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Simulated multi-crystalline silicon solar cells with aluminum back surface field

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ABSTRACT

In photovoltaic solar cells manufacturing, we are confronted to the perpetual challenge for conversion efficiency enhancing.

We propose in this work to quantify the back surface field aluminium (Al-BSF) rear contact effect deposited by screen printing metallization.

Al-BSF numerical simulation has been performed by the use of softwares dedicated to photovoltaic like PC1D, SCAPS 2.7 and AFORS-HET.

In this work, a SiN_x/Si(n^+)/ Si(p)/Si(p^+) structure is studied. This means that we have a classical junction np passivated at the front face with SiNx anti-reflective coating (ARC) and at the rear face a screen printed Aluminum contact.

The back Al-BSF, must to be thick (no least 10µm) and highly p-doped (holes concentration between 10^{18} and 10^{19} cm^{-3}) in order to reduce effective rear recombination velocity, yielding to an enhancement of the Al layer performance.

Were inserted in the software parameters data: the lifetime measured for the inner bulk (τ_n=30 µs and τ_p=90 µs) with Al diffusion (10.8 µm deep).

For emitter doping equals to $1.5*10^{20}$ cm^{-3}, front surface recombination velocity S_f=8600 cm/s and the effective minority diffusion length L_{eff}=227 µm.

After simulation of the input parameters, an efficiency of 18.0% is obtained by PC1D, in good accordance with the results presented in the literature. While the obtained efficiencies results with AFORS-HET and SCAPS 2.7 are 17.15% and 18.73% respectively. A rapprochement occurs between PC1D and SCAPS quantum efficiency curves with begin values ~ 70% QE while AFORS-HET is so far with ~ 34% QE.

KEYWORDS

Solar cells;
Multi-crystalline silicon;
BSF;
PC1D;
SCAPS;
AFORS-HET;
Aluminium.

INTRODUCTION

Multi-crystalline silicon solar cells represent an unavoidable alternative to mono-crystalline silicon for large scale industrial fabrication[1,2]. However, multi-crystalline silicon properties are really different than mono-crystalline Czochralski (CZ) or Float zone (FZ) silicon growth. This is due essentially to the grain boundary

presence which reduces the diffusion length and enhances the defects concentration.

Aluminum is generally used as back contact in photovoltaic cells thanks to its properties. It creates a heavily doped p^+ region that provides a good (low resistivity) ohmic contact on the p-type silicon forming a back surface field[3]. As we know, the eutectic point of Al-Si diagram occurs at T_E=577°C and its melting point is 660°C. In solar cells technology, we work at temperatures higher than the eutectic point and the melting point of aluminium. So, during the heating process, silicon dissolves in aluminium for $T<T_E$ and continues to dissolve for $T>T_E$. While in the cooling process, the silicon quantity exceeding the eutectic composition will form the well known p^+ BSF layer. Its thickness is of about 10µm.

A highly doped BSF permits to reduce the back recombination velocity at the contact metal-semiconductor. But very high doping exceeding 5.10^{19} may have the inverse effect[4].

In this work, we propose to simulate a BSF in the multi-crystalline silicon structure $SiN_x/Si(n^+)/Si(p)/Si(p^+)$ by the employment of three main photovoltaic dedicated softwares such: PC1D version 5.9, SCAPS version 2.7 and AFORS-HET version 2.2.

PC-1D program solves the nonlinear equations of quasi one-dimensional transport of electrons and holes in semiconductor devices, including photovoltaic devices in one dimension by using the finite element method[5]. While SCAPS-1D program solves the equations for structures containing a number of semiconductor layers which have an arbitrary doping profile (as a function of the position) with an arbitrary distribution of energy levels deep donors or acceptors in different types of illumination. Iterations resolutions equations are made until algorithm convergence[6,7].

AFORS-HET allows to model homo-as well as hetero-junction devices. An arbitrary sequence of semiconducting layers can be modelled. A variety of boundary conditions can be chosen. The program solves the one dimensional semiconductor equations in steady-state and for a small sinusoidal ac-perturbation[8].

DEVICE MODELLING

The structure to model is composed of multi-crystalline silicon wafer type p which undergoes phosphorus diffusion at the front face in order to create a n^+/p junction. In our case, we will insert the real technological parameters used in our laboratory such a junction depth of 0.7µm and $1.85\ 10^{20}$ cm^{-3} electrons concentration. A passivated and ARC layer of SiN_X (thickness: 79 nm and refractive index 2) is deposited. The rear contact forms a BSF by creating the junction P^+/P. Figure 1 below illustrates the modelled structure $SiN_x/Si(n^+)/Si(p)/Si(p^+)$.

In industrial solar cells covered with screen printed aluminum, forming an Al-BSF, the rear contact has a back reflectance of 65% and a back recombination velocity (BSRV) of 1000 cm/s on 1Ωcm silicon wafer[9].

The back Al-BSF must to be thick (no least 10µm)[10] and highly doped (holes concentration p between 10^{18} and 10^{19} cm^{-3}) in order to reduce effective rear recombination velocity[11], yielding to an enhancement of the Al layer performance.

We insert for Al-BSF layers the lifetime measured for the inner bulk (τ_n=30 µs and τ_p=90 µs) for multi-crystalline silicon cells with Aluminum diffusion of 10.8 µm in depth[12]. TABLE 1 resumes the input data used for modeling the multi-crystalline BSF structure.

TABLE 1 : Input data for PC1D, SCAPS and AFORS-HET.

Device	
Device area	**1cm²**
Single layer Anti-reflective coating[13] Front reflexion	n=2.0 t=79nm
ABSORBER REGION	
Thickness	280µm[14]
Material	From Si.mat
Dielectric constant	11.9
Band gap	1.124 eV
Intrinsic concentration at 300K	1E10 cm^{-3}
Refractive index	3.58
Absorption coefficient	From internal model
Free carrier absorption	enabled
P-type background doping	1E16
Front diffusion	N-type 1.85E20 junction n/p=0.7µm
1st rear diffusion	P-type 1E19 junction p+/p=10µm
Bulk recombination	τ_n=30µs, τ_p=90µs
Front surface recombination	$S_n=S_p$=8600 cm/s[15]
Rear surface recombination	$S_n=S_p$=1000 cm/s[9]
Excitation	
Excitation from	One-sun AM1.5
Constant intensity	0.1 Wcm^{-2}

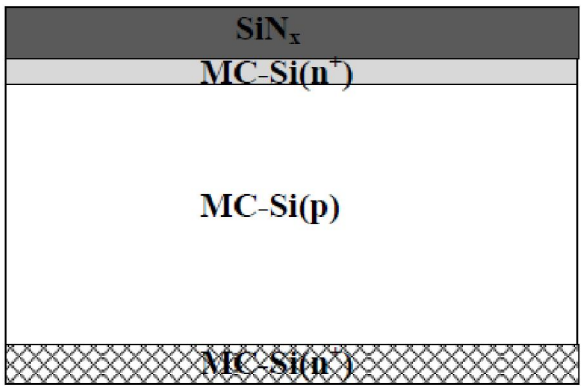

Figure 1 : SiN_x/Si(n⁺)/ Si(p)/Si(p⁺) multi-crystalline silicon based solar cell proposed to simulation.

RESULTS & DISCUSSION

After inserting the input parameters of the structure SiN_x/Si(n⁺)/ Si(p)/Si(p⁺). The obtained results I(V) and quantum efficiency curves are represented in Figure 2, Figure 3 and Figure 4 for PC1D, SCAPS and AFORS-HET.

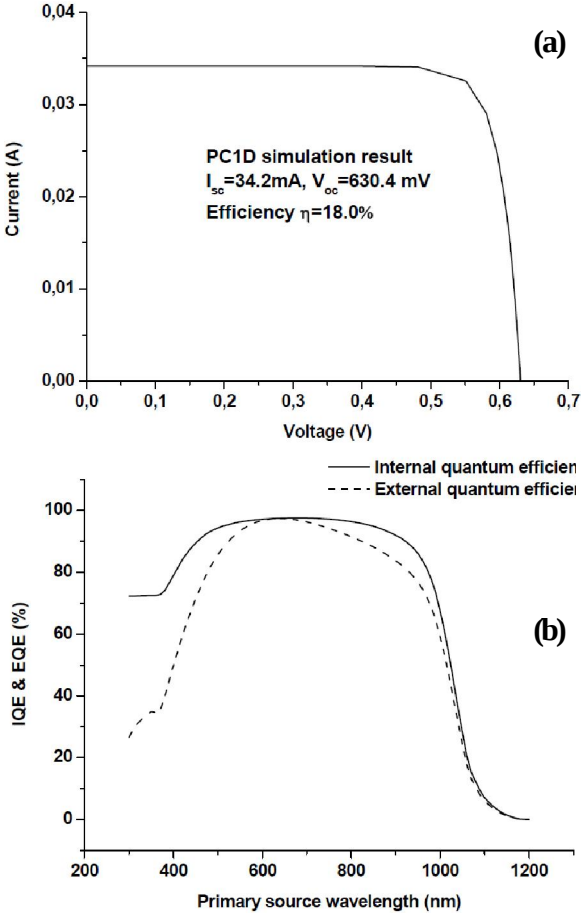

Figure 2 : PC1D 5.9 simulation results for SiN_x/Si(n⁺)/ Si(p)/ Si(p⁺) : (a) I(V), (b) quantum efficiency.

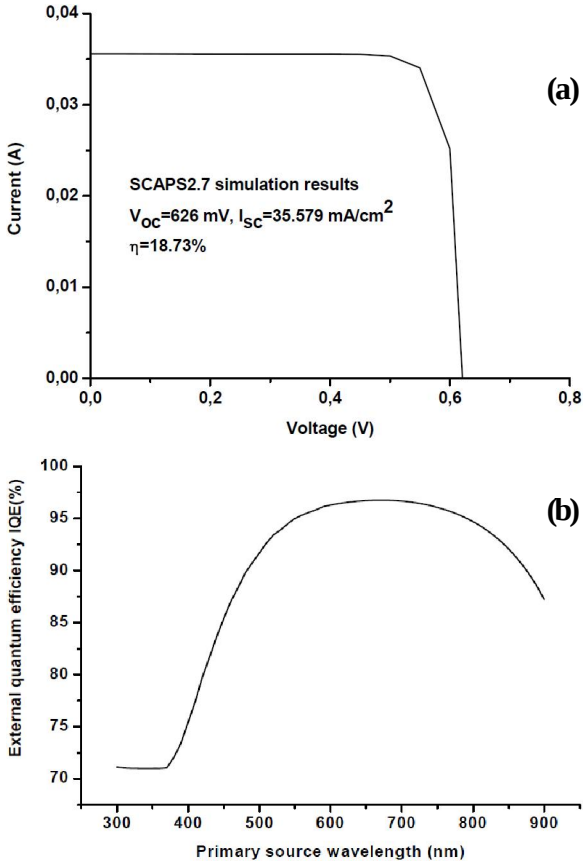

Figure 3 : SCAPS 2.7 simulation results for SiN_x/Si(n⁺)/ Si(p)/Si(p⁺) : (a) I(V), (b) quantum efficiency.

The obtained results are summarized in the TABLE 2 below:

Conventional structures without BSF give a conversion efficiency around 14%, as developed by Van Sark et al.[16].

It is so therefore clear that a structure with BSF increases the conversion efficiency until reaching 17 to 18% depending on the used software.

The question that arises: why is there a difference in the results depending on the software?

For PC1D, an efficiency of 18% was obtained while SCAPS give us 18.73% and AFORS-HET 17.15%. Concerning the quantum efficiency, as represented in Figures 2b, 3b and 3c, one can remark that the curves have the same shape but for:

- PC1D, the first level occurs at approximately 350nm with 72.4% QE and reaches a maximum at 97.51% for 1060nm.
- SCAPS, the first level occurs at approximately 350nm with 71.0% QE and reaches a maximum at 96.71% for 900nm.

- AFORS-HET, the first level occurs at approximately 350nm with 34% QE and reaches a maximum at 98% for 1100nm.

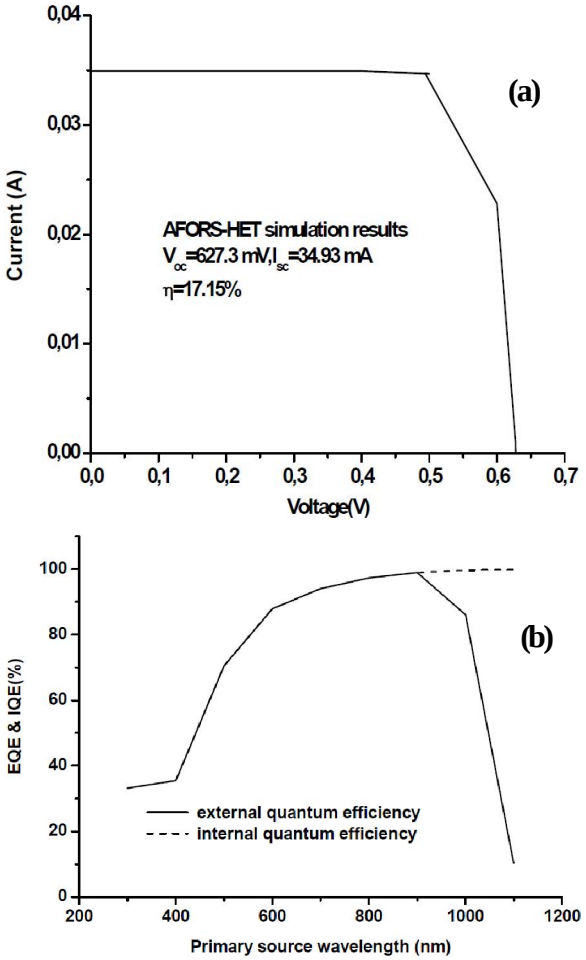

Figure 4 : AFORS-HET simulation results for SiN_x/Si(n^+)/ Si(p)/Si(p^+) : (a) I(V), (b) quantum efficiency.

TABLE 2 : SiN_x/Si(n^+)/ Si(p)/Si(p^+) simulation results summary by using PC1D, SCAPS and AFORS-HET.

Software	Voc (mV)	Isc (mA)	FF (%)	η (%)
Without BSF[16]	602.8	31.19	77.07	14.19
PC1D	630.4	34.2	83.48	18.00
SCAPS 2.7	626	35.57	84.05	18.73
AFORS-HET	627.3	34.93	78.25	17.15

We remark a rapprochement between PC1D and SCAPS quantum efficiency curves with begin values ~ 70% QE while AFORS-HET is so far with ~ 34% QE.

The PC1D is mainly dedicated to silicon. It is well suitable for our structure to simulate. The obtained values coincide with the literature[14]. But don't take into account the deep interface states and profound bulk states like in AFORS- HET and SCAPS[17].

While the recent version 2.7 of SCAPS treat thick substrates and therefore is suitable to our problem. But with a limit for the high degeneracy at the front junction to 10^{20} cm^{-3}. So our value $1.85*10^{20}$ can not be taken into consideration.

Regarding to AFORS-HET, it is obvious that it is rather dedicated to hetero-junction structures like HIT layers and thin films than our kind of homo-junction with thick substrate.

CONCLUSION

Multi-crystalline silicon solar cells with back surface field BSF and SiN_x anti-reflective coating have been simulated by using photovoltaic dedicated softwares.

Three programs have been employed: PC1D; SCAPS and AFORS-HET.

By combining the experimental values with those obtained in the literature, an input data table for BSF multi-crystalline silicon has been formed.

The obtained conversion efficiencies are: 18%, 18.73% and 17.15% for PC1D, SCAPS and AFORS-HET respectively.

PC1D and SCAPS quantum efficiency curves converge with begin values ~ 70% QE while AFORS-HET is so far with ~ 34% QE.

One can deduce that PC1D is the most suitable software for silicon. While the recent version 2.7 of SCAPS treats thick substrates but has a limit for the high degeneracy electron concentration.

AFORS-HET is the non adaptable software for our BSF structure because it is dedicated to hetero-junction structures like HIT layers and thin films than our kind of homo-junction with thick substrate.

In conclusion, simulation with PC1D and SCAPS are more suitable to the structure SiN_x/Si(n^+)/ Si(p)/ Si(p^+) than afors-Het.

The BSF is a significant parameter in increasing the conversion efficiency of solar cells based on multi-crystalline silicon. It requires a finer thickness of silicon wafer which should be greater than 200μm for a good substrate quality[18].

Experimentally, the BSF is easily integrated into the multi-crystalline silicon solar cells fabrication process, since simultaneous annealing for Ag and Al contacts and SiN_x passivation can be done[19].

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