NOVEL METAL JET PRINTING TECHNIQUE FOR THE FRONT SIDE METALLIZATION OF HIGHLY EFFICIENT INDUSTRIAL SILICON SOLAR CELLS

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ABSTRACT: A new technique for the front side metallization of silicon solar cells is presented, based on the idea to form a two-layer contact structure. The first layer needs to have low contact resistance and good mechanical adhesion to the silicon surface; the second layer, which is formed by light-induced plating requires high line conductivity. If the first layer is sufficiently narrow, excellent aspect ratios can be achieved. This paper focuses on the creation of the first layer with a metal aerosol jet printer. A metal containing aerosol is focused via a second surrounding gas stream through a nozzle onto the substrate, which reduces clogging significantly. Another advantage of this non-contact printing technique is that the width of the deposited line is smaller than the outlet diameter of the nozzle. Fine and continuous lines with a width of 30 µm were printed using a nano-particle ink. As the adhesion of these layers was not sufficient, a commercially available screen-printing paste for solar cell metallization was modified and tested. 50x50 mm² multicrystalline silicon solar cells were processed, achieving efficiencies up to 16.4% with an Al-BSF.
Keywords: metallization, high-efficiency, plating

1 INTRODUCTION

The industrial implementation of high-efficiency concepts for silicon solar cells is currently under extensive investigation. One of the main potentials for improvement is offered by the front side metallization technology.

For the front side metallization a non-contact deposition technology with a high machine uptime and the ability to create contacts with a small width is preferable. The created contact itself should feature a low contact resistivity to the emitter of the solar cell as well as high line conductivity. Conventional screen-printing, the most commonly applied technique in industry, does not fulfill these requirements [1].

With the laboratory process, used for processing high-efficiency solar cells, front side contacts with a good aspect ratio (height to width) at a small finger width, high line conductivity and low contact resistivity are achieved [2]. However, this process includes several complex steps as photolithography, which is not economic for mass production.

A well-known example for an industrially applied advanced contact scheme is the laser-buried contact cell [3,4]. This process is based on a two-layer contact structure: The first layer (Ni) provides a low contact resistivity to the emitter whereas the second layer is made up of a good conductor (Cu) to transport the collected current as loss-free as possible to the busbar. Nevertheless this process still includes several additional process steps as the formation of laser grooves and an additional heavy diffusion.

Our approach is to use a simple two-layer process: Creating a seed layer with the novel metal jet printing process followed by light-induced plating (LIP) [5]. This implies the great advantage that both layers can be optimized individually. If the line width of the first layer is sufficiently narrow, excellent aspect ratios are achieved.

2 SEED LAYER AND PLATING

The first layer of our two-layer contact structure should form a good electrical and mechanical contact to the silicon surface. Additionally it should act as a seed layer for the plating process, used to form the second layer. This second layer should have a good line conductivity to minimize resistivity losses in the finger, this is the reason why silver (63 x 10^6 S/m) or copper (59.6 x 10^6 S/m) as first-class conductors are preferred materials.

An industrially feasible technique for the formation of the second, i.e. the conductive layer is the light-induced plating process [5]. The principle of this technique, which is in use since a decade at Fraunhofer ISE, is illustrated in Figure 1. The significant advantage compared to ordinary electroplating processes is that no electrical contact needs to be connected to the front side metal grid, as the illuminated solar cell itself generates the required current and serves as cathode. Compared to an electroless plating process, the light-induced plating rate is significantly higher. This process will be transferred from lab to industrial scale.

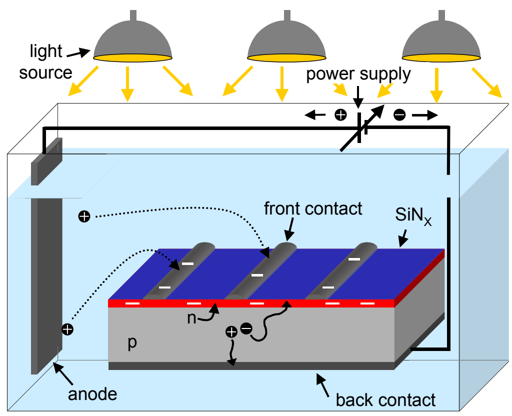

Figure 1: Scheme of the light-induced plating process.

To form the first layer different metallization techniques are currently under investigation at Fraunhofer ISE [6]. In the approach presented in this paper the seed layer is created with a novel metal jet printing process that allows printing fine and continuous metal lines.

3 METAL AEROSOL JET PRINTING

3.1 Background

A non contact deposition technology that could be suitable for solar cell front side metallization is ink jet printing. This idea and first experimental results were already published in 1988 by Teng and West [7]. The technique is still under investigation [8].

In our opinion the main limitation is that the entire contact structure was tried to be build up by ink jet printing. The viscosity of the ink needs to be much lower to be printable with an ink jet printer than for a screen printer. This means that the maximum metal content in those inks is only about 10 to 20 mass percent. The resulting contact would have a height of about 100 nm to 200 nm, if the deposited line (before drying) had a height of 10 µm. To achieve contacts of sufficient conductivity, multi layer prints would be necessary, which is not suitable for mass production. Additionally, the amount of used solvents is high.

Using an ink jet printing system in combination with the light-induced plating process could be an alternative, but still has some disadvantages compared to the novel technique presented here.

The ink jet printed line has a width usually wider than the nozzle outlet. Hence, a fine nozzle has to be used to print narrow lines, which on the other hand increases the danger of clogging. Either very expensive nano-particle inks or metal-organic inks have to be used. With the novel metal aerosol jet system the range of physical properties of the used ink is much wider and also the width of the deposited line can be far less than the diameter of the nozzle outlet.

3.2 Working principle of the system

The process flow of the aerosol metal jet system is illustrated in Figure 2. The process gas N_2 is adjusted by the process control module before it is transferred to the pneumatic atomizer and the deposition head. In the atomizer the metal-containing ink is nebulized. As this requires a high gas flow, some of the carrier gas will be removed in a virtual impactor. The produced metal aerosol is then transported to the deposition head via a

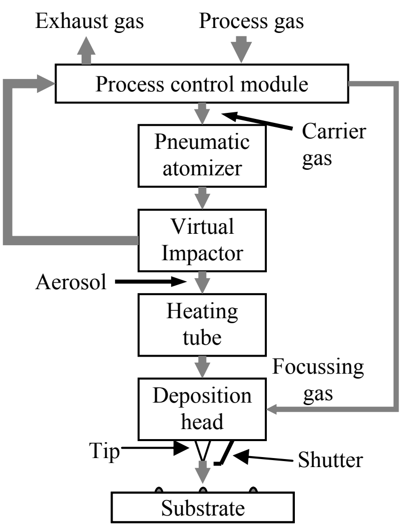

Figure 2: Gas flow diagram of the aerosol metal jet unit.

heatable tube, in which the viscosity of the ink can be controlled. In the deposition head the aerosol stream is focussed by a second gas stream and deposited through a tip onto the surface of the substrate. The continuous aerosol stream can be interrupted by a mechanical shutter.

The two main components of this system are the pneumatic atomizer and the deposition head. The working principle of the pneumatic atomizer is shown in Figure 3. Compressed gas is expanded through the atomizer nozzle, producing a high velocity gas stream. Due to the venturi principle, the ink is sucked off the reservoir into the atomizer nozzle. The dynamic pressure at the end of the atomizer nozzle increases because of the high flow velocity of the gas.

As the static pressure in the atomizer nozzle decreases, the higher pressure in the reservoir causes the ink to incline in the nozzle. Subsequently, the high-velocity gas stream breaks the liquid stream into droplets and suspends them in the flow. In the reservoir the gas jet containing the droplets impinge against the sidewalls so that the larger droplets are removed. The smaller particles remain in the gas and are transported to the deposition head.

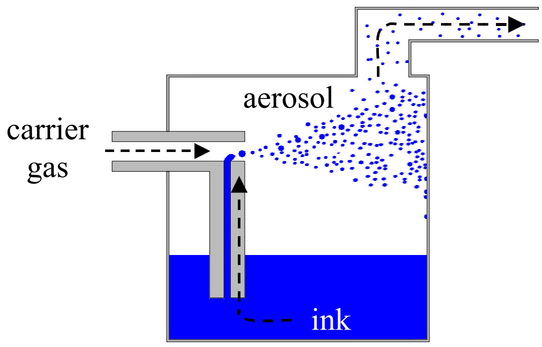

Figure 3: Working principle of the pneumatic atomizer.

In the deposition head the metal containing aerosol stream is focussed by a second gas stream, which is the big advantage of this system: The focussing gas surrounds the aerosol entirely so that the droplets do not touch the inner wall of the nozzle. Hence there is no problem with clogging, one of the main drawbacks of conventional ink jet printers. In addition, because the aerosol stream is focussed by the second gas stream, the width of the deposited line can be far smaller than the width of the nozzle. Also the distance between tip and substrate may vary a few millimeters, making it a suitable technology for uneven surfaces.

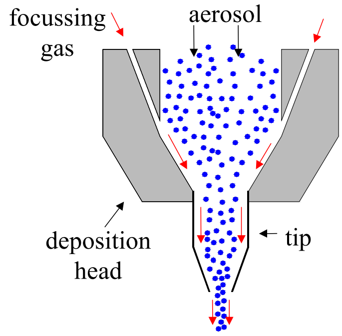

Figure 4: Working principle of the deposition head.

3.3 Printing results

A wide variety of inks was tested at Fraunhofer ISE and the optimum printing settings for each type were found. The printed lines were optically characterized. This included edge definition as well as line width and height. Especially the viscosity and the maximum particle size of the inks mainly influence the printing settings.

Our experiments have shown that the line width can be up to four times smaller than the nozzle outlet. For example using a nozzle with an outlet diameter of 200 µm, printed lines with 50 µm width were achieved. Figure 5 shows a printed line on glass substrate using a nano-particle ink. The nozzle outlet had a width of 100 µm.

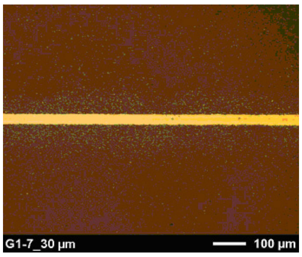

Figure 5: Microscope picture of a 30 µm fine aerosol metal jet printed line on glass substrate using a nano-particle ink.

Furthermore the adhesion of the deposited line after annealing was tested (standard tape test). Although the adhesion of most nano-particle inks on glass substrates was good, it was not sufficient when printing on a silicon surface.

This is why modified commercially available screen printing pastes were tested. Despite the relatively large particle size of about 3 to 5 µm the ink was successfully printed with the aerosol metal jet system. After conventional contact firing in a rapid thermal firing furnace, the adhesion to the silicon surface was of high quality. Unexpectedly the thin deposited layer even etched through the SiN_X antireflection coating during the firing process yielding in a good electrical contact.

A topographic picture of a contact finger on a textured silicon solar cell printed with the metal aerosol jet technique and plated by the light-induced silver plating process is shown in Figure 6. The seed layer had a width of about 60 µm and a height of less than 1 µm. After the plating process the contact was about 100 µm wide and 20 µm high.

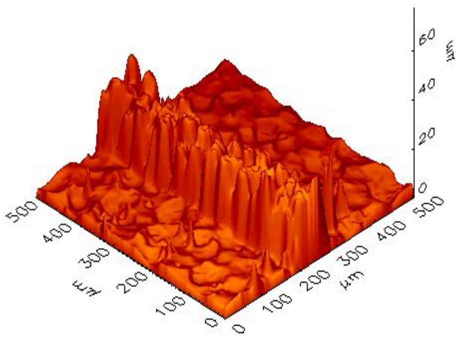

Figure 6: Topographic image of a contact finger on a textured silicon solar cell.

4 SOLAR CELL RESULTS

4.1 Solar cell processing

156 x 156 mm² multicrystalline silicon wafers were industrially processed up to the SiN_x-layer with a sheet resistivity of about 55 Ω/sq and an iso-textured surface. They were further processed at Fraunhofer ISE according to the process flow shown in Figure 7.

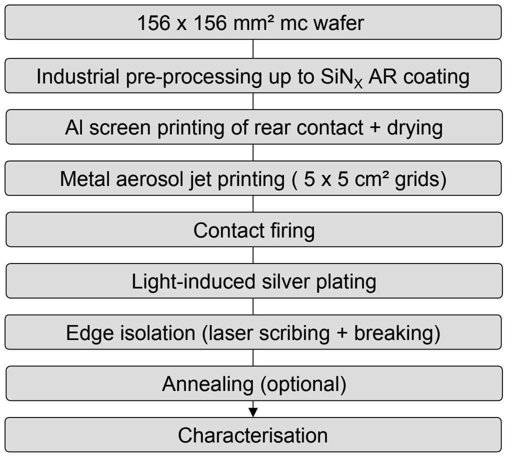

Figure 7: Process flow diagram of processed multicrystalline silicon solar cells.

The backside of the wafers was conventionally screen-printed and dried. Then on the front side the first layer, the contact layer, was deposited using the metal aerosol jet system. For printing, a commercially available screen-printing paste, modified mainly in its viscosity, was used. On each 156 x 156 mm² wafer several grids with a size of 50 x 50 mm² were printed. Afterwards the cells were fired in an inline fast firing furnace. The formation of the second layer, the highly conductive layer, was performed by light-induced silver plating. Optionally an annealing step followed. The solar cells were finally separated by backside laser scribing and breaking.

4.2 Optical and electrical characterization

Process parameters as for instance aerosol flow, process speed, temperature settings and viscosity of the ink were varied. The impact of theses variations on the solar cell results were optically and electrically characterized.

A picture of a processed solar cell is shown in Figure 8. In this case the busbar was made by printing several lines adjacent to each other.

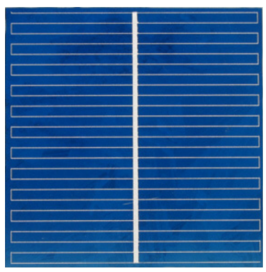

Figure 8: Picture of a processed 50 x 50 mm² mc-Si solar cell.

As a result of the process variation, fingers of different width were printed. With the same tip featuring an inner diameter of 200 µm, metal lines with a width between 50 µm and 140 µm were deposited. After the firing and the light-induced plating process the width of the contact finger increased by about 20 to 30 µm. Figure 9 shows a microscope picture of contact fingers with a width of 160 µm (left) and 70 µm (right) after plating.

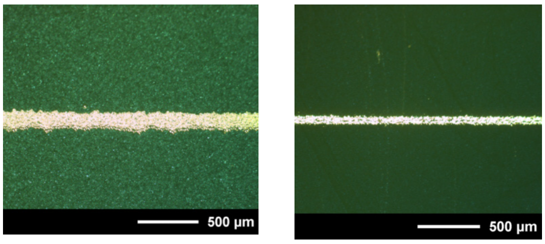

Figure 9: Microscope pictures of a printed and plated finger with 160 µm (left) and 70 µm (right) line widths

The IV-parameters of these two cells before and after the annealing step are presented in Table 1. Fill factor and short circuit current differ strongly.

The lower j_{SC} for the solar cell with the wider finger can be explained with the larger shaded area. The 25 160 µm wide fingers shade about 8% of the 50x50 mm² sized solar cell surface compared to 3.5% for the solar cell with 70 µm wide fingers. This is the main reason for the about 4.5% lower j_{SC} value.

The lower fill factor of the cell with the 70 µm wide contacts compared to the 160 µm contacts is due to the increased series resistance, caused by the higher contact resistance. Thus the inks need to be further optimized to achieve a low contact resistance to the emitter surface, which is necessary for fine line printing.

The solar cells were characterized before and after the annealing step. For both cells the efficiency increased by 0.2% to 0.3% absolute after the annealing step, caused by the gain in the fill factor. It is assumed that the quality of the contact between the silicon surface and the deposited metal as well as the contact between the deposited and the plated metal is improved, reducing the series resistance significantly. The annealing temperature and time depends on the one hand on the emitter profile, on the other hand on the deposited ink. For a contact of good quality a high annealing temperature is preferable, but at the same time the danger of damaging the space charge region is increased. For the processed cells the optimum annealing temperature was between 300°C and 400°C for a time of about 5 minutes to 10 minutes.

Table 1: IV-parameters of the best 50 x 50 mm² mc-Si solar cells measured before and after the annealing step. The best 156 x 156 mm² screen-printed reference cell, processed and measured in an industrial line, achieved an efficiency of 15.8%.

finger width [µm]	Voc [mV]	jsc [mA/cm2]	FF [%]	η [%]
160 µm finger width				
after plating	618.8	32.7	78.4	15.8
after annealing	617.1	32.7	79.4	16.0
70 µm finger width				
after plating	619.2	34.0	76.2	16.1
after annealing	617.5	34.2	77.4	16.4

4 CONCLUSION

A new process for the front side metallization of silicon solar cells with a high potential is presented. Compared to most other metallization technologies this is a non-contact process.

However the biggest advantage, especially compared to a standard ink jet printer, is given by the working principle of the deposition head: The metal aerosol stream is surrounded by a second gas stream and then focussed through the nozzle onto the substrate. This prevents a clogging of the tip. Additionally, the width of the deposited line is much smaller than the size of the nozzle outlet.

50x50 mm² textured multicrystalline silicon solar cells with a standard Al-BSF have been processed with a modified commercially available screen printing paste reaching efficiencies up to 16.4%.

Further investigation will concentrate on the use of metal containing inks optimized to give a lower contact resistance.

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