PRODUCTION OF LOW COST BACK CONTACT BASED PV MODULES

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ABSTRACT: In this paper, two developments targeted at reducing the production cost of back-contact modules are presented. The first cost reduction potential is realised by replacing the conductive copper layer with aluminium with a very thin and locally applied copper coating using cold spray technology. This results in a 2% PV module cost saving while also meeting industrial requirements for production speed and reduction of contamination. Prototype mini-modules manufactured using this method have shown very good performances and passed selected IEC reliability tests (Damp Heat and Thermal Cycling).The second cost reduction comes from reduction of encapsulant usage. By using powder coating technology, encapsulant thicknesses below 100 microns can be achieved. This not only results in the reduction of encapsulant usage as compared to standard modules, but it also increases production flexibility. Application of powder coated encapsulant results in a cost reduction of 1%. An additional cost advantage of the implementation of thinner encapsulants is a reduction of conductive adhesive of at least 60%, which can result in an additional 2% cost reduction.
Keywords: Back Contact, Cost reduction, Encapsulation, Cold Spray, Powder Coating

1 INTRODUCTION

The foil-based back-contact c-Si PV module technology offers possibilities to increase efficiencies and reduces the cell-to-module fill factor loss compared to standard tabbed front-to-back contact technology. It also offers improved design flexibility, and is compatible with any back-contact cell type [1-6]. This module technology is ready for large-scale implementation, with equipment manufacturers and material suppliers offering qualified and diverse commercial solutions [2]. In the past few years, a significant reduction of the costs per Wp for foil-based back-contact PV modules has been achieved by reducing the material and process costs [3]. Despite these cost reductions industrial implementation is still slow due to the relatively high BoM costs, the need for investment in new equipment and limited long-term field performance data. Improvements in the cost-performance ratio of high-efficiency back-contact cells such as n-type metal wrap through (n-MWT) and interdigitated back contact (IBC) [4,5], and implementation of novel module processing solutions and materials combined with extensive reliability studies on module level should lower the threshold for market introduction.

The Dutch R&D project Los Bacos, a consortium consisting of ECN, DSM and Dycomet Europe, is developing technologies to reduce the material costs of back-contact PV modules. This project focuses on reducing the amount of copper, silver and encapsulant by replacing the copper foil with aluminium foil and by applying thinner encapsulation. Aluminium foils combined with copper cold sprayed layers have been investigated in the past, resulting in reliable PV modules [7,8]. Using powder coating technology, thin thermoplastic encapsulant layers can be applied, thus reducing the amount of conductive adhesive needed to overcome the height of the encapsulant. The application of powder coating significantly improves and simplifies the application of the encapsulant since there is no need for punching or lasering holes and often troublesome handling of thin encapsulant films.

This paper reports the results of implementing two solutions, i.e. aluminium conductive foil in combination with copper cold spray and powder coated encapsulant to achieve thin encapsulant layers. The implementation of these material cost savings could have a major impact on the reduction of the overall back-contact PV module costs.

2 EXPERIMENTAL

2.1 Optimization copper cold spray process

Low pressure cold spray is a coating deposition method [8] used for several ductile metals such as copper. Copper powders (1 to 50 um in diameter) are accelerated in a supersonic gas jet to velocities up to 500–1000 m/s. During impact with the substrate, particles undergo plastic deformation and adhere to the surface. A huge benefit is that the temperature of the particle during impact on the surface is below 100 degrees C. The used equipment for cold spray is shown in Figure 1.

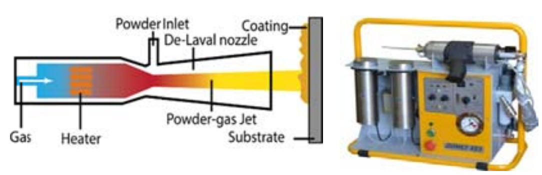

Figure 1: Schematic view of cold spray technology (left) and the used equipment, Dymet 423 (right)

In the past several mini-modules were produced using this process and were subjected to Damp Heat (DH) and Thermal Cycling (TC) tests, resulting in reliable modules with less than 5% power loss after 3 times DH and TC testing according to the IEC 61215 standard [7]. The main focus of this paper is on realizing further cost reductions while maintaining the level of reliability. There are important parameters that can be improved to reduce the cost of the copper cold spray process. One important parameter is the price of the copper powder, which is strongly related to the morphology, particle size and the powder yield during the processing of the powder. Powders from several powder suppliers were tested using standard spray conditions and deposited on aluminium based back-contact foil. Based on visual inspection of the layer and contact resistance measurements, potential powder candidates were selected; see Figure 2

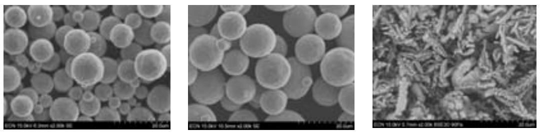

Figure 2: Used powders from left to right: spherical 10 micron (A), spherical 20 micron (B) and dendrite <25 micron (C)

Several -4-cell back-contact (MWT) mini- modules were produced using the different selected powder morphologies. The modules were measured using the PASAN IIIb flash tester and tested in DH and TC according to IEC 61215.

One powder was selected, based on lowest price and production capacity as claimed by the supplier. With this powder several parameters influencing the spray efficiency were investigated and optimized, such as powder flow, temperature, gas pressure, gas composition (compressed air or nitrogen), robot speed required to cover the dimensions of full size foil in less than 1 minute and spray nozzle geometry . The produced copper layers on aluminium based back-contact foil were visually inspected and some were selected for contact resistance measurements as shown in Figure 3. The contact areas were deposited with copper. Both foils were connected to each other using conductive adhesive. An electrically isolating encapsulant foil with punched holes was placed between the two metal foils. The contact resistance measurement was executed using a four point probe measuring method with a Keithley 2430 pulse source meter.

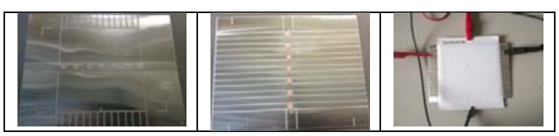

Figure 3: Set-up of the sample used to measure contact resistances. Base foil (left), tab foil (middle) and 4 point probe measurement using Keithley 2430 pulse source meter (right)

The powder particles that do not adhere to the foil were removed using a vacuum cleaner and captured in a cyclone (see Figure 4). Further research is needed to test whether this material can be re-used for secondary spraying, as starting material for other deposition techniques or as recycled material for the production of virgin copper powder.

For IBC module design more contact pads are available and a higher accuracy is required because of the small connection area. Several IBC mini-modules were produced to test the robustness of the cold spray process for IBC PV modules. For mini-modules in the MWT concept with 4x4 vias, 14 lines are sprayed, compared to 18 lines for the IBC module (see Figure 5), resulting in an increased copper material usage of around 30 %. The produced IBC modules are measured using IV, EL and DLIT.

Figure 4: Vacuum system to collect the powder that does not adhere to the foil (left) and the cyclone to separate the powder from the air flow

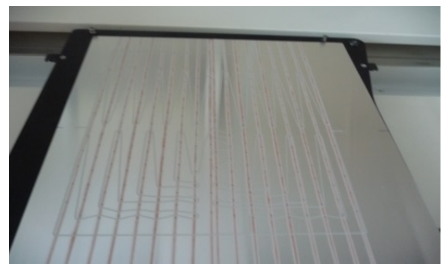

Figure 5: 18 lines of copper cold spray corresponding with the position of the front and back contacts

2.2 Powder coated encapsulant

The production of EVA encapsulant foils with a thickness less than < 200 micron is a technical challenge. The bottleneck for thin encapsulant layers can be solved by using the powder coating technology. Powder coating is a type of deposition that is applied as a free-flowing, dry powder. The coating is typically applied electrostatically and is then cured under heat to allow it to flow, forming a "skin". The powder may be a thermoplastic or a thermoset polymer. The used powder coating equipment is shown in Figure 6.

Figure 6: Photograph of the used powder coat facility (Norton Encore spray controller and spray booth)

An industrial thermoplastic powder was used for process optimization. It was known that this powder could not lead to reliable PV modules under DH conditions, because of the melting temperature of approximately 80 degrees C, but it was suitable to demonstrate the process.

With the set-up illustrated in Figure 3, powders were applied on the back side of back-contact cells. The attached powder on the contact pads was removed by vacuum using a contact point cleaner (CPC-unit), see Figure 7.

The powder is pre-heated in an IR heated belt furnace under conditions that just make the thermoplastic material melt, and in case of thermoset powders the curing is minimal.

Figure 7: Photograph of the CPC-unit

The spraying and pre-heating conditions were optimized to achieve homogeneous layers ranging from 80 to 150 microns.

Secondly, the glass was coated with layers of 150 to 200 microns thick using the same powder. PV modules were produced using optimized conditions for the applied powders. The modules were characterized on their initial performance using the PASAN IIIb flash tester.

2.3 Reduction Conductive adhesive

One of the production methods used in contact foil technology is printing of conductive adhesive on the patterned metal foil. The height of the adhesive dot is in line with the thickness of the punched encapsulant. For stencil printing a certain ratio between hole diameter and stencil thickness is required to fulfil the release properties of the adhesive from the walls in the stencil. The height of the conductive adhesive dot is fixed by the height of the encapsulant. For a 200 micron thick encapsulant a 400 micron thick stencil is needed and for release of the adhesive, a hole diameter of 1.7 mm is needed. For an encapsulant thickness of 100 microns a stencil thickness of 200 microns is needed and a hole diameter of 1 mm is possible. The applied amount of conductive adhesive using the stencils mentioned above will be investigated.

3 RESULTS AND DISCUSSION

3.1 Optimization copper cold spray process

First optimization was done to find a relation between copper usage (extrapolated to full-size foil), observed intensity of the copper line and the contact resistance between two foils and conductive adhesive. This resulted in a copper usage of 50 g per full-size foil and the contact resistance was below 1 mΩ. Further optimisation by increasing the air pressure and temperature of pre-heating the carrier gas resulted in a copper usage of less than 20 g without influencing the contact resistance. Under these deposition conditions the spray efficiency was approximately 5-10%. The spray efficiency can be increased by activating the aluminium surface by bombarding the surface with an inert 'grit' powder. This surface roughness has a positive effect on the adhesion properties of the sprayed copper powder. The copper usage can be reduced to less than 10 g and the spray efficiency increased to 40%. At industrial processing speeds, coating full-size foils in less than 1 minute, the spray efficiency decreased to 20%. Further optimization of spray parameters, such as nozzle design and distance of the spray nozzle to the substrate, is necessary to further reduce the copper powder consumption and increase the spray efficiency. Contact resistance measurements were performed on foils with and without copper deposited with a semi-optimised cold spray process; see table I. These results show that the contact resistance between foil and conductive adhesive is significantly reduced when using copper cold spray applied on aluminium foil. The reason is that the native oxide on the aluminium is removed. An additional layer of copper cold spray on copper foil also reduces the contact resistance, probably caused by removing the surface protection layer (OSP) and increasing the contact area by roughening the surface.

Table I: Contact resistances on foils with and without cold spray copper (CS Cu)

	Average	Standard deviation
Copper foil	2.3	1.2
Copper foil + CS Cu	0.19	0.06
Aluminium foil	150	230
Aluminium foil + CS Cu	0.19	0.12

The back-contact copper foil used in back-contact PV modules is protected against corrosion by an OSP layer when stored under atmospheric conditions. For the foils applied with copper using the cold spray technology, such an OSP layer is not needed. Contact resistance measurements were performed on aged aluminium foils with copper cold spray contacts. It turned out that after one year of storage the contact resistance was still below 0.3 mΩ.

The shape and diameter of the applied powder for cold spray technology is an important parameter for cost reduction. Using different types of copper powder (A, B or C), -4-cell back-contact (MWT) mini-modules were produced with aluminium foils, characterised using the PASAN IIIb flash tester and tested under DH and TC test conditions according to IEC 61215. No differences were observed in cell-to-module (CtM) fill-factor losses when a different powder was applied, compared to modules fabricated using a copper conductive back-contact foil. For mini-modules a standard CtM loss of 2.5% is acceptable. The power and fill-factor decay as function of the testing time of the different powders is shown in Figure 8. No difference in reliability behaviour has been observed. During TC, the fill factor decay was less than 1% after 200 cycles. The power loss during TC was higher than expected, especially for the first 100 cycles, i.e. approximately 3%. Reliability data of modules in which standard copper based back-contact foils were applied and identical solar cells were used, showed the same decay during the first 100 cycles in a TC test. Investigation made clear that this decay was caused by current induced degradation (CID) that is comparable to light induced degradation (LID), which is often observed for P-type silicon solar cells [9].

Using the vacuum and separation set-up to collect the unattached copper from the aluminium surface during the cold spray process showed that it is possible to have a clean coating process without excessive contamination of the foil and surroundings of the spray unit. Wiping the foil with a piece of paper after spraying showed no copper on the paper. The unattached powder was during spraying immediately removed from the surface through suction and separated from the gas stream by using a cyclone. The collected powder is shown in Figure 9.

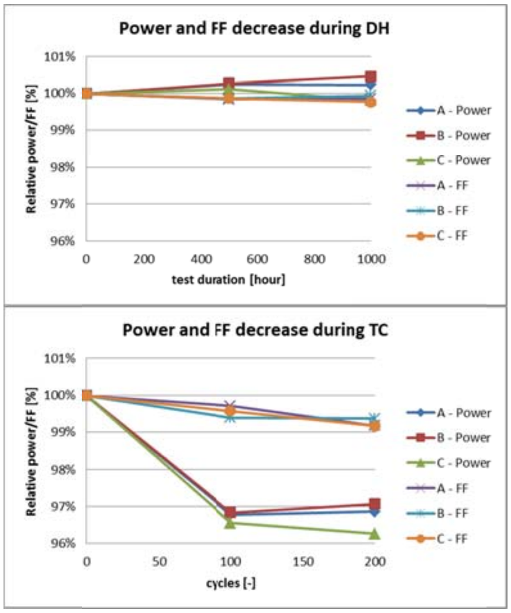

Figure 8: Change of power and fill factor during testing modules under DH (left) and TC (right) conditions

Figure 9: Collected copper powder after cold spray process

Four IBC modules (-4-cell mini modules) were produced to investigate the possibility to perform the cold spray technology also on back-contact cell concepts that require a higher accuracy in module manufacturing. Figure 10 shows a picture of a semi-fabricate of an IBC module.

The IV characteristics of The IBC modules were measured using a PASAN IIIb flash tester. The average value of the IV data is listed in table II. The module characteristics were compared with IBC modules produced with standard copper conductive back sheets (the used solar cells were slightly higher in performance).

Figure 10: An in production IBC mini-module after pre-tacking, before lamination process

Table II: Average IV data of four IBC modules built with aluminium foil and copper cold spray (IBC Al+CS) compared with average IV data of 4 IBC modules built with copper foil (IBC Cu)

	Isc [A]	Voc [V]	Fill factor [%]	Effici-ency [%]	Power [W]
IBC Cu	9.622	2.603	74.6	19.55	18.69
IBC Al+CS	9.465	2.602	74.9	19.33	18.44

3.2 Powder coated encapsulant

To develop a module manufacturing process using powder coated encapsulant, a commercially available powder based on thermoplastic material was used. With this powder layers were applied on glass and solar cells. Optimisation was required to find the right deposition conditions of the powder, the uniformity in the applied layer and the conditions to pre-heat the powder to enable handling of the coated component.

After optimization, thicknesses of 150-200 µm were applied on glass and thicknesses of approximately 130 +/- 20 µm on solar cells. Further optimization is required to reduce the thickness of the powder coated encapsulant to below 100 µm with a variation of less than +/- 10 µm between the solar cells. The glass and solar cells with applied powder coated encapsulant were used to produce MWT mini-modules; see Figure 11.

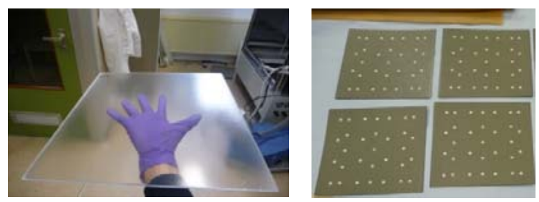

Figure 11: Powder coated and pre-heated glass and solar cells (contact areas are cleaned from encapsulant before pre-heating using the contact point cleaner)

Reference modules were produced using fast cure EVA from STR. The modules were measured using the Pasan. The average performance values of the modules are mentioned in table III.

Table III: Average IV characteristics for modules with fast cure EVA (Reference EVA) and powder coated encapsulant (thermoplastic A)

	Isc [A]	Voc [V]	FF [%]	Power [W]
EVA	8.75	2.52	75.9	16.66
Thermoplastic A	8.81	2.52	75.9	16.82

The results shows that the Isc for modules using thermoplastic A is slightly higher than for the reference modules with EVA. The current gain could be explained by the higher transmission of the applied thermoplastic or be the result of the expected lower absorption due to the thinner encapsulant thickness.

Applying encapsulant thicknesses of 100 µm or less for module manufacturing offers the possibility to print adhesive dots with a lower stencil thickness and maintain the same aspect ratio. In table III the amounts of conductive adhesive are depicted when conductive adhesive is printed using a 400 µm thick stencil and hole diameter of 1.7 mm (stencil A) compared with 200 µm thick stencils and a hole diameter of 1.0 mm (stencil B).

The adhesive dots were printed on bare solar cells. For comparison conductive adhesive has been printed on solar cells that were powder coated with a thermoplastic encapsulant with a thickness of approximately 130 µm.

Table III: Printed grams of conductive adhesive on solar cells with and without powder coated encapsulant

	Bare solar cell	Cell + encapsulant
Stencil A	0.085	0.155
Stencil B	0.018	0.036
Gain B-A	79%	78%

From these results it is clear that printing on solar cells with encapsulant roughly doubles the amount of adhesive required compared to printing on solar cells without encapsulant. If thinner stencils are used, the saving in conductive adhesive for printing on solar cells with or without applied encapsulant is approximately 78% . This indicates that the presence of encapsulant has no influence on the savings of adhesive. Comparing the printed grams on solar cells using the 400 µm thick stencil and 1.7 mm holes, approximately 60% less adhesive is consumed using the 200 µm thick stencil and 1 mm holes and printed on solar cell with powder coating.

Powder coating of encapsulant on a solar cell has technical advantages over punching holes in encapsulant foil, because of the elimination of a punch-unit. The application of encapsulant is done in the processing sequence before the printing step of the conductive adhesive. The amount of applied conductive adhesive is a factor 2 higher for cells with the encapsulant than for cells without encapsulant. The applied conductive adhesive using stencil A (required for 200 µm encapsulant thickness) on solar cells without powder coated encapsulant is compared to the combination stencil B and solar cell with encapsulant. It has been observed that with encapsulant thicknesses of 130 µm applied on solar cells there is already a saving of conductive adhesive of approximately 60%. Further savings in conductive adhesives are expected for printing on solar cells where an encapsulant with a thickness of 100 micron or lower is applied.

3.3 Calculation cost reduction PV modules after implementation copper cold spray and powder coated encapsulant

First cost calculation studies have been done using several assumptions. They reveal that the module components are contributing to approximately 1/3 of the total module cost price (see figure 15 upper figure). From this part, the conductive back-sheet, conductive adhesive and encapsulant contribute approximately 45% (see figure 15 lower figure) which amounts to 15% of the ~total module costs.

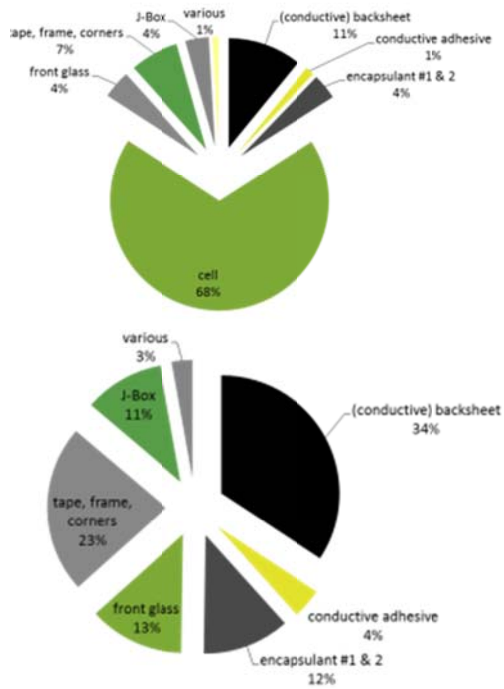

Figure 15: Build-up module cost (upper figure) and the contribution of the several module material costs (lower figure)

In order to reveal the cost reduction potential of the replacement of copper by aluminium, assuming that all other factors remain the same, the following calculations were made. As a starting point we assumed copper and aluminium price levels to be €3,-/m^2 and €0,75/m^2 respectively The cold spray process is optimized such that the powder consumption is approximately 3 g/m^2 (as mentioned earlier in this paper 5 g/1.6 m^2). By using the lowest price of the copper powder mentioned in this paper, a price of €0,13/m^2 can be calculated for the copper powder, which does not include the potential revenue of recycled powder. There are potential copper powder suppliers in the market who aim at a further reduction of the copper price to a level of around €20,-/kg. Before implementing use of this powder additional research needs to be done to test deposition conditions and to find out if this material also leads to reliable PV modules.

As shown in this study with optimized powder coated encapsulant on solar cells at a thickness of 130 µm, so far a reduction of 60% in conductive adhesive consumption has been achieved. This already leads to a cost reduction of more than 2% per module. Further reduction of the adhesive is expected to be feasible after further reduction of the encapsulant thickness and optimising the stencil aspect ratio to minimize the adhesive consumption without increasing the contact resistance between solar cell contacts and conductive back-sheet and maintaining the reliability.

4 CONCLUSIONS

The work presented in this paper summarises two approaches to reducing the cost of back-contact modules made using MWT or IBC cells. The first approach concerns the use of an aluminium conductive back-sheet with a very thin and locally applied copper coating, realized by using cold spray technology. Similar performance and reliability are observed when compared to the current back-contact module build.

The second approach concerns the use of powder coating technology for the deposition of encapsulants with a thicknesses lower than 100 microns, resulting in a significantly reduced conductive adhesive consumption. The potential of this technology, in terms of processing, has been demonstrated by very good initial performances of back-contact modules using thermoplastic powder encapsulants compared to reference modules with standard EVA encapsulation. Further investigations are ongoing to test novel powder encapsulants with the aim to show improved reliability.

An overall cost saving approaching 5% should be possible by combining the two approaches, which would significantly increase the competitiveness of back-contact modules with MWT or IBC cells when compared with conventional modules.

5 ACKNOWLEDGEMENTS

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