BACK-END INTERCONNECTION, A GENERIC CONCEPT FOR HIGH VOLUME MANUFACTURING

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ABSTRACT: The general method to realize series connection in thin film PV modules is monolithical interconnection through a sequence of laser scribes (P1, P2 and P3) and layer depositions. This method however implies that the deposition processes are interrupted several times, an undesirable situation in high volume processing. In order to eliminate this drawback we focus our developments on the so called “back-end interconnection concept” in which series interconnection takes place AFTER the deposition of the functional layers of the thin film PV device.

The process of making a back-end interconnection combines laser scribing, curing, sintering and inkjet processes. These different processes interacts with each other and are investigated in order to create processing strategies that are robust to ensure high volume production. The generic approach created a technology base that can be applied to any thin film PV technology.

Keywords: Back-end interconnection, laser, inkjet, high volume production.

1 BACK-END SERIAL INTERCONNECTION

The development of back-end series interconnection is driven by several factors: increase module performance: dead zone < 200 µm, no interruption of layer deposition sequence, cell size optimization and fit-to-purpose finger design, shunt elimination, intrinsic and accurate alignment and handling, high volume and high speed manufacturing, optimized process flow: CoO reduction, freedom of design and shape.

Back-end series interconnection is achieved by integrated depth-selective laser scribing and printing of isolating and conductive lines. The concept itself leads to a significant increase of panel performance through increase of active area in combination with elimination of detrimental influences during build-up of the device stack. Also this concept might lead to changes in the value chain of thin-film PV. PV producers can ship semi-manufactures to e.g. building element producers who can make fit-to-purpose module lay-outs and geometries for their building integrated products.

2 TECHNOLOGY STEPS

The concept of back-end interconnection is achieved through a combination of technology steps. In the Produzo (Process system for interconnection of thin film solar cells) project these technologies steps resulted in the building of a back-end interconnection system.

The concept development is done so far mainly on thin film Si nip cells (Figure 1).

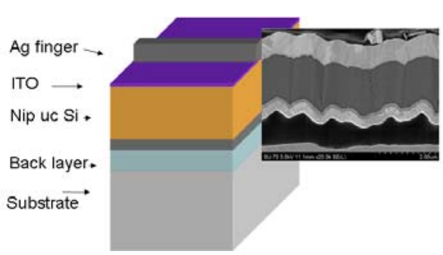

Figure 1: Si: nip cell structure with SEM picture and corresponding layer definitions

2.1 Cell Size optimization

The cell size determines also the amount of interconnections that are needed to create a module. The optimum cell size is a tradeoff between Ohmic losses and optical losses. Ohmic losses are caused by sheet resistance of the front TCO and contact resistance when a metal grid is applied. Optical losses arise through absorption by the front TCO and shadow of the metallic grid. For the concept with metallic grid on top of the front TCO, our model calculations (for thin film Si nip) predict an efficient cell size of 5 mm (See Table I). An increase of 40% in generated power density is possible in this case. This depends on the quality of the TCO. This relative cell size is only possible if the interconnection has minimized dimensions. The scribe widths and their distance between the scribes are set to 20 µm. This dimension of the dead zone area is 120 µm.

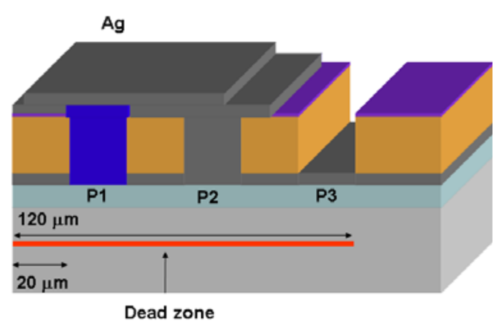

Figure 2: Si: nip cell interconnection structure with the dead zone (blue: isolating ink, gray: conductive Ag ink)

Table I: Cell sizes and their Generated power density.

Cell Size	Generated power density [mW/cm^2]	Relative to 20 mm cell.
3 mm	5.9	1.40
5 mm	5.9	1.40
10 mm	5.3	1,26
20 mm	4.2	1

2.2 Finger reduction

For a further optimization of the interconnection process we modeled the effect of finger reduction for the different cell sizes (See Figure 3). The model includes a dead area zone for the interconnection of 120 micron. The idea behind this modeling is to see if it is possible to minimize the amount of silver used to create the finger patterns. This can be made visible using the inkjet area vs. the cell area (See Figure 4).

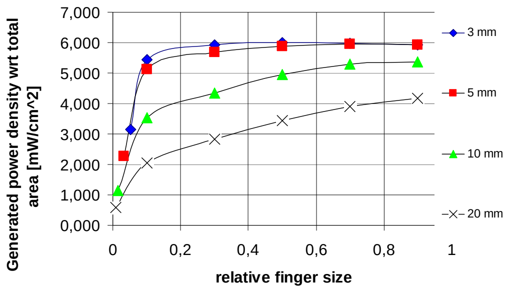

Figure 3: Cell size model calculation and relative finger length

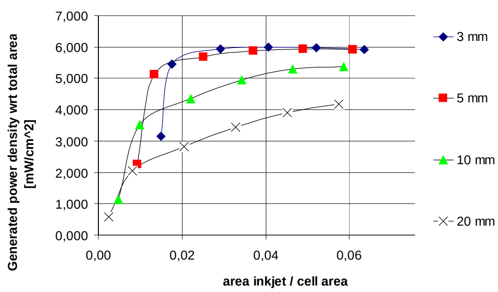

Figure 4: Cell size model calculation and area inkjet vs. cell area

The minimum use of silver in combination with a high generated power is found in the upper left corner. The 5 mm cell with a relative finger size of 0.1 uses only 1.3% of the cell area for connection. While the 20 mm cell with the relative finger size of 0.9 uses 5.7% of the cell area. Almost a factor 4 more silver is used with less generated power.

2.3 Shunt elimination

The shunt that is caused in conventional processing through the deposition of PV material in the P1 scribe is modeled in Figure 4 as the resistance R1.2. Although the PV material deposited in the scribe is not very conductive, a small shunt is still present. The top resistance R1.1 describes the ITO connection. If the model is used to describe the back-end interconnection the resistance R1.2 describes the conduction over the insulating line (blue areas in Figure 2). Micro probe measurements showed that the resistance of the insulating line is in the order of 10^{13} Ω. The resistance R1.1 is the conduction in the inkjet silver line over the covered P1 scribe. For a 100 µm line resistances of less than 0.2 Ω were measured. The resistance R1.3 and R1.4 are the shunts generated by the P1 scribe.

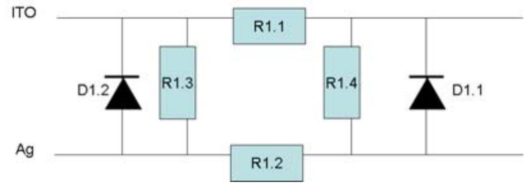

Figure 5: Steady state electrical model of the P1 scribe

To measure the several resistance values an isolated stack is scribed and measured using an IC micro probe station with microprobes with a 20 µm contact diameter. Also the diode characteristics can be measured using this technique.

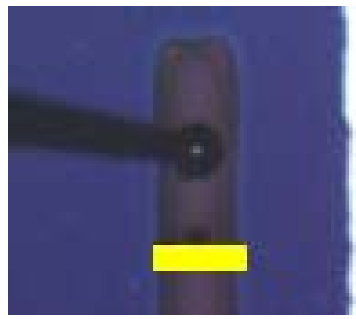

Figure 6: Close up of micro probe on isolation print (yellow bar width is 300 µm)

Similar schemes can also be drawn for the P2 and P3 scribes and combined with the Ag inkjet connection into a complete electrical description of the interconnection.

2.4 Process flow optimization through back-end interconnection

Depth-selective laser ablation is the key to allow structuring after all layers are deposited. It uses differences in absorption - and thermal expansion to selectively remove layers. The pulse length, pulse intensity and wavelength of the laser determine how much of the laser energy is absorbed by the target layer and how much is reflected or transported to other layers. These parameters define the process window for a specific removal of layers. For every stack of layers another combination has to be found.

For example scribing the P1 demands the highest pulse energy in relation to the P2 and P3 scribe. And scribing the P1 is a relative simple process. Normally all layers are removed. The process stops when all materials are removed. When the P1 is scribed on glass the intensity and power should be kept below the drive in value. Drive in or alloying is a process in which silver or another conductive material will diffuse into the glass surface creating a conductive surface layer. The reduction of the average power often is enough to get a non conductive scribe. Scribing a P1 on an isolating layer demands a better control of pulse energy and overlap . The adhesion of the layer also plays a role in the removal of the stack. The P3 scribe has some larger tolerances than P2. The removal of the top electrode already is sufficient. But a complete stack removal leaving most of the front electrode creates also an acceptable P3. In practice the P3 scribe is identical to the P2 scribe.

The Gaussian intensity distribution that is used causes a build up of heat during the ablation. The material that is processed is heated. Also at picosecond (ps) levels an increase of temperature is present. Only the material below the threshold intensity is not removed during the processing and has the possibility to heat up during subsequent pulses. Decreasing the overlap is in these cases an effective strategy.

Applying a top hat profile will not work at these small dimensions (10 – 20 μm spot diameter). Because the top-hat is a convolution of this same Gaussian distribution, the edges will show the same intensity gradient as a 10 μm focus. For large spot sizes this strategy can be used but the focal depth of the small spot-size is already very small, to even allow a further decrease. Active focus adjustment will add more complexity to the optical system.

Pulse lengths from 1 – 10 ps are sufficient to selectively remove most layers. If the absorption coefficient of the layers is similar and the adhesion between the layers is strong only depth selective laser ablation is possible. In this case a high repetition rate in combination with a small material removal rate per pulse gives a stable process. A high removal rate per pulse will be too unstable because small pulse energy changes will have a large effect.

2.5 Alignment and handling

The total back-end series interconnection consists of 7 different processes. (See Table II). To be able to integrate these different processes without active alignment of the substrate a stable platform is needed. The first process, scribing the P1 will make the sheet specific and all other processes have to be in line with this first process.

Table II: Back-end Interconnection sub processes

	Sub-process	Method
1	P1	Laser, ablation
2	P2	Laser, selective ablation
3	P3	Laser, selective ablation
4	ISO	Inkjet, polymer ink
5	Ag	Inkjet, nanoparticles Ag
6	UV curing	UV leds
7	Thermal sintering	Selective laser sintering

The high accuracy can easily be achieved if the substrate or sheet is kept attached to the same platform. A transfer to other systems would result in a loss of alignment. A way to eliminate thermal drift is to place the processes in time close after each other. These constraints result in a machine that transports a substrate along 7 process stations with a build-in accuracy. Only the alignment of the several processes to the first scribe remains. This can be solved through mechanical means.

The processes themselves create position errors. The sum of these error distributions is called error budget. This is kept as low as possible through stabilization of the platform and the process stations.

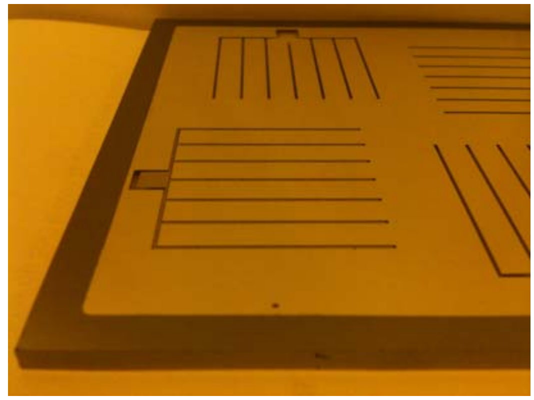

Figure 7: Inkjet printed Ag electrode structure inside laser ablated structure

Figure 7 shows a 20 mm long printed finger electrode on an a-Si:pin cell through the subsequent alignment of the inkjet printer to a existing pattern. A 200 μm extra space was needed to accommodate the alignment of the inkjet. For a 100 μm line 500 μm material was ablated increasing additional shadow loss.

With the use of scanner optics and a off line camera alignment an inkjet line was split by laser ablation at a speed of 500 mm/s (See Figure 8).

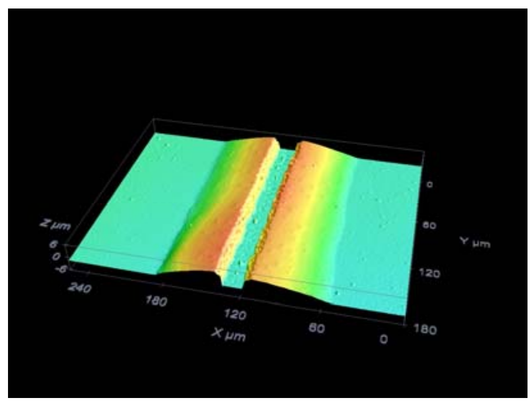

Figure 8: Laser ablation placed in 125 μm wide inkjet line. Laser width 20 μm

2.6 High volume and speed

High volume manufacturing requires scribing at high speeds and laser scribing can be performed at speeds up to 2 m/s. The amount of material that can be printed by the inkjet is the limiting factor and a speed of 0,5 m/s has been shown. To achieve these speeds a R2R transport system, with an indexed belt system would be a good choice.

In the Produzo project such an indexed belt system is integrated with two industrial inkjet print systems one for conductive Ag print and the other for isolation polymer print (See Figure 9). These two print stations are combined with three laser stations and one UV curing position. The system is also equipped with an intelligent camera that can inspect one scribe at processing speed. The system is built from several modules each covering 67 mm of the entire width of the belt. In order to achieve the high production speed of 0,5 m/s the laser systems are multiplexed by diffractive optics to create the amount of scribes lines per 67 mm.

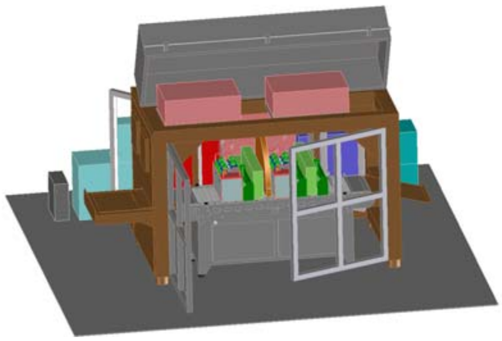

Figure 9: Produzo laser system inside laser safety cabinet

In this project the partners Smit Ovens, CCM, Stork, IBS, TNO and ECN work together to build the first back-end interconnect machine. This system will be used to demonstrate at full production speed interconnection.

3 CONCLUSION

The Produzo project demonstrates the feasibility of the back-end series interconnection approach. In this system all processes involved are brought together in close proximity. The demonstrator system is being built with all the aspects of a full industrial machine but reduced in width comprising two adjacent ink jet print heads having a stitching area in between them. This machine will show how the concept will work on a width of 134 mm.