

FAST CUTTING AND SCRIBING OF SILICON PV CELLS USING THE WATER-JET-GUIDED LASER TECHNOLOGY

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ABSTRACT: Since its creation more than 10 years ago, the water-jet-guided laser technology has been successfully used for many applications, including the cutting and edge isolation of silicon PV cells. This paper will first present this innovative technology, of which study was conducted in 2006 by the Fraunhofer-Institut for Solar Energy Systems ISE, on edge isolation of silicon PV solar cells treated with the water-jet-guided laser. This study includes testing the electrical parameters of the cells after edge isolation, thermography measurements, SunsVoc measurements, SEM and optical microscope images and breakage tests. The water-jet-guided laser was compared to a reference process – a standard industrial edge-isolation process, based on conventional dry laser technology. The water-jet-guided laser was also tested in different configurations.

Keywords: *laser, edge isolation, scribing*

1 WATER-JET-GUIDED LASER

1.1 Basic principle

The principle of this unique technology, also called Laser MicroJet, is to couple a high-power, pulsed laser beam into a hair-thin, low-pressure water jet. The laser beam is conducted by fiber to the system center where it passes through a transparent window and enters a chamber filled with water. The laser beam is focused after the window into a nozzle where it is coupled with the water jet exiting the chamber. From this point, the laser beam is guided along the cylindrical jet by reflection at the air/water interface, due to the difference of refractive indexes (see Figure 1). When it reaches the work piece, the laser cuts the material by heating (thermal ablation by the laser).

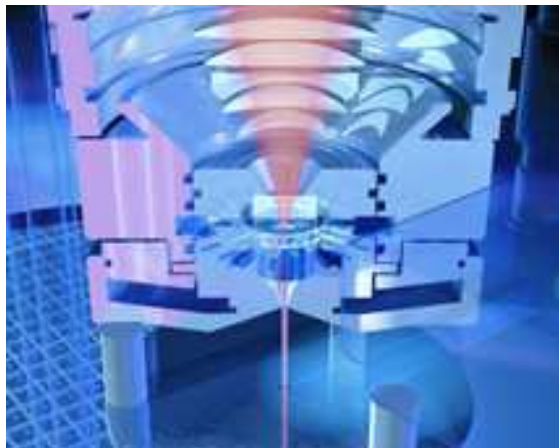


Figure 1: Basic principle of the water-jet-guided laser

1.2 Technical parameters

Different laser sources can be used for coupling with a water jet: flash-lamp-pumped IR pulsed lasers with pulse durations of less than 100 μ s or multimode diode-pumped Q-switched lasers, operating at 1064 nm (infrared), 532 nm (green), or 355 nm (UV). The only constraint on the laser wavelength is that it must be compatible within the water transmission spectrum. Lasers are only pulsed, enabling the water jet to cool the material during the lapse between the pulses. Pure de-ionized, filtered water is used. The water is pressurized between 100 and 500 bars, depending on the nozzle diameter, and small water jets of down to 23 μ m

in diameter can be obtained. Water consumption is therefore very low – about 1.5 liter per hour at 300 bar water pressure. The mechanical force applied by the water jet is in consequence, very low, (less than 0.1 N) hence not damaging the material.

The nozzles for coupling laser and water are made of sapphire or diamond in order to generate a long, stable water jets with diameters ranging from 25 to 150 μ m.

1.3 Not a conventional dry laser

The Laser MicroJet technology draws on the advantages of lasers, notably omni-directional cutting, high cutting speeds on thin materials (up to 300 mm/s in 50- μ m thick silicon) and flexibility. Furthermore, using a water jet offers several benefits, well known as unobtainable, when applying conventional, “dry” laser cutting. To cite a few, extended working distance, heat control and particle removal.

Contrary to conventional laser techniques, the laser beam, guided in water, is not conical when hitting the work piece, but cylindrical. Resultingly, kerf walls are parallel and the working distance is much longer (up to several centimeters long, depending on the nozzle diameter).

The heat-affected zone (HAZ) is not problematic as with conventional lasers, remaining contained inside the cut, thus not affecting its immediate surroundings, due to the water jet efficiently cooling the material between the laser pulses.

Contamination is also greatly reduced compared to conventional lasers, as the water jet expels the molten material more efficiently than the assist gas usually applied in dry laser cutting. The remaining particles are impeded from adhering to the material, due to a thin water film is maintained on the surface of the work piece during cutting.

2 LASER MICROJET FOR EDGE ISOLATION

In 2006, the Fraunhofer Institute for Solar Energy Systems ISE conducted a study aiming at testing the capabilities of the water-jet-guided laser technology for edge isolation (EI) of silicon PV solar cells in comparison to a reference standard process.

125 commercial solar cells were edge-isolated using a standard EI process and the LMJ process (equipped with an infrared laser at different power and pulse frequency).

After edge isolation, illuminated and dark IV-curves of the cells were measured. Additional SunsVoc and thermography measurements were also performed. Thereafter, all cells were break tested (4-line-bending apparatus) and both optical microscope and SEM pictures were made of the laser grooves.

2.1 Electrical parameters

The electrical parameters of the LMJ edge isolation are comparable to commercial lasers, i.e. the electrical quality of the reference process (standard-industry EI) are achieved with the LMJ. For the dark IV-curves, lower values of the second ideal factor n_2 can be fitted continuously. This indicates a reduced damage in the p-n-junction and emitter respectively.

The fact that LMJ process has obtained these results is very positive, because the process parameters of LMJ where sub-optimal in some areas due to experimental restrictions:

- An IR-laser was used with LMJ instead of an UV-laser. This increased the penetration depth of the laser light.
- The corners of the solar cells were not isolated; only straight lines with a constant scanning speed were processed due to technical restrictions with the lab-type system at Fraunhofer ISE.
- The width of the laser groove was 2-3 times wider than for the commercial laser systems since a 100 μm nozzle has been used, which increased accordingly the recombination losses.

For this reason, one can expect better results for LMJ by using a UV light source and a smaller nozzle.

A very positive result was the successful edge isolation on the back side of the solar cell. This kind of isolation is preferred to the front side edge isolation in principle, because the active cell area is reduced in the latter case. With LMJ, nearly the same efficiencies as found on the front side can be achieved. However the fill factor was still not optimal. But this is compensated by the increase of the short-circuit current (J_{SC}). With regards to the emitter damage, J_{02} can be optimized.

A 20 μm deep laser groove was sufficient for good edge isolation while a 5 μm deep groove seemed to be too shallow. The laser frequency played no important role for the LMJ. Both frequencies (13 kHz and 20 kHz) showed good results. With a fast scanning speed of 250 mm/sec just as good of results were obtained as with a lower scanning speed of 100 mm/sec. Consequently a 156 x 156 mm^2 solar cell could be edge isolated in $4 * 156 \text{ mm} / 250 \text{ mm/s} = 2.5 \text{ sec}$. Even higher scanning speeds for the used lasers are possible, because a groove depth of 10 μm (compared to the standard lasers) is enough. A transfer rate of 1-2 sec per wafer is for this reason realistic for the LMJ.

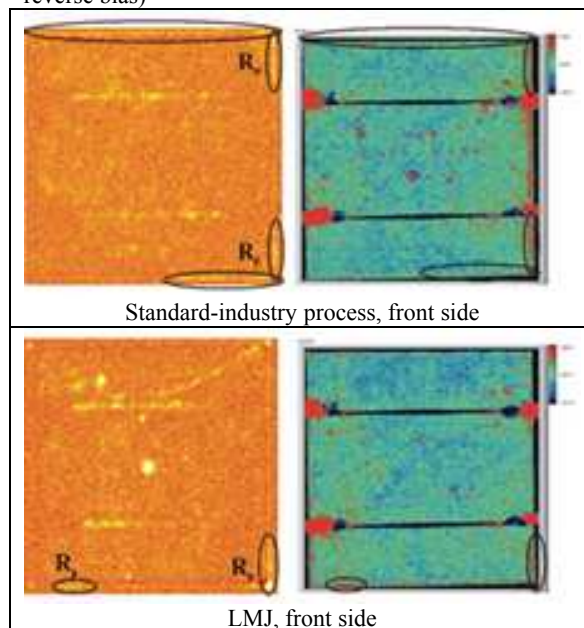
2.2 Thermography measurements

Shunts of solar cells under different operating conditions have been detected via thermography. In the case of edge isolation ohmic shunts could be distinguished from increased emitter recombination by comparison of thermography maps made in forward bias (V_{OC}) and reverse bias. An ohmic shunt exists if the current losses are visible in both kinds of maps because the direct connection of emitter and back side metallization isn't separated completely (this becomes apparent by a reduced parallel resistance R_p). A diode

shunt was responsible for the current losses if they appeared only in one image. This can be explained e.g. by increased recombination in the p-n-junction (J_{02}).

The thermography images in Table 1 depict that for the standard-industry-EI still ohmic shunts exists, whereas for LMJ they are generally removed. For the edge isolations on the back side both kinds of shunts (R_p , J_{02}) are still present; there is a demand of further optimization.

Table 1: Thermography measurements (left: Voc; right: reverse bias)



2.3 SunsVoc measurements

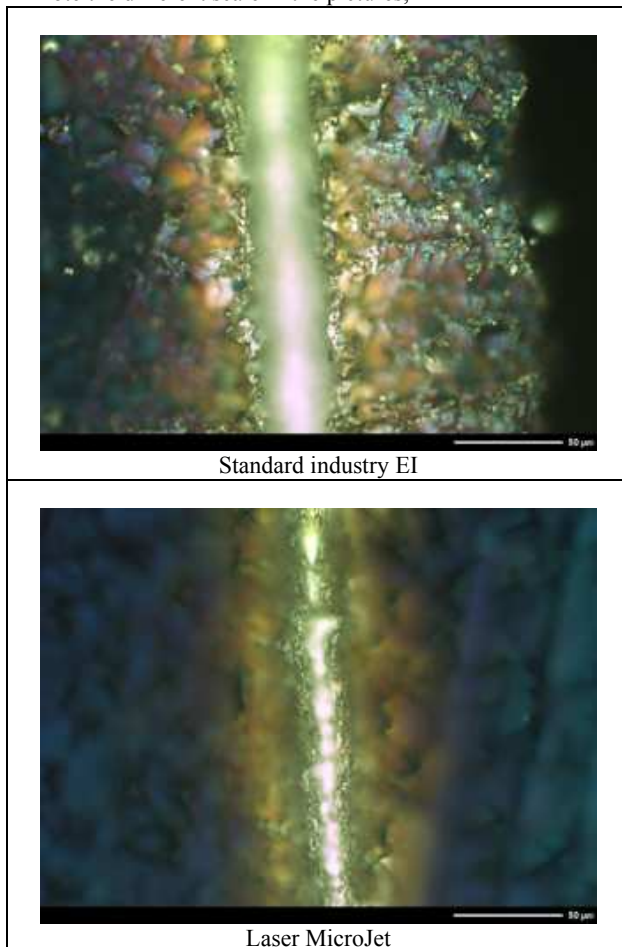
A series resistance free IV-curve could be measured with SunsVoc which enabled to find out the potential of the solar cell if the series resistance would be zero. With this, one could appreciate the limitation of the cell by other parameters (R_p , J_{02}) which are directly influenced by the edge isolation.

The losses by series resistance were for all cells approximately equal. This denotes that series resistances of the analyzed cells did not spread in a wide range and reduced the maximum achievable fill factors of approximately 5%_{rel}.

The stronger limitation of the fill factor to approximately 0.80 with the configuration of IR laser at 45.2 W and 20- μm deep groove for the LMJ was caused by the not yet optimized p-n-separation on the back side edge isolation. The limitation however was compensated by the increase in J_{SC} so that the efficiencies were comparable with the front side efficiencies of the LMJ edge isolated cells. With further optimization, a process could possibly be achieved which would exceed the front side process.

2.4 Optical microscope images of edge isolation

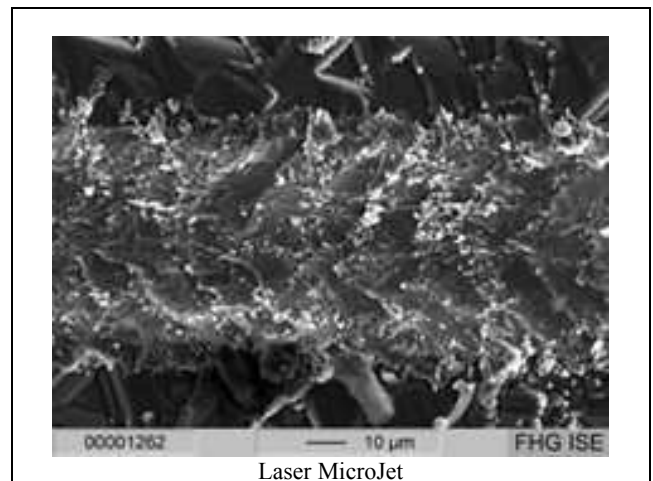
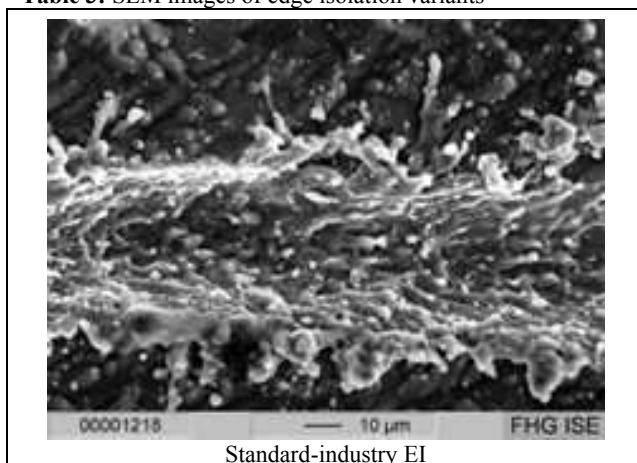
Table 2: Comparison of edge isolation variants. Please note the different scale in the pictures,



2.5 SEM images

Table 3 shows a comparison between the two different edge isolation processes. The laser groove of the standard-industry process was very inhomogeneous across the cell and a lot of molten silicon was ejected. Less ejected silicon was found with the LMJ process in comparison to the standard laser process and the LMJ-EI was more homogeneous across the cell. In evidence: LMJ laser groove was much wider due to the 100 µm nozzle.

Table 3: SEM images of edge isolation variants



2.6 Breakage test

To analyze the mechanical strength all cells were break tested with a Zwick BasicLine 4-line-bending apparatus. The maximum breakage force was detected.

The required breakage forces area depicted in Figure 1 for all EI-variants.

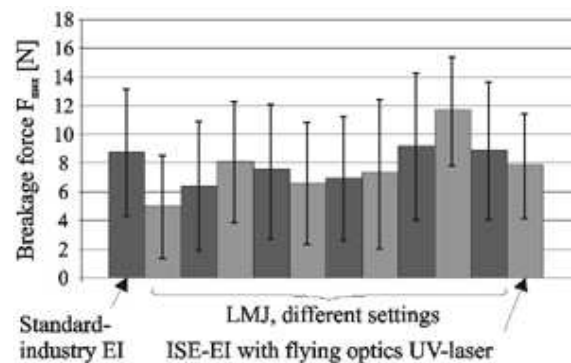


Figure 1: Comparison of the breakage forces of different EI-variants

The broad distribution of the results is due to the small number of tested cells. It also indicates that only limited large cracks were generated by the edge isolation (with numerous large micro cracks the breakage force would have constant smaller values). This is confirmed by the fact that the cell fragments were large. The cells didn't split as it would have been typical for high breakage strengths and high concentration of small micro cracks. This was visible, especially for the standard-industry isolated cells. 30 cells were break tested and even so the standard deviation was approximately 50 %.

The assumption is that the breakage emanates from laser-induced damage on the edge of the solar cell, thus the results depended primarily from the varying edge isolation induced damage by the single processes.

An interesting issue is that an increase in groove depths with LMJ does not lead to a decrease in breakage force necessarily.

3 SUMMARY

On the basis of the reached results one can ascertain that the water-jet-guided laser has been proven suitable for the edge isolation of solar cells. The same electrical

parameters than with the comparative standard laser processes can be achieved.

The highest fill factors of the tested solar cells are obtained with the LMJ, but the number of processed cells per variant has been too low to compile sufficient statistical information.

However, it has to be emphasized that the LMJ has reached standard-industry results in spite of sub-optimal testing parameters. The recent results of the LMJ could have even exceeded the standard-industry-process by using a UV-light source, a smaller nozzle and a laser-axis coupled CNC controller. Herewith edge isolation with lower recombination losses via reduced melt layer thickness, smaller groove widths and isolated cell edges can be expected. The potential of the LMJ process could not be fully utilized in this study because of the absent availability of a UV-light source at Fraunhofer ISE labs.

Even with this experimental barrier of the LMJ, indications for an advanced process have been noticed:

- Constant lower n_2 -values for LMJ, possibly caused by reduced emitter damage.
- Single processes with higher breakage forces.
- Back side edge isolation partly successful (fill factors are not optimal, but compensated by increase of current).
- Better groove quality and homogeneity.