Cell metallization by screen printing: Cost, limits and alternatives

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ABSTRACT
Although considerable progress has been made in reducing the amount of Ag required per wafer in the classic screen-printing metallization of Si solar cells, the total cost of ownership of the metallization process today accounts for more than 50% of the total cell-process-related cost. There has been pressure on cell and module manufacturers to further reduce this cost, by either improving the metallization process or applying alternative contacting technologies. In this paper, the classic screen printing of standard Si-based solar cells, which has been the main metallization technique for many years, is described in detail. The required paste volume for providing the contacts in a state-of-the-art cell production process is calculated on the basis of the contact dimensions (fingers and busbars on the front, Al layer and Al/Ag pads on the back). Taking into account today's paste prices, equipment investment, screen cost, energy, maintenance, yield, material utilization and necessary labour, the total cost of ownership of the cell metallization is also determined. The main cost drivers are discussed in detail. The cost reduction is estimated when improved printing processes – such as double, dual or stencil printing – are employed. Other promising alternative front-contact metallization technologies are listed and their potential is briefly discussed. To evaluate the competitiveness of these technologies, the limit of today's screen-printing method and its further cost-reduction potential are estimated on the basis of the physical properties of cells and printing pastes.

Introduction

The screen printing of Si solar cell contacts with silver- and aluminium-based pastes was first reported in 1975 [1]. Since then, screen printing has evolved to become the dominant contact metallization technique: more than 95% of today's wafer-based commercial Si solar cells feature screen-printed H-pattern Ag contacts on the front side and a full-area Al contact with Al/Ag solder pads on the rear. Commercial screen-printing equipment today is fully automated, and the process is simple, reliable and robust while providing high throughput. Many different suppliers exist for manufacturing tools, printing screens and pastes.

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Significant progress has been made in efforts to reduce the amount of Ag required per wafer, but the total cost of ownership of the metallization process today still accounts for around 50% of the total cell-process-related cost. Cell and module manufacturers are consequently investigating ways of further reducing this cost, for example by improving the metallization process or employing alternative contacting technologies.

In this paper, the total cost of ownership of the classic screen-printing metallization of standard Si-based solar cells is calculated taking into account all relevant data in a cell production line. Furthermore, estimates are given for the cost reduction in the case of improved printing processes, as well as for the cost limit determined by the physical properties of the cell device and pastes. Several promising front-contact metallization technologies are listed and discussed, along with potential hurdles for their industrial introduction.

Front side

On the front side of the cell, the metal grid consists of silver paste. The main structure consists of the fingers (which collect the current from the emitter of the solar cell) and the busbars (which collect the current from the fingers and provide the solder contact area to the ribbons when a string is formed). The standard structure of the front contacts nowadays is the three-busbar design: the fingers usually have a spacing of 2–3mm and a width of 60–100µm, the busbars are 1.5–2mm wide, and the height of the structure is approximately 25µm. Many different and partially conflicting requirements of the front-side grid and the respective Ag-based paste have to be fulfilled:

- Low shadowing area.
- Minimum contribution to the series resistance of the cell: low contact resistance to the emitter and low finger bulk resistivity.
- Grid fingers with a high aspect ratio to allow both a low fraction of shaded cell area and a low series-resistance contribution.
- Low silver usage to save material cost.
- Sufficient etching of the paste through the SiN_x anti-reflection layer, to form good electrical contacts.
- Adequate adhesion to the Si wafer.
- Good solderability for string formation.
- High reliability/durability when the cells are deployed for field operation.
- High print quality, with a minimum number of finger interruptions and a homogeneous structure, even for fine-line printing.
- Paste with a long shelf and pot life, constant and stable rheology, and no critical agglomerates or segregations.

Being one of the best conductors, silver in the form of powder is the main paste component, with 70–85 wt%. At low temperatures silver does not react with SiN_x and Si: therefore, 1–10 wt% lead-borosilicate glass powder is typically added to the paste – its main task is to etch through the SiN_x layer and to establish an electrical and mechanical contact to the silicon. The binder and solvents are used to tune and guarantee good printing properties and a high shelf life.

The efficiency losses related to front-side metallization are due to:

- Recombination of photo-generated charge carriers (not discussed here).
- Shadowing of 5–10% active cell area (resulting mainly in short-circuit current – I_{sc} – loss).
- Series resistivity contribution of the finger contact resistance and the finger bulk resistivity (resulting in fill factor – *FF* – loss).

To keep the active area loss at a low level, the finger width has to be reduced; however, in order to avoid the resulting high series resistance losses, the finger height – i.e. the aspect ratio of the fingers – has to be increased.

Rear side

In comparison to the front side, the requirements for the rear-side metal contact are relaxed, since the main material – aluminium – is less expensive, and the dimensions of the printed structures are not in the critical range with respect to the screen geometry. Thick-film pastes for the metallization of the boron-doped base are applied to the full cell area: therefore, neither a low specific contact resistance nor a high aspect ratio is required. For this type of paste the challenge is to reduce recombination on the rear side of the cell. In common industry-standard cells, a heavily doped p region – or back-surface field (BSF) – is introduced below the metal contact. This is realized by using aluminium as the active metal in the rear paste, because it acts as a p type dopant in silicon.

The rheology of an Al paste for full-area metallization is different from that of a front-side paste. The binder and solvent have to ensure that the substrates do not stick to the screen after a printing step. The paste must be deposited with a homogeneous thickness over the whole area. The viscosity of the paste compared with front-side pastes is therefore often lower. Glass is not necessarily added to a rear-side paste.

An important consideration for Al pastes is the coefficient of thermal expansion (CTE) during drying and firing. The CTE is optimized for minimum mechanical stress, and therefore lowest possible wafer bowing, which reduces cell breakage rates in manufacturing.

As aluminium in not solderable, the contact area for the interconnection with ribbons on the rear side is provided by Ag/Al pads, and the rear-side Ag paste for these pads has a lower Ag content than the front-side Ag paste.

No. of fingers	78	No. of busbars	3
Finger width	80µm	Busbar width	1.5mm
Finger height	25µm	Busbar height	25µm
Finger length	14.95cm	Busbar length	154mm
Finger area	9.33cm^2	Busbar area	6.93cm^2
Finger volume	0.0233cm^3	Busbar volume	0.0173cm^3
Finger area fraction	3.83%	Busbar area fraction	2.85%
Total area covered	16.26cm^3	Total paste volume	0.0407cm^3
Cell area	243.36cm^2	Paste density	3.25g/cm^3
Shaded area	6.68%	Ag paste required	0.132g

Table 1. Front-side properties.

Screen printing and firing process

For the printing process, a fine-mesh print screen, mounted within a frame, is placed over the wafer; the screen blocks off certain areas and leaves other areas open, where the printing paste can penetrate. After a predefined amount of paste is dispensed onto the screen, a squeegee distributes the paste over the screen, to fill the screen openings: as the squeegee moves across the screen, it presses the paste through the screen openings and onto the wafer surface. In order to obtain a high print quality, this process must be tightly controlled for temperature, squeegee pressure, angle, speed, screen and squeegee materials and properties, paste specifications, etc. [2].

After each printing step, the wafer proceeds to a drying furnace to solidify the paste at a temperature of 200–300°C for typically 20–120 seconds, depending on the specific pastes being used. The wafer is then transferred to another printer for printing additional lines on either the front or rear side of the wafer. When all printing steps have been completed, the wafer is 'co-fired' in a high-temperature furnace, where the final formation of the contacts – especially the etching of the SiN_x and the formation of the BSF – takes place at temperatures of around 850°C. Since both the back- and front-side contacts form at the same time and same sequence in the process, this step is called 'co-firing'. Because the front-side requirements are more stringent, the firing process is optimized for the front-side metallization, and on that basis, the rear-side metallization is adjusted to suit these firing conditions.

No. of pads	18
Pad size	0.2025cm^2
Al laydown	5.50mg/cm^2
Al-coated area	239.715cm^2
Al paste required	1.318g
Ag/Al laydown	4.2mg/cm^2
Ag/Al pad area	3.645cm^2
Ag/Al paste required	0.0153g

Table 2. Rear-side properties.

The metallization – in particular the firing stage – is the most complex process step in the production of industrial solar cells: in none of the other steps do so many processes occur simultaneously.

> "The metallization is the most complex process step in the production of industrial solar cells."

Detailed grid dimensions and paste usage

In determining the amount of paste that is required for the formation of a state-of-the-art front- and rear-side metallization, the paste properties and dimensions shown in Tables 1 and 2 are assumed. With these assumptions of 80µm finger width, 25µm finger and busbar heights, and 1.5mm busbar width, the requirements per wafer are 132mg Ag paste for the front-side grid, 1318mg Al paste for the rear side, and 15.3mg Ag/Al paste for the rear-side solder pads. The shaded front-side area is about 6.7%.

It is assumed that 130mg of Ag paste per wafer is today's best-in-class result in high-volume industrial production by using off-the-shelf screen-printing equipment and high-quality screens and Ag pastes in a one-step printing process.

Because of cost-saving pressure, Ag usage has significantly decreased in recent years. Yet, in 2010 the Ag usage was around 300mg per wafer [3]. The reduction in silver consumption has been realized by the following improvements:

- Lower contact resistances, allowing narrower fingers without fill factor losses.
- Rheology adjustments to permit the printing of finer lines with better homogeneity and aspect ratio. Clogging of the fine meshes by paste agglomerates is reduced.
- Screen printers that have greater accuracy.
- Screens with finer meshes, so that finer finger lines without finger interruptions can be printed.

Total cost of ownership calculation

The basic assumptions for this calculation are as follows:

1. Screen printer and production numbers

Throughput is 3200 wafers/hour, corresponding to about 100MW/year, with 18% cell efficiency, consisting of three print heads, three drying ovens and one firing furnace. Necessary building space is around 200m². Specified wafer breakage rate is <0.15%. Number of production days per year is 360, with 24/7 four-shift operation. Equipment uptime is 90%, metallization line yield is 99.7% (0.15% breakage and 0.15% optical/electrical loss). Cells with 18% efficiency (4.2Wp) are used, and each scrapped cell in the metallization line is accounted for by a cost of €0.8.

2. Investment

Depreciation time for this calculation is five years. Investment for metallization line – including dryers, firing furnace and screen-washing station, but with no advanced quality-control systems or manufacturing execution system (MES) – is €2,500,000.

3. Labour cost

In a production configuration with multiple metallization lines and 24/7 four-shift operation, it is estimated that one engineer (€50,000/yr), four technicians (€35,000/yr) and eight operators (€20,000/yr) are necessary per metallization line of 3200 wafers/hour.

4. Energy cost

Average power consumption of 100kW is estimated for the operation of the line, including technical supply. Energy cost of €0.06/kWh is accounted.

5. Building and technical infrastructure cost

Around 200m² floor space per line is necessary. Building cost, including technical infrastructure, is accounted at €2500/m².

6. Maintenance cost

Estimate of 5% yearly of initial equipment investment is reckoned for maintenance of the metallization line, including technical infrastructure but excluding printing screens.

7. Printing paste required per wafer

According to the dimensions assumed in Tables 1 and 2, ~0.13g Ag paste for the front-side grid is calculated. For the rear side, ~1.3g Al paste and ~0.015g Ag/Al paste per wafer is needed. Paste laydown for the rear side is in accordance with the specification of leading paste suppliers. Material utilization of 98% is estimated.

8. Paste cost

The selling prices of Ag-containing pastes are usually coupled to the Ag world market prices. For this calculation, the price assumptions are €750/kg for the front Ag paste, €600/kg for the rear-side pad paste, and around €18/kg for the Al paste.

9. Printing-screen cost

Printing screens generally have a wide window of cost vs. quality (i.e. maximum number of good prints). Values of €100 per 10,000 print steps for front-side screens and €28 per 10,000 print steps for rear-side screens are assumed.

> "The total cost of ownership is dominated by the materials cost."

When all the above data is fed into the cost model, the results shown in Table 3 are obtained. The total cost of ownership is €ct4.69/Wp and is dominated by the materials cost, which together add up to €ct3.18/Wp, or around two-thirds of the total cost. The cost of the Ag front-side paste, at €ct2.38/Wp, contributes to over 50% of the total value (Fig. 1). Other main cost drivers are, at close to 10% each, production equipment investment (10.2%), labour cost (7.2%) and screen cost (8.0%). The other categories – maintenance, building investment, energy and scrap – collectively account for around 7% of the total cost.

	€ct/Wp	%
Scrap	0.06	1.2
Investment	0.48	10.2
Labour	0.34	7.2
Energy	0.05	1.1
Building	0.10	2.0
Maintenance	0.12	2.6
Ag paste	2.38	50.6
Ag/Al paste	0.23	5.0
Al paste	0.57	12.1
Screens	0.38	8.0
Total	4.69	100.0

Table 3. Total cost of ownership as calculated using PICON Solar's model.

When the total cost is divided between the front and rear sides, around two-thirds (€ct3.18/Wp) is attributable to the front contact and one-third (€ct1.51/Wp) to the rear contact (Fig. 2).

The Ag paste for the front side is the main cost driver and its price is very unstable. As already mentioned, the paste consists of 75–85% silver. Usually, manufacturers link the selling price of their pastes to the Ag cost on the world market at the time of ordering. The above metallization cost of around €ct4.7/Wp is calculated on the basis of a silver paste cost of roughly €750/kg. If it is assumed that 80% of the selling price of the paste is coupled to the Ag market price, and this assumption and the last five years' extreme Ag stock prices of $10 and $50 per troy oz [4] are transferred to PICON Solar's cost model, the cost of screen-printed cell metallization might be as low as €ct4/Wp or as high as €ct8/Wp.

The high sensitivity of paste cost to the Ag market price is a serious issue for cell and module manufacturers. PV has been one of the main drivers for the increase in Ag market volume during the last 10 years. In 2013 the PV-generated silver demand was around 100M ounces, which already corresponded to 15% of the world Ag market [5].

> "PV has been one of the main drivers for the increase in Ag market volume during the last 10 years."

It is not within the scope of this work to project future Ag prices, or future PV production and its influence on

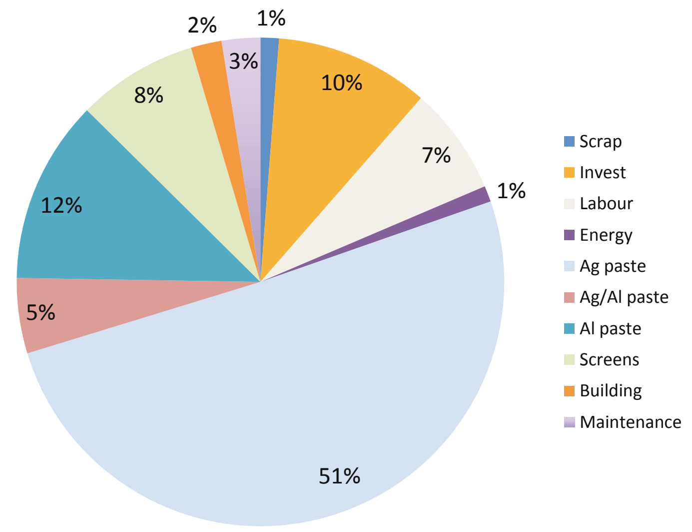

Figure 1. Metallization process cost structure.

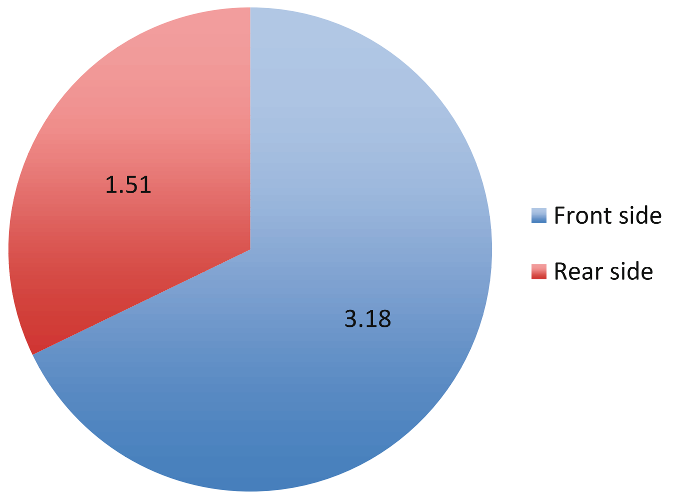

Figure 2. Costs related to front and rear contacts.

silver paste cost. However, it needs to be stated that this factor represents a major uncertainty in predicting the future cost of Ag-based screen printing, and that this fact is important if alternative metallization methods are considered.

Cost limits of screen-printing technology

Dual-printing and double-printing methods allow the aspect ratio of the finger lines to be increased and/or the printing of busbar and grid lines to be decoupled using different screens and pastes which are adapted to each purpose. Ideally:

- The grid lines are ≥20µm high and optimized for contact as well as bulk resistance.
- The busbars are ≤10µm high and are optimized for bulk conductivity. To avoid very powerful short circuits under the busbars, the paste should not etch the SiN_x, i.e. should not contain glass frit.

The two printing processes are defined as follows. *Double printing*, in theory, means to print two identical structures one on top of the other; this helps to achieve a better finger aspect ratio, because the lower height allows more accurate paste transfer, and drying after each printing step stabilizes the paste, keeping it from spreading. *Dual printing*, in theory, means to print the grid lines and the busbars separately; this allows two different structures of different heights and with different pastes to be printed.

In practice, however, double printing is often combined with dual printing, and this can be accomplished as follows. In the first step, the grid fingers of ~10µm in height are printed using a contact-optimized paste, and then dried. In the second step, the complete H pattern of ~10µm in height is printed exactly over the first print pattern, but with a paste optimized for bulk conductivity, and then dried again. The double/dual-printing approach offers a combination of features:

- An improved aspect ratio for the grid lines (i.e. less cell shadowing), with no increase in series resistance.
- A 50% saving of Ag paste for the busbars.
- The avoidance of shorts under the busbars by using a non-etching paste, thus improving cell performance.

As a result of the geometrical grid model, it is estimated that the cell efficiency can rise by 1–2% (relative), and that the Ag front-side paste usage can be reduced by around 35%. The drawbacks of this approach are that the alignment precision of the first and second print steps must be better than ±10µm, otherwise there will be finger interruptions or the fingers will be too wide. To achieve this alignment accuracy between the two printing steps, there are several requirements:

- The machine precision must be improved to enable the screen frame to be accurately positioned.
- Alignment marks on the cell together with an optical control system must be used for automated overlay positioning.
- A high matching accuracy of ±5µm and distortion-free screens (≤10µm over the lifetime) must be used to allow good overlay.

As additional investment for this process, another print head and drier are necessary, advanced process control for alignment and screen distortion monitoring needs to be implemented, and high-quality screens must be used. On the basis of the additional tool investment, the higher front-side screen cost and the increased engineering labour cost to maintain the more complex process, a payback period of around two years is calculated.

The principal cost limit of the Ag-paste-based H-pattern screen-printing technology will be discussed next. The current standard process is basically limited by two factors:

- The printing of fine lines with a high aspect ratio, while keeping the screen cost and equipment/process complexity low.

- The use of pastes having mechanical properties suitable for fine-line printing, low contact resistance for high-ohm emitters, and high finger conductivity.

On the assumption that these aspects will be further improved in the next few years, a theoretical calculation can be carried out to determine the minimum amount of silver paste needed for optimized Ag grids. Hannebauer et al. [6] calculated the optical and electrical loss contribution of the grid as a function of paste resistivity, finger width, and aspect ratio. On the basis of a realistic aspect ratio of 0.5 and state-of-the-art and future-optimized pastes (a quarter the contact resistance and around twice the finger conductivity compared with today's values), an optimum finger width in the range of 30–35µm is calculated. If, additionally, segmented busbars (1.5mm in width, 12µm in height) are assumed, and these values are fed into the geometrical model, the result for the standard three-busbar H-pattern geometry is a Ag paste usage of about 40mg for the front side.

With similar assumptions to those for double/dual printing (increased equipment investment, engineering resources, screen cost), the result is a total cost of ownership that is higher than the low silver consumption suggests.

An overview of the cost of ownership for the single-print and double/dual-print approaches and the future 40mg scenario, as a function of current, halved or doubled Ag paste prices, is given in Fig. 3.

The cost advantage of reduced Ag paste usage is not as pronounced as might be expected, because it will be partially counteracted by the higher screen cost and increased process and equipment complexity. However, in the case of rising Ag prices, the advantage is very clear.

"The cost advantage of reduced Ag paste usage is not as pronounced as might be expected."

Potential alternatives

Other possible options are in principle the following lines of approach:

1. Retain the printing process:
   (a) use non-Ag-based pastes, or
   (b) stay with Ag and reduce requirements by employing an alternative cell interconnection.

2. Integrate an alternative metallization process:
   (a) stay with Ag and reduce consumption, or
   (b) keep Ag as a seed layer and use low-cost bulk conductor material, or
   (c) completely replace Ag by other materials.

A full discussion of all alternative processes, materials and methods is beyond the scope of this paper, but some general thoughts should be given on a few of the ones for which industrial application is imminent:

- The *multi-busbar approach* belongs to category 1(b) above. Theoretically, with a 15-wire geometry, reduced series-resistance loss and greater active area, the cell efficiency could be increased compared with a three-busbar setup [7]. An effective electrical grid finger path length of around 5mm means that the need for high aspect ratio grid fingers is greatly relaxed and 17µm-wide fingers would be sufficient. This would result in a theoretical silver paste requirement of less than 10mg per Wp [7]. While requirements of less than 70mg have already been published, a further significant reduction would demand techniques other than grid screen printing, such as ink jetting an Ag seed layer and adding a cheaper bulk conductor by plating. Concerns from the authors' point of view are the higher equipment investment in modified stringers and the increased string/module scrap in production as a result of the soldering and handling of fragile multiwire strings.

- The *smart wire approach*, again in category 1(b), also enables improved efficiencies by both lowering the series resistance and avoiding the shading of the active cell area by large busbar structures [8]. In this technique only the finger structures are screen printed on the cell. Copper wires covered with a low-temperature melting alloy, which are integrated in a transparent polymer film, form the contact to the rectangular grid fingers in the lamination process. Again, because of a low effective finger length, high aspect ratio grid fingers are not necessary, and the silver consumption can be greatly reduced. The authors' concern here is that when the low-temperature melting alloy covering the Cu wires is indium based, the cost-reduction potential of this method might be insufficient.

- The *copper plating approach*, which falls into category 2(b) or 2(c), could be implemented in many different ways. An Ag-based paste could still be used to form the contact to Si; as the bulk conductor, Cu

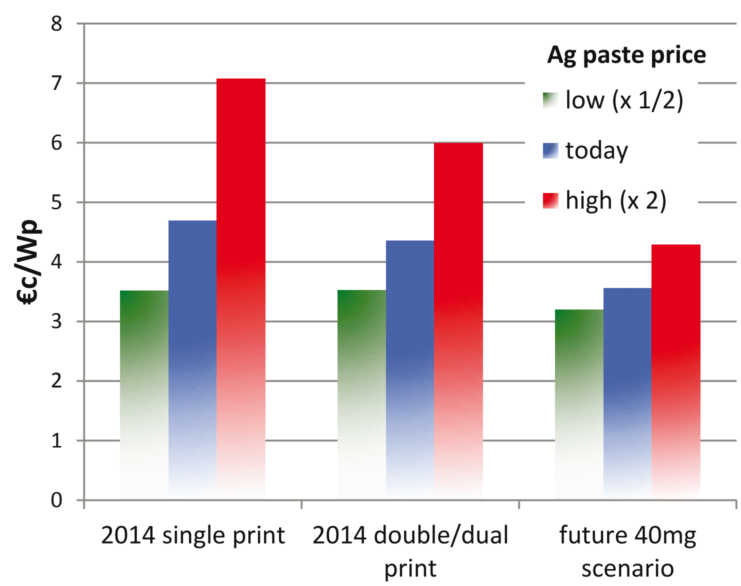

Figure 3. Metallization cost as a function of the type of process and the paste price.

could then be plated on top of the paste, followed by a Sn capping layer for soldering. An even more attractive option appears to be a Ni/Cu/Sn grid structure, with the metal material cost reduced by a factor of around 100. Challenges for this process are, in particular, controlling the formation both of the NiSi contact and of the anti-reflection layer opening (the latter by laser structuring or a chemical etching process). The authors' concerns are possible reliability issues due to Cu diffusion, especially in the case where no masking layer is applied during copper deposition. If a masking layer were applied, the process might become too complex and consequently expensive.

Conclusion and outlook

From a cost perspective it is clear that potential alternative metallization processes need to demonstrate a total cost of ownership today below €ct4.7/Wp, and a cost-reduction roadmap that targets a value significantly below this.

> "Achieving a sufficient cost-reduction potential for the front side is one of the major challenges."

For all alternatives that are relatively close to being industrially applied, the authors believe that achieving a sufficient cost-reduction potential for the front side is one of the major challenges. Besides this, reliability-related concerns as a result of introducing new methods, especially with respect to compatibility with various material combinations in a PV module, have to be eliminated. Performance stability in the face of accelerated testing under standard and certain non-standard IEC conditions must be ensured, which might be a huge hurdle for the introduction of a new technology into mass production. Additionally, for all alternative contacting and interconnection methods, it needs to be proved that sub 160–180µm wafers can be handled without a significant increase in production scrap.

Rising Ag market prices in the future, however, will intensify the pressure on cell and module manufacturers to pursue alternative methods. A detailed investigation of the cost and reliability of these methods will reveal which alternative process is the best option for the future.

References

[1] Ralph, E.L. 1975, "Recent advancements in low cost solar cell processing", *Proc. 11th IEEE PVSC*, Scottsdale, Arizona, USA, pp. 315–316.

[2] Pan, J. et al. 1998, "Screen printing process design of experiments for fine line printing of thick film ceramic substrates", Report No. 98T-012, Lehigh University, Bethlehem, USA.

[3] SEMI PV Group Europe 2012, "International technology roadmap for photovoltaic (ITRVP): Results 2011", 2nd edn (March) [http://www.itrpv.net/Reports/Downloads/].

[4] SILVERPRICE [www.silverprice.org].

[5] Thomson Reuters Gold Field Metal Services 2011, "The future of silver industrial demand".

[6] Hannebauer, H. et al. 2013, "Record low paste consumption of 67.7mg with dual print", *Energy Procedia*, Vol. 43, pp. 66–71.

[7] Braun, S. et al. 2013, "The multi-busbar design: An overview", *Energy Procedia*, Vol. 43, pp. 86–92.

[8] Meyer Burger 2013, "SmartWire Connection Technology" [http://www.meyerburger.com/en/products-systems/technologies/photovoltaic/swct/].

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