Harnessing the extreme ultraviolet for critical dimension metrology

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INTRODUCTION

The semiconductor industry has long adopted visible and ultraviolet wavelengths for optical critical dimension (OCD) measurements. Decreasing feature sizes, increasing architecture complexity, and troublesome parametric correlations all motivate approaches leveraging shorter wavelengths into the vacuum- and extreme-ultraviolet (VUV, EUV) spectral regions. Straightforward extendibility of established OCD techniques from the visible range into these vacuum wavelengths is greatly hampered by absorption. We review the initial and developing efforts to utilize these vacuum wavelengths for model-based measurements of CD, often labeled "EUV scatterometry" in the literature. The predominant mode for EUV-based CD metrology is diffraction, while our group at the National Institute of Standards and Technology (NIST) is pursuing both EUV diffractometry and spectroscopic ellipsometry at VUV and EUV wavelengths. Current progress will be presented in the context of a gaps analysis of EUV scatterometry for near-line and in-line process control.

OPTICAL SCATTEROMETRY AND EUV SCATTEROMETRY

The terms "scatterometry" and "OCD" (for optical critical dimension metrology) are now practically interchangeable. Nigel Smith defined these at FCMN 2024 as the "non-destructive optical measurement of many dimensional parameters of interest for semiconductor process control…based on either single-wavelength or spectral ellipsometers with a very narrow range of incident angles."[1] This consensus definition of scatterometry has evolved with its underlying technologies. At one time, an "optical scatterometer" was a reflectometer outfitted with an array of detectors to capture diffused light [2]; experts in that methodology recognized that one could capture diffraction patterns off periodic patterned gratings. Later, industrial measurements could be optimized by positioning photodiodes to the angular positions of diffraction orders [3], then further improved using the spectroscopic 0^{th} order reflection with analysis of changes in polarization state, *i.e.*, ellipsometry [4]. As metrology challenges increased with decreasing feature size, industrial applications of full Mueller matrix spectroscopic ellipsometry (MMSE) also emerged [5] which also exploits depolarization. Improvements in the application of optical techniques led to the optical scatterometry employed today by this industry as the workhorse of nondestructive metrology.

When considering the extendibility of optical techniques to shorter wavelengths, two key questions emerge. First, what is "EUV scatterometry?" The initial report in the literature of EUV scatterometry came from synchrotron-based experiments of EUV masks, a work that defined scatterometry as "the analysis of light diffracted from a periodic structure".[6] Laboratory experiments utilizing high-harmonic generation (HHG) for producing EUV wavelengths followed, with some research groups measuring masks [7] and others measuring gratings.[8] These types of experiments have been repeated as lithographic technology has improved. A notable recent effort [9,10] seeks to commercialize diffraction in the 10 nm to 20 nm range, which overlaps the soft-x-ray (SXR) region and is thus termed

"SXR Scatterometry". Our team at the National Institute of Standards and Technology (NIST) has recently reported our collaborative diffraction experiments with the University of Colorado-Boulder [11] in 2025; we will defer from repeating the results here.

A second question is whether it is possible to perform industrial scatterometry (spectroscopic ellipsometry, or SE) at EUV wavelengths. Our NIST project team is also leveraging NIST's Synchrotron Ultraviolet Radiation Facility (SURF-III) to test a new NIST-patented [12] concept for performing Mueller matrix spectroscopic ellipsometry (MMSE) at these shorter wavelengths. Our two-pronged approach (diffractometry, SE) allows NIST to develop world-class laboratory diffraction methods for semiconductor metrology while also extending SE capabilities down to 10x shorter wavelengths.

EXTENDING SPECTROSCOPIC ELLIPSOMETRY TOWARDS THE EUV

At time of abstract submission, we are preparing for our initial demonstration of an ultrahigh-vacuum-compatible spectroscopic ellipsometer using SURF-III. Thus far, we have fabricated its optical and sample manipulation instrumentation as shown in Fig. 1(a). The polarization stage generator (PSG) and polarization state analyzer (PSA) are four-bounce chevrons, with piezoelectric motors rotating the PSG and PSA at proportional speeds. The PSG and PSA each contain four Si blanks, which should yield both sufficiently broadband reflections and modifications of the incident linear polarization state in the 50 nm to 150 nm wavelength range.

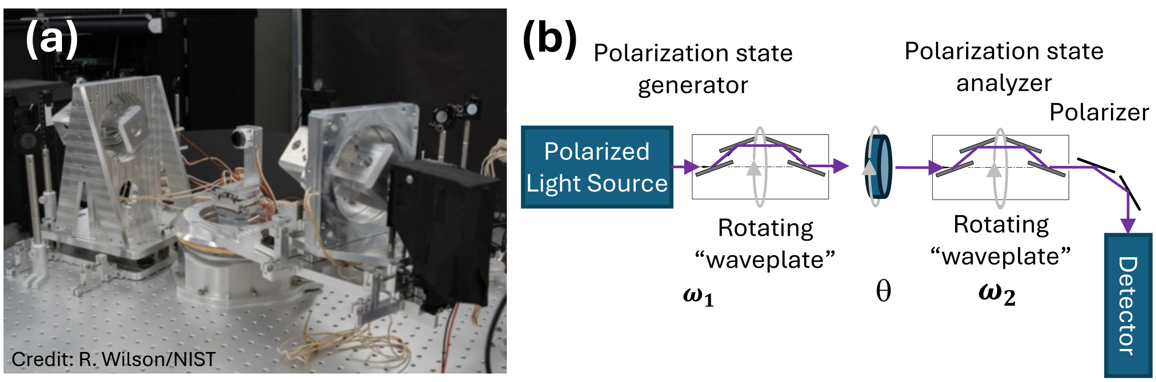

FIGURE 1. (a) Newly constructed UHV fully reflective spectroscopic ellipsometer (SE) tested on an optical bench prior to synchrotron experiments. (b) Schematic of initial experiment with a quarter-wave plate (QWP).

Our confidence in this equipment prior to these synchrotron experiments is based upon tabletop testing using a 266 nm wavelength laser. Figure 2(a) shows the ellipsometry signal for a quarter-wave plate (QWP) at four different QWP rotation angles (θ) and a straight-through measurement. Figure 2(b) shows the ellipsometric quantities (N,C,S) identified correctly for a QWP.

Known challenges for the SURF-III experiments we will address include beam size control, normalization of synchrotron output, and filtering of 2nd order light from the monochromator. We will discuss upcoming steps to demonstrate the technology on an EUV high-harmonic generation source (HHG) using more industrially relevant targets. We will compare the extensibility of EUV diffractometry and EUV spectroscopic ellipsometry for higher throughput as needed by the industry.

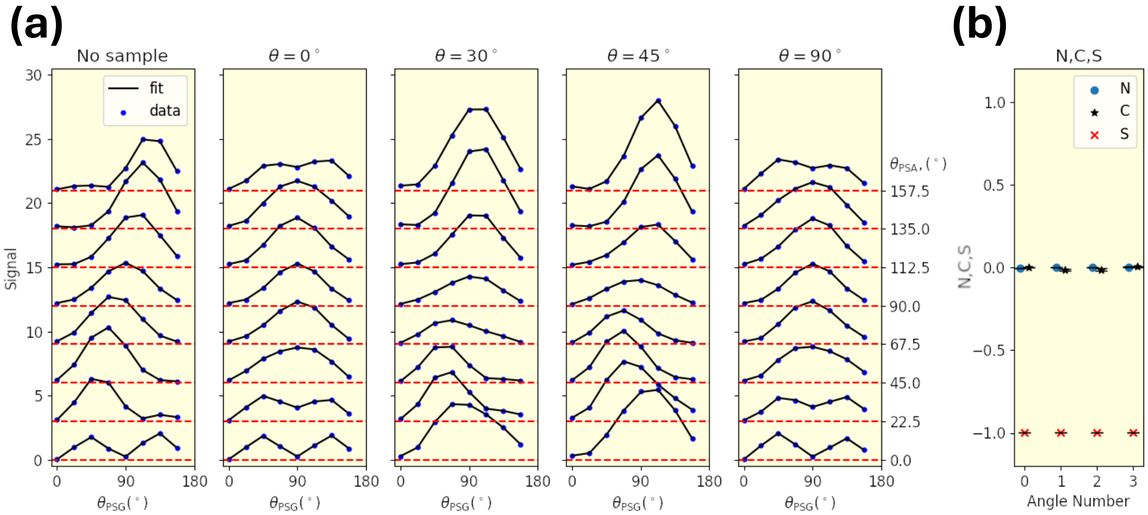

FIGURE 2. (a) Measurement signal with fitting for the QWP experiment at 266 nm wavelength, varying the QWP rotation. Data at varying values of θ_{PSA} are offset for clarity. (b) Fully reflective SE qualitatively identifies the ellipsometric quantities (N,C,S) correctly. Systematic errors were treated nonparametrically as in Ref. [13], with care to avoid parameter confounding.

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KEYWORDS

Extreme ultraviolet, scatterometry, diffractometry, spectroscopic ellipsometry, vacuum ultraviolet