Investigation of Scribing Quality Defect of Thin Film Solar Cell Using Machine Vision

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Abstract. Laser micromachining provide significant effect in thin film solar industrial field especially in determining cell efficiency of each panels. However, there is an issue in determining scribing failure or defect on solar module. This research aims to investigate the defects of laser micromachining process in thin film solar module in manufacturing fields. Machine vision inspection system is used as inspection tools and to investigate the defect of laser micromachining in thin film solar cells. As a result, two major defects is define which is scribe line quality and scribe line position defects in every scribe line. By identifying the defect cause by laser micromachining through machine vision, quality control plan can be taken together to prevent reoccurrence.

1. Introduction
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 [1]. 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 [2].

The most common thin film technology used today is cadmium telluride (CdTe) film cells type [3]. Figure 1 show the deposition layer of thin film solar cell based on CdTe semiconductor properties and how it convert sun rays into electrical power. The light from sunrays entering through the Transparent Conductive Oxide (TCO) glass substrate. It cause free movement of electron in between CdTe & CdS (cadmium sulphide) layer which both substrate formed a p-n junction semiconductor properties [4]. The free movement of electron in the thin film layers generate the electricity. The rear surface is seal with laminated glass to protect the deposition layer from moisture.

In order to accomplish high-efficiency in producing electrical energy, large sheets of flat glass panel used as substrates [5]. 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 is subdivided into many individual solar cells, from 100 up to 200 scribe grids [6].
To fabricate scribe grid of interconnected cell in deposited glass sheet, laser micromachining is used [7]. The advantage of laser micromachining is it capable to make scribe cutting in micron size with precision, smoother hole walls, and cost-effective in high volume production [8]. Laser micromachining cut the thin film layers into a grid pattern of long narrow strips and provide the series of interconnection of p-n junction [9]. This scribing method creates a series of connected cells that behave as +ve and –ve terminals of a battery in a series connection [10]. Figure 2 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 illumination of sunlight.

The three-scribe series is the key component in interconnection separation during laser scribing process defined as P1, P2 and P3 [11]. The scribes were patterned and constructed after each other on top of several layers of deposition substrate. The step of process illustrated in figure 3. The first scribe, called the P1 patterned after the deposition on the substrate of the first conductive layer of CdTe and CdS [12]. It divides the interconnect path via the front electrode of the TCO contact layer and filled with shunt resistance layer. The second scribe P2 drilled before deposition of the conductive coating. P2’s groove then filled with the electrical contact of metal substrate. The third scribe P3 completes the cut off at the top electrode. The P3 scribe dividing the modules into isolated cells and to make possible their connection in series. There will be hundreds of active cells in one module when all three cuts completed and it define as monolithic serial interconnection [13].
Figure 3. Typical process of laser structuring after each of the different materials of thin films are deposited.

Figure 4 shows position of all three-scribe series. 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 [14]. 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. However, these interconnects must have low series resistance and high shunt resistance with minimum dead area between cells [15].

Figure 4. The three-scribe series interconnects each layer of isolated cells in a CdTe solar module.

Laser micromachining designed for the production line comes with a very high repetition speed availability [16]. Therefore, it is capable of processing a single cell in a few microsecond. However, machine efficiency is still a major concern in a manufacturing process, as it cannot meet the highest levels of accuracy and availability. In a high volume and fast processing throughput, laser micromachining can only meet up to 98% of its reliability. Another 2% is a defect occurs from the laser micromachining [17]. Defect occurs on the thin film solar cell leads to poor electrical properties in the semiconductor film. Hence, any overlapping of pulse can lead to the decline of overall module performance. Thus, to avoid waste and gain a high production yield in manufacturing process, a fail cause analysis need to conduct by using a proper inspection tool.

Machine vision method was chose as inspection tool in this investigation [18]. This method uses an optical image processing system that integrated with the laser micromachining process. The optical vision system capable to perform image acquisition and analysis of any subject captured by the image sensor. Image acquisition is a process whereby a photo detector used to generate an optical image which it converted into a digital image. The digital images are then processed using image processing algorithm software that regulates recognition of any scribe patterns that beyond control measure. By identifying the defect occur on solar panel, failure analysis can be conducted to find out the root cause.
2. Methodology

The investigation of laser micromachining defect in thin film solar modules involve machine vision development and experimental set-up configuration. The inspection system designed to capture and detect defect images of laser scribing on thin film solar panel within conveyor system. Figure 5 show components that involved in this set-up. The machine vision inspection system consists of seven vital components which is lighting configuration, part sensor, camera, digital I/O connection, inspection software and PC platform.

![Experimental setup](image)

**Figure 5.** Experimental setup

The first stage and the most critical phase of the setup is system control setup and selections of cameras, optic and lighting. The camera required specification queries for high speed image processing to accommodate with fast and continuous moving conveyor. Line-scan camera with fast electronic shutter is suited in this research. It comes with monochrome sensors as it provides appropriate visual data image for this type of application. However, to ensure proper measurement of visual data, high resolution cameras is used. This allows the device to detect extreme microscopic size spot along the laser scribe cutting. In addition, this camera is reliable and durable to withstand mechanical vibration that might distort the image captured.

Deriving an image will not only depend on the best camera selection. It must come together with good optics and adequate lighting. Both of this factors should be considered to acquire best image resolution. Despite this, proper illumination condition must be in place to obtain high quality of image being inspect. Here, LEDs type of lighting is in use to provide low contrast images. It less expensive and robust in manufacturing floor.

The next step in image acquisition, is to consider right combination of proper lenses. Lenses that come with wide focal length offer high image resolutions. Hence, the machine vision system use lens with 50mm focal length that commercially use in semiconductor environment. As the panel being inspect is in moving conveyor and is potentially very fast, triggering sensor is placed together into the processing system. This sensor will activate the frame grabber as part being inspect is in correct position. Frame grabber is an image processing hardware that convert digital image data from analogue signal of the vision camera. Modern frame grabber come in the form of plug-in circuit board installed in PC. It also provides control signals of the camera parameters such as shutter speed, triggering motion and exposure time. Generally, machine vision inspection system required appropriate package of PC platform that can minimize processes time for each image. Modern
personal computer with the choice of high speed processors used in this system. It processes image
data together with algorithm command simultaneously without time delay.

Another essential elements of a typical machine vision are inspection software and digital I/O
connection. Inspection software play vital role to execute sequence of command which have been
develop to process image being inspect together with decision making program. It is the brain unit of
an inspection system. Therefore, it is very important to identify proper software platform that capable
of processing huge volume of data and at the same time generating PASS/FAIL result to match the
application requirements.

The structure of machine vision is not complete without digital I/O connection. It providing an
interface to an external industrial system such as network connection and PLC logic controller. The
PLC hardware is a part of instrument control to perform function of selection mechanism used to
isolate defect product from the good ones.

2.1. Inspection Algorithm
As describe in previous subchapter, laser cutting which penetrate the CdTe and CdS semiconductor
layers allows any light to pass through the streak pattern. This methodology is ideal to identify laser
cutting defects within the illuminated scattered light area. Thus, to acquire clean and sharp images,
LED lighting was utilized to provide adequate illumination during the inspection process. Light
direction that parallel to the orientation of P1, P2 and P3 streaked pattern will appear as 3 different
bright images shown in Figure 3.2 a). To indicate digital image for the laser cutting pattern, the dark-
field microscopy application used to process the optical images.

Dark-field microscopy is suited in probing thin film structure due to high contrast and visibility
images. It broader the back ground and details of the dark-field images which in this application it
produce an images with dark background for thin film layers and enhance the contrast of the streak
pattern of P1, P2 & P3 laser scribe. With this technique, scribe lines appeared in much more details in
dark zone for further image data processing. In situation where one of the 3 laser scribe gone missing,
the streak pattern is missing in digital image due to blockages of scattered light. Therefore the missing
scribe which is not reveal in the image is identified as scribe defect. Figure 6 (b) show an examples of
missing P2 scribe image due to defect from laser micromachining.

![Figure 6. Revealing laser cutting pattern. (a) 3 lighting penetrate pass through all P1, P2 & P3 cutting. (b) Lighting blockage at P2 due to missing in laser cutting](image_url)
3. Result and Discussion

3.1. Good scribe line in thin film solar cell
Figure 7 show the sample of a good quality and position of scribe line at thin film solar cell. The scribe line for P1, P2, P3 follow the line width requirement which is the measurement between P1 and P2 is ≤ 50µ while P2 and P3 is ≤ 40µ. By controlling the width of scribe line, the thin film cell will provide the most efficient in power generation from single glass module.

![Figure 7. Good quality and position scribe line](image)

3.2. Position and quality defect in scribe P1
Figure 8 (a) show the defect occur at scribe line P1 where the scribe line is out from expected location. The width between P1 and P2 over the specification limit. It is found that this defect occurs due to the panel alignment issue during laser micromachining and lead to scribing offset at the starting point position. The vibration at the conveyor stopper cause the panel shifted. To overcome this issue, integrated conveyor stopper control system in laser machining can be introduce to ensure laser cutting will only take part if alignment is in correct position.

Apart from the position, machine vision system also manage to figure quality defect for scribe line P1. Figure 8 (b) show the image captured from the system. It show scribe line P1 was not clean-cut with several different cutting width from each other. This defect occurs due to uneven laser cutting energy density at the central focal spot. The focus lens in laser cutting machine not able to perform smooth hole wall cut. It failed to provide sufficient focus from the laser gun and cause laser beam scattered around cutting hole. It is been identified as wear and tear condition over the time. Preventive maintenance schedule in replacing focus lens can prevent this condition being repeated.

![Figure 8. Scribe P1 (a) Position defect (b) Quality defect](image)

3.3. Position and quality defect in scribe P2
Picture shown in figure 9 (a) is the position scribe defect occur at scribe P2, where it overlap with laser scribe P1. This defect detected when the optical position is not setting as per specification before laser scribing. Laser setting specification is define manually before cutting process take into place. However wrong setting or manual adjustment by unauthorized person will cause this defect being process in
production panels. Thus, a password protected login and pop-up window base system required to avoid unauthorized person modified setup position setting.

Another defects that relate with scribe P2 is quality defect as shown in figure 9 (b). This defect occurs due to the uneven thickness substrate based material that prevent successful laser micromachining. In normal condition, laser beam power setting being fixed accordance to substrate thickness. Any microscopic debris or substrate thickness beyond acceptance control will impact to laser scribing. Substrate thin film area is not being completely remove due to this issue. Upstream process control to detect any debris or uneven substrate coating is very critical to ensure successful scribe process.

![Figure 9. Scribe P2 (a) Position defect (b) Quality defect](image)

3.4. Position and quality defect in scribe P3
For scribe P3 position defect, machine vision image manage to detect image as shown in figure 10 (a). This picture show no P3 line after P2. The defect occurred due to diode laser pump malfunction during micromachining process. In laser micromachining machine, main power and secondary power supply provide diode laser pump sufficient power to blast laser during cutting process. A faulty power supply contribute to laser pump malfunction with no cutting at thin film substrate. In addition, power surge or droppage can also impacting to cutting process. This condition will cause sludge in cutting depth and width. Figure 10 (b) shown the quality defect occurs at P3 due to this condition. An automatic lockups system can prevent this issue from impacting production panel during laser micromachining.

![Figure 10. Scribe P3 (a) Position defect (b) Quality defect](image)

4. Conclusion
This paper presented implementation of machine vision system in identifying of laser micromachining defect occurs on thin film solar panel. Experimental data indicate that there are two type of defects at every scribe line, which is position defect and quality defect. This defect detection allowed us to identify and address laser micromachining performance issue that contribute to yield loss in production floor. With this data, laser micromachining process can be optimize at high performance for maximum productivity.
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