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Roll-to-Roll Processing and Inspection:
An Analysis of Optical Defect Inspection of Aluminum Depositions on Flexible Substrates

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Abstract: Thin film manufacturing is integral to the packaging of integrated circuits onto flexible substrates. In Roll-to-Roll (R2R) manufacturing it is important to possess the capability to continuously inspect deposited materials and to acquire defects data for each sample. The team designed a mounting bracket to fit into a Roll Conveyance Tool for the installation of a non-contact optical sensor. Image processing algorithms were developed to locate and record defects, based on images captured from the sensor. The completed R2R Inspection System examined deposition quality via a 13 mm width line scan of aluminum depositions on polyethylene terephthalate (PET). After verification experiments, it was determined that this system is comparable to using a human operator, with additional benefits: defect categorization, location tracking, and reduced variability in results.

Keywords: Roll-to-Roll, Thin Film, Thin Film Inspection, Optical Inspection, Aluminum Deposition, Raspberry Pi

1. Introduction

Innovative electronics packaging solutions are required for the progression of technology. The utilization of thin film manufacturing allows for the fabrication of integrated circuits for different device applications. In the last decade, scaling up of this nanofabrication method from wafer level processing has been realized with the concept of Roll to Roll (R2R) processing. The R2R process is demonstrated at the Center for Advanced Microelectronics Manufacturing (CAMM). This Research and Development (R&D) facility takes flexible rolled substrates and processes them through several deposition and patterning steps, allowing the lab to produce target film stacks on a larger scale for the required prototype applications (Binghamton University, 2016). This process is prone to error, as defects can be introduced at each stage of fabrication. Defects such as scratches and particulate matter can compromise the film quality, and thus can affect the device functionality. Thus, non-contact examination of different depositions on various substrate types is required to ensure optimal film and device integrity.

1.1. Background

Thin-Film manufacturing, in the context of electronics, is the deposition of a target metal or dielectric material onto a desired flexible substrate, followed by patterning steps to fabricate the desired electrical application in each layer, typically less than 0.5 microns thick. This technology is used for various electronics applications, such as thin-film transistors, which are used in photovoltaics, lightweight displays, and wearable electronics (Reuss et al., 2005). Thin-film is manufactured in cleanroom settings by academic and industry entities providing thin-film solutions for desired applications, including optical coatings, protective coatings, and electronics solutions, the latter being the focus of this project. In producing thin-film prototype electronics, defects in depositions and substrates are of concern to the operators, as they can affect the functionality of the device (Tummala, 2001). For example, scratches in the deposition or substrate at any stage could prevent functionality of the etched connections on the prototype. To identify and prevent defects for Thin-Film deposited prototype electronics, the substrate and depositions are inspected at each step of the process with optical methods to ensure the deposition and substrate can be further developed.

At CAMM, rolled flexible substrates with depositions were inspected in a Class 10,000 clean room on a Roll to Roll Conveyance Tool (R2R CT) with solely visual inspection methods. Visual inspection of the substrate and deposition with the eyesight of the operator is prone to human error and increases the time required for operator involvement. An operator could spend this inspection time conducting other processes within the laboratory. In addition, automated inspection allows for more precise defect inspection. Lastly, this project identifies primary considerations for designing similar thin-film inspection systems.

1.2. Project Overview

For this project, the focus was to design a Roll to Roll Inspection Platform (R2R IP) with an optical Defect Sensor purchased from the company SunOptical Systems LLC. The team designed a customized mounting bracket to install the Defect Sensor into the R2R CT. Image processing algorithms, written in Python and MATLAB, were developed to analyze images captured from the Defect Sensor. The algorithms can differentiate between two types of defects: surface scratches and particulate matter. An experiment was conducted to validate that the system is comparable to a human operator. Deposition of aluminum on flexible polymer substrates was the primary focus of inspection of quality and experimentation, because it is the most frequently used.

2. Methodology

Our design solution focused on using an Optical Defect Sensor provided by SunOptical Systems for image acquisition. The Defect Sensor is mounted inside the R2R CT with a 3D printed mounting bracket. The Defect Sensor captures a line-scan of the substrate with a width of approximately 1.3 cm, and can identify scratches on the substrate equal to or larger than 0.1 mm. The Data Acquisition Computer (DAQ PC) inside the CAMM cleanroom acquires images from the Defect Sensor and analyzes generated data. The Defect Sensor captures images of the substrate and compares each image to a defect-free reference image. If there are significant differences between the two images, the picture is flagged as a defect.

An operator first mounts a roll into the R2R CT. Once secured, the operator activates the sensor from the Graphical User Interface (GUI) on the DAQ Computer. Then, the operator starts the R2R CT to begin conveying the roll for inspection. For a continuous line-scan of the substrate, images are captured every 1 second. If any defects are found, the location of each are available to the operator and a corresponding image will be available on the DAQ PC for further inspection. Refer to Figure 1 for a flowchart of the inspection process.

2.1. Risk Mitigation

During the system design, our team identified several noise factors that had to be mitigated to allow for ideal operation. The team found the following factors to degrade the quality of the images acquired: roller concentricity, roll reflections, external vibrations, working distance, and image focus. Excess concentricity on the inspection roller would impact the images taken. Reflections from the roller would add noise to acquired images. Vibrations within the system would have reduced the focus and overall quality of the acquired images. Improper working distance for the Defect Sensor reduces focus from acquired images (Fisher, 2010). Mitigation of these risks helped to maximize image focus.

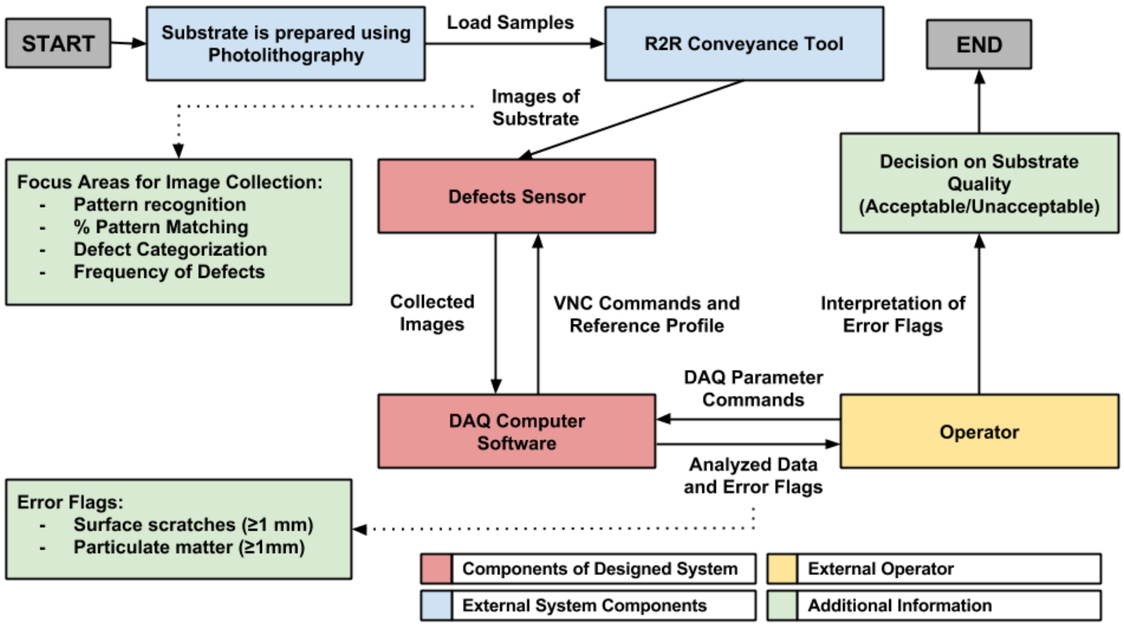

Figure 1. R2R IP Process Overview

2.2. Hardware Overview

There are two primary components of the designed system: the Defect Sensor built by SunOptical Systems and the DAQ PC. The Defect Sensor is controlled via a Raspberry Pi Model 2. The Raspberry Pi is a credit-card sized computer that can complete various electronic projects (Raspberry Pi Foundation, 2017). This device includes 40 I/O pins for interfacing with external devices. The sensor includes four colored LEDs for illumination of the substrate. The CMOS camera installed on the Defect Sensor has a resolution of 1920x1080 pixels, with a max Field of View (FOV) of 7.25mm by 13mm. The DAQ PC was purchased from Dell with Windows 7 installed. MATLAB was installed for image processing (MathWorks, 2017).

2.3. Device Networking

To calibrate the Defect Sensor, the team needed a method for the Raspberry Pi to be remotely controlled by the DAQ PC. This was completed via a Virtual Network Computing (VNC) connection, hosted through the Raspberry Pi. The DAQ PC connects to the VNC server, which allows remote access of the Defect Sensor. For the VNC connection, the team used a Cat5e cable and Transmission Control Protocol/Internet Protocol (TCP/IP), because there is an abundance of documentation with implementing this standard. The networking code was written in Python 3.0. This language was used because it easily interfaced with the analysis code provided by SunOptical Systems. After the DAQ PC and Defect Sensor were successfully networked, the team began developing image processing algorithms.

2.4. Image Processing

Image processing on the DAQ PC was desired over processing on the Raspberry Pi, due to concerns regarding the data processing capability of the Raspberry Pi. With these constraints, the team planned to transfer all captured images from the Defect Sensor to the DAQ PC. The DAQ PC can then run image processing algorithms to categorize each type of defect. The DAQ PC also needed a method to calculate the approximate location of defects on the substrate, so an operator may manually inspect the defects and take appropriate action.

The DAQ PC receives images of the substrate from the Raspberry Pi. In addition, the Raspberry Pi collects pattern matching percentages in the X and Y axes, corresponding to a reference picture that is taken from a defect-free sample. The DAQ PC stores the streamed images into a subdirectory on the PC Desktop. A GUI is used to initiate the test. The GUI also allows specification of: R2R CT roller speed, length of the test, and title of the test. Each test generates a Comma Separated

Values (CSV) file that contains: the name of the picture streamed, the time it was received relative to the start time of the test, position on the roll of where the picture was taken, and any flags for defects. If any defects are identified, further image processing is used to analyze the severity and types of defects in the picture.

The image processing code used is written with the Image Processing Toolbox provided in MATLAB 2016. Included in the Image Processing Toolbox are built in functions to make image processing more efficient. The program initializes with an image that contains defects, and then converts the image to grayscale. To get a clearer image, the image is then transformed into black and white pixels, where lighter gray pixels become white and darker gray pixels become pure black. The cutoff point for this conversion is set by the operator as a threshold value. Built-in functions for tracing objects were used from the toolbox to differentiate between different sections of white in the picture.

Each individual section of white is labeled as a possible defect. To filter out noise and reflections from the camera on the substrate, specific thresholds are established to identify what defects are present. Any sections of white that had an extremely large pixel area was filtered out, since the camera reflection was large and did show in images due to the reflective Aluminum deposition on the substrate. Pixel areas that were significantly small in pixel area were also filtered out, as those are most likely noise or small scatterings of light. Sections of white that fit in the size constraint go through another test for the value of their eccentricity. Eccentricity values ≥ 0.8 are recorded as scratches and eccentricity values <0.8 are recorded as particulate matter. This threshold was determined after averaging the eccentricity values for several scratches and dust particles.

Refer to Figure 2 for an example output file of the MATLAB program. The top left image is the original image taken from the Defect Sensor, converted to grayscale. The middle top image is the binary conversion from grayscale. The top right image is the binary image with camera reflections removed. The bottom two rows contain the defects identified within the specific image. Each defect is labeled with the following parameters: pixel diameter, area in pixels, eccentricity, and mean light intensity. In Figure 2, Defect #2 and Defect #5 would be classified as a scratch, based on their high eccentricity values. The other defects would be classified as particulate matter.

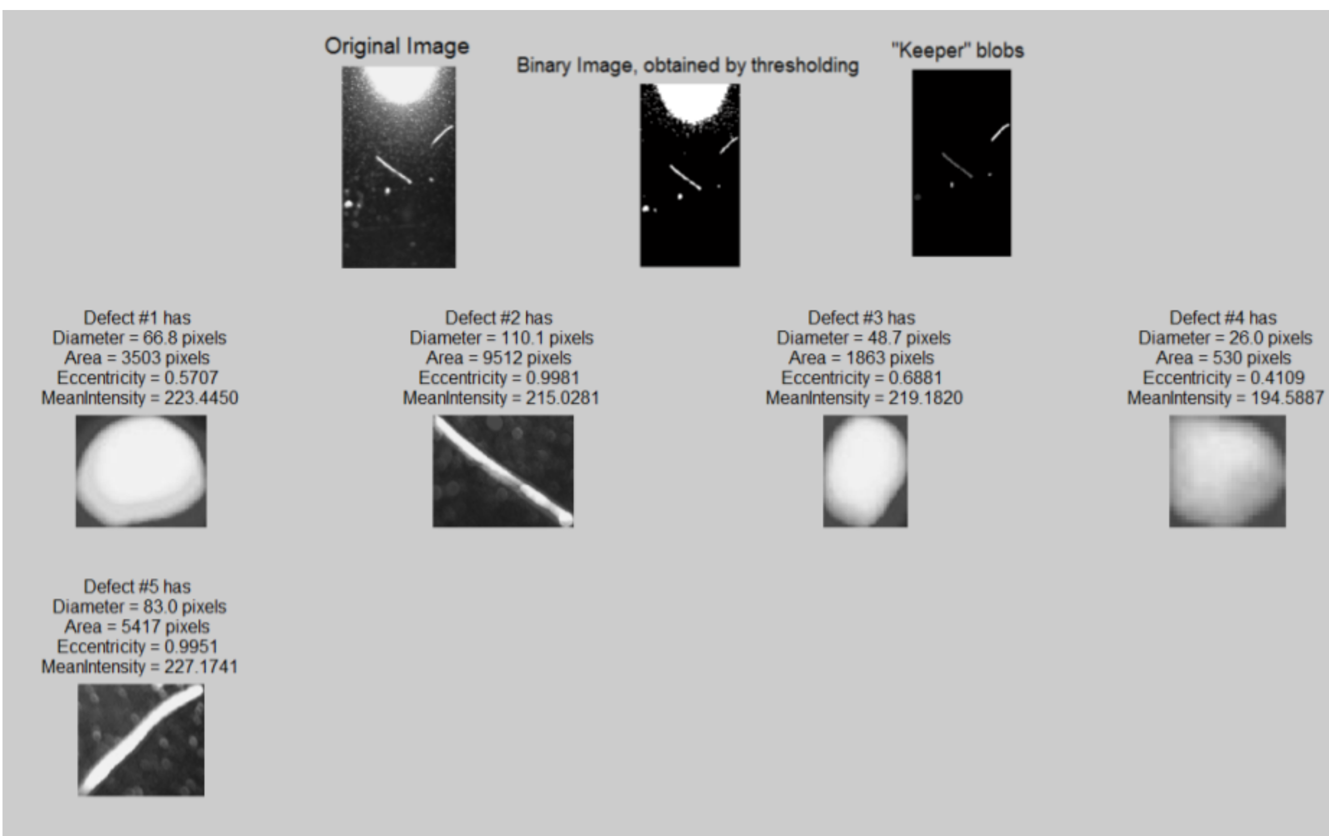

Figure 2. MATLAB Image Processing Output

2.5. Mounting Bracket Fabrication and Installation

Due to the risks outlined in Section 2.1, the team determined that stable mounting bracket was critical to the reliability of the system. Mounting the Defect Sensor inside the R2R CT required consideration of: 1) stress caused by the weight of the sensor, 2) vibrations from the surrounding environment, and 3) the ability to adjust the working distance as needed. The mount was designed in a triangular shape to minimize stress concentration points and to distribute the weight of the sensor evenly. The mount was designed to be isolated from the rest of the R2R CT to reduce the effects of external vibrations. The mount was designed to allow for an adjustable working distance between 5mm and 5cm. The mount was made to fit into an integrated mounting bracket within the R2R CT. This was accomplished by taking measurements of the R2R CT by hand and modeling it in Creo Parametric 3.0 M110. This model was then used to adjust the mount dimensions to ensure that it fit properly into the R2R CT. The Defect Sensor mount was 3D printed because of the benefits compared to other fabrication methods. The 3D printed mount was easier to prototype, lighter, and had a smaller footprint.

After all components of the Defect Sensor mounting bracket were acquired, the team set to install the components inside the R2R CT. Installation of the bracket was difficult due to the large size of the R2R CT. The 3D printed portion of the bracket required additional milling for adequate stability. Cable ties were used to ensure that no wires would interfere with the inspection process. Refer to Figure 3 for an external view of the R2R CT, the Defect Sensor is mounted inside the black box. Refer to Figure 4 for an internal view of the R2R CT with the Defect Sensor mounted inside.

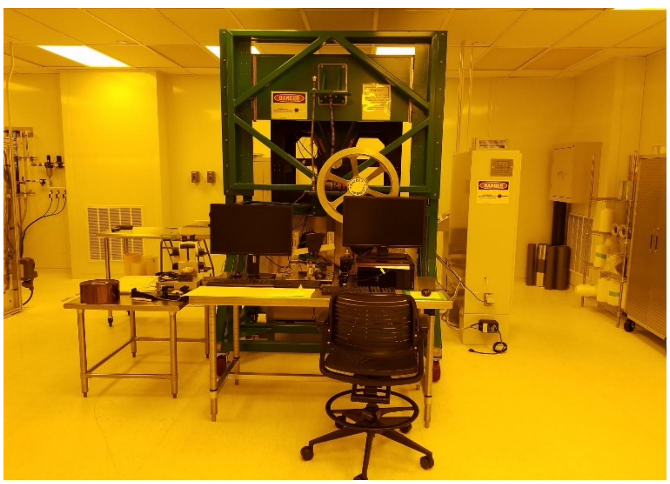

Figure 3. DAQ PC and R2R CT

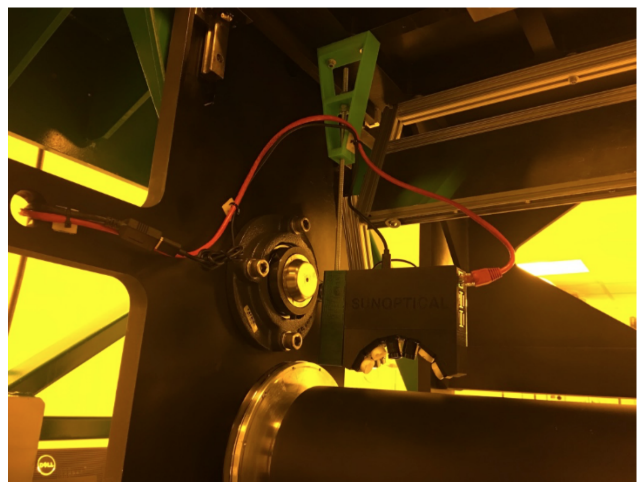

Figure 4. Defect Sensor within R2R CT

2.6. System Validation Procedures

Following the successful installation of the R2R IP, experiments were conducted to validate that this new inspection system is more effective for counting frequency of defects, compared to operator visual inspection. Aluminum was deposited using Physical Vapor Deposition (PVD) onto a 10 meter roll of PET. For this experiment, the team compared the defect identification ability of a human operator versus the R2R IP. The response variable was the number of defects identified by either entity. Control variables included: total scratches introduced onto the sample, the roll speed of the R2R CT, and the Defect Sensor LED intensities. A team member systematically introduced 120 scratches onto the substrate. The roll speed was kept at 20 inches per minute (IPM). The experiment contained four runs for each entity, examining scratches on the deposition each pass and the mean number of defects identified was calculated from the four runs.

First, a human operator stood to inspect the roll manually, this operator counted scratches as they appeared and tallied the results afterward. This was repeated with four different operators, to reduce potential bias. The deposited roll was then inspected by the R2R IP, where images were acquired for analysis on the DAQ PC. For each run, the R2R IP generated 200 images of the substrate with a corresponding CSV file with pattern matching data. Afterward, resulting defects were identified via thresholding techniques outlined in Section 2.4. The CSV file was used in Minitab 17 to complete tests for significant statistical differences. The data acquired was used to compare the number of defects identified by the R2R IP versus the human operator.

3. Results and Discussion

A hypothesis test examined the mean number of defects identified by the R2R IP and operator, which identified if there was a statistically significant difference. Based on the P-Value of 0.452, we determined that the R2R IP and the operator are not statistically different when identifying number of defects. The R2R IP identified 101 defects on average and the operator could identify 92 defects on average. Both runs had 120 total defects introduced. The standard deviation for the R2R IP was 3.464 defects, while the human operators had a standard deviation of 20.857 defects.

Based on the evidence provided, the R2R IP can identify comparable numbers of defects as the operator. However, there are advantages to utilizing the R2R IP, despite the lack of statistical significance. The Defect Sensor can record the exact location of defects on the roll and the approximate size of those defects via the defect inspection program on the DAQ PC. In addition, the variation in results is significantly reduced when utilizing the R2R IP. Using different operators with varying levels of experience can impact the total number of defects identified. Lastly, there is significant time saved for each run, as the operator is not required to examine the substrate manually. For example, assuming the roll speed for the R2R IP is 20 inches per minute, and the roll is 20 meters long, the R2R IP would scan the roll in 39.37 minutes, allowing the operator to conduct other tasks.

It is worth noting that this experiment was conducted to provide the team with an understanding of the capability of the R2R IP at current parameters. Sample size was small due to time constraints, and thus may have affected the results. The system requires further refinement with additional experimentation of thresholds within the Defect Sensor program, which will further improve the inspection capability of the R2R IP.

4. Conclusions and Future Research

This project was conducted with the objective of designing a defects inspection system for R2R processing. Information regarding optical inspection methods and possible noise factors was acquired through research and accounted for in the system design. The mounting bracket was designed to account for vibrations from the R2R CT and allow for variable working distance. The Defect Sensor provided by SunOptical Systems was networked to the DAQ PC, allowing for remote access to the Raspberry Pi interface. Software for defect detection and pattern matching for aluminum depositions on flexible substrates was developed. The completed R2R IP was verified by inspecting an aluminum deposition on PET, and the locations of defects were identified. Finally, standard operation procedures were developed for future use of the R2R IP.

Due to the time constraints of the project, there are several deposition and substrate combinations that were not covered. In future projects, the system should be verified with other deposition types and target film stacks, such as Indium Zinc Oxide, Silicon Dioxide, Indium Tin Oxide, and Indium Gallium Zinc Oxide on other flexible substrates such as Polyethylene Naphthalate and Polyimide. Noise factors were mitigated with system design, but were not eliminated from the system. The impact of vibrations and concentricity should be quantified in future studies. While installing the inspection device with the mounting bracket, it became apparent that ease of installation should be considered in future studies.

Future work can be done to create additional functionality for the R2R IP, such as characterization of inspected depositions. Further experimentation is recommended to validate the R2R IP capabilities. To conclude, R2R defects inspection is a complex system to design, and appropriate caution should be used to design the system for robustness toward noise factors and reliable acquisition of measured defects data.

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