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LASER SCRIBING OF THIN-FILM PV MODULES
OHUTKALVOAURINKOPANEELIEN LASERKAIVERRUS

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

a-Si	Amorphous silicon
a-Si:H	Hydrogenated amorphous silicon
CdTe	Cadmium telluride
CIGS/ CIS	Copper indium gallium diselenide
DPSSL	Diode-pumped solid-state laser
PV	Photovoltaic
SSL	Solid-state laser
TCO	Transparent conducting oxide
µc-Si	Microcrystalline silicon

1 INTRODUCTION

Solar energy can be converted directly into electricity by photovoltaics. When light is absorbed by matter, electrons are excited into a state of higher energy. When they return back into equilibrium, a state of lower energy, they give away the photon energy. In a solar cell part of this energy goes directly into a circuit and is converted into electricity. The first efficient solar cell was a silicon cell made in 1954. Today several different types of solar cells made of different materials are used and in the 2000s industrial effort has been made to help photovoltaics become an alternative to other methods of energy production. (Lincot, 2013, p. 170.) In this paper the use of laser processing in photovoltaic (PV) applications is studied. The research focuses on laser scribing in thin-film module manufacturing.

1.1 Background

Due to climate change and rising prices of power, renewable sources of energy are becoming more and more important. The Sun is a practically limitless source of clean energy, which should be used more to reduce the use of fossil fuels. (Baharoon et al., 2015, p. 997.) One way to capture the Sun's energy is photovoltaics. Thin-film applications require less materials and are more flexible than wafer-based crystalline silicon applications (Bartlome et al., 2010, p. 427), yet the latter hold the majority of the market share of PV technologies. Thin-film cells have lower efficiency than wafer-based silicon cells, which might be one of the reasons for the smaller market share. To better compete with crystalline and polycrystalline silicon PV modules, the efficiency of thin-film modules needs to be improved. (Bosio et al., 2014, p. 638.) One way to achieve that is to improve the production methods, in which laser scribing plays an important role.

1.2 Research problem

Laser scribing has been one of the tools in solar cell manufacturing for some time and there is plenty of information available about it. However, the quality of laser scribing is affected by several factors and in thin-film solar cells the number of different materials used is quite large, which is why the information is scattered and individual articles usually only cover a small and specific part of the technology. Finding, recognizing and compiling relevant information can therefore be challenging.

1.3 Goals and research questions

The goal of this work is to find possible ways to improve the efficiency of different types of thin film solar cells using laser scribing and to make a coherent compilation of this information. Research questions are used to handle and analyse the information found in a logical manner.

This paper attempts to answer the following research questions:

- Why is laser scribing used in solar module manufacturing instead of other methods?
- How does the laser scribing process affect the quality of thin-film solar modules?
- How can laser scribing be used to increase efficiency of thin-film solar modules?

1.4 Scope

This research concerns laser scribing in thin-film PV module manufacturing. Only monolithically connected modules are studied because of the role laser processing has in achieving this connection. The research is done mostly on studies about modules based on CIGS (copper indium gallium diselenide), a-Si (amorphous silicon), and CdTe (cadmium telluride), since they are among the most common absorber materials in the industry and also have some differences in the scribing process. The focus is on the efficiency of the modules, because the quality of laser scribing can affect it greatly. Other properties, such as manufacturability and reliability, are not included in the research.

1.5 Research methods

This work is a literature review. The research was done by cross-reviewing the contents of journal articles and other scientific literature written about the subject. The articles and books referenced in this paper were found using the following databases and search engines: ScienceDirect, Springer Link, Scopus, Web of Science, Nelli-portaali, LUT Library and Google Scholar. When searching for articles or books the publication date was not limited to any specific time period. However, there is a significant increase in the amount of information available about the subject from the year 2009 onwards. This can be seen, for example, by making a Scopus search with the words “laser scribing” AND “solar cell” AND “thin film” (figure 1) or other similar strings. The increase suggests that the subject process may be rapidly evolving, which is why the earliest allowed publication year of the sources used in this paper was set to 2009 to keep the information valid, although eventually this did not result in exclusion of any article or book studied.

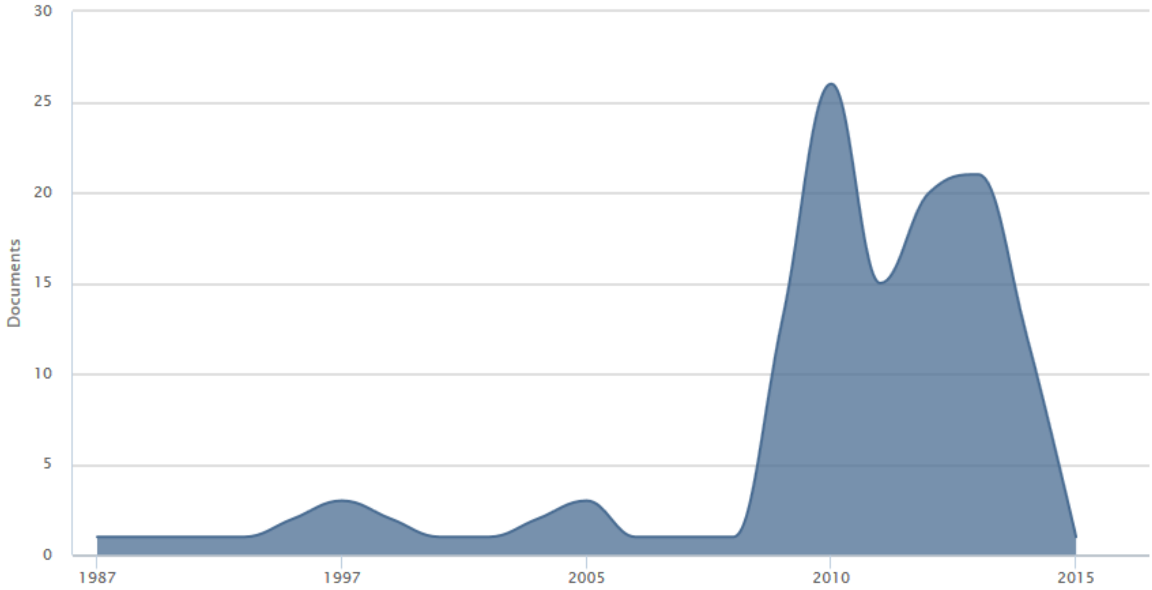

Figure 1. Graph showing the number of published documents each year using the search words “laser scribing” AND “solar cell” AND “thin film” (Scopus).

2 INTRODUCTION TO THIN-FILM SOLAR MODULES

Many different materials are used in thin-film solar modules but their structure is always a similar three-layered system. A semiconductor film, which absorbs the solar energy, is placed between two contact films, which conduct electricity. The three films are deposited on a substrate. (Bovatsek et al., 2010, p. 2898.) The cells in a thin-film module are usually interconnected monolithically, but they can also be connected externally (Zimmer et al., 2014, p. 1025). An example of a monolithically connected module is depicted in figure 2.

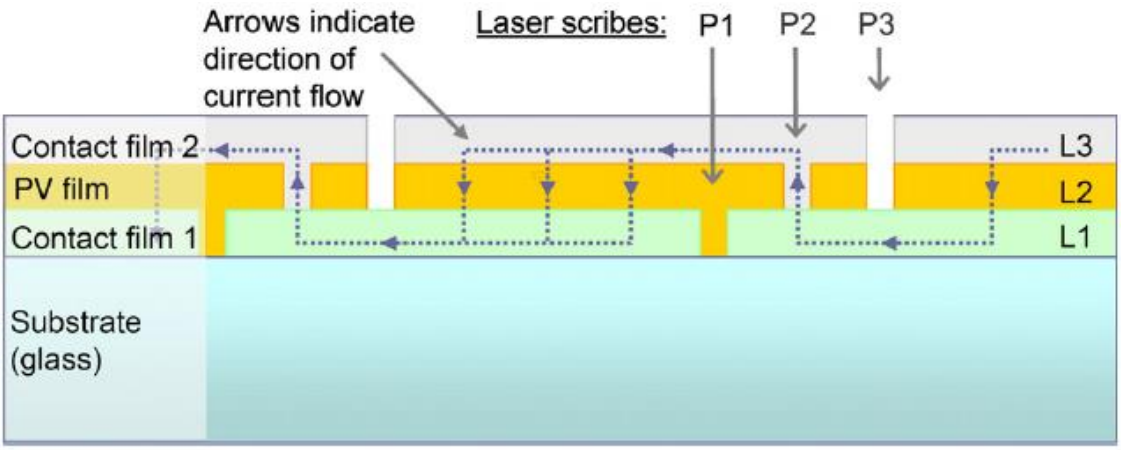

Figure 2. Geometry of a thin-film PV (photovoltaic) module. PV film is the semiconductor material. P1, P2, and P3 scribes are used to divide the cell area into smaller cells. (Bovatsek et al., 2010, p. 2898.) These scribes are explained in chapter 3.3.

Thickness of the films in a module depends on the materials used. For example, a CdTe absorber layer is typically around 3-7 µm thick while a CIGS layer is about 1-2 µm and an a-Si layer 0.15-0.3 µm thick. The other layers range from tens of nanometers to about 1 µm. (Rau & Shock, 2013, p. 269; Petti, Hilali & Prabhu, 2012, p. 328; Shah, 2013, p. 184.) Figure 3 shows a typical CdTe layout with layer thicknesses.

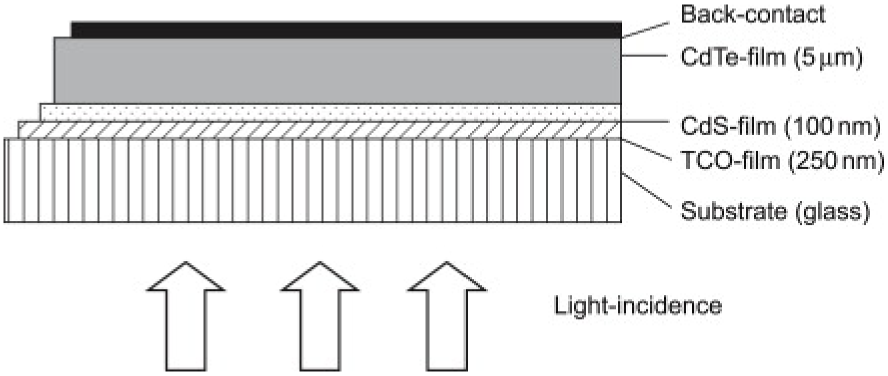

Figure 3. Layout of films in a thin-film CdTe PV module (Bonnet, 2013, p. 226).

The films can be either in a substrate or superstrate configuration. Superstrate configuration requires a transparent substrate, since the substrate faces the sunlight. The transparent conducting oxide film is the first layer to be deposited. In substrate configuration it is the last layer deposited and it faces the sunlight directly. This configuration allows the use of opaque substrates, such as metals, since the substrate is under the films. (Bartlome et al., 2010, p. 428-429.) The difference between these configurations is shown in figure 4.

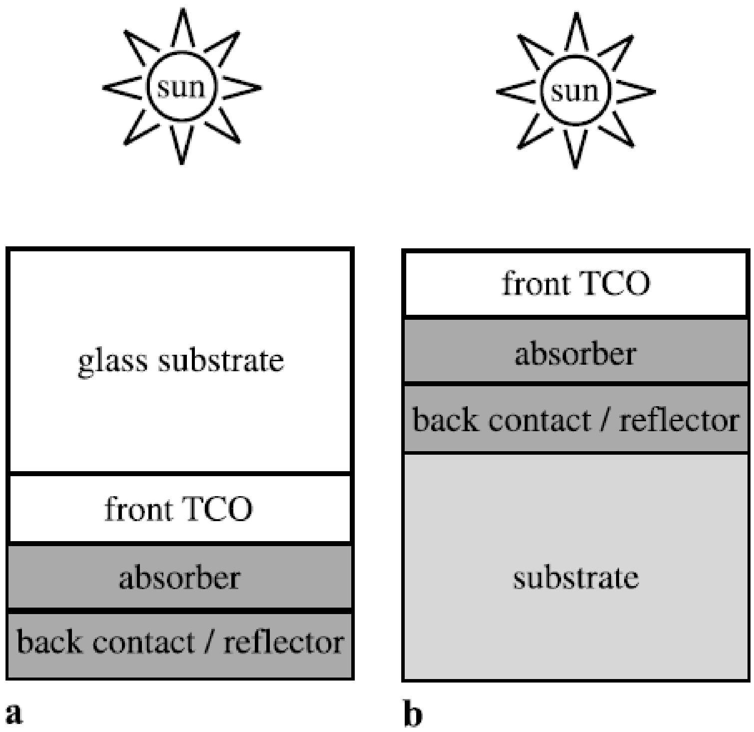

Figure 4. a) Superstrate and b) substrate configuration in a thin-film PV cell. TCO stands for transparent conducting oxide. (Bartlome et al., 2010, p. 428.)

The most common materials used as the absorber in thin-film photovoltaics are amorphous silicon (a-Si) or microcrystalline silicon (μc-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (Cu(InGa)Se_2 or CIGS). (Petti, Hilali & Prabhu, 2012, p. 313.) Besides having their own advantages and disadvantages, the processing of modules based on these materials have some differences. (Bovatsek et al., 2010, p. 2897-2898.) As of late 2014, the highest reported efficiencies (measured following standards IEC 60904-03: 2008 and ASTM G-173-03) for solar cells based on these materials are 21.0±0.4% for CdTe, 20.5±0.6% for CIGS and 10.2±0.3% for a-Si. For thin-film devices the efficiencies drop to 17.5±0.7% and 15.7±0.5% for CdTe and CIGS, respectively, while a-Si/nano- or microcrystalline thin-film multijunction modules have reached 13.4±0.4%. (Green et al., 2015, p. 2-3).

3 LASER SCRIBING IN THIN-FILM SOLAR MODULE MANUFACTURING

Lasers can be used in many ways in manufacturing thin-film PV devices. The processes include laser scribing, laser-induced crystallization and pulsed laser deposition, of which only laser scribing has so far become the industry standard. It is a cost-effective and accurate method that is suitable for many different materials. (Bartlome et al., 2010, p. 428.) It has important advantages compared to mechanical scribing, such as better scribe quality and faster processing (Wang et al., 2014, p. 194). It also removes the significant cost of replacing scribing needles (Heise et al., 2012, p. 703).

3.1 Lasers used in thin-film scribing

Solid-state laser (SSL) is currently the laser of choice in thin-film PV module scribing. (Bosio et al., 2014, p. 639.) According to Burn et al. (2013, p. 714), useful characteristics of a high-end solid-state laser include very good beam quality, high pulse energy and short pulse length. They also go on to say that due to their bulk solid-state lasers are difficult to use in moving head configurations and instead usually require long beam paths and moving mirrors, the alignment and cleaning of which takes time. As a better alternative they suggest fibre laser, as do Bosio et al. (2014, p. 638.) In addition to flexibility list other advantages of fibre laser. They include better conversion efficiency, high beam quality at any available power, stable output power, and better heat dissipation and therefore easier cooling, (Bosio et al., 2014, p. 638.)

3.2 Mechanics of thin-film laser scribing

Laser scribing of thin films can be a complex process and all the phenomena involved are not yet fully understood. Mechanics of material removal depend on many factors, such as laser parameters, material and whether the scribing is done through the substrate or from the film-side. (Lutey, 2013, p. 1; Wang et al., 2013a, p. 1.)

3.2.1 Substrate-side scribing

Substrate-side scribing has a lower thermal effect and higher efficiency compared to film-side scribing, although it still causes defects (Wang et al., 2013a, p. 1). Laser scribing through the substrate does not always require melting and evaporation of the whole thickness of the film. Removal of the film can instead be caused by stresses induced by heating of the absorption point. (Canteli et al., 2013a, p. 224.) Using micro-explosion processing, for example, removal of thin film happens mostly mechanically. The laser beam travels through the substrate and is then absorbed by only a thin part of the film, which results in plasma generation. The film on top of the processed area is removed due to the pressure caused by the expanding plasma. (Wang et al., 2013a, p. 1.)

Bovatsek et al. (2010, p. 2899) offer a three step explanation for the mechanics of thin film removal in substrate-side scribing. Using laser to raise the temperature at the absorption point results in strain and thermal effects, which eventually leads to film removal (Bovatsek et al., 2010, p. 2899.) The process is shown in figure 5.

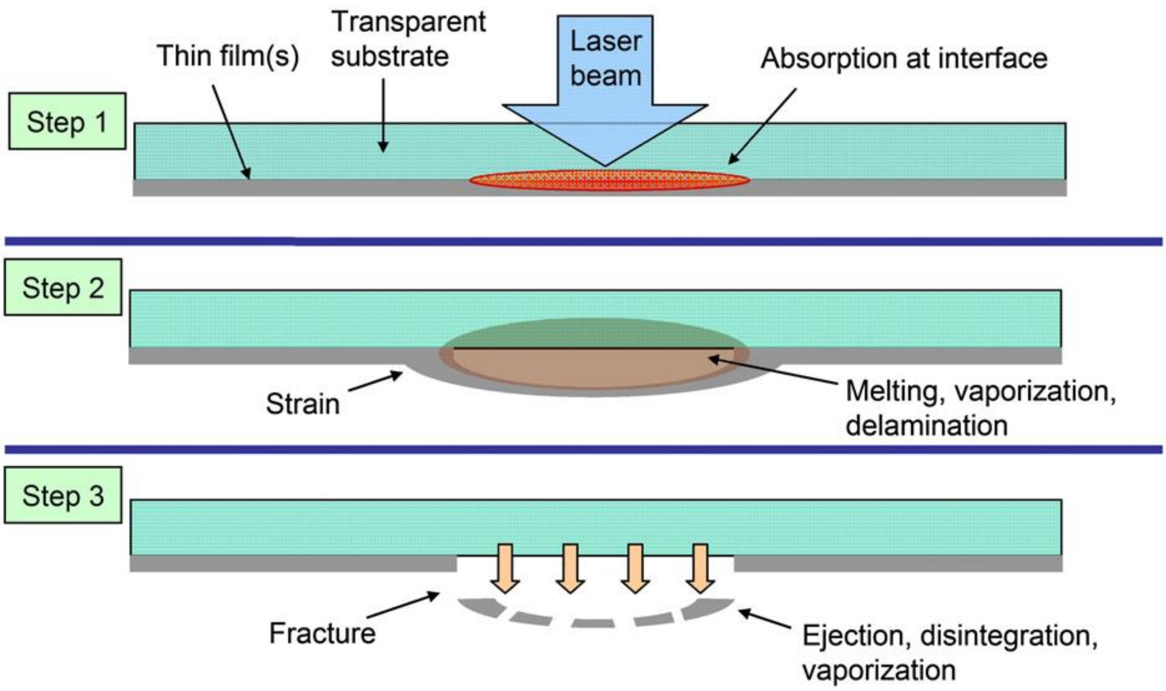

Figure 5. Mechanics and potential contributing factors in thin film removal in substrate-side scribing (Bovatsek et al., 2010, p. 2988).

3.2.2 Film-side scribing

Laser scribing from the film side is more problematic than from the substrate side. Creating abrupt edges of the scribing grooves is more difficult, for example, and an insulating layer may be needed on substrates that conduct electricity before depositing the other layers. (Ku et al., 2012, p. 355.) Material removal happens mostly thermally, by melting and evaporating the area irradiated by laser (Canteli et al., 2013a, p. 223-224). Selectiveness of the process is a key factor, since it is important not to damage other layers. To achieve this, laser parameters must be accurate and highly optimised. (Bosio et al., 2014, p. 641; Račiukaitis et al., 2013, p. 93.)

When using film-side scribing, it is difficult to avoid some defects, such as melted area at the edges of the grooves. Mechanical material removal would avoid thermal effects detrimental to efficiency. Gecys et al. (2013, p. 742,745) managed to achieve this from the film side by selecting the process parameters so that high absorption happens at the interface of the films. This raises the temperature locally and the resulting spalling effect causes material removal and melting is avoided. In their tests on a CZTS thin film both P2 and P3 (explanation in chapter 3.3) could be scribed without thermal damage. (Gecys et al., 2013, p. 742, 745.)

3.3 P1, P2, and P3 scribes

The main application of laser scribing in thin-film solar module manufacturing is connecting cells monolithically in large PV modules. (Bartlome et al., 2010, p. 428.) Increasing the area of a single cell leads to higher current densities, which cause electrical losses. To avoid losing efficiency, large cells can be divided into serially connected smaller cells (Burn et al., 2013, p. 713) to achieve a more efficient device that provides low current and high voltage. Dividing these cells is done with three scribes, usually known as P1, P2 and P3. (Bovatsek et al., 2010, p. 2898.)

The first scribe, P1, is performed on the contact film connected to the substrate. It is done to separate the contacts of adjacent cells. Then the absorber is deposited on top of the contact film and P2 scribe is made to remove it from the first contact film. The second contact film is deposited on top of the absorbent film. P2 scribe allows it to connect to the first contact film of the next cell. Finally, P3 scribe is made to remove both the second contact film and the absorbent film. Now the individual cells are defined and serially connected. (García-Ballesteros et al., 2010, p. 294.; Bosio et al., 2014, p. 640.) This process is shown in figure 6. Figure 7 shows how current flows in a scribed CIS ($Cu(In,Ga)(S,Se)_2$) thin-film module.

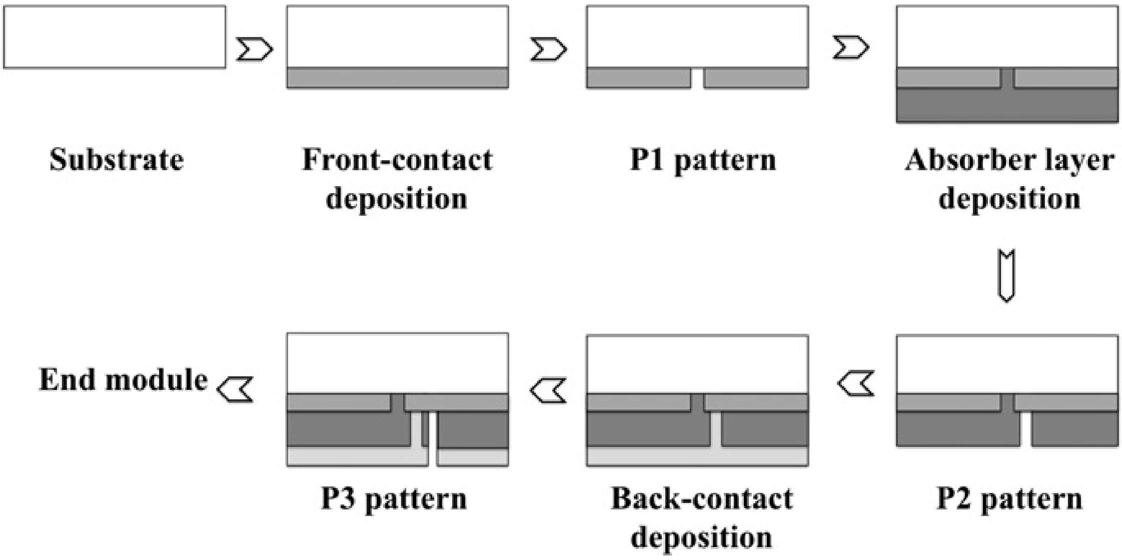

Figure 6. Production process of a CdTe thin-film module (Bosio et al., 2014, p. 640).

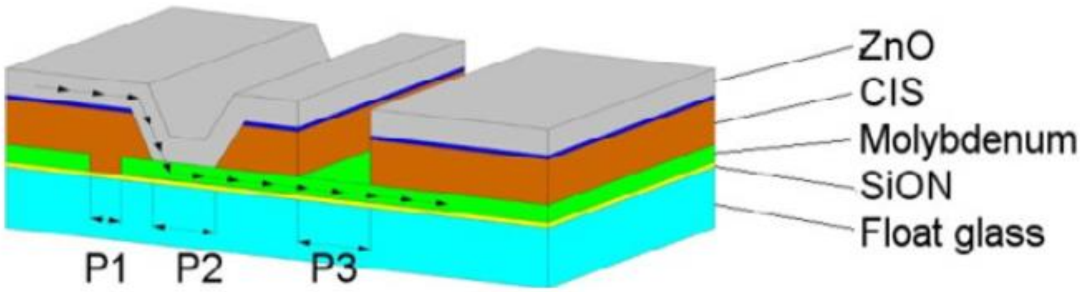

Figure 7. Flow of current in CIS ($Cu(In,Ga)(S,Se)_2$) thin-film module. ZnO is the top contact and Molybdenum is the bottom contact. SiON is an insulating layer and it is not scribed. The arrows show the flow of current. (Heise et al., 2012, p. 703.)

The scribed area (figure 8) produces no electricity (Burn et al., 2013, p. 714.) In this work the term dead area refers to this area. Its size depends on the tools used and also the reproducibility of the scribes. For CIGS, for example, a typical width of the scribed area is around 300 µm, which typically means that about 3-5% of the total area of a module is dead area. (Rau & Schock, 2013, p. 277.)

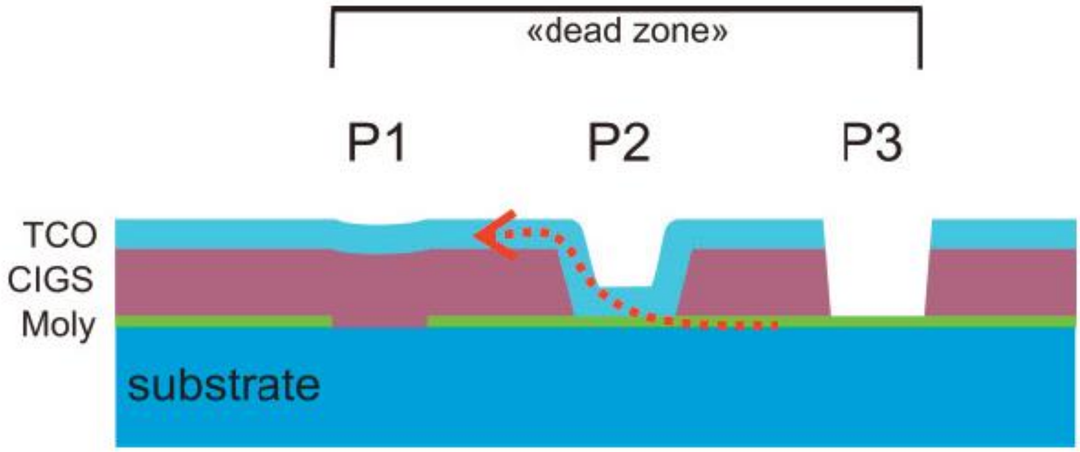

Figure 8. Dead area (or dead zone) in a CIGS module (Burn et al., 2013, p. 714).

If the width of individual cells is increased, fewer scribes are needed and the total dead area is reduced. Doing this also increases series resistance, however, and reduces the efficiency of the module. Therefore, an optimal distance between scribed areas, meaning the cell width, can be found for each different type of thin-film solar module depending on the current densities and voltages of individual cells. For example, for CdTe modules the distance is around 9-10 mm and for CIS modules it is around 6 mm. (Bonnet, 2013, p. 244-245.)

3.3.1 Criteria for quality

As told above, the three scribes serve different purposes and thus need to meet different requirements. Then main requirement of P1 scribe is to provide adequate insulation between cells. Possible leaking current needs to negligible compared to the current individual cells produce. (Bosio et al., 2014, p. 640.) This means that the ideal width of the scribe is a compromise between insulation and minimized dead area (Bartlome et al., 2010, p. 428.)

P2 scribe makes the connection between front- and back-contacts possible. To achieve good electrical connection, the scribing process must leave the exposed front- or back-contact, depending on the configuration (figure 4), clean enough of the removed absorber layer while not deteriorating surface quality of the contact itself. (Bosio et al., 2014, p. 640.; Burn et al., 2013, p. 718.)

P3 scribe needs to separate the front- or back-contact (again depending on the configuration) of adjacent cells. In this step it is important to minimize damages caused by heat and to create a well-defined groove to avoid shunt formation and short circuits caused by remaining connections between cells. (Bosio et al., 2014, p. 641.; Burn et al., 2013, p. 719.)

3.3.2 Copper indium gallium diselenide

CIGS modules are used in substrate configuration (figure 4) and the first layer deposited is opaque molybdenum, which means that P2 and P3 scribing cannot be done in any traditional manner from the substrate side. (Westin et al., 2012, p. 172.) The molybdenum layer is usually laser scribed using nanosecond pulses (Chang, Chen & Wang, 2013, p. 382). Laser scribing from the film side can be more challenging than from the substrate side (chapter 3.2.2), and mechanical scribing is still used for P2 and P3 scribes of CIGS modules in the industry, although laser scribing could be a more cost-effective solution (Zimmer et al., 2014, p. 1025). Laser scribing is also more accurate than mechanical scribing and can achieve a much smaller dead area (Ku et al., 2012, p. 355), partly because mechanical scribing also requires higher safety margins between the scribes due to chipping of the layers (Westin, 2011, p. 1064), as shown in figure 9**.** According to Karg (2012, p. 279), using laser instead of mechanical scribing for the P2 scribe can reduce the losses caused by dead area in a CIGS module by about 30% (Karg, 2012, p. 279).

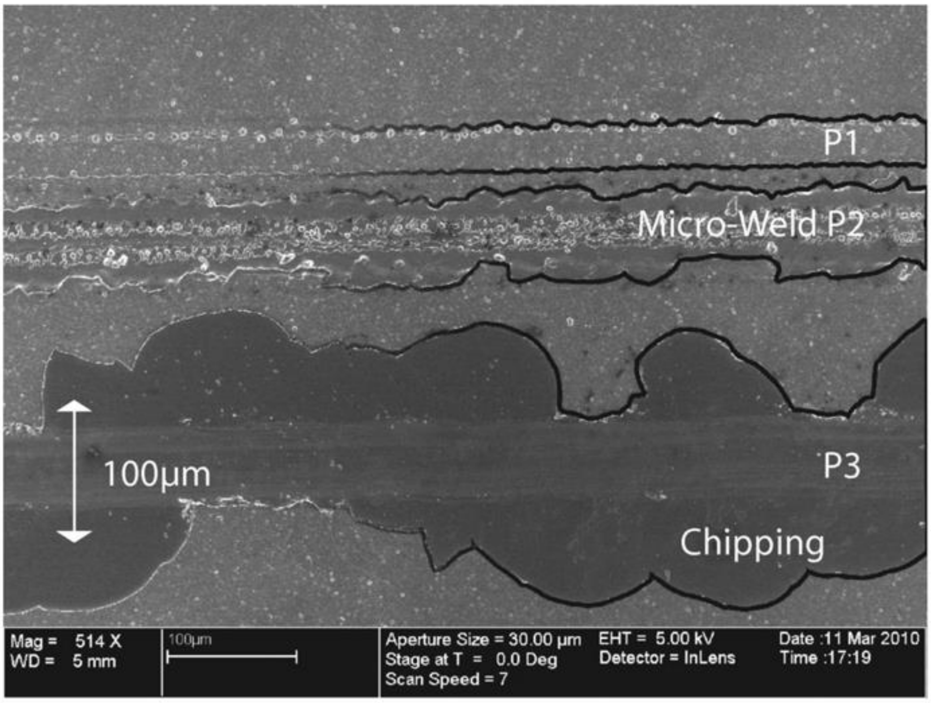

Figure 9. SEM image of scribed CIGS thin-film cell. Mechanically scribed P3 scribe shows chipping and requires a large safety margin between itself and the P2 scribe, in this case an experimental Micro-Weld. The black lines are added for contrast. (Westin, 2011, p. 1064.)

Using laser for all three scribes in CIGS modules has been studied and shown to be technically feasible (Wang et al., 2014, p. 194). For example, Burn et al. (2013, p. 719, 722) tested a 50 picosecond pulsed fibre laser as a scribing tool and concluded that state-of-the-art fibre lasers are reliable and can achieve good quality in this application. Their demonstrator module had an efficiency of 15.3% and its dead zone width was 125µm. They also noted that the removal of the CIGS layer during P3 scribing is not always necessary. (Burn et al., 2013, p. 719, 722.) Lemke, Ashkenasi and Eichler (2013, p. 770, 773) also pointed this out and achieved better results when removing only the TCO layer, finding their CIGS ablation process unreliable. They too managed to selectively remove different layers using ultra-short (picosecond) pulses. (Lemke, Ashkenasi & Eichler 2013, p. 770, 773.)

To avoid the problems of film-side scribing, Kim et al. (2013 p. 1290-1292.) proposed a way to perform P2 scribe in a CIGS module from the substrate side. According to their findings, with the right parameters it is possible to use a picosecond laser to bulge the molybdenum layer in such way that it itself is not badly damaged but the CIGS absorber layer above the processed molybdenum is completely removed. This process is shown in figure 10. Pulse energy needed for complete ablation of CIGS layer by this method was found to be 5.3 µJ, while film-side scribing of P2 required significantly more, 78 µJ. Neither layer also showed heat affected zone or melting. As shown in figure 11, the bulges do not overlap, which can result both in increased scribing speed and better characteristics of the exposed molybdenum according to Kim et al. (Kim et al., 2013, p. 1290-1292.)

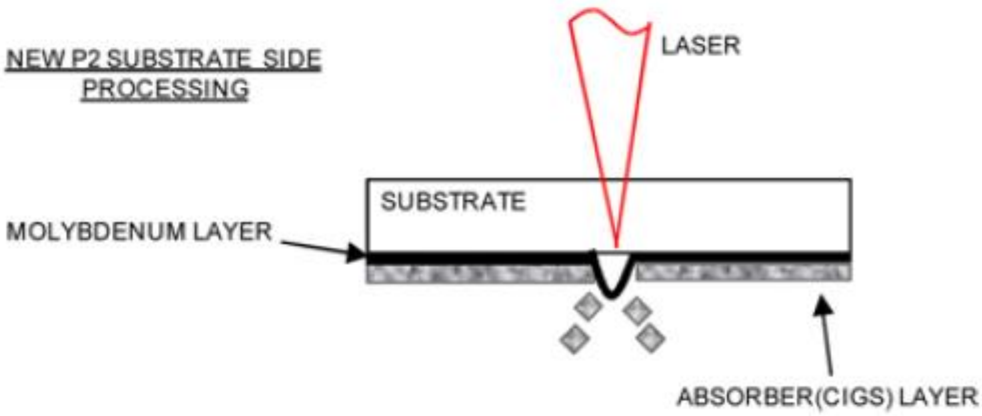

Figure 10. Performing P2 scribe through the substrate in a CIGS cell by bulging the molybdenum with laser energy (Kim et al., 2013, p. 1291).

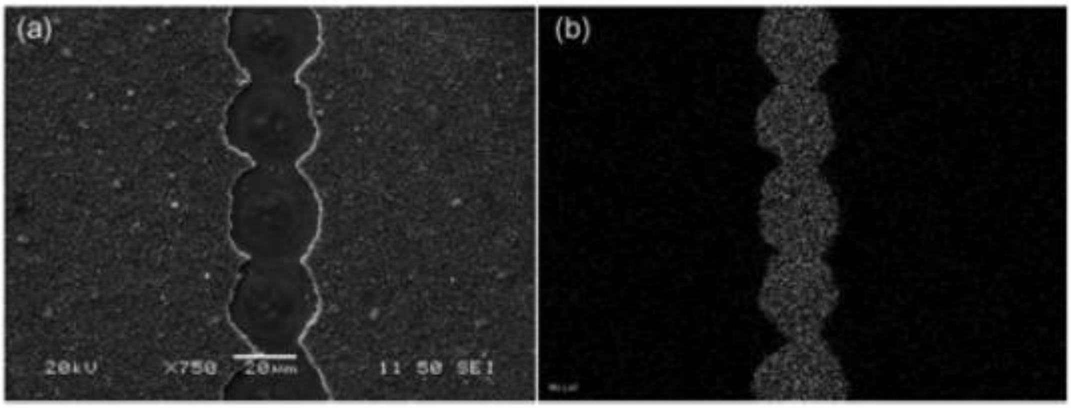

Figure 11. a) A SEM image of a P2 scribe made on a CIGS module by molybdenum bulging. b) Exposed molybdenum observed by energy dispersive spectroscopy. (Kim et al., 2013, p. 1291.)

3.3.3 Cadmium telluride

CdTe cells are used in superstrate configuration, as shown in figure 3. Laser is used for every step of the scribing process (Booth, 2010, p. 184.) In P1 scribing the TCO layer, the front contact, is scribed most commonly using a diode-pumped solid-state laser (DPSSL) with a wavelength of 1064 or 355 nm. P2 and P3 are also made with a DPSSL, using wavelength of 532 nm. These scribes are made from the glass side, which is easier for several reasons, some of which are mentioned in chapter 3.2.1. (Bosio et al., 2014, p. 640.)

Soda lime glass is a cheap substrate for CdTe modules. Using it may however result in reduction of efficiency due to diffusion of sodium into the active layer during processing, which weakens the PV properties. (Kranz et al., 2012, p. 213.) P1 scribe usually exposes the substrate which leads to sodium diffusion, which is not a problem for either CIGS or amorphous silicon. This exposure can be avoided by depositing the CdTe layer before the P1 scribe and then filling the scribe with photoresist. This technique increases the cost of manufacturing the modules, however. Rekow et al. (2011, p. 2813-2819) tested the possibility of removing only the top conducting layer of the three layered front contact (figure 12) by selective laser scribing, which would allow the bottom two layers to isolate the CdTe layer from the glass and remove the photoresist step from the process. Using a fibre laser with an optimised pulse shape, they demonstrated that it is possible to produce continuous scribes on the top layer alone. Some residual conductivity in the scribe was observed, but according to Rekow et al. the achieved resistance should be high enough to produce efficient solar modules. (Rekow et al., 2011, p. 2813-2819.)

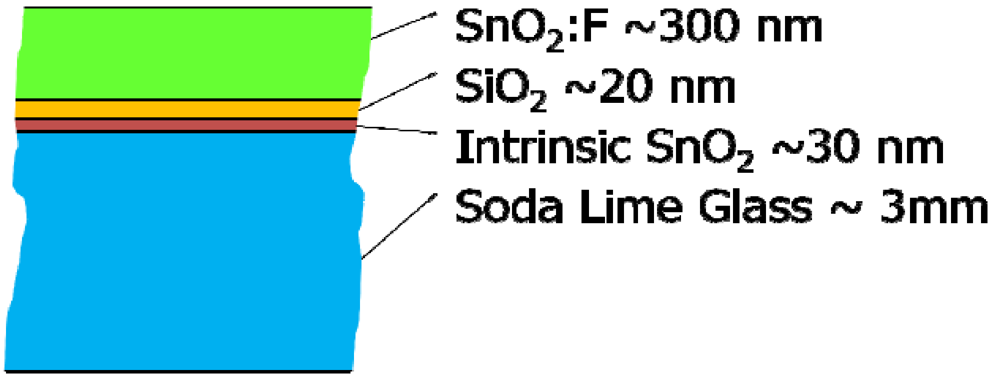

Figure 12. Geometry of the front contact of CdTe module on soda lime glass substrate. SnO_2:F is the conducting layer. (Rekow et al., 2011, p. 2813.)

3.3.4 Amorphous silicon

Laser scribing is the industry standard for all three scribes of a-Si and a-Si:H (hydrogenated amorphous silicon) thin-film modules. Typically the scribing is done with diode-pumped solid-state lasers. Using superstrate configuration (figure 4), P1 scribe is usually made from the film-side on the TCO acting as the front contact with infrared (wavelength 1064 nm) or UV (wavelength 355 nm) laser. Visible light (wavelength 532 nm) is used to make P2 and P3 scribes. They are done through the substrate, which needs to be transparent. (Canteli et al., 2013b, 695.) In P3 scribing the absorbing layer is usually scribed, although ideally only the back contact should be removed. If opaque substrates are used, scribing has to be done by direct-scribing instead of back-scribing. (Colina et al., 2010, p. 5331.) A study conducted by Lauzurica et al. (2011, p. 5231, 5235) suggests that a nanosecond or picosecond pulsed laser with a wavelength of 355 nm can be used to selectively remove each layer from the film side, potentially also in industrial settings (Lauzurica et al., 2011, p. 5231, 5235).

Although laser processing is already established as the method of choice for scribing amorphous silicon modules, improvements in module performance can still be achieved by optimising parameters. For example, Turan, Haas and Steger (2014, p. 78, 85, 86) studied the P1 scribing process and managed to reduce the width of the scribe from the standard 40 µm to 10 µm, which results in a smaller dead area and increased efficiency. Their results show that the process is stable enough and with post-treatment the electrical properties of the module are not affected. With further optimisation easier post-processing could also be achieved. (Turan, Haas & Steger, 2014, p. 78, 85, 86.)

3.4 Improving efficiency of thin-film PV modules by laser scribing

Although it affects other properties as well, successful laser scribing of thin-film PV modules is especially important for achieving high efficiency. By optimising parameters some defects can be avoided. (Wang et al., 2014, p. 194.) With accurate scribing the area surrounding the scribe is not affected and higher efficiency can be achieved (Bosio et al., 2014, p. 639).

3.4.1 Optimising laser parameters

Using shorter laser pulses can improve the quality of thin-film PV modules. Compared to nanosecond pulses, the benefits of picosecond pulses include higher accuracy of scribing and smaller heat-affected zones. This results in larger active area and therefore also higher efficiency of a PV device. (Canteli et al., 2013b, p. 695, 699; Chang & Chen & Wang, 2013, p. 381.) However, according to Gečys et al. (2014, p. 231) using even shorter pulses, in femtosecond range instead of picosecond range, does not provide significant benefits in thin-film scribing (Gečys et al., 2014, p. 231).

Other parameters need to be carefully tuned as well. For example, film-side P2 scribing of CdTe with minimized thermal damage requires short pulses with high intensity. The pulses have high enough power to damage the front-contact, and it becomes very important to calibrate the energy input so that only the CdTe layer is ablated. This can be challenging, since the CdTe layer is several times thicker than the front contact. (Bosio et al., 2014, p. 641.)

3.4.2 Mitigating effects of shunts

Formation of certain defects occurs during processing of thin-film PV modules. One type of these defects is ohmic shunts. They act as short circuits and reduce the efficiency of cells significantly. (Fecher et al., 2014, p. 494.)

The way the cells are connected in a thin-film device prevents selective removal of shunted cells or areas. Dongaonkar and Alam (2013, p. 324-331) studied the use of laser scribing to isolate the shunts in in-line post-processing instead by overlapping P1 and P3 scribes, which removes and disconnects all the layers. Since the shunted cells also affect their neighbouring cells and thereby lower the efficiency of the module even further, isolating shunts at the cost of larger dead area can result in increased efficiency. Dongaonkar and Alam introduce three methods: Periodic lengthwise scribing, partial isolation by selective scribing, and full isolation by selective scribing (figure 13), of which the latter turned out to yield the highest efficiency despite also producing the largest dead area. According to their simulations of an a-Si:H module with an efficiency of 7.22%, full isolation of only the largest 3% of the shunts results in an efficiency increase of about 1.1 percentage points. They also say that the techniques introduced are suitable not only for a-Si:H but for other types of thin-film modules as well. (Dongaonkar & Alam, 2013, p. 324-331.)

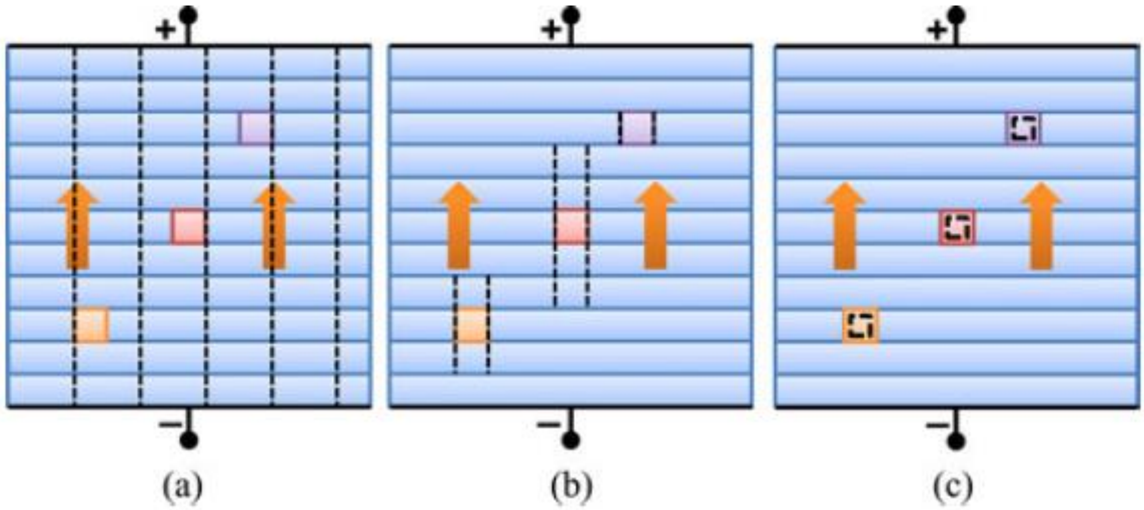

Figure 13. Depiction of different methods of isolating shunted areas (which are shown as coloured squares), where a) is periodic lengthwise scribing, b) is partial isolation by selective scribing, and c) is full isolation by selective scribing. Arrows indicate current flow and dashed lines are the isolating scribes. (Dongaonkar & Alam, 2013, p. 328.)

Amorphous silicon is used in see-through PV modules, which are wanted in building integrated devices. Transparency is usually achieved by laser scribing the silicon layer and the back contact (figure 14), which, depending on the level of transparency wanted, decreases the active area and also causes formation of shunts, which usually happens along the scribes. Shunts are especially detrimental to efficiency under low illumination intensity, which is occasionally unavoidable in building integrated applications. (Wang et al., 2013b, p. 1206, 1209.)

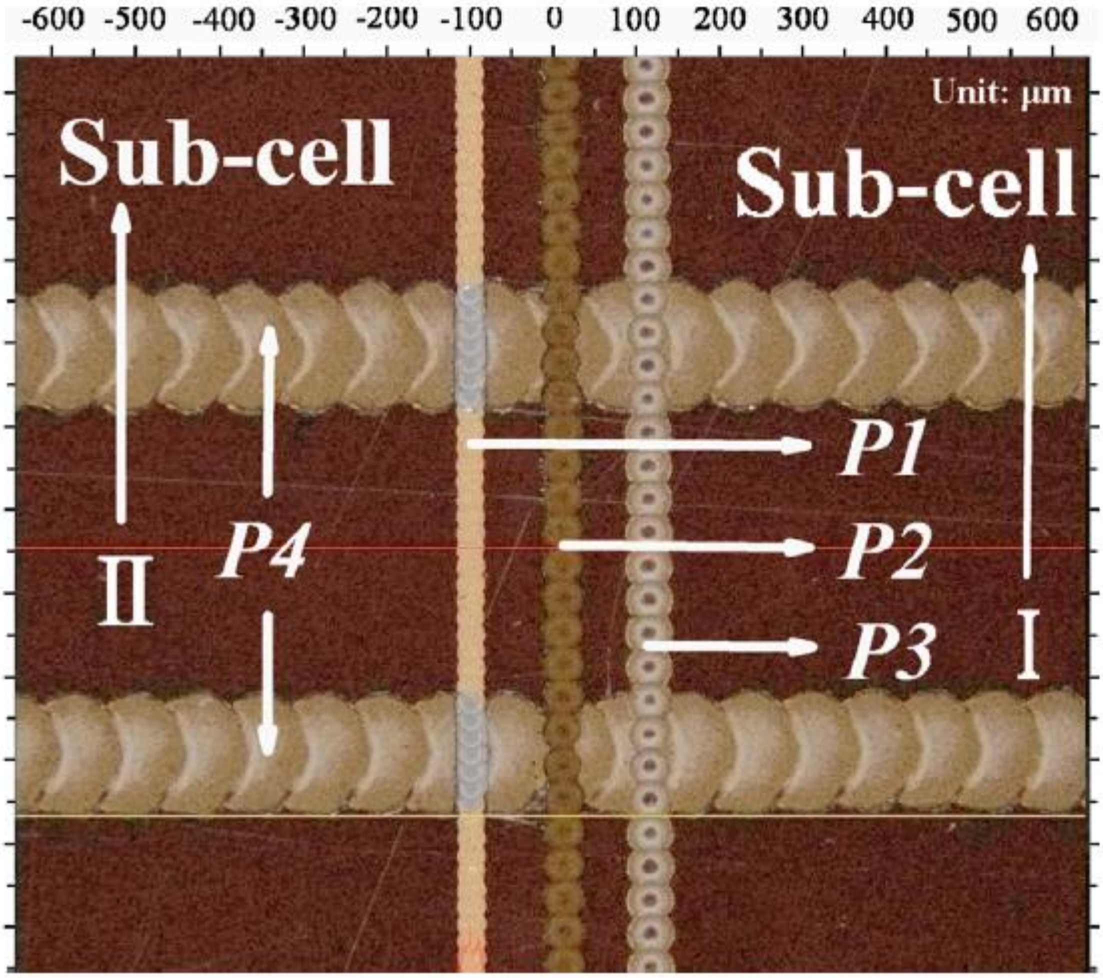

Figure 14. Micrograph of a transparent a-Si:H cell. P4 scribe removes the silicon layer and the back contact making the scribed area transparent. (Wang et al., 2013b, p. 1207.)

As a way to decrease the number of the shunts while still achieving the required transparency, Wang et al. (2013b, p. 1211) tested a multi-line laser technique to produce wider scribes and thereby reduce the number of required scribes and the total scribe length. In their tests, the efficiency of a-Si:H modules with a transparency of 30% and scribe widths of 150 µm and 450 µm was tested under different light intensities. The modules with 450 µm scribe lines were measured to be 10% more efficient with light intensity of 600 W/ m^2 and 13% more efficient with light intensity of 200 W/ m^2 than the ones with 150 µm scribes. This difference in efficiency they attributed to the reduced number of shunts and concluded that noticeably better efficiency is to be expected in real applications as well. (Wang et al., 2013b, p. 1211.)

4 DISCUSSION

In this chapter the key findings of the research are presented and objectivity, reliability and validity of the research are evaluated. Some possibilities for useful future research are also introduced.

4.1 Key findings

According to the literature reviewed for the purposes of this work, laser scribing can produce the highest quality and achieve the fastest processing speeds in thin-film solar module manufacturing. As a more accurate process that also allows selectivity in film removal, laser scribing is a better choice than mechanical scribing when striving for flexibility of production or optimal efficiency of the modules. Feasibility and benefits of laser scribing are already well documented and currently a lot of diverse and novel research seems to be done. Therefore it seems likely that laser scribing will eventually be the method of choice for every scribing step in the industry for most monolithically connected thin-film PV modules, including CIGS based modules.

Material removal mechanics in thin-film laser scribing are complex and highly dependent on the parameters chosen, especially when scribing from the film side. When not properly optimised, laser scribing can cause defects such as shunt formation and material modification. These defects reduce efficiency of PV modules, but they can be partially or completely avoided by selecting correct parameters or changing the processing methods.

Minimizing dead area by optimised laser scribing is one of the simplest ways to increase the efficiency of thin-film PV modules. Another possibility is avoiding the effects and reducing the number of shunts. They are very detrimental to efficiency, and if shunt isolation by laser scribing can be integrated to the manufacturing process as suggested by some research, it may result in significant increase in efficiency in industrially manufactured thin-film modules.

4.2 Objectivity of the research

Writing this paper is in no way connected to laser processing or PV industries or influenced by any other external factors, so an objective viewpoint was easy to maintain. Previous experience did not affect the contents of this paper. There were no intentions to try to prove the superiority of laser scribing in thin-film solar module manufacturing. If any critical information about the subject within the scope is missing, it is not a conscious exclusion but rather a result of unsuccessful research. With the source material used an objective researcher should come to similar conclusions.

4.3 Reliability and validity of the research

The goal was to find all the information presented in this paper from multiple sources to ensure its reliability. Due to the scattered nature of the available information and the novelty of some of it this was not always possible, which is why it was often necessary to rely on a single source. Original sources were used when available.

Some studies on new or improved processing methods are introduced in this paper, such as P2 scribing of CIGS by distorting molybdenum and shunt isolation in a-Si modules. Feasibility of these methods could not be verified from other sources, since the methods may not yet have been tested or the studies reviewed by other researchers. This is why this information is presented as a summary of the research rather than as a fact. The studies are showcased in this paper because the methods presented may be potentially useful and they also show what kind of research is being done on the subject.

Only journal articles and other scientific literature were used as sources of information. As an effort to ensure objectivity commercial sources were avoided. Since thin-film solar modules and their manufacturing methods are being improved quickly the sources had to be relatively recent for the information to be considered valid. No article and or book referenced in this work was published more than five years ago.

4.4 Future research

Gaining a better understanding of material removal and defect formation mechanics in thin-film laser scribing would allow more accurate modelling of the process, which in turn would make optimising the parameters easier. Improving film-side laser scribing is important to allow the use of opaque substrates and possibly increase flexibility of the manufacturing process. Further modelling and optimising P2 and P3 laser scribing in CIGS thin-film modules may be necessary for the process to be adapted by the industry.

5 SUMMARY

This study is a literature review on laser scribing in monolithically interconnected thin-film PV modules, focusing on efficiency of modules based on absorber materials CIGS, CdTe and a-Si. Basics of thin-film PV modules and main applications of laser scribing in them are introduced along with some benefits and challenges of thin-film laser scribing.

In thin-film PV module manufacturing scribing is used to interconnect individual cells monolithically by P1, P2 and P3 scribes. Laser scribing has several advantages compared to mechanical scribing for this purpose and is already used for every scribe in a-Si and CdTe. However, laser scribing of thin-films can be a challenging process and may induce efficiency reducing defects. Some of these defects can be avoided by improving optimisation or processing methods.

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