YIELD LOSS IMPROVEMENT BASED REAL TIME AUTOMATED MACHINE VISION INSPECTION SYSTEM (MVIS) APPLICATION FOR THIN FILM SOLAR CELL LASER MICROMACHINING

by

Rus Helmi bin Shuaimi
(1430111508)

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"Verily, all praise is for Allah, we praise Him and we seek His assistance and we ask for His forgiveness. And we seek refuge in Allah from the evils of ourselves and from the evils of our actions."

"Whoever Allah guides, there is no one that can lead him astray, and whoever is led astray, there is no guide for him. I bear witness that there is no deity that has the right to be worshipped except Allah- alone and with no partner- and I bear witness that Muhammad is His slave and messenger."

"To proceed": …

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LIST OF ABBREVIATIONS

a-Si	Amorphous silicone
AVI	Automated visual inspection
$CdCl^2$	Cadmium chloride
CdS	Cadmium sulfide
CdTe	Cadmium telluride
CIS	Copper indium selenide
Cu	Copper
DPSS	Diode pump solid-state
EVA	Ethylene vinyl acetate
I/O	Input output
LED	Light emitting diode
MFD	Module profile data
Mo	Molybdenum
MVIS	Machine vision inspection system
P1	Scribing step 1
P2	Scribing step 2
P3	Scribing step 3
PC	Personal computer
PV	Photovoltaic
TCO	Transparent conductive oxides
VTD	Vapor transport deposition

LIST OF SYMBOLS

+ve	Positive
-ve	Negative
ºC	Degree Celsius

Penambahbaikan Kehilangan Hasil melalui Aplikasi Sistem Automatik Visi Mesin dalam Pemotongan Laser Sel Solar Transistor Filem Nipis

ABSTRAK

Fabrikasi laser memainkan peranan penting dalam pembentukan sel solar dalam sesebuah modul solar fotovoltaik (PV) transistor filem nipis. Garis pemotongan yang dihasilkan oleh alat laser berkadaran pengulangan-tinggi atau micro-fabrikasi laser, menentukan ukuran kawasan aktif yang memisahkan modul menjadi sel-sel kuasa yang lebih kecil. Kedua-dua resolusi dan ketepatan merupakan faktor penting dalam aplikasi fabrikasi laser semasa pengeluaran tinggi terhadap modul solar PV. Adalah penting untuk mengekalkan pemotongan yang berkualiti tinggi dan meminimumkan sebarang kecacatan. Bagaimanapun seperti kebanyakan mesin laser yang lain, terdapat masalah dalam menentukan kegagalan pemotongan atau kecacatan dalam modul solar. Sistem pemeriksaan konvensional menggunakan kamera aras-kawasan dan terhad dalam mengambil gambar kecil di dalam modul solar adalah satu-satunya kaedah yang tepat dan boleh mengesan mana-mana kecacatan dalam sesuatu pemotongan. Walau bagaimanapun, sistem ini tidak dapat bertolak ansur dengan persekitaran pemprosesan yang pantas yang memerlukan pemantauan masa yang nyata dan penting untuk mengelakkan kegagalan yang tinggi dan mencegah kehilangan hasil bagi produk yang siap. Oleh itu, kajian ini ditulis untuk menyiasat penambahbaikan terhadap kerugian hasil melalui pelaksanaan teknik pencitraan visi mesin. Sistem pencitraan visi mesin ini dibina dan direka secara bersepadu dan automatik dengan aliran berterusan proses pembuatan sel PV. Ia merangkumi semua pemotongan laser di permukaan modul solar dibandingkan dengan pensampelan bahagian kecil dari pemeriksaan manual dan analisis kamera aras-kawasan yang memakan masa. Sistem pemeriksaan automatik ini dijangka dapat mengurangkan kos pembuatan lebih dari $17,000 sebulan dan meningkatkan kawalan kualiti yang ada terhadap produk yang cacat. Ia juga dianggar dapat mengurangkan 70% dari kehilangan hasil pengeluaran daripada proses micro-fabrikasi laser yang sedia ada.

Yield Loss Improvement based real time Automated Machine Vision Inspection System (MVIS) application for Thin Film Solar Cell Laser Micromachining

ABSTRACT

Laser scribing plays an important role in defining the solar cell area of thin film photovoltaic (PV) solar modules. The scribing lines produced by high-repetition-rate laser tools or laser micromachining, define the dimensions of the active area that separate the modules into smaller individual power cells. Both resolution and precision are important in laser micromachining applications during mass production of PV solar modules. It is critical to maintain high quality scribes and minimize scribing defects. However, like many others laser machines, there is an issue in determining scribing failure or defects in solar modules. A conventional inspection system using area-array cameras to snapshot small sections of the solar module is the only available method that can accurately detect any cut-quality defects. Nonetheless, this system is unable to tolerate a fast throughput environment that requires real time monitoring which is crucial to avoid high fall out and prevent yield loss for finished products. Hence, this research was written to investigate yield loss improvement through the implementation of imaging technique of machine vision. Machine vision inspection system are builds and design in a fully integrated and automated manner with the continuous flow of the PV cell manufacturing process. It covers all laser cuts on the surface of the solar modules compared with small section samplings from manual inspection and time consuming area-array camera analysis. This automated inspection system is expected to reduce manufacturing cost more than $17,000 per month and improve existing quality control over defect product. It is also estimated to reduce 70% of production yield loss from the existing laser micromachining process.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

In this part, background of the research project is presented, followed by brief of the problem statement. The objective of the research will be clarified together with the research scope. At the end, the structure of the thesis is reviewed.

1.2 Background

Laser micromachining perform important steps in thin-film PV solar cell manufacturing. It enables clean scribe cutting to form the required pattern of electrically isolated area in a conductive film cell. Recent technological improvement in cell scribing offers high process accuracy and flexibility with cost-effective in solar module production. The use of nano and picosecond laser system has become one of the most ideal tools that enable micro fabrication for solar cell segmentation and interconnection. In thin-film fabs, laser processing by diode pump solid-state (DPSS) offering a clean scribe patterning with repeatable properties cell structure. It replaces and eliminates costly processing steps that previously required for scribing solar cell interconnects. It is made by scribing module into parallel sectioning and define interconnect electrode circuitry in smaller track that are typically ~25-50µm wide displaced by ~30-50µm in each film. The more sectioning in active area within a conductive film cell, the highest efficiency of current collection produced for a single solar module.

A goal of PV thin-film solar cell laser micromachining is to provide consistent quality of material removal over the entire workpiece. The laser tools used must offer a non-contact with clean scribe patterning with repeatable properties in multiple layer of thin film modules. To obtain high quality micromachining result, several requirements of the drilling work must be fulfilled in an optimal way during the ablation process. The prerequisite features laser beam pulse parameter associate with beam power, spot size, repetition rate, pulse shape and wavelength. A precise alignment of all these parameters will help to achieve finer fabrication of solar cell patterning during micromachining. Therefore, proper control of cutting parameter is important for laser micromachining to deliver good quality scribes.

1.3 Problem Statement

In the recent year, industrial use of laser micromachining becomes one of the important tools in large volume thin film PV process. However, the tight component tolerance especially in high-speed moving process has taken laser micromachining to a higher standard of performance. Laser tools are now facing the new challenge of delivering maximum output with lower yield loss, especially in thin film PV fabs. The devices need to be free from all defects that effected to manufacturing process. A defect drilling result such as rough cutting line, uneven hole formation, surface cracks and others may contribute to the losses of yield. Hence, process monitoring becomes main aspect to reduce and eliminate the defect cause by drilling tools. A quality control assessment is used to identify error cause by the machine. It helps to prevent and contaminate laser defects from impacting to process yield.

The most and common methods used for quality control were visual inspection. In thin film PV fabs, this method involved in sampling test module for visual appearance after completing scribe cutting process. It is done by utilizing examination tools during inspection. However, the manual inspection process is often difficult to control, full of distractions and time consuming, as it is mostly performed by human inspectors. The performance of an inspector sometime inadequate due to several limitations, such as feeling fatigue, lack of competency skills (Huang and Pan, 2015), and diagnostic capability (Dave *et al*., 2015) issues in detecting defects variations. Apart from manual inspection, another approach is by utilizing optical tool systems in manufacturing processes. However, this is remotely done and is separated from the production line, which deploys the statistical sampling method. A few modules are taken from the production line and inspection is done using area-array cameras. Even with the help of advanced optical inspection tools, offline inspection methods are highly vulnerable to continuous and repetitive defect due to the lack of integration with the high speed moving process of a manufacturing line.

1.4 Research Objective

The objectives of this research are:

1. To investigate the type of defect that caused to the yield losses from laser micromachining in thin film photovoltaic (PV) solar panel manufacturing and its detection methods.

2. To develop an automated inspection system as a process control for laser micromachining base on machine vision application which will provide quick and accurate detection in real time process monitoring.

3. To analyse on quantitative data of yield loss improvement and turn into cost saving from the implementation of Machine Vision Inspection System in the PV solar cell on the production line.

1.5 Research Scope

The research is started by exploring scribing defect cause by laser micromachining in semiconductor properties of PV solar modules. There were different types of defects and classification is made based on the scribe positioning error and the quality of cell pattern. It will followed by an extensive investigation and reviews of existing quality control systems of laser scribe profiles in thin film PV solar cell properties. This will include the analysis of the control measure and major drawbacks that arose from the previous technique. In order to improve defect detection after scribing process, a more robust inspection method will be designed to reduce these defects-impacted costs. An optical vision system will be introduced in this design and modelled to create highly efficient inspection tools in detecting laser scribe defects.

Next, after choosing the proper hardware design of machine vision, the system is tested with several numbers of modules that having different type of defects to ensure the capability to detect failure. Finally the equipment is installed and tested alongside actual manufacturing process to access the feasibility of final design. Proper control system will also be included in the design to enhance quality control. Additional to this, data for a success rate of detection capability will be taken and measured. In this phase, the collected data can be analysed to evaluate the effectiveness of the proposed system.

1.6 Thesis Structure

This paper is organized into several sections, as follows. Chapter 1 describes the overview of the research, problem statement, research objectives and scopes. Chapter 2 presents a brief review on thin film PV solar modules. The content is focuses on the methodology of scribing semiconductor subtract on PV cell to create a series of interconnection. Further discussion includes the variety of defect categories during laser micromachining process together with the quality control system. Chapter 2 will be concluded with the purpose of this research. It will be presented as the results for the improvement of the existing quality control in a production line. Chapter 3 covers the research objectives and the methodology, starting with the planning until the end of this research. The current work and preliminary result data will be presented in Chapter 4. The conclusion in Chapter 5 provides a brief outlook of the research contribution to engineering quality control ended by recommendation of future work.

CHAPTER 2 : LITERATURE REVIEW

2.1 Thin Film Solar Cell Overview

Thin film photovoltaic solar cell is a solar module device that consists of multiple thin layers of a semiconductor material deposited on a glass substrate. In general, the semiconductor materials used in this technology are photo-electric active materials, which have photovoltaic (PV) effect when exposed directly to sunlight. Photovoltaic is a technology involving the direct conversion of solar radiation into electricity using solar cells (Sampaio and González, 2017). Various semiconductor materials are suitable for light absorbing layers, such as amorphous silicone (a-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS). However, in a thin film deposition process, especially for doping compounds, CdTe is preferred since it is chemically stable, has higher efficiency and the most cost-effective compared to other semiconductor materials (Metzger *et al.,* 2019).

This thesis focus on CdTe film cells with reverse sequence deposition configuration, together with the formation of cadmium sulphide (CdS) stacked over the Transparent Conductive Oxide (TCO) layer (Luo *et al*., 2016). Figure 2.1 shows the substrate configuration in a typical CdTe thin film solar cell technology. CdTe are doped together with CdS to form the ideal p-n diode junction that contains charge carrier separation. The CdS doping enhance the solar conversion efficiency and provide better long-term stability (Chen *et al*., 2015). In between the semiconductor layers, conductive films serve as electrodes. The front electrode contact is the TCO, while the rear or back electrode is made of a metal compound known as molybdenum (Mo). The principal features of a typical solar cell are based on the photovoltaic energy conversion process. The structure of a crystalline silicone solar cell is formed by a thick p-type base where most of the light incidence is absorbed and the most power is generated (Markvart and Castañer, 2018).

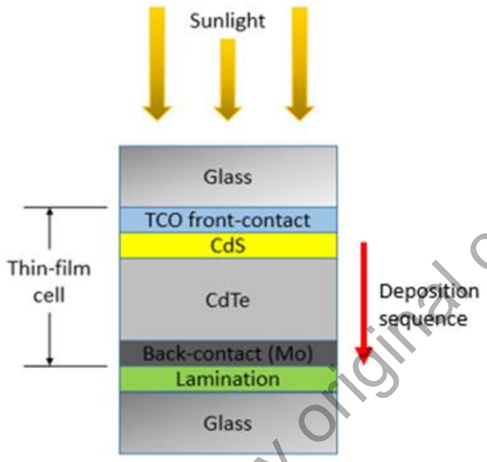

Figure 2.1 Thin film solar cell base on CdTe semiconductor. Light enters through the TCO glass substrate. The rear surface is sealed with laminated glass

A solar cell's operation begins when sunlight enters the glass substrate. Sunlight is composed of energy packets known as photons (Inganäs and Sundström, 2016). Photons in solar rays are absorbed and consumed through the space charge region of the p-n junction. The photon's energy will be transferred to electrons. This will excite the electrons and causes them to flow to the positive side of the semiconductor, which in this case, is the CdTe material since it has p-type properties. When the electrons leave their positions, holes are formed in the p-n junction and they flow to the negative side of the n-type CdS material. The free electron movement, each carrying the negative charge from the p-n junction towards the p-type semiconductor, generates electricity. When the surfaces of the p and n type semiconductors are connected to two different electrodes (front and back) and an external load, electron current will flow and electrical power will be available at the load. Figure 2.2 shows the detailed concept of the photovoltaic effect in a CdTe solar cell.

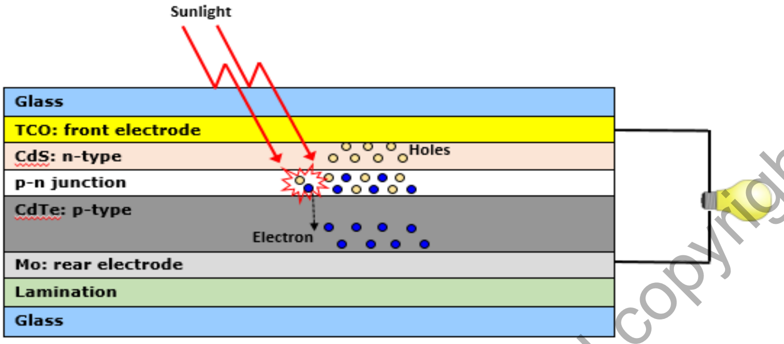

Figure 2.2 Creation of electron-hole pairs through the absorption of photon energy from sunlight

In order to accomplish maximum efficiency in producing electrical energy, large sheets of flat glass panels are used as substrates. These glass panels are necessary to produce large numbers of interconnection cells in a single module. The current industrial-standard dimensions are 1100 x 1300 mm and 2200 x 2600 mm, which are subdivided into a large number of individual solar cells, from 100 up to 200 scribe grids (Dunsky and Colville, 2008). Laser micromachining is used to cut the thin film layers into a grid pattern of long narrow strips and provide the series of interconnection. This scribing method creates a series of connected cells that behave as +ve and –ve terminals of a battery in a series connection (Hanak, 1981). Figure 2.3 shows a three-scribe series that defines the series of interconnection cells. As the area of the solar cell increases, the generated current is also increased during the illumination of sunlight.

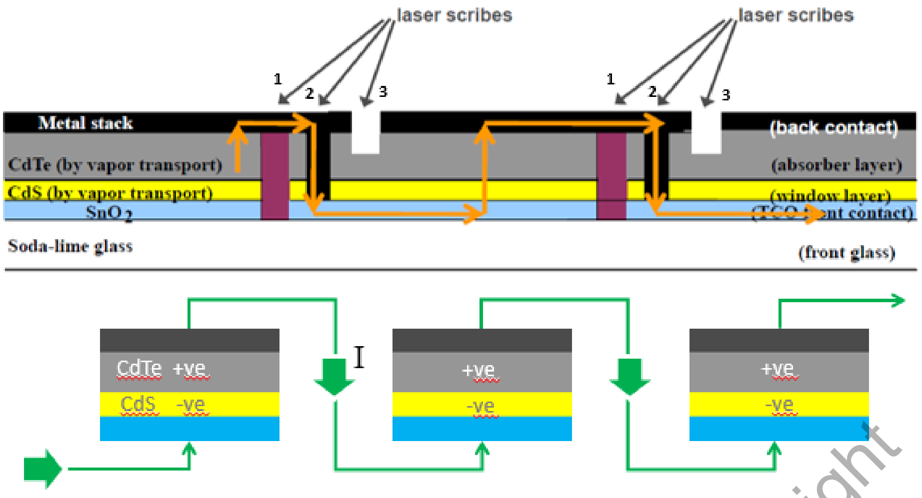

Figure 2.3 Series interconnection of a three-scribe series construction in the cell structure

The three-scribe series, defined as P1, P2 and P3 (Litmanen, 2015), are the key-components in the interconnect separation during the laser scribing process. Each laser scribes are patterned and constructed after each layer has been deposited onto the glass substrate. Figure 2.4 shows the position of all three-scribe series.

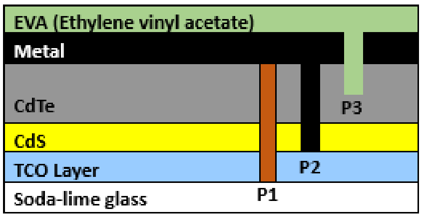

Figure 2.4 The three-scribe series interconnects each layer of isolated cells in a CdTe solar module

The first scribe, called the P1 is patterned after the deposition on the substrate of the first conductive layer. It divides the interconnect path via the front electrode of the TCO contact layer. The second scribe (P2) is patterned before the deposition of the conductive coating. P2's groove will be filled with the electrical contact of Mo. The third scribe (P3) completes the cut off at the top electrode. It is aimed at dividing the whole module into isolated cells and to make possible their connection in series (Lai *et al*., 2020). There will be 216 active cells in one module when all three cuts are completed. Scribes lines are currently in the order of several tens of microns in width, with an offset separation between P1 and P3 of tens to hundreds of microns. This means that narrow scribes that are placed as close to each other as possible will increase the efficiency of current conversion from solar energy (Chu *et al*., 2019). However, these interconnect must have low series resistance and high shunt resistance with minimum dead area between cells (Ruschel *et al*., 2016).

2.2 CdTe Thin Film Manufacturing Process

The entire manufacturing process can be described by the geometrical arrangements shown in Figure 2.5. Development of thin film PV solar module requires three different sections: Plate Coating, Sub Module and Final Assembly. Each section defines the phases of glass substrate process throughout the entire line.

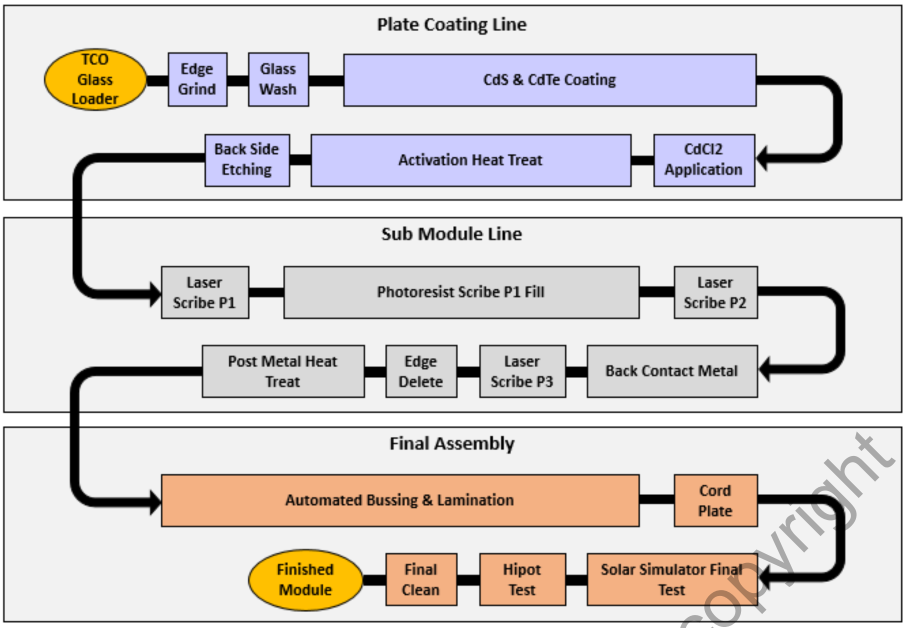

Figure 2.5 Process flow of the PV thin film manufacturing process

The first section (plate coating) is defined as the deposition of the thin film semiconductor layer. At this stage, TCO glass is prepared by smoothing all the glass edges. Mechanical grinding machine will clean up any sharp edges that are prone to stress cracks and chipping during the manufacturing process. After cleaning, TCO glass is fed into the Vapour Transport Deposition (VTD) chamber for the semiconductor film deposition. High quality CdTe and CdS layers are structured on top of the TCO glass at approximately 3.3µm thickness. These layers will be activated with the influence of cadmium chloride (CdCl2) using an applicator spray and heated in a treatment oven at approximately 400ºC. At the end of the plate coating line, a solar stripper chemical is used to remove film residues at the front side or sunny side of the glass substrate. Any residue that remains at the front side of the TCO glass will affect the quality of laser scribing in the next process.

The second section in the PV thin film manufacturing process is the sub module line. Cell definition and interconnection using laser application are located in this section. A high pulse-repetition laser micromachining is used to make cuts for the thin film layer and creates P1 and P2 scribe series with the total number of 152 cell interconnections. Next, a conductive film is deposited using the sputtering system of the metallization process. This metal film is also ablated by the laser micromachining for P3 cell separation. At this stage, the glass substrate with interconnecting cells is called the sub-module panel. This panel is then placed into the edge-delete machine. The purpose of this process is to isolate the cell from the frame by removing the thin film deposition on the outer circumference of the substrate. It encompasses the perimeter of the whole dimension of the solar module. Edge-deletion can also enhance the high-voltage isolation of the cell from the frame and reduce moisture ingress at the module parameter (Wohlgemuth, 2020). Before the module is transferred for the final assembly process, the metal film layer will be cured inside the post-metal heat treatment oven.

In the final assembly section, the sub-module panel is prepared for the finished and consumable product. The fully automated in-line bussing machine will attach the lead wire and contact current busses onto the module. Normally, the contact band or lead wire will be the Sn-plated copper (Cu) ribbon. Then, the panel is encapsulated with the back sheet of ethylene vinyl acetate (EVA), together with the back cover glass to protect the cell from moisture. The cover glass and EVA back sheet lamination has a hole through which the lead end of the Cu ribbon can be pulled out for the next process. A terminal contact box known as the cord plate is attached onto the pulled-out lead wire. The lead wire is soldered at the –ve and +ve terminal stable’s current guide with plugs (called the Male and Female wires), which will be used to connect the modules to user’s circuit.