Printing Techniques in the c-Si PV Industry – a Brief Technological Overview

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Printing technologies have been applied in mass production of crystalline silicon solar cells for several decades. This article intends to give a brief overview of current and emerging printing techniques in this field by showing their application spectrum as well as their advantages and drawbacks.
In the 1970s, the introduction of thick-film printing technology enabled the photovoltaic (PV) industry to move away from expensive and slow evaporation processing in combination with photolithographic structuring for the metallization of crystalline silicon (c-Si) solar cells. By using the screen printing method to create the front and back contact of the solar cell a comparatively easy, reliable and fast process was established. Today screen printing is the dominant metallization method for cost-driven and mass produced terrestrial solar cells. But screen printing is only one out of several printing technologies that may be applied. And the metallization step is also just one out of several process steps that can be realized by a printing method. This article intends to give a brief overview of current and emerging printing technologies used in the production of crystalline silicon solar cells.

Printing technology has been applied in the c-Si photovoltaic industry for several decades now. Being a classic reproduction technique it is well established as a structuring technology which allows for cost-efficient mass production at high throughput rates. Through further research and development in this field, printing technologies take part in the recent progress of renewable energy to become capable of competing with fossil and nuclear energy production.

How does a mass produced c-Si solar cell look like?

A solar cell is a semiconductor device that enables the conversion of light energy into electrical energy. Crystalline silicon is used as base material of a standard mass produced terrestrial solar cell. The single wafer (thickness ~200 µm, format up to 210x210 mm² but today in most cases 156x156 mm²) used as solar cell substrate is cut from a silicon block which is doped with boron to create a p-type doping of the base material. The highly doped n-type emitter on the front side (= side where sunlight is irradiating) is created in a high-temperature diffusion step under a phosphorus containing atmosphere. At the interface of these two contrarily doped layers the so called p-n-junction is formed. In this region, the free electron-hole-pairs which are generated by the irradiated light energy are separated, enabling a current flow. To reduce optical reflection losses, two process steps are carried out: (i) a wet-chemical etching step textures the surface and enables more efficient light trapping and (ii) an anti-reflection coating is applied to the front surface. This silicon nitride coating, typically produced by plasma-enhanced chemical vapor deposition (PECVD), further enhances light trapping and additionally passivates the silicon surface. To enable the generated current to be transported to a load, metallic contacts on both sides of the cell need to be applied. The rear surface is typically covered with solder areas surrounded by an aluminium layer. Both layers are commonly deposited by means of screen printing. The solder pads are printed with a silver or silver/aluminium paste. These areas correspond to the busbars on the front side because the single cells are interconnected by copper strings from the rear side to the front side in module fabrication. The aluminium layer has the function to contact the rear side, laterally conduct the current and to overcompensate the parasitic n-emitter, which is created during diffusion since this process step is not side selective, but covers the entire wafer surface. The mentioned overcompensation results in a highly doped p-region, which also reduces recombination of carriers at the rear side. On the front side, a metallic finger structure with two or also three so called busbars for later cell interconnection is created by screen printing silver paste. In order to perform the above described processes, the metallization sequence is completed by a high temperature process at 800°C. Finally, the still existing parasitic emitter at the wafer edge needs to be interrupted so that no short circuit occurs between front and rear side. This is typically done by creating a laser groove near the edge or by a wet-chemical removal of the whole rear side emitter sooner in the cell production process. By far, most of the produced crystalline silicon solar cells follow this or a similar process scheme enabling an energy conversion efficiency of 15-18% depending on the used silicon material type and process scheme. Figure 1 shows a typical structure of such a standard crystalline silicon solar cell.

Figure 1: Schematic drawing of a standard mass produced crystalline silicon solar cell.

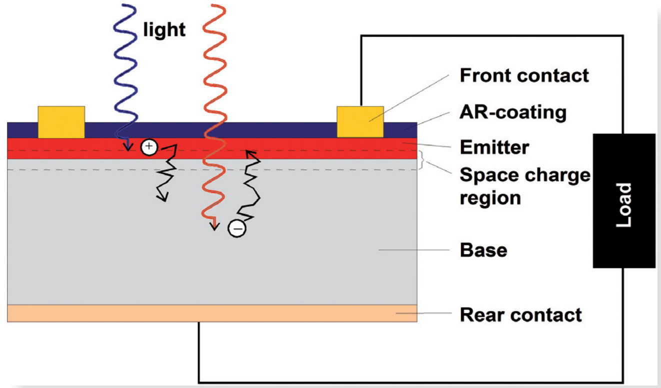

Figure 1: cell-scheme

Figure 2: Front side of a standard c-Si solar cell with conductive lines and three busbars for cell interconnection (2b) and standard rear side with aluminium layer and three silver stripes for cell interconnection (2a).

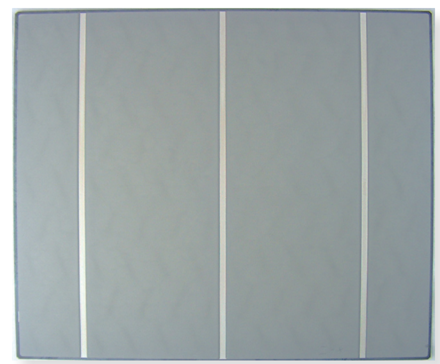

Figure 2a: rearside

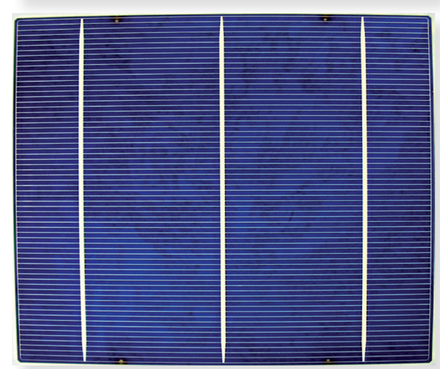

Figure 2b: frontside

Which process steps can be realized by a printing method?

The following processes in solar cell production are or can be realized by means of printing technologies.

(i) Emitter creation
Instead of a deposition and diffusion of phosphorus in a tube furnace, a dopant paste containing a phosphorus source can be screen printed onto the wafer. After drying, the wafer is treated with a high-temperature process where the phosphorus diffuses from the printed layer into the silicon [1].
(ii) Rear side metallization
In mass production, this step is typically carried out by screen printing and, although more rarely, pad printing. Figure 2a shows a typical rear side layout with solder pads surrounded by aluminium.
(iii) Front side metallization
As state-of-the-art technology screen printing is used to create the front side contact structure (Figure 2b). Other techniques like stencil printing [2,3,4,5], pad printing [6,7,8], ink jet printing [9] and aerosol jet printing [10,11] are possible. The next chapters will give a more detailed insight into this process step and its requirements as well as feasible technologies.
(iiii) Edge isolation
This step can also be realized by printing methods, e.g. by screen printing, ink jet printing or dispensing an etching paste that chemically removes the emitter at the wafer edge [12,13].

Light and shadow: The solar cell front side

Sunlight enters the solar cell on the front side. The more radiation penetrates the cell, the higher is the possibly generated power output. The generated current laterally flows within the emitter layer to a conductive metal line in which it is transported to one of the busbars which are later connected to a load. It is apparent that no light can enter the cell where the metallization grid is located. A conventionally screen printed front side grid results in a shadowed area fraction of approximately 7-8% of the cell area. Around 30-40% of the covered area corresponds to the busbars which are needed for cell interconnection inside the module. Due to process requirements (soldering of copper strings to interconnect cells) in module fabrication, the busbar width can not be reduced below 1.5 mm at this stage of development.

Therefore, a lot of efforts concentrate on the reduction of the shadowing loss by minimizing the width or amount of the fine conductive lines. Typical screen printed lines show a width of 100-130 µm and an average thickness of 10-20 µm (Figure 3). By simply reducing the printed finger width through a reduction of line width in the stencil, the electrical loss of the cell increases. This is mainly due to the fact that the cross section area of the printed line is reduced simultaneously, resulting in an increased line resistance [14]. Furthermore the contact resistance between the conductive line and the n-type emitter increases for fine lines below 80 µm line width [8]. This effect may be compensated by printing a larger amount of conductive lines – resulting in an increased shaded area. It is obvious that only a trade-off between both loss mechanisms leads to an optimal cell performance.

With screen printing, the front side metallization is carried out in a single process step. In the last few years an industrially applicable two-step-metallization process has been established based on light induced silver plating [15]. As first step a seed layer which is supposed to create a good contact to the emitter without the need of having good line conductivity is deposited. Therefore, a line thickness of a few microns is sufficient while a line width of < 40 µm is desired. Sufficient line conductivity is assured in a second step by thickening of the seed layer with plated silver (Figure 4).

The vital dinosaur: Screen printing

Screen printing has already been known as thick-film deposition technology in the printed circuit board (PCB) industry when it was introduced to the photovoltaic industry in the 1970s [e.g. 16,17]. In this decade first publications also showed a process in which both sides were metalized by screen printing featuring a single fire-through process [18], a process scheme that is applied in PV industry to this day. In comparison to the requirements in PCB industry, conductive devices had to be produced that do not only transport a signal but electrical energy itself. For screen printing is a fast (and therefore cheap) and reliable thick-film process it later became the most popular metallization method for mass produced crystalline silicon solar cells. Formerly applied techniques like photolithography and evaporation can yield a very high accuracy and capability to create very fine lines < 10 µm, but are too slow and expensive for mass production.

Although screen printing is known in PV industry for more than thirty years, there is still a lot of ongoing development to improve printing results regarding the reduction of line width, the increase of line thickness and the reduction of electrical losses caused by the metallization. As an example, the hotmelt technology may be mentioned. Hotmelt pastes have a melting point of ~70°C so that all components in touch with the paste need to be heated: screen, squeegee and also substrate. It was shown that the application of this method results in an increased line thickness what reduces the line resistance and provides an improved cell efficiency [19,20].

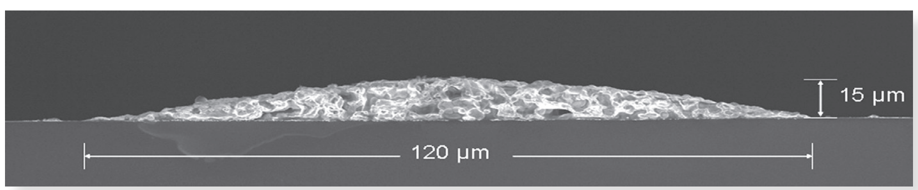

Figure 3: Cross section of a typical screen printed line.

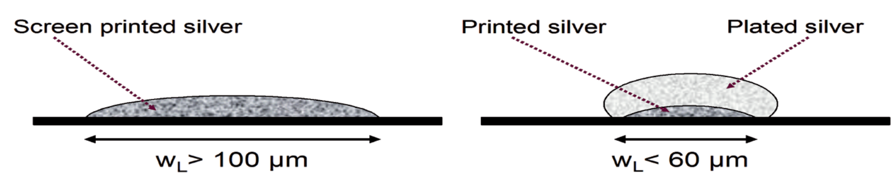

Figure 4: Schematic drawing of a single- and a two-step-metallization concept.

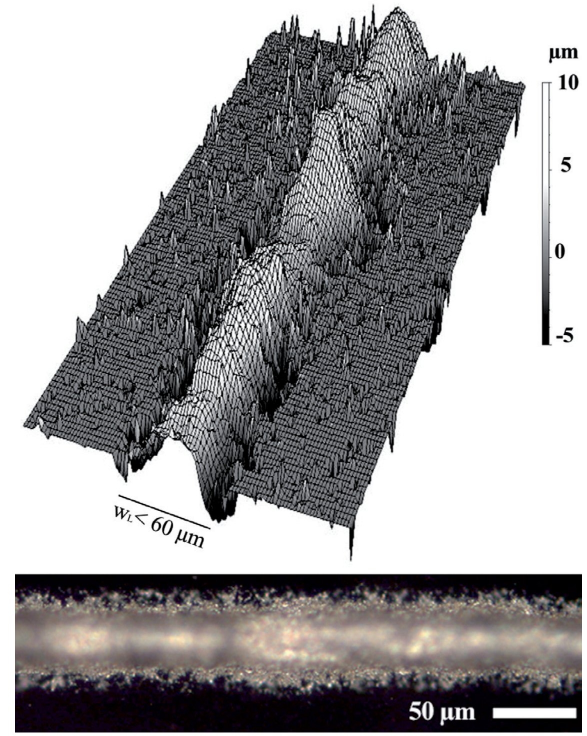

Figure 5: 3D-topography / microscopic picture of a fine screen printed line on textured Cz-silicon surface with a width < 60 µm [22].

A challenge in screen printing is to achieve uninterrupted very fine lines while assuring a stable mass production [21]. It is still ambitious to produce line widths below 80 µm in a production line, depending on the paste and the wafer surface. Especially with a textured mono-crystalline surface consisting of small pyramids, it is challenging to set up a reliable fine line screen printing process due to seepage effects causing the line width to increase. However there is a lot of recent progress in this field showing that even these fine structures might be in reach of screen printing. Processes and methods in laboratory-scale have proved the possibility to print conductive metal lines on a textured mono-crystalline silicon wafer surface with a width below 60 µm (Figure 5) [22]. Even though this printing technique creates thick films compared to other deposition technologies, screen printed seed layers need to be plated afterwards to achieve sufficient lateral conductivity.

It is to mention that a big advantage of screen printing is its flexibility to be used for various applications, whether it is metallization (front and rear side) or deposition of a dopant source, edge isolation or creation of a mask as an etching resist layer [26]. It is especially advantageous when thick films (e.g. aluminium rear side layer: thickness ~ 25-30 µm) are required. Although most efforts in research and development in the field of screen printing concentrate on the front side metallization, the aluminium pastes for the rear side are also further optimized regarding electrical performance and the reduction of the bending effect [23,24,25].

As a similar method stencil printing is a potential printing technology for various applications. Although good results in the field of front side metallization have been shown (e.g. a 50 µm wide line with a thickness of 20 µm [3]), it did not find its way to mass production yet. One possible reason for this may be the H-pattern which is typically used as the front side layout. Bars in the inner of the layout structures are necessary which cause the stencil to get more complex in manufacturing and therefore more expensive. Although this is technically feasible [2,3,4], the stencil cost rises causing this printing method to become economically unattractive compared to conventional screen printing.

Silicone touches silicon: Pad Printing

Pad printing as an indirect gravure printing technique (also called gravure offset) is already used in c-Si PV industry in order to produce small silver areas on the rear side of the cell which function as solder pads for cell interconnection. Even though it has been shown that very fine conductive lines with a width below 50 µm can be printed on the front side (Figure 6) [6,7], this technique is not applied in mass production for this purpose yet. Pad printing is, like screen printing, a reproduction technique that induces mechanical stress to the substrate. As an additional drawback, conventional pad printing is restricted to comparatively small areas (125x125 mm² cell size maximum, standard size is 156x156 mm²) due to the fact that with increasing transfer pad size, the homogeneity of print pressure and thus print quality decreases. An advantage of pad printing is its capability to print on uneven Si-materials like EFG (edge-defined film-fed growth) [6,7]. Due to the low deposited layer thickness, pad printed lines are supposed to function as first step of an above mentioned two-step-metallization process. Still, pad printing is under investigation in PV fields, especially rotational pad printing may be a promising alternative.

Fine and fast: Aerosol jet printing

In recent years aerosol jet printing has been emerging as an alternative metallization technique [10,11]. It was developed to create fine lines on the front side of the cell which function as a seed layer for later plating. Aerosol jet printing is not one of the classic printing techniques but more similar to dispensing or ink jet printing. To enable printing, the silver ink is turned into an aerosol in an atomizer. This aerosol is transported to a deposition head with a nozzle where the particle gas stream is guided by a second gas stream to focus the aerosol and to prevent it from touching the nozzle walls (Figure 7). By this, very fine lines even below 20 µm with a thickness of a few microns have already been shown (Figure 8) [11], promising high cell efficiency. Unlike screen or pad printing, aerosol jet printing is a contactless method. Therefore no mechanical stress is induced to the wafer. This is commonly desired by the industry in order to minimize breakage rates of the fragile silicon wafers. This method is currently on the verge of being applied as a mass production process and is likely to be a good alternative to conventional screen printing.

Drop by drop: Ink jet printing

Ink jet printing is a printing method that is under ambitious investigation to be used as production technology in the PV industry. Like aerosol jet printing, it is a contactless technique having the above mentioned advantages. Ink jet printing may for instance be used in order to deposit a local diffusion barrier to create a selective emitter structure [27]. Another feasible application is to deposit an etch resistant structured mask onto the wafer surface for a later chemical etching step [28,29]. For masking purposes, standard print-heads with multi-nozzle systems (e.g. combined with a drop-on-demand technique) can be used to create droplets in the picoliter range. Mask openings of 10-20 µm have already been achieved with hot melt ink printed onto a textured c-Si substrate [28,29]. With such a process, for instance silicon nitride may be locally opened to create the seed opening of a front side contact. Figure 9 shows such a contact opening that was plated with Ni in order to create a seed layer for later silver plating. The use of ink jet printing for direct front side metallization is also intensively investigated at this point of time. For this purpose, special inks have to be used which need to be filled with nano-particles to prevent the ink from clogging inside the nozzle. Still, the reduction of seepage effects is a challenge because the metal ink is likely to spread after being transferred to the wafer surface. A printed line width of 120 µm on a non-textured Si-Ribbon surface [30,9] and 150 µm on a textured silicon surface [31] has already been reported. Due to the low thickness of the printed layer, silver plating or multi-layer printing is needed to improve lateral conductivity of the line causing the printed structure to be further broadened. Nevertheless, ink jet printing could be a promising alternative to state-of-the-art metallization processes assumed that a reduction of printed line width is achieved.

Coarse, but flexible: Dispensing

Dispensing, well-known from PCB industry, has the advantage of being very flexible regarding printable pastes and applications. Metallization pastes as well as acidic fluids or etch masks can be printed without inducing mechanical stress to the substrate. On a solar cell surface, laboratory experiments showed a line width of 75 µm produced with silver paste [32]. Nevertheless, most applications do only achieve a line width > 150 µm, especially on textured silicon surfaces. Besides metallization, there are other possible applications. One is to deposit an etching paste at the edge of the wafer to locally remove the emitter (edge isolation) [13]. As long as comparatively coarse structures with a high deposited layer thickness are needed, dispensing may function as a flexible and fast deposition method. Still, dispensing is rarely used in PV industry.

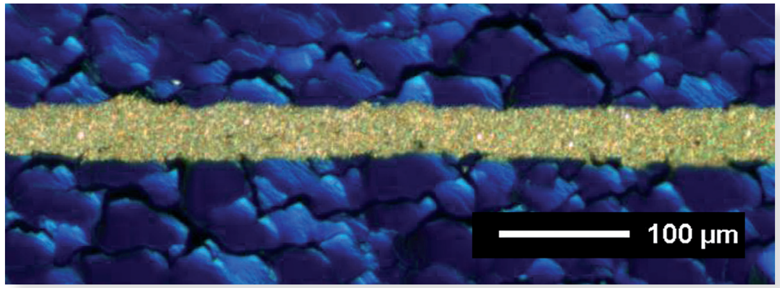

Figure 6:
Picture of a very fine line with a width of 50 µm realized by means of pad printing.

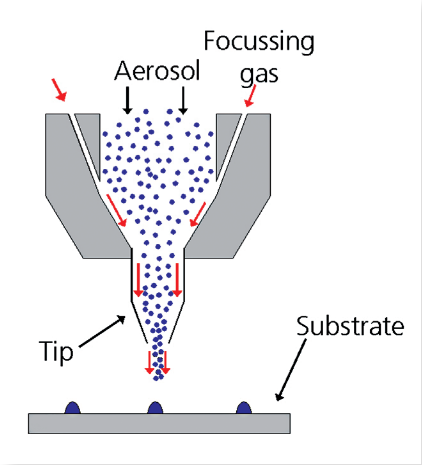

Figure 7:
Schematic drawing of an aerosol jet printing device [8].

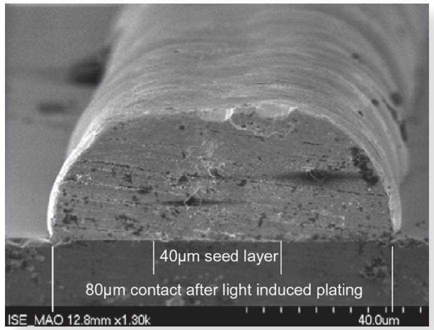

Figure 8:
picture of a fine line with a width of 40 µm realized by means of aerosol jet printing with plated silver on top [11].

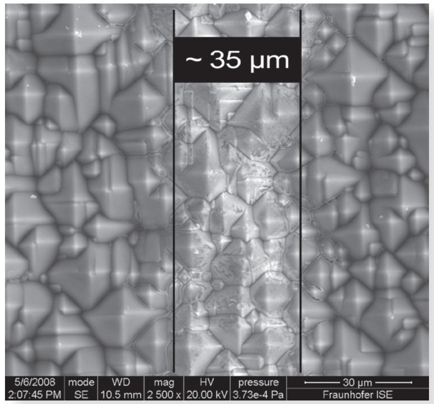

Figure 9:
Seed layer for silver plating on a textured silicon surface. The seed opening in the silicon nitride layer has been produced by ink jet masking and etching followed by nickel plating [29].

What about offset, gravure or flexographic printing?

With pad printing an indirect gravure printing technology has already been found to be usable for PV industry. It would be even more interesting to use it as a rotational process on large cell areas producing fine lines at high throughput rates. It could also be thought of direct gravure printing when using a flexible cliché instead of a metal cylinder. Flexographic printing may be used to create a thin seed layer on the cell front side [33]. Additionally flexographic printing may be suitable to create doping layers or etching masks. Classic offset printing, basing on its hydrophobic / hydrophilic process system seems to be unsuitable for PV needs, but waterless offset printing could be an alternative [32].

Conclusion

Screen printing still is the dominant printing technology in the c-Si photovoltaic industry featuring stable and flexible process possibilities. But there are a couple of other technologies like aerosol jet printing, ink jet printing or pad printing which have a high potential to fit industrial needs and further push solar cell efficiencies. In research and development of silicon solar cells, printing technology as a classic reproduction tool is appreciated as an important part of further development to increase the cell efficiency on one hand and to decrease cell costs on the other hand. This can be seen in the various efforts being made in this field.

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References:

[1] Horzel J., Szlufcik J., et al., „A simple processing sequence for selective emittters", 26th IEEE PVSC (Anaheim, USA), 1997

[2] Van Kerschaver E., Choulat P., et al., "Stable and reliable metallisation-by application of electro-formed Ni-stencils", 16th EUPVSEC (Glasgow, UK), 2000

[3] De Moor H.H.C., Hoornstra J., et al., "Printing high and fine metal lines using stencils", 14th EUPVSEC (Barcelona, Spain), 1997

[4] Hoornstra J., Roberts S., et al., "First experiences with double layer stencil printing for low cost production solar cells", 2nd WPVSC (Vienna, Austria), 1998

[5] Hoornstra J., de Moor H.H.C., et al.,"Improved front side metallization on silicon solar cells with stencil printing", 16th EUPVSEC (Glasgow, UK), 2000

[6] Hahne P., Reis I., et al., "Pad printing - a novel thick-film technique of fine-line printing for solar cells", 2nd WPVSC (Vienna, Austria), 1998

[7] Huljic D. M., Thormann S., et al., "Pad printed front contacts for c-Si solar cells - a technological and economical evaluation", 29th IEEE PVSC (New Orleans, USA), 2002

[8] Mette A., "New concepts for front side metallization of industrial silicon solar cells", Ph.D. Thesis, University of Freiburg (Germany), 2007

[9] Curtis C.J., van Hest M., et al., "Multi-layer inkjet printed contacts to Si", DOE Solar Energy Technologies (Denver, Colorado, USA), 2005

[10] Mette A., Richter P.L., et al., „Novel metal jet printing technique for the front side metallization of highly efficient industrial silicon solar cells", 21st EU-PVSEC (Dresden, Germany), 2006

[11] Hörteis M., Mette A., et al., „Further progress in metal aerosol jet printing for front side metallization of silicon solar cells", 22nd EU-PVSEC (Milan, Italy), 2007

[12] Klein S., A. Kübelbeck, et al., "A new advanced material for removing edge shunts in silicon solar cells", PV in Europe - From PV Technology to Energy Solutions (Rome, Italy), 2002

[13] Köhler I., Stockum W., et al., „A new advanced material for removing edge shunts in silicon solar cells", 23rd EU-PVSEC (Valencia, Spain), 2008

[14] Mette A., Emanuel G., et al., "High efficiencies on large area screen printed silicon solar cells and contacting high sheet resistance emitters using hotmelt ink", 21st EU-PVSEC (Dresden, Germany), 2006

[15] Mette A., Schetter C., et al., „Increasing the efficiency of screen-printed silicon solar cells by light-induced silver plating", 12th WCPVEC (Hawaii, USA), 2006

[16] Field M.B. et al., "Application of thick-film technology to solar cell fabrication", 12th IEEE PVSC (Baton Rouge, USA), 1976

[17] Frisson L. et al., "Screen printed contacts on silicon solar cells with low series resistance", 13th IEEE PVSC (Washington, USA),1978

[18] Haigh A.D., "Fired through printed contacts on antireflection coated silicon terrestrial solar cells", 12th IEEE PVSC (Baton Rouge, USA), 1976

[19] Mette A., Erath D., et al., "Hot melt ink for the front side metallisation of silicon solar cells", 20th EU-PVSEC (Barcelona, Spain), 2005

[20] Erath D., Mette A., Hübner G., „Neue Technologie für Solarzellendruck", in Deutscher Drucker Nr. 27/7.9.2006

[21] Nijs J., Demesmaeker E., et al., "Latest efficiency results with the screenprinting technology and comparison with the buried contact structure", 1st WCPVEC (Hawaii, USA), 1994

[22] Erath D., Filipovic A., et al., "Advanced screen printing technique for high definition front side metallization of crystalline silicon solar cells", 17th IMRC Conference (Cancun, Mexico), 2008

[23] Kim S., Sridharan S., et al., "Aluminum pastes (lead-free/low-bow) for thin wafers", 31th IEEE PVSC (Orlando, USA), 2005

[24] Huster F., „Aluminium- back surface field: bow investigation and elimination", 20th EU-PVSEC (Barcelona,Spain), 2005

[25] Bittoni L., Calvelli R., et al., "Aluminium pastes suitable for wide range thin crystalline silicon solar cells processing. Blistering and bowing effects reduction", 21st EU-PVSEC (Dresden, Germany), 2006

[26] Granek F., Hermle M., et al., „High-efficiency back-contact back-junction silicon solar cell research at Fraunhofer ISE", 23rd EU-PVSEC (Valencia, Spain), 2008

[27] Köhler I., Stockum W., et al., „New inkjet solution for direct printing of local diffusion barriers on solar cells", 23rd EU-PVSEC (Valencia, Spain), 2008

[28] Biro D., Erath D., et al., „Inkjet printing for high definition industrial masking processes for solar cell production", 17th IPVSEC Conference (Fukuoka, Japan), 2007

[29] Specht J., Biro D., et al., "Using hotmelt-inkjet as a structuring method for higher efficiency industrial silicon solar cells", Digital Fabrication (Pittsburgh, USA), 2008

[30] Kaydanova T., Miedaner A., et al., "Ink jet printing approaches to solar cell contacts", Solar Program Review Meeting (Denver, Colorado, USA), 2003

[31] Hladik J., Vanek J., et al., „Characterization of solar cells contacts deposited by direct writing approach", 30th ISSE (Cluj-Napoca, Romania), 2007

[32] Hahne P., „Innovative Druck- und Metallisierungsverfahren für die Solarzellentechnologie", Ph.D. Thesis, University of Hagen (Germany), 2000

[33] Ogawa, T., Asai T., et al., "New thick-film copper paste for ultra-fine-line circuits", IEEE Transaction on Components, Hybrids, and Manufacturing Technology, 1989

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