

# Tailor Cutting of Crystalline Solar Cells by Laser Micro Jet<sup>®</sup>

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## ABSTRACT

Coupling a laser into a hair thin water micro jet (Laser Micro Jet, LMJ) for cutting applications offers a wide range of processes that are quite unique. As the laser beam is guided by internal reflections inside of a liquid cylinder, the cuts are naturally straight and do not reflect any divergence as otherwise occurs with an unguided laser beam. Furthermore, having a liquid media at the point of contact ensures a fast removal of heat and eventual debris ensuring clean cuts, which are free of any burrs. Many applications have indeed been developed for a large variety of materials, which are as different as e.g. diamond, silicon, aluminum, ceramic and hard metals.

The photovoltaic industry has enjoyed in the last decades tremendous growth rates, which are still projected into the future. We focus here on the segment of Building Integrated PV (BIPV), which requests tailored solutions to actual buildings and not-one-fits-it-all standardized modules. Having the option to tailor cut solar cells opens a new field of BIPV applications.

For the first time, finished crystalline solar cells have been LMJ cut into predetermined shapes. First results show that the cut is clean and neat. Preliminary solar performance measurements are positive. This opens a new avenue of tailored made modules instead of having to rely on the one-fits-alloy approach used so far.

**Keywords:** Laser Micro Jet processing, solar cell cutting, shunts, JV measurements, BIPV, watch

## 1. INTRODUCTION

The photovoltaic industry has shown sustained growth rates over the last decades due to a necessity of environmentally friendly energy sources. One niche market, Building Integrated Photovoltaic (BIPV), has recently gained more attention, also in terms of Feed in Tariff: this solution, however, still requires R&D efforts. We focus here on a solution bridging the gap between standardized solar cells (156 x 156 cm<sup>2</sup>) and tailored cut solar cells.

Different approaches have been investigated hitherto to cut solar cells such as sawing, plasma etching, grinding and dry laser cutting to reduce the inherent losses of conversion efficiency current and finally current [1]. All techniques exhibit ohmic and/or diode like shunts to same extend [2].

In all techniques, only laser cutting allows full flexibility of the cut. Using a “dry” laser process often leads to a detrimental leakage current. It also results in re-deposition of the metallization, inter-diffusion between n and p doped silicon in the bulk or mainly in undesirable changes in crystallographic structures caused by the thermal budget of the process [3].

In this paper, we introduce an industrial solution by using the LMJ technique [4, 5]. Now, the process development presented in this paper permits to tailor cut solar cells (both poly & mono crystalline silicon) by LMJ without significant loss in performances.

### 1.1 Conventional solar cell cutting methods

Two main industrially employed approaches are mechanical break and material ablation. The first one uses a scribe followed by a manual cleavage; it is also feasible to cut through a solar cell with a diamond saw. Each approach offers excellent electrical properties to the final mini-solar cells [1]. Nevertheless, these solutions only permit straight line cut. Alternative solutions are required to provide higher speed, better cut consistency and a capability to process thinner wafers. Such a solution is based on the laser-matter interactions by using a dry laser. The p-n junction is opened by the doped silicon ablation or melt by a “dry” laser.

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## 1.2 Shunts caused by cutting of solar cell

In general, shunts reduce the overall solar cell's conversion efficiency. There are two types of shunts, showing either a linear (ohmic) I-V characteristic or a non-linear (diode-like) characteristic [2].

As far as linear shunts are concerned, the parallel resistance  $R_p$  is subject to vary with:

- The creation of aluminum or other metallic alloys with the Silicon matrix.
- The inter-diffusion of dopants or metallic impurities. It generates a preferentially ohmic contact to the p-base.
- The crystallization of highly n-conducting SiC,  $Si_xN_y$  or AlSi filaments or crystallites crossing the cell, or grain boundaries [3, 6, 7].
- The cracks induced by the cutting process.

## 1.3 The LMJ approach as compared to the “dry” laser

Conceptually, lasers have inherently the advantage of free-shape cutting combined with a relatively high cutting speed. In the patented LMJ process, the laser is confined in a hair thin water jet (Figure 1). The concept is to focus and to guide a laser beam into a nozzle [4]. The low-pressure water jet emitted from the diamond nozzle guides the laser beam by means of total internal reflection at the water/air interface, in a manner similar to conventional glass fibers. The water jet acts thus as a fluid optical wave-guide over the whole length of the water jet.

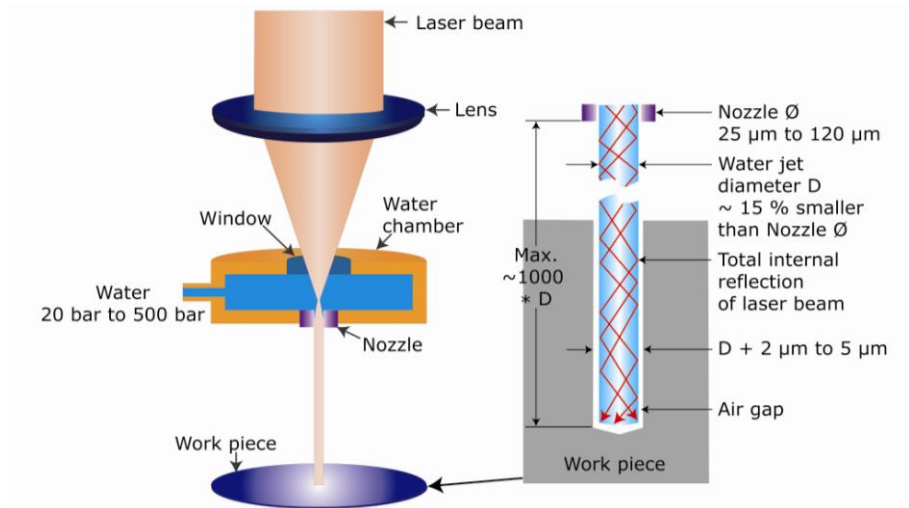


Figure 1. Schematic principle of the LMJ process.

The jet remains stable while penetrating into the material, which means that the beam size impacting the material is always constant. Only the laser is used for ablation; the main function of the water jet is to guide the laser beam onto the work piece. It ensures the consistency of the spot diameter and consequently enables a single, centimeters-long focus without significant fluency losses.

In a “dry” laser approach, the laser beam has a conical shape as given by the laser divergence. Here, the water jet has other beneficial effects that are interesting for the cutting of the silicon: maintaining clean kerfs, simultaneously cooling the edges and limiting the Heat Affected Zone (HAZ) between the laser pulses and thus expelling the molten material from the cut. Hence the water jet-guided laser can be called a “cold laser”.

Usually, the main instrumental parameters for “cold lasers” are the wavelength and pulse width. The pulse duration has to be fewer than 10 ns to limit the thermal effects on the material: this demand considerably increases the total cost of ownership. This photo ablation aspect specific to the “dry” laser, is a very slow process and cannot be applied for volume production. The other “dry” laser sources generate re-crystallized structures at the edge causing shunts [1].

## 2. EXPERIMENTAL

### 2.1 Methodology for characterization and patterning

In this paper, we have chosen the pseudo Fill Factor (pFF) to quantify the drop of conversion efficiency. It has been identified as the most appropriate measurement to quantify the generated linear shunts due to the laser-material interaction [2, 6, 7, 8 and 9]. Tailor cut solar cells are usually used under low illuminations (typically in watch applications).

Seventy 125 x 125 mm<sup>2</sup> industrial multi-crystalline solar cells have been cut through according to the designed shape (14 mm x 125 mm) as shown in Figure 2 on the LCS 300 machine model from Synova S.A. Before and after cut, cells were photo-electrically measured by a SINTON Suns-Voc device. Sizes of cuts were measured with a Zeiss optical microscope.

We have chosen to cut at constant speed straight lines in between the fingers to have both a good working base as well as a constant ablation rate. Edge isolation was added to obtain a highly representative laser cut and to avoid cell inherent shunts. The cutting parameters were adapted to be close to the 25 μm edge isolation depth [6]. We found that it has to be processed at 200 μm from the edge on the front side to get the better edge isolation configuration [10].

It has been shown that the quantity of shunts increases when the number of cross metallization increases while processing with a dry laser [7]. By consequence, it has been decided to cut only across the busbars to minimize the probability to create metal re-deposition.

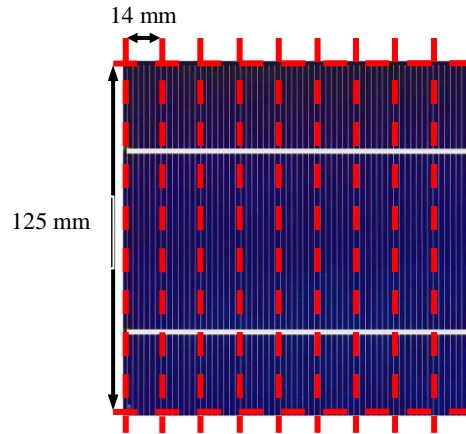


Figure 2. Schematic cutting pattern on mono crystalline solar cell.

### 2.2 Cutting sources and operating protocol

Once the cutting pattern determined, we had to select the laser source for the here presented development. The choice is theoretically based both on the material linear coefficient of absorption and on the pulse width. The higher the material absorption to the incident laser wavelength, the smaller is the induced HAZ. The cutting is then rather ablative than thermal, thus reducing the HAZ and metal re-deposition. The second influent parameter is the pulse width combined with the peak power. If the provided energy is higher than the chemical-bond one, the ablation is called photo-ablation. The pulse width has to be lower than the dissipation time to photo-ablate with a “dry” laser (FWHM < 10 ns).

The choice of working laser had to be done between 2 sources, listed in Table 1.

Table 1. Lasers overview.

Wavelength (nm)	1064 (IR)	532 (Green)
Pulse width (ns)	300 - 540	80 - 600

Theoretically, the bulk absorption in silicon is one thousand times higher at 532 nm (second harmonic Nd:YAG) than at 1064 nm (first harmonic Nd:YAG).

Several laser parameters have been tested with each laser source on a simple line combined with a multi-pass strategy.

These first results are in agreement with the theory. The green source produces less shunts ( $pFF = 0.746$ ) than the IR laser ( $pFF = 0.702$ ) probably due to relative absorption and heat generated effects. Results lead us to work with a Q-switched laser green source.

We found no significant shunt creations due to either industrial types of fixture or water induced oxidation.

A repeatability study has shown that the measurement uncertainty is less than 0.525%, thus producing a  $pFF$  uncertainty of  $\pm 0.0035$ . So, we conclude that the  $pFF$  measurements are highly repeatable. Therefore, a specific cleaning and handling procedure have been determined to optimize the breakage rate and the human induced repeatability. A 50  $\mu m$  diameter nozzle has been used to obtain a 42  $\mu m$  kerf cut width. A Helium gas has been used to assist the low pressure water jet (350 bars).

### 2.3 Optimization procedure

The investigation has been done through two guidelines: the laser parameters' improvements and the cutting pattern. Repetition rate, laser power in water jet, speed and pulse width were investigated to cut through solar cells with the pattern seen in Figure 2.

Two designs of experiments (DOE) were generated to study interactions between laser and machine (DOE 1) and the intrinsic laser configurations (DOE 2). We have determined, with the help of the MODDE 9.0 software, the most suitable methodology in order to qualify the principal and second interactions levels between variables.

The DOE 1 purpose is to study the main to the 4<sup>th</sup> level interactions between the frequency, the laser power and the cutting speed with one single output: the  $pFF$ .

The DOE 2 studies the main and 2<sup>nd</sup> level interactions between the repetition rate, the power and the pulse duration. The speed has been kept constant to 100 mm/s and the number of passes was adjusted to cut through.

Then, seven different cutting patterns were developed in order to minimize or avoid altogether any metal contamination (re-deposition at the solar cell's edge). Let us review these patterns as shown in Figure 3: a simple line strategy (Figure 3.a) used in the DOEs, has been completed with an extra overlapping pass (situated at 20  $\mu m$ ) on each cutting side to eliminate the metallic re-deposition (Figure 3.b). A stair strategy with a 25  $\mu m$  overlapped pass has been processed (Figure 3.c). Next, two other strategies have been developed to eliminate the metallization on the front side before cutting. The first method is to remove the Al/Ag paste in three parallel passes followed by a central cut through (Figure 3.d). The second one uses an extra-finishing pass on each side on the previous silver cleanup path (Figure 3.e). The purpose was to evaporate the residual metallic paste, which could remain after the cleanup phase.

The two last methods try to by-pass this problem with one or two edge isolations (Figure 3.f and Figure 3.g) located 150  $\mu m$  on each side of the cutting. These groovings open the p-n junctions. Therefore, the center cutting parameters do not influence the electrical efficiency conversion anymore.

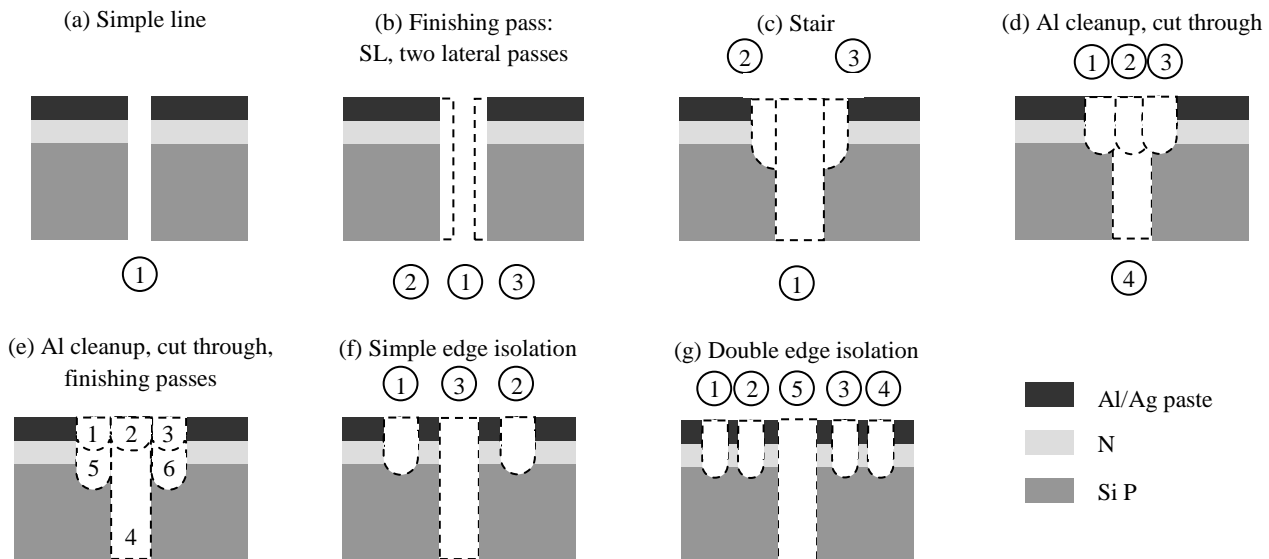


Figure 3. Schematic through-cutting pattern to avoid metallic re-deposition.

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Laser and cutting parameters

The DOE 1 and 2 results are respectively summarized in Table 3 and 4. Each solar cell has been electrically measured before processing to estimate the relative loss due to processing.

DOE 1 shows that the speed parameter and its second level interactions are not significant.

DOE 2 reveal that the pFF clearly varies at the main and second levels interactions with the pulse width. As the frequency decreases, the overlap of pulse will decrease and peak power increases. In other words, a lower repetition rate corresponds to shorter laser-material interaction time and smaller HAZ.

We noted however that the best visual quality, obtained with high pulse durations and high repetition rates, is not in correlation with the resulting electrical properties.

Repetitive tests have been done to confirm these results and have shown an excellent process repeatability (relative variation of pFF = +/- 6 %). The best configurations allow guaranteeing a minimum loss inferior to 3 % of pFF.

Table 3. Design of experiments 1 and results.

Order	Frequency [kHz]	Power in water jet [W]	Speed [mm/s]	Number of passes	Pulse width [ns]	Average pFF*	Relative pFF loss due to cutting [%]
1	37	10	50	25	480	0.742	7.72
2	22	13.5	50	5	~500	0.684	15.23
3	7	17	50	4	200	0.745	8.69
4	7	10	50	4	~290	0.738	8.69
5	7	17	150	12	200	0.763	4.80
6	22	13.5	150	7	~500	0.725	10.21
7	22	10	100	6	~450	0.714	11.35
8	22	13.5	100	5	~500	0.707	12.39
9	22	13.5	100	5	~500	0.679	15.95
10	37	17	50	5	507	0.693	14.14
11	37	10	150	100	~500	0.757	6.62
12	37	13.5	100	6	~450	0.724	10.21
13	37	17	150	5	507	0.697	13.57
14	7	10	150	13	~290	0.731	9.72
15	7	13.5	100	8	~300	0.748	6.79
16	22	13.5	100	7	~500	0.695	13.64
17	22	17	100	3	463	0.719	9.93

□ Input variables      ■ Output result

Table 4. Design of experiments 2 and results.

Order	Frequency [kHz]	Power in water jet [W]	RF offtime [μs]	Pulse width [ns]	Average pFF*	Relative pFF loss due to cutting [%]
1	7	12	4	295	0.747	7.22
2	22	17	4	463	0.712	11.74
3	22	12	1	82	0.779	3.74
4	22	12	4	502	0.717	11.14
5	7	17	4	200	0.738	8.53
6	7	12	1	101	0.787	2.45
7	7	17	1	130	0.778	3.35
8	22	17	1	94	0.737	8.15

□ Input variables      ■ Output result

\* Each average pFF corresponds to an average of 8 strips cut with the same parameters from the same solar cell.

Finally, two more test runs have been done using an optimized parameter set (DOE 2 run 6) and worst parameter set (DOE 2 run 4). Solar cells were cut from the backside to evaluate the impact of front/rear metallization re-deposition and the dopants inter-diffusion on shunting.

The results reveal exactly the same pFF after processing ( $pFF_{\text{average}} = 0.773$ ) thus generating a relative pFF loss close to 3.3 %. The main conclusion is that only the manner to open the p-n junction interferes here. The diffusion seems to be restricted. The p-n junction is probably opened by the laser pulses impacts and the water pressure, thus permitting excellent electrical properties.

### 3.2 Cutting strategies

Different cutting strategies have been applied on pre-scanned solar cells with the same laser parameters. The laser's repetition rate has been fixed at 20 kHz, the average power set to 13.5 W in the water jet with a cutting speed of 200 mm/s. The pulse width was close to 450 ns. The results are given in the Table 5.

Table 5. Cutting strategies results.

Cutting Strategy	Specific figure	Relative pFF loss [%]
Simple line	3.a and 4.a	6.25
Finishing passes	3.b	6.19
Stairs	3.c	7.50
Al cleanup, cut through	3.d	8.95
Al cleanup, cut through and finishing passes	3.e	9.68
Edge isolation	3.f, 4.b, 4.c	5.45
Double edge isolation	3. g	6.60

The results reveal that the best solution remains the simple line strategy owing to the minimized processing time and pFF losses. Each cutting strategy has to be developed with the latest best laser parameters to conclude. Nevertheless, these results can give us an excellent overview of the different cutting strategies to cut efficiently crystalline solar cells.

The finishing passes strategy has no significant effect on shunt creation comparatively to the simple line strategy. The relative losses should be due to a doping diffusion, thus shunting the solar cell.

Aluminum cleanup based strategies are not interesting to industrial uses due to its relative process time and its electrical properties.

The added edge isolation is an excellent industrial solution, allowing being free from the through cutting parameters and its cutting time.

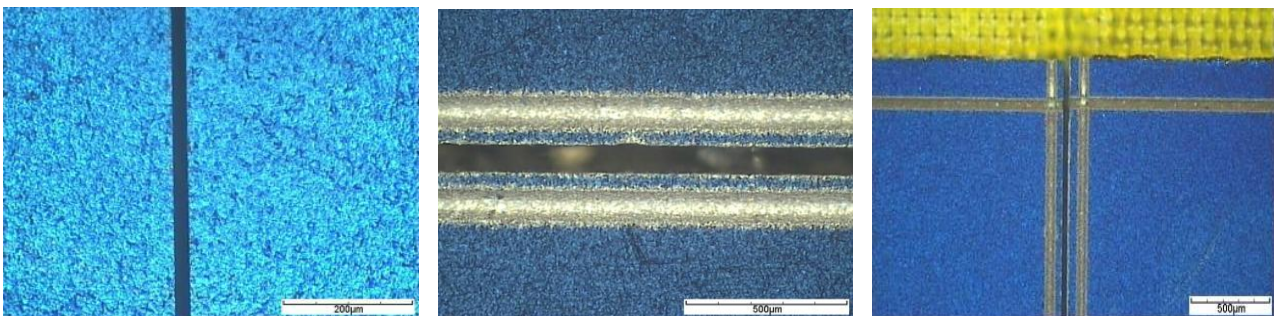


Figure 4. Crystalline solar cell cutting with a simple line strategy (a) and an edge isolation strategy (b), (c).

### 3.3 Tailor cutting

A tailor cut of crystalline solar cells can only be electrically efficient if the process parameters are kept constant. That means firstly to keep the same laser and cutting parameters but also to keep the same ablation rate while cutting. It leads to keep a constant cutting speed avoiding jagged outlines. The best parameters of DOE 2 have been used with the same laser source: a Q-switched green laser. So, we used a laser repetition rate of 7 kHz, a power in water jet equal to 12 W and a FWHM close to 100 ns. The pFF losses are thus only to 2.5 %. Several examples are shown in Figure 5.

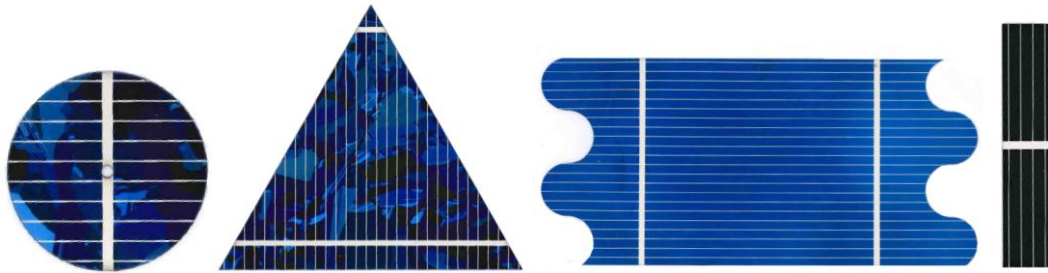


Figure 5. Examples of tailor cutting of crystalline solar cell. On the left, we show polycrystalline and on the right crystalline solar cells.

In all cases, we could cut any predetermined shape, regardless of the LMJ crossing contact fingers or even much contact busbars.

#### 4. CONCLUSION

This paper shows a process development with the industrial LMJ technology to tailor cut crystalline and polycrystalline solar cells with minimum electrical losses. In addition to other approaches, complete freedom of line path is viable now. Pseudo-Fill-Factor relative losses after cut are down to 2.45 %. As expected, results tend to employ lower laser pulse width according the incident wavelength absorption.

Now, virtually any shape of solar cells can be tailor-cut to meet requirements of BIPV and also watch making industry. In the case of BIPV, new developments are enabled, either to tailor cut solar cells, or to make new optically attractive designs. In the watch application, the LMJ solution opens the door to tailor cut new shapes. While the proof is given now, that the LMJ can cut solar cells with minimal losses, it is also clear that the set of process parameters has to be developed for the specific type of solar cell. In essence, for the first time, finished solar cells can be cut into any shape with minimal losses.

#### REFERENCES

- [1] Hauser, A., Hahn, G., Spiegel, M., Feist, H., Breitenstein, O., Rakotoniaina, J.P., Fath, P., and Bucher, E., "Comparison of different techniques for edge isolation," Proceedings of the 17th European Photovoltaic Solar Energy Conference, 1739-1742 (2001).
- [2] Breitenstein, O., "Understanding shunting mechanisms in silicon cells: A review," Proceedings of the 17th NREL Workshop on Crystalline Silicon Solar Cells and Modules: Materials and Processes, 61-70 (2007).
- [3] Richter, S., Naumann, V., Lausch, D., Werner, M., März, B., Ilse, K. and Hagendorf, C. "Trace elemental analysis of precipitates in multicrystalline silicon and investigation of solar cell shunting," Proceedings of the 25<sup>th</sup> European Photovoltaic Solar Energy Conference, 1254-1258 (2010).
- [4] Richerzhagen, B., [Entwicklung und Konstruktion eines Systems zur Übertragung von Laserenergie für die Laserzahnbehandlung], Ecole Polytechnique Fédérale de Lausanne, Lausanne (1994).
- [5] Kray, D., Hopman, S., Spiegel, A., Richerzhagen, B. and Willeke, G. P., "Study on the edge isolation of industrial silicon solar cells with waterjet-guided laser," Solar Energy Materials & Solar Cells 91, 1638-1644 (2007).
- [6] Correia, S. A., Lossen, J. and Bähr, M., "Eliminating shunts from industrial silicon solar cells by spatially resolved analysis," Proceedings of the 21st European Photovoltaic Solar Energy Conference, 1297-1300 (2006).
- [7] Abbott, M. D., Trupke, T., Hartmann, H. P., Gupta, R. and Breitenstein, O. "Laser isolation of shunted regions in industrial solar cells," Progress in Photovoltaics: Research and Applications 15, 613-620 (2007).
- [8] Sugianto, A., Tjahjono, B. S., Mai, L. and Wenham, S. R. "Investigation of unusual shunting behaviour due to phototransistor effect in n-type aluminium-alloyed rear junction solar cells," Proceedings of the 24<sup>th</sup> European Photovoltaic Solar Energy Conference, 930-933 (2009).
- [9] Greulich, J., Glatthaar, M. and Rein, S. "Fill factor analysis of solar cells' current-voltage curves," Progress in Photovoltaics: Research and Applications 18, 511-515 (2010).
- [10] Doering, M., Meyer, K., Kaps, A., Krokoszinski, H. J. and Eschrich, H. "Rear side versus front side laser edge isolation: A detailed theoretical and experimental investigation," Proceedings of the 25<sup>th</sup> European Photovoltaic Solar Energy Conference, 1778-1781 (2010).