Optimisation of Laser Scribing of Back Contact for Photovoltaic Modules

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ABSTRACT

Thin film technology offers a promising development toward more economic solar electricity. A key step in thin-film module production is the isolative laser scribing of metal back contact layers on glass substrates. Successful scribing yields reproducible, clean scribes without buckling, ridges or collars on the scribe edges. It is also desirable that scribes are narrow, to minimise loss of active solar cell area, and that they can be processed rapidly.

During this investigation laser scribing of a Mo back contact layer for solar module production has been considered for optimisation. The laser system used is a lamp-pumped, green solid-state Nd:YAG laser, operating at 532nm output wavelength. This system has been characterized in order to determine the output energy, laser spot size and average energy density. Scribing results have been evaluated qualitatively for different laser parameters. Furthermore, scribing has been evaluated on Mo that has been deposited under different conditions. Using a double lens configuration has been evaluated for the possibility of, by simple optical manipulation, affecting the scribe quality and width.

Using the results from the qualitative investigation of laser scribing a standard process for module fabrication has been established, providing clean, reproducible scribes with little or no buckling of the scribe edges. It has also been shown that these laser scribing parameters yielded good results across a range of Mo sputtered under different pressures. Finally it has been shown that the scribe width can be reduced, in this case from 70µm to 50µm, using the double lens configuration.
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1 INTRODUCTION

1.1 Solar energy/photovoltaics

As environmental awareness rises and there is a growing interest in halting the use of fossil fuels as a source for energy, eyes gazing to the sky for answers may find just that. Great quantities of energy is constantly showering the face of our planet, most of which is naturally harnessed and stored both physically, by land and sea masses, and chemically, by plants and animals through processes such as the photo-synthesis and the conversion of D-vitamins in the skin of humans. The industrious Mankind is continually learning of new ways to benefit from this practically inexhaustible source of energy. Modern applications include solar heating of water and air to use for heating and also to, for example via turbines, transform the solar energy into electrical energy.

Directly tapping the solar energy flow in the form of electrical energy can also be done, utilising the photovoltaic effect discovered in the middle of the 19th century and developed during the second half of the 20th[1] The photovoltaic effect causes the junction of two (semiconductor) materials to generate an electrical tension. Connecting the two via an electrical load will generate a closed circuit and the photovoltaic cell can be likened to a battery, providing an output DC current (Fig 1). Cells are traditionally manufactured using Si crystals, which are fitted with metal contacts [1].

![Fig 1 - A solar module under sunlight produces electricity in the same form as a battery.](image)

1.2 Thin Film solar cells

Ever since the introduction of photovoltaic (PV) cells for electrical power generation by Bell Laboratories in 1954 [2], one of the principle hurdles to overcome has been, and unfortunately still is today, to produce electricity at a cost that can compete with other sources [17]. This is where thin film technology may come to make a great difference. By depositing the PV cell material on the surface of a structural component, in most cases a plate of glass, the amount of semiconductor material can be dramatically reduced, as it is no longer required to present mechanical strength. Only 1/1000th of a mm is required for the material to function as a photovoltaic absorber. Using this technique means also that the area of a solar cell is no longer restricted by the size of silicon crystals, but only limited to the size of the substrate. Manufacturing interconnected modules1 with thin film technology is also done very elegantly simply by sandwiching the semiconductor material between two

---

1 A solar module is an array of connected solar cells.
conducting layers and isolating these layers from each other and repeating this at regular intervals to make up consecutive cells (Fig 2).

The first thin film cells were based on amorphous silicon (a-Si), but since the amount of material used is so low many other, more expensive, materials are being developed and manufactured. Examples of such materials are CdTe, CIS (CuInSe₂) and its alloy CIGS (Cu(In,Ga)Se₂ which is being investigated at ÅSC), GaAs [2].

1.3 The CIGS solar cell

The CIGS solar cell consists basically of three components: 1) a metal back contact, made from molybdenum, 2) the semiconductor CIGS layer which is the photovoltaic active layer, 3) a front/top contact consisting of a ZnO layer, also referred to as the transparent conductive oxide or TCO. In addition to these functional layers the cell is dependent on a structural layer to support the solar cell mechanically, in our case a glass substrate. The ZnO front contact is in fact two separately sputtered ZnO layers where the first layer is a thin, undoped ZnO buffer layer and the second is an Al:doped ZnO layer. Between the CIGS and ZnO layers there is also a buffer-layer, a very thin film of CdS.

Fig 2 - Schematic representation of a thin film solar cell structure of the type that is manufactured at ÅSC. The scribes (P1-P3) in the layers are necessary to manufacture solar modules but will reduce the effective surface.

To make the step from single solar cell to solar module the different layers are isolated and connected by making grooves, or scribes, in the structure (see Fig 2). These scribes can be created in various ways, depending on the material properties. Scribing with laser is generally preferred because of the superior precision and the possibility to make very narrow scribes. The P1 scribe is made to isolate consecutive solar cell back contacts from each other. Through the CIGS layer a second scribe, P2, is made (mechanically) in order to permit the overlying ZnO front contact to make contact with the back contact of the preceding cell. Finally the P3 scribe (also mechanical) is made, isolating the front contacts of consecutive cells.

In this investigation only the 1st layer, the molybdenum back contact and the P1 laser scribe are included. However, in order to better understand the solar modules whose fabrication it is the aim of this investigation to improve, a brief
look on the different layers and their methods of fabrication is given in a later chapter (2.1.1). The choice of Mo for back contact material is based on the requirements imposed by the application and the different processing steps. Mo presents stability at processing temperatures, resistance to alloying with absorber layer elements such as Cu and In, and a low contact resistivity to CIGS [11].

1.4 Problems

When performing the initial P1 laser scribe there are a few key results that are desired. Primarily, the scribe is to isolate the solar cell back contacts from each other, hence the scribe line must under no conditions contain bridges or process residue (see Fig 3, scribe 3) in the groove that could cause an electrical connection and short-circuit (shunt) the cells. Shunting of the cells can also be caused if the scribe demonstrates an irregular profile, which often occurs when the laser parameters are not properly adapted to the Mo properties. More precisely, with a scribe profile of like that of no.2 in Fig 3, the height of the walls may be sufficient to protrude through the CIGS layer, effectively connecting the Mo to the ZnO and short-circuiting the cells. The formation of these walls is suspected to be linked to the melting/splashing of Mo or of film delamination.

Another issue when considering the scribe results is of course the scribe width. Essentially the combined surface of the scribes P1, P2 and P3 will make up the entire loss of active area of the solar module (as seen in Fig 2). The narrower the scribes and the closer they are spaced together, the more efficient the solar module, as solar module efficiency is based on the entire module area.

1.5 Objectives

The objectives of this investigation is to increase the understanding of the processes surrounding laser scribing of the Mo thin film and to obtain reproducible, “clean” scribe lines without the presence of bridges, walls or debris. This is to be achieved by defining the appropriate combination of laser parameters and sputtered molybdenum properties, without deteriorating the performance of the back contact in other respects.
1.6 Previous investigations

Sputtered molybdenum thin films have been shown to exhibit a columnar microstructure that is porous and predominantly under tensile stress when deposited at lower pressures and denser and under compressive stress as the process pressure is increased [11][12][13]. The sputter pressure has also been shown to influence the adhesive properties of the Mo film [11]

Laser scribing is a process that is commonly used in the machining of thin film materials for photovoltaic applications. Several investigations have been carried out in order to characterise the influence of the laser scribing parameters and conditions on the scribe quality.

Compaaan et al have performed extensive investigations into the subject [5][6][7] using several different types of lasers and optics. The results show among other things that

1) Efficiency in material removal was dependent on the wavelength/material coupling, i.e. different layers are preferentially scribed using different laser systems.

2) Longer pulse durations (>250ns) are more energy efficient for material removal but increase the conductive heating effects on the surrounding film.

3) A suitable energy level for scribing was five times the ablation threshold, defined as the energy density at which visible damage would appear on the scribed film

4) To avoid the issue of too much energy at the centre of the focal spot, the use of a cylindrical lens focusing was found beneficial, improving considerably the scribe profile. Focusing with a cylindrical lens provides a line image of the laser beam instead of a spot.

5) Scribing the film through the glass substrate (so called back-side or film-side scribing) was found also to improve the kerf profile, minimizing the appearance of ridges and collars.

6) Defocusing the optics slightly improved the kerf (scribe) by eliminating ridge formations at the edges

7) The most efficient type of laser was the diode-pumped Nd:YAG laser.

8) Furthermore, it has been shown that the P2 scribe also can be done with a laser. Scribing at a lower intensity that will not damage the Mo film, a “self-limiting” scribe line removing only the CIGS layer could be achieved using a Nd:YAG laser.

The merits of glass-side scribing, as well as the advantages of defocusing to improve scribe edges, are also stated by Avagliano et al [8]. The problem of laser scribing of thin films has been approached numerically by Avagliano et al.[9]

Some previous in-house work suggests that scribing at the higher end of the laser power spectrum and at higher relative sample speeds showed the most promising results. It has also been noted that scribing through the glass substrate produces advantageous results.

\[\text{It should be noted that this only pertains to the volume of material removed per unit energy and does not involve qualitative evaluation.}\]
2 MATERIALS AND METHODS

2.1 General

2.1.1 Brief overview of the module process

The manufacturing of solar modules consists of a series of steps (see Fig 4).

Step 1: The glass substrates are cleaned and rinsed
Step 2: A molybdenum layer is deposited on the substrates through DC sputtering
Step 3: The metal layer is divided into consecutive cell back-contacts by isolative laser scribing denoted as $P_1$
Step 4: CIGS is deposited through co-evaporation of Cu, In, Ga and Se
Step 5: A thin (~50nm) film of CdS is deposited in a chemical bath
Step 6: A thin (~50nm) film of intrinsic ZnO is deposited through sputtering
Step 7: Slightly offset from the $P_1$ scribe a second mechanical scribe, denoted $P_2$, is made permitting connection between the TCO and the back contact
Step 8: A layer of Al:doped ZnO is deposited through sputtering
Step 9: Offset from the $P_2$ scribe the final mechanical scribe, $P_3$, isolates the cell front contacts from each other
Step 10: In post-processing the modules are fitted with contacts and laminated with a superstrate of plastic or glass

In this investigation the processes of scribing and sputtering have been considered more in detail in order to improve the scribe quality. The other process steps have been carried out in a few cases when entire modules have been fabricated with optimised parameters.

Fig 4 - From glass substrate to solar module, steps 2-9 of the module process
2.1.2 Laser scribing

A brief introduction to laser

The word LASER is an acronym for the most significant feature of laser action: Light Amplification by Stimulated Emission of Radiation. The material at the core of a laser responsible for the light amplification effect is called a gain medium and works by increasing the energy of the radiation passing through it. The physical principle of stimulated emission was discovered by Albert Einstein in 1916 but the first laser was not constructed until 1960 by T.H. Maiman [4]. In “Lasers” by Milonni and Eberly they suggest four key elements composing a laser:

1. A collection of atoms or other material which amplifies a light that passes through it
2. This gain medium or core material is enclosed in a reflecting cavity that will maintain the amplified light, in effect redirecting it back through the medium for repeated amplifications
3. A source or feed of light/energy
4. Finally some means for extracting the radiation, either by a pinhole or (as in this case) by a partially reflecting front mirror

Schematically the heart of a laser will have the appearance as seen in Fig 5 where the above-mentioned elements are noted. Additional components often found are shutters and reflecting and focusing optics.

A solid-state laser, as used in this investigation, refers to the gain medium being a solid. In our case Nd\(^{3+}\) ions are suspended in a crystalline YAG (Yttrium, Aluminium, Garnet) crystal. Electrons in the Nd\(^{3+}\) ions are excited by the light from the laser lamp, referred to as pumping, and the decay of excited electrons is what emits the characteristic 1.06µm radiation. The YAG crystal serves to spread the energy among the ions and has a good thermal dissipation, which allows elevated operating powers. This is a reason why Nd:YAG lasers have characteristically high output powers when compared to other common lasers [15].
Laser material processing [3]

Laser material processing provides many advantages over traditional methods and the applications are innumerable. Using a focussed laser beam to cut, mark or drill a material is preferable principally since it is unsurpassed regarding precision, cut size and material waste, it is economical, has a small heat affected zone (HAZ) around the cut and is rapid. Furthermore there is little mechanical disturbance from the machining and no tool wear to consider.

Roughly, laser cutting of metal materials can be divided into two main methods; vaporization cutting and melt-and-blow cutting. In vaporization cutting the material is rapidly heated to vaporisation temperature and removed, spontaneously, as vapour. Melt-and-blow heats the material to melting temperature while a jet of gas blows the melt away from the surface. Generally an inert (Ar, often) gas is used but there is also the possibility to use a reactive gas that, via exothermal reactions with the melt, increases the efficiency of heating the material. The term laser scribing is essentially used when referring to laser cutting of a very thin material or grooving of a material surface followed by mechanically breaking the workpiece.

When considering the process of laser scribing it is necessary to be familiar some of the parameters that are involved. The principle parameters are laser power, laser spot size and mode, speed of the workpiece and material thickness. The most important of these is the spot size as a smaller spot will increase the power density and decrease the cut width. The mode of the beam also influences the quality of the cut; the most efficient and smallest spot sizes are achieved with so-called low-order modes, or near-gaussian beam profiles. The true TEM<sub>00</sub> mode, which is observed when using an Nd:YAG laser, is a Gaussian beam and gives a single spot. Examples of higher order modes are given in Fig 6. The laser mode is dependent of the laser cavity and the core material.

Increasing the laser power will generally allow higher process speeds and/or greater cut depths. Potential disadvantages are increasing the cut width, burning the edges and deteriorating the edge finish. The material thickness will, following the conditions of the laser output, regulate the optimum speed of the workpiece.
Laser – material interaction[16]

Although a very complicated matter, some effort should be spent considering the theoretical aspects of laser material removal.

When a material is exposed to electromagnetic radiation of any kind the interactions are usually of a photothermal nature, where the photon energy is converted to thermal energy in the material\(^3\), and vice versa. Whenever the radiation passes the interface between two materials a certain portion of the energy will be reflected and the remaining energy will be absorbed by the material or transmitted through it. This is summarized in the absorption relation:

\[
A = 1 - R - T
\]

Where \(A\) represents the part of impinging energy that is absorbed and \(R\) and \(T\) respectively represent the reflected portion and the transmitted portion. As the radiation progresses through the material it follows the Lambert law of absorption.

\[
I(z) = I_A \cdot e^{(-\alpha z)} = I_0 \cdot (1 - R - T) \cdot e^{(-\alpha z)}
\]

Where \(I\) is the intensity of the radiation, \(z\) is the depth of penetration from the surface, \(I_0\) the intensity at \(z=0\) and \(\alpha\) is the Lambert absorption coefficient or damping coefficient. It should be noted that metal materials are generally considered to be opaque, to have 0 transmission, when the radiation is in or near the visible portion of the spectrum, which is due to their high absorption.

In metals the radiation is predominantly absorbed by the free electrons, the electron cloud, which are free to oscillate and reradiate without disturbing the solid atomic structure, which is the reason for the high reflectivity (and low transmission) of metals. Some of the energy however will be restricted by the material lattice phonons and will be transferred from the electrons in the form of thermal energy. The vibrations of the atoms, i.e. the heat, will then be transferred to the rest of the structure through normal diffusion processes, following Fourier’s laws on heat conduction.

\[
\frac{q_A}{A} = -k \frac{dT}{dx}
\]

As more energy is absorbed by the lattice, the vibrations become so intense that they stretch the inter-atomic bonds to the point where the mechanical strength no longer supports itself structurally. The material is said to have reached the point, or temperature, of melting. Further absorption will raise the temperature to the point where all intermolecular bonds are broken and the material evaporates. These transitions are generally represented as the stages of laser cutting processes.

Modelling of laser cutting

Accurate modelling of laser cutting requires considerations of radiation-material interactions, heat conduction in a heterogeneous medium and fluid mechanics. One needs also to consider the thermal dependence of many material properties such as the reflectivity, heat capacities, etc. Since the three-

\(^3\) As opposed to photochemical laser cutting, where the photon energy corresponds directly to the bonding energy of the material and cutting occurs practically without heating effects. This however is exclusive to polymers.
dimensional heat conduction equations require numerical solutions, an extensive FEM study would be interesting to perform. However, during the course of this investigation the calculations will be kept on an estimative level. See further 3.3.4.

The Laser system

The laser system employed is a Permanova® laser scribing system (SLA 411-01), whose core is a Krypton cw-lamp-pumped\(^4\) Nd:YAG laser cavity (1) (Carl Baasel BSL 62). The output laser wavelength is 1064 nm infrared but the laser is fitted with a frequency doubling unit (5) and the green 532 nm laser is used for Mo scribing. Other components are the pulse frequency regulating \(Q\)-switch (3) with a range of 1-50kHz. The beam passes through a set of reflecting optics (7) and is finally focused onto the horizontal XY-table by a lens (8). The laser is also fitted with safety shutters (4) and a rear and front mirror (2 and 6). The front mirror (6) transmits a portion of the laser energy.

![Fig 7 - The laser setup showing the various components of the laser system and the path of the laser beam.](image)

An external power supply controls the laser system by controlling the \textit{lamp current} (in the laser cavity, 1) and \textit{pulse frequency} of the \(Q\)-switch (3). The XY-table (speed and direction) and the safety shutters are controlled by a BOSCH control unit. In the laser hood the focus distance \(d\) can be varied.

2.1.3 Mo sputtering

The Mo back contact film is deposited onto soda-lime glass substrates using DC sputtering. Standard (baseline) sputtering was performed with a [MRC 603 III] system. The Mo film was deposited in a single run at 8cm/min substrate speed yielding a film thickness of around 0.4-0.5µm. Baseline sputter/Ar pressure was set to 6mTorr and the sputter power 1500W and this type of Mo is referred to as “baseline” Mo.

\(^4\) cw stands for \textit{continuous wave}, and refers to the lamp being continuously lit as opposed to pulsed lamps
In the sputter, the substrates are located on a vertical plate. The 10x10 substrates are sputtered 2x3 and the 12.5x12.5 substrates are sputtered 2x2, as shown in Fig 8.

2.2 Investigations

Several sets of experiments have been performed in order to characterize and understand the laser system the goal of which was to determine the magnitude of the energy density exerted on the back-contact under different scribing conditions and to relate this to the qualitative evaluation of the laser scribes.

2.2.1 Laser energy measurements

Using an OPHIR NOVA display fitted with an OPHIR pyroelectric head (PE10), the energy per pulse was measured as a function of the laser Lamp current and the frequency of the Q-switch. These measurements were performed exposing the head to a sequence of 5000 consecutive pulses and averaging the energy to determine the mean pulse energy. Measurements were repeated three times to each plot point. Laser energy was also evaluated for single pulse operation. Pulses were triggered manually and measured individually. For each Lamp current value 36 measurements were taken.

Glass absorption

Since scribing has been found preferential through the glass substrate, energy measurements were performed to estimate the magnitude of energy absorbed by the passage through the glass. From these measurements the glass absorption was then estimated as a constant percentage of the incident radiation.

2.2.2 Laser spot size

In order to determine the laser beam spot size, several methods were attempted. Substrates with Mo were statically exposed to sequences of ~100 pulses in order to define “standard” holes on Mo. The same procedure was repeated on laser paper and on white (cleanroom) paper, since burning a hole in paper would avoid the issue of heat conduction. For spot radius determination the half scribe width was also considered, suggested as a measure of effective spot radius by Avagliano et al.[10].
2.2.3 Laser energy density

Combining the above experiments, 2.3.3 and 2.3.4, would permit calculations of the average pulse energy density.

2.2.4 Sputter process variations

In order to get a good idea of the situation and the challenges when scribing the Mo back contact one of the first questions posed was “What is the stability and continuity of the material that is to be processed?” Some initial scribing experiments suggested that laser parameters suitable for one sample were not necessarily suitable for another. To answer this question a series of samples were sputtered according to baseline and evaluated for Mo-thickness and sheet resistivity. Evaluations were made 1) across the entire sputter plate (6 substrates denoted A-F in Fig 8) and 2) of substrate F from 4 separate baseline runs.

2.2.5 Varying sputter pressure

Two runs were then made with elevated\textsuperscript{5} sputter pressures. Varying the sputter pressure will affect the density, microstructure [vsd91, DKV97, [13][12]] and resistivity [ggh98] [14] of the film, properties that in turn will influence the performance of the Mo film as back contact and during the scribing step. These Mo films were evaluated for film thickness, resistivity, ablation threshold, scribe width and scribe quality.

2.2.6 Ablation threshold

In order to measure something that relates to the scribing properties of the film, ablation threshold tests were performed. Single laser pulses were shot onto the surface of Mo films at different laser energy densities. The films were then examined for visible surface damage (optical microscope, 10x magnification). Since variations in pulse energy were inevitable, the following procedure was followed: 5 exposures were made for each level of laser energy (6 different lamp currents were used). An energy density range, defined as mean energy density $\pm$ standard deviation, was set up for each laser energy level, from the results of 2.2.3-2.2.5. This energy range was divided into 5 steps to correspond to the number of spots. The number of visible spots was then counted, each spot stepwise lowering the threshold energy density for surface ablation within each laser energy. If there was a discrepancy between two energy levels, the mean value of energy density was chosen as threshold value.

For example, the diagram below (Fig 9) the film shows surface damage at 4 steps of 17A exposure two steps of 16.1A\textsuperscript{6}, which is a lower value than that of the lowest level at 17A. Hence, the threshold energy density was determined as the mean between the two indicated values.

\textsuperscript{5} The 6 mTorr pressure is tangent to the lowest working pressure of the sputter system, so lower pressures were not possible to evaluate.

\textsuperscript{6} 16.1 A was chosen as operating level due to some stability issues when trying to maintain 16A. Same argument for 13.1A.
2.2.7 Scribe-quality

Since the definition of a “good” scribing result is vague and somewhat unscientific in its nature, the scribing properties of the sputtered molybdenum back contact have initially been evaluated in an empirical manner. That is, various scribing parameters have been isolated and investigated, and the results have been evaluated for their apparent suitability. This has been made primarily through optical inspections and in some cases verified through stylus profilometer traces and measurements of inter-cell resistivity.

These experiments were performed scribing 20mm long grooves in the Mo film, successively investigating different scribing parameters. The Y-direction of the XY-table was consistently the same as the vertical direction of the sputter system since the variations in Mo properties are expected to vary predominantly in this direction. The different parameters that were varied during this part of the investigation are presented in Table 1.

Scribing quality variations with Laser parameters

In order to verify previous in-house experiences and general results from other investigators, some initial scribing experiments were performed. Comparison was made between film-side and glass-side scribing.

The lamp current, effectively the laser energy, was varied within a range of 12-17A (total range of the system). Variations were also made with laser pulse frequency, workpiece speed and focussing conditions. An additional lens was added to the focussing optics of the system and the scribing performance was evaluated. The intention was to reduce the spot size by focussing the beam more tightly.
Table 1 – Laser scribing parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp Current (in effect, laser energy)</td>
<td>12A – 17A</td>
</tr>
<tr>
<td>Laser frequency</td>
<td>1kHz – 10 kHz (50kHz)</td>
</tr>
<tr>
<td>XY-Table speed</td>
<td>100mm/min – 4000 mm/min</td>
</tr>
<tr>
<td>Focussing distance, d</td>
<td>95mm – 124mm (f₁=120mm)</td>
</tr>
<tr>
<td></td>
<td>70-85mm (using doublet, f₂=73.84mm)</td>
</tr>
</tbody>
</table>

_Scribing quality variations with Mo prop_

Scribing evaluations were also performed with the different Mo films introduced in 2.2.5. The different films were inspected optically for variations in scribe quality and the scribe widths were also measured.

### 2.2.8 Module Scribing

Entire modules have also been fabricated. Scribing was performed using parameters that were indicated to provide good scribe quality\(^7\). The modules have followed all the steps mentioned previously (Brief overview of the module process, 2.1.1). The modules have then been characterised for performance, determining the cell efficiency and fill factor parameters.

Characterisation of solar cells and modules [1] is made by special setup that measures output current and voltage while exposing the sample to light of a known incident power, \(P_{in}\). The results are received as a current-voltage-curve (IV-curve, see Fig 10) from which one generally will consider such values as short-circuit current (\(I_{sc}\)), open-circuit voltage (\(V_{oc}\)), and the maximum power output current and voltage (\(I_{mp}\), \(V_{mp}\)). From these values, cell/module fill factor and efficiency can be calculated, the fill factor being an indication of how _optimal_ the cell/module is.

\[
FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}}
\]

\[
\eta = \frac{V_{mp} \times I_{mp}}{P_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}
\]

![Fig 10 - A typical IV - curve describing the different parameters used to define the efficiency of a solar cell or module.](image)

---

\(^7\) These parameters are currently used as baseline parameters for module manufacturing
2.3 Experimental methods

The sputtered molybdenum was characterized and investigated by several methods both destructive and non-destructive, the object being to both investigate the intrinsic variations in the sputtering system, the influence of varied sputter parameters on the Mo properties and to help understand the influence of the molybdenum properties on the laser scribing process.

The specimens are referred to by the sequence number of the glass substrate onto which it has been sputtered (normally a 4 digit number, ex. Mo1838). There are two different types of glass substrates: 2mm thick 12.5x12.5 cm that have been used mainly for qualitative scribe evaluation and module scribing, and 1mm thick 10x10 cm substrates that have been used for the quantitative evaluations. The 10x10cm substrates were divided into 20 1cm² (Fig 11) sectors over the surface of the film, in order to obtain a test population that was processable and yet offered a good density of points. The slightly higher density of points in the vertical direction is due to the indication from previous experience (in house) that properties will vary more significantly in this direction. Resistivity (2.3.2) and XRF (2.3.3) measurements were taken across entire samples (20 sectors) whereas stylus profilometry references (2.3.4) were taken in the B column (5 sectors) and threshold energy density measurements were made on sectors B2, B4 and C2 (see Fig 11).

![Fig 11 - Sectors where the molybdenum film was investigated](image)

2.3.1 Optical microscopy

For many of the investigations related to the laser and laser scribing, the primary instrument employed was a simple optical microscope for rapid evaluation and another, more powerful microscope [Olympus® AX70 Provis], fitted with a camera [Sony® DKC 5000] and imaging software [Image Acces – Analys, Bildanalyssystem AB, Sweden] for imaging and measurements on the micrometer scale.

2.3.2 Sheet Resistivity

Measuring the sheet resistivity is a non-destructive method to determine the electrical properties of a thin film material. The results from the sheet resistivity measurements are given in ohms per arbitrary surface unit. Hence, these results can be related to the thickness of the material to determine its actual resistivity. Sheet resistivity measurements also give a first approximate measure of the variation of the film thickness without damaging the material. Measurements were made using a conventional 4-point probe setup.
2.3.3 XRF

The second non-destructive\(^8\) method employed to investigate the thickness of the sputtered Mo was by X-ray Fluorescence. During XRF analysis the sample is irradiated by high-energy photons. The photons bombarding the material will excite or eject electrons from the inner orbitals of the atoms. Subsequently an electron from a higher-energy orbital will spontaneously transfer to the vacant electron position. During this transition energy will be released in the form of a photon, by the electron. These fluorescent photons will then be collected to provide an XRF spectrum relating the wavelength and intensity of collected photons.

Analysing this spectrum will provide information about the sample. Firstly, since the transitional energy between orbitals is always the same in a specific element, the energy of the emitted photons will be a fingerprint of the elements present in the sample. Secondly, the intensity, the number of photons observed, will be relative to the volume of fluorescent material. By calibrating with a sample of the same material and density, having known thickness, the XRF results can be used to estimate the thickness of a deposited film. The Mo peak that was evaluated was situated between 17.15 – 17.71 keV.

2.3.4 Profilometry

Finally steps were etched in the Mo films in a HCl/HNO3/Aqua mix (1:3:8), using a Kapton® tape to define the step. The height of these steps, the film thickness, was then measured in a stylus profilometer (Dektak V-series, 200-Si) at the centre of the 1cm\(^2\) sectors that was defined as the measurement area. In order to ascertain an average, three measurements were made on each sample. Profilometer traces were also used in this investigation for qualitative evaluation of the scribe lines. Due to unfortunate events the profilometer was out of commission during the later part of this investigation, which hindered the acquisition of graphical data from the profilometer traces.

2.3.5 Interferometry

The profilometer being out of order also promoted the use of an interferometer for some of the thickness measurements. The interferometer relies on reflected diffraction patterns from samples to determine surface appearance.

2.3.6 SEM

A very brief session with SEM evaluation of some scribes was also amended to the investigation. Scanning Electron Microscopy uses a primary beam of accelerated electrons to eject secondary electrons from the sample. The escape depth, i.e. how many electrons that are being ejected will depend mostly on topographical, but also on material, properties of the sample. This information can be used to create an image of the sample.

\(^8\) However non-destructive in theory, specimens were necessary to cut down to size in order to perform the XRF measurements.
3 RESULTS

3.1 The Laser characteristics

3.1.1 Laser energy

Measurements of the laser energy show how the output laser pulse energy increases with the input lamp current, as would be expected. It is also evident how the Q-switched frequency affects the output energy. Higher frequencies give lower energies per pulse. This is probably due to the shorter intervals between pulses and thus shorter time for energy accumulation in the laser cavity. What is also noted in the measurements of laser energy is the low pulse energy of the single pulse exposures. Probably this is due to there not being any significant accumulation of energy in the laser cavity between pulses.

![Average Pulse Energy as a function of Lamp Current](image)

Fig 12 - laser pulse energy variation with lamp current and pulse frequency.

3.1.2 Spot size

The spot sizes were evaluated on molybdenum film by measuring the radius of the removed spot. Spot size was also measured as the radius of exposed area on on laser paper, as burned hole through white cleanroom paper and evaluated as half scribe width on Mo. The diagram below shows how the laser paper and half scribe width radii of the spot vary with the focusing distance d (as defined previously). Results from white paper were omitted because of the difficulty of measurements and the poor definition of the spots. Mo spot results were omitted because of the influence of blow-off, where the sizes of the spots were irregular. The focus of the beam seems to lie around d=120mm for the standard 1-lens scribing, which is to be expected since the lens focal distance is 120mm. In a simplifying way one can make the distinction that the size of the molybdenum ablation spots represents an “effective spot radius”, within which the energy density is sufficient for material removal, whereas the laser paper
spot radii represent the maximum spot size including the lower intensity fringes. The focused effective spot radius is measured to R=33.9µm.

![Spot Radius](image1.png)

*Fig 13 - Variation of laser spot radius w focusing distance.*

When evaluating the spot radius for the doublet lens setup it is observed how the radii are smaller in focus but has a smaller depth of focus. Theoretical focal distance of the doublet setup was calculated to 74.13mm (dashed line in Fig 14) but the experimental results suggest a centre of focus around 77-78mm, and furthermore the smallest effective spot radius is found @ 76.5mm. These discrepancies may, in part, be due to some mistake in the estimation of the inter-lens distance. The difference in focusing distance between smallest spot radius and smallest effective spot radius may be explained by some diffractive phenomenon, but this is speculative. Since scribe quality was a principal factor in the investigation, and since good scribe quality with doublet generally had been found @ d=77.5mm, this effective spot radius was used for energy density calculations. It was measured to R=25.6µm.

![Spot Radius w doublet](image2.png)

*Fig 14 - Variation of spot radius with focusing distance using a doublet lens setup. The dashed line shows the calculated focal distance. (see 3.3.4)*
3.1.3 Energy density

Following the results from laser energy and spot size measurements, we are able to determine the energy density of the focused laser beam during scribing. When determining the energy density it was deemed more valid to use the radius of the half scribe measurements, in a way the “effective spot size”, since it was assumed that the largest part of the laser energy was within this spot (note that the theoretical standard for spot size defines it as the area within which $1/e^2$ of the laser energy is found [3]). The results are presented as the energy density as a function of the focusing distance $d$ [@17A, 1000Hz] and the lamp current, $LC [@d=90mm, 1000Hz]$ for standard 1-lens setup.

The laser energy density was evaluated also for the case of doublet operation. As expected, with a smaller focused spot size, the energy density is higher than for single lens operation.

Figur 15 - Energy density variations with focusing distance, and as a function of Lamp Current and Pulse Frequency.

Figur 16 - Energy density as a function of Lamp Current for doublet operation. Frequency =1000Hz, $d=77.5mm$. 

3.2 The Molybdenum Layer

3.2.1 Relation between XRF and Profilometer results

In order to utilise the measurements by XRF it was necessary to establish a relation between the thickness of the metal film and the number of counts in the XRF spectra. One primary assumption is made to motivate the use of this technique and this is that the relation between XRF counts and film thickness is linear.

\[
\text{Thickness} = k \times (\text{XRF counts})
\]

\[
k = \frac{\text{Thickness}}{\text{XRF counts}}
\]

Furthermore, for there to be any gain in using the XRF technique to estimate the film thickness, it must be assumed that the relation is constant within the same sputter run. In other words it is assumed that the density of the film is a function of the sputter conditions.

Measurements were made in sectors B1-B5 with both XRF and profilometry on substrate A of Mo1805. The relation between XRF counts and profilometer thickness was then approximated according to

\[
k = \frac{\text{Thickness}}{(\text{XRF counts})}
\]

This relation was then used to estimate the thickness across the sputter plate, making measurements with XRF.

3.2.2 Intrinsic process variations

First we look at the results of measuring the thickness across the sputter plate. We can see that the influence of the racetrack is evident in the thickness distribution and that we find thicker molybdenum around the edges of the plate. The variation across the sputter plate is 482 ±52 nm with a mean thickness of 466 nm with a standard dev. of 18.4 nm (4%) (see Fig 17). However, when we look at the sheet resistivity, the variations are even larger with a mean of 353 Ω/sq and standard dev. of 39.1 Ω/sq (11%). This suggests that the measure of sheet resistivity does not relate linearly or directly to the thickness and that other factors may affect the sheet resistivity.

The observed variation of thickness across the plate is not negligible nor catastrophic. Care should be taken to investigate scribe quality on opposite sides of substrates in the vertical direction. The indication that variations are greatest in the vertical direction appears to be verified.
Fig 17 - Thickness variation across the sputter plate.

Fig 18 - Sheet resistivity variation across the sputter plate.
In the following diagram we consider the variations between several baseline sputtering runs. The process conditions such as sputter pressure, sputter time and effect are unchanged between the substrates. Arbitrarily, the bottom right substrate (designated as substrate F, Fig 8) was chosen for thickness and resistivity measurements between runs. Again one can note that the variations in thickness [468±9.54nm (2%)] are not as large as the variations in sheet resistivity[354±52.5mΩ/sq (15%)] but that they tend to correlate in that the thicker samples have a lower sheet resistivity. Measurements of Mo1829 were made with interferometry, after the failure of the profilometer and should be treated with some caution.

The variations found between baseline runs appear to be small which must be considered as a positive result. Note that the variations are considerably greater over the sputter plate than between runs.

![Baseline variations](image)

Fig 19 - Variations of thickness and sheet resistivity during baseline operation.

### 3.2.3 Variations with Sputter pressure

Variations of film properties with sputter pressure can be seen in Fig 20. It is observed that the film thickness decreases with increased sputter pressure and the sheet resistivity increases. It should be noted that these thickness measurements were made using the interferometer and should not be compared with earlier results found with profilometry.

One could make the speculation that the higher-pressure samples will present better scribes if the film thickness is the most important variable for scribing results. More on this in “Using different Mo’, 3.3.2.
3.3 Scribing Results

3.3.1 Varying laser parameters

*Back side vs. film side scribing [see Fig 28, page 33]*

Results from back side and front side scribing were compared. Optical investigation immediately verified the advantage of glass side scribing, since the film-side scribing presented significant process residue in and around the scribe. This phenomenon was not detectable when comparing with scribing through the glass.

*High energies preferential*

From in-house experiences, results suggest that better scribes are achieved at high lamp currents i.e. high energy densities. These results were also verified as a general trend (Fig 29, p33). However, at certain scribe parameters, namely low lamp current together with low speeds of the workpiece and defocusing of the optics, the scribes were superior to the high-energy scribes in two immediate respects: 1) The scribe profile had sharply defined edges without significant formation of walls, and 2) the glass remained undamaged, glass damage invariably appearing at higher energy densities. However, the great results were extremely rare and seemed to occur within a process window of miniscule proportions. During the extensive experimentation only a handful of 20mm scribes were achieved with good results.

Nonetheless, the excellent quality of theses scribes invite to speculation as to whether some alterations could be made to the system in order to achieve such scribes for a wider process window. Notable observations for these scribe
results were the appearance of long filaments of Mo at the end of the scribes showing how the scribe was made as if by a chisel, as a solid thread of metal. Scribe results near the great were often terrible, with big shards and cracks (see Fig 30 to Fig 32, p34).

The high energy scribe results that are referred to as good on the other hand are not square. Viewed from the top they have a typical pulse-to-pulse appearance of slightly overlapping circular holes. If the workpiece speed is too high the pulses will lose their overlap and bridges will occur. If the workpiece slows down the “lips” that protrude into the scribe tend to flake up more readily. A flaking lip was observed by SEM (Fig 21). The magnitude of this is 2-3 times the layer thickness, i.e. 1-1.5µm, and could be enough to shunt the cell by connecting the Mo back contact to the TCO layer.

Fig 21 - SEM picture displaying the scribe edge. One of the “lips” has been flaked up. This kind of defect risks to protrude through the CIGS absorber and shunt the cell.

A summary of the results observed can be seen in Table 2
Table 2 – An overview of the general trends observed when scribing the Mo back contact.

<table>
<thead>
<tr>
<th>Lamp Current (in effect laser energy)</th>
<th>Scribe quality assessment</th>
<th>Table Speed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;500</td>
<td>1000</td>
</tr>
<tr>
<td>17A</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>16A</td>
<td>Bad</td>
<td>Bad</td>
</tr>
<tr>
<td>15A</td>
<td>Good/great</td>
<td>Bad</td>
</tr>
<tr>
<td>14A</td>
<td>Good/great</td>
<td>Bad</td>
</tr>
<tr>
<td>13A</td>
<td>Good/great</td>
<td>Bad</td>
</tr>
<tr>
<td>12A</td>
<td>-/Good</td>
<td>-/Bad</td>
</tr>
</tbody>
</table>

**Double focusing optics**

Scribing with the added lens proved to give very positive results such as good scribe quality, equal to that of high energy scribing previously detailed, and with reduced scribe width. Good scribes were achieved with scribe widths of ~50µm. Because of the smaller spot size, the optimal scribing conditions required an elevated laser frequency (good results were achieved with 17A LC and 1500Hz pulse frequency) or slightly lower workpiece velocity.

### 3.3.2 Using different Mo

**Scribe quality**

The variations observed when evaluating the scribe quality for different Mo samples suggested that low-energy scribing would be more sensitive to variations in the Mo. As can be observed in Fig 22 the results are very similar when scribing at high energy, whereas the low energy scribes seem to deteriorate with higher pressure Mo (Fig 23).

![Fig 22 - Comparison between high-energy scribes on Mo sputtered under different pressures. From left to right the sputter pressures are: 6mTorr (baseline) - 10mTorr - 14mTorr. Scribing conditions are: 17A, 1000Hz, d=120mm, v=3000mm/min.](image-url)
Threshold energies

The evaluation of surface ablation threshold energies provided inconclusive results. The variations within the investigated baseline samples were considerable (0.30 ± 0.03 J/cm²) and the high sputter pressure samples did not distinguish significantly from this.

![Threshold energy density for surface ablation](image)

**Fig 24** - Threshold energy density for surface ablation

### 3.3.3 Module Results

The diagram below shows the efficiency results (introduced in 2.2.8) of 4 modules manufactured during the course of this project. Two were part of an experimental module series and therefore consist of 8 cells on a surface of 4x5 cm² and the following two are true baseline modules on 12.5x12.5 cm² glass substrates.
In Fig 26 the different IV-curves of the modules are compared with a reference module (1593) fabricated in spring, the smaller module (1946-1947) results having been scaled up proportionally to allow the comparison. The main features to notice is the steeper "drop" of the curve for the reference module compared to the recently fabricated modules. This suggests an increase in series resistance across the module, something that can be caused by an elevated resistivity of the front contact TCO layer, and in the soldering of the module contacts. Elevated current values of Mo1946 and 1947 may be due to underestimated surface areas (these modules were not of standard size and appearance). The low $V_{oc}$ of the Mo1947 suggests that one of the cells was short-circuited and therefore did not contribute to the voltage of the module. The relatively parallel curves at lower voltages indicate that no shunting of the cells occurred.
3.3.4 Calculations

When adding the extra lens, to make a so-called doublet, a new focal distance needed to be calculated. The original lens has a focusing distance of 120 mm and the added lens 160 mm. According to basic optical relations, the new focal distance \( f_{12} \) can be calculated from the separate lens focal distances, \( f_1 \) and \( f_2 \), and the inter-lens distance \( d_{\text{doublet}} \).

\[
f_{12} = \frac{f_1 \cdot f_2}{f_1 + f_2 - d_{\text{doublet}}} = \frac{120 \cdot 160}{120 + 160 - 21} \text{mm} = 74.13\ldots \text{mm}
\]

**Geometrical visualisation**

Some calculations were made in order to establish the geometrical situation during the laser pulse. Given that the laser spot has a radius \( R \) and is repeated with a frequency \( f \) onto a sample that is moving with the speed \( v \) one can express the surface area \( A^* \) of each consecutive pulse as the spot size minus the overlap of pulses (see Fig 27). This area can be considered as the area of film removed per pulse.

\[
A^* = \pi R^2 - 2 \left( R^2 \arccos \left( \frac{\Delta Y}{2R} \right) - \frac{\Delta Y}{2} \sqrt{R^2 - \left( \frac{\Delta Y}{2} \right)^2} \right)
\]

Where \( \Delta Y \) is the distance between consecutive pulse centres.

\[
\Delta Y = v \cdot \frac{1}{f}
\]

The distance travelled during the pulse, \( \partial y \), can be expressed with the pulse duration \( \partial t_p \).

\[
\partial y = v \cdot \partial t_p
\]

This distance will be neglected in any calculations as \( 1/f \ll \partial t_p \), and the problem will be simplified to a static situation.

![Fig 27 - Geometrical representation of exposed area](image)

**Energy Considerations**

The energy input to the film can be calculated from the energy measurements (2.2.1) as the total pulse energy \( PE_{\text{TOT}} \) minus the energy absorbed in the glass and reflected by the glass or Mo surfaces. Combined absorption and reflection of the glass can be taken from experimental measurements whereas reflectivity of Mo can be found as tabulated data (see Appendix III). Correction must also be made for the overlap surface. The Mo film can only absorb energy over the...
area $A^*$. This will give us a measure of the energy that is available for material removal, $PE_{film}^*$:

$$PE_{film}^* = PE_{TOT}^* (1 - A_{glass})^* (1 - R_{Mo})$$

$$PE_{film}^* = PE_{film}^* \frac{A^*}{A_{spot}} = PE_{TOT}^* \frac{A^*}{A_{spot}} (1 - A_{glass})^* (1 - R_{Mo})$$

We then proceed by estimating the quantities of energy necessary for removing all material by vaporisation, and set up an expression for the maximum film thickness evaporated by the deposited energy. Heat conduction effects are summarily ignored.

$$V_{mat} = A^* \Delta Z_{film}$$

$$E_{vap} = V_{mat} \mu \rho_{Mo} \left\{ C_p \left( T_v - T_0 \right) + \Delta H_{melt}^{Mo} + \Delta H_{vap}^{Mo} \right\}$$

$$\Delta Z_{film}^{max} = \frac{PE_{film}^*}{\rho_{Mo} \mu \frac{A^*}{A_{spot}} \left\{ C_p \left( T_v - T_0 \right) + \Delta H_{melt}^{Mo} + \Delta H_{vap}^{Mo} \right\}}$$

Similar calculations are suggested by Steen [3], making the assumption that the penetration velocity into the material is larger than the heat conduction and that the material is removed solely by vaporisation.

These calculations will serve as basis for discussion of the laser material removal mechanism, using the experimental values for deposited laser energy $PE_{TOT}$.

**Results**

Now, using the results that have been found experimentally and the equations introduced above, we can calculate some values for comparison between high energy scribing and low energy scribing. Scribing was performed at 1000Hz in both cases.

Table 3 - Summary of calculated values comparing High energy and Low energy Scribing

<table>
<thead>
<tr>
<th></th>
<th>High Energy Scribing</th>
<th>Low Energy Scribing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Energy:</td>
<td>70µJ</td>
<td>35µJ</td>
</tr>
<tr>
<td>Table Speed:</td>
<td>3000 mm/min</td>
<td>500 mm/min</td>
</tr>
<tr>
<td>Focus distance:</td>
<td>120mm</td>
<td>118.5mm</td>
</tr>
<tr>
<td><strong>Calculated</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A^*$ [$10^{-10}$ m$^2$]</td>
<td>34.4</td>
<td>5.8</td>
</tr>
<tr>
<td>(% of effective spot size):</td>
<td>(78.17%)</td>
<td>(15.12%)</td>
</tr>
<tr>
<td>$PE_{film}^*$:</td>
<td>18µJ</td>
<td>1.8µJ</td>
</tr>
<tr>
<td>$E_{vap}^*$:</td>
<td>120µJ</td>
<td>20µJ</td>
</tr>
<tr>
<td>Maximum evaporated thickness, $\Delta Z$:</td>
<td>68nm</td>
<td>39nm</td>
</tr>
</tbody>
</table>
To summarize the information in Table 3, the high-energy scribing advances the scribe significantly more per pulse than the low-energy scribing. The most interesting result however is how neither of the two scribing conditions allows enough energy to be absorbed for the entire film thickness to be removed by vaporisation. For low-energy scribing this had already been indicated in the experimental results from the large chiselled debris encountered, but for high-energy scribing vaporisation had been assumed to be the process of material removal. This will be discussed in chapter 4.
4 DISCUSSION

Some results from this investigation merit further comments. Firstly, the mechanism of material removal that occurs should be considered. In spite of the previous investigations of thin film scribing for photovoltaic applications no investigator has ventured an explanation of the material removal in detail, but rather concentrated on experimental results and empirical process improvement. Even though this investigation also had primarily process improvement as a goal, it cannot be left aside to consider the underlying mechanisms.

According to the results of energy measurements and calculations the removal of all material by evaporation is not possible. The energy deposited on the film is sufficient for vaporization of 68nm of material (for the case of high-energy scribing), which is less than 1/5 of the entire film thickness. How is the rest of the film removed? Without further calculations this investigator would like to hypothesise that, as the laser impinges on the film surface in the interface between glass and Mo, nearly all of the energy is absorbed within a thin layer of the film. This is also supported by the notion that heat conduction during such short pulses ($10^{-7}$ sec) is very small. As this thin layer reaches its vaporization temperature, the pressure caused by the expansion of this layer will cause the rest of the film to be removed by explosive forces. This may also explain the damage observed on the glass.

When considering the results obtained under lower laser energy and/or lower laser energy density this certainly seems to be the type of mechanism in play. For example, the photo in Fig 32 clearly shows how the solid film is detached from the glass and cracks are progressing in the scribe direction. The differences to consider between what has been referred to as high-energy and low-energy scribing are workpiece speed, laser energy density and focusing conditions. High-energy scribes have shown good results at high speeds (~3000mm/min), focused or slightly defocused ($d=120\pm1.5$ mm) and laser pulse energies of ~70µJ. Low-energy scribes on the other hand have shown good (occasionally great) results with low speeds (500-1000mm/min), defocused ($d\sim122.5/\sim118.5$ mm) and with pulse energies of ~35µJ.

What do these differences mean? A more tightly focused beam will have a near-gaussian energy distribution with much higher energy densities at the centre of the beam than at the fringes. More defocused, the energy will be more evenly distributed across the spot surface. The difference in speed makes for two quite different situations, where at higher speeds almost the entire spot surface is used effectively for material removal and the overlap is small (<12%). At lower speeds the overlap is substantial (~85% of the spot area) suggesting either a large waste of energy or that material is removed during several pulses.

Considering the mechanism put forward above, the difference in results between low pressure sputtered Mo and higher pressure sputtered Mo may find it’s explanation in the results of Scofield et al [11] showing better adhesive properties with films deposited at higher pressures. Films deposited at lower pressures, i.e. with weaker adhesion, would be easier to remove.
5 CONCLUSION

During the course of this project the process of laser scribing for thin-film photovoltaic module manufacturing has been considered. Laser parameters have been determined that provide reproducible, good scribes, that do not present bridges and/or excessive process debris. Scribing is performed at energy densities of around 2J/cm² with a pulse-to-pulse overlap of ~80% regulated by the relation between workpiece speed and laser pulse frequency. Solar modules have been processed and evaluated with positive results for such scribing parameters, yielding module efficiency over 12%.

It has been determined that, considering the laser scribing step, molybdenum deposited under low sputtering pressures yield slightly superior results, even though laser scribing as described above showed comparable results over the pressures investigated.

Adding an extra lens to the focusing optics proved to give very positive results, with narrower scribes and maintained scribe quality.

Superior scribing results, showing no glass damage or walls, were encountered when scribing at lower energies, smaller spot overlaps (~15%) and less tightly focused spots. This is believed to be due to a more even distribution of energy across the spot area. These results however were only rarely obtained and cannot be considered as reproducible. Therefore they have not been used for module processing.

The positive results from doublet operation along with the indication that an even distribution of laser intensity will yield great scribes suggest that maybe considering customized optics is a path to improving the laser scribing process further. Using a lens that would provide smaller spot size and a rectangular intensity distribution may be a way to obtain the great results only rarely obtained with the standard optics.

Further development of the laser scribing process can also be done laterally. Having determined a threshold value for surface damaging of the Mo film, one could envision the use of lower energy densities for scribing of the P2 scribe. The possibility of such a scribe has been shown by Compaan et al [5].
6 References


7 APPENDIX I – PHOTOS OF SCRIBE RESULTS

Fig 28 - Comparison between glass-side (left) and film side (right) scribing. One can observe the difference in process residue in and around the scribe when scribing the film directly.

Fig 29 - High energy scribes with ok appearance. Glass damage is observable as light grey areas. No large walls or shards are apparent. Scribe width is around 70µm. Scribing conditions: 17A, 1000Hz, d=90 and 91.5mm (left to right), 3000mm/min.
Fig 30 - Excellent scribe at low energy scribing. Scribe obtained @15A, 1000Hz, 500mm/min, d=91.5mm on module substrate (2mm glass). Noteworthy are the even edges, the undamaged glass and a good scribe width (~60µm).

Fig 31 - This photo shows how the, rarely achieved, excellent scribe results were very sensitive and could turn over into horrible results.
Fig 32 - Detail from Fig 31 showing how the centre of the scribe buckles up and cracks are formed along the edges of the scribe.

Fig 33 - Scribing condition neighbouring great scribes. The photo shows defects referred to as shards and cracks. A great scribe has no residual shards and the edges are well defined and square (as where the shard is broken off from the layer).
# Appendix II – Laser System Specifications

<table>
<thead>
<tr>
<th>Laser system specifications provided by manufacturer</th>
<th>Krypton 1.0…4.5kW</th>
<th>Arc</th>
<th>Lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamp: Resonator length:</td>
<td>960 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YAG rod dimensions:</td>
<td>Ø4*79 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength:</td>
<td>532 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CW power (max):</td>
<td>1W @ 5 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse frequency range:</td>
<td>1..50kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Divergence (Full Angle):</td>
<td>1.4 mrad (1/e²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Ø at output mirror:</td>
<td>0.5 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse frequency:</td>
<td>5 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Peak Power:</td>
<td>2 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Energy:</td>
<td>0.4 mJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Width:</td>
<td>100 ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse/pulse fluctuations:</td>
<td>6 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smallest spot:</td>
<td>20 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focal distance, lens 1:</td>
<td>120 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focal distance, lens 2:</td>
<td>160 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doublet focal distance:</td>
<td>74.13 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9 Appendix III – Reflectivity Spectrum of Molybdenum.

Fig 34 - Shows the reflectivity spectrum of Mo. The two dotted lines represent the laser wavelength available with Nd:YAG laser cavity: 1064nm and frequency doubled 532nm. One can note the difference in reflectivity explaining the choice of wavelength for scribing.