the near field, most of scatterometric approaches are realized within the far field. The research presented in this paper looks into comparison of sensitivity in both the near and the far fields in order to analyse if there is a correlation between them. It was determined that the wavelengths for the highest sensitivity to the change of the grating height and the sidewall angle in both near and far fields were $\lambda=585$ nm and $\lambda=975$ nm respectively. Therefore, by combining two different wavelengths on the same periodic subwavelength silicon grating one could obtain higher sensitivity to several parameters at once and in such way increase the precision of grating parameter retrieval in comparison with single wavelength scatterometry. Since $\lambda=585$ nm and $\lambda=975$ nm corresponds to the phase shift of $\pi/1.375$ and $\pi/3.625$ respectively, it is possible that even higher sensitivity could be achieved by selecting wavelengths in smaller steps. In the future work it is planned to analyse and develop the multiple wavelength approach in combination with coherent Fourier scatterometry with the conical incidence.

ACKNOWLEDGEMENTS

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 707404. The opinions expressed in this document reflect only the author’s view. The European Commission is not responsible for any use that may be made of the information it contains.”

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