Etching of PVD Metal Layers for Contact Separation of Back Contact Silicon Solar Cells using Inkjet-Printing

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Abstract

Back contact solar cell concepts feature both metal contact polarities on the rear side of the wafer. PVD (Physical Vapor Deposition) is one option for high quality metal layers. To create a working device the metal contacts must be separated. This work reports on the evaluation of an economic process route using an etching ink that is inkjet-printed onto metal layers. Drop on demand inkjet technology is very well suited for the deposition of such etchants onto the thin wafers as it allows for the well-defined deposition of complex structures needed e.g. for the rear side of back-contact solar cells. It is investigated how the amount of ink and thus reactive species influences the width of the etched structures and if they are electrically isolated. The width of the etched structures has been reduced down to 65 µm on 1000 nm thick Al-layers by adjusting the amount of ink printed on the metal layers. The separation was demonstrated by measuring the electrical resistance between the separated metal areas. The presented process provides a structuring solution for the cost effective contact separation for back contact solar cells. The feasibility has been shown by printing a meander structure which is the typical contact separation layout for a BC-BJ (Back-Bontact Back-Junction) solar cell.

Introduction

The main goal of the photovoltaic industry is fabricating solar cells with higher conversion efficiency at lower production costs. To reach this goal new cell designs, like the MWT (Metal Wrap Through) solar cell [1], the EWT (Emitter-Wrap-Through) solar cell [2] and BC-BJ (Back-Contact Back-Junction) solar cell [3] have been introduced. What they have in common is that the different polarities are formed on the rear side of the wafer.

For BC-BJ solar cells it was demonstrated that the efficiency can be raised when the pitch of the doped areas is reduced from 2000 µm to 500 µm [4]. Since both metal polarities have to fit into this distance, the width of the contact separation should be preferably well below 100 µm. This can hardly be done using conventional screen printing metallization, which is limited in lateral resolution as well as in terms of specific resistivity. One option is to use PVD (Physical Vapor Deposition) for the deposition of metals with low specific resistivity. Amongst others, Al and NiV are metals of choice for the metallization of back contact solar cells. In the semiconductor industry the structuring of these full area deposited metal layers is typically done by masking and etching processes using photolithography followed by a subsequent wet chemical or plasma etching step. Also solar cells with a very high efficiency have been reported using these processes [5, 6]. Another option is a lift-off process where no etching is involved but still masking is necessary. Previous work showed that hotmelt inkjet technology can be used both as masking layer and as lift-off mask [7]. However, due to the enormous cost pressure in the photovoltaic sector it is beneficial to avoid sacrificial mask layers.

For the formation of separated contact areas this paper presents a novel approach to replace the complex and costly process sequence of masking, etching and mask removal. Therefore an etching ink is inkjet-printed onto sputtered metal layers. Drop on demand inkjet technology is very well suited for the deposition of such etchants onto the thin wafers as it allows for the well-defined deposition of complex structures that are needed for the rear side structuring of back contact solar cells. Furthermore, due to its contactless working principle wafer breakage rate can be minimized. Inkjet-printing and PVD are perfectly suited for back-contact solar cell structures since both technologies allow the separate and independent processing of only one side of the wafer.

For the development of the etching process it is investigated how the amount of ink and thus also reactive species influences the width of the etched structures. They are characterized regarding their dimensions and regarding the electrical insulation.

Experimental Details

For the investigations Czochralski grown p-type Si wafers were used. The wafers have an edge length of 156 mm, which is the typical dimension for solar cell wafers. The saw damage of the wafers was removed in a KOH-bath. An electrically insulating thermal silicon oxide (200 nm thick) was grown on both sides of the wafer. The wafers were then divided into groups and Al or NiV were deposited on one side of the wafer using PVD. A schematic process flow of the realized structure is depicted in **Figure 1**.

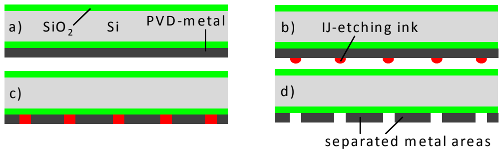


***Figure 1** Process scheme for the production of separated PVD metal areas on a Si substrate.*

a) Cz wafer with thermal SiO_2 and PVD metal

b) Inkjet-printing of etching ink on areas that need to be etched

c) etching through the metal layers

d) removal of etching ink and reaction products in DI-water resulting in separated metal areas.

The nominal thickness of the Al layers was 150 nm, 500 nm and 1000 nm, whereas the investigated NiV layers had a thickness of 50 nm and 150 nm. A laser was used to cut the wafers into squares of 50 x 50 mm^2 for the printing and etching experiments. A Dimatix DPM 2881 inkjet printer with a 10 pl cartridge was used to deposit the etching ink onto the wafers. The print head is able to jet with 16 nozzles. To ensure reproducibility in this early stage of development all experiments were performed with only three activated neighboring nozzles. The experiment plan for the investigations is shown in **Figure 2**.

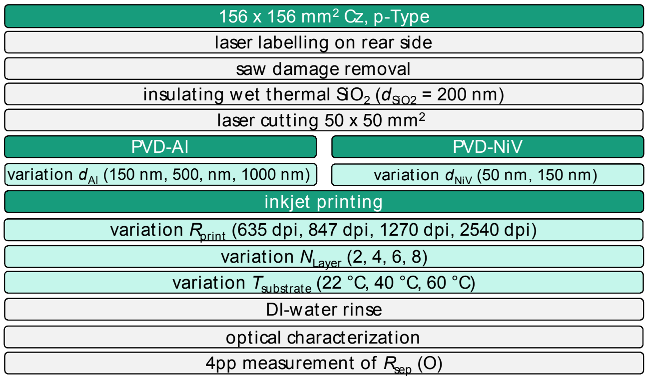


***Figure 2** Experiment plan for the inkjet etching experiment. For the metal deposition the layer thickness d_{Al} of Al and d_{NiV} of NiV was varied. For printing and etching the printing resolution R_{dpi}, the number of layers printed on top of each other N_{Layer} and the temperature of the substrate table $T_{substrate}$ were varied.*

For the optical characterization of the variations a test pattern was chosen where 2 cm long lines with a width of two pixels were inkjet printed with a set of variations, which is schematically depicted in **Figure 3 a.**

The amount of ink deposited on the wafer was varied by the printing resolution R_{print} and the number of layers N_{Layer} printed on top of each other. Both variations have the effect that more etching ink is present on the substrate. The printing resolution was changed by the drop spacing d_s [µm] between the printed droplets. It was reduced from 40 µm to 10 µm in a step size of 10 µm, resulting in printing resolutions R_{print} of 635 dpi, 847 dpi, 1270 dpi and 2540 dpi (dots per inch).

For the variation of the number of layers and the substrate temperature the printing resolution was set to 1270 dpi.

The number of layers was varied between two and eight layers in a step size of two. For printing the wafers were put on the substrate table and the line pattern was printed. According to the number of layers this procedure was repeated without removing the substrate. For enhanced etching through thermal activation the temperature of the substrate table $T_{\text{Substrate}}$ was varied between 22 °C (room temperature), 40 °C and 60 °C. For all experiments, after printing, the wafers were kept for five minutes on the substrate table. Then they were removed and washed with DI-water to remove the etching ink and the reaction products. Drying of the wafers was performed under nitrogen gas flow. The width of the etched lines was characterized at six spots with an optical microscope. SEM (Scanning Electron Microscope) images were taken at the edges of these structures.

For electrical characterization samples were prepared that consisted of 17 lines with a length of 40 mm printed at a fixed distance of approximately 2 mm below each other. After etching a one cm wide stripe was cut out of the wafers with a laser. A schematic view of the layout is shown in **Figure 3 b**. The four-point-probe measurement system KB-100 from “Kalio Binder Gbr.” was used to measure the resistance R_{sep} between these separated metal areas. The tool allows for the measurement between eight separated lines in one measurement cycle and resistance values of up to 30 kΩ can be measured.

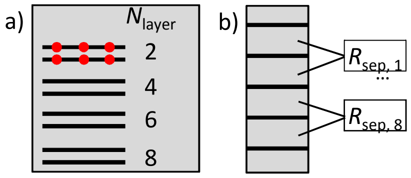


***Figure 3** Sample design for the evaluations. The grey areas represent the PVD-metal. The black lines indicate the inkjet-printed and etched areas.*

a) Variation of the number of layers N_{layer}. For each layer two lines were printed. For each variation the width was measured at six spots, indicated by the red dots

b) Measurement of the resistance R_{sep} between two adjacent separated areas. The measurement was performed on eight positions over the samples that were cut out of the 50 x 50mm^2 wafers with a laser.

Print and Etch Results

The density of droplets printed on the wafer and thus the amount of reactive species can be influenced by the printing resolution. This variation was performed on samples with Al-metallization with a thickness of 500 nm. The substrate table was heated to 60 °C and the printing resolution was varied from 635 dpi to 2540 dpi. However, it was found that the variation of the printing resolution alone is not an adequate solution to create homogeneously opened lines. Microscope images of the etched structures which are shown in **Figure 4 a** show that for all chosen printing resolutions only point-like openings in the metal layer were achieved. This indicates that the droplets did not wet the substrate, but rather connected to larger droplets on the Al-surface.

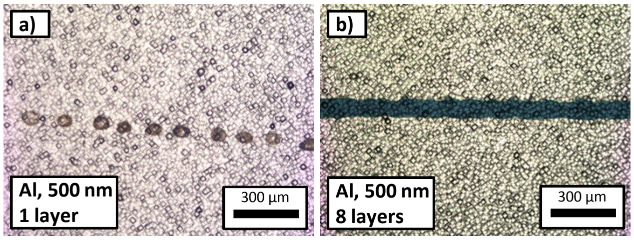


Figure 4 Optical micrographs of samples with an Al-layer with a thickness of 500 nm showing the influence of the number of layers printed. Both samples were printed at a printing resolution of 1270 dpi.

a) Printing of one layer. The Al is only partly etched.

b) Printing of eight layers. The Al is etched completely and a uniform line opening is formed.

By printing more than one layer of etching ink on top of each other the etching results can be improved significantly, which is shown in **Figure 4 b**.

Generally, the etched line width increases with the number of layers and the substrate temperature. For each metal layer and metal layer thickness a respective minimal amount of layers and a minimal temperature is necessary to etch through the metal and to form a completely opened line. When printing was performed at room temperature none of the metal layers was etched through completely after five minutes of etching. This was observed regardless of the number of layers printed. The widths of the etched lines in respect of the number of layers printed are depicted in **Figure 5** for Al and in **Figure 6** for NiV.

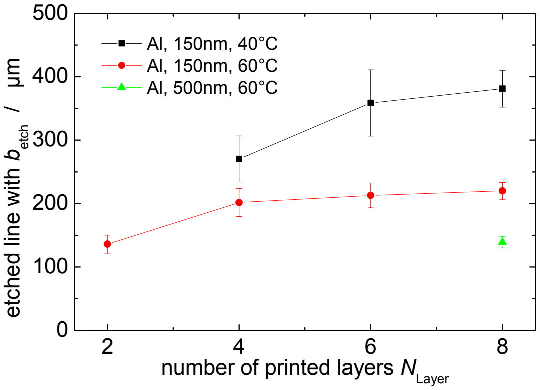


***Figure 5** Width of the etched line openings of the Al-layers in dependance of the number of layers printed and the substrate temperature. Only completely etched structures are plotted.*

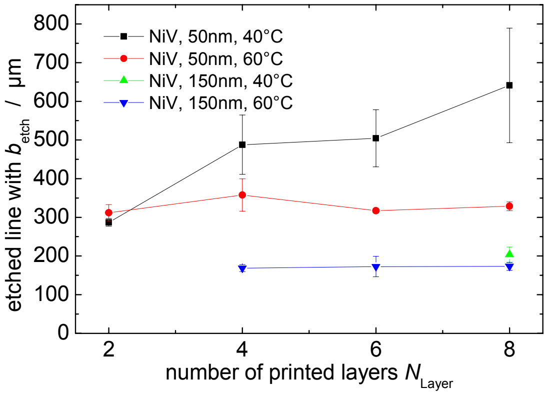


***Figure 6** Width of the etched line openings of the NiV-layers in dependance of the number of layers printed and the substrate temperature.Only completely etched sturctures are plotted.*

Al 150 nm: The width of the etched lines of aluminum with a thickness of 150 nm printed at 40 °C rises from 270 µm (4 layers) to 381 µm (8 layers). Two printed layers do not form an opened line. At a temperature of 60 C a minimal average line width of 136 µm can be achieved.

Al 500 nm: For aluminum with a thickness of 500 nm eight printed layers and a substrate temperature of 60 °C are necessary to completely etch the metal. Line openings with a width of 139 µm have been realized.

Al 1000 nm: Aluminum with a thickness of 1000 nm was not etched completely with the chosen parameters. However, it is possible with an increased number of printed layers which is described later.

In the case of NiV, the etching ink shows a decreased etch rate compared to Al.

NiV 50nm: The NiV-samples with a thickness of 50 nm printed at a substrate temperature of 40 °C show an increase of the etched line width from 287 µm (2 layers) to 641 µm (8 layers). At 60 °C the line width stays relatively constant between 312 µm (2 layers) and 329 µm (8 layers).

NiV 150 nm: For the wafers with a NiV-thickness 150 nm and a substrate temperature of 40 °C eight layers are necessary to form a continuous line opening. If the substrate table is heated to 60 °C the width stays constant between 169 µm (4 layers) and 173 µm (8 layers).

Based on the results the number of layers was increased to demonstrate the ability of etching Al-layers as thick as 1000 nm.

It is possible to realize line openings with a width of down to 65 µm with the number of printed layer set to $N_{layer} = 14$. This is consistent with the overall observation, that finer structure sizes could be achieved on thicker metal layers. These samples show an excellent edge definition as can be seen in the microscope images in **Figure 7 a**. However for these thick layers there is a slight transition in thickness of the metal layer between the completely etched area and the Al which can be seen in the SEM-images in **Figure 7 a and b**. This transition might be reduced by an adaption of the ink formulation, a surface pre-treatment, an increase in the substrate temperature or a decrease of the etching time.

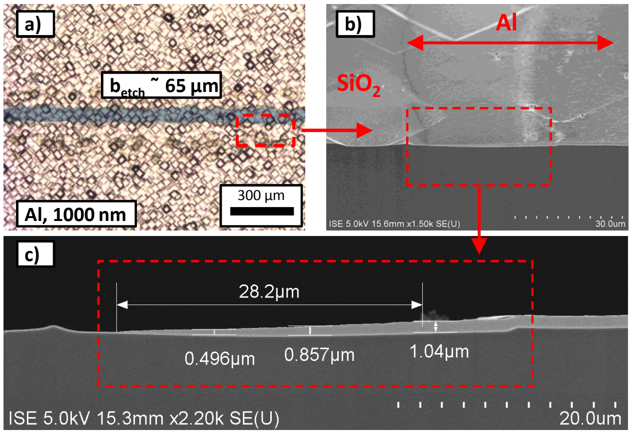


***Figure 7** Line Openings on Al-layer with a thickness of 1000 nm.*
a) Optical micrograph showing a homogeneous line opening.
b) Cross-section SEM images of the edge of a line opening, showing the transition between the insulating SiO2 and the Al at an angle of 30 °.
c) Cross-section SEM images of the edge of a line opening, showing the transition between the insulating SiO2 and the Al at an angle of 90 °.

To show the feasibility for e.g. the contact separation of a BC-BJ solar cell, a meander structure with a pitch of 2 mm was inkjet printed on a sample with NiV with a layer thickness of 150 nm, which can be seen in **Figure 8**. The horizontal and the vertical lines were printed in two subsequent steps that were aligned to each other. The etched structures have an average width of approximately 160 µm and are free of interruptions. The printer setup would also allow creating structures with a pitch of 500 µm which will be the focus of future investigations that will additionally be performed on wafers with a size of 156 x 156 mm^2.

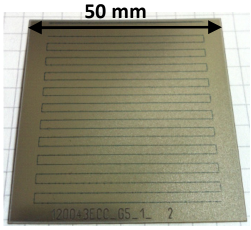
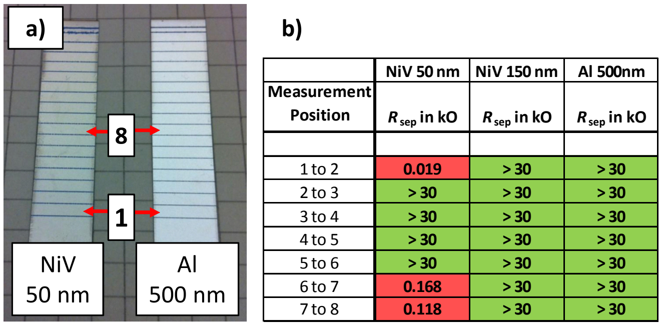


Figure 8 *Meander structure on a NiV-layer with a thickness of 150 nm. The pattern was printed in two steps that are aligned to each other.*

Contact Separation

In addition to the optical characterization the quality of the etched areas were also evaluated electrically. Therefore the resistance R_{sep} was measured between eight separated metal areas. Wafers with an Al-thickness of 150 nm and a NiV-thickness of 50 nm and 150 nm were used. For all samples the substrate temperature during printing and etching was set to 60 °C. Based on the results of the parameter variations for the Al-wafer eight layers were printed on top of each other. For the NiV-samples with a layer thickness of 50 nm two layers and for 150 nm 4 layers were chosen. According to the measurement setup that can measure a voltage of maximum 300 V at a current of 10 mA the maximum resistance detected can be 30 kΩ, which is regarded as being sufficient for the contact separation resistance for any kind of solar cell. A photograph of the samples and the results of the resistance measurements are shown in **Figure 9**.



	NiV 50 nm	NiV 150 nm	Al 500nm
Measurement Position	R_{sep} in kO	R_{sep} in kO	R_{sep} in kO
1 to 2	0.019	> 30	> 30
2 to 3	> 30	> 30	> 30
3 to 4	> 30	> 30	> 30
4 to 5	> 30	> 30	> 30
5 to 6	> 30	> 30	> 30
6 to 7	0.168	> 30	> 30
7 to 8	0.118	> 30	> 30

Figure 9 *Contact separation measurement.*
a) Photograph of the printed and etched samples. The numbers and arrows schematically show the measurement position.
b) Results of the resistance measurements.

For the NiV-samples with a thickness of 150 nm and the Al-samples with a thickness of 500 nm all measured resistances were above 30 kΩ. For the NiV-samples with 50 nm lower resistance was measured in three spots. These etched lines showed visible interruptions. Special attention has to be paid in future work to guarantee completely etched lines across the whole wafer area. On areas without interruptions, the resistances measured were above 30 kΩ. The optical appearance of the wafers aligns very well with the electrical results. This means that if the line appears completely etched in e.g. microscope images, the electrical insulation is also confirmed.

Conclusion and Outlook

This paper presents a novel process route to create separated metal structures, suitable for the metallization of back contact solar cells. Inkjet-patterning of the contacts was successfully demonstrated for Al- and NiV-layers with varying thickness deposited by PVD. A set of experiments was performed to evaluate the etching properties in terms of the printing resolution, the number of layers printed and the substrate temperature during inkjet printing. The structures were characterized optically and electrically.

Etched line openings with a width of approximately 65 µm were realized on 1000 nm thick Al-layers. The resistance of the completely opened structures was above 30 kΩ and meets the requirement for the production of back contact solar cells. A meander structure, free of interruptions was demonstrated on a 150 nm thick NiV-layer over a 50 x 50 mm^2 wafer sample.

The process is not limited to the fabrication of solar cells and may also be applied for e.g. the production of RFID-antennas, printed circuit boards or electrodes for batteries or fuel cells.

Future work will focus on a detailed understanding of the wetting properties of the ink on the substrate. This is necessary to further reduce the line dimensions and to guarantee structures free of interruptions. The process will be applied on other metal layers and stacks of metal layers. Also wafer formats of 156 x 156 mm^2 will be used to further prove the ability of the process to be suitable for an industrial implementation.

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Author Biography

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