Taguchi methodology for the optimization of n^+pp^+ type silicon solar photovoltaic conversion efficiency.

A.Habbou, H.Chaffoui, B.Hartiti

Laboratory of Material Physics and Applications of the Renewable Energies
FST of Mohammedia BP 146, 20630 Mohammedia, Morocco,
E-mail: habbouabder@yahoo.fr

This study deals with n^+pp^+ type crystalline silicon solar cells performances using the Taguchi method in its optimum. We; then, discuss physical parameters influence on efficiency solar cell, and also, we determine photovoltaic parameters of our structure by numeric simulation (PC1D).

Most previous work has used relatively low wafer resistivities (0.1-0.5Ωcm). The modeling in this work showed that high efficiencies could also be achieved with 1.0 Ωcm in the p-region and the flexibility in front junction depth and back junction depth.

Key words: Taguchi methodology, numeric simulation (PC1D), solar cells, silicon, wafer resistivities, n^+pp^+ structure, front junction depth, back junction depth, conversion efficiency.

I – INTRODUCTION

The photovoltaic cells production with crystalline silicon represents the most dominant technology [1,2] compared to other technologies (thin layers). 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 use of classical method 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^+pp^+ type silicon solar cells performances with thickness W=200 µm, with following characteristics: cell area of $1cm^2$, front surface textured with inverted pyramids (angle 54.74°), and rear surface no textured and antireflection layer is not used.

We studied material parameters influence on the efficiency conversion: Minority carrier diffusion length L_D, emitter sheet resistance R_{n+}, wafer resistivity R_p , back resistivity R_{p+} , front junction depth J_1 , back junction depth J_2 , front-surface recombination velocity S_F and back-surface recombination velocity S_R.

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.

Most previous work has used relatively low wafer resistivities (0.1-0.5Ωcm). The modeling in this work showed that high efficiencies could also be achieved with 1.0 Ωcm material.

II – TAGUCHI METHODOLOGY

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 (η) 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: $$\eta = FF \frac{Voc \ \ Isc}{P_I} \qquad (1)$$

P_I designates the incident power (P_I = 0.1 W/cm^2 under illumination AM1,5G) [7]

$$FF = \frac{P_{max}}{Voc \ \ Isc} \qquad (2)$$

II-2 – Factors selection and their test values

We studied eight material parameters influence on the efficiency conversion: Minority carrier diffusion length L_D, emitter sheet resistance R_{n+}, wafer resistivity R_p , back resistivity R_{p+} , front junction depth J_1 , back junction depth J_2 , front-surface recombination velocity S_F and back-surface recombination velocity S_R. We took into consideration two levels for every material parameter. Values to test are collected in the table 1:

Factor	L_D(µm)	R_{n+}(Ω/∂)	R_{p+}(Ω/∂)	R_p(Ωcm)	J_1(µm)	J_2(µm)	S_F(cm/s)	S_R(cm/s)
Level 1	150	50	50	0.1	0.1	0.1	10^2	10^2
Level 2	200	300	300	1.0	0.5	0.5	10^7	10^7

Table n°1 : Values to test of material parameters

II-3 – Selection of the experience matrix to use

The study of efficiencies of 8 factors each of them having two levels requires 2^8 in the traditional approach. That's why we chose to use the reduced plans of Taguchi of type L_{16} (resolution IV) which require only 16 tests. The columns assignment is given in the following table 2:

Factors	L_D	R_{p+}	R_p	J_2	J_1	R_{n+}	S_F	S_R
Columns	1	2	4	7	8	11	13	14

Table n°2: Reduced plan of Taguchi of type L16 (resolution IV)

Table of research of the interactions

The table n°3 was drawn up starting from the triangle of the interactions of the L_{16} table.

L_DR_{p+}	3	L_DR_p	5	$L_D J_2$	6	L_DJ_1	9	L_DR_{n+}	10	L_DS_F	12	L_DS_R	15
$R_{p+}R_p$	6	$R_{p+}J_2$	5	$R_{p+}J_1$	10	$R_{p+}R_{n+}$	9	$R_{p+}S_F$	15	$R_{p+}S_R$	12		
R_pJ_2	3	R_pJ_1	12	R_pR_{n+}	15	R_pS_F	9	R_pS_R	10				
J_2J_1	15	J_2R_{n+}	12	J_2S_F	10	J_2S_R	9						
J_1R_{n+}	3	J_1S_F	5	J_1S_R	6								
$R_{n+}S_F$	6	$R_{n+}S_R$	5										
S_FS_R	3												

Table n°3 : Triangle of the interactions of the L16 table

Alias table is given in the following table 4

In a resolution plan IV, the factors (order I) are alias with the order III interactions. Order II interactions are alias with other interactions of order II. Thus, we can consider that in a resolution plan IV, each factor is given without ambiguity (with the assumption that order III interactions are unimportant).

Action of the model	Columns	Alias
L_D	1	
R_{p+}	2	
R_p	4	
J_2	7	
J_1	8	
R_{n+}	11	

S_F	13	
S_R	14	
L_DR_{p+}	3	$R_pJ_2 + J_1R_{n+} + S_FS_R$
L_DR_p	5	$R_{p+}J_2 + J_1S_F + R_{n+}S_R$
$R_{p+}R_p$	6	$L_DJ_2 + J_1S_R + R_{n+}S_F$
J_2S_R	9	$L_DJ_1 + R_{p+}R_{n+} + R_pS_F$
L_DR_{n+}	10	$R_{p+}J_1 + R_pS_R + J_2S_F$
L_DS_F	12	$R_{p+}S_R + R_pJ_1 + J_2R_{n+}$
J_1J_2	15	$L_DS_R + R_{p+}S_F + R_pR_{n+}$

Table n°4: Alias table

II-4 – Tests results and factors middle effects calculation

While applying the formula of middle effect calculation:

With □ as the efficiency of the pattern, and η_{avg} the general average

Middle effect of factor A at the level I is:

E_{Ai} = (Average of the η when A is at the level i) – η_{avg} (3)

Interaction of factor A at level I and factor B at level j is:

I_{AiBj} = (Average of the η when A is at the level I and B at level j) – E_{Ai} –E_{Bj} – η_{avg} (4)

Effects of factors are collected in table 5:

Factor	L_D	R_{n+}	R_{p+}	R_p	J_1	J_2	S_F	S_R
E_1	-0.17	-0.05	-0.15	-0.03	-0.12	0.258	1.37	0.208
E_2	0.158	0.045	0.145	0.02	0.108	-0.27	-1.38	-0.22

Table n°5 : Effects of factors

Effects of interaction between factor A and factor B are:

$$I(L_D R_{p+}) = \begin{bmatrix} 0.015 & -0.005 \\ -0.013 & 0.017 \end{bmatrix} I(L_D R_p) = \begin{bmatrix} -0.355 & 0.37 \\ 0.37 & -0.358 \end{bmatrix}$$

$$I(R_{p+} R_p) = \begin{bmatrix} 0.05 & -0.05 \\ -0.045 & 0.055 \end{bmatrix} \quad I(J_2 S_R) = \begin{bmatrix} 0.004 & 0.007 \\ 0.007 & 0.006 \end{bmatrix}$$

$$I(L_D R_{n+}) = \begin{bmatrix} 0.24 & -0.23 \\ -0.238 & 0.242 \end{bmatrix} I(L_D S_F) = \begin{bmatrix} -0.08 & 0.095 \\ 0.095 & -0.083 \end{bmatrix}$$

$$I(J_1 J_2) = \begin{bmatrix} -0{,}568 & 0.585 \\ 0.585 & -0.568 \end{bmatrix}$$

II-5 – Results analysis and optimum configuration research

II-5-1 – The next matrix pattern Survey

$$\eta = \eta_{avg} + [E_1\ E_2]\,[L_D] + [E_1\ E_2]\,[R_{n+}] + [E_1\ E_2]\,[R_p] + [E_1\ E_2]\,[R_{p+}] + [E_1\ E_2]\,[J_1] + [E_1\ E_2]\,[J_2] + [E_1\ E_2]\,[S_F] + [E_1\ E_2]\,[S_R] + {}^t[L_D]\,[I_{AiBj}]\,[R_{p+}] + {}^t[L_D]\,[I_{AiBj}]\,[R_p] + {}^t[R_{p+}]\,[I_{AiBj}]\,[R_p] + {}^t[L_D]\,[I_{AiBj}]\,[R_{n+}] + {}^t[L_D]\,[I_{AiBj}]\,[S_F] + {}^t[J_1]\,[I_{AiBj}]\,[J_2] + {}^t[J_2]\,[I_{AiBj}]\,[S_R] \quad (5)$$

η_{avg} is the efficiency general means, [A] as indicator of level of the factor A and $[I_{AiBj}]$ as indicator of level of the interaction between factor A and factor B.

$$\eta_{avg} = \frac{1}{N}\sum_{i=1}^{N}\eta_i = 17.08\ \% \quad (6)$$

N is the number of tests in the experiences scheme (N = 16).

First case: only the 1st order actions are considered. In this case, we take no account of interactions between factor A and factor B. It is simply to take the highest points effects of the factor, so that the theoretical efficiency of the pattern is maximized: $\eta = 19.4\ \%$

Second case: interactions are considered. When, we take account of interactions. We add the I_{AiBj} element of matrix that haves the highest value, the result got by the matrix model is: $\eta_{model} = 20.73\ \%$

II-5-2 – Variance analysis

The squares sum of the factor A is:

$$S_A = (N/n_A)\sum (E_A)^2 \quad (7)$$

The squares sum of the interaction factor A and factor B is: $S_{AB} = (N/(n_A n_B))\sum (I_{AiBj})^2$ (8)

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.

$$S_{Total} = \sum S_A + \sum S_{AB} + S_{Residue} \quad (9)$$

with $S_{Total} = \sum_{i=1}^{16} (\sum_i - \sum_{avg})^2 = 41.62$ (10)

and $\sum S_A + \sum S_{AB} = 40.02$ (11)

of or $S_{Residue} = S_{Total} - \sum S_A - \sum S_{AB} = 1.6$ (12)

$S_{Residue}$ is the residue squares sum.

The squares sum of the factor and the interaction are collected in table 6:

Factor	L_D	R_{n+}	R_{p+}	R_p	J_1	J_2	S_F	S_R
S_A	0.430	0.036	0.348	0.01	0.184	1.116	30.25	0.733
Interaction	$L_D R_{p+}$	$L_D R_p$	$R_{p+} R_p$	$J_2 S_R$	$L_D R_{n+}$	$L_D S_F$	$J_1 J_2$	
S_{AB}	0.00018	0.579	0.0402	0.00085	0.902	0.123	5.267	

Table n°6: Squares sum of the factor and the interaction

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_p , R_{n+} , R_{p+},

J_1 also interactions L_DR_{p+} , $R_{p+}R_p$, L_DS_F and J_2S_R), since the residue has a null degree of freedom (ddl=n_A-1). We used Snedecor test [8] to compare factor V_A variance and residual variance V_R. The test results are gathered in table 7.

Factor	S	ddl	Variance(V_A)=S/ddl	$F_{calculated}(V_A/V_R)$	$F_{theoretical}$	Significant ?
L_D	0.430	1	0.430	1.65	5.12	no
J_2	1.116	1	1.116	4.29	5.12	no
S_F	30.25	1	30.25	116.35	5.12	yes
S_R	0.733	1	0.733	2.82	5.12	no
L_DR_p	0.579	1	0.579	2.23	5.12	no
L_DR_{n+}	0.902	1	0.902	3.45	5.12	no
J_1J_2	5.267	1	5.267	20.26	5.12	yes
Residue	2.34	9	0.26			
S_{Total}	41.62	16				

Table n°7: Variance analysis

$F_{theoretical}(1,9)$ in this case is equal to 5.12 at a risk of 5% (Snedecor Table for p=0.95).
The variance analysis showed that the factor S_F and interaction J_1J_2 are most significant. Don't forget that the interaction J_1J_2 is alias with interactions L_DS_R, $R_{p+}S_F$ and R_pR_{n+}.

II-6- The pattern interpretation and confirmation test

The matrix pattern represents the system behavior to the grid nodes. In our case to have a maximum efficiency, it is necessary to place factors so that the system response is maximized.
First case: only the 1st order actions are considered

We will get the maximum when the factors reach levels given in table 8:

Factor	L_D(µm)	R_{n+}(Ω/ ð)	R_{p+}(Ω/ð)	R_p(Ωcm)	J_1(µm)	J_2(µm)	S_F(cm/s)	S_R(cm/s)
Levels	200	300	300	1.0	0.5	0.1	10^2	10^2

Table n°8 : Factors levels for the maximum of the efficiency (interactions not considered)

Second case: interactions are considered

The I_{AiBj} element of matrix that have the highest value, which determine I or j level of factor. We deduce the following elements from previously calculated matrix:
$(L_DR_{p+})_{22}$, $(L_DR_p)_{21}$, $(R_{p+}R_p)_{22}$, $(J_2S_R)_{21}$, $(L_DR_{n+})_{22}$, $(L_DS_F)_{21}$ and $(J_1J_2)_{12}$ or $(J_1J_2)_{21}$.
In this case incompatibilities exist with the results previously found. The interaction; then, compensates the factor effect. It is the case of the interaction L_DR_p which maximizes the efficiency when L_D = 200 µm and R_p = 0.1 Ωcm, whereas while considering only the principal effects we had L_D = 200 µm and R_p = 1.0 Ωcm. It is the same way in the case of J_1J_2 interaction which maximizes the efficiency when J_1 = 0.1 µm and J_2 = 0.5 µm or J_1 = 0.5 µm and J_2 = 0.1 µm, whereas while considering only the principal effects we had J_1 = 0.5 µm and J_2 = 0.1 µm. But in the case of the interaction $R_{p+}R_p$ which maximizes the efficiency when R_{p+} = 300 Ω/ **ð** and R_p = 1.0 Ωcm, this is the same result when only the 1st order actions are considered.
The analysis objective is to maximize the efficiency. To do so, it is necessary to make a total optimization while being based on the factors effects, interactions and matrix model.
The study of the matrix model gives us indeed the total optimum since the interaction J_1J_2 is more important regarding the effects factors of the J_1 and J_2; while being based on variance analysis, which raise the incompatibility mentioned previously.

The maximum of the efficiency is obtained for the following configurations:

Factor	L_D(µm)	R_{n+}(Ω/ ð)	R_{p+}(Ω/ ð)	R_p(Ωcm)	J_1(µm)	J_2(µm)	S_F(cm/s)	S_R(cm/s)
Configuration1	200	300	300	0.1	0.1	0.5	10^2	10^2
Configuration2	200	300	300	0.1	0.5	0.1	10^2	10^2

Table n°9: Factors levels for the maximum of the efficiency (interactions are considered)

It is necessary to make a confirmation test. If the efficiency given by PC1D makes certain the hypothesis of the theoretical efficiency, the result got by PC1D is:

$\eta_{(PC1D)}$ = 21 % for configuration 1 and $\eta_{(PC1D)}$ = 21.2 % for configuration 2
The theoretical efficiency of the pattern is: η_{model} = 20.68 % for the two configurations.

Our pattern is very satisfying, the efficiency is close to the predicted one.

In our model the maximum of the efficiency η_{model} =20.73% is obtained for the following configuration:

Factor	$L_D(\mu m)$	$R_{n+}(\Omega/\delta)$	$R_{p+}(\Omega/\delta)$	$R_p(\Omega cm)$	$J_1(\mu m)$	$J_2(\mu m)$	S_F(cm/s)	S_R(cm/s)
Configuration	200	300	300	1.0	0.1	0.5	10^2	10^2

Table n°10: Factors levels for the maximum of the efficiency in our model

The photovoltaic parameters got from these configurations are:

	Icc(mA)	Voc(mV)	$\eta_{(PC1D)}$	η_{model}
Configuration 1	35.9	692.1	21 %	20.68%
Configuration 2	35.7	702.9	21.2 %	20.68%

Table n°11: Photovoltaic parameters

The corresponding characteristic I-V to these configurations is given in figure n°1. It shows a nearly oblong behavior.

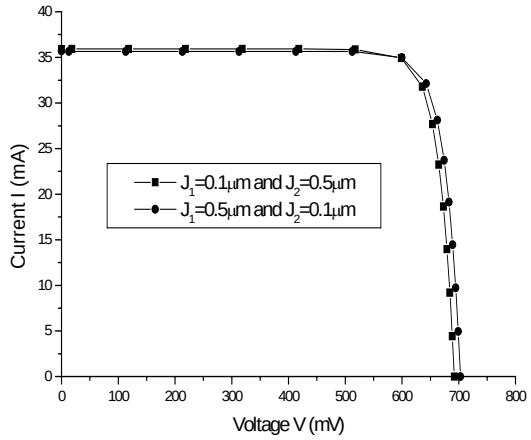

Figure n°1: Characteristic Current-Voltage for n^+pp^+ cell with thickness W=200µm, diffusion length L_D=200µm, 0.1Ωcm wafer resistivitiy,300Ω/ð emitter sheet resistance R_{n+} and 300Ω/ð back resistivity R_{p+}.

III – RESULTS AND DISCUSSION

III-1 Effect of wafer resistivitie

Two different values of base doping concentration in the p-region are taken. They are 2.3 10^{17} cm^{-3} (0.1 Ωcm) and 1.5 10^{16} cm^{-3} (1.0 Ωcm). The modelling in this work showed that the difference in efficiency between the two different values of wafer resistivities, was very weak. We have η_{model} = 20.68% and 20.73% for 0.1 Ωcm and 1.0 Ωcm respectively, as show in values of middle effect of factor E (Rp=0.1 Ωcm)=-0.03 and E (Rp=1.0 Ωcm)=0.02. We can conclude, that high efficiencies could also achieve with 1.0 Ωcm material. The present results concur well with result of Catchpole et al [9] for a passivated emitter and rear cell (PERC) structure.

III-2 Effect of Back Surface Field

The efficiency improvement achievable through the use Back surface Field of n^+pp^+ structure was significant. The improvement was 1.63% absolute from 19.1% of n^+p structure [10] to 20.73% n^+pp^+ structure. So that, the back surface doping concentration of n^+pp^+ cell is more high than the base doping concentration in the p-region, of the sort than the minority carriers would be send back and than the effective recombination would be very weak.

The variance factor S_R (back-surface recombination velocity) is not significant, because the minority carriers diffusion length L_D=200µm in the base is not sufficiently large compared to the substrate W= 200µm. But the variance factor S_F (front-surface recombination velocity) is very significant (with 72 % level influence). So that, to increase solar cells performance, it is necessary to reduce the front-surface recombination velocity of the emitter S_F by the passivation method [11] , while using, either deposition techniques of a thin oxide layer of 60 to 100Å, or by defects neutralization techniques and the hanging binding of surface by hydrogenation.

III- 3 Effect of interaction J_1J_2.

Two different widths 0.1µm and 0.5µm were used for each junction (front junction J_1 and back junction J_2). The effect of interaction between factor J_1 and factor J_2 showed that $I(J_1J_2)_{12}$ is equal to $I(J_1J_2)_{21}$, then we have the same efficiency in two cases [(J_1=0.1µm,J_2=0.5µm) and (J_1=0.5µm,J_2=0.1µm)]. From this result, we can conclude that pattern interpretation gives flexibility in the cell design.

III-4 Comparison with PERC and PERL (see table n°12)

The best laboratory efficiency for single crystal silicon is today 24.7% [12]. This efficiency can only be realized with very elaborate technology.

	n^+pp^+(this work)	PERC [9]	PERL [12]
Textured frond surface	yes	Yes	yes
Textured rear surface	no	Yes	yes
Antireflection coating	no	Yes	yes
Efficiency η %	21.2	21.8	24.7

Table n°12

The efficiency difference is 3.5% absolute for our cell and Passivated Emitter and Rear Locally diffused (PERL) cell structure, this difference is attributed to the local p^+-doped BSF (back surface field) in PERL structure. And also the program PC1D has not the possibility to create a layer with the local p^+-doped.

If we compare our work with PERC cell structure, the difference in efficiency is small (0.6% absolute), although we have not used antireflection coating layer and textured rear surface. It's absolutely certain that the combination of textured surface and antireflection coating contributed to improving efficiency.

IV- CONCLUSION

On one hand, the efficiency of n^+pp^+ structure is always higher than its conventional n^+p solar cell due to the back surface field. On the other hand, the Taguchi method used this work showed that n^+pp^+ structure allows a large degree of flexibility in cell designing and manufacturing for two reasons. The first is that high efficiency could also be achieved with 1.0 Ωcm material. The second then there is little difference in the efficiencies for both cases [(J_1=0.1μm,J_2=0.5μm) and (J_1=0.5μm,J_2=0.1μm)]. From these results, we can conclude that the Taguchi method allows manufacturing engineers to have the flexibility in cell designing.

V – References

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