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Roll to Roll Inspection Platform: Development of Optical Inspection for Flexible Thin Films

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Abstract: Optical thin film measurement and inspection is a crucial step in Roll-to-Roll flexible microelectronics manufacturing, currently under development at the Center for Advanced Microelectronics Manufacturing of Binghamton University. To achieve this, a light scattering defect sensor and an inline spectroscopic reflectometer, both sensors of SunOptical Systems LLC, are integrated with an existing system of Energy Conversion Device. The defect sensor is mounted above the main roller, at a height determined by focal range characterization, and captures images which are analyzed for scratches or particles with a MATLAB program. The inline reflectometer is calibrated with SiO2 coated Si wafers of known SiO2 thickness. A Filmetrics spectroscopic reflectometer is used to determine the index of refraction for SiO2 and to act as baseline data. A MATLAB program is then developed for the SunOptical reflectometer to determine film thickness from spectrum data.

Keywords: Flexible Microelectronics, Roll-to-Roll Manufacturing, Thin Film, Optical Inspection, Optical Profiling

1. Background

The field of flexible microelectronics is a burgeoning industry with applications to many applications such as medical devices, military and homeland security, flexible displays and electronics, space and energy, computers and telecommunications, and additional consumer products. Roll-to-Roll manufacturing process development is the focus for research and development facilities at Binghamton University's Center for Advanced Microelectronics Manufacturing (CAMM). The thin films fabricated in these manufacturing processes can be in the nanometer range. Optical inspection is needed for these processes, as the thin film electronics may be damaged due to degradation issues such as small scratches, contaminate particles or deposition issues such as nonuniformity or undesired thickness. Currently, CAMM staff must personally inspect webs as they are rolled through the Energy and Conversion Device and In-line Inspection Tool (ECD). An autonomous optical inspection platform could improve the overall roll-to-roll manufacturing process as inspection should be conducted between each layer deposited onto the roll.

Systems existing at the CAMM prior to this project include the ECD, which conveys the webs (the roll materials), the individual sensors from SunOptical Systems LLC, which conduct the inspection, and a DELL PC, which is the operator interface. The following project details all relate to understanding these components or connecting them to form a roll-to-roll inspection platform. Mainly, understanding the two sensors and connecting the defect sensor.

2. Development

In an effort to inspect multiple characteristics of the web, multiple types of sensors are in development. The SunOptical Defect Sensor is designed to use light scattering and microscopy to detect degradation defects such as scratches or contaminate particles. The SunOptical Spectroscopic Reflectometer was chosen to ensure expected deposition thickness.

2.1 SunOptical Light Scattering Defect Sensor

This defect inspection sensor captures microscopic images with 4 oblique illuminations of point-source LED with different colors, Red(620-625nm), Green(520-530), Blue (465-480nm), and white (400-730nm), independently triggered for as short as 2µs duration. Two independent detectors were combined in the sensor, one large format (1920x1080 pixels) forin high-resolution, low-speed algorithm study, and one low-format (256x256 pixels) for high-speed (1500 frames-per-second) inline inspection. The inline sensor is driven directly by a field programmable gate array (FPGA), connected to the host embedded Linux microcontroller through serial peripheral interface (SPI). Once the effective algorithms were developed, they can be implemented into the FPGA for real-time inspection for production.

Our development of the defect sensor focuses on two purposes. First, convert the measurement of pixels into a real world value such as micrometers using MATLAB to develop inspection algorithms. Second, determine the optimal mounting height methods with our new design. A focal range of approximately 50mm to 80mm was found with noticeably higher resolution at closer working distances, as seen in figure 1. From this, a mounting height of 55mm was chosen.

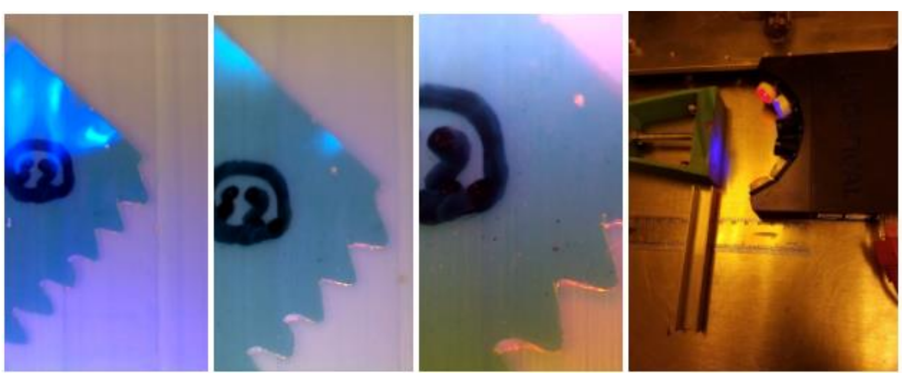

Figure 1: Focal Range Characterization of SunOptical Defect Sensor

(left to right: 78.5mm, 65mm, 50mm)

This design was chosen because it fulfills the physical requirements and desires previously established by the team. There are two points of contact between the ECD and casing, as well as multiple points of contact between the casing and the sensor; this design helps mitigate vibrations. The team decided an adjustable height is unnecessary but a variable horizontal position is important as it allows scanning different lanes of the web. The sensor casing can slide from side to side along the track that the casing is mounted to. This design would also easily allow additional sensors for total coverage of rolls in future development. The redesign utilizes 1" x 1" 80/20 extrusion material. This material was constructed in a framing fashion that is mounted to the ECD using pre-existing tapped holes. The length of the frame allows the sensor to sit at the optimal scanning height. The height (above the point of inspection) was decided based on the sensor resolution and roll speed of the machine. The sensor stays in the casing by friction fit and set screws. The 3D printed casing holds the sensor firmly in an attempt to dull the motion and vibrations of the system.

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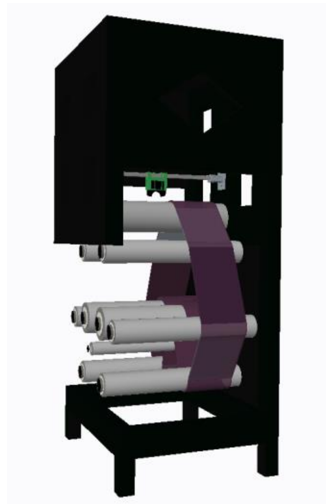

Figure 2: ECD with mount and sensor

In order to verify that the defect sensor is accurate in finding readings, the readings from the sensor were to be compared against a known and accurate system using statistical analysis. The Optical Profiler Wyko NT 1100 is a surface analysis tool at the Analytical and Diagnostics Laboratory at Binghamton University that can give sub-nanometer to millimeter measurements of any imperfections on a surface. It was used on samples of UPILEX-125s Polyimide to get a three dimensional reading of the surface with average dimensions of each scratch. An example of the results is shown in figure 3, below.

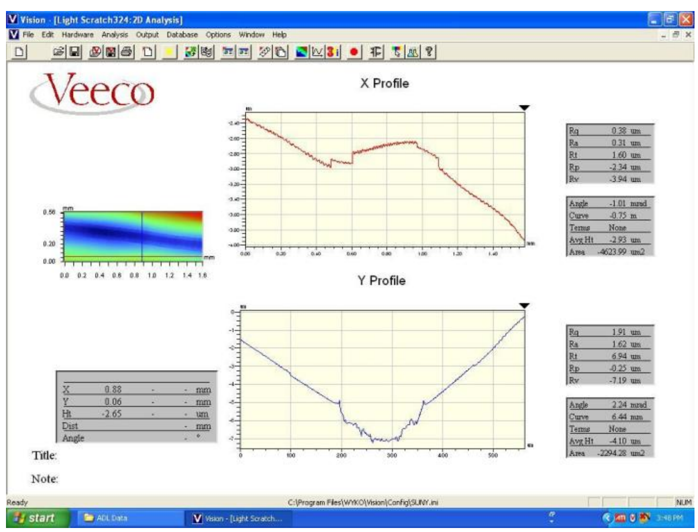

Figure 3: An example of Optical Profiler Results

Random samples of width and depth were taken from 30 different points on the scratch and averaged to determine the characteristics of the depth. This was repeated on multiple scratches. The results were then to be compared to the output of the defect sensor using a t-test to determine whether there is any significant difference in the readings between the two systems. However, the defect sensor code was found to output insufficient data to compare between the two systems.

2.2 SunOptical 3-Mag Motorized Inline Spectroscopic Reflectometer

Reflectometry is a way to determine thickness of thin films. A spectroscopic reflectometer outputs a beam of light and measures intensity and phase information of the reflected light. This information can then be used to determine film thickness, given index of refraction. It requires little sample preparation and is non-destructive to samples being measured.

The SunOptical Spectroscopic Reflectometer focuses white light illumination (400-730nm) on the flexible film through a 2X, 10X, or 20X objective lens, collects the reflection spectrum by a BitFlow spectrometer, and analyzes the film thickness and material property from the intensity and phases information against the saved calibrations.

The reflectometer must be calibrated. We used SiO2 coated Si wafers as the calibration reference. The thickness and refraction index for the SiO2 film were determined with the Filmetrics reflectometer at CAMM. After these steps, a MATLAB program was developed that analyzes the peaks of the spectrum data from the sensor and outputs thickness of the film.

The Filmetrics reflectometer is used to acquire index of refraction, which is needed in MATLAB calculations prior to testing of the SunOptical reflectometer. It is also used as a baseline reading of thickness that can be used for comparison with readings output from our sensor and code. Below, figure 4 shows a reading of 1.44 for SiO2 refractive index.

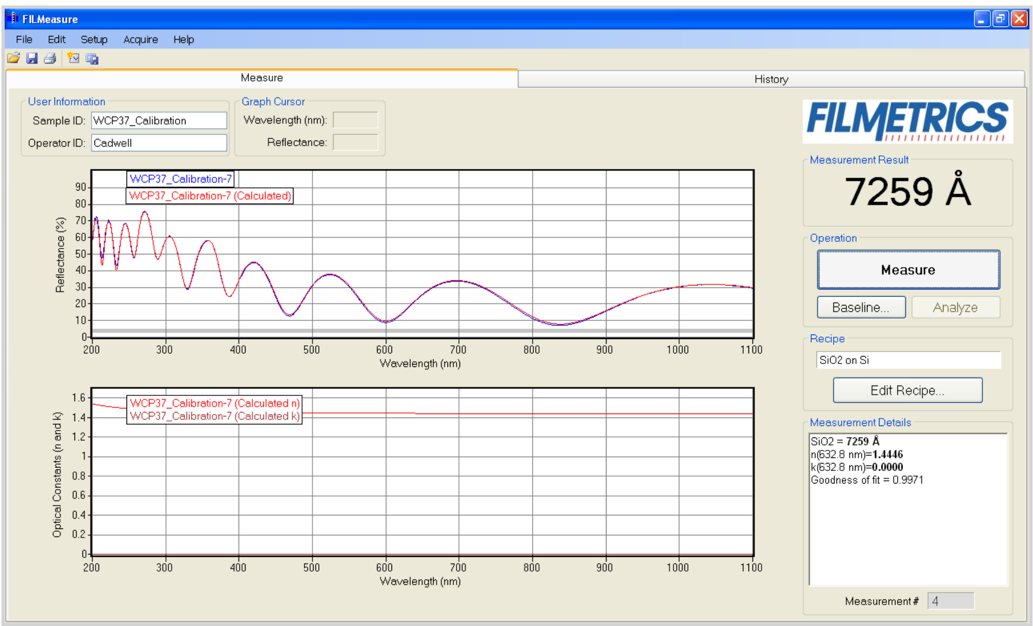

Figure 4: Filmetrics Reflectometer Reading of Filmetrics SiO2/Si Wafer

In figure 5, below, the spectrum output from the SunOptical reflectometer is shown. The upper graph is raw data, which is a relative measurement of intensity versus wavelength. The lower graph is of reflectance percentage versus wavelength. In this graph, the peaks and troughs of the Filmetrics wafer, the blue waveform, occur at the same wavelengths as in the reading from the Filmetrics reflectometer (wavelengths: ~540nm, ~600nm, ~680nm).

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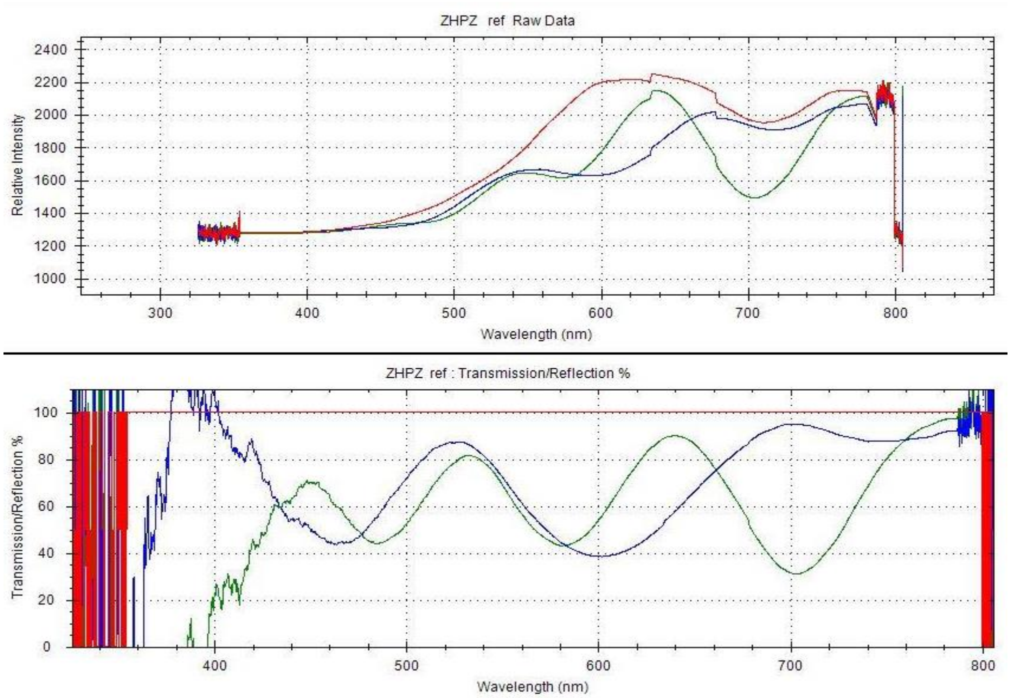

Figure 5: SunOptical Reflectometer Reading of SiO2/Si Wafers (Plain Si wafer in red, Filmetrics in blue, NLAB in green)

To determine film thickness from the waveforms shown in figure 5, a peak analysis tactic was used. This was determined though discussion with Professor Vladimir Nikulin at Binghamton University and from the Filmetrics spectral reflectance guide (Filmetrics, Inc., 2012). As peaks occur at smaller differences of wavelength, this means the film of a given material, SiO2 for example, is thicker – as illustrated in figure 6. Hence, the pair of equations following figure 6 were implemented in MATLAB.

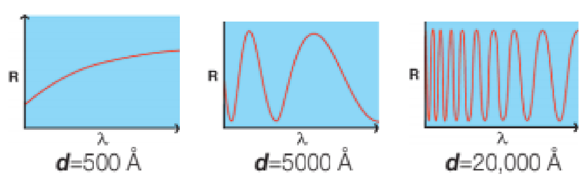

Figure 6: Thickness versus spectral peaks (as shown in Filmetrics spectral reflectance guide)

$$\frac{4*pi}{\lambda 1} * d * n = 2 * \pi * i \qquad || \qquad \frac{4*pi}{\lambda 2} * d * n = 2 * \pi * (i - 1) \tag{1}$$

In these equations, pi is the constant pi, λ1 is the wavelength that the first peak occurs at, λ2 is the wavelength that the second peak occurs at, d is the thickness, n is the index of refraction, and i is the wavenumber. These two equations can be solved for the two unknowns: d and i.

In order to implement this equation in a MATLAB program, we first needed a function to find us the waveform peaks. Figure 7, below shows the success of that function. However, for a given waveform the operator may need to adjust the threshold of how close along the x-axis that two peaks are allowed to be found. Otherwise, local peaks may be present in the data that are not actually peaks due to the overall sinusoidal oscillation.

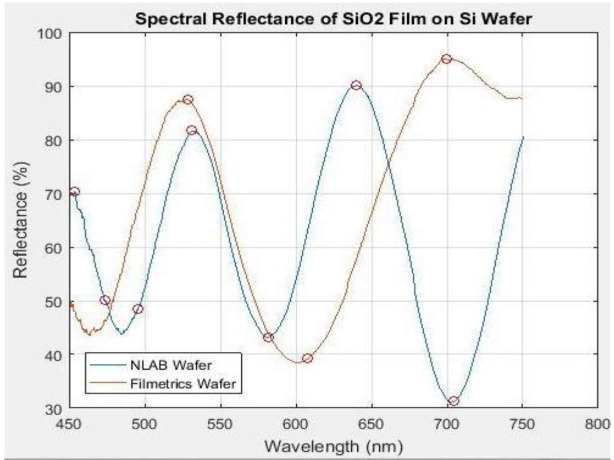

Figure 7: Peak/Trough Analysis with MATLAB program

Reading the distance along the x-axis between the peaks, the program output the thicknesses for the Filmetrics and NLAB wafers as approximately 750nm and 1088nm, respectively. The Filmetrics reflectometer reading of the Filmetrics wafer was 725.9nm and the NLAB wafer was determined by NLAB to be approximately 1000nm.

4. Conclusions

A mount was developed for the defect sensor and a basic understanding of the reflectometer has been formed. Suggested next steps include developing a mount for the reflectometer and a systematic experiment design for analyzing defect detection performance.

One important note for further development of the thickness inspection: films sufficiently thin may have a spectral waveform like the one shown on the left in figure 6, in section 2.2. Since our MATLAB program is based on distance between multiple peaks, it would not be able to calculate the film thickness of this spectrum. For this, an intermediate step is required. A model waveform must be determined, possibly in the form of equation 2 as shown in the Filmetrics spectral reflectance guide (Filmetrics, Inc., 2012), where R is reflectance, A and B are fitting parameters (tuning constants), λ is wavelength, π is the constant pi, n is index of refraction, and d is thickness. This would allow extension of the waveform to at least two periods of oscillation; this can be analyzed by our existing MATLAB function. This would also reduce some of the thresholding issue mentioned in section 2.2, as there would be no local peaks that are not due to the sinusoid.

$$R = A + B * cos(\frac{4*\pi}{\lambda}) * n * d \tag{2}$$

Further development of the inspection platform may be done by adding multiple defect sensors to enable inspection of the entire web, calibrating the inline reflectometer for more materials or for multiple layer films, adding new sensors for qualities such as roughness detection, or accounting for nuisance factors such as vibrations or the eccentricity of the drum that the web is conveyed on.

5. Citations and References

Filmetrics, Inc. (2012). Understanding Film-Thickness Measurements. Retrieved April 03, 2018, from https://www.filmetrics.com/technology