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The stencil printing for front contact formation on the silicon solar cells

Streszczenie. *W pracy opisano proces nadruku kontaktów przednich przy użyciu szablonu na krzemowe ogniwa monokrystaliczne z powierzchnią posiadającą teksturę. Finalne parametry ogniw z elektrodami naniesionymi z wykorzystaniem rakli o różnej twardości uzyskano na podstawie pomiarów SEM, Corescan, LBIC oraz charakterystyk prądowo-napięciowych I-V. Wyniki poddano analizie, co pozwoliło zaobserwować fakt, że zastosowanie techniki nadruku kontaktów za pomocą szablonu doprowadziło do redukcji obszaru pokrytego zmetalizowanymi elektrodami o 7,5%. Powoduje to ograniczenie strat w parametrach wyjściowych ogniw poprzez zwiększenie powierzchni czynnej ogniw. Zastosowanie szablonu nadruku o szerokości przekroju pojedynczej ścieżki 100 μm oraz współczynniku wzajemnej relacji (wys. do szer.) 0,5, pozwala uzyskać ogniwo cechujące się: gęstością prądu zwarcia J_{sc} ok. 34,7 mA/cm^2, napięciem obwodu otwartego 606 mV, współczynnikiem wypełnienia 0,768 oraz sprawnością 16,16%. Sprawność osiągana dla ogniwa z kontaktami wykonanymi klasyczną techniką sitodruku to 15,33%.* ***(Technika nadruku kontaktów przednich na krzemowe ogniwa słoneczne przy użyciu szablonu)****.*

Abstract*. This study reports the stencil printing process of a front contact electrode on monocrystalline (Cz-Si), textured silicon solar cells. The final parameters of the cells obtained by applying the squeegee blades with different hardness and detected by SEM, Corescanner, LBIC and I-V systems are analysed. By using stencil technique, the front side metallization has been reduced by 7.5%, resulting in the limiting of shading losses and improvement of the Si solar cell output parameters. The stencil printing of 100 µm fingers width with aspect ratio of 0.50 resulted in short circuit current density of 34.7 mA/cm^2, open circuit voltage of 606 mV, fill factor of 0.768 and cell conversion efficiency of 16.16% compared to 15.33% with screen printed contacts.*

Słowa kluczowe: krzemowe ogniwa słoneczne, elektrody przednie, szablon, sprawność,
Keywords: silicon solar cells, front contact, stencil, efficiency,

Introduction

A challenge in the silicon solar cells manufacturing process concerning front contact electrode deposition is to reduce the grid width to limit shading losses without reducing the conductivity of the front electrode lines what can be obtained by increase the aspect ratio (i.e. height over width) of the front line [1]. The metal contacts are deposited on the front of the silicon solar cells, usually following a standard H pattern geometry. Commercially used pastes contain silver particles, in the form of spherical grains with a mean diameter of 1-2 µm, glass frits, organic binder, and optionally the metallic oxide additives, where the silver amount is between 50-90 wt. % of the mixture. The glass, which usually contains lead oxide (PbO), is less than 5 wt. %. However, it plays a major role in the contact formation during the high temperature firing stage. It wets and dissolves silver particles at lowered temperatures, etches and dissolves the antireflection coating, and enhances the formation of silver crystallites [2].

The contact deposition process has to fulfil industrial requirements such as high throughput and low cost. This excludes such processes like photolithography, the vacuum based deposition techniques and a lot of chemical methods including too many production steps [3]. There are different industrial applicable techniques in which front contact electrode can be deposited [4]. The most common of them is the screen printing method, which is simple and fast. However, it has a lower aspect ratio of 0.29 of the final grid line [5] and produces a series resistance of up to 1.2 Ωcm^2 for the commercial solar cells [6]. Over the last years, the design of screen-printers was improved such that throughputs of more than 1500 cells per hour become possible. As a new technique, the ink-jet printing technology is rapidly becoming one of the most promising and the best alternative deposition technique compared to screen printing. However, this disadvantage is lower printing speed and the inks, containing about 20 wt.% of metallic silver particles, which must fit physical and rheological requirements of fluid flow [7].

Among the promising metallization techniques, the formation of metal contacts using the stencil printing technique is assumed to be one of the most viable candidates for the high-efficiency solar cells [8].

This study presents the stencil printing process of the front contact electrode on monocrystalline (Cz-Si) textured silicon solar cells. The final parameters of the cells obtained by applying the squeegee blades with different hardness are presented.

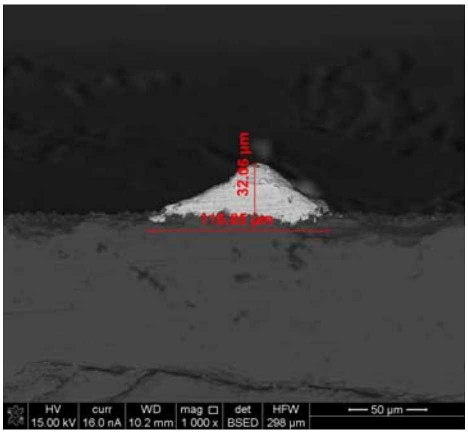
Experimental

The silicon solar cells were fabricated on the laboratory technological line with TiO_2 as the antireflective (ARC) layer and with a low resistivity emitter. This approach limited their final photoconversion efficiency [9]. The 1.3 Ωcm p-type Cz-Si (100), 170 µm thick wafers were used as a base material. The cells of the 5 x 5 cm^2 size and with the textured surface after processing in an alkaline bath were used. The diffusion process was carried out in quartz tube furnace from $POCl_3$ donor source at a temperature of 850^{o}C for 30 min. The sheet resistance of the final emitter was within 47.4±1.8 Ω/□. After edge isolation and the phosphosilicate glass removal processes by chemical method, the surface passivation was achieved by the growth of 15 nm thick SiO_2 grown at 850^{o}C in dry air for 10 min. To assure the ARC front layer, the 70 nm thick titanium dioxide layer was deposited by CVD method using $Ti(C_2H_5O)_4$ as a source.

For front electrode deposition, the Du Pont PV18A paste was applied. Screen printing processes were carried out with 320 mesh screen. The screen and stencil, used for print on the wafer with an area of 5x5 cm^2 have the same number of 19 grid finger lines, each 100 µm wide and 48 mm long. The stencil printing process was realised by using the 70 µm thick stainless steel 1H18N9 pattern with a particular contact line of 100 µm width made with laser. The front contact for stencil printing was formed in a two-step process. The first contact of a greed line was printed and the second, perpendicularly directed, was the bus bar electrode with a width of 2 mm. The stencil printed contacts were deposited at varying hardness of the polyurethane double bevel squeegee blades, from 65A to 95A in Shore's scale with the speed of 10 cm/s. The rear side of all cells were screen printed being 30 μm thick with the use of Al PV381 paste. After drying in air at 200°C the printed pastes were co-fired in the IR belt furnace running at the belt speed of 200 cm/min at the temperature of 780°C at peak. The IR conveyor furnace applied in the experiment has three heating zones, respectively: 19 cm, 19 cm and 38 cm long. The metallization process was performed in a purified and dried natural atmosphere.

Results and discussion

The front side printed paths of the greed were imaged by the dual beam high-resolution scanning electron microscopy (SEM) FEI Quanta 3D FEG integrated with the EDAX Trident system. It was found that the 100 μm wide stencil printed fingers with their trapezoidal shape, exhibit high value of the aspect ratio (AS), depending on squeegee blades hardness. Typical cross sections and line shapes of front grid lines are shown in Figure 1a), 1b), 2a) and 2b).


a)

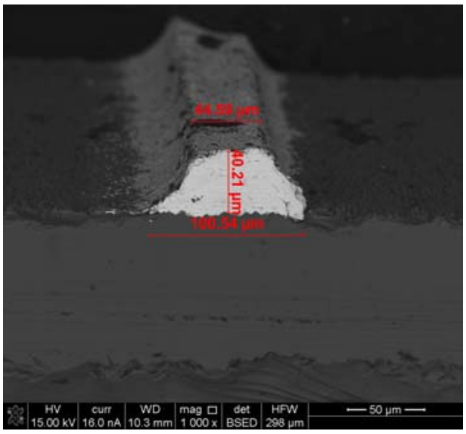
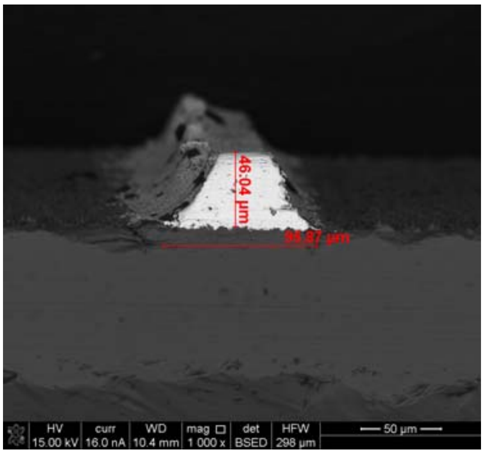

b)

Fig. 1. The SEM micrographs of a cross section of solar cell contacts obtained by technique: a) a screen printed, b) stencil printed, by applying the squeegee blade with hardness of 65A

The area of front side grid on screen printed cell is 198.26 mm^2 and results in metallization fraction value of 7.93%. For stencil printed cell the area is 183.40 mm^2 what results in metallization fraction of 7.33%. By using stencil technique, the front side metallization has been reduced by 7.5%, resulting in a limiting of shading losses and improvement of the Si solar cell parameters.

The light beam induced current (LBIC) map was performed on the previously imaged paths, by using a 20 mW diode laser with incident light at 404 nm of a wavelength and spot resolution of about 10 μm. Figure 3 shows highly degraded area of the photoconversion process under the front electrode (blue colour areas).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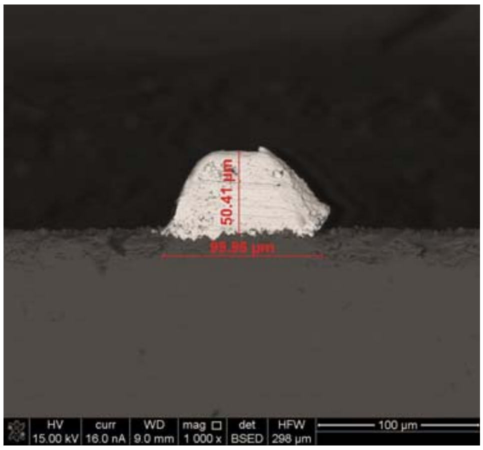
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Fig. 2. The SEM micrographs of a cross section of solar cell contacts obtained by technique: a) stencil printed – the squeegee blade with hardness of 80A and b) stencil printed – the squeegee blade with hardness of 95A

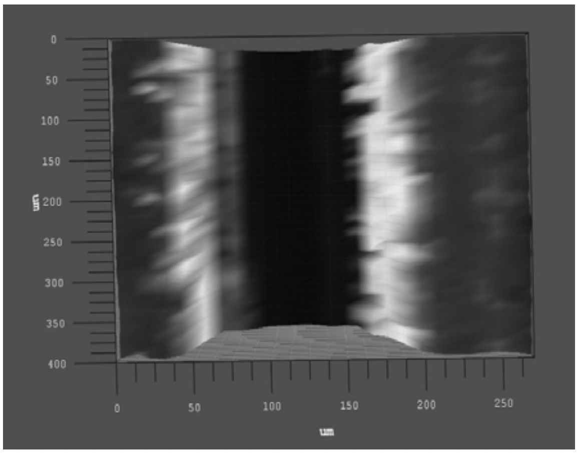

Fig. 3. The light beam induced current (LBIC) map obtained by a 20 mW diode laser with spot resolution of about 10 μm for the greed line of the Stencil – 95A cell

The border line between stencil printed contact and textured surface is not sharp which suggests that the stencil method should be optimised in the aspects of print speed, squeegee blade pressure and paste viscosity. The distance between border lines from the two sides of the finger, shown as a blue area in the LBIC map, is about 100 μm, which is appropriate to the finger width determined by SEM.

The relationship between the printing methods and solar cell contact parameters was investigated by Corescanner system. The specific contact resistance (R_c) was calculated using the proportion of potential across the contact (V_c) at zero potential to current density (J_c) of contact for a linear relationship of both, according to the following formula:

$$R_c = \frac{V_c}{J_c} \quad (1)$$

The J_c and V_c parameters between the finger edges and centre are sensitive to non-uniform values of the sheet resistance R_{sheet} of the emitter below the finger. For that reason the most favourable way to calculate the characteristic parameters of contact is to define the line contact resistance (R_{cl}) using the proportion of the Vc at the edge of the finger to a total current flowing through the contact area per unit length of finger (I_c) [10]. The R_c and R_{cl} values were calculated at Corescanner system for screen printed and stencil printed cell, respectively. The resolution in the direction perpendicular to the fingers was 0.1 mm, and the 2D representation for one cell is shown in Figure 4. In the above-presented experiment, the separation between fingers was 2.5 mm. The design of the metal grid is limited by the separation between the fingers that results in the losses induced by the metallization (shading or resistive losses). Taking the cell with 150 μm wide fingers printed on emitter with the sheet resistance of 50 Ω/□, an optimal separation between fingers is 3.0 mm. For the cell with 28 μm wide finger, printed on the emitter with the sheet resistance of 100 Ω/□ the optimal spacing is 1.1 mm [11].

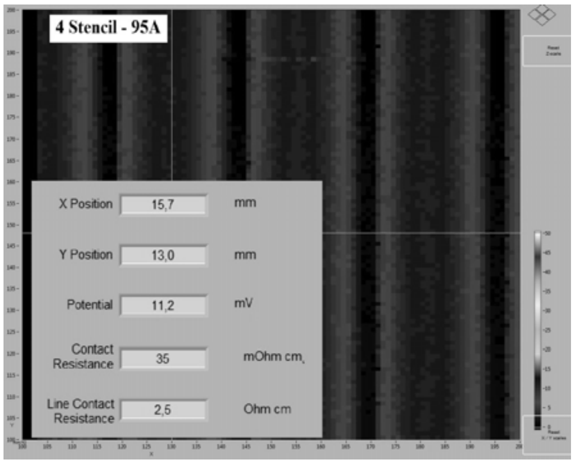

Fig. 4. The 2D representation of contact resistance measurement result with the Corescanner of Stencil – 95A cell.

Furthermore, the solar cells were characterised by the current-voltage (I-V) measurements at Solar Simulator SS200 AAA class EM Photo Emission Tech., Inc. with Solar Cells I-V Curve Tracer SS I-V CT-02 PV. The data were obtained under AM1.5 global spectrum at 1000 W/m^2 light intensity at the temperature of 25^{o}C. The I-V characteristics of the cells were numerically fitted with the double diode exponential relationship (DEM). The results are summarised in Table 1. The table does not include the cell shunt resistance parameter (R_{sh}), because of all cells R_{sh} was kept between 139 – 146 Ω. The data in the first column exhibit the kind of a deposition method and hardness of the used squeegee blades denoted in Shore scale.

Table 1. The electrical I-V parameters of textured Cz-Si solar cells (of area 25 cm^2) fabricated with the screen printed and stencil printed methods, after metallization process in IR belt furnace.

Printing method – squeegee blade	AS	I_{sc} [A]	V_{oc} [V]	FF	R_s [mΩ]	R_c [mΩcm^2]	R_{cl} [Ωcm]	I_{s1} [pA]	E_{ff} [%]
Screen – 65A	0.27	0.843	0.600	0.757	53.9	45	3.2	29.84	15.33
Stencil – 65A	0.40	0.860	0.605	0.759	49.7	37	2.9	24.17	15.79
Stencil – 80A	0.48	0.866	0.605	0.763	48.2	35	2.6	24.29	16.00
Stencil – 95A	0.50	0.868	0.606	0.768	48.1	35	2.5	23.93	16.16

where: AS – aspect ratio, I_{sc} - short circuit current, V_{oc} – open circuit voltage, FF – fill factor, R_s – series resistance of cell, R_c – specific contact resistance, R_{cl} – line contact resistance, I_{S1} – saturation current of dark current diffusion component, E_{ff} – conversion efficiency.

As all cells having this same rear side metallization, emitter sheet resistance, passivation and antireflective layer, the positive increase of V_{oc} and I_{sc} for stencil printed cells can be explained by the reduced contact area of the front electrode. The reduced metallization coverage for all stencil printed cells results in an increase of I_{sc} due to a larger active area of the cell, as well as a rise in V_{oc} due to reduction of diffusion component of the dark saturation current.

The increase of the squeegee blades hardness from 65A to 95A resulted in an increase of an aspect ratio and a FF profit change of 0.009, what allows reaching the conversion efficiency above 16% for stencil printed cell – Fig. 5. Using the squeegee blades with a hardness of 95A, the 100 μm wide and 50 μm thick fingers were stencil printed, leading to the aspect ratio of 0.50, higher than those obtained by screen printed grid line with the AS of 0.27. However, its impact on the FF and Eff is not as strong as expected, especially not for cell stencil printed by squeegee with a hardness of 95A, where the value of AS is 20% higher in comparison to stencil printed cell by squeegee 65A.

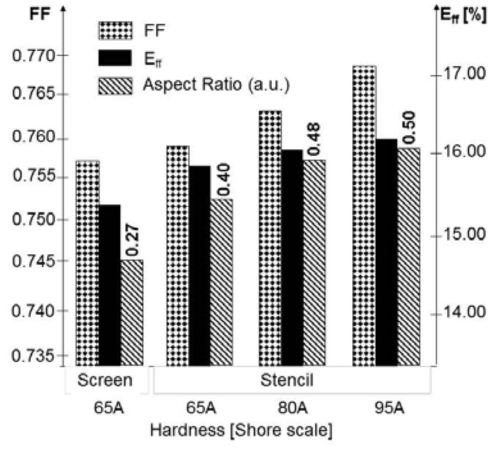

Fig. 5. The dependence of fill factor, solar cell efficiency and aspect ratio on hardness of the used squeegee blades in stencil printing process. For comparison, the parameters of the screen printed solar cell are enclosed also.

The difference in specific contact resistance between screen printed and stencil printed cells is reflected by the difference in the total series resistances and FF of the cells (Table 1). The reason is simply to be found in the stencil printed paste densification, because all the cells were co-fired under this same temperature condition. In stencil printing method a deposited paste is not detached from the surrounding wires of the screen but only from the walls of the stainless steel pattern.

Conclusions

The solar cells with sheet resistance of the final emitter of 47 Ω/□ with stencil printed contacts exhibit conversion efficiency up to 16.16%. The lower viscosity of screen printed paste causes higher flow on the substrates compare to stencil printed materials resulting in the higher width of the electrode. The reduced width of the electrode fingers obtained by stencil printing increased the solar cell efficiency by reducing the shadow loss. This result shows that the stencil printing of contacts offers a viable alternative to screen printing technique. Moreover, the stencil printing is a very attractive method for pastes with a higher viscosity over 380 Pa·s, than those used for screen printing and for organics pastes applying as contacts on TCO films, which often, under air ambient, are rapidly changing viscosity.

The PV sector analysis emphasizes that the share of screen printing method as a base technique for contact deposition will decrease, from currently 98% to about 50% by 2025, mainly by an increase of the stencil-printing method, from current minimum level of about 1% to 20% over the next ten years [12].

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