Optimized EUV Scatterometry Measurements with Tunable High Harmonic Generation and the Fisher Information Matrix

Clay Klein*[a], Nicholas Jenkins[a], Yunzhe Shao[a], Yunhao Li[a], Seungbeom Park[b], Wookrae Kim[c], Henry Kapteyn[a,d], Margaret Murnane[a]

[a]Department of Physics, JILA & STROBE NSF Science & Technology Center, University of Colorado & NIST, Boulder, Colorado, USA; [b]Core Technology R&D Team, Mechatronics Research, Samsung Electronics Co., Ltd., Hwasung, Republic of Korea; [c]Advanced Process Development Team 4, Semiconductor R&D Center, Samsung Electronics Co., Ltd., Hwasung, Republic of Korea; [d]Kapteyn-Murnane Laboratories, Inc., 4775 Walnut Street, #102, Boulder, Colorado 80301, USA

*clay.klein@colorado.edu

ABSTRACT

We present the use of high harmonic generation (HHG) to achieve sub-nanometer sensitivity to out-of-plane geometric features on an industrially relevant damascene sample with extreme ultraviolet (EUV) scatterometry. We also demonstrate a methodology to take advantage of the tuneability of HHG by selecting experimental conditions that maximize the sensitivity of EUV scatterometry. The method uses the Fisher information matrix to encode prior knowledge about the sample into a robust mathematical framework that enables automated selection of the optimal experimental conditions such as wavelength and incidence angles. Importantly, HHG allows us to use wavelength tunability across the EUV spectrum through precisely controlled phase matching to achieve these conditions. We apply this to our damascene sample to show that EUV light at ~13nm will maximize the sensitivity of our scatterometry measurements and the angle selection will break correlations between parameters to enable a reliable solution to the inverse problem. Using this approach, we are able to take full advantage of the wavelength tunability of HHG based EUV sources to support accurate metrology for next generation semiconductor devices.

Keywords: EUV metrology, scatterometry, reflectometry, high harmonic generation, Fisher information matrix

1. INTRODUCTION

With the recent development of extreme ultraviolet (EUV) lithography producing feature sizes on the order of single nanometers, there is an increasing demand for fast, accurate, and reliable metrology that can provide feedback on the manufactured nanostructures to help drive EUV lithography to its fundamental physical limitations and provide efficient process control. High harmonic generation (HHG) is particularly well suited to the production of EUV light for metrology due to its coherent laser-like emission of wavelength-tunable light spanning the EUV spectrum in a compact tabletop setup [1]. For periodic samples such as interconnects, EUV scatterometry using HHG is a metrology technique that shows promise to meet this demand, and recent advances show the utility of HHG EUV light in semiconductor metrology [2-4]. Because of this, there is significant interest as to what the optimal experimental conditions (e.g. wavelength and angle) are for EUV scatterometry in regards to both the underlying sensitivity of the measurement and inter-parameter correlations which can hinder a reliable and repeatable solution to the inverse problem of scatterometry [5]. Here we first demonstrate EUV scatterometry using a HHG source at 29nm to measure out-of-plane features on a periodic damascene sample with sub-nanometer accuracy. Then we describe how a mathematical framework based on the Fisher information matrix enables us to calculate the optimal experimental conditions that maximize the sensitivity of scatterometry measurements. The method is applied to the damascene sample to show that by maximizing an eigenvalue of the Fisher information matrix, we have a maximal sensitivity at ~13nm and the selected angles can break correlations between the model parameters. We will present how, in conjunction with the tunability of HHG, this enables us to experimentally and mathematically optimize EUV scatterometry measurements.

2. EXPERIMENTAL RESULTS

The damascene sample we measured consists of a periodic array of copper pads arranged on top of a SiO_2 substrate and separated by a thin ~100nm layer of SiCN. The copper pads are depressed into the sample by a small amount on the order

Metrology, Inspection, and Process Control XXXIX, edited by Matthew J. Sendelbach, Nivea G. Schuch, Proc. of SPIE Vol. 13426, 1342607 · © 2025 SPIE
0277-786X · doi: 10.1117/12.3051113

of single nanometers due to differences in the polishing rate of each material, and we want to measure the exact value of this step height. Using a 29nm HHG source, we collected the diffraction efficiency data shown in Fig. 1(a). This data was then modeled with rigorous coupled wave analysis to accurately determine the step height. The fit to the data is shown in Fig. 1(a), along with single nanometer variations in the step height, showing excellent sensitivity to the step height.

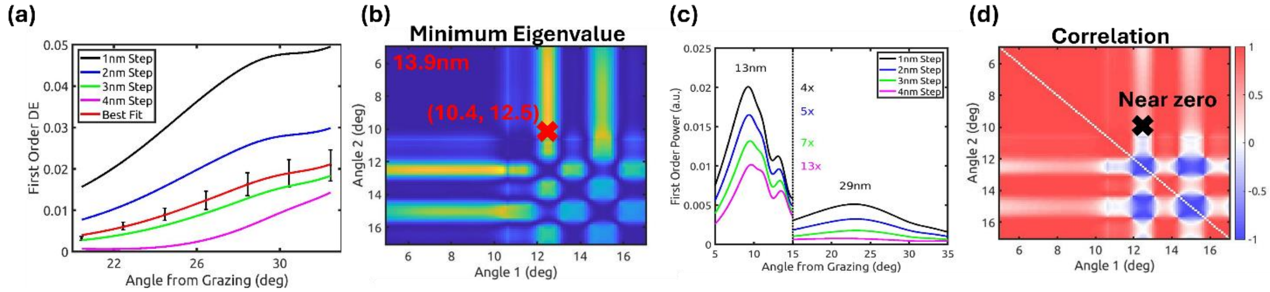

Figure 1. (a) Experimental data and modeled diffraction efficiency curves showing the best fit (red curve) and 1nm variations in step height. (b) Results of a global optimization of the minimum eigenvalue of the Fisher information matrix indicating a maximal sensitivity at 13.9nm and the angles shown. (c) Increase in diffracted power at 13nm as compared to 29nm which will provide a higher SNR, and (d) a low correlation between model parameters at the optimized angles as compared to other pairs.

3. OPTIMAL EXPERIMENTAL CONDITIONS

The Fisher information matrix is a well-developed tool for experimental design and has been applied to many other areas of research, most notably neutron reflectometry and x-ray diffraction [6,7]. In the work here, we use a Poisson noise model on the photon count propagated through the diffraction efficiency, which we define as

$$DE = \frac{N_{+1} + N_{-1}}{N_{+1} + N_{-1} + N_0},$$

where N_i indicates the number of photons in the ith diffracted order. With the assumptions of high flux and that the DC power is significantly higher than the diffracted power, the signal to noise is approximately given by $SNR \approx \sqrt{2(DP)}$, where DP is the number of photons in the first diffracted order. Thus, we expect that the optimal wavelength for scatterometry will likely occur where the diffracted power is highest and at a range of angles around the peak in the diffracted power. Using this noise model, we constructed the Fisher information matrix for two unknown sample parameters with realistic priors, the step height and a global angle offset. The wavelength and two angles were left as free parameters to optimize. By maximizing the minimum eigenvalue of the Fisher information matrix using a global optimizer, we determine that the sensitivity of our measurement will be maximized at 13.9nm. A map of the eigenvalues for 13.9nm is shown in Fig. 1(b). As we should expect, this leads to a significantly higher diffracted power as shown in Fig. 1(c) and consequently a higher signal to noise. Furthermore, the angles optimized in this way occur around the peak in the diffracted power and additionally lead to a small correlation coefficient between the two parameters as shown in Fig. 1(d). Thus, in tuning HHG to measure the sample with these experimental conditions, we have a higher sensitivity to model parameters.

REFERENCES

[1] Bartels, Randy A., et al. "Generation of spatially coherent light at extreme ultraviolet wavelengths." Science 297.5580 (2002): 376-378.

[2] Esashi, Yuka, et al. "Tabletop extreme ultraviolet reflectometer for quantitative nanoscale reflectometry, scatterometry, and imaging." Review of Scientific Instruments 94.12 (2023).

[3] Tanksalvala, Michael, et al. "Nondestructive, high-resolution, chemically specific 3D nanostructure characterization using phase-sensitive EUV imaging reflectometry." Science Advances 7.5 (2021): eabd9667.

[4] Shanblatt, Elisabeth R., et al. "Quantitative chemically specific coherent diffractive imaging of reactions at buried interfaces with few nanometer precision." Nano letters 16.9 (2016): 5444-5450.

[5] Ansuinelli, Paolo, Wim MJ Coene, and H. P. Urbach. "Automatic feature selection in EUV scatterometry." *Applied Optics* 58.22 (2019): 5916-5923.

[6] Durant, James H., et al. "Determining the maximum information gain and optimizing experimental design in neutron reflectometry using the Fisher information." *Journal of Applied Crystallography* 54.4 (2021): 1100-1110.

[7] Mikhalychev, Alexander, et al. "Fisher information for optimal planning of X-ray diffraction experiments." *Journal of applied crystallography* 54.6 (2021): 1676-1697.