

Optimisation of monocrystalline silicon solar cell

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The results of investigation of monocrystalline silicon solar cells with screen-printed metallisation are presented. The efficiency of typical cell is about 15%. The participation of all responsible factors for reducing the efficiency was determined based on PC-1D program. It was shown that the profile of the donor dopant in the emitter n^+ is the most critical factor which reduces the efficiency by about 9% in comparison with the maximal theoretical value. The second important factor is the area of the top grid contact which reduces the efficiency by about 7%. The other factors are reflectance from $TiO_x/SiO_2/Si$, series resistance and high saturation current which is caused by recombination in the space charge region of cell. To achieve higher efficiency and to approach 20% efficiency, cell design needs to evolve significant and further improvement in the fine-line screen-printing. Moreover, elaboration of selective emitter technique suitable for mass production is necessary.

Keywords: solar cells, crystalline silicon, manufacturing and processing.

1. Introduction

Crystalline silicon is a dominant material for solar cell production over 20 years. However, the multicrystalline silicon will be dominant in the future, nevertheless, a market for high-efficiency monocrystalline silicon solar cells will always exist. The monocrystalline solar cells could be used in regions where the amount of solar radiation is low or in applications where space is limited [1]. Therefore, monocrystalline silicon could be an important material for solar cells in the future if cost effective and high-efficiency solar cell will be elaborated. The best laboratory cell based on high-cost float-zone (FZ) wafer silicon received efficiency higher than 24% for non-concentrated AM1.5 solar spectrum [2]. The best laboratory cell based on industrial quality Cz wafers receive about 20% efficiency. However, it was shown that efficiency of boron doped Cz silicon is reduced by about 10% when it is exposed to sunlight [3]. This effect can be explained by boron-oxygen complex which becomes activated by sunlight. Therefore magnetic Cz silicon with no oxygen or gallium-doped Cz wafers has potential for high- efficiency solar cells in the future [4]. Despite these high efficiency laboratory cells, the industrial solar cells are in the range from 13% to 15% for monocrystalline and 12% to 13% for multicrystalline wafers. Many of the processes used for the fabrication of high-efficiency laboratory cells are too complex and costly to be involved in mass production. Due to the economical factor the industrial technology must be simple, capable of high throughput and must be characterized by high yields. On the other hand, a certain performance level must be

achieved because it is necessary take into account balance of a system cost.

Major differences between the best laboratory cells and industrial cells are caused by top grid contact design. In the high efficiency laboratory cell, the top grid contact is made by vacuum evaporation and photolithography process. This technique offers fine line-width, high conductivity and low contact resistance but it is not acceptable for mass production. The technology commonly used by most of the manufacturers by over 20 years is based on the screen-printing technique [5]. It is well known that this technique has many disadvantages such as a relatively large line-width of about 150 μm and a high penetration of the silver paste into a junction region which increases the shunting current and recombination in the space charge region. Therefore depth of the junction must be relatively profound and the emitter must be heavily doped what reduces cells spectral response for a short wavelength due to a “dead layer” in the top surface. However, there is continues progress in the composition of the pastes and screen-printings technique which makes possible to use more optimal profile of the emitter and in effect increase in cells efficiency.

In this work, we present our results on the development of monocrystalline silicon solar cell technology with screen-printed metallisation.

2. Method of optimisation of solar cell

The optimisation of solar cells has been made by PC-1D computer program [6] which solves the two-carrier time-dependent semiconductor transport equation in one dimension. The program allows the user to specify all necessary parameters which determine device performance.

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The program was used for analysing all the parameters of cells determined from I-V characteristics. The simulation of an ideal cell without any optical or electrical losses was made for given parameters of silicon material. In the next step, the simulation of cells with real parameters measured in experiments was performed. This allowed us to determine which technological steps should be improved to increase the cells efficiency (Fig. 1).

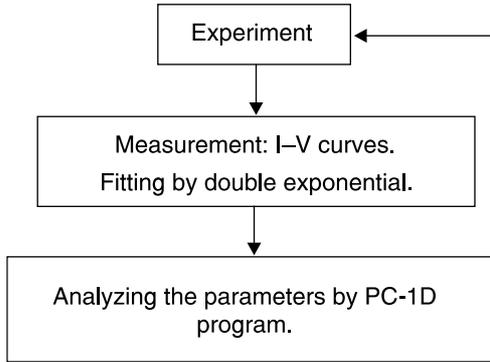


Fig. 1. Optimisation of solar cells technology.

The measurements of I-V characteristics allow us to determine the basic parameters: I_{sc} is the short circuit current, V_{oc} is the open circuit voltage, FF is the fill factor, and E_{ff} is the efficiency. The I-V curves were fitted with the double exponential relationship of the following form

$$I = I_{ph} - I_{s1} \left[\exp\left(\frac{V + IR_s}{A_1 V_t}\right) - 1 \right] - I_{s2} \left[\exp\left(\frac{V + IR_s}{A_2 V_t}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where I_{ph} is the generated photocurrent, R_s is the series resistance, R_{sh} is the shunt resistance, A_1 and A_2 are diode ideality factors, I_{s1} and I_{s2} are saturation currents. V_t is equal to kT/e where k , e and T have their usual meaning. In order to accomplish this task, an interactive computer program was used [7]. The A_1 equal to 1.0 and A_2 equal to 2.0 were taken. In such a case, the first diode represents diffusion current which is connected with the neutral regions, either emitter or base, whereas the second diode is attributed to generation-recombination phenomena in the space charge region of solar cell.

3. Solar cell fabrication

3.1. Cell processing sequence

The substrates used in this work were “as-cut” boron doped p-type, $1 \Omega \text{ cm}$ (100), Cz-silicon wafers from Bayer Solar Corporation. The thickness of the wafers was $300 \mu\text{m}$ and carrier minority lifetime $\tau \geq 10 \mu\text{s}$. The manufacturing sequence for the cell fabrication can be divided in the following main steps (Fig. 2).

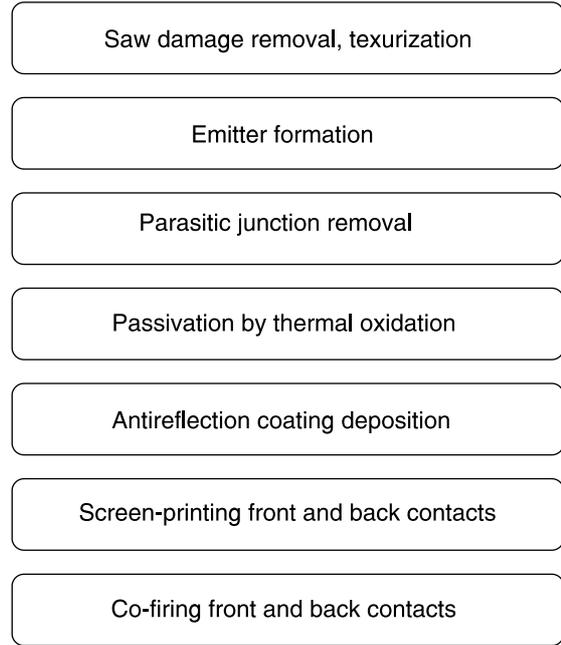


Fig. 2. Flow chart of the standard process at IMMS-PASs.

3.2. Saw damage removal, texturisation

The wafers were etched in 30% KOH solution to remove saw damage. The texturisation has been made in the solution containing 6% IPA, 2% KOH and 92% H₂O (IPA –

isoproxide). After texturisation, the monocrystalline Si wafers with (100) surface orientation were covered by microscopic pyramids with (111) crystallographic planes.

3.3. Emitter formation

The n⁺-p junctions were made in conventional furnace at 900°C using a gas mixture of POCl₃, oxygen and nitrogen. Annealing for 15 min. resulted in the $40 \Omega/\text{sq}$ sheet resistance of the n⁺ layer and $0.5 \mu\text{m}$ depth of junction. Secondary ion mass spectroscopy profile of phosphorous atoms in the emitter n⁺ of solar cell is presented in the Fig. 3.

3.4. Passivation

In order to obtain high efficiency, it is necessary to reduce the surface recombination losses. The standard technique for the reduction of the surface state density at Si is the thermal oxidation. In the experiment the thin SiO₂ layer was created at 800°C for 10 min in dry oxygen.

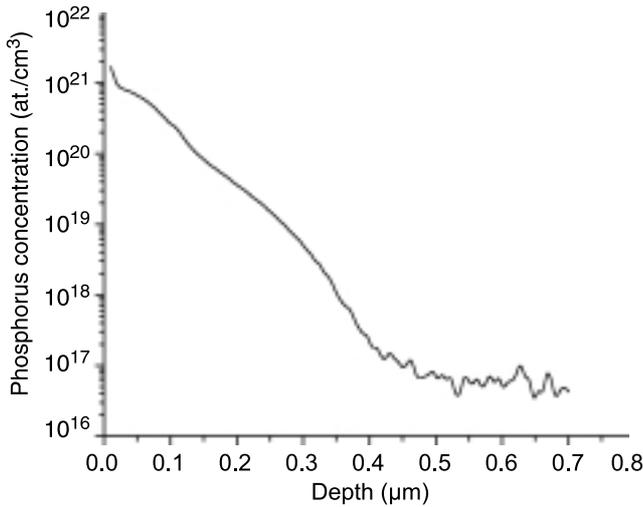


Fig. 3. Secondary ion mass spectroscopy (SIMS) profile of phosphorus atoms in emitter n^+ of solar cell.

3.5. Antireflection coating deposition

The TiO_x antireflection coating was deposited by spray-on of tetraethylorthotitanat ($(C_2H_5O)_4Ti$) compounds. Deposited at $300^\circ C$ for 5 seconds resulted in 80 nm thick layer. Figure 4 shows the reflectance from Si texturised surfaces with and without ARC TiO_x/SiO_2 layer.

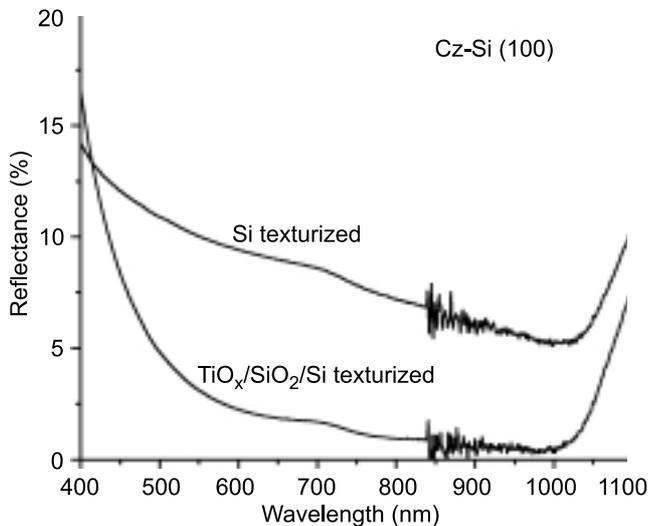


Fig. 4. Reflectance from texturised Si surface without and with the TiO_x ARC layer.

3.6. Metallisation

The front and rear contacts were deposited by the screen-printing method. Commercial Ag paste was used for the front and Al paste for the rear contact. After screening each side, pastes were dried by heating at $200^\circ C$ and subsequently fired at about $700^\circ C$ in infrared furnace (IR) for 30 seconds. The lines width of the finger was $150 \mu m$ and the

spacing between the metal fingers 2.5 mm . The coverage of the surface cell by grid contact was 7%.

4. Results of experiments

The electrical parameters of the typical solar cell are presented in Table 1. These parameters were obtained from I–V characteristics illuminated under AM1.5 (1 kW/m^2) and at $25^\circ C$. The parameters obtained by fitting I–V curve are shown in Table 2.

Table 1. Typical electrical parameters of monocrystalline Si 100 cm^2 cells.

ARC	I_{sc} (mA)	V_{oc} (mV)	FF (%)	E_{ff} (%)
TiO_x/SiO_2	3278	603	76.2	15.10

Table 2. The parameters obtained by approximation I–V characteristic by double exponential model for $A_1 = 1$ and $A_2 = 2$.

R_s (m Ω)	G_{sh} (S)	I_{s1} (A)	I_{s2} (A)	Stdev
7.8	0.022	1.84×10^{-10}	3.84×10^{-6}	3.9×10^{-5}

(Stdev is the standard deviation, G_{sh} is the shunt conductance, $G_{sh} = 1/R_{sh}$).

5. Analysis of results by PC1D simulation

The parameters of solar cell were calculated for silicon material with diffusion length of carriers $215 \mu m$ and $\tau = 20 \mu s$. The thickness of the wafers was $d = 300 \mu m$ and resistivity $\sigma = 1 \Omega \text{ cm}$. The simulation was carried out for the cells with the following parameters for ideal solar cell – reference cell (No. 1):

- Front and back surface recombination $S_n = S_p = 0 \text{ cm/s}$.
- Front surface reflectance = 0%.
- Shadow by top contact = 0%.
- Low doped emitter (LDE): $2 \times 10^{19} \text{ cm}^{-3}$, $x_j = 0.2 \mu m$, $400 \Omega/\text{sq}$.
- $R_s = 0 \Omega$, $G_{sh} = 0 \text{ S}$ (where $G_{sh} = 1/R_{sh}$).

Subsequently, next simulations of the cells (Nos. 2–8) were obtained including experimental data. For example, simulated cell No. 2 has emitter with a real profile of the dopant measured by SIMS method with resistance of the surface $R_s = 40 \Omega/\text{sq}$, surface concentration $N = 1 \times 10^{21} \text{ cm}^{-3}$ and depth of the junction $x_j = 0.5 \mu m$ (Fig. 3), cell No. 4 has the experimental reflectance from $TiO_x/SiO_2/Si$ (Fig. 4). The results of the simulation are presented in Table 1. It can be seen the influence of the different parameters (profile of the emitters, recombination of the front surface R_{front} , series R_s and shunt conductance G_{sh} , reflectance and shadow top surface by metallisation and the saturation current I_{s2}) on the parameters of a solar cell.

Table 3. Results of simulation by PC-1D.

No.	Emitter	R_{front} (cm/s)	R_s (m Ω)	G_{sh} (S)	I_{o2} (A)	Refl.	Shadow (%)	I_{sc} (mA)	V_{oc} (mV)	FF (%)	E_{ff} (%)
1	“LDE”	0	0	0	0	0	0	3902	627	83.4	20.4
2	real	0	0	0	0	0	0	3666	611	83.1	18.62
3	real	10^3	0	0	0	0	0	3653	610	83.1	18.53
4	real	10^3	0	0	0	TiO _x	0	3549	610	82.3	17.81
5	real	10^3	0	0	0	TiO _x	7	3293	608	82.9	16.60
6	real	10^3	7.8	0	0	TiO _x	7	3293	608	78.9	15.79
7	real	10^3	7.8	0.022	0	TiO _x	7	3293	608	78.6	15.73
8	real	10^3	7.8	0.022	3.84	TiO _x	7	3293	603	76.7	15.23
9	real	10^6	7.8	0.022	3.84	TiO _x	7	3245	601	76.7	14.97

It can be concluded from Table 3 that the profile of impurities in the emitter layer is the factor which reduces efficiency the most (8.7%). The second factor which has a significant effect on the efficiency value is a shadow top surface by the front contact which causes the reduction the current and efficiency by about 6.8%. The third factor is the series resistance (4.9%). There is some effect of the reflectance from the TiO_x/SiO₂/Si surface (3.9%) and recombination in the space charge region (3.3%) and shunt resistance (shunt conductance) which reduces the efficiency by 0.4%.

The parameters of the simulated cell No. 8 are very close to real parameters of a cell (Table 1). A small difference can be caused by measurement errors and absorption of the light in the TiO_x layer which was not taken into account.

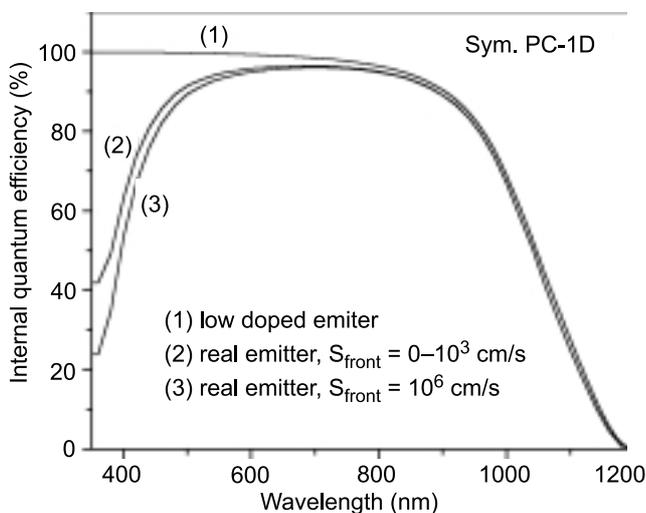


Fig. 5. Internal quantum efficiency of simulated cells by PC-1D.

The influence of the profile of the emitter on the short circuit current I_{sc} can be attributed to internal quantum efficiency curves simulated by PC-1D cells which are presented in Fig. 5.

Additionally, it can be seen that the curves are identical for the surface recombination in the period of 0– 10^3 cm/s. If this parameter has the value of 10^6 cm/s, which is appropriate for not passivated emitter, some reduction of IQE is also observed.

6. Conclusions

The typical efficiency of monocrystalline silicon solar cell was about 15%. This is considerably less than maximal theoretical value of 20% adequate for the medium quality of Si. It was found that the main factor which reduces the efficiency is the emitter profile of phosphorous dopant. The surface concentration of the phosphorous is too high and the junction is too profound. The second factor causing losses is a high shadow top surface by metallisation. To achieve higher efficiency close to 20%, cell design needs to evolve significantly and improvement in the fine-line screen-printing. Especially the width of the finger must be reduced and elaboration of selective emitter technique suitable for mass production is required.

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