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NEW CONCEPTS FOR THE FRONT SIDE METALLIZATION OF SILICON SOLAR CELLS

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ABSTRACT: For the fabrication of front side grids with a higher efficiency potential than screen-printed contacts, two-layer processes are very promising. In the *seed* step a thin metal line is deposited which forms the mechanical and electrical contact to the emitter. In the *growth* step this seed layer is thickened by a plating process to increase line conductivity. In our approach the plating is performed using the so-called light-induced plating process. For this process the solar cell has to be contacted only at the rear which facilitates the transfer into industrial production with high through-put. Several methods to create the seed layer are discussed in this paper: Fine-line pad printing of silver screen-printing pastes, laser sintering/melting of metal powders, chemical Ni plating on solar cells with a structured dielectric layer and aerosol metal jetting. Very encouraging results are achieved for all these technologies.

Keywords: Silicon, Contact, High Efficiency

1. INTRODUCTION

Due to its robust process technology and high through-put, screen-printing is the most common technique for the metallization of today's industrial solar cells. However, there are several undesirable features as a poor aspect ratio of the grid lines, a high line resistance and a high doping concentration of the underlying emitter which is necessary to achieve acceptable contact resistance. These aspects make it worth to look for alternative metallization concepts. This effort is also justified by the tremendous growth of cell area, leading to a strong increase of resistive losses in the front side grid.

After screening previous work on alternative metallization schemes, there seems to be no thick-film technique which can compete with screen-printing. Thus, we have decided to develop a *two-layer process*. In the first step a narrow metallization line, the *seed layer*, is created on the silicon surface. This seed layer should create a good mechanical and electrical contact to the silicon surface. In the subsequent *growth* step this line is thickened by silver electro-plating to increase the line conductivity. Using such a two-layer process, it is possible to optimize both steps in terms of metals used and process parameters separately and to clearly improve the performance of the front surface metallization. Actually, all high-efficiency cells in our lab are processed using a multi-layer process.

In our lab the plating is performed using the so called light-induced plating process in which only the rear side of the cell has to be contacted. The light-induced electroplating process was recently used to increase the conductivity of screen-printed industrial cells and a considerable increase in efficiency was observed [1]. Cost calculations, taking into account the reduced consumption of screen-printing paste and the higher efficiency potential, have shown that an industrial application of this robust process is reasonable in the near future. Nevertheless, the full potential of the two-step metallization concept can only be reached with new seed layer deposition techniques beyond screen-printing.

Thus, the main challenge is to develop an efficient process for the fabrication of the seed layer. Some new techniques which already showed remarkable results will be presented in this paper.

2. LIGHT-INDUCED PLATING

For thickening of all seed layers presented in this paper, we use the light-induced electro-plating process, which utilizes the photovoltaic effect of the cell and allows to contact only the fully metallized rear surface. Thus, the complexity of this selective process is considerably reduced. Furthermore this process has a much higher deposition rate compared to electro-less plating.

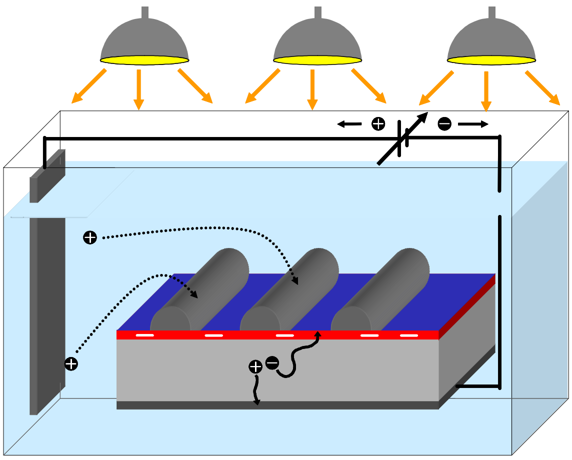

Figure 1 Scheme of the light-induced electro-plating process. The cell is immersed in an electro-plating bath with an Ag-electrode (left side) and only contacted at the fully metallized rear. The applied potential suppresses dissolution on this side. By illuminating the cells, the front electrodes are on a more negative potential, high enough to stimulate deposition of Ag ions. This plating concept simplifies industrial transfer considerable.

The process has been used for our high-efficiency cells for more than a decade and results in highly conducting front contacts with an aspect ratio close to 1:2 (height:width). A small batch-type semi-automated electro-plating system was set up several years ago and is reliably working without complex maintenance. Recently, this process was used for increasing the conductivity of narrow screen-printed lines. A significant efficiency increase on 15.6x15.6 cm^2 industrial multicrystalline cells of 0.3 to 0.5% was shown [1], while saving silver paste in the screen-printing step. Thus, a short-time-scale transfer of this process into an industrial environment does not seem to be too optimistic.

Of course, the full potential of the light-induced plating process can only be achieved if the seed layer has better electrical and geometrical properties than screen printed contacts. In the following sections four different seed layer technologies, currently under development at Fraunhofer ISE, are discussed.

3. PAD PRINTING

Pad printing is a very interesting alternative to screen-printing since smaller structures in the range of less than 50 µm can be printed. Furthermore, it is a mature industrial high-volume technology and modified standard screen-printing pastes can be used. Thus, this technology was investigated intensively at Fraunhofer ISE [2]. Although it was possible to print very narrow lines, the height of the printed contacts is simultaneously reduced decreasing the line conductivity.

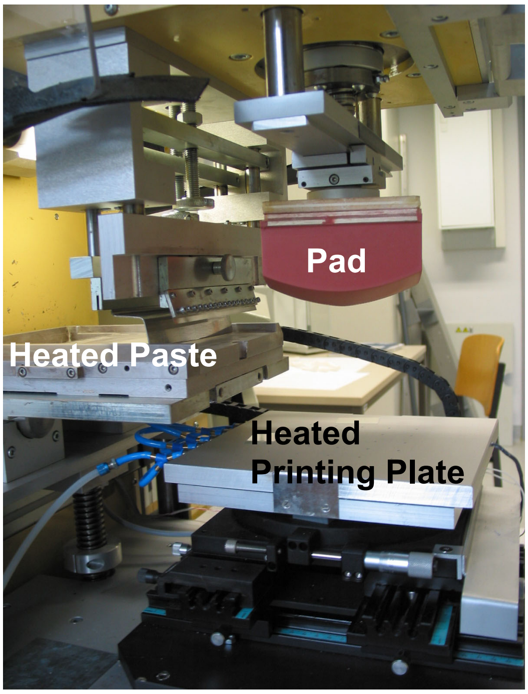

Figure 2 Pad printing set-up at Fraunhofer ISE.

However, in combination with a subsequent light-induced plating process, pad printing would be ideal to form the seed layer. To further increase the printing resolution and the paste transfer from pad to solar cell, we have used hot-melt pastes which have shown very promising results in screen-printing as well [3]. For the use of hot melt pastes it was necessary to modify the pad printer i.e. to heat the printing pattern and the printing table. The process temperatures, printing patterns and other process parameters have been optimized in order to achieve narrow and continuous lines and a complete transfer of the paste. With this process we processed solar cells on textured 100x100 mm^2 Czochralski silicon using the following principal sequence:

- Chemical texturing
- Emitter diffusion 60 Ω/sq + PSG etch
- Sputtering of SiN_x:H on the front side
- Screen-printing of Al on the rear
- Pad printing of front grid
- Co-Firing
- Edge isolation
- Light-induced plating

The printed lines had a width of 50 µm. Cell parameters as shown in Tab. I have been achieved.

Table I: Results of 100x100 mm^2 Cz-Si solar cells. The front grid structure was fabricated using pad printing, firing and light-induced plating.

Paste	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	η [%]
Hot-melt	624	36.1	79.7	17.9
Conventional	627	36.2	76.9	17.4

The achieved efficiency of 17.9% shows the high potential of the technology. A similar result was achieved using conventional silver screen-printing paste.

4. LASER SINTERING/MELTING OF METAL POWDER

A powder of metal particles is deposited on the surface of the cell. The metal powder is sintered/melted locally by a scanning laser to form the contact lines (see Figure 3). The rest of the powder is removed easily from the surface leaving laser-sintered contact lines [4]. Although it is possible to form very high contact lines by a repetition of the process, we have decided to form only a small seed layer which is subsequently thickened by light-induced silver plating which makes the approach more economic.

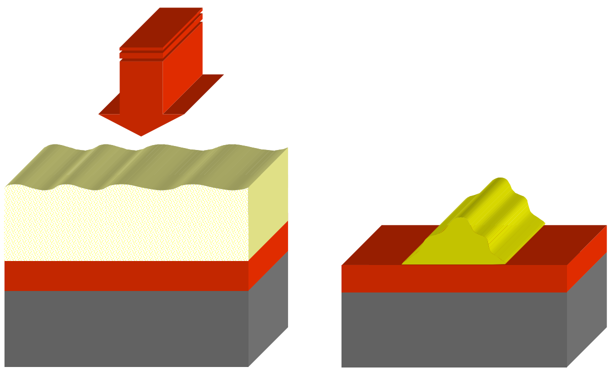

Figure 3 Laser micro-sintering of metal powder on the front surface of solar cells.

Figure 4 shows the structure of a laser-sintered finger after the subsequent light-induced plating step. The contact formed by laser sintering is very fine and thin, while the line conductivity is generated by the plated silver on top of this seed layer.

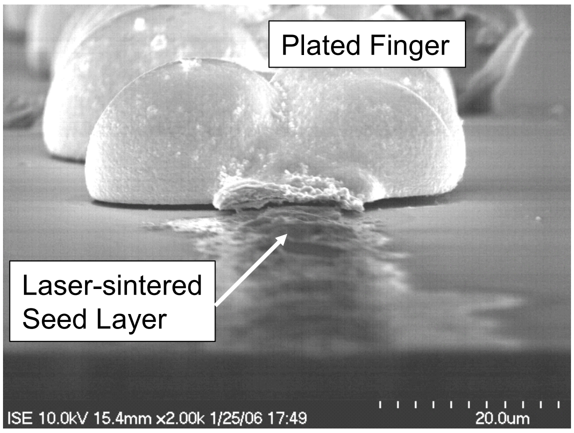

Figure 4 SEM image of a seed layer created by laser micro-sintering thickened by light-induced electroplating.

First cell results on small cell areas (1x1 cm^2) have shown efficiencies of 14.0% although a heavily doped emitter (18 Ω/sq.) was chosen for these first experiments. We have achieved an open-circuit voltage of 622 mV and very high pseudo FF measured using SunsVoc which shows that this process does not generate severe damage in the emitter or space charge region. Further investigation with optimized cell structures is on its way.

5. CHEMICAL PLATING OF Ni

Nickel plating is well-known from the laser-buried contact process used by BP Solar to fabricate high-efficiency industrial solar cells [5]. However, in this process sequence it is necessary to form a groove in the silicon surface which then receives a damage etch and a heavily doped phosphorus diffusion. Instead, it would be desirable to use a one-step process to form a front surface structure which initializes the local electroless Ni plating process.

We are using a laser ablation process to remove a line of the front surface SiN_x layer of standard cells similar to the apprauch by Dube et al. [6]. SunsVoc measurements have shown that this process does not damage the underlying silicon i.e. the *pn* junction [7].

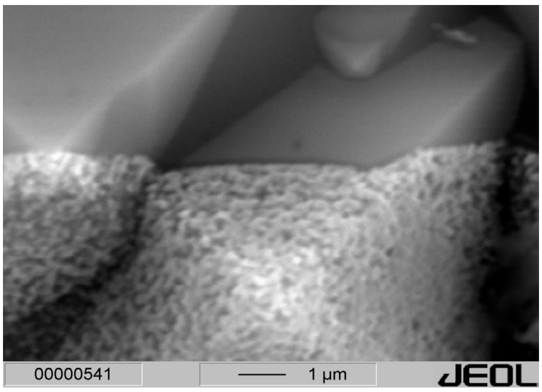

Figure 5 Ni plating on a textured silicon surface

The Ni plating process was optimized to work on non-grooved surfaces and medium-doped emitter profiles. With the optimised process it is possible to initiate a sufficient Ni plating process (see Figure 5).

For the first experiments on cell level however we have used cell structures with an oxide-passivated emitter and rear surface. Due to the unfavourable absorption coefficient of silicon oxide, it is not possible to ablate the oxide without damaging the silicon underneath. Thus, in these experiments a photo-resist was used to mask a chemical etching step to open the grid structure in the front oxide. The efficiency of 18.9% shows the quality of the developed plating process although there is still room for improvement by reducing the series resistance.

Table II: Results of 20x20 mm^2 oxide-passivated Fz-Si solar cells. The front grid structured was fabricated using electroless Ni plating and light-induced plating.

	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	*η* [%]
Ni plating + LIP	661	38.9	73.4	18.9

6. METAL AEROSOL JETTING

A very elegant way to deposit the seed layer on top of the solar cell would be metal jetting. However, if using standard pastes with its quite big particles (5 – 10 µm) plugging is a severe problem. As a rule of thumb the diameter of the nozzle should be at least seven times bigger than the particle size. Thus, the resulting line width would be in the range of screen-printed fingers, which would not justify any additional effort.

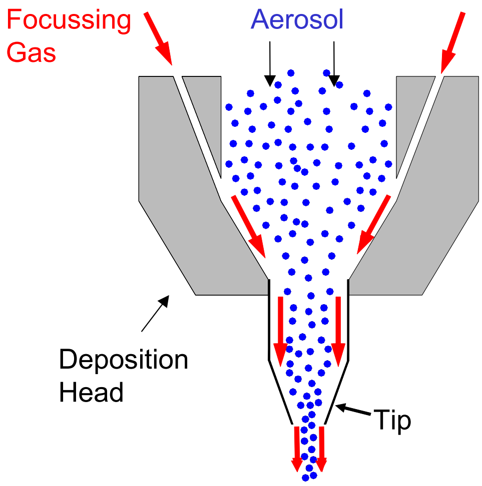

Figure 6 Printing head of the metal aerosol printing technique.

Therefore, in our set-up the paste is not printed directly but a metal aerosol is generated [8]. This metal aerosol is conducted into a specially designed printing head (see Figure 6). In this printing head the aerosol is wrapped up in a ring-shaped gas flow which avoids the contact between aerosol and nozzle tip. The aerosol is therefore focused by the ring-shaped gas flow and line widths considerable smaller than the tip diameter can be achieved. For example using a nozzle with an outlet diameter of 200 µm, printed lines with 50 µm width were achieved. Additionally the printing result is rather independent of the distance between nozzle and substrate which makes the technique suitable for uneven substrates.

A great variety of modified commercially pastes and nano-particle inks were tested. Although the printing results (line width, etc) of the nano-particle inks were excellent, the electrical (contact resistance and conductivity) and mechanical (adhesion) properties were not satisfying. Thus, we have used modified standard Ag pastes and despite the quite big particles, we managed to get small line widths of around 50 - 60 µm. This process was used to fabricate the front grid of industrial multicrystalline solar cells.

- Textured multicrystalline silicon
- Emitter diffusion (55 Ω/sq) + PSG etch
- Deposition of PECVD SiN_x
- Screen-printing of Al-BSF
- Aerosol Printing (Modified commercial Ag Paste)
- Co-Firing
- Edge isolation
- Light-induced plating

Two different finger width were printed resulting finger width of 160 µm and 70 µm after plating, respectively (see Fig. 7)

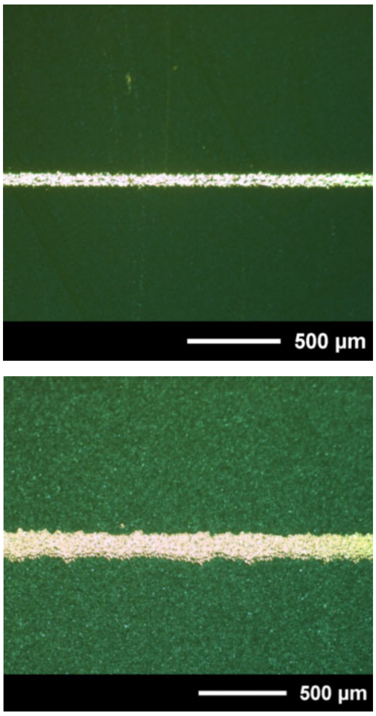

Figure 7: The microscope pictures show a printed and plated finger with 70 µm (top) and 160 µm (bottom) line widths.

Tab. III shows the results of the finished solar cells as measured at Fraunhofer ISE CalLab. The cells with a finger width of 160 µm show a high fill factor which demonstrates that the contact formation works excellent. However, since the shadowing loss is not reduced, the efficiency is similar to the screen-printing references. The cells with 70 µm fingers show a much smaller shadowing loss than standard cells which results in a strongly increased current and significantly higher efficiency of 16.4%. The fill factor is satisfying but it is believed that with pastes especially developed for this new and promising technique, the over-all benefit could be even higher.

Table III: Results of 50x50 mm^2 multicrystalline solar cells. The front grid structure was fabricated using metal aerosol jet printing, firing and light-induced plating.

Finger width	V_{oc} **[mV]**	J_{sc} **[mA/cm^2]**	***FF*** **[%]**	η **[%]**
160 µm	617	32.7	79.4	16.0
70 µm	618	34.2	77.4	16.4

7. CONCLUSION

With the technologies presented in this paper it is possible to form thin contact lines with good mechanical and electrical properties. These seed layers are subsequently thickened by the light-induced plating process to achieve sufficient line conductivity. It is believed that in the medium-term at least one of these different two-layer processes could substitute the current screen-printing process.

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