Development of Non-Destructive Optical Mapping Tools without Moving Parts for Macro- and Micro-Scale Spectroscopic Ellipsometry

A Ph.D. Dissertation submitted in fulfillment of the requirements for the degree of Doctor of Physics and Materials Science

By

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Budapest, Hungary

2026

1 Background of the research

Ellipsometry is an optical technique that measures the relative change in the polarization state of the measurement beam induced by reflection from or transmission through a sample. During conventional ellipsometric measurements, the data collection is relatively slow and measures one spot at a time, leading into a longer acquisition time compared with our new non-destructive optical mapping tools.

Previously, numerous studies were conducted in this field to investigate and optimize the application of this non-destructive optical mapping technique, spectroscopic ellipsometry. These investigations can be categorized into four main types namely;

a). Large-area scanning/mapping: Industrial systems like the Semilab FPT (Flat Panel Testing) system [1] and the Woollam AccuMap [2] are such systems designed to support large-area thin film metrology.

Semilab PT system is explicitly designed on thin films mapping across wafers, glass substrates and photovoltaic panels, while the Woollam AccuMap system focuses on higher speed mechanical scanning on large-area ellipsometric and reflectometric mapping techniques. It

focuses mostly on wafer-scale like large glass substrates but on a relatively smaller mapping area scale, compared to that of the Semilap FPT systems.

b). Small area scanning/mapping: Dynamic Imaging Micro-ellipsometry (DIM) is a high-resolution, rapid full-field mapping/imaging ellipsometric technique [3] which utilizes focused monochromatic (laser) light to achieve high lateral resolution and combines the traditional ellipsometry with advanced image processing. It operates with various optical configurations.

A special measuring technique is the Fourier scatterometry [4], when a focused spot is created by a high numerical aperture (NA) microscope objective (MO), and the scattered illumination is collected by the same MO. In this configuration, each point of the back focal plane of the MO is uniquely related to a given reflection and azimuth angle.

c). Large-area imaging: Previously, our Laboratory proposed a divergent light source configuration for large-area imaging [5]. In this arrangement, the surface is illuminated from a divergent point source, and the reflection from the measured surface is imaged by a spherical or

parabolic mirror and correction optics to a charge-coupled device (CCD). All the pixels on the CCD correspond to one point of the sample surface. Spectroscopic macro-imaging ellipsometry can only be realized in this configuration by measuring maps at different wavelengths one by one. Several expanded-beam spectroscopic ellipsometer prototypes were developed for different (150-300-450-600 mm) sample size [6].

d). Small-area imaging: The first microscopic imaging ellipsometer was constructed in 1988. [7] One interesting application is micro-mechanically exfoliated mono- and multilayers investigation of graphen-like 2D materials by spectroscopic imaging ellipsometry. With a spatial resolution of 2 µm, the complex dielectric functions of such layers and the lateral homogeneity were investigated.

This small area imaging tool ellipsometry setup uses a collimated light source with a polarizer-compensator-sample-analyzer configuration for the reflected light.

Our newly developed optical mapping tools use multi-color (RGB) light sources. In our macro imaging ellipsometer, an LCD-LED monitor emits out a Red (650 nm), Green (550 nm) and Blue (450 nm) polarized color

band light sources, whereas the microscopic ellipsometer, RGB Laser module emits out a Red (638 nm), Green (520 nm) and Blue (450 nm) as a point-like light from laser diodes. Both systems use a polarization sensitive camera, integrated with a Sony CMOS Pregius Polarsens IMX250MZR/ IMX250MYR sensor.

Despite some minor limitations (imperfections) that arise from a narrow range RGB spectra and ‘0.1 degree’ angle uncertainty, the newly developed imaging tools assembled from inexpensive components, when compared to the conventional J. A. Woollam M2000 DI ellipsometer, are

- Fast imaging (take only seconds)
- Large-surface area sample imaging, where up to a 150 cm diameter sized samples is possible, when big LCD TV are used instead of a simple monitor.
- No moving parts, leading to higher stability

2 Objectives

The primary objective of this research work is to develop and validate non-destructive optical mapping systems using inexpensive parts like LCD-LED monitors, large TVs or laser diodes as a light source and polarization sensitive camera as a detector with a final aim of assessing the reliability and limitations of these developed mapping

systems. These systems are mainly used for thin film characterization of mono and multilayer structures.

This research project is very relevant with the current and future trends of the materials science and technology research areas, specially with the semiconductor or PV industry vital importance in the current era. The research focuses on developing non-destructive imaging systems using inexpensive components but fast, capable of measuring large surface area samples, compared to the conventional standard ellipsometers.

Since it is a fast and exponentially growing field of interest nowadays, the research focuses on a fast and effective way of dealing with small and large surface area thin films characterizations using cost effective components.

The main sub-tasks of the research are:

- Develop, validate and assess prototypes of non-destructive optical imaging devices from inexpensive parts.
- Programming the data collection and data processing software and
- Making measurements on selected samples and determining the precision of the newly developed prototype devices.

3 Research methods

Fundamentally, this research is based on non-destructive optical mapping methods, to be specific spectroscopic and microscopic ellipsometry, which is used to characterize simple and multilayer thin film structures deposited, mostly on silicon substrates on the way of developing prototype imaging tools from inexpensive components.

The optical configuration setup contains the following parts.

a) Light source: In our large-area imaging tool, an LCD-LED monitor (Dell UltraSharp U2412M, GB-LED backlight) is used as a polarized RGB light source. In case of our microscopic ellipsometer, an RGB laser module is used as a light source.

b) Sample and Sample holder: this is a section, where the selected sample, like SiO_2 on Silicon wafer, is held on the sample holder for analysis.

c) Light detector: This is the polarization-sensitive camera (CMOS Pregius Polarsens sensor of model IMX250MYR/ IMX250MZR) with a pinhole of sub-mm size in front of it, used to detect and record the polarized light reflected off the sample surface.

The two newly developed ellipsometers, the macro and micro imaging devices from inexpensive components are shown in the figures below.

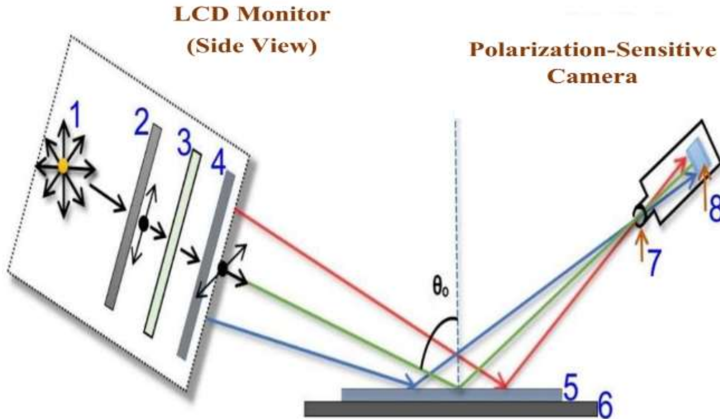

Figure 3.1. *Schematic diagram of the non-collimated beam large area imaging (Macro) ellipsometer experimental setup.*

The main components of the non-collimated ellipsometer:

1) Light source
2) Vertical polarizer
3) Liquid crystal cell
4) Horizontal polarizer
5) Sample
6) Sample holder
7) Pin hole (sub-mm size)
8) Camera sensor

In the above Figure, θ_o indicates the angle of incidence of the measurement beam at that point.

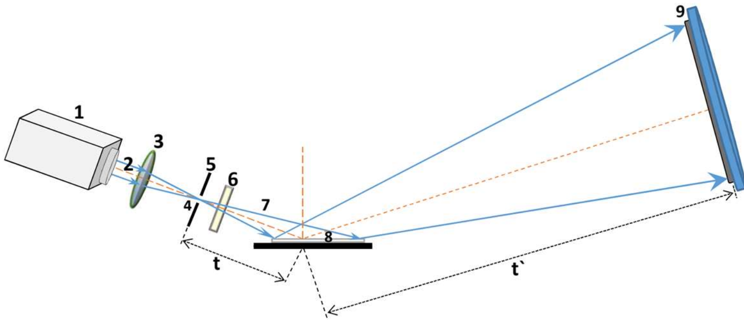

Figure 3.2. *Schematic diagram of the experimental setup for small surface area imaging, microscopic ellipsometer.*

The main components of the microscopic:

1) Light source	2) Collimated light	3) Lens
4) Point source	5) Pinhole	6) Film polarizer
7) Divergent beam	8) Sample	9) Camera sensor

The ratio of the distance of the pinhole pattern (t) to the sample-camera distance (t') determines the magnification. Note that the polarization-sensitive camera in Figure 3.1. is the color version of the CMOS Pregius Polarsens sensor model IMX250MYR, while the camera in Figure 3.2. is the monochrome version of the CMOS Pregius Polarsens sensor, model IMX250MZR.

The investigated samples in this research mainly consist of silicon oxides and polycrystalline silicon thin films of different sizes, thicknesses and layer structures.

The core steps in the entire data analysis procedures in both these newly developed non-destructive optical imaging tools from inexpensive components can be summarized as follows;

Calibration: This step establishes the experimental setup`s precision and accuracy, evaluating the orientation of the optical systems, like the light source, analyzer, polarizer, light detector or their optical and manufacturing imperfections. This was done by selecting mostly, the well-established SiO_2/Si system measurement. For example, using rho correction method, a monitor calibration was carried out which resulted in minimizing a 2 nm thickness measurement deviation below 1 nm, between our newly developed mapping systems and the conventional Woollam M2000DI ellipsometer.

Verification: this step ensures whether the calibrated parameters, usually the angle of incidence and film thickness, give the expected values when compared with the standard reference values. The Woollam M2000DI ellipsometer was used for this purpose.

Measurement: after successful verification of the calibration of the experimental configuration, the actual

measurement starts. The sample of interest is set on the ellipsometer and the measurement is done by collecting the raw data spectra (the ellipsometric angles- the amplitude ratio (Ψ) and phase difference Δ) from the change in polarization of the measurement beam reflected off the sample surface.

Validation: This step is the last step where model fitting and evaluation is conducted. The measured data is compared with a similar generated ellipsometric data from the constructed physical and optical model that appropriately describes the sample of interest, to approve whether the established model fits the measured data, example using the mean square error (MSE) error estimator. The final result is usually the thickness, angle of incidence and other optical parameters that fully define the sample. In our case, this result was again cross-checked against an independent measurements obtained from the M2000DI ellipsometer for the same sample.

4 New scientific results

4.1 1.5. Thesis Statements

1. I have shown that it is possible to make a non-destructive optical imaging device from inexpensive parts (LCD-LED monitors, TVs for light source and polarization sensitive camera as a light detector) to measure in one shot on large, macro area, sample sizes. [T1, T2, T4-7]
2. I have shown that it is possible to make a non-destructive optical imaging devices from inexpensive parts (RGB laser diodes for light source and polarization sensitive camera as a light detector) to measure in one shot on small (mm size), micro area, sample sizes. [T3, C1, C2]
3. After an appropriate subsequent calibration processes, I have shown that the devices (in points 1 and 2) can image a sample surface with a 1 nm thickness resolution on several 10 thousand pixels. [T1-7, C1, C2]

5 Potential for use of the results

The newly developed multi-color imaging systems can efficiently be utilized in quick quality control, real-time process monitoring and in situ control, uniformity mapping during thin film characterization such as in semiconductor

production, photovoltaics development, display technologies, and thin film based protective coatings.

In addition, they can be used in industrial, agricultural, and quality control applications that involve microscopy — such as by jewellers, geologists, and currency counterfeiting as well as for laboratory and research purposes.

In biotechnology and medical fields, these systems can be used for a variety of purposes, including early tumor diagnosis, detection of clinical therapeutic markers, monitoring the binding of various molecules to surfaces, tracking environmental pollutants.

6 List of references/ Biblography

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7 Publications

7.1 Scientific publications related to the thesis points

[T1] Berhane N. Zereay, Sándor Kálvin, György Juhász, Csaba Major, Péter Petrik, Zoltán G. Horváth, Miklós Fried, "*Optical Calibration of a Multi-Color Ellipsometric Mapping Tool Fabricated Using Cheap Parts*" PHOTONICS 11 : 11 Paper: 1036 , 11 p. (2024) IF: 2.1 Q2 https://doi.org/10.3390/photonics11111036

[T2] Sándor Kálvin, Berhane N. Zereay, György Juhász, Csaba Major, Péter Petrik, Zoltán György Horváth, Miklós Fried, "*A new method to evaluate multi-color ellipsometric mapping on big area samples*", Sci 8(1), p. 17 (2026) IF: 3.28 Q1 (Multidisciplinary). https://doi.org/10.3390/sci8010017

[T3] Csaba Major, Berhane Nugusse Zereay, György Juhász, Péter Petrik, Zoltán György Horváth, Péter Fürjes, Boglárka Kovács, György Zoltán Radnóczi, Sándor Kurunczi, Róbert Horváth, Levente Illes, Tamás Kolonits, Csaba Dücső and Miklós Fried, "*A new type of microscopic ellipsometer utilizing point-like light source*" submitted to Optics Express, IF: 3.3 Q1.

In Proceedings

[T4] Kálvin Sándor, Zereay Berhane Nugusse, Juhász György, Major Csaba, Petrik Péter, Horváth György Zoltán, Fried Miklós, „A new method to evaluate multi-color ellipsometric mapping on big area samples", In: Fried, Miklós (ed.) Symposium on Materials Science - Mátraháza, Hungary, September 24-26, 2025, Budapest, Magyarország: Óbudai Egyetem (2026) pp. 28-52. ISBN: 9789634494157

[T5] Nugusse, Berhane ; Juhász, György ; Major, Csaba ; Petrik, Péter ; Kálvin, Sándor ; Horváth, Zoltán György ; Fried, Miklós, „Multi-color ellipsometric mapping tool from cheap parts", PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING 12428 pp. 134-141, p. 8 (2023) IF: 0.28 https://doi.org/10.1117/12.2649926

[T6] Nugusse, Berhane ; Juhász, György ; Major, Csaba ; Petrik, Péter ; Kálvin, Sándor ; Horváth, György Zoltán ; Fried, Miklós, "Optical calibration of the ellipsometric mapping tool from cheap parts" In: Fried, Miklós (szerk.) Symposium on Materials Science 2024 Mátraháza, Magyarország : Óbudai Egyetem (2025) pp. 26-32, 7 p. October 9-11, 2024) ISBN 978-963-449-376-1

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[T7] Nugusse, Berhane ; Juhász, György ; Major, Csaba ; Petrik, Péter ; Kálvin, Sándor ; Horváth, Zoltán György ; Fried, Miklós "Multi-color ellipsometric mapping tool from cheap parts" In: Fried, Miklós (szerk.) Symposium on Materials Science Mátraháza, Hungary, October 5-7, 2022) ISBN 978-963-449-320-4
https://m2.mtmt.hu/api/publication/33751705

In Conference lectures

[C1] Berhane Nugusse Zereay, Petrik Peter, Fried Miklós: *A new type of microscopic ellipsometer utilizing a point-like light source,* Wührl Tibor (Szerkesztő)
XLI. Kandó Konferencia: Kiadvány kötet 2025
Budapest, Magyarország : Óbudai Egyetem, Kandó Kálmán Villamosmérnöki Kar (2026) , 657 p. ISBN: 9789634493983 https://konf.kvk.uni-obuda.hu/wp-content/uploads/2025/11/KandoTrefort-Konferencia-2025v2.pdf
[C2] Csaba Major, Berhane Nugusse, György Juhász, Péter Petrik, Zoltán György Horváth, Miklós Fried, *Prototype of a new microscopic ellipsometer using point light source*, 10th International Conference on Spectroscopic Ellipsometry, June 08-13, 2025, Boulder, Colorado, USA,
https://icse10.ellipsometry.us/program/abstract-booklet/