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Analysis and modeling of depolarization effects in Mueller matrix spectroscopic ellipsometry data

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Abstract

In this paper we present importance of depolarization effects modeling to fit spectroscopic Mueller matrix ellipsometry data. The relevant theoretical background based on Mueller matrix formalism is presented. The sample of SiO_2 layer (approx. 1μm thick) on silicon substrate is used to demonstrate depolarization effects in obtained experimental data. In the first step the presence of interferences in the layer is used for modeling of depolarization effects caused by finite spectral resolution of the Mueller matrix ellipsometer. In the next step the depolarization caused by focusing of the probe light is analyzed and modeled. Both finite spectral resolution and beam focusing is a common issue in the optical characterization of samples with lateral dimensions smaller than (commonly used) collimated beam. Therefore to fit experimental data with model it is important to assume those depolarization effect into model.

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1. Introduction

Nowadays, the development of lithographic method allows production of very complex periodic structures, e.g. photonics crystals, plasmonic gratings, etc. But the lateral dimensions of many structures are very small, in order of tens of hundreds of micrometers. Those structures are commonly characterized by optical methods: reflectivity, transmission, ellipsometry, and polarimetry or Mueller matrix spectroscopy. In experimental data from optical methods based on light-polarization the depolarization may occur. The depolarization originates from incoherent superposition of different polarization states transmitting or reflecting from the sample. The depolarization effects

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could come from the apparatus itself or/and from a measured structure. We can summarize the physical phenomena that generate partially polarized light as follows [Fujiwara (2007)]: (a)-incident angle variation originating from focusing of the probe light, (b)-wavelength variation caused by the finite spectral resolution of the monochromator, (c)-surface light scattering caused by a large surface roughness of a sample, (d)-thickness inhomogeneity of layers in the structure, (e)-backside reflection in a thick substrate.

In our paper we are focused on issues (a) and (b), depolarization caused by focused beam and finite spectral resolution of monochromator. The main motivation for the study of depolarization effect due to focused beam is directly related to the problem of characterization of nanostructures with lateral dimension smaller than beam spot. Therefore there are three possible approaches how to obtain (and model) experimental data. In first the size of collimated beam may be reduced by iris diaphragm, but the signal to noise ratio is reduced. Second way is to measure and to model system where the beam illuminates the structure and substrate. Therefore experimental data contains depolarization caused by both contributions of optical response from the structure and the substrate. Such a system may be modeled by Mueller matrix as a weighted sum of Mueller matrices from structure and substrate calculated separately [Foldyna (2009)]. The third option, discussed in this paper, is to reduce spot size by the focusing lens. In this case the intensity of beam is (almost) unaffected, but the measured data represents sum of data related to all incidence angles over the divergence of the focused beam and are weighted with spatial intensity distribution [Halagacka (2014)].

The study is further improved by analysis of is analysis of depolarization effects caused by finite spectral resolution of used experimental setup [issue (b)]. The light diffracted by a grating monochromator has a finite bandwidth and thus different wavelengths are measured simultaneously by the single light detector element. If the bandwidth of the monochromator is too broad, depolarization occurs due to the wavelength dependence of the optical properties of the sample.

The paper is organized as follows. Section 2 introduces the experimental setup, Mueller matrix ellipsometer and studied samples. A brief summary of the theory necessary for modeling of our samples, definition depolarization, and introduction functions used for depolarization modeling is presented. Section 3 shows the results of depolarization modeling and fitting in two steps. In the first, the data measured without focusing probes (with collimated beam) are used to fit finite spectral resolution. In the second step, experimental data measured with the focusing optics are fitted in order to determine contribution of focusing optics to the depolarization. In the second step the model contains already determined depolarization from finite spectral resolution.

2. Experimental configuration and theory

Ellipsometric spectra were obtained in spectral range from 0.74eV to 6.42eV using Woolam RC2-DI two rotating compensator ellipsometer [Collins (1999)]. The ellipsometer consist of light source (halogen bulb and deuterium lamp), polarizer, first rotating compensator, sample, second rotating compensator, analyzer and diffraction grating with CCD array detector. In addition focusing probes have been used to focus beam spot to the samples. Figure 1 shows ellipsometer schematically. For optical characterization of small samples, focusing optics can be installed. The focal length of the lenses is 27 mm and the diameter of the spot is 150 µm.

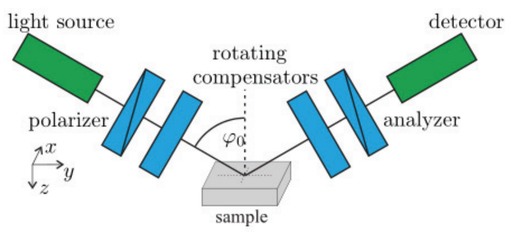

Figure 1: Ellipsometer configuration is shown schematically.

The reflectivity of non-depolarizing optical system can be described by the 2×2 Jones matrix formalism [Jones (1947)]: