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/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 Aluminium 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_{eeff}=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.

INTRODUCTION

Multi-crystalline silicon solar cells represent an unavoidable alternative to mono-crystalline silicon for large scale industrial fabrication[12]. 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
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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 $T_E = 577\, ^\circ C$ and its melting point is $660\, ^\circ C$. In solar cells technology, we work at temperatures higher than the eutectic point and the melting point of aluminum. So, during the heating process, silicon dissolves in aluminum 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 $5 \times 10^{19}$ 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 as a junction depth of 0.7µm and $1.85 \times 10^{19}$ 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 ($\tau_n = 30\, \mu s$ and $\tau_p = 90\, \mu s$) for multi-crystalline silicon cells with Aluminum diffusion of 10.8 µm in depth[12]. TABLE 1 resumes the input data used for modelling the multi-crystalline BSF structure.

<table>
<thead>
<tr>
<th>Device</th>
<th>Device area</th>
<th>1cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single layer Anti-reflective coating[13]</td>
<td>n=2.0 t=79nm</td>
<td></td>
</tr>
</tbody>
</table>

#### ABSORBER REGION

| Thickness | 280µm[14] | Material | From Si.mat |
| 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 | P-type 1E19 junction p+/p=10µm |
| Bulk recombination | $\tau_n = 30\, \mu s$, $\tau_p = 90\, \mu s$ | Front surface recombination | $S_n=S_p=8600$ cm$^{-2}$/s[15] |
| Rear surface recombination | $S_n=S_p=1000$ cm$^{-2}$/s[9] |

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

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

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.$^{[19]}$
REFERENCES


