Structuring Technology and Simulation of High Efficiency 
Back-Contact Back-Junction Silicon Solar Cells 
Under Low Concentration

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Abstract: Industrially feasible structuring techniques as screen-printing and inkjet are investigated with regard to the minimal feature size that can be reached on back-contact back-junction silicon solar cells. The two received different pitches and all further parameters as e.g. diffusion profiles and surface recombination velocities are used as input parameters for the simulation program Sentaurus Device in order to calculate the cell parameters. The smallest pitch that can be processed only with screen-printing technology and a ratio of emitter to back surface field of at least 1.5 (2 mm) and theoretically allows efficiencies of 21% at a concentration of 5 suns. With inkjet structuring technologies structure sizes of about 10 µm and an alignment accuracy of 13.8 µm the pitch can be reduced to 500 µm which results in a possible cell performance of 23.2% under 5 suns.

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INTRODUCTION

The use of cost effective silicon solar cell technologies for concentrating photovoltaic systems is a promising approach to reach grid parity as soon as possible. Sinton and Swanson already achieved 27.5% under 100 suns with a silicon solar cell [1], [2]. Since with smaller structures the series resistance is reduced and the collection probability of the minority carriers increases it is mandatory to develop industrial fabrication technologies which allow cost effective realization of small device features. Two different types of back-contact back-junction (BC-BJ) cells are investigated: one which is structured and metalized by screen-printing and one which is structured with inkjet and also metalized with thick film technology.

STRUCTURING TECHNOLOGIES

In order to reach high efficiency back-contact back-junction solar cells very fine structures need to be realized on the rear side. Additionally the structuring technology must be very precise to well align subsequent masking steps.

Screen-Printing

In the following the deviation in printing accuracy is divided into the image definition of a certain process technology, the geometrical distortion of the printing master, the spread of the printing medium during the printing process and the alignment connected to the equipment.

Several aspects need to be taken into account when transferring a digital plan to the screen, generating the image definition $\delta_{im}$. The maximal deviation is the distance from the center of the image to the edge of a 125x125 mm$^2$ wafer, leaving 1 mm distance to the edge:

- The digital plan e.g. CAD-file of a mask is transferred by a laser to a transparent foil with an accuracy of about 1.5 µm.
- In the next step the screen is exposed with the structures of the foil defining the subsequent printing pattern on the screen. A higher temperature during exposure compared to foil fabrication results in both a larger foil and an increased printing frame. For the printing
frame material steel is favored because the coefficient of expansion is by a factor of 2 smaller than aluminum. In total, due to the temperature influence, the deviation is only 0.8 µm while keeping the temperature variation smaller than 2°C.

- The impact of changing the relative humidity of 5% corresponds to a deviation of 3.7 µm of the foil size and so is the printing pattern that is generated on the screen.

The overall largest possible deviation in image definition from the design to the processed screen is then \( \delta_{im} = 6 \mu m \).

The geometrical distortion \( \delta_{gd} \) of the screen is caused by the squeegee [3]. The distortion

- is zero at the centre of the screen and increases towards the edge.
- decreases with a larger screen.
- is larger perpendicular to the printing direction because the screen gets stretched stronger.
- is \( \delta_{gd} = 9 \mu m \) for a type 7 screen (490x410 mm\(^2\)) at the edge of the wafer perpendicular to the printing direction with a screen lift-off of 2.5 mm and a squeegee length of 200 mm.

Further printing deviations can be avoided or reduced during the printing if the different screens have identical properties and:

- the printing frame consists of the same material, size and profile.
- the screen tension is high.
- the squeegee pressure and printing speed is low.
- the squeegee is short.

Immediately after printing, the screen-printed paste or ink spreads and thus a line gets wider and an opening gets narrower than the dimension in the screen. The magnitude of the spread \( \delta_s \) depends on the surface of the substrate, the printing parameters and the paste or ink used. The parameter of the paste that influences the spread most is the viscosity. Screen-printed line openings of ink that are printed for structuring oxide and other passivation layers are reduced by 11 µm ± 7 µm, with the ink used in this study, compared to the defined image of the screen. The reduction of the opening can be taken into account when designing the screens but the deviation will stay, leading to \( \delta_s = 7 \mu m \). The deviation when printing aluminum and silver pastes is of same order of magnitude although the pastes spread out more strongly, especially the aluminum paste because of the low viscosity.

The accuracy of the alignment \( \delta_a \) between the screen and the underlying wafer depends on the screen printer and its software. It has to recognize the edges of the wafer as well as the screen via a camera system. Reinstalling a screen into the printer can lead to a deviation of the printed structure of about 50 µm. So the screen has to be readjusted to the wafer. The following wafers are then printed with the so called repeating accuracy. In an experiment identical fiducial structures were printed on the same wafer in different printing steps. The measured deviation was determined to be \( \delta_s = 20 \mu m \).

Assuming all errors to be independent from each other the total error of screen-printing \( \delta_{s,tot} \) is

\[
\delta_{s,tot} = \delta_{gd} + \delta_{s} + \delta_{a} = (6 + 9 + 7 + 20)\mu m = 42 \mu m
\]

For realizing a screen-printed BC-BJ solar cell four screen-printing steps have to be aligned on each other. The safety space has been chosen \( 2x \delta_{s,tot} \) resulting in a cell with a pitch of 2 mm.

**Inkjet Printing**

Using inkjet as structuring technology very narrow structures can be defined. [4] This can be seen in Figure 1.

![FIGURE 1.](image) The image shows a wafer with a printed inkjet mask that has openings of 10 µm.

The alignment accuracy of the inkjet system was analyzed in an experiment (see Figure 2) where four lines were printed onto two wafers with thermally grown SiO\(_2\) surfaces. Each line was printed within four steps (s1-s4). Between each printing step the wafer
was taken out of the printer and again inserted and printed.

**FIGURE 2.** The big square symbolizes a 125x125 mm² wafer. On the top (T), bottom (B), right (R) and left (L) side lines were printed onto the wafer. First a quarter of each line (s1) is printed. Afterwards the wafer was taken out of the machine and put back and the next part of each line (s2) was printed. This procedure was repeated three times. With this sequence the alignment accuracy can be determined by measuring the width of the lines and the diameter of the droplets. The bottom line is printed parallel to the print head movement and has long stretched ink drops. The drops of the right line are more roundish.

As illustrated on the sketch of the printed line and also visible on the microscope pictures the line is not straight but some droplets deviate from the middle line. However, no offset between the different printing steps can be found. For a production process in addition it has to be tested what deviation exists from machine to machine since the printing of the different steps must be done in different machines in order to allow an economically viable production process.

For the cell process small openings will be printed so that only the deviation to one side is important. Therefore the decisive parameter for the inkjet system is the deviation \( \delta_{i, tot} \) of a droplet of the middle line

\[
\delta_{i, tot} = \frac{w - d}{2}
\]

with \( w \) the width of the printed line and \( d \) the diameter of the droplet. For the left and right line with the measured values \( w = 92.3 \pm 1.0 \) μm and \( d = 64.8 \pm 3.4 \) μm a deviation of \( \delta_{i, tot} = 13.8 \pm 3.5 \) μm was determined. For the stretched droplets of the top and bottom line the deviation is 16.2 ± 7.6 μm. The same experiment has been performed with wafers with a PECVD SiNₓ surface, leading to similar results. The lower deviation and the more defined solidified droplets of the left and right line are the reasons why the openings will be printed perpendicular to the printing direction.

With inkjet as structuring technology a pitch of a BC-BJ cell of 500 μm can be reached.

**SIMULATION OF BACK-CONTACT BACK-JUNCTION CELLS**

The two BC-BJ solar cells - both with an emitter to back surface field (BSF) ratio of 1.5 but different pitches of 500 μm and 2000 μm - were simulated with Sentaurus Device, an advanced multidimensional device simulator from Synopsis. The following simulations were executed in 2D. In good approximation solar cell simulations can be calculated separately in an optical and an electronic part. The wavelength and depth dependent spectral generation \( G_i(z) \) is calculated via an integrated raytracer. By using the transfer matrix method an antireflection coating is accounted for. To generate a white light generation profile \( G_i(z) \) is multiplied and integrated with the AM1.5g spectrum. For the calculation of the IV characteristics the generation profile is incorporated in a meshed symmetry element of the designed solar cell and loaded into Sentaurus Device. By solving the set of semiconductor transport equations numerically for different applied voltages, the IV-curve is computed. Finally the measured specific contact resistances \( \rho_c \) of 4 mΩcm² for the aluminum contact, 5 mΩcm² for the silver contact and the series resistance due to the limited finger conductivity \( R_{s,finger} \) of the aluminum and the silver screen-printed paste are added. The cell area is 2x2 cm² with 18 mm long fingers.

For input parameters of the simulated solar cell a 250 μm thick n-type wafer with a bulk lifetime of 1 ms is chosen. The base resistivity is varied between 1 Ωcm to 100 Ωcm. The following sheet resistances with deep driven-in phosphorous profiles are used: \( R_{sh,BSF} = 148 \) Ω/sq, \( R_{sh,FSF} = 8 \) Ω/sq with a recombination according to Cuevas et al. [5]. The aluminum emitter is 7 μm deep, has a reduced SRH lifetime \( \tau_{SRH} \) as recently mentioned by Altermatt et al. [6] and an S value for SiO₂ passivated surfaces have been taken into account [7].

The simulated short circuit current density \( j_{sc} \) increases almost linearly with the illumination intensity (Figure 3). For each illumination intensity \( j_{sc} \) increases with increasing base resistivity because the collection probability for minority carriers is the higher the lower the doping concentration. A smaller pitch i.e. smaller BSF area reduces the distance for the holes to reach the emitter if they are generated above the BSF. This reduced electrical shading effect increases \( j_{sc} \) as well.
A higher short circuit current density results in a much higher open circuit voltage $V_{oc}$ (see Figure 4) with increasing concentration. This agrees with the one diode formula, where it can be seen, that $V_{oc}$ scales with the logarithm of $J_{sc}$.

The fill factor $FF$ decreases with increasing base resistivity, increasing illumination intensity and increasing pitch (Figure 5). The reason is the impact of the lateral resistance in the bulk due to the majority carries, which are the electrons and have to reach the n-contact.

The cell with 1 Ω/cm base material is plotted additionally without the resistance due to the specific contact resistance $r_{s,\text{contact}}$ and $r_{s,\text{finger}}$. The cell with a pitch of 2 mm has already a fill factor reduction due to the resistance in the base under concentration. In contrast to this the cell with a pitch of 500 μm virtually shows no reduction in the fill factor.

The efficiency $\eta$ increases with illumination (Figure 6) until about 5 suns. This is due to the voltage increase. With even higher light intensities $\eta$ decreases because of the drop of the fill factor. Neglecting $r_{s,\text{contact}}$ and $r_{s,\text{finger}}$, an almost constant and very high efficiency can be reached for the inkjet cell.

As simulated above, a very low series resistance is crucial for concentrator solar cells. In order to interconnect such BC-BJ solar cells in a module or concentrator system, an advanced rear side concept is proposed as can be seen in Figure 7. The idea is to install only small metal points on the rear of the cell instead of a full grid leading to several advantages. Optimizing the cell more passivated area can be realized and only the contact resistance has to be
improved with the metal point contacts not being relevant for the lateral current transport. The lateral conductance is provided by interconnection tabs or by a printed circuit board (PCB). The transfer of the lateral conductivity of the current from the cell to the module allows realizing small structures on the cell as well as easy fabricable thick metal layers on the module side.

FIGURE 7. Sketch of the interconnection of the rear side of three solar cells. An interconnection tab or a structured printed circuit board connects the metal points of one polarity (+) of a cell with the opposite (-) of the next one.

CONCLUSION

The analysis of the accuracy of the structuring technologies screen-printing and inkjet shows that the deviation of screen-printing is \( \delta_{\text{s,tot}} = 52 \, \mu m \) and of inkjet \( \delta_{\text{i,tot}} = 13.8 \, \mu m \). This leads to the fact that the pitch for a back-contact back-junction cell can be reduced to 500 \( \mu m \) using inkjet as structuring technology compared to 2 mm with screen-printing.

The simulated cells comprehend a screen-printed aluminum emitter which promise a cheaper production sequence compared to boron diffusions. The simulation results show that a cell with a pitch of 2 mm performs reasonably until an illumination intensity of about 5 suns where \( \eta = 21\% \) is reached. Going to even higher concentrations the cell is limited due to series resistances of the base and of the finger conductivity. The inkjet structured cell reaches a higher maximum efficiency above 23\% but at the same concentration factor of 5. \( \eta \) decreases more slowly leading to efficiencies > 20\% at 30 suns. The inkjet structured cell is only limited by lateral series resistances of the finger. Especially the inkjet cells are very suitable for low and middle concentrator systems.

An advanced module interconnection of cells with metal points can considerably lower the series resistance and therefore increase the efficiency.

REFERENCES


