Contribution to the optimization of n^+p type silicon solar cells photovoltaic parameters

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This study deals with n^+p type crystalline silicon solar cells performances using the Taguchi method in its optimum. We; then, discuss different physical parameters influence on photovoltaic material propreties.
Key words: solar cells, silicon, junction n^+p, conversion efficiency, Taguchi methodology, numeric simulation (PC1D)

I – Introduction

A variety of technologies are in competition for photovoltaic cells production (PV), however crystalline silicon has shown to be a dominant technology [1,2]. Nowadays, industrial priorities for high quality and lower investment cost require knowledge and quantification of every different physical material parameter influence level . Because of the great number of tests required, the classical method use is fastidious and time consuming. To overcome this problem we propose in this paper to use the Taguchi method in its optimum [3,4] to study n^+p type silicon solar cells performances with thickness W=300 m. Photovoltaic parameters calculation is obtained by means of the software PC1D [5,6], which solves the fully coupled time-dependent non-linear equations for the quasi-one-dimensional transport of electrons and the hole in crystalline semiconductor devices.

II - Methodology Taguchi

This method consists of carrying out a series of organized and reduced tests according to a well defined logic.

II-1 - Definition of features to study and of survey modes

The efficiency of a solar cell is deduced out of the three photovoltaic parameters: open-circuit voltage (Voc), short-circuit current (Isc) and fill factor (FF).

It is given by : = FF * Voc * Isc (1 / P_I)

and FF = P_{max} / (Voc * Isc)

P_I designates the incident power (P_I = 0.1 W/cm2 under illumination AM1,5G)

II-2 - Factors selection and their test values

We studied six material parameters influence on the efficiency conversion: Resistivity of substrate R_p , emitter sheet resistance R_{n+} , junction depth J , minority carrier diffusion length L_D , front-surface recombination velocity S_F and back-surface recombination velocity S_R .We took into consideration five levels for every material parameter.

Values to test are collected in the table 1:

Factor	L_D(µm)	R_{n+}(Ω/)	R_p(Ωcm)	J(µm)	S_F(cm/s)	S_R(cm/s)
Level 1	**50**	**50**	**0.1**	**0.1**	**10^3**	**10^3**
Level 2	**100**	**75**	**0.3**	**0.2**	**10^4**	**10^4**
Level 3	**150**	**100**	**0.5**	**0.3**	**10^5**	**10^5**
Level 4	**200**	**125**	**0.7**	**0.4**	**10^6**	**10^6**
Level 5	**250**	**150**	**1.0**	**0.5**	**10^7**	**10^7**

Table n°1

II-3 - Selection of the experience matrix to use

Having 6 factors, an experience scheme including 5 levels for every parameter and to study ideally all parameters influence in a precise way would require 5^6 (or 15625 tests). That's why we chose to use the reduced plans of Taguchi of type L_{25} (5^6) which require only 25 tests. The columns assignment is given in the following table n°2:

Factor	S_F	S_R	R_p	L_D	J	R_{n+}
Columns	1	2	3	4	5	6

Table n°2

II-4 - Tests results and factors middle effects calculation

While applying the formula of middle effect calculation:

With Y as the response of the pattern, and M the general average

Middle effect of factor A at the level i is: E_{Ai} = (Average of the Y when A is at the level i) - M

Effects of factors are collected in table 3:

Factors	S_F	S_R	R_p	L_D	J	R_{n+}
E_1	**0.984**	**0.224**	**0.104**	**-1.876**	**0.144**	**-0.036**
E_2	1.024	**-0.076**	0.304	**-0.116**	**0.004**	**-0.056**
E_3	**0.0284**	**-0.296**	**0.124**	**0.604**	0.264	**-0.236**
E_4	**-0.976**	**-0.116**	**-0.176**	**0.684**	**-0.136**	0.304
E_5	**-1.316**	0.264	**-0.356**	0.704	**-0.276**	**0.024**

Table n°3

II-5 - Results analysis and optimum configuration research

II-5-1 - The next matrix pattern Survey

η = M + [E_1 E_2 E_3 E_4 E_5] [S_F] + [E_1 E_2 E_3 E_4 E_5] [S_R] + [E_1 E_2 E_3 E_4 E_5] [R_p]
+ [E_1 E_2 E_3 E_4 E_5] [L_D] + [E_1 E_2 E_3 E_4 E_5] [J] + [E_1 E_2 E_3 E_4 E_5] [R_{n+}]

The efficiency general average is 16.656% and [A] as indicator of level of the factor A.

II-5-2 - Variance analysis

The squares sum of the factor A is: $S_A = (N/n_A) \sum(E_A)^2$

N is the number of tests in the experiences scheme; n_A is the number of factor A levels ; and E_A is the factor A effect.

$S_{Total} = \sum S_A + S_R$ with $S_{Total} = \sum(\eta_i - \eta_{avg})^2$ = 52.421 and $\sum S_A$ = 52.014 of or S_R = 0.407

To achieve a variance analysis we used a method called " regrouping " which consists of regrouping factors that apparently have no meaningful effects on residue (in our case it is the factor R_{n+} that has an S value of 0.765), since the residue has a null degree of freedom (ddl=n_A -1). We used Snedecor test test [7] to compare factor V_A variance and residual variance V_R . The test results are gathered in table 4.

Factor	S	ddl	Variance(V_A)=S/ddl	$F_{calculated}$(V_A/V_R)	$F_{theoretical}$	Significatif ?
S_F	**23.51**	**4**	**5.877**	**17.65**	**6.39**	**yes**
S_R	1.133	4	0.28	0.84	6.39	no
R_p	1.381	4	0.345	1.03	6.39	no
L_D	**24.30**	**4**	**6.075**	**18.24**	**6.39**	**yes**
J	0.925	4	0.231	0.69	6.39	no
Residue	1.332	4	0.333			

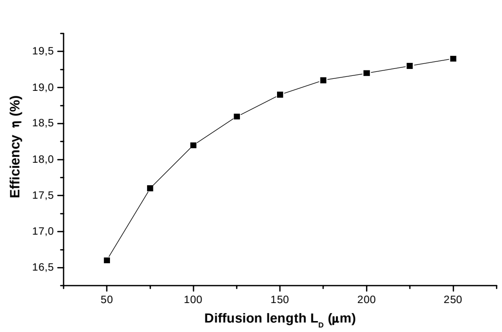
Table n°4 : Variance analysis

$F_{theoretical}(4,4)$ in this case is equal to 6.39 at a risk of 5% (Snedecor Table for p=0.95).

Table n°4 shows meaningful physical parameters (L_D and S_F) got by numeric simulation (PC1D), in photovoltaic efficiency conversion evolution.

The efficiency evolution according to L_D and S_F is shown in figures 1 and 2:

Fig n°1: Efficiency η as a function of diffusion length L_D



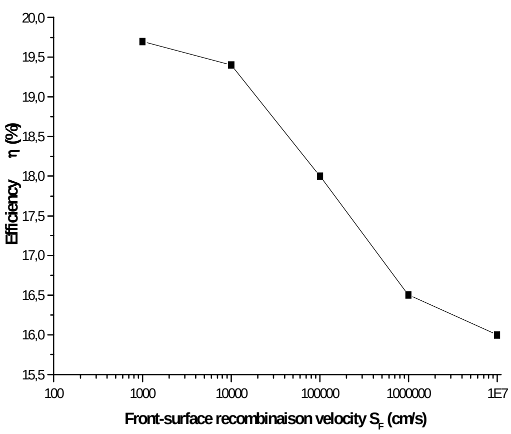


Fig n°2: Efficiency η as a function of S_F

This result confirms the importance of these parameters which is strongly related to crystal nature growth material technique (CZ "Czochralski " [8] that contains more defects than the FZ " Float Zone ") and the emitter realization technology.

II-6 - The pattern interpretation and confirmation test

The matrix pattern represents the system behaviouring to the grid nodes. In our case to have a maximum response, it is necessary to place factors so that the system response is maximized. We will get the maximum when the factors reach levels given in table 5:

Factors	S_F	S_R	R_p	L_D	J	R_{n+}
Levels	10^4	10^7	0.3	250	0.3	125

Table n° 5

The theoretical response of the pattern = 19.52%
It is necessary to make a confirmation test. If the response given by PC1D makes certain the hypothesis of the theoretical response, the result got by PC1D is:

Icc = 35 mA Voc = 652.2 mV
= 19.1 %
Our pattern is very satisfying (2.15% difference), the response is close to the predicted one, and interactions are probably null or very weak.
We can refine levels of factors while taking those of table n°6.

Factors	S_F	S_R	R_p	L_D	J	R_{n+}
Levels	10^4	10^7	0.2	250	0.3	115

Table n° 6

The photovoltaic parameters got from this configuration are:
Icc = 35 mA Voc = 660 mV
= 19.4 %
The corresponding characteristic I-V to this configuration is given in figure n° 3. It shows a nearly oblong behaviouring.

III - Physical Interpretation

On one hand, to increase solar cells performance, it is necessary to reduce the front-surface recombination velocity of the emitter S_F (figure 2) by the passivation method, while using, either deposition techniques of a thin oxide layer of 60 to 100 , or by defects neutralization techniques and the hanging binding of surface by hydrogenation.
The back-surface passivation is less important and only useful, if the minority carrier diffusion length (figure 1) is sufficiently big in relation to the substrate. On the other hand, it is necessary to achieve a junction superficial J 0.3 m and of

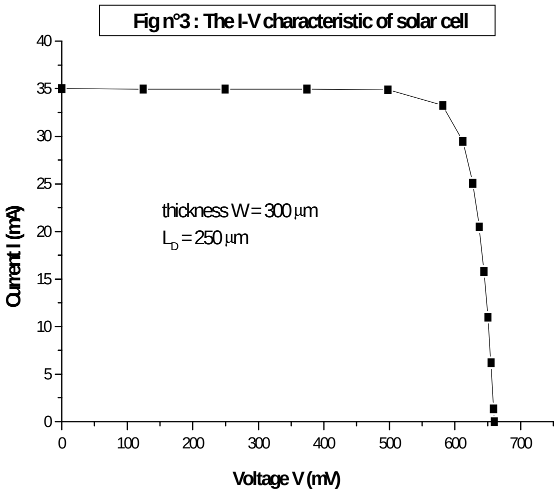


Fig n°3 : The I-V characteristic of solar cell

sheet resistance R_{n+} of 100 / , in order to reduce the surface recombination effect. In addition, the necessity to have a p-substrate of weak resistance R_p 0.3 cm.

IV – Conclusion

The objective of the Taguchi method use in this work was not only to improve the quality of solar cells; but also to reduce the manufacturing cost.

In this work, we showed that physical parameters are more decisive in photovoltaic parameter evolution than the minority carrier diffusion length (with 46.35% level influence) on the basis of the solar cells and the front-surface recombination velocity emitter (with 44.85% level influence).

At this stage, our work was concentrated on preparing the necessary tools to study solar cells optimization performance .

The different effects quantification of solar cells physical factors allows manufacturing engineers to have a clear and precise idea on the range and level of investment to engage for a new product manufacturing process.

V - Bibliography

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