Light Interactions with Periodic Nanoline Arrays for Nanoelectronic Applications

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Summary:
Andrzej Gawlik's dissertation covers the periodic waveguide approach to determining the feature shape and dimensions of nanoscale structures used to fabricate integrated circuits. This thesis provides useful insight into the effect of materials and structural properties on the interaction of light with these periodic structures. The thesis derives a simplified model for these interactions. This approach provides physical insight into how light interacts with these structures that is missing from the Rigorous Coupled Wave Approximation (RCWA) typically used to interpret scatterometry data obtained from these structures.

The general term for the use of light scattering to measure feature shape and dimension is scatterometry. In scatterometry, periodic structures consisting of consistently spaced features are routinely used as test structures. Here, pitch refers to the spacing between the lines and critical dimension to the width of the lines. In this thesis, the line – space structures have a dielectric material between the lines. Light diffracts from the periodic structures and the scattering is wavelength and polarization dependent. Experimentally, the light scattering is measured using a spectroscopic ellipsometer or a reflectometer. Spectroscopic light scattering provides a powerful means of measuring feature shape and dimension. The Rigorous Coupled Wave Approximation (RCWA) can be used to solve Maxwell's equations which describe the interaction of light with the structure being measured. RCWA is the most commonly used approach to solving Maxwell's equations in commercial scatterometry software. Typically, the sensitivity to changes in feature shape and dimension are determined through systematic simulations. The dimension and structural shape is determined from experimental data by fitting simulated spectra to RCWA calculations from a proposed structural model by varying key dimensions. This dissertation provided a well written and important resource for understanding the waveguide approach and comparing its capabilities with the RCWA approach.

The dissertation provides a clear description of the sensitivity of light to changes in the critical dimensions and pitch of line – space structures using the waveguide approach. A variety of materials sets are discussed including semiconductor – dielectric as well as metal – dielectric line space structures. An effective medium model for the line space structures is developed and then extended to have a depth dependence. A major highlight of this thesis is discussion of the comparison of polarization dependent reflectivity for this model to experimental data from tapered silicon fins. A critical aspect of the comparison is that the two planes of incidence used in the study align the plane of incidence along the length or perpendicular to the length of the lines. This alignment is central to the discussion in Chapters 3, 4, and 5 also. This model (perhaps unexpectedly) provides a quantitively good representation of the experimental data for fins with a top CD= 5 nm/bottom CD=17 nm with a pitch of 90 nm.

Other highlights, include the discussion of the impact of pitch and linewidth on the validity of the effective medium model for both metal line – dielectric spaces and semiconductor line – dielectric spaces.

This dissertation is of the highest quality and in this reviewer's opinion surpasses the requirements for Doctor of Science, Physics. In this reviewer's opinion, this dissertation meets all requirements.

<u>Comments for consideration for future research:</u>

Introduction

p1+p2: Considering automated sample preparation using a dual column FIB and lamella removal system, it is possible to get statistically significant dimensional information from TEM cross-sections. For reference, ask Paul van der Heidi at IMEC.

Chapter 2

p8: You mention in footnote 1 that this thesis is for linear media. It is also for linear optical processes. When you have a higher light intensity, you can get non-linear optical processes from materials that give a linear optical response at lower light intensities. Examples of this include second harmonic generation. I also note that non-linear ellipsometry measurements have been performed using high intensity lasers.

Chapter 3

p 58-59: The following information may be useful for subsequent research after you complete your degree requirements. There are several forms of effective medium theory including Clausius-Mossotti, Bruggeman, and Maxwell-Garnett. Different effective medium theories apply to different structural situations. The limitations of EMA are discussed in the literature. Some useful references are:

D.E. Aspnes, Plasmonics and effective-medium theories, Thin Solid Films 519 (2011), 2571-2574

D.E. Aspnes, Local-field effects and effective medium theory: A microscopic perspective, American Journal of Physics 50, (1982), 704-709.

Book chapters of interest:

J. Humlicek, Ch.3 Data Analysis for Nanomaterials: Effective Medium Approximation, Its Limits and Implications, in M. Losurdo and K. Hengerl, Ellipsometry at the Nanoscale, (Springer, Heidelberg, 2013), p 145- 178.
D.E. Aspnes, Ch. 5 Plasmonics and Effective Medium Theory, in M. Losurdo and K. Hengerl, Ellipsometry at the Nanoscale, (Springer, Heidelberg, 2013) p 203-224.

p83 to p89 Nicely described presentation about the band structures of periodic array of waveguides and the propagation of electromagnetic modes.

P216 – For your information, spectroscopic ellipsometry and Mueller Matrix Spectroscopic Ellipsometry are also commonly used methods for scatterometry. Not just reflectometry.. Nova is one brand. KLA and Onto Innovations (formerly Nanometrics) use ellipsometry typically at non-normal incidence. At times, they included a separate optical path for reflectometry. Yes, these systems also determine polarized reflectance data.

General comment: Consider section 4.3 p 116 and elsewhere. In the future you might consider how plasmons might participate in the interaction of light with periodic structures. You avoid discussing plasmons. Plasmons can easily be launched in copper grating structures of appropriate pitch and dimension. The plasmons can easily be observed in reflection and Mueller Matrix data. Considering the vast literature on ellipsometry of metal gratings (e.g., M. Bergmair, K. Hingerl, and P. Zeppenfield, Ch. 7 Spectroscopic Ellipsometry on Metallic Gratings, in M. Losurdo and K. Hengerl, Ellipsometry at the Nanoscale, (Springer, Heidelberg, 2013), p 257-312.). I suggest you discuss the grating dimensions that result in plasmons and provide reference(s). I think that the grating pitch and linewidth used in this thesis will not result in plasmons, but it is a topic of interest in the scatterometry community. It deserves mention.

The summary tables in Chapter 4, e.g. Tables 4.1, etc. are well done and provide a convenient location for finding critical information when one returns to the thesis to review the results. The height dependent periodicity in the p polarized reflectance of certain structures is an interesting point to remember.

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