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Shingling Technology For Cell Interconnection: Technological Aspects And Process Integration

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Abstract

Shingling technology is an extremely interesting development of cell interconnection in a photovoltaic module due to higher power densities at the same or lower cost, and increasing availability of suitable Electrically Conductive Adhesives (ECAs) and equipment. The shingling approach provides several advantages compared to standard modules, namely: lower ohmic losses, better area utilization, lower processing temperature, lower operating temperature resulting in enhanced energy yield, improved aesthetics. In this work, we demonstrate the performance gain obtained with shingling interconnection technology in terms of module output power and efficiency. Moreover, we describe the technological challenges for each step in the shingling assembly process flow.

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Keywords: shingling; solar panels; interconnection technology; c-Silicon; conductive adhesives

1. Purpose and approach of the work

Shingling technology for cell interconnection in a module is not new in photovoltaics (PV): in fact, it was one of the first methods used to create the series between the strings, for example it was adopted in early space applications [1]. In recent years, there was a revamping of this technology due to increased need for differentiation among module

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manufacturers, specifically aiming at higher power densities [2], also triggered by availability of suitable Electrically Conductive Adhesives (ECAs) [3] and equipment. The shingling approach provides several advantages compared to standard PV modules:

- **Lower ohmic losses:** overall string current is lower than traditional ribbon-connected strings because of the smaller area of the shingles connected in series. This greatly reduces the ohmic losses.
- **Better area utilization:** since there is no need for cell-to-cell gap, denser cell packing can be obtained in the same area.
- **Lower T processing:** ECA’s curing temperature is lower than ribbon soldering, reducing residual cell stress and bowing.
- **Lower operating temperature related to lower current** – hence increasing energy generation in real world operations.
- **Improved aesthetics thanks to the absence of visible busbars (BB) and ribbons.**

In this work, we demonstrate the performance gain obtained with shingling interconnection technology in terms of module output power, efficiency, and reliability. Moreover, we describe the technological challenges for each step in the shingling assembly process flow.

2. **Technological aspects**

In the shingled module scheme, a solar cell is cut into 3 to 6 stripes (the so-called shingles) that are subsequently assembled in strings by connecting the front of each shingle to the back of the next one by means of a suitable Electrically Conductive Adhesive (ECA), which can be printed or dispensed on the shingle’s surface (Fig. 1). In order to match the required module layout, the number of shingles making the strings can be adjusted and the length of the string varied consequently. Strings up to 2 m long (equivalent to the longer side of a traditional 72-cells module) are typically assembled. Strings are then connected together by bussing ribbons and processed using the traditional PV module fabrication procedure. The series and parallel arrangement of the strings is chosen to match the typical I-V curve of a standard module.

![Fig. 1. Shingling interconnection scheme](image-url)

Cutting a cell in n shingles gives a reduction in the short circuit current ($I_{sc}$) of roughly 1/n because the active area of each shingle is 1/n of the original cell; at the same time, shingles have larger contour/area ratio than a standard cell due to the appearance of a cleaved border. This can lead to potential recombination losses at the newly formed edges, unless special passivation concepts like the SPEER approach are used [4]. The ohmic losses are thus reduced by 1/n², providing significant advantages in terms of power output of the module and lowering the operating temperature. In turn, this leads to higher energy yield. Moreover, the dense packing of the shingles and the absence of visible BBs leads to better area utilization, increasing the efficiency of the module compared to a standard one of the same area, because the gaps between ribbon-interconnected cells in a traditional module are no longer needed. It is worth noting that, due to the denser packing of cells in a shingled module, the amount of the cells used compared to a standard module is higher, but the final power gain obtained is greater than the contribution due to the improved material utilization alone [5].

Shingles are attached one to the other using ECAs, which cure at low temperature and are flexible enough to accommodate the thermal stresses during processing - and thus contributes to improving the reliability of the device.
Since the shingling approach affects only the way that cells are interconnected to form strings, it can be applied to any cell architecture as long as contacts are on both sides of the cell. It can be applied with almost no process modifications to BSF, PERC, bifacial-PERC, n-PERT/PERL, HJ, among others.

3. Process Integration

In the shingling module process flow, the traditional stringing & tabbing steps are replaced by three additional ones, namely: cell cutting, ECA deposition, and shingles assembling in a string. In order to allow the different connection scheme, also the cell grid layout has to be modified, replacing the standard H-pattern with fingers connected to a busbar on both ends by an array of pseudo–BBs with the finger connected to one end only and a gap on the other side at the separation position. The downstream process and the module BOM are not affected and do not require changing.

In this section, we analyze the major process steps changes, highlighting the effects on device performances and yield.

3.1. Cell Layout

Moving from a standard 4-5 BBs layout to a shingling one requires some grid modifications. The fingers must be interrupted to guarantee a good separation of the cell into shingles, while the front and back pseudo-BBs layout must be changed in accordance with the shingles attachment scheme (each shingle has a pseudo-BB on the front at one end and one in the back at the other end – as in Fig. 1).

In the shingled cell layout, fingers are attached to pseudo-BBs only on one end, so the path current has to flow through is longer compared to a standard 4 BB layout. Hence the number of fingers and their aspect ratio require some optimization to keep satisfactory FF at cell and shingle level; moreover, having interruption-free fingers becomes more important to avoid resistance losses.

3.2. Singulation

Separation of the cell into shingles is done using a laser scribing and mechanical cleaving approach. To do this, a pulsed infrared laser is used to induce a crack at the separation position and a subsequent mechanical action completes the singulation process. Laser power, repetition rate, and scanning speed have been carefully selected to minimize the amount of damage to the cell. Scribing can be performed from the back or the front side of the cell. In order to study the possible impact of the side the laser is fired to, we ran a comparison test based on half cut cells. We measured the saturation current density or J0 of half-cut cells before laser scribing, after scribing and after the complete separation to understand how the reverse behavior is affected by laser processing.

As shown in Fig. 2, laser scribing does not create relevant bulk defects (J01 is not changing), but affects the junction quality when scribing on the front side (J02 increases). This justifies the adoption of backside scribing throughout the remaining of the work.

Laser accuracy is fundamental to obtain uniform shingles, so alignment precision, consistency of pitch between shingles, and scribing depth repeatability were carefully tested. Our experiments show that alignment precision of < ± 50 µm, pitch repeatability better than ± 10 µm, and scribing depth variation range of ± 10 µm are attainable (Fig. 3).
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Fig. 2. J$_0$ measurement on half-cut cells: scribing on the front side (left) and on the backside (right). Backside scribing does not damage the junction, J$_0$ left unvaried.

In this section, we analyze the major process steps changes, highlighting the effects on device performances and system integration.

### Alignement accuracy of laser scribing

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<thead>
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<th>Laser precision [um]</th>
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Fig. 3. Alignment accuracy of laser scribing

3.3. ECA printing

The shingle-to-shingle interconnection has a double function: 1) guarantee the electrical continuity along the string and 2) provide enough mechanical strength to avoid detachments during the module making process and in the operating life of the finished panel. ECAs offer a viable solution based on proven reliability in other fields; however, they have not been widely used in photovoltaic technologies.

There are mainly two competing ways to deposit ECA on a shingle with the required accuracy, precision, and weight control - dispensing and screen printing. Between them, we believe screen printing is the most suitable solution because it is a proven technology with a decades-long history of production in c-Si photovoltaics. In fact, it is a simple, robust and fast process, capable of delivering with high throughput fine control of the ECA laydown with no issues like nozzle clogging and cumbersome cleaning.
Tests done using specifically designed screens allowed depositing less than 10 mg/cell of ECA without compromising the electrical performances and thus greatly contributing to reduce the total cost of ownership of the shingling process and, ultimately, the cost per W of the final module.

3.4. String assembly

The most important parameter of the shingle assembling process is the overlap between one shingle and the next one: a big overlap guarantees a higher mechanical strength of the interconnection because the area available for ECA deposition is bigger, but at the same time reduces the active (illuminated) area of each shingle, and affects the material utilization, because more shingles are needed to obtain strings of a given length. Moreover, small overlaps enable a reduction of silver consumption in the screen printing of the cell grid, because narrower busbars can be designed, and also a reduction of the amount of ECA that has to be deposited for the interconnection.

A careful design of the ECA printing layout can guarantee satisfactory mechanical strength, and good electrical conductance even with shingle-to-shingle overlap of about 0.8 mm or less.

Figure 4 shows the results of a simulation done using Fraunhofer ISE’s SmartCalc.CTM software, depicting the effect of overlap on CTM losses of the module and on cell usage per module. As can be seen, the CTM improves linearly with reducing shingle overlap and, in a 60-cell equivalent layout, reducing the overlap to 0.9 mm allows to save 2 cells per module and consequently reduce the materials cost.

Other parameters to be taken into account in shingle assembly are the accuracy of the shingle-to-shingle alignment and the total string length. These parameters are important for achieving uniform power output, reliability, and aesthetic consistency among all the strings. High alignment accuracy is needed to avoid contacting issues that can result in increased contact resistance.

3.5. ECA curing

ECAs tested so far are thermally cured and require process temperatures lower than 200°C. ECAs differ from traditional silver pastes for the front side cell grid because they do not have (or have very limited) solvents that evaporate. Instead they contain an organic matrix which reticulates upon the application of heat, providing mechanical
strength while forcing the silver particles to be in contact with one another to create a percolation path for current flow. The curing reaction is exothermic and can be easily studied by Differential Scanning Calorimetry (DSC). DSC provides a way to determine if the reaction went to completion: we analyzed the fresh ECAs and compared them to thermally treated samples, as shown in Fig. 5. The exothermic peak completely disappear in the cured samples, meaning the curing reaction is completed in the oven and no residual uncured ECA is left, avoiding any out-gassing effect during lamination or module service. Non complete curing during thermal processing can lead to adhesion issues in shingling interconnection.

![DSC analysis of an ECA before and after the thermal curing. The exothermic peak of the curing reaction disappears after the thermal treatment, meaning the reaction was already completed in the oven.](image)

4. Device performances

4.1. Module power

The first assessment of PV module power gain was conducted on 60-cell equivalent modules. Eighteen modules were assembled at a customer site and then tested. Baseline was a conventional commercial module made with the same starting material (mono PERC cell); all the shingled modules outdid the baseline power value, giving an average gain of 9.6%, with four modules exceeding 10% of power gain compared to a 290-W standard module baseline (Fig. 6).

![Test results on eighteen 60-cell equivalent shingled modules: all the samples surpassed the baseline, giving an average power gain of 9.6%](image)

A second test was performed on modules equivalent in size to 72 cells conventional. Since starting cells were pseudo-square, two kinds of modules were assembled: 1) those made by the central shingles of the cell, thus being rectangular in shape, and 2) those made by the first and last shingle of each cell, thus having rounded corners. As expected,
modules made by pseudosquare shingles present a smaller power gain compared to full rectangular ones, due to the smaller active area. Figure 7 shows the power gain for the two kind of modules; in the case of full-area shingles a gain of up to 8% can be achieved.

4.2. Effect of ECA deposit on module power

In a shingled module, the amount of ECA contributes significantly to the overall CoO, so we tested the effect of the amount of ECA on the overall performances, adjusting the print layout to minimize the deposit.

Tests on small-sized modules (1-cell equivalent) showed that a dramatic reduction of the ECA laydown is possible without affecting the electrical performances. The graphs in Fig. 8 show the power reduction for two different ECAs. We obtained a power loss of less than 2% when reducing the wet deposit from 25 to 4 mg/cell. In particular, the second ECA allows getting to extremely low deposit without any significant performance degradation.

Fig. 7. Power gain for 72 cells equivalent shingled modules. Rounded (left) and full rectangular (right) shingles. As expected the power gain is lower for modules made by rounded shingles, because of the reduced active area.

Fig. 8. Power losses Vs ECA laydown on minimodule testing for two different ECAs.
4.3. Reliability tests

Shingling modules do not have an extensive history of reliability data, so a deep analysis on this aspect is needed. First results of thermal cycling are promising: three modules have been tested up to TC1000 [6], showing power losses lower than 3% for two of the three materials tested (Fig. 9, left) with no significant damage revealed by electroluminescence imaging. Static mechanical load tests [7] were also performed, showing results better than standard reference modules, a further evidence of the reliability of the EC-based interconnection approach and of the robustness of the shingling design (Fig. 9, right).

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5. Conclusions

Shingled modules can be realized with almost all the existing cell technologies (BSF, PERC, bifacial-PERC, n-PERT/PERL, HJ) without major process modifications, allowing higher power density and better energy yield vs. standard modules and with high reliability.

In this work, we analyzed the main technological changes and the required process integration steps needed to mass-produce shingled modules. Sample modules in two separate tests showed an increase of power per module up to 10%. Keeping cost per W at the same level, or even lower, than conventional modules looks possible by better material utilization and ECA laydown reduction. While ECA adoption is definitely not yet widespread in the solar industry, thermal cycling tests showed limited power losses after TC1000, supporting the reliability of this kind of approach.

Overall, this work demonstrates the potential of the technology from a cost, performance, and reliability standpoint. Of course, introducing the technology in high-volume manufacturing will require a number of further assessments and developments.

References